Jacobs

Humber 2100+

Extreme Water Levels

ENV0000300C-CH2-ZZ-3A0-RP-HY-0010 | C03

20 November 2020

Environment Agency

Project Delivery Partners

Jacobs

Humber 2100+

Project No:	692947CH
Document Title:	Extreme Water Levels
Document No.:	ENV0000300C-CH2-ZZ-3A0-RP-HY-0010
Revision:	C03
Document Status:	Final
Date:	20 November 2020
Client Name:	Environment Agency
Project Manager:	Stephen Pimperton
Author:	Chris Weeks / Robert Bird (JACOBS)
File Name:	ENV0000300C-CH2-ZZ-3A0-RP-HY-0010.docx

Jacobs Consultancy Ltd.

1 City Walk
Leeds, West Yorkshire LS11 9DX
United Kingdom
T +44 (0)113 242 6771
F +44 (0)113 389 1389
[redacted]

Project delivery partners

Jacobs is the lead supplier for the delivery of the Humber 2100+ Strategy. Key elements of the project are being delivered by our principle project delivery partners Arup and HR Wallingford.

Company	Contact Name	Address	Telephone
Arup	Louise Parry	Admiral House, 78 East Street, Leeds, West Yorkshire, LS9 8EE, United Kingdom	[redacted]
HR Wallingford	Caroline Hazlewood	Howbery Park, Wallingford, Oxfordshire, OX10 8BA, United Kingdom	[redacted]

Document history and status

Revision	Date	Description	Author	Checked	Reviewed	Approved
P01	06/03/20	Draft for comment	CW/RB	AP	RC	SP
P02	09/10/20	Finalised following addressing client comments to version P01 and updated modelling	CW	RB	AP	SP
C03	20/11/20	Final Version	CW	RB	AP	SP

Contents

Glossary

Annual Exceedance Probability (AEP) – probability of exceeding a specified flow or level in any year. For example, 1% AEP flood has a 1% chance of being exceeded in any year.

Astronomic tide – tidal levels resulting from gravitational effects (Earth, Sun and Moon).

Boundary conditions – used in this report to refer to the (upstream) fluvial inflow time series and (downstream) sea level time series (astronomic tide plus surge) that are the primary hydraulic forcing variables controlling still water levels within the Humber estuary and the tidal rivers.

Dependency - the extent to which one variable depends on another variable. Ranges from fully dependent to fully independent. The method described in this report uses the dependence measure χ (chi) to define the degree of dependence.

Extreme – unusually high water levels or waves caused by severe weather, more formally defined using AEPs.

EWL – extreme water level

FD2308 – used in this report to signify the 'desk study' approach described in the Defra/Environment Agency, 2005, R&D Technical Report 'Joint probability: Dependence mapping and best practice: Technical report on dependence mapping', FD2308/TR1 (also referenced as HR Wallingford SR Report SR623).

Joint probability (JP) – probability of two or more conditions occurring at the same time. For example, the probability of specific wave heights occurring at the same time as specific water levels.

JP scenario – used in this report to mean sets of boundary conditions that can all result in the same JP.

Marginal extreme or probability – probability of a flow or level occurring unconditional on any other event.

Still water level – water level resulting from astronomic tides, surge and/or fluvial flows, but without the influence of waves.

Surge – change in sea level caused by a storm (high winds and low pressure).

Uncertainty – a measure of our confidence in a specific value. Can be considered to consist of our knowledge uncertainty (caused by limitations in method, equation, model or data) and natural variability (uncertainties arising from the inherent randomness and basic unpredictability in the natural world).

1. Introduction

1.1 Background

The target audience for this report is technical specialists working for the Environment Agency with knowledge of the Humber and the Humber 2100+ project. While it may also be useful for other readers, technical language and method descriptions are used that assume an appropriate level of technical knowledge.

The Humber 2100+ project is being undertaken by a partnership between the Environment Agency, the 12 Local Authorities from around the Humber and the Humber Local Enterprise Partnership (LEP), to develop a new strategic approach to tidal flood risk management around the estuary over the next 100 years. A sound understanding of estuarine processes and associated flood risk on the tidal floodplain around the Humber estuary and the tidal rivers is required to provide key evidence to underpin the new strategy.

Extreme still water levels, together with wave extremes in parts of the Estuary, are important for many aspects of flood risk management in the Humber study area (Figure 1.1). Depending on location, the extremes can be a result of multiple driving conditions, such as tide, surge, fluvial flows, wind and wave effects. The term 'extremes' means the maximum value of water level, wave height etc, more formally defined using Annual Exceedance Probabilities (AEP).

There have been numerous previous studies of extremes in the study area (summarised in chapter 1.2). However, none of these previous studies provides up to date outputs that fully meet the needs of the Humber 2100+ study or the wider needs of the Environment Agency and partner organisations.

This report describes the work undertaken to provide the first consistent modelled set of extreme water levels (EWL) for the whole study area. The modelling approach adopted will allow the extreme water levels to be easily updated to represent interventions changes to defences and changes to climate change guidance.

There are a number of assumptions and limitations with the approach to deriving extreme water levels, which need to be considered when using the outputs. The key assumptions/limitations are discussed in chapter 8.2.

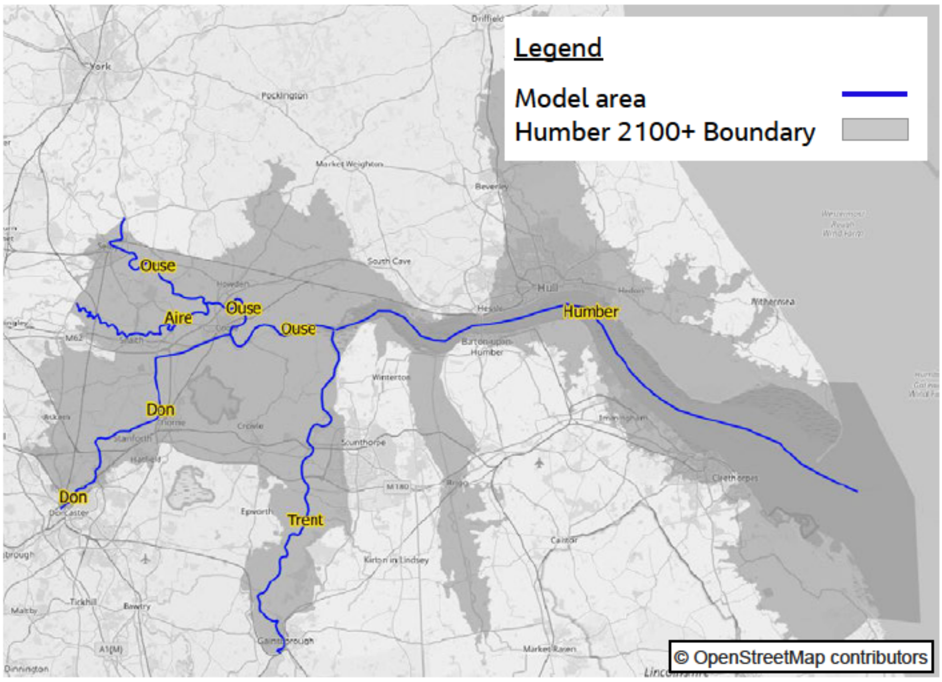


Figure 1.1: Humber 2100+ study area

1.2 Previous extremes analyses on the Humber

This chapter provides a short overview of recent extremes analysis studies in the Humber study area – it is not intended to be comprehensive, rather it provides context for the remainder of this report.

There have been numerous extremes analyses on the Humber study area, including:

- Posford Duvivier, 1991, Humber estuary tidal defences: data collection and analysis
- ABPmer, 1999 and 2007, Humber tidal database and joint probability analysis of large waves and high-water levels
- Environment Agency, 2015, Humber Estuary 2014 Interim Water Level Profile
- JBA, 2016, Upper Humber flood risk mapping study
- Jacobs & ABPmer, 2020, Humber Estuary Extreme Water Levels (HEWL) project

In addition, national studies of extreme sea levels have included extremes analysis for the outer estuary:

- Dixon and Tawn, 1997, Estimates of extreme sea conditions
- Environment Agency, 2011, Coastal Flood Boundary (CFB) conditions for UK mainland and islands
- Environment Agency, 2019, Coastal Flood Boundary conditions for UK mainland and islands update (CFB18)

These studies have had a range of objectives with some focusing on extreme still water levels, others on extreme waves and their joint probability with extreme still water levels. They cover different geographic extents and make use of different data and methods. Rather than critique each study, it is more relevant to highlight the issues identified during the recent HEWL project[1], Jacobs (2020) that preceded this study.

HEWL was initially intended as a detailed project to determine extreme water levels and waves for the Humber to underpin the Humber 2100+ project and provide extremes data for wider uses. The project included:

- Significant review and improvements to data
- Development of a new calibrated MIKE model of the estuary with a 2D representation in the Estuary, 1D representation in the tidal rivers, and partial inclusion of floodplain losses
- Dependency analysis of gauge data
- Wave modelling and extremes analysis in the Estuary
- Simulation of 100 real events from the 21-year period 1994 to 2015, using inflow hydrographs to the tidal rivers and hindcast modelled water levels of the sea including the tide and surge
- Statistical analysis of the simulated events to derive draft estimates of extreme water levels throughout the estuary.

The HEWL study, notwithstanding the significant reliability and consistency issues in the data sets delivered a highly detailed and well calibrated coupled 2D-1D model of the estuary and tidal rivers, and an estuary wave model, both of which could be confidently used in future projects. Conversely, it was not possible to deliver a robust set of extreme water level results for the whole of the estuary and tidal rivers under HEWL. The limited time period of reliable data and limited number of extreme events that included flooding meant that the statistical approach adopted by the study, for deriving extreme water levels, was not universally applicable. Where physical processes were well represented in the data (i.e. up to the top of defence level/bank top) there was high confidence in the results. However, where there are changes to the physical process at levels beyond those represented in the data, the results in these locations were either not plausible or insufficiently robust.

[1] Jacobs & ABPmer, (2020). Humber Extreme Water Levels, Interim Final Report.
A report produced by Jacobs and ABPmer for Environment Agency, March 2020

Due to the above factors the H2100+ project took on the delivery of the extreme water levels for both the H2100+ project and the wider business using the 1D Flood Modeller Model that had already been developed for the strategy.

The HEWL study significantly improved the understanding of the key issues and the challenges associated with the approach taken to the extreme analysis. The approach taken to extreme still water level modelling in this report has utilised lessons learnt from HEWL study.

1.3 General approach to Extreme Water Level analysis

The purpose of this report is to describe the approach taken for the extreme still water level analysis for the Humber 2100+ study area. It builds on previous studies both for the Humber and nationally, with a focus on meeting the needs of the Humber 2100+ while also delivering results for wider usage.

Figure 1.2 provides an overview of the approach taken to derive the extreme water levels (EWL) which is summarised in the following steps:

- Develop, calibrate and verify a hydrodynamic model of the study area which will enable water levels to be calculated at all locations with the study area for any combination of boundary conditions.
- Undertake a dependency analysis to quantify the degree of dependency (from full independent through to fully dependent) between boundaries (river inflow peaks and extreme sea levels).
- Based on the FD2308 method (Joint Probability - Dependence Mapping and Best Practice guidance), use the dependency analysis to generate a set of joint probability (JP) scenario tables for each target AEP – each table contains a set of combinations of boundary AEP which are expected to lead to the target AEP at one or more locations in the study area.
- Define 'design' event boundaries for each river inflow and the sea in terms of flow/level time series and their relative timings together with peak values for the full range of AEPs.
- Generate and run hydrodynamic model simulations for each row in each JP scenarios table (using the standard event boundaries representing the boundary AEPs from the JP scenarios table).
- Extract the maximum water level at each model node from each simulation (row) within the JP scenarios table for the target AEP. This gives the target AEP water level at the location. Repeat for all target AEPs.
- Verify the extremes using gauge data and previous extremes results and through assessing the physical plausibility of the results.
- Format extremes into the required deliverables: spreadsheets, tables, shapefiles and reporting.

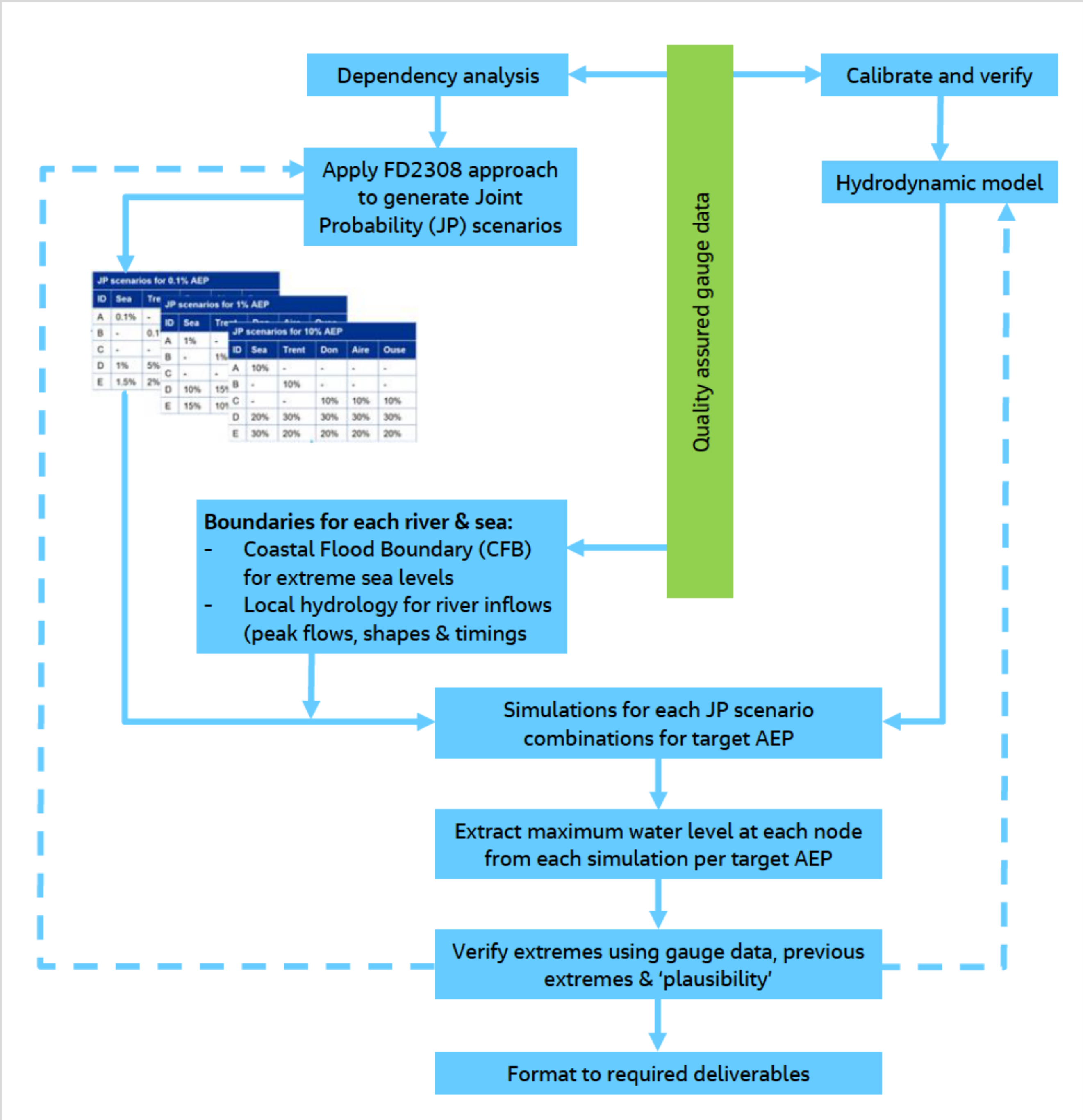


Figure 1.2: Flow chart to derive extreme water levels

1.4 Structure of this report

This report is structured as follows:

- Chapter 2 describes hydrodynamic model developed during the Humber 2100+ project and updates made to the model to improve the confidence in the extreme water level predictions.
- Chapter 3 describes the joint probability approach.
- Chapter 4 summarises the methods followed to generate the tide/fluvial boundary conditions and impact of future climate scenarios.

- Chapter 5 comments on the review of the first iteration of present day extreme water levels updates and provides results to the final set of extreme water levels, verification and uncertainty.
- Chapter 6 discusses the accuracy and confidence limits which can be assigned to extreme water levels
- Chapter 7 lists the study deliverables
- Chapter 8 provides conclusions, limitations and recommendations

2. Hydrodynamic Modelling

2.1 Overview

The hydrodynamic model used for deriving the extreme water levels is a 1D model (Flood Modeller) which extends beyond the Humber 2100+ study area. The model was specifically developed for the Humber 2100+ project by Jacobs in 2019. The model was constructed from existing Environment Agency approved 1D/2D models (Flood Modeller and TUFLOW) and has been calibrated to seven historical flood events, which included the December 2013 tidal surge.

The final technical reports covering the model build and initial calibration[2] and final calibration[3] (of the seven events) should be referenced for details of the model. An eighth calibration event for the November 2019 flooding was assessed during this EWL study. This event focused on the River Don at Fishlake and is detailed in Appendix N. The calibration statistics presented in chapter 6.3 are based on the original seven events and do not include the November 2019 event.

2.2 Model Updates

The model was updated with the 2021 defences and run to produce an initial set of extreme water levels for present day conditions. Following review of the initial set of results (including their use for MDSF2), high level broadscale modelling work (e.g. bank raising) and recent flood events (November 2019 and February 2020), further updates to the model were required.

The following updates were made to the model (all of which were implemented for the final EWL production runs):

- Additional schematisation for the 2021 defence.
- Bridge overtopping (in-line).
- Defence level consistency checks and updates based on MDSF2 defence line data.
- Floodplain volume checks.
- Bank/Defence spill coefficient (reduced by 20%), applied using Flood Modeller IED file. Validated by sensitivity testing on the calibration model using the December 2013 event (Appendix B)
- Additional detail to the floodplain of the River Trent between Gainsborough and Stockwith
- River Don left bank defence downstream of Stainforth Road Bridge set to a minimum level of 7.0 mAOD. Based on the Fishlake Recovery works (2020)
- The River Don section of the model was also updated following the flood events of November 2019 and February 2020 which resulted in some of the highest water levels recorded. Full details of the update and calibration to the November 2019 event are included in Appendix N.

Full details on the model updates are described in Appendix A and information on the initial extreme water level review is included in Appendix D. Information on the hydraulic model setup, simulations and performance is included in Appendix E.

[2] Model Proving and Calibration: ENV0000300C-CH2-ZZ-3A0-RP-HY-0003, 17th September 2019
[3] Model Update and Additional Calibration: ENV0000300C-CH2-ZZ-3A0-RP-HY-0005, 17th September 2019

3. Dependency analysis and generation of Joint Probability scenarios

A Joint Probability (JP) approach was taken to generate sets of model inputs which give modelled water levels at locations within the estuary taking account of dependency between extreme river flows at the upstream boundary and extreme tide and surge conditions at the North Sea boundary and their impacts on water levels through the estuary. For example, a water level with AEP 10% for a specific site may be generated by a flow on one of the rivers with AEP 10%, or a water level at the estuary entrance with AEP 10%, or by a combination of lower river flow and water level inputs. The output of this part of the work was a set of scenarios of groups of input combinations having the correct joint AEPs.

This chapter describes the detailed steps taken to implement the so-called Desk Study approach to Joint Probability Analysis described in 'FD2308 Joint Probability - Dependence Mapping and Best Practice' guidance.

3.1 Dependency analysis

The dependency analysis required estimation of the key dependence measure χ (chi) which is required as a step in implementing the FD2308 tool for calculating Joint Probability scenarios. This measure was required for all pairs of inputs of the form (river flow, sea level). The measure can be thought of as the propensity for both variables to be extreme concurrently.

Work had already been undertaken and reported within preceding HEWL study, to provide a description of the extremal dependencies between the relevant model inputs (peak river flow on each of the rivers Don, Aire, Ouse, Trent and extreme water level at sites around the mouth of the estuary). The purpose of the HEWL work was to give a basic understanding of the extremal dependencies within the estuary and so was more descriptive in nature than required for the current project, which necessitates the derivation of a single value of χ for each pair. Thus, some additional analysis was undertaken to determine an appropriate single threshold for estimation of χ, and to obtain its estimate for each (flow, sea level) pair. All of the required data for this step were already available and indeed had already been analysed in a very similar way for the more descriptive work delivered in HEWL.

The HEWL work examined water levels at six locations around the Humber estuary, and for the current project we required to determine a single relevant location. Spurn Point was selected as this is closest to the location at which downstream tidal boundary conditions are applied in the modelling.

The derivation of χ values for each of the four (river flow, sea level) pairs was undertaken by J. Heffernan Consulting Limited and is reported in Appendix L[4]. Derived χ values are listed below.

- Aire: χ = 0.05
- Don: χ = 0.04
- Ouse: χ = 0.06
- Trent: χ = 0.03

[4] HEWL review of river flow dependence, Janet Heffernan, September 2018
Humber Extremes: Dependence Analysis, HSCR Extremes, J Heffernan Consulting Limited, May 2019

3.2 Joint Probability Derivation

3.2.1 Joint probability matrices for river flows and sea levels

Having determined the values of χ for each of the four (river flow, sea level) pairs – one for each river – the next step is to populate Joint Probability Matrices for each pair. This was carried out using the FD2308 Excel spreadsheet version of the desk study approach described in the FD2308 Guide to best practice R&D Technical Report FD2308/TR2, and which accompanies that report. The spreadsheet tool takes the following three inputs:

- Value of χ for the extreme pairs
- Design AEPs (the AEPs of the JP pairs to be estimated): 50% (1:2), 20% (1:5), 10% (1:10), 5% (1:20), 2% (1:50), 1.33% (1:75), 1% (1:100), 0.5% (1:200), 0.2% (1:500) and 0.1% (1:1000)
- Marginal extreme level AEPs assumed to be as above

The required Joint Probability Matrices are returned as output by the tool, with return periods given in years, which are trivially then converted to AEPs (%).

Joint probability matrices derived by the FD2308 desktop approach for the fluvial/tidal design conditions in the Ouse, Aire, Don and Trent are detailed in Table 3.1 to Table 3.4. The derived value of χ was set between 0.03 to 0.06.

Table 3.1: Joint probability matrix – Ouse, Spurn

		Design AEP (%)									
x = 0.06		50	20	10	5	2	1.33	1	0.5	0.2	0.1
		Marginal Fluvial AEP (%)									
Marginal Water Level AEP (%)	>100	>100	>100	55.556	13.889	2.222	1.333	1.000	0.500	0.200	0.100
	>100	>100	>100	>100	34.722	5.556	2.469	1.389	0.500	0.200	0.100
	75	>100	>100	>100	92.593	14.815	6.584	3.704	0.926	0.200	0.100
	20	>100	>100	>100	>100	22.222	9.877	5.556	1.389	0.222	0.100
	10		>100	>100	>100	55.556	24.691	13.889	3.472	0.556	0.139
	5			>100	>100	>100	49.383	27.778	6.944	1.111	0.278
	2				>100	>100	98.765	55.556	13.889	2.222	0.556
	1.33					>100	>100	>100	34.722	5.556	1.389
	1						>100	>100	52.083	8.333	2.083
	0.5							>100	69.444	11.111	2.778
	0.2								>100	22.222	5.556
	0.1									55.556	13.889

Table 3.2: Joint probability matrix – Aire, Spurn

		Design AEP (%)									
x = 0.04		50	20	10	5	2	1.33	1	0.5	0.2	0.1
		Marginal Fluvial AEP (%)									
Marginal Water Level AEP (%)	>100	>100	>100	>100	31.25	5.00	2.22	1.25	0.50	0.20	0.10
	>100	>100	>100	>100	78.13	12.50	5.56	3.13	0.78	0.20	0.10
	75	>100	>100	>100	>100	33.33	14.81	8.33	2.08	0.33	0.10
	20	>100	>100	>100	>100	50.00	22.22	12.50	3.13	0.50	0.13
	10		>100	>100	>100	>100	55.56	31.25	7.81	1.25	0.31
	5			>100	>100	>100	>100	62.50	15.63	2.50	0.63
	2				>100	>100	>100	>100	31.25	5.00	1.25
	1.33					>100	>100	>100	78.13	12.50	3.13
	1						>100	>100	>100	18.75	4.69
	0.5							>100	>100	25.00	6.25
	0.2								>100	50.00	12.50
	0.1									>100	31.25

Table 3.3: Joint probability matrix – Don, Spurn

		Design AEP (%)									
x = 0.03		50	20	10	5	2	1.33	1	0.5	0.2	0.1
		Marginal Fluvial AEP (%)									
Marginal Water Level AEP (%)	>100	>100	>100	>100	55.556	8.889	3.951	2.222	0.556	0.200	0.100
	>100	>100	>100	>100	>100	22.222	9.877	5.556	1.389	0.222	0.100
	75	>100	>100	>100	>100	59.259	26.337	14.815	3.704	0.593	0.148
	20	>100	>100	>100	>100	88.889	39.506	22.222	5.556	0.889	0.222
	10		>100	>100	>100	>100	98.765	55.556	13.889	2.222	0.556
	5			>100	>100	>100	>100	>100	27.778	4.444	1.111
	2				>100	>100	>100	>100	55.556	8.889	2.222
	1.33					>100	>100	>100	>100	22.222	5.556
	1						>100	>100	>100	33.333	8.333
	0.5							>100	>100	44.444	11.111
	0.2								>100	88.889	22.222
	0.1									>100	55.556

Table 3.4: Joint probability matrix – Trent, Spurn

		Design AEP (%)									
x = 0.04		50	20	10	5	2	1.33	1	0.5	0.2	0.1
		Marginal Fluvial AEP (%)									
Marginal Water Level AEP (%)	**>100**	>100	>100	>100	31.25	5.00	2.22	1.25	0.50	0.20	0.10
	>100	>100	>100	>100	78.13	12.50	5.56	3.13	0.78	0.20	0.10
	75	>100	>100	>100	>100	33.33	14.81	8.33	2.08	0.33	0.10
	20	>100	>100	>100	>100	50.00	22.22	12.50	3.13	0.50	0.13
	10		>100	>100	>100	>100	55.56	31.25	7.81	1.25	0.31
	5			>100	>100	>100	>100	62.50	15.63	2.50	0.63
	2				>100	>100	>100	>100	31.25	5.00	1.25
	1.33					>100	>100	>100	78.13	12.50	3.13
	1						>100	>100	>100	18.75	4.69
	0.5							>100	>100	25.00	6.25
	0.2								>100	50.00	12.50
	0.1									>100	31.25

3.2.2 Constructing joint probability scenarios

The final step in this section of the work is to assemble individual columns from the Joint Probability Matrices for the four rivers into a set of Joint Probability Scenarios. This gives one set of JP scenarios for each design AEP. Each set was initially collated as follows:

- For a given design AEP the column of the Joint Probability Matrix is selected for one river which gives the marginal fluvial AEPs on that river which correspond to that design AEP, and the associated marginal sea level AEPs which correspond to those fluvial values.
- The marginal sea level AEPs are used to select the marginal fluvial AEP values for each of the remaining rivers by matching the fluvial AEPs from the design AEP column of the river in question with the sea level AEPs.
- Where there are repeated values of sea level AEP different combinations of rivers having elevated flow values were represented to give multiple scenarios in which all or only a subset of rivers have elevated flow.

The final step in the above clearly has the potential to multiply the combinations of flow scenarios. In practice, the approach adopted to retain a representative selection of scenarios which covers a range of combinations without overpopulating the set of scenarios. In any case, the most conservative scenario is that in which all the rivers attain their smallest AEP concurrently, and this scenario is always represented.

After assembling the set of potential scenarios according to the above steps, the scenarios were rationalised to reduce the number which were ultimately used as model inputs. Marginal fluvial AEPs were rounded to values which are common to multiple scenarios to avoid redundant modelled AEPs.

3.2.3 Adjustment for FD2308 under-estimation tendency

There is a tendency for the FD2308 desktop method (spreadsheet method) to underestimate joint exceedance probabilities of responses to, in our case, joint tidal and fluvial conditions. This is explained in FD2308-TR1 chapter 3.5.3, and also covered in FD2308-TR2 chapter 5.1.5. Whilst the example presented in FD2308 TR1 is for joint wave height/water level events, the same logic also applies to other variable pairs (e.g. tidal / fluvial events for this study).

FD2308 recommends unless there are other conservative assumptions in constructing the joint events (e.g. assuming both extreme conditions occur with a “worst case” relative timing), an adjustment is made for this bias in the methodology - typically scaling the joint exceedance probabilities by approximately 2 such that, for example, joint event combinations initially derived for the 100 year return period are assigned a return period of 50 years. Whilst the adjustment itself is uncertain (the bias in estimating return periods would be different for different responses), applying a plausible adjustment is considered preferable to no adjustment.

The construction of Humber joint events is not really conservative as (i) the marginal extremes are unbiased best estimates and (ii) the duration of design fluvial events is significantly longer than that of tidal extreme events, and so matching peak timing of fluvial and tidal events is not likely to significantly affect resulting EWLs. We have therefore undertaken an adjustment for the Humber project, scaling the joint exceedance probabilities by 2 for the joint events. We have also simulated the case of full dependence as an “upper limit” sensitivity test.

Table 3.5 and Table 3.6 present the initial and adjusted joint probability event combinations for the 0.5% AEP event (adjusted combinations are highlighted blue in Table 3.6). The tables present the events in the form 1 in X-year. Full tables are in Appendix G.

Table 3.5: Initial Joint Probability matrix 0.5% AEP

RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
200	200	200	200	200	<1	Fluvial - complete fluvial dependence	Fd
200	200	<1	<1	<1	<1	Fluvial – independent: River Aire	FiA
200	<1	200	<1	<1	<1	Fluvial – independent: River Don	FiD
200	<1	<1	200	<1	<1	Fluvial – independent: River Ouse	FiO
200	<1	<1	<1	200	<1	Fluvial – independent: River Trent	FiT
200	50	50	50	50	<1	Fluvial - less dependence	Fd2
200	20	20	50	20	2	Mixed tidal/fluvial	FT1
200	10	5	20	10	5	Mixed tidal/fluvial	FT2
200	5	5	10	5	10	Mixed tidal/fluvial	FT3
200	2	2	5	2	20	Mixed tidal/fluvial	FT4
200	2	<1	2	2	50	Mixed tidal/fluvial	FT5
200	<1	<1	2	<1	100	Mixed tidal/fluvial	FT6
200	<1	<1	<1	<1	200	Tidal	T
200	200	200	200	200	200	FULL dependency	Full / Full_LR

Table 3.6: Adjusted Joint Probability matrix 0.5% AEP

RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
200	200	200	200	200	5	Fluvial - complete fluvial dependence	Fd
200	200	<1	<1	<1	2	Fluvial – independent: River Aire	FiA
200	<1	200	<1	<1	2	Fluvial – independent: River Don	FiD
200	<1	<1	200	<1	5	Fluvial – independent: River Ouse	FiO
200	<1	<1	<1	200	2	Fluvial – independent: River Trent	FiT
200	50	50	50	50	5	Fluvial - less dependence	Fd2
200	100	50	200	100	5	Mixed tidal/fluvial	FT1
200	50	20	100	50	10	Mixed tidal/fluvial	FT2
200	20	10	50	20	20	Mixed tidal/fluvial	FT3
200	10	5	20	10	50	Mixed tidal/fluvial	FT4
200	5	2	10	5	100	Mixed tidal/fluvial	FT5
200	2	2	5	2	200	Tidal	T
200	200	200	200	200	200	FULL dependency	Full / Full_LR

Changes to initial matrix highlighted blue

3.3 Discussion of approach

This approach assumes that the dependence between the various fluvial and sea level inputs are well described by the pairwise dependence measure χ which focuses only on the dependence between extremes of sea level and the various fluvial inputs. The approach could be seen as slightly conservative as it assumes the worst case scenario of all rivers attaining their highest marginal flow values concurrently. Dependence analysis which examined extremal dependence between the flows themselves, carried out under HEWL, suggests that this assumption is liable to be slightly over cautious - whilst the river flows have high extremal dependence, they are not perfectly dependent at high levels. The extent of this conservatism will be assessed through the inclusion of JP scenarios, as described above, in which some but not all river flows are extreme. We will be able to assess the impact of this assumption on sites which are fluvially or tidally dominated although it is anticipated that the impact on the ultimate estimation of water levels at any single given location will be minimal.

The approach is well justified in terms of its credibility for use in such settings. The estimation of the dependence measure χ is widely adopted practice in this setting. The approach to obtaining the joint probability scenarios by using the FD2308 desk study analysis is well recognised as an appropriate and relatively simple tool for JP analysis in such settings and is compliant with current good practice guidance. In the future it is expected that more refined methods will become accepted practice. The Environment Agency is currently looking to update FD2308 although it is not clear whether the update will provide a better method for estuaries and any such update will not be published prior to 2020. The NERC funded CHEST research at Hull University has been reviewed and it is confirmed that it does not provide an improved method for JP analysis of estuary water levels (FD2308 update and CHEST information received from Sue Manson (Environment Agency) on 14/2/2019).

4. Boundary Conditions

4.1 Overview

Tide and fluvial boundary conditions were prepared to derive 15 sets of EWL for 5 epochs and 3 emission scenarios. The tidal boundary has been derived following the coastal flood boundary guidance. The fluvial boundaries were extracted from the design simulation results of the existing 1D/2D approved models (refer to Table 4.4) for the Rivers Ouse, Aire and Trent. New design flows were derived for the River Don.

The tide and fluvial boundary data duration was set at 200 hours, this was to allow for the receding hydrographs of the fluvial boundary. The peaks within the boundaries have been aligned so peak flows and tide occur at a similar time (75 hours). The locations of the boundaries are detailed in Figure 4.1.

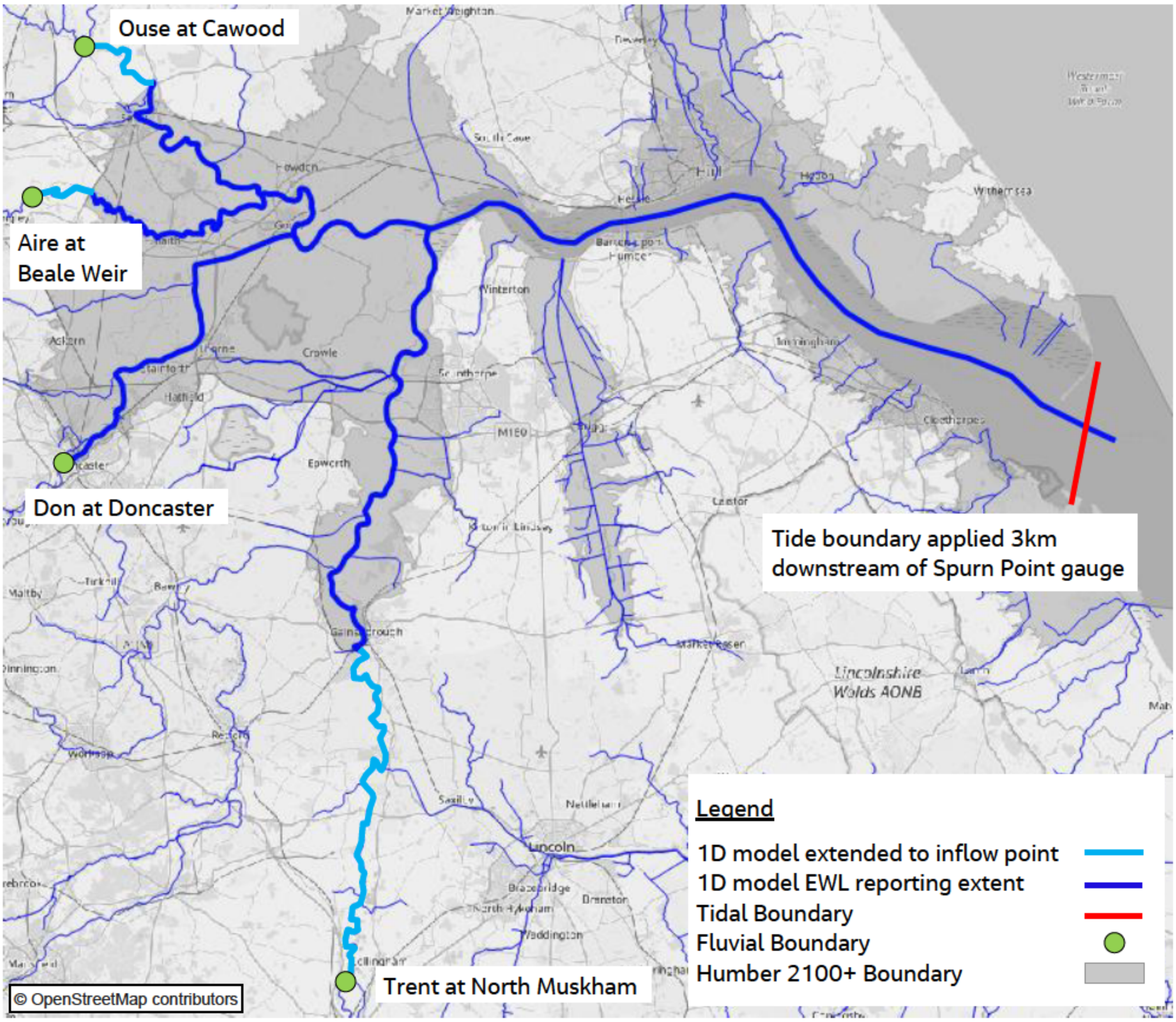


Figure 4.1: Model boundary locations (Tide and fluvial)

The derivation of the base tide boundary and fluvial boundaries are detailed in chapter 4.4 and chapter 4.5. Boundaries have been derived for the 50%, 20%, 10%, 5%, 2%, 1.3%, 1%, 0.5%, 0.2% and 0.1% AEP (1 in 2, 5, 10, 20, 50, 75, 100, 200, 500 and 1000 year).

4.2 Approach to Climate Change Allowances

The sea level rise (SLR) and fluvial uplifts applied to the boundaries to derive the design conditions are detailed in Table 4.1, and described below:

- Sea level rise allowances are derived based on the current UKCP18 climate change projections for the UKCP18 "RCP8.5" climate change scenario, in accordance with the recommendations in the current (July 2020) version of the Environment Agency's climate change allowances for schemes and strategies (https://www.gov.uk/guidance/flood-and-coastal-risk-projects-schemes-and-strategies-climate-change-allowances). As recommended in the guidance, the allowance for the H++ sea level rise for 2121 was developed in consultation with the Environment Agency.

- River flow allowances applied are those published in the current (July 2020) version of the Environment Agency's climate change allowances for schemes and strategies (https://www.gov.uk/guidance/flood-and-coastal-risk-projects-schemes-and-strategies-climate-change-allowances) and flood risk assessments (https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances. These river flow allowances are based on UKCP09 climate change projections and have not been updated since the UKCP18 climate change projections became available.

Details of how the approach has been applied with EA guidance is detailed in chapter 4.3.

Table 4.2 presents the naming conventions used in modelling outputs which reference the epoch and emission scenario (Epoch 2021, 2040, 2046, 2071 and 2121, emission scenario higher central = M, upper = H and H++ = HPP).

The peak flows and tide boundary conditions for all epoch/scenarios are tabulated in Appendix C.

Table 4.1: Sea level rise (SLR) and fluvial uplifts for present day and future epochs

	Epoch				
Emission Scenario	**Present day (2021)**	**2040**	**25 years (2046)**	**50 years (2071)**	**100 years (2121)**
SLR: UKCP18, RCP8.5, 70th %ile Flows: UKCP09, higher central (70th %ile)	0.02m SLR +15% flows	0.14m SLR +20% flows	0.19m SLR +20% flows	0.42m SLR +30% flows	1.02m SLR +30% flows
SLR: UKCP18, RCP8.5, 95th %ile Flows: UKCP09, upper (90th %ile)	0.03m SLR +20% flows	0.18m SLR +30% flows	0.23m SLR +30% flows	0.54m SLR +50% flows	1.38m SLR +50% flows
SLR: UKCP09, H++, plus UKCP18 surge Flows: UKCP09 H++	0.03m SLR +20% flows	0.28m SLR +35% flows	0.37m SLR +35% flows	0.97m SLR +65% flows	2.64m SLR +65% flows

Table 4.2: Naming conventions for boundary conditions

	Epoch				
Emission Scenario	**Present day (2021)**	**2040**	**25 years (2046)**	**50 years (2071)**	**100 years (2121)**
SLR: UKCP18, RCP8.5, 70th %ile Flows: UKCP09, higher central (70th %ile)	2021_M	2040_M	2046_M	2071_M	2121_M
SLR: UKCP18, RCP8.5, 95th %ile Flows: UKCP09, upper (90th %ile)	2021_H	2040_H	2046_H	2071_H	2121_H
SLR: UKCP09, H++, plus UKCP18 surge Flows: UKCP09 H++	2021_HPP	2040_HPP	2046_HPP	2071_HPP	2121_HPP

4.3 Application of Environment Agency Guidance

Since the publication of UKCP18, EA national teams have been working to review and update the climate change guidance, to ensure that the latest evidence is being used to inform water management activities consistently across the business. New guidance on applying UKCP18 to estimate sea level rise was first released in December 2019, and the EA published fully updated climate change guidance for appraisal in July 2020. The Humber 2100+ approach is consistent with this guidance.

Changes in fluvial flows under UKCP18 are broadly similar to those expected under UKCP09. Therefore, at the time of writing, the guidance on estimating future river flows has not changed and the fluvial climate change allowances used by Humber 2100+ are based on the UKCP09 data. The EA is currently considering how changes in rainfall intensity could impact flood risk with a view to publish updated guidance later this financial year (2020/21).

The H++ scenario has also not been updated as part of UKCP18 and extreme changes to fluvial flows and sea levels are therefore based on UKCP09 data. However, UKCP18 did identify significant complexity and uncertainty around changes to storm surge. Guidance therefore prescribes that 2mm of surge per year is added onto H++ sea levels. The consideration of additional surge is not required as part of any other climate change scenarios.

The new guidance does not provide a central allowance (50th percentile) for sea level. The Humber 2100+ medium climate change scenario is therefore based on the consistent application of the higher central (70th percentile) allowance for both river flows and sea level rise, as outlined in in Table 4.1 above. This is the precautionary approach as it applies a more conservative allowance to 'design' river flows. This approach has been applied on the basis that the fact the Humber is a tidally dominant estuary and the Humber 2100+ extreme water level outputs will be used by the wider business to support flood risk assessments, which are likely to need results in line with the higher central and upper end allowances (as per the latest guidance). This approach was discussed with and supported by EA National colleagues who are involved in developing the climate change guidance.

In addition to recently updating the climate change guidance, the EA also updated the Partnership Funding Calculator and related guidance in May 2020. Subsequently, it is now necessary for to assess and report on the number of households (OM2s) at risk in 2040. Humber 2100+ is making provision to do this by considering climate change up to this date.

4.4 Model Boundary Tidal Curves

4.4.1 Tide levels

Extreme tide levels for the model boundary have been obtained from the Coastal Flood Boundary 2018 (CFB2018) dataset at chainage 3912 (Figure 4.2) and are listed in Table 4.3, together with the corresponding confidence intervals. This data point corresponds approximately to the downstream extent of the model. Chainage _3856 is also located along the model boundary and is included for comparison as it shows the variation in the data across the estuary. As the water level is constant along the width of the 1D model boundary, the higher levels at 3912 were selected. Chainage points at 3860 and 3888 are also listed as they are located near the gauge at Spurn Point and Immingham.

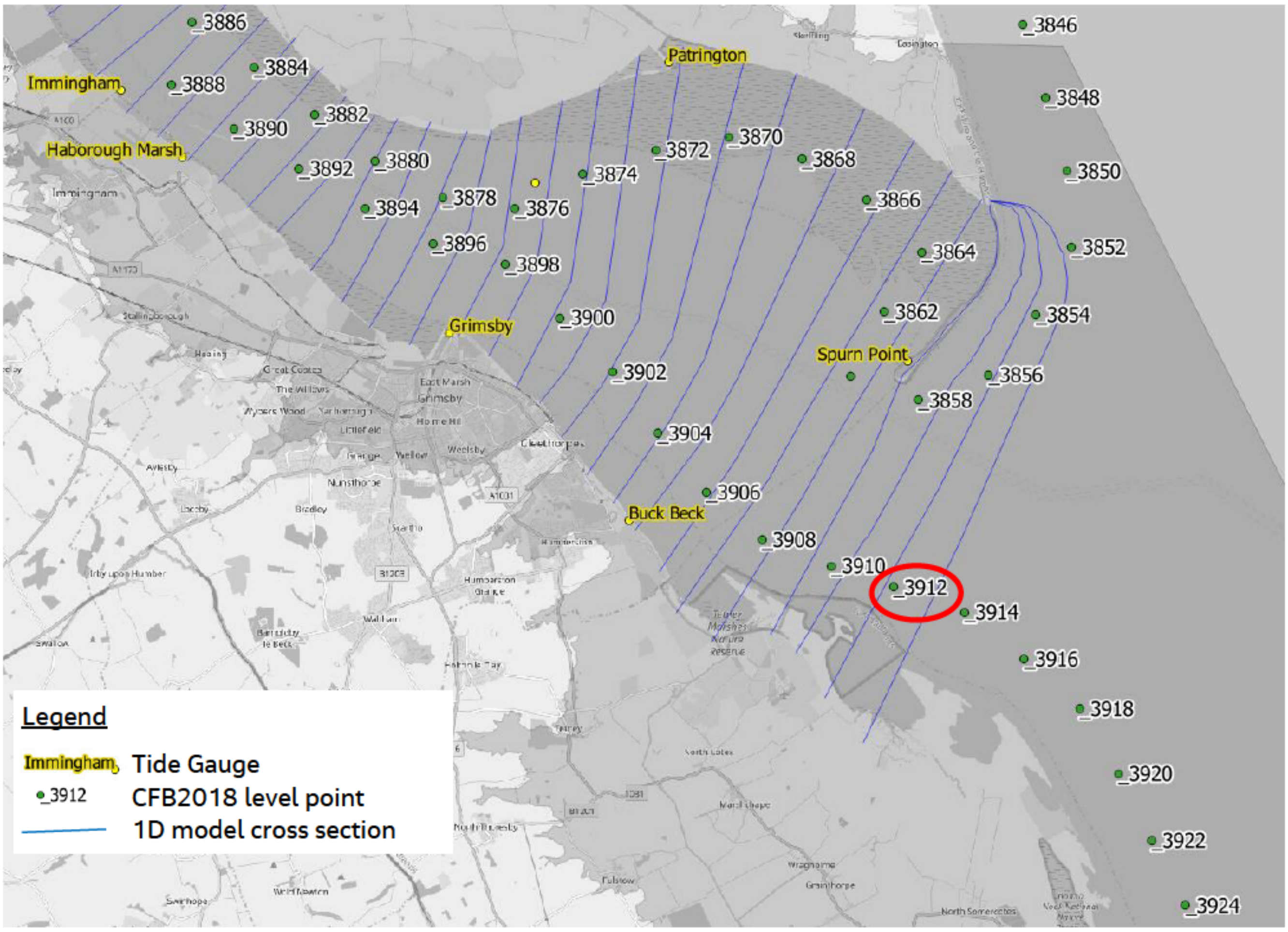


Figure 4.2: CFB2018 Extreme Sea Level data points

Table 4.3: CFB2018 Extreme tidal estimates (Base Year 2017)

AEP (%)	RP (1 in X year)	Still water level (mAOD) at chainage _3912 and confidence levels (%)			Adjacent Chainage points		
		_3912	2.5%	97.5%	_3856	_3860	_3888
100	1	3.85	3.84	3.87	3.82	3.86	4.17
50	2	3.96	3.94	4.00	3.92	3.96	4.27
20	5	4.10	4.06	4.15	4.06	4.10	4.42
10	10	4.21	4.16	4.29	4.17	4.21	4.53
5	20	4.33	4.27	4.45	4.28	4.32	4.65
4	25	4.37	4.30	4.50	4.32	4.36	4.68
2	50	4.49	4.39	4.66	4.43	4.47	4.80
1.33	75	4.56	4.46	4.78	4.49	4.53	4.88
1	100	4.61	4.49	4.86	4.53	4.58	4.93
0.67	150	4.69	4.55	4.99	4.61	4.65	5.00
0.5	200	4.75	4.59	5.10	4.66	4.70	5.06
0.4	250	4.78	4.60	5.15	4.69	4.73	5.10
0.33	300	4.82	4.62	5.21	4.73	4.77	5.14
0.2	500	4.93	4.71	5.40	4.82	4.86	5.24
0.1	1000	5.07	4.80	5.66	4.94	4.99	5.38

4.4.2 Derivation of model tidal curves

The tidal water level time series, or tide curve, for the model downstream boundary has been derived using the methodology set out in SC060064/TR4: Practical guidance design sea levels (EA/DEFRA, 2011), recommended in the guidance document to the Coastal Flood Boundary database.

The astronomical tide curve at Spurn Head (from TotalTide) from 2nd December to 10th December 2013 has been used as the base astronomical curve. This tidal curve meets the guidance criteria from the SC060064/TR4 of selecting data with an appropriate level between Highest Astronomical Tide (HAT) and Mean High Water Springs (MHWS). The highest astronomical level in this period (3.36mODN at 18:50 on 5 December 2013) is between Mean High Water Springs (2.96mODN) and Highest Astronomical Tide (3.81mODN) for the station. The period extends for three days before the highest astronomical level and for five days after the highest level.

Design tide curves have been produced by adding a scaled surge shape to the astronomical tide curve to achieve the required maximum design tide level, obtained from the Coastal Flood Boundary data in Table 4.3, for the year 2017. The Coastal Flood Boundary surge shape for Immingham is applied coincidentally with the peak astronomical tide level.

Figure 4.3 shows an example of the derivation of the 0.5% AEP tide curve in year 2018 using the Coastal Flood Boundary surge shape for Immingham.

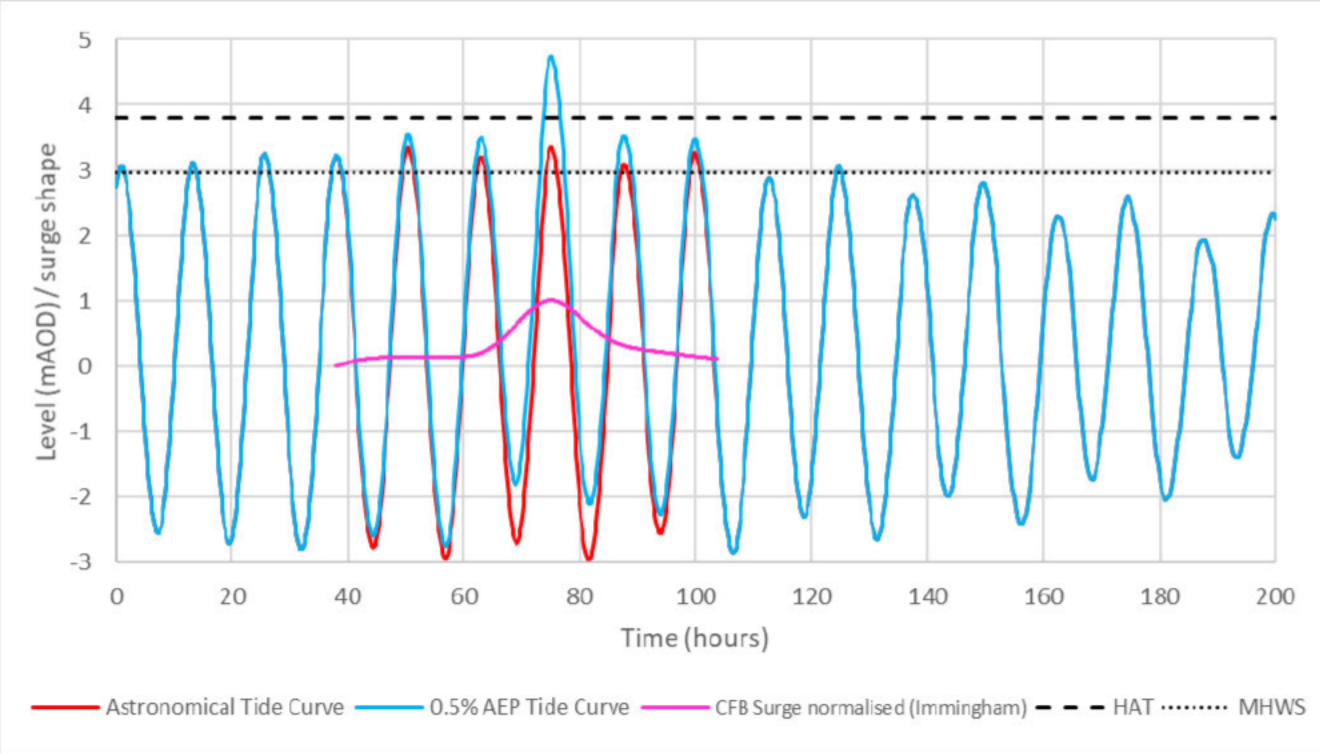


Figure 4.3: Derivation of 0.5% AEP tide curve using Immingham coastal flood boundary surge shape

4.4.3 Allowance for sea level rise to present day (2021)

The sea level rise allowances detailed in Table 4.2 were applied to the full duration of the tide curve (0-200 hours), this includes an uplift for the 'Present Day' epoch to represent 2021 (uplift from the 2017 CBF2018 baseline).

4.5 Model Fluvial Boundaries

The study included a flood hydrology review[5] which compared the existing data (from modelling studies), and recommended the approach summarised in Table 4.4. The design hydrographs for the Ouse, Aire, Don and Trent are detailed in Figure 4.4 to Figure 4.7. The hydrology review note and River Don FEH calulation record are included in Appendix M.

Table 4.4: Summary of data for fluvial boundaries

Watercourse	Boundary Source (Study)	Comment	Approach taken
Ouse	Ouse and Wharfe Washlands Optimisation Study. Mott MacDonald, July 2018	Ouse and Wharfe gauges are located approximately 22 km and 18 km upstream of the model boundary on the Ouse. Using flows derived at the gauging stations would not account for the travel time and floodplain attenuation	Flow boundaries extracted at Cawood using design model results (total flow from 1D and 2D PO lines).

[5] ENV0000300C-CH2-ZZ-3A0-RP-HY-0008: Fluvial flood hydrology review Jacobs, October 2020

Watercourse	Boundary Source (Study)	Comment	Approach taken
Aire	Northern Forecasting Package: Lower Aire Model. JBA, July 2017	Beale gauging station on the River Aire is bypassed and recorded flows are capped around 320 m^3/s.	Flow boundaries extracted at Beale Weir using design model results (total flow from 1D and 2D PO lines).
Don	Don Catchment Model: Hydrology Report JBA, February 2017. (not used to derive boundaries)	Review of the design flows based on continuous simulation modelling concluded that the estimation of highest flows is particularly uncertain	New extreme flows derived by the FEH statistical and Archers method hydrographs (refer to Appendix M).
Trent	Tidal Trent Modelling and Mapping Study Addendum. Mott MacDonald, Jan 2015	Tidal Trent study derived inflows at North Muskham gauging station	North Muskham design flow boundaries re-used (no adjustments)

4.5.1 Allowance for climate change

The climate change uplifts detailed in Table 4.2 were applied to the design hydrographs, this includes an uplift for the ‘Present Day’ epoch to represent 2021 to account for the impacts of climate change which have already occurred to the base data (and this is in accord with the current version of the Environment Agency’s climate change allowances for both Flood Risk Assessments (https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances) and FCERM scheme appraisals (https://www.gov.uk//guidance/flood-and-coastal-risk-projects-schemes-and-strategies-climate-change-allowances).

The climate change uplifts for the fluvial boundaries are applied directly to the present day boundaries. This potentially does not account for storage in the floodplains upstream of the model boundary and could therefore, overestimate the future epoch flows.

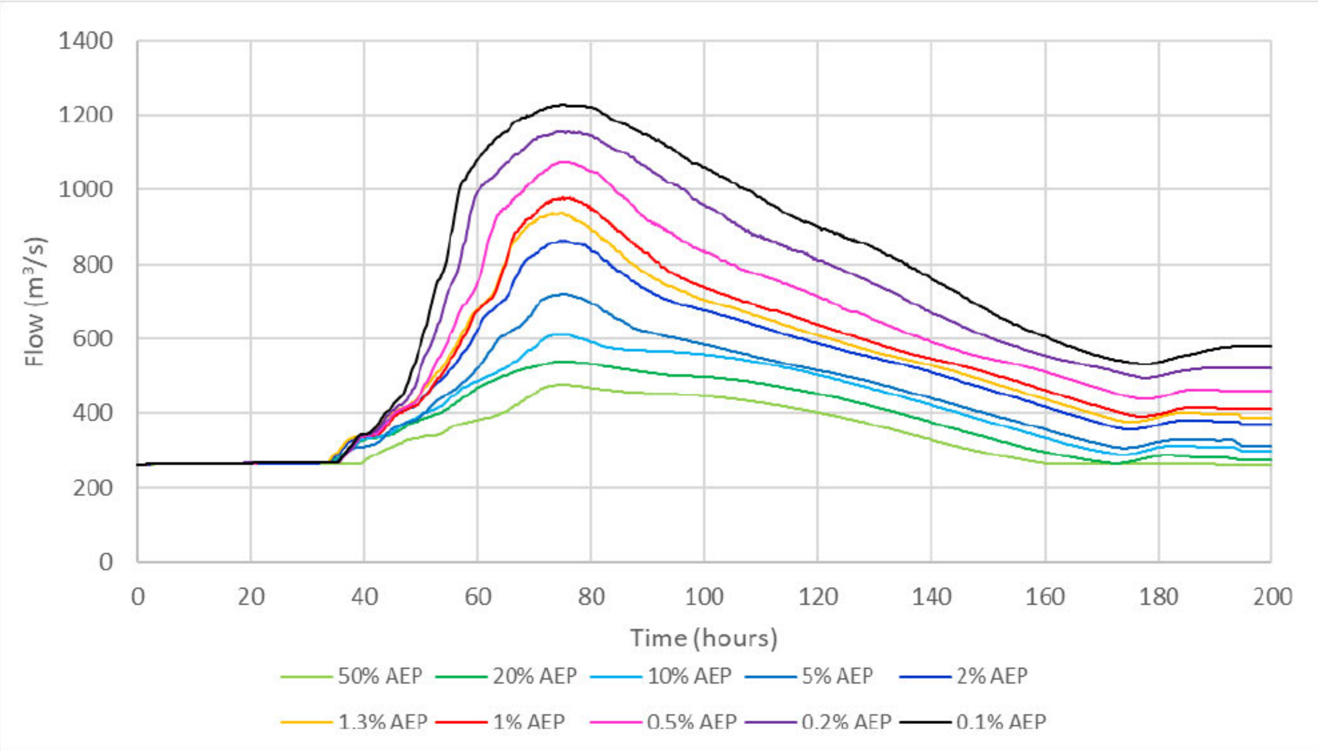


Figure 4.4: Model fluvial inflows on the River Ouse

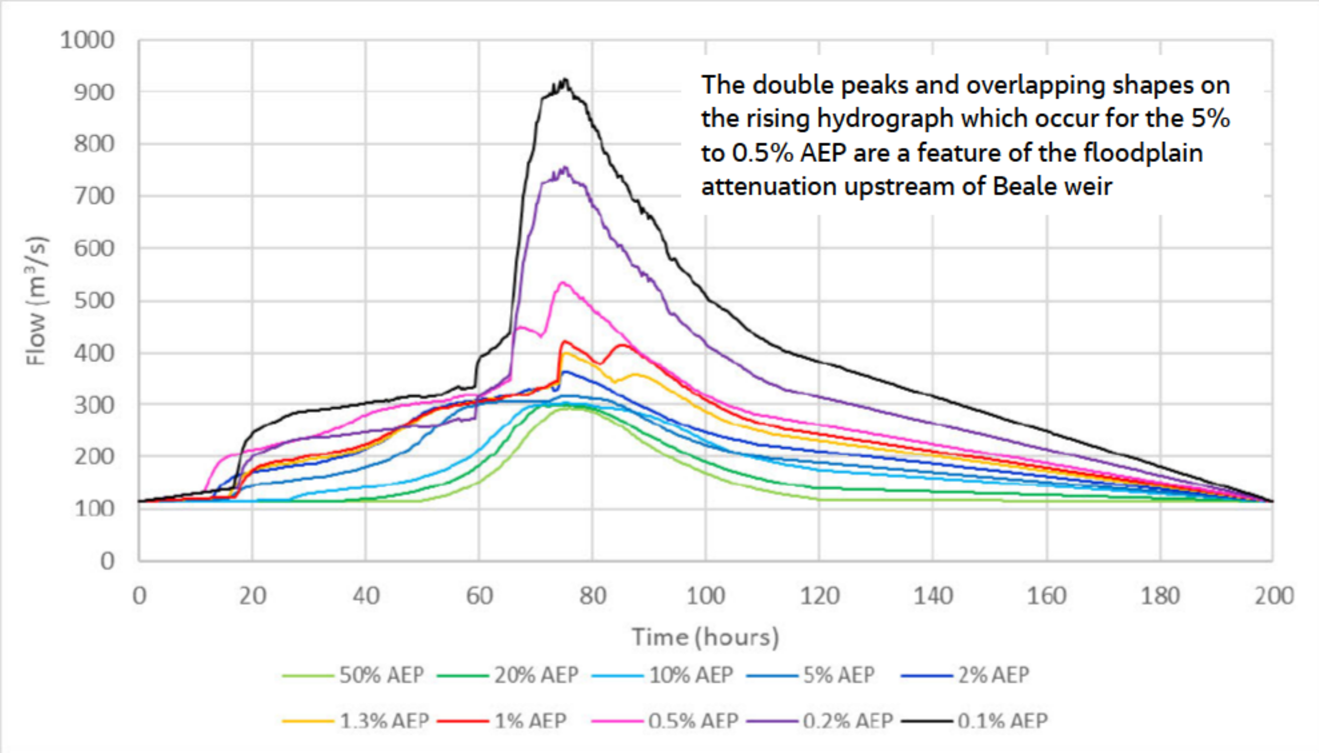


Figure 4.5: Model fluvial inflows on the River Aire

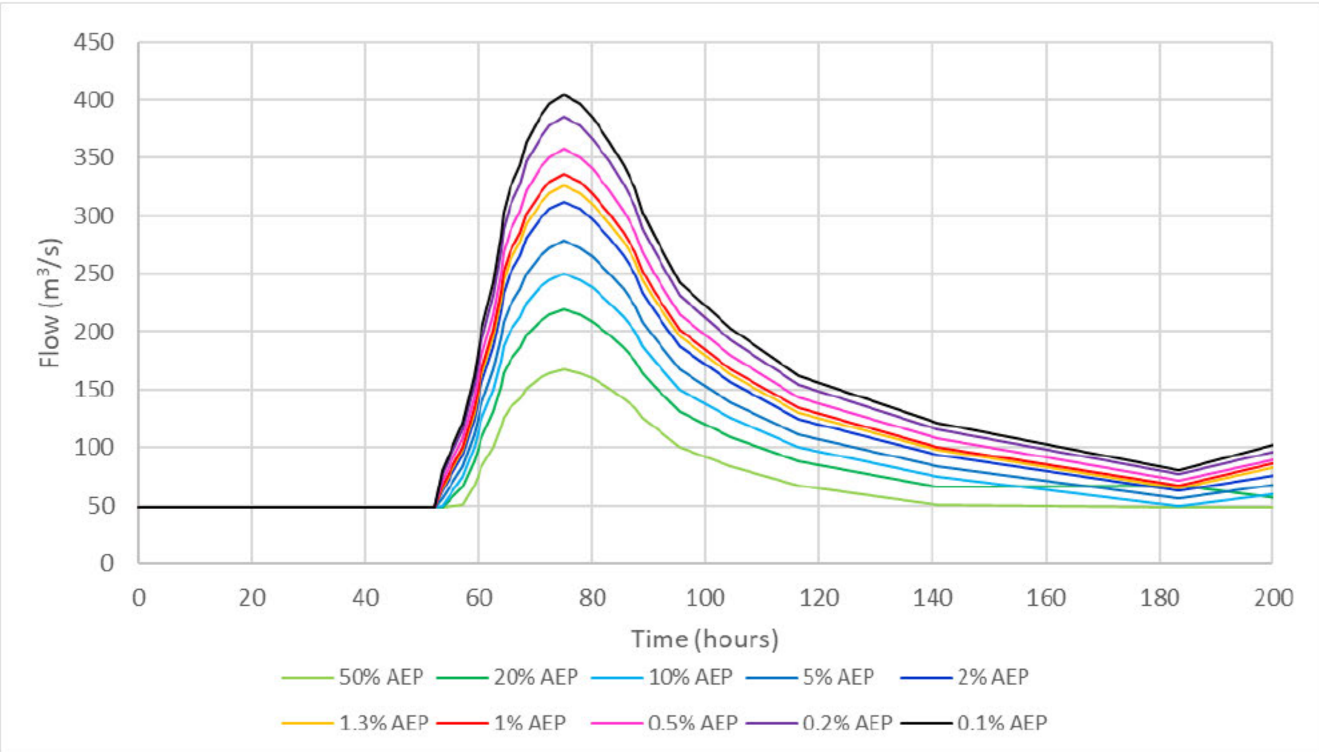


Figure 4.6: Model fluvial inflows on the River Don

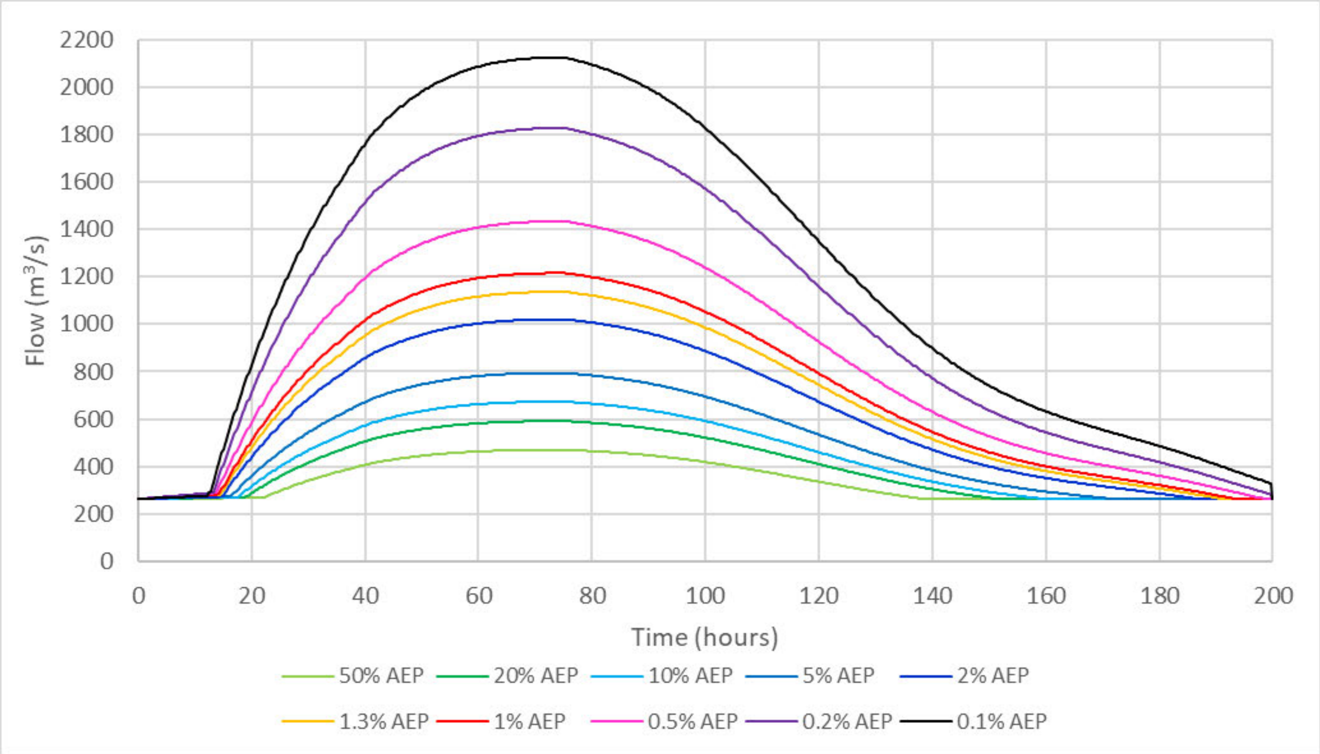


Figure 4.7: Model fluvial inflows on the River Trent

5. Extreme Water Levels

5.1 Initial results

The model was run to derive an initial set of present day extreme water levels for verification purposes. This task was undertaken prior to the confirmation of the uplifts for the epochs/scenarios, resulting in present day boundaries which do not include the SLR and fluvial uplifts (note that these results do not form part of the EWL deliverable, and are replaced by the adjusted set following updates to the climate change, JP method and model).

Changes were made to the model and joint probability matrix following the review of the initial extreme water levels (which included the verification tasks and subsequent sensitivity tests). The changes included:

- Additional 1D model ('Trent fluvial' model with +15% roughness between Gainsborough and confluence with the River Ouse) to be used only for the JP simulations which had a fluvial component on the Trent.
- 20% spill coefficient reduction was adopted for the final set of EWL, based on the findings of the initial EWL and roughness sensitivity test (applied to the 1D models using an IED file).
- Adjusted joint probability matrix adopted for the final set of EWL, showed small increases in peak level at the gauge sites where the December 2013 event recorded water levels exceeded the initial present day EWL.
- Model Update to the Don following the 2019/2020 floods (to improve the confidence in the results at Fishlake).
- Improvements to the floodplain at Gainsborough

Details of the initial extreme water level review is included in Appendix D.

5.2 Final extreme water levels (still water)

The final model using the adjusted joint probability matrix was run to predict the extreme still water levels for the 15 sets of scenarios (combinations of epoch and emission scenario). The reported water level at each model node is taken as the maximum from the full set of JP model simulations for each AEP.

The extreme still water levels at the gauge locations detailed in Figure 5.1 are presented in Table 5.1 (2021_H - upper) and Table 5.2 (2121_H - upper)

Figure 5.2 (2021) and Figure 5.3 (2121) show the joint probability type which produces the maximum levels. The blue dots represent the pure tidal event, red dots pure fluvial and the green dot show where one of the JP scenarios results in the maximum level.

In the upper (inland) reaches the extremes are from the pure fluvial events (red) and the downstream reaches (seaward) the extremes are from the pure tidal events (blue). The zones where the maximum levels arise from one of the joint probability combinations (green) tend to be located between Keadby and Owston on the Trent and upstream of Goole to Carlton Bridge (Aire), Kirk Bramwith (Don) and Selby (Ouse).

For higher AEP's (e.g. 1%), the JP type which produces the maximum level can switch from JP/tidal/JP and back to tidal, this occurs when the EWL is influenced by the defence level and model predicts similar levels for all JPs (i.e. within 0.01m or less).

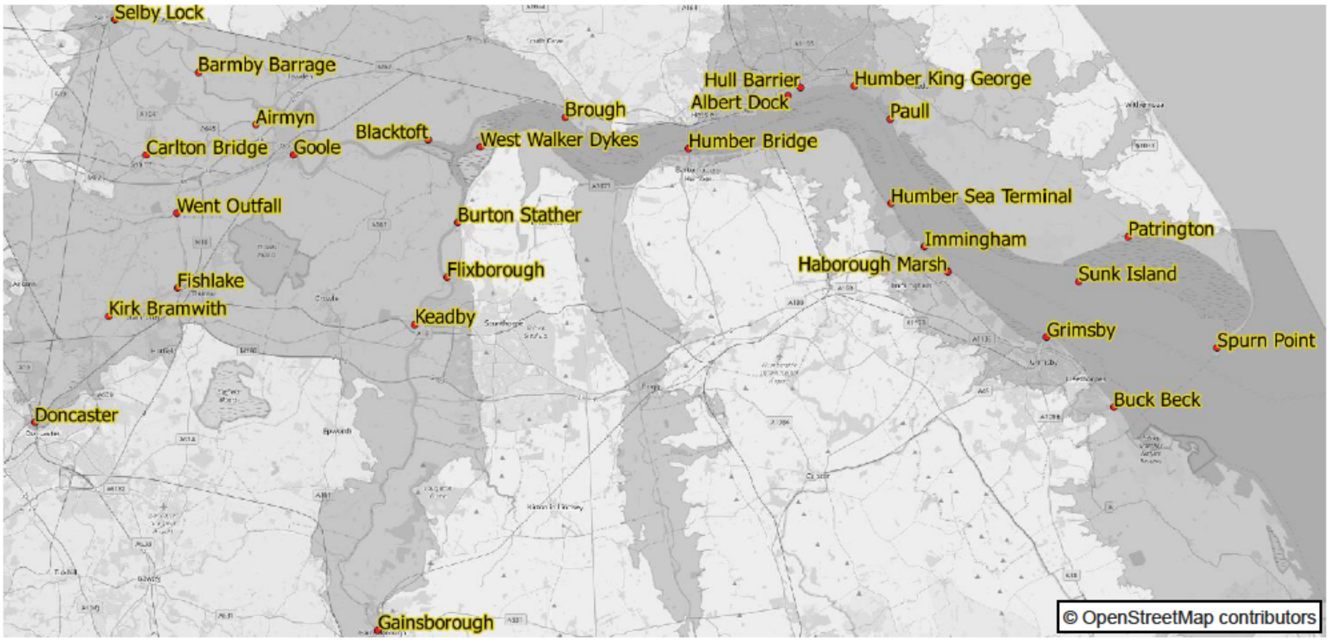


Figure 5.1: Gauge locations

Table 5.1: 2021 Extreme still water levels (2021_H upper scenario)

Location	Easting	Northing	EWL (mAOD) for Design AEP (%)									
			50	20	10	5	2	1.33	1	0.5	0.2	0.1
Spurn Point	539856	410943	4.02	4.16	4.27	4.39	4.55	4.62	4.67	4.81	4.99	5.13
Buck Beck	532700	406580	4.08	4.22	4.33	4.45	4.61	4.68	4.73	4.87	5.05	5.19
Patrington	533399	418557	4.12	4.26	4.36	4.49	4.65	4.72	4.77	4.91	5.09	5.24
Sunk Island	530007	415325	4.14	4.28	4.39	4.51	4.67	4.75	4.80	4.94	5.12	5.26
Grimsby	527878	411346	4.16	4.30	4.41	4.53	4.69	4.76	4.81	4.96	5.14	5.28
Haborough Marsh	520790	415740	4.28	4.42	4.53	4.65	4.82	4.89	4.94	5.10	5.28	5.42
Immingham	519141	417449	4.32	4.46	4.58	4.70	4.86	4.94	4.99	5.15	5.33	5.47
Humber Sea Terminal	516710	420393	4.39	4.53	4.64	4.77	4.93	5.01	5.07	5.22	5.40	5.54
Paull	516516	426331	4.49	4.64	4.75	4.88	5.05	5.13	5.18	5.34	5.52	5.65
Humber King George	513950	428543	4.54	4.69	4.80	4.93	5.10	5.18	5.23	5.39	5.57	5.70
Hull Barrier	510194	428354	4.61	4.76	4.88	5.00	5.17	5.25	5.30	5.47	5.64	5.77
Albert Dock	509346	427749	4.63	4.78	4.89	5.02	5.19	5.27	5.32	5.49	5.66	5.78
Humber Bridge	502478	423914	4.84	4.99	5.11	5.24	5.40	5.48	5.53	5.70	5.86	5.97
Brough	493792	425938	5.03	5.18	5.30	5.43	5.60	5.69	5.74	5.90	6.02	6.11
West Walker Dykes	487883	423725	5.13	5.28	5.40	5.53	5.69	5.79	5.83	5.97	6.07	6.13
Burton Stather	486416	418432	5.16	5.32	5.44	5.57	5.73	5.83	5.87	6.02	6.10	6.14
Flixborough	485739	414584	5.25	5.40	5.52	5.65	5.81	5.91	5.94	6.10	6.16	6.20
Keadby	483557	411268	5.34	5.49	5.61	5.74	5.89	5.99	6.03	6.17	6.22	6.26
Gainsborough	481340	389770	5.58	5.59	5.59	5.76	6.15	6.45	6.50	6.55	6.87	6.99
Blacktoft	484247	424190	5.14	5.30	5.42	5.55	5.70	5.80	5.84	5.96	6.04	6.08
Goole	474857	422960	5.32	5.46	5.57	5.70	5.85	5.94	5.96	6.04	6.06	6.08
Barmby Barrage	468081	428630	5.65	5.77	5.85	6.00	6.06	6.09	6.10	6.12	6.12	6.13
Selby Lock	462227	432200	6.00	6.03	6.06	6.20	6.23	6.52	6.54	6.56	6.60	6.61
Went Outfall	466761	418738	5.66	6.00	6.04	6.04	6.15	6.19	6.21	6.24	6.25	6.26
Airmyn	472175	425015	5.57	5.69	5.78	5.95	6.01	6.05	6.06	6.08	6.09	6.11
Carlton Bridge	464550	422783	6.01	6.02	6.02	6.08	6.09	6.13	6.19	6.22	6.25	6.30
Fishlake	466841	413512	6.39	6.81	6.84	6.84	6.85	6.87	6.87	6.88	6.88	6.89
Kirk Bramwith	462055	411498	7.06	7.60	7.64	7.64	7.65	7.65	7.65	7.65	7.65	7.66
Doncaster	456991	404004	9.22	10.04	10.36	10.52	10.64	10.68	10.71	10.77	10.84	10.88

Table 5.2: 2121 Extreme still water levels (2121_H upper scenario)

Location	Easting	Northing	EWL (mAOD) for Design AEP (%)									
			50	20	10	5	2	1.33	1	0.5	0.2	0.1
Spurn Point	539856	410943	5.37	5.51	5.62	5.74	5.89	5.96	6.01	6.15	6.33	6.46
Buck Beck	532700	406580	5.43	5.57	5.68	5.79	5.95	6.01	6.06	6.19	6.37	6.53
Patrington	533399	418557	5.47	5.60	5.71	5.83	5.98	6.04	6.09	6.22	6.40	6.54
Sunk Island	530007	415325	5.50	5.63	5.74	5.86	6.00	6.07	6.11	6.23	6.41	6.55
Grimsby	527878	411346	5.51	5.65	5.75	5.87	6.01	6.08	6.12	6.24	6.41	6.55
Haborough Marsh	520790	415740	5.64	5.77	5.87	5.97	6.10	6.16	6.20	6.30	6.43	6.56
Immingham	519141	417449	5.68	5.81	5.91	6.01	6.14	6.19	6.22	6.33	6.45	6.56
Humber Sea Terminal	516710	420393	5.75	5.87	5.96	6.06	6.17	6.22	6.26	6.35	6.46	6.59
Paull	516516	426331	5.84	5.95	6.04	6.12	6.23	6.27	6.30	6.39	6.49	6.63
Humber King George	513950	428543	5.88	5.99	6.07	6.15	6.26	6.30	6.33	6.41	6.53	6.66
Hull Barrier	510194	428354	5.93	6.04	6.12	6.19	6.29	6.33	6.36	6.45	6.56	6.68
Albert Dock	509346	427749	5.95	6.05	6.12	6.20	6.30	6.34	6.36	6.46	6.56	6.68
Humber Bridge	502478	423914	6.10	6.18	6.25	6.31	6.41	6.45	6.48	6.55	6.63	6.71
Brough	493792	425938	6.19	6.26	6.30	6.34	6.40	6.44	6.46	6.52	6.58	6.63
West Walker Dykes	487883	423725	6.18	6.25	6.30	6.34	6.39	6.42	6.43	6.48	6.53	6.56
Burton Stather	486416	418432	6.18	6.23	6.26	6.28	6.31	6.32	6.34	6.36	6.38	6.39
Flixborough	485739	414584	6.21	6.25	6.28	6.30	6.32	6.33	6.33	6.35	6.36	6.38
Keadby	483557	411268	6.24	6.27	6.29	6.31	6.33	6.36	6.36	6.37	6.39	6.41
Gainsborough	481340	389770	5.91	5.93	6.09	6.38	6.57	6.74	6.75	6.91	7.06	7.17
Blacktoft	484247	424190	6.12	6.17	6.20	6.23	6.27	6.29	6.30	6.34	6.37	6.39
Goole	474857	422960	6.06	6.08	6.10	6.11	6.13	6.15	6.16	6.18	6.19	6.21
Barmby Barrage	468081	428630	6.08	6.08	6.08	6.13	6.14	6.14	6.14	6.15	6.15	6.16
Selby Lock	462227	432200	6.30	6.30	6.46	6.53	6.59	6.61	6.61	6.62	6.66	6.68
Went Outfall	466761	418738	6.22	6.24	6.24	6.26	6.27	6.27	6.27	6.27	6.28	6.28
Airmyn	472175	425015	6.06	6.06	6.06	6.11	6.12	6.13	6.13	6.14	6.14	6.14
Carlton Bridge	464550	422783	6.12	6.12	6.14	6.20	6.23	6.28	6.29	6.33	6.35	6.38
Fishlake	466841	413512	6.86	6.89	6.89	6.89	6.89	6.90	6.90	6.90	6.90	6.90
Kirk Bramwith	462055	411498	7.58	7.65	7.65	7.65	7.66	7.66	7.66	7.66	7.66	7.66
Doncaster	456991	404004	9.93	10.50	10.64	10.74	10.85	10.89	10.91	10.97	11.03	11.07

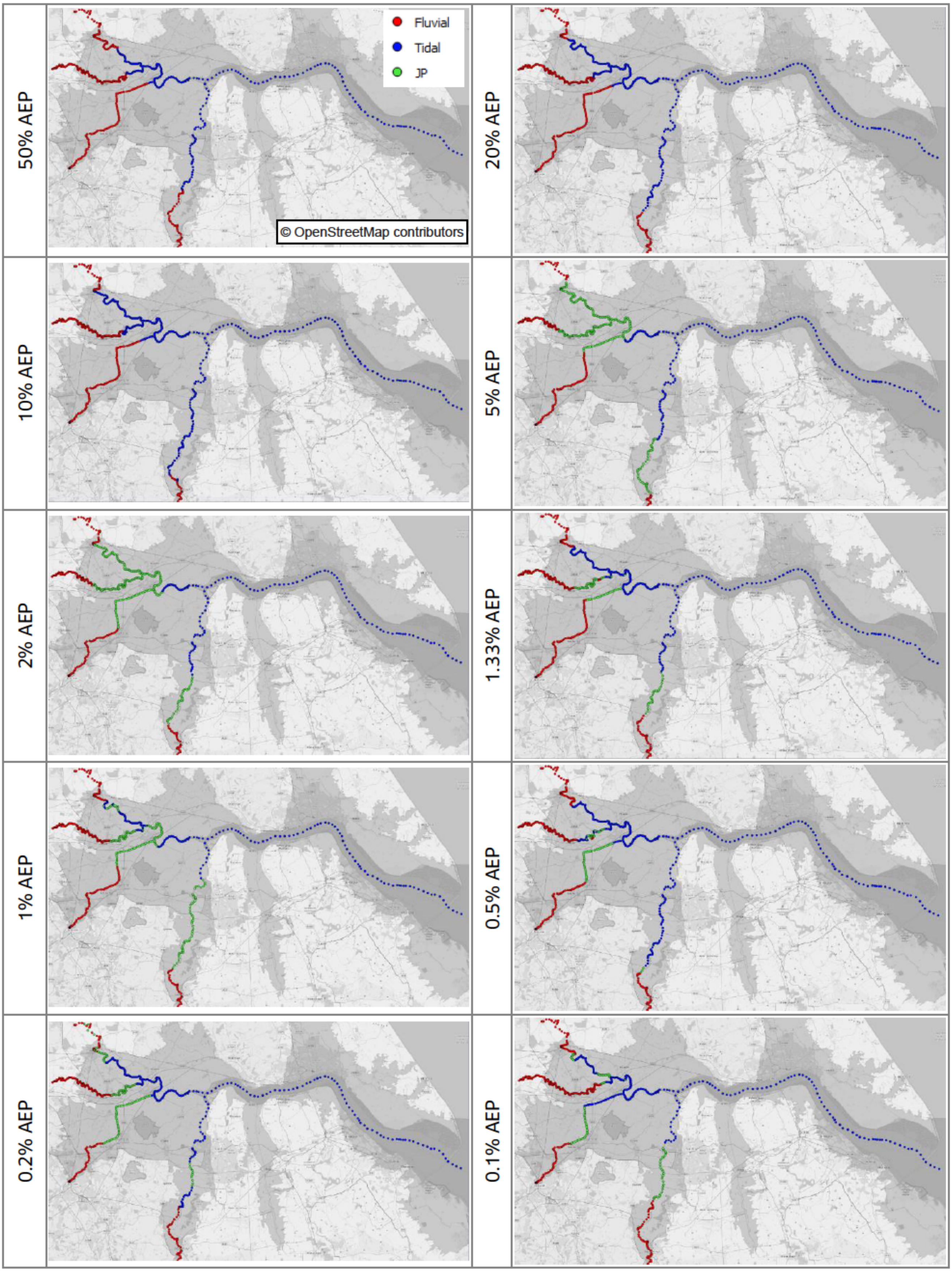


Figure 5.2: Event type which produces extreme water level – 2021 H

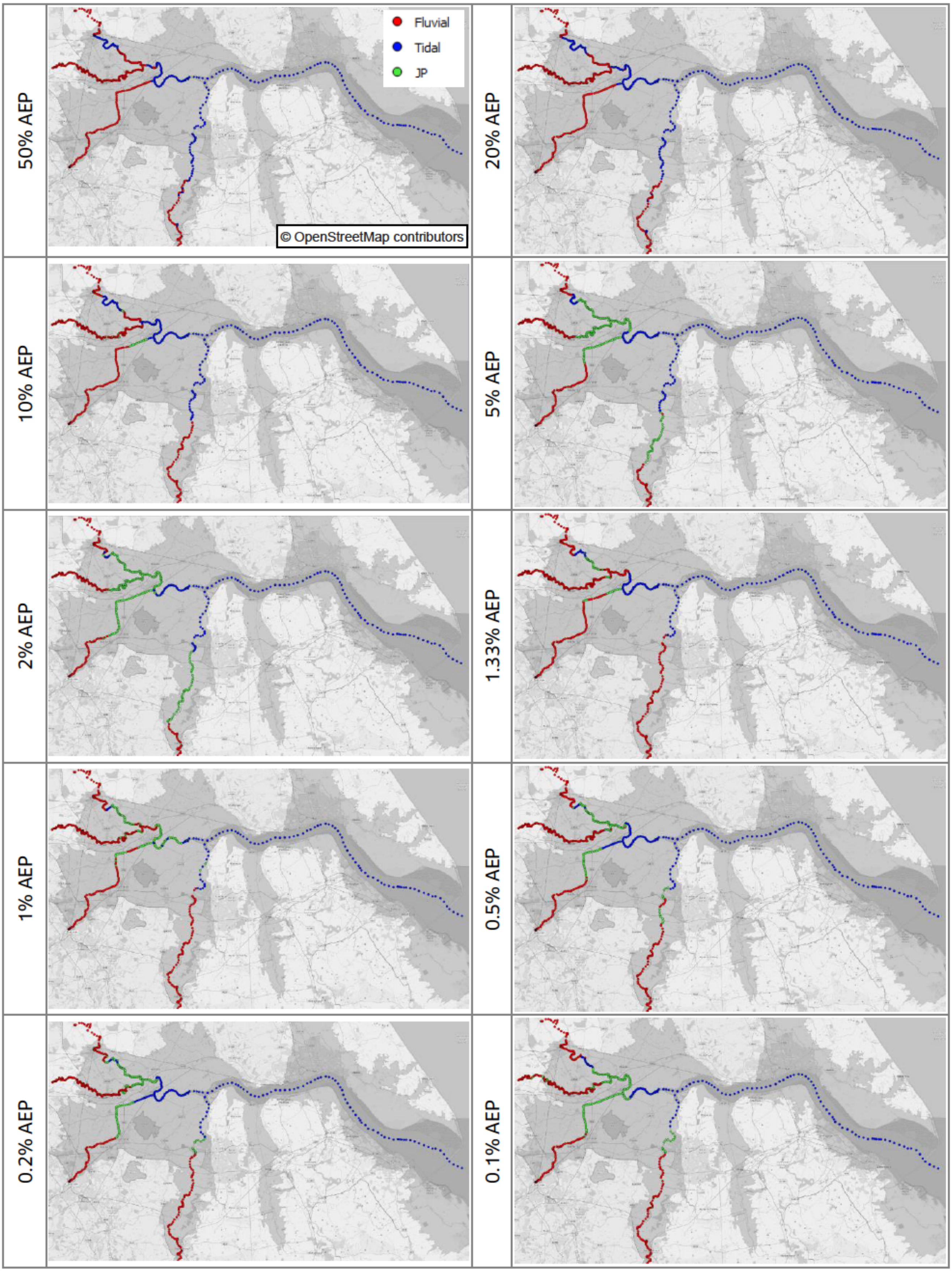


Figure 5.3: Event type which produces extreme water level – 2121 H

5.3 Verification of extremes

The verification was undertaken to assess the plausibility of the extremes. Table 5.3 lists the approaches taken for the verification.

Table 5.3: Verification approaches for the extreme water levels

No.	Verification Approach	Comment
V1	Graphs of extreme water level against probability for key locations (including locations with gauge data), with selected recorded gauge values and selected defence crest levels added Refer to Chapter 5.3.1 and Appendix H.	The historic water levels are limited to the events used for model calibration. Additional historic water levels for the recent 2019 and 2020 floods are also included at relevant gauges on the Ouse, Aire and Don. The defence levels are indicative and based on the average levels near the gauge. If overtopping away from the gauge acts as a control on water levels the indicative defence could be misleading. Between Spurn and Humber bridge the profile is reasonably linear due to the proximity to the model boundary and limited defence overtopping. Between Keadby to Brough the shape starts to flatten around the 1% AEP due to overtopping of defences On the Don, defences impact water levels at Kirk Bramwith and Fishlake from the 20% AEP
V2	For Immingham, tabulate against CFB18 extremes. Refer to Chapter 5.3.2	The modelled results are higher than CFB18 (between 0.04m to 0.09m higher) but follow a similar shape and lower than the CFB18 upper bound.
V3	Graphs of extreme water level against probability the 2014 interim water level profile added Refer to Chapter 5.3.3 and Appendix I	At Immingham the modelled results are similar to the 2014 IWL (0.01m higher for 0.5% AEP, same for higher events). Similar comparisons can be made to the gauges downstream of Immingham. Between Paull and Humber Bridge and at Goole the modelled levels are lower (maximum 0.29m lower) At Gainsborough the modelled levels are much higher as the IWL 2014 did not consider fluvial events At Brough, Blacktoft, Burton Stather, Flixborough, Keadby, and Owston the modelled levels tend to be lower for AEPs below 1% and higher for AEPs above the 1%.
V4	For the tidal rivers, compare with extremes from previous studies where available Refer to Chapter 5.3.4 and Appendix J	Where boundary conditions allow for a comparison the 2021 extremes are consistent with other studies. The majority of the model results are within +/-0.2m, where the differences are larger, the principle reason is that the 2021 extremes include a fluvial uplift (+20% for upper).
V5	Long section plots of extreme water levels (for all AEPs) against distance from Spurn (four plots to cover the Ouse, Aire, Don and Trent) Refer to Chapter 5.3.5	The variation in extremes along the estuary and tidal rivers looks plausible. The keys feature of the profiles for 2021 are: ▪ Overtopping of defences upstream of Brough to Selby (Ouse), Went Outfall (Don) and Snaith (Aire) show peak levels to become similar (around 6.1m – 6.2m) for the 0.5% AEP and higher events. ▪ The step in level at Selby is due to the bridges (~0.4m loss was recorded between gauges at Selby Westmill and Selby Lock for fluvial calibration events). The bridges are unchanged from the EA approved model (Upper Humber Flood Risk Mapping Study, JBA,

No.	Verification Approach	Comment
		August 2016), there was no survey information available to undertake any checks, ▪ The step in level which starts on the 0.2% AEP on the Aire at (chainage 109km) is due to the East Coast railway line embankment. ▪ The step in level between Kirk Bramwith and Fishlake on the Don is due to Stainforth Bridge. ▪ The change in level around Stockwith is due to floodplain flow on the western floodplain spilling back to the river Trent and the hydraulics associated at the change in maximum levels from the JP for tidal/fluvial events The keys feature of the profiles for 2121 are: ▪ The profile of water levels increasing from the downstream boundary at Spurn and peaking around Humber Bridge is due to the inland tide increasing levels as the channel becomes narrower and causes a constriction. ▪ All AEP events are overtopping defences upstream of Brough to Selby (Ouse), Went Outfall (Don) and Snaith (Aire) showing a flatter profiles (control is the defence levels). ▪ The range between the lower and higher AEP events is reduced as water levels are influenced by spilling over defences.
V6	As A5 with contributing JP scenario ID displayed Refer to Chapter 5.3.6	Results show (0.5% AEP commented on) that the maxima at each location is derived by the expected joint probability event i.e. fluvial in upper reaches, tidal in lower reaches and joint probability between.

5.3.1 Comparison with recorded flood data

The 2021 extreme water levels are compared to all gauges (gauge locations in Figure 5.1) in Appendix H. Where there are changes in the AEP water level profiles, commentary has been added to the plots in Figure 5.4 to Figure 5.9. This includes the gauges at Selby Lock, Carlton Bridge, Gainsborough, Went, Fishlake and Kirk Bramwith.

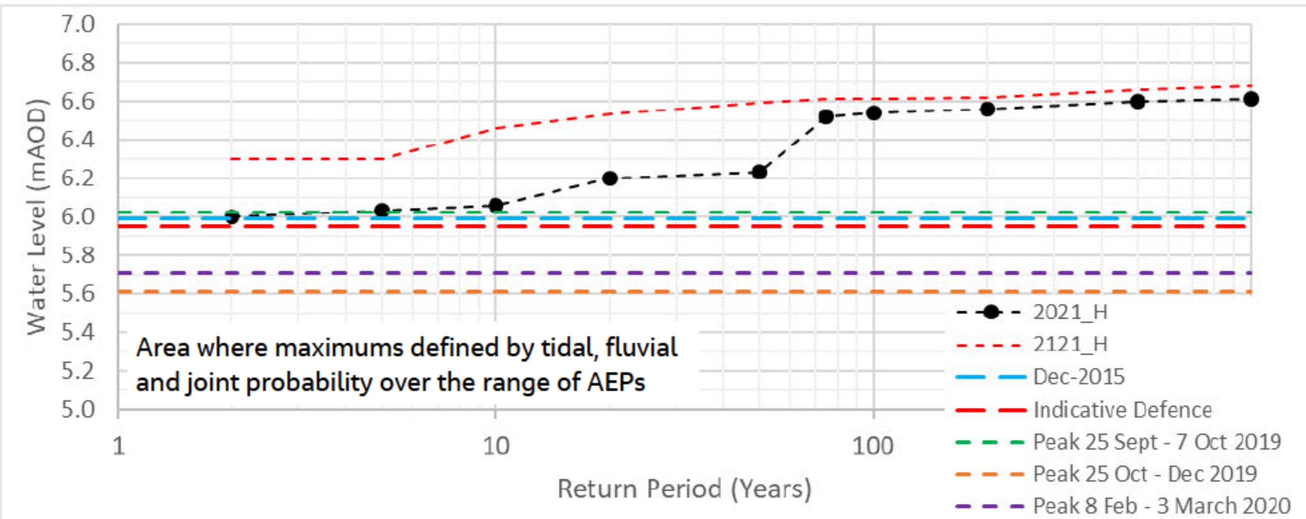


Figure 5.4: 2021 EWL with historic flood and indicative defence levels – Selby Lock

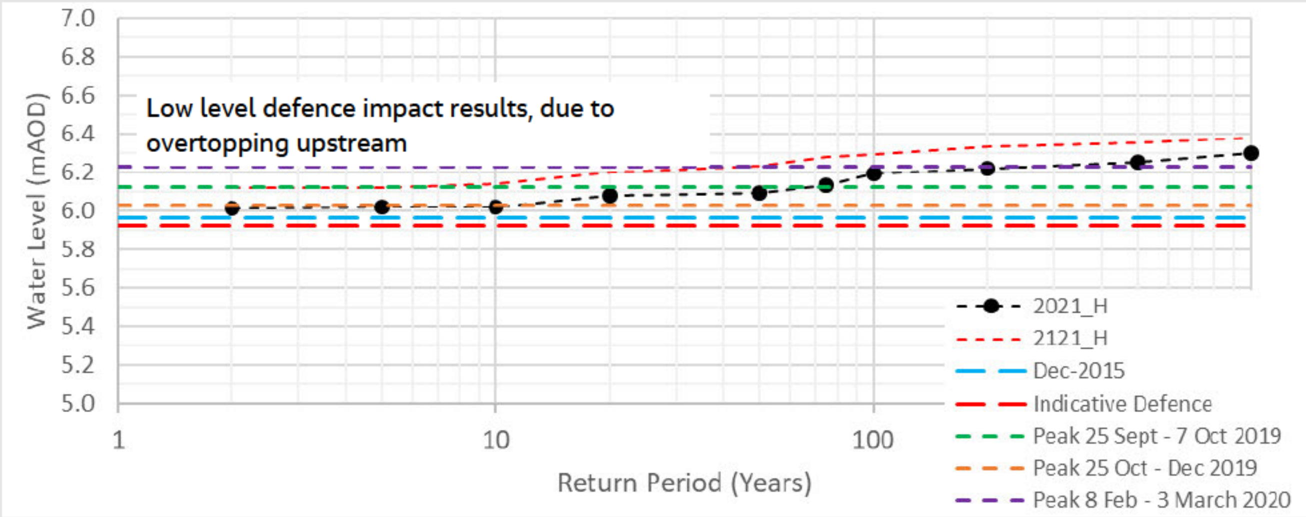


Figure 5.5: 2021 EWL with historic flood and indicative defence levels – Carlton Bridge

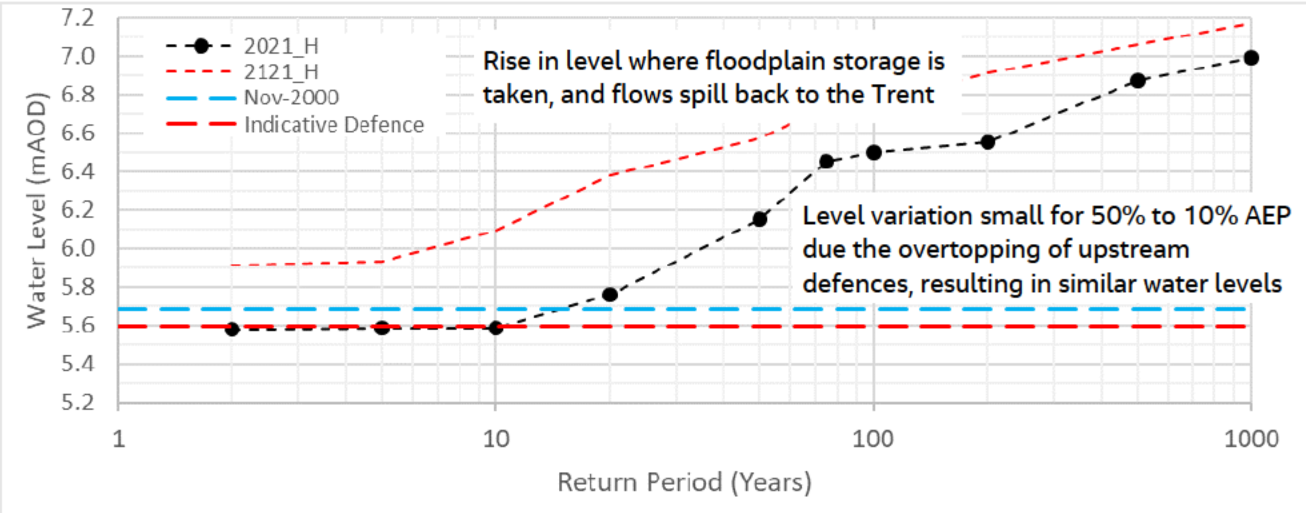


Figure 5.6: 2021 EWL with historic flood and indicative defence levels – Gainsborough

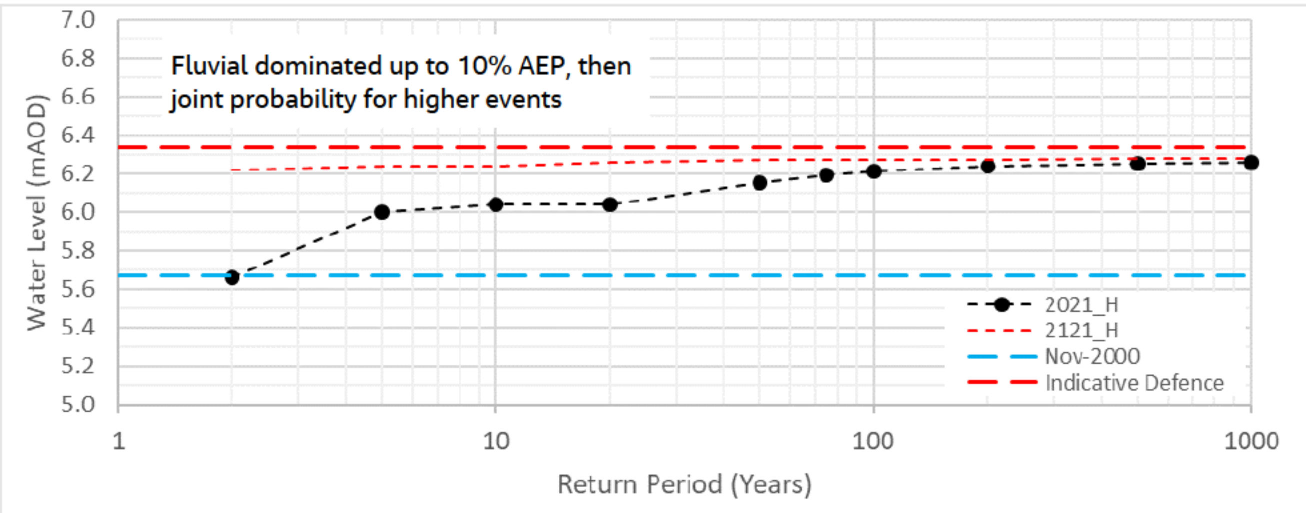


Figure 5.7: 2021 EWL with historic flood and indicative defence levels – Went Outfall

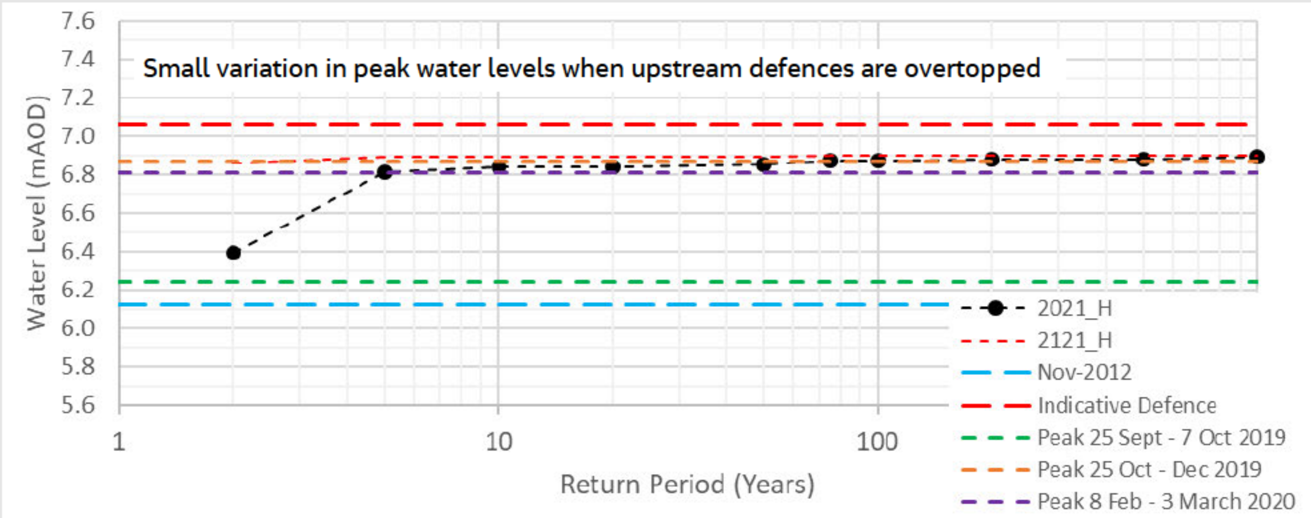


Figure 5.8: 2021 EWL with historic flood and indicative defence levels – Fishlake

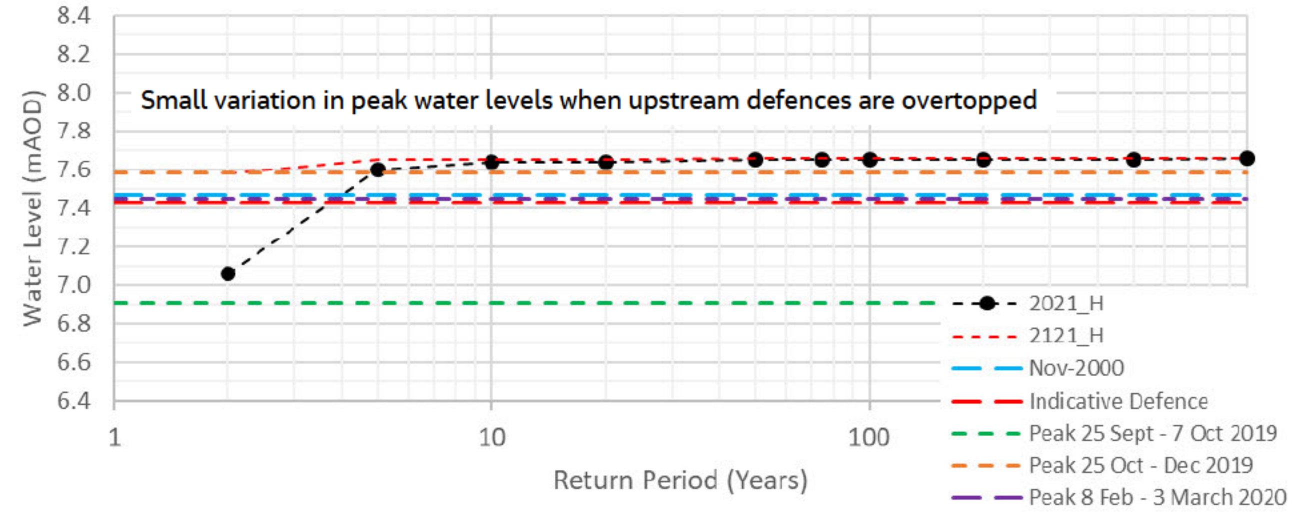


Figure 5.9: 2021 EWL with historic flood and indicative defence levels – Kirk Bramwith

5.3.2 Comparison with CFB2018 at Immingham

Modelled extreme water levels for the three 2021 scenarios are compared to the CFB2018 predictions in Table 5.4 and Figure 5.10. The modelled results are higher than the CFB2018 (0.09m for 0.5% AEP) but sit within the upper and lower estimates. The reason for the higher level is due to the combination of sea level rise (0.03m applied for the 2021_H – upper scenario) and the model hydraulics between Immingham and the downstream boundary.

Table 5.4: 2021 Extremes compared to CFB2018 at Immingham

Scenario/Source	EWL (mAOD) for Design AEP (%)									
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
2021 M	4.31	4.45	4.57	4.69	4.85	4.93	4.98	5.14	5.32	5.46
2021 H	4.32	4.46	4.58	4.70	4.86	4.94	4.99	5.15	5.33	5.47
2021 H++	4.32	4.46	4.58	4.70	4.86	4.94	4.99	5.15	5.33	5.47
CFB 2018	4.27	4.42	4.53	4.65	4.80	4.88	4.93	5.06	5.24	5.38
CFB 2018 Lower	4.26	4.39	4.50	4.60	4.73	4.79	4.83	4.93	5.05	5.15
CFB 2018 Upper	4.31	4.47	4.62	4.77	5.00	5.11	5.19	5.41	5.73	6.01

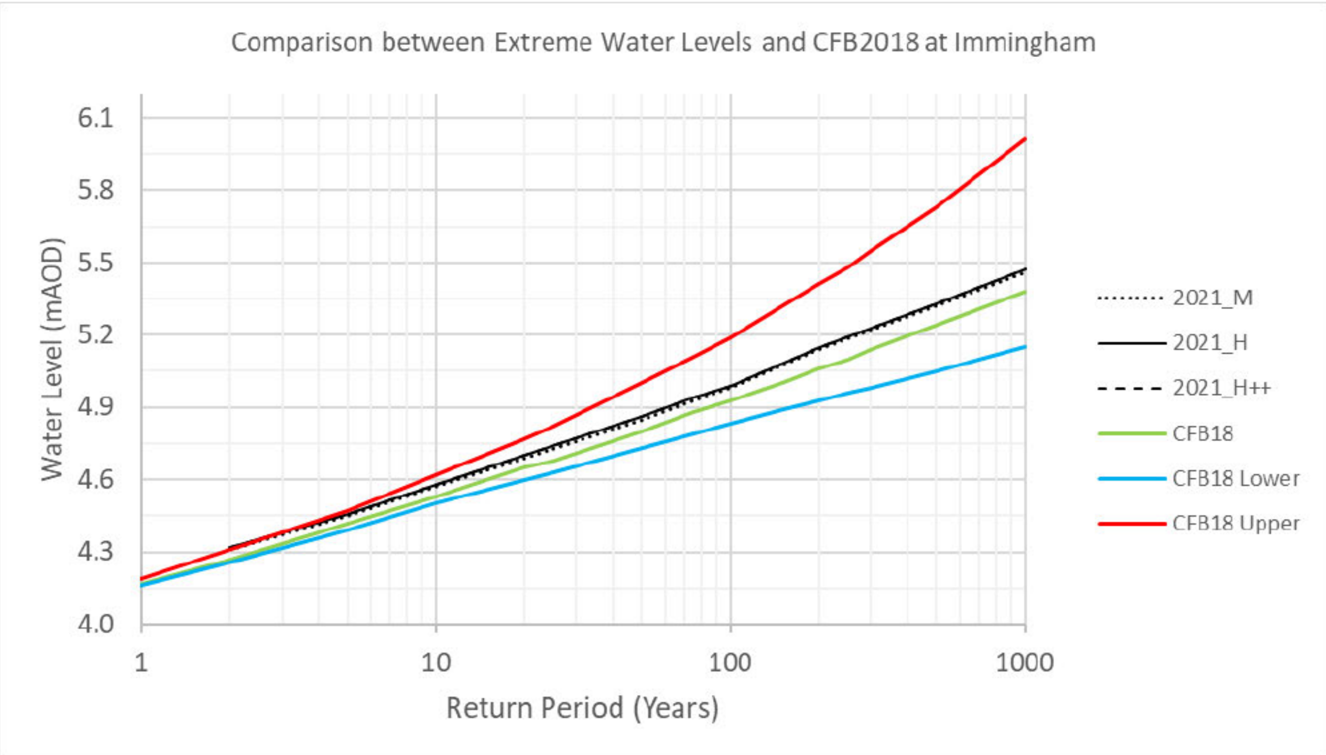


Figure 5.10: 2021 Extremes compared to CFB2018 at Immingham

5.3.3 Comparison with 2014 Interim water levels

The 2014 interim water levels were based on a review and analysis of the tidal gauge data along the Humber estuary, following the extreme tidal surge of 5th December 2013. They were termed interim as they were issued in response to the 2013 surge for interim use whilst more detailed modelling and analysis was undertaken.

The 2014 study undertook an extreme value analysis of extremes at Immingham and carried out a regression analysis to predict extreme water levels at other locations in the Humber Estuary, based on the Immingham levels to provide preliminary estimates of extremes at these locations. The 2014 study method would not provide an allowance for bank overtopping apart from areas where gauge data is impacted by overtopping. The 2014 study also did not allow for fluvial extremes (as highlighted in the interim levels at Gainsborough). The approach now adopted for the EWL is now more robust (i.e. full JP, defence overtopping etc).

The 2014 interim water levels at the gauge locations detailed in Figure 5.11 are compared to the new extreme water levels. The figure includes commentary on the differences between the modelled extremes and the 2014 IWL. The comparison at Immingham, Goole and Keadby are detailed in Figure 5.12, all gauge comparisons are included in Appendix I.

The 2014 interim water levels at Immingham are compared to the modelled EWL in Table 5.5, the modelled results are slightly lower for the 10%, 2% and 1% AEP, 0.01m higher for the 0.5% AEP and predict the same water level for the 0.2% and 0.1% AEP. At Goole the modelled levels are lower than the 2014 IWL and at Keadby modelled levels are lower for AEPs below 1% and higher for AEPs above the 1%.

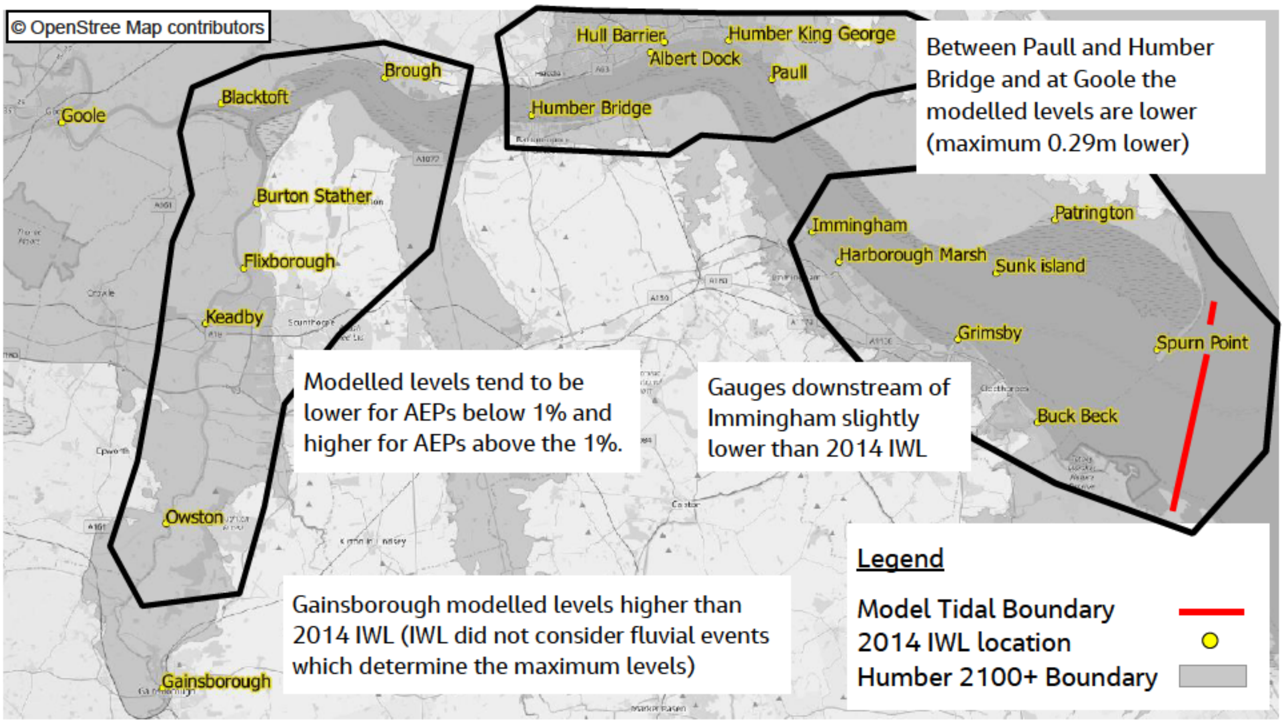


Figure 5.11: 2014 Interim Water Level locations

Table 5.5: 2014 Interim water level comparison at Immingham

AEP (%)	RP (1 in X year)	2014 IWL	New EWL (2021_H)	Difference (m)
10	10	4.61	4.58	-0.03
2	50	4.88	4.86	-0.02
1	100	5.01	4.99	-0.02
0.5	200	5.14	5.15	0.01
0.2	500	5.33	5.33	0.00
0.1	1000	5.47	5.47	0.00

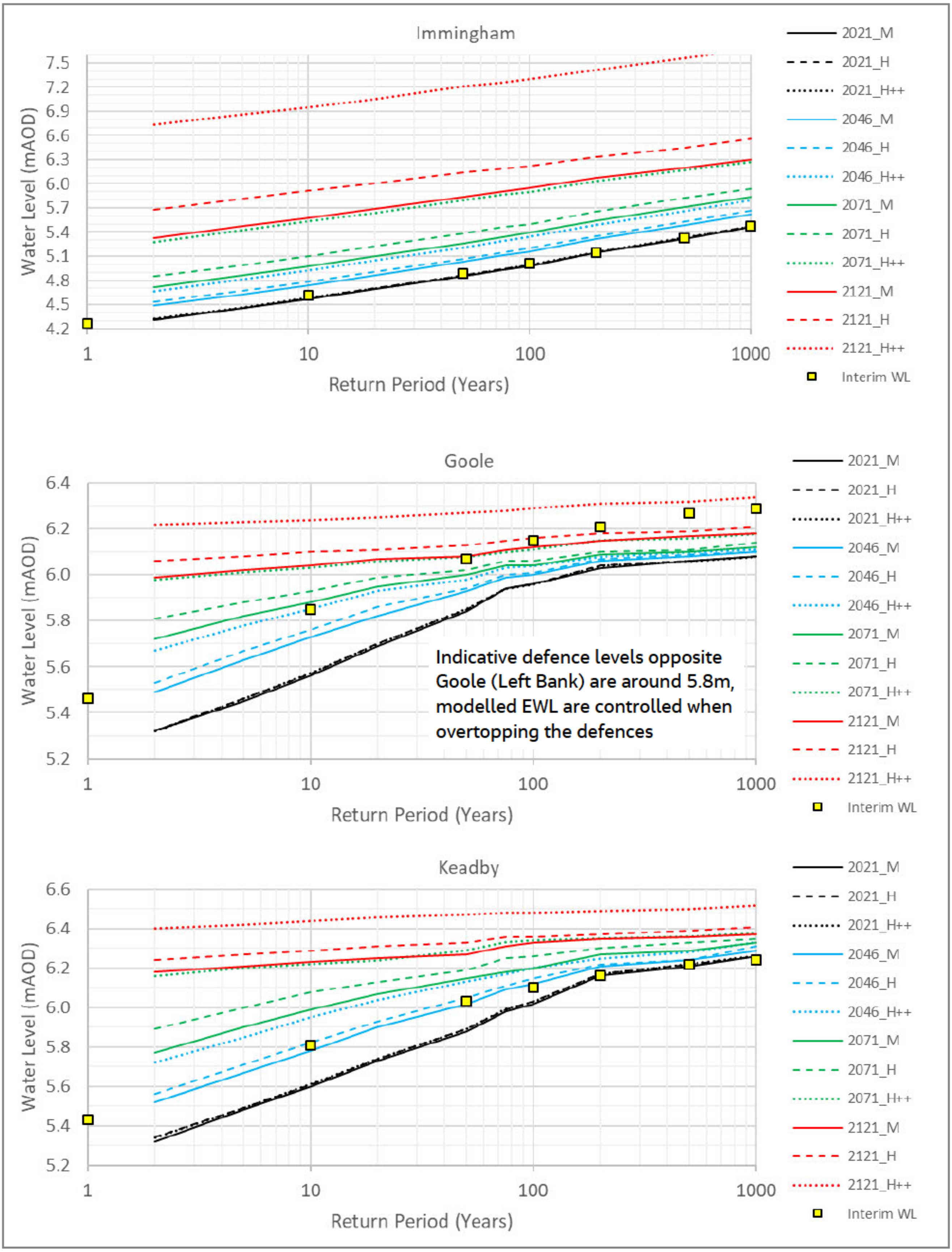


Figure 5.12: Extreme water levels compared to 2014 IWL at Immingham, Goole and Keadby

5.3.4 Comparison to previous studies

The 2021 extreme water levels are compared to existing modelling at gauges where comparisons could be made. The existing modelling studies used for the comparison are detailed in Table 5.6.

The full set of comparison profiles are detailed in Appendix J, Figure 5.12 to Figure 5.15 show example comparisons at Goole, Fishlake and Gainsborough.

Table 5.6: Existing modelling studies used to verify 2021 extreme water levels

Existing Study	Gauges compared	Legend used level charts
Ouse and Wharfe Washlands Optimisation Study. Mott MacDonald, July 2018	Blacktoft, Goole, Selby Lock, Selby Westmill	Ouse Volume Peak Ouse Tidal
Northern Forecasting Package: Lower Aire Model. JBA, July 2017	Chapel Haddlesey	Aire Fluvial
Don Catchment Model: Hydrology Report. JBA, February 2017.	Fishlake, Kirk Bramwith, Doncaster, Went Outfall	Don Fluvial
Tidal Trent Modelling and Mapping Study. Addendum. Mott MacDonald, Jan 2015	Burton Stather, Flixborough, Keadby, Gainsborough	Trent Tidal Trent Fluvial
Upper Humber Flood Risk Mapping Study. JBA, August 2016	Burton Stather, Flixborough, Blacktoft, Goole, Barmby Barrage, Selby Lock, Went Outfall, Airmyn, Carton Bridge, Fishlake, Kirk Bramwith, Selby Westmill, and River Aire at Snaith/Gowdall/Hensall Ings	Upper Humber

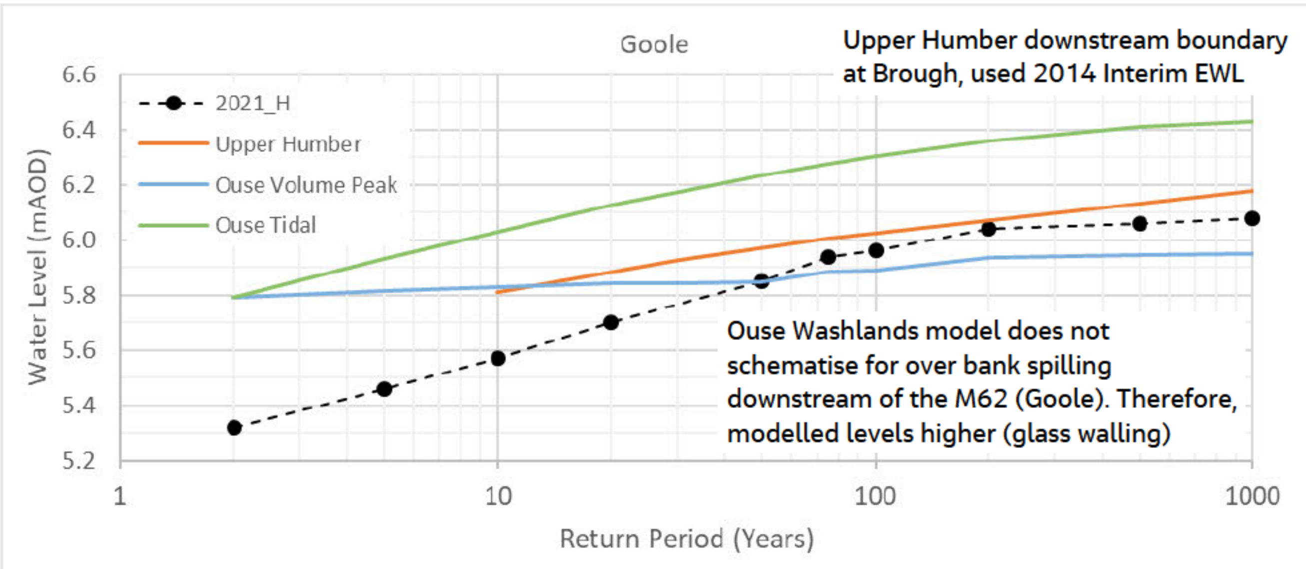


Figure 5.13: Extreme 2021 water levels compared to existing model results - Goole

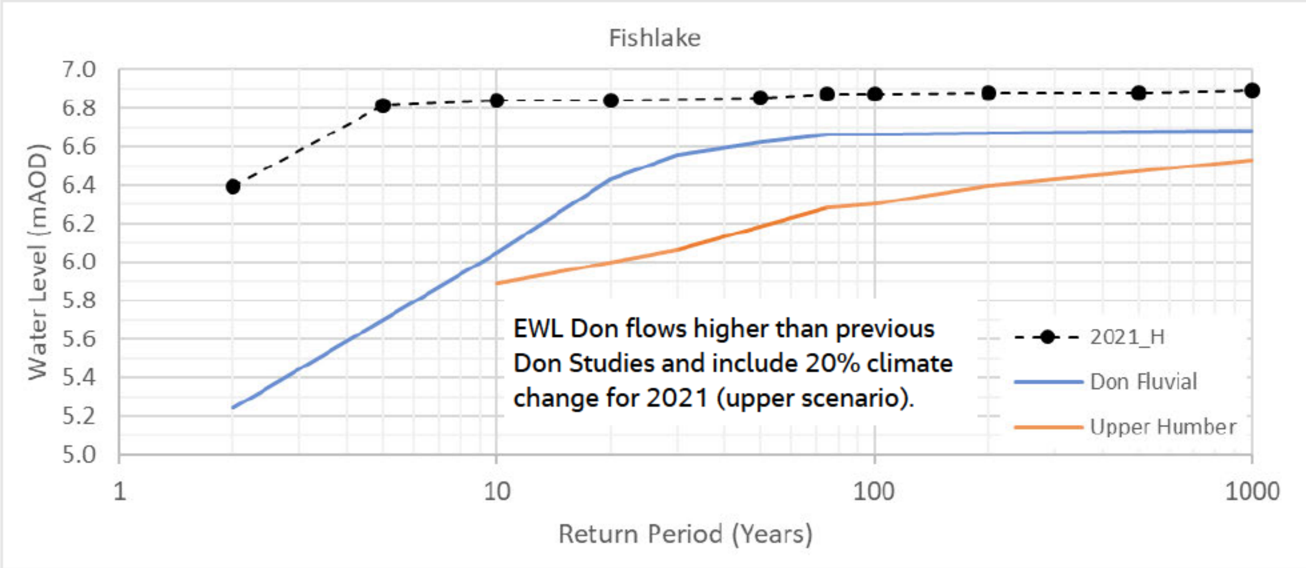


Figure 5.14: Extreme 2021 water levels compared to existing model results - Fishlake

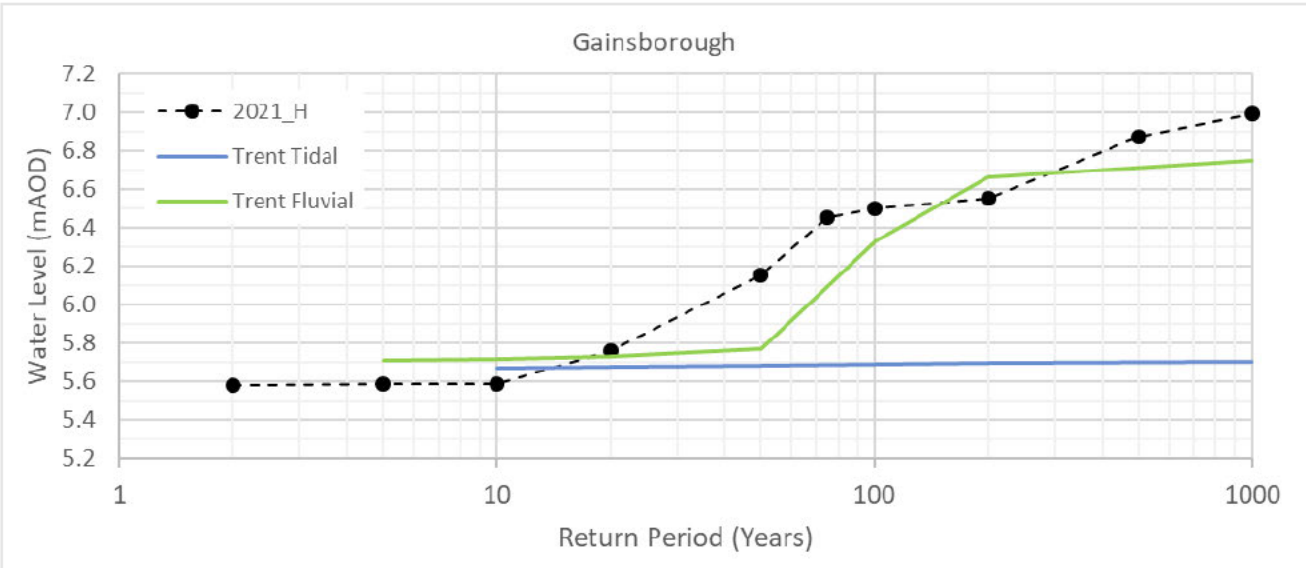
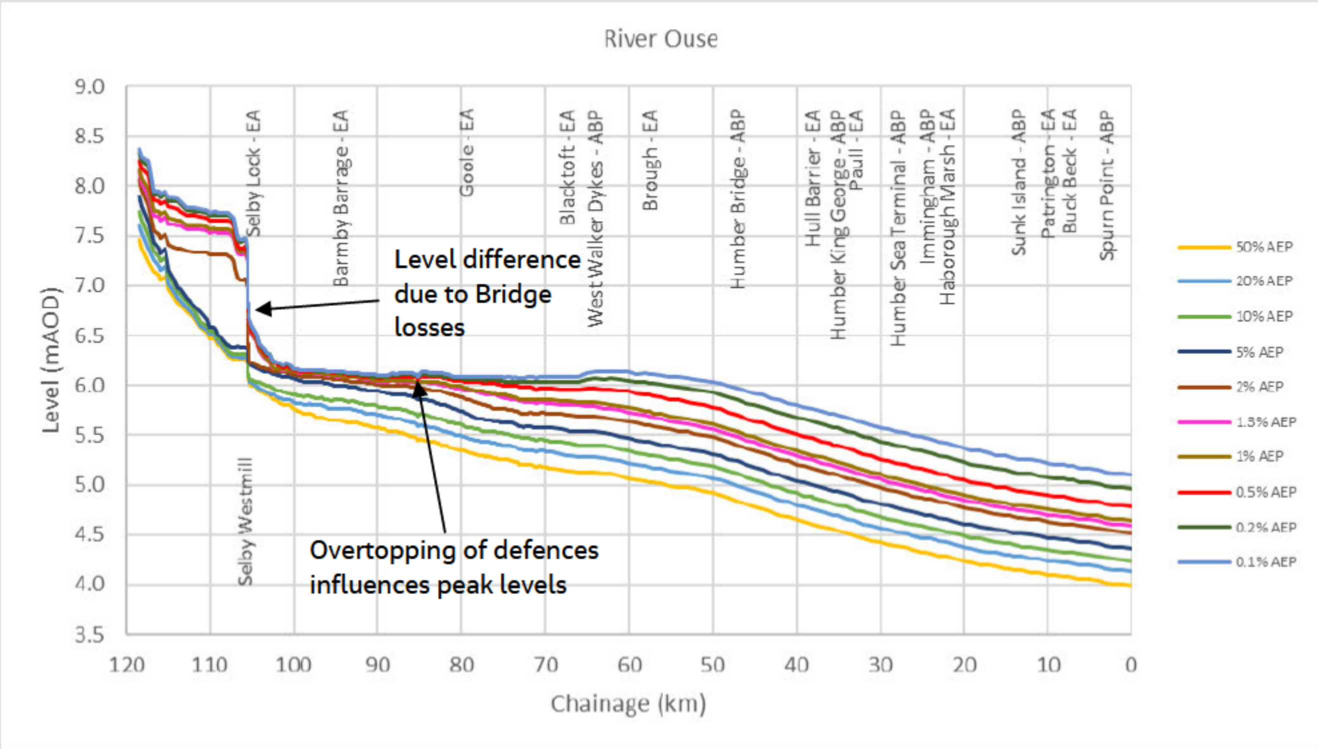


Figure 5.15: Extreme 2021 water levels compared to existing model results - Gainsborough

5.3.5 Long section profiles for extreme water levels (all AEP)

Long section profiles which include all AEP maximum water levels for the 2021 and 2121 (upper) scenarios are detailed in Figure 5.16 (Ouse), Figure 5.17 (Aire), Figure 5.18 (Don) and Figure 5.19 (Trent).



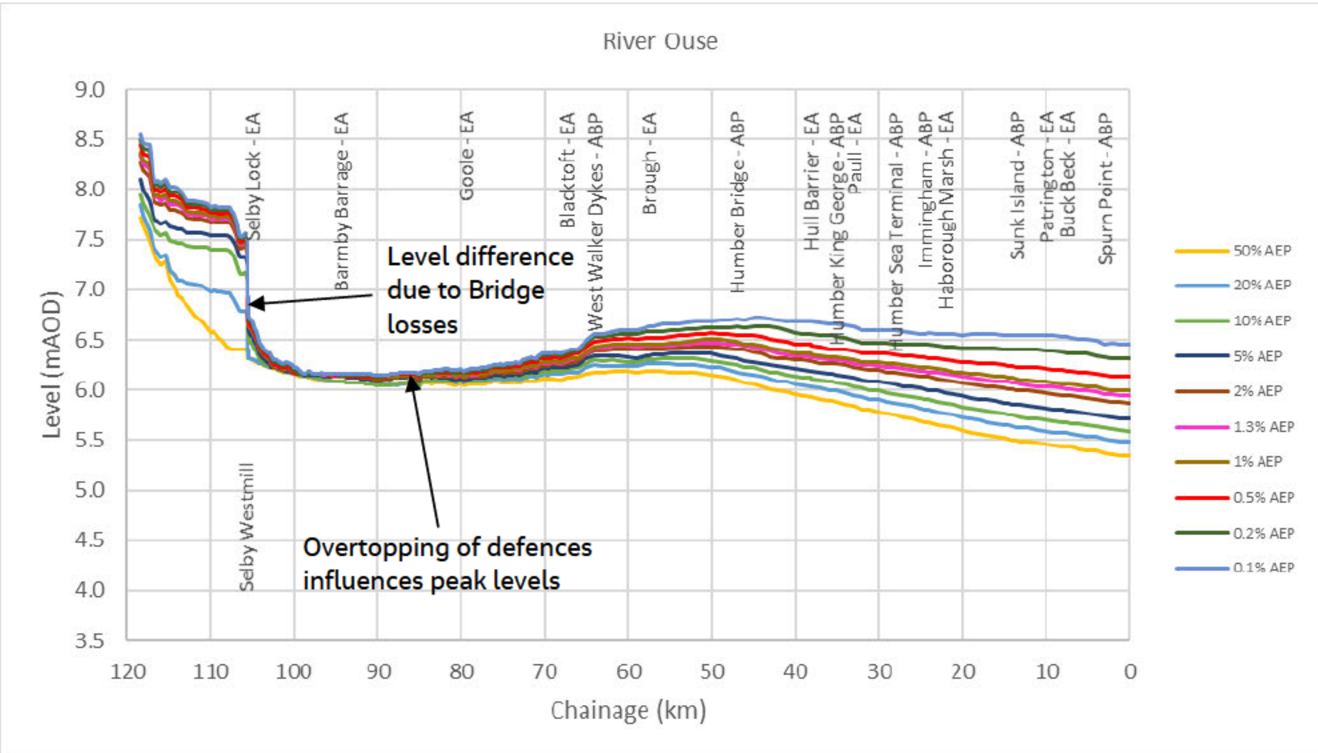
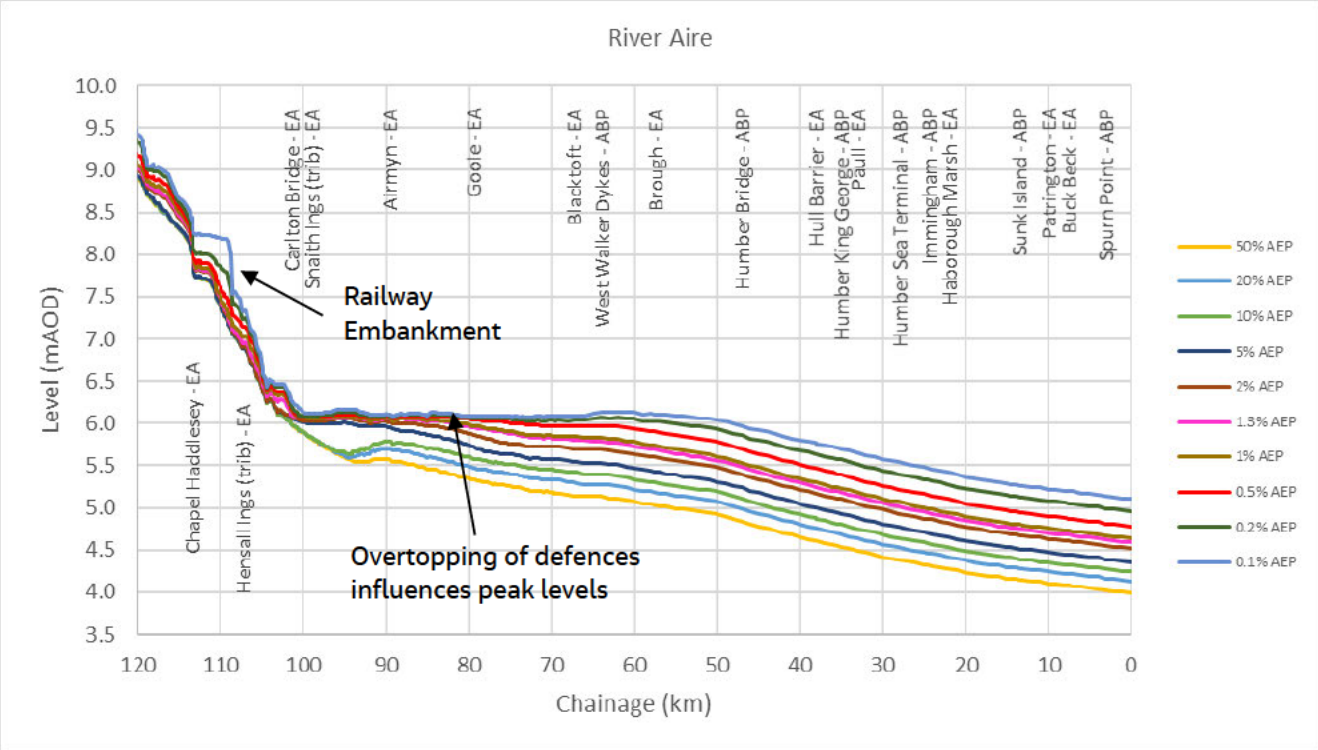


Figure 5.16: River Ouse extreme water levels – 2021 H (upper chart) and 2121H (lower chart)



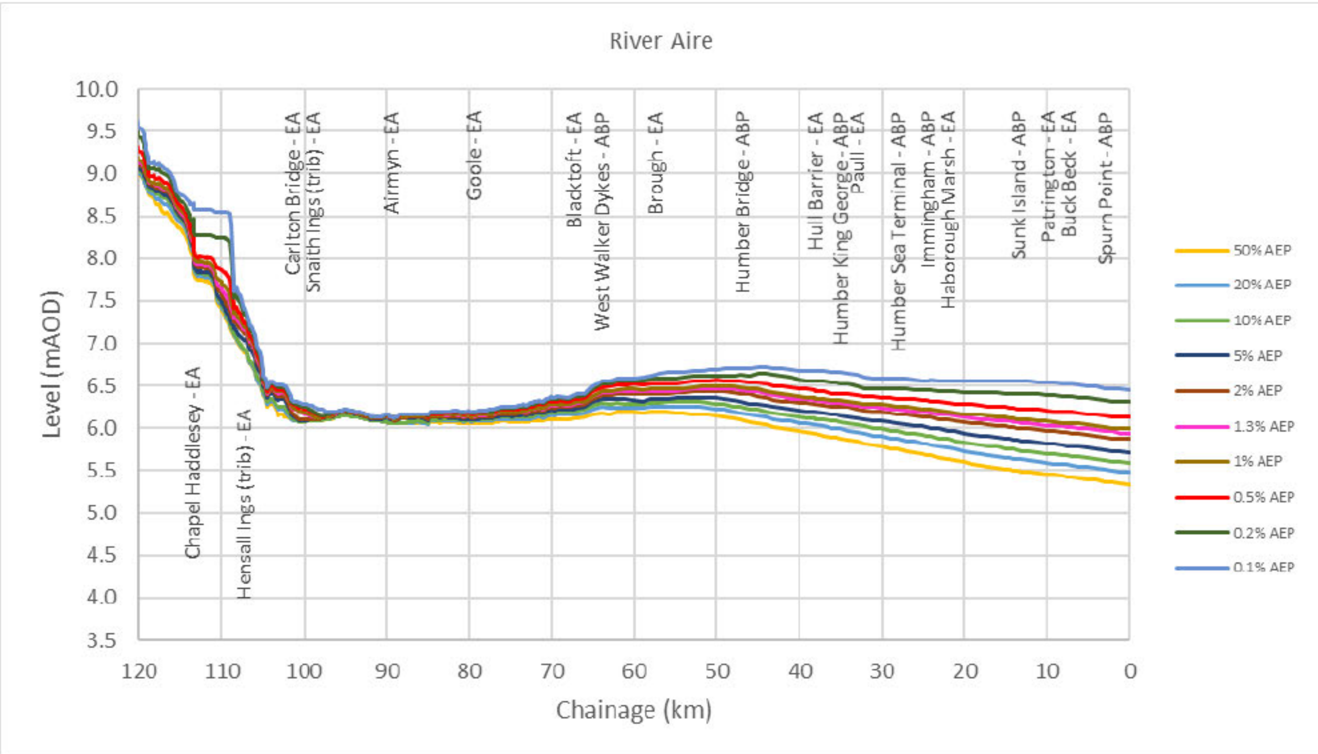
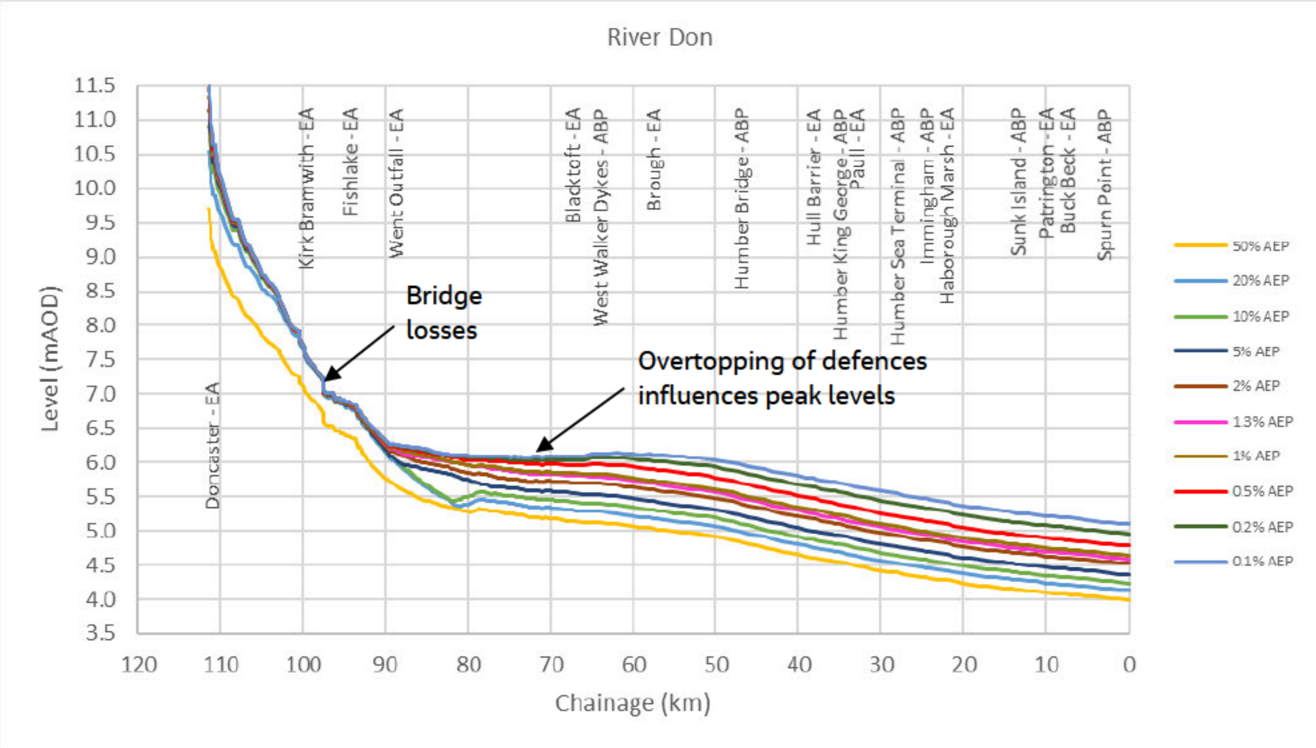


Figure 5.17: River Aire extreme water levels – 2021 H (upper chart) and 2121H (lower chart)



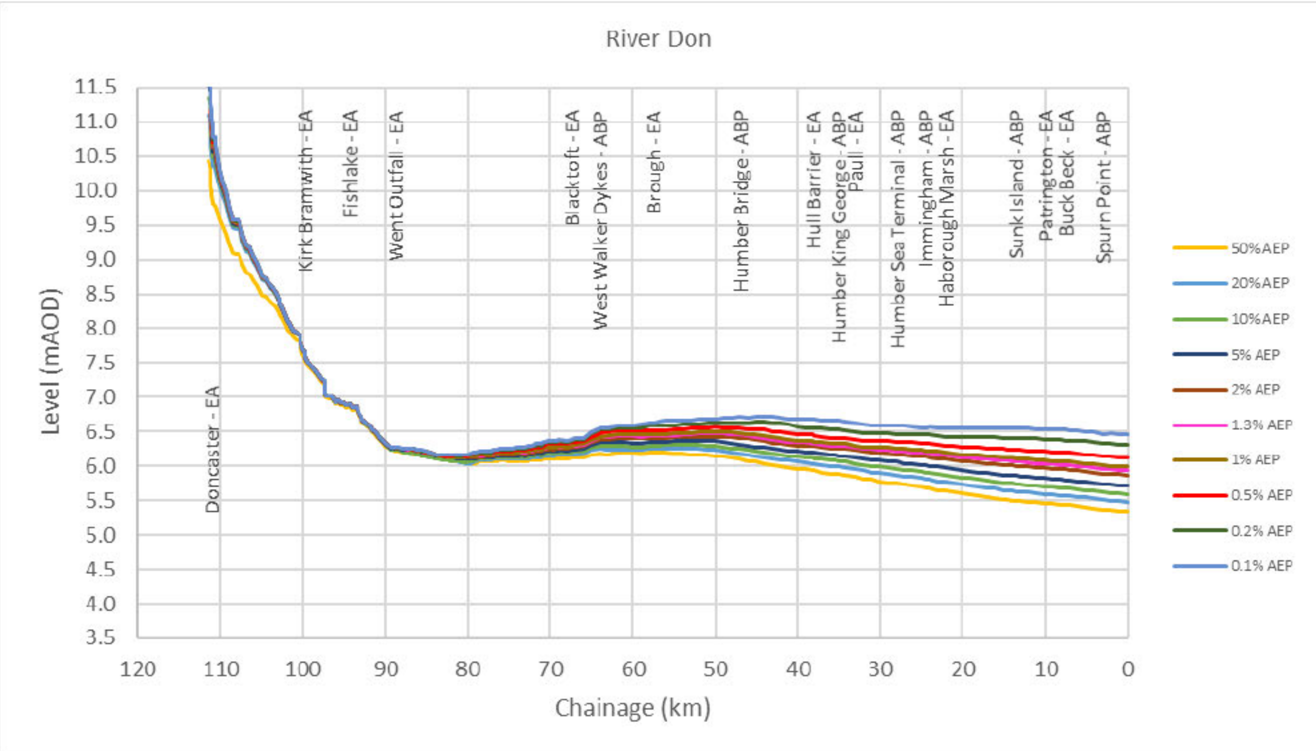
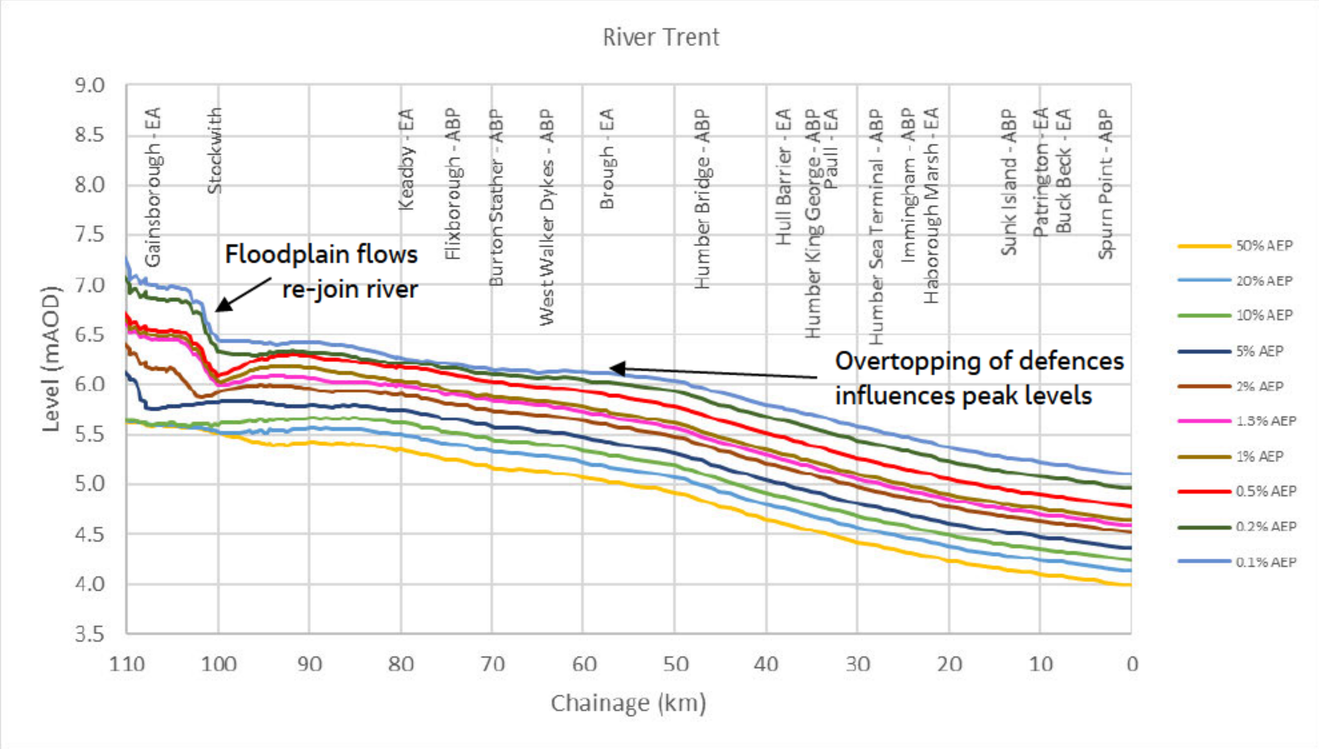


Figure 5.18: River Don extreme water levels – 2021 H (upper chart) and 2121H (lower chart)



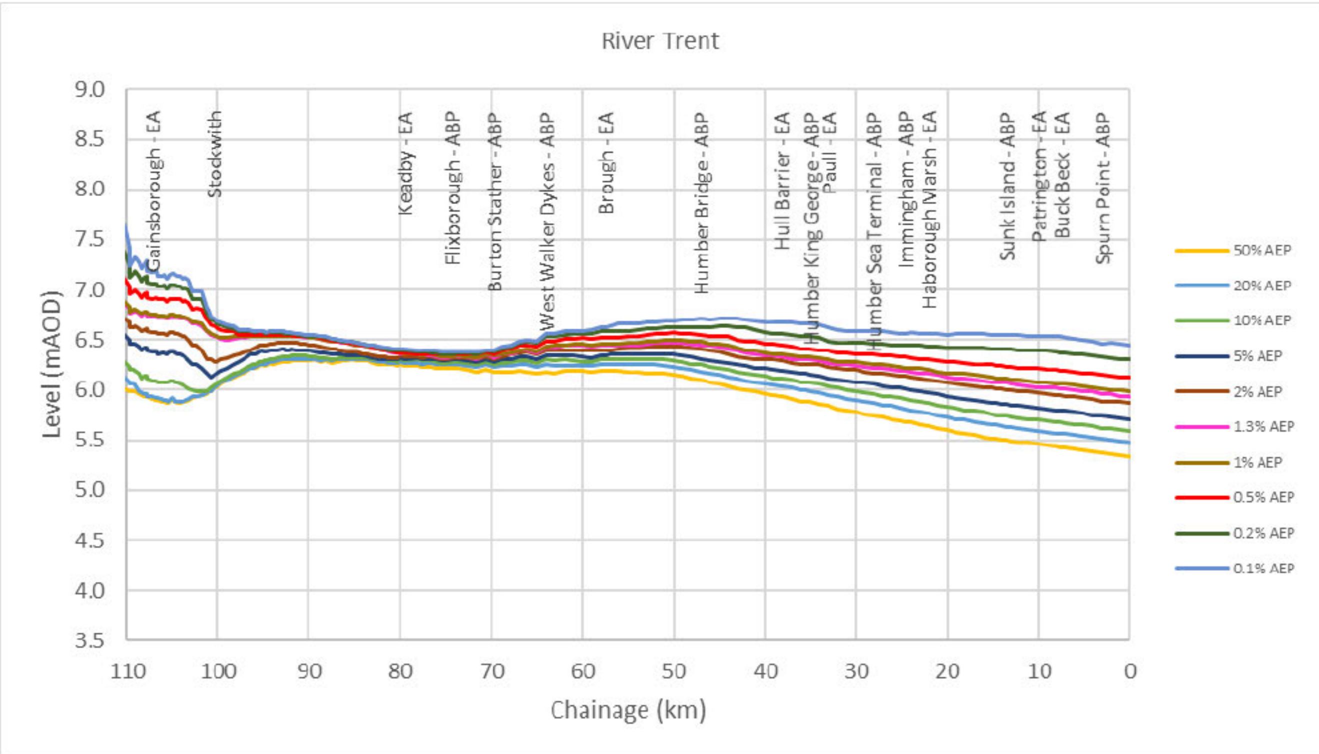
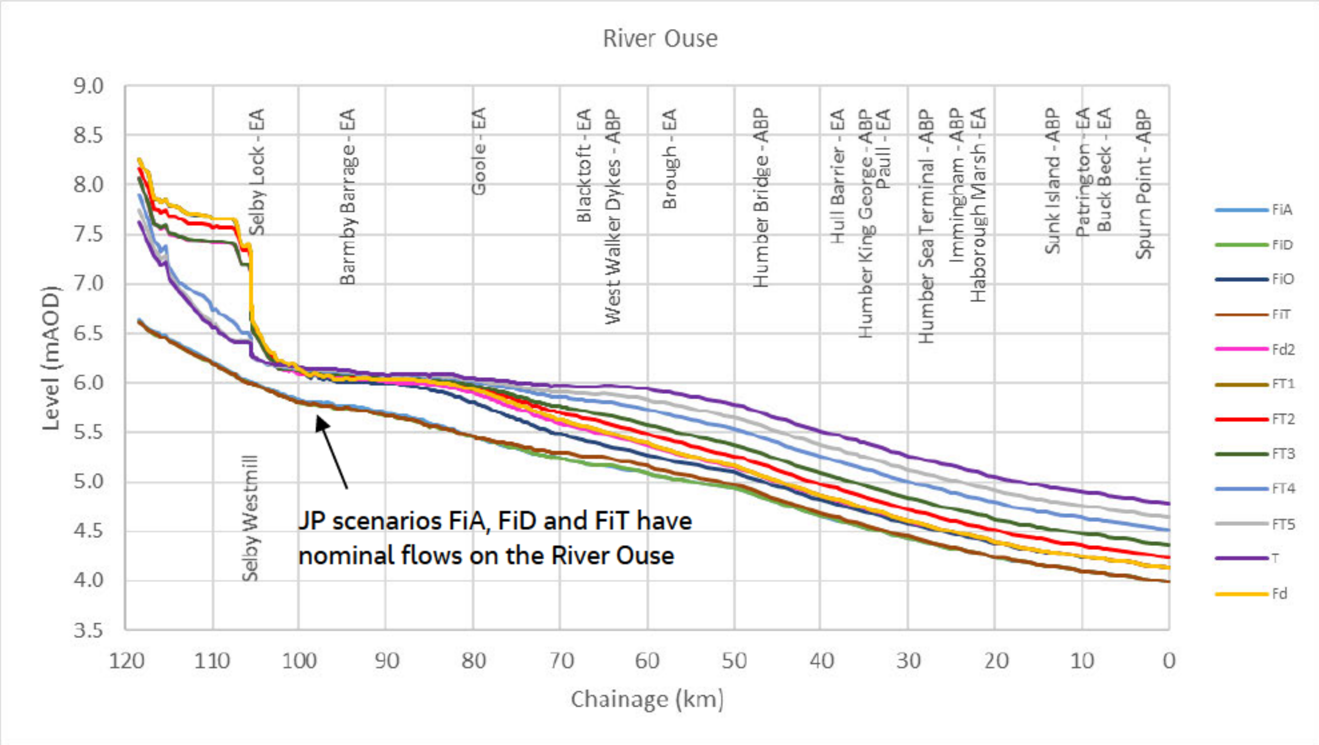


Figure 5.19: River Trent extreme water levels – 2021 H (upper chart) and 2121H (lower chart)

5.3.6 Long section profiles for 0.5% AEP (all joint probability events)

Long sections profiles for the 2021 and 2121 (upper) scenarios are detailed in Figure 5.20 (Ouse), Figure 5.21 (Aire), Figure 5.22 (Don) and Figure 5.23 (Trent).



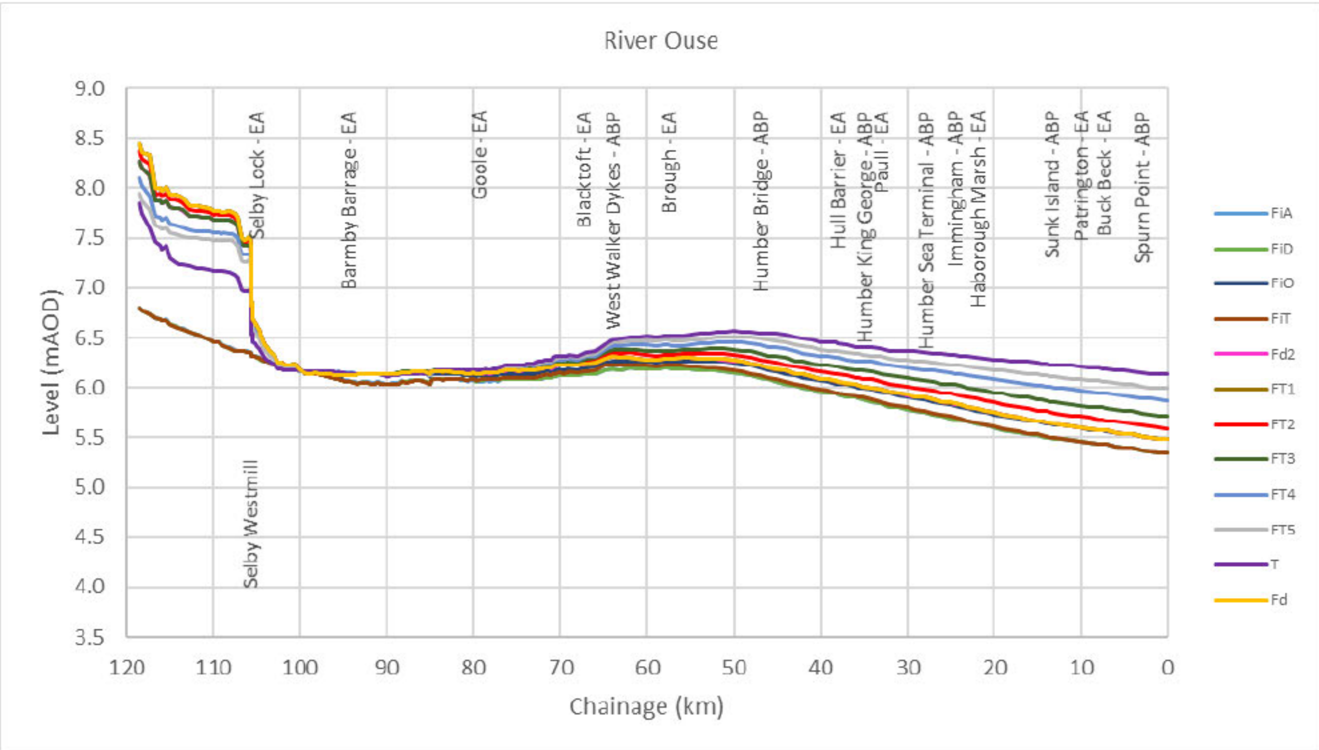
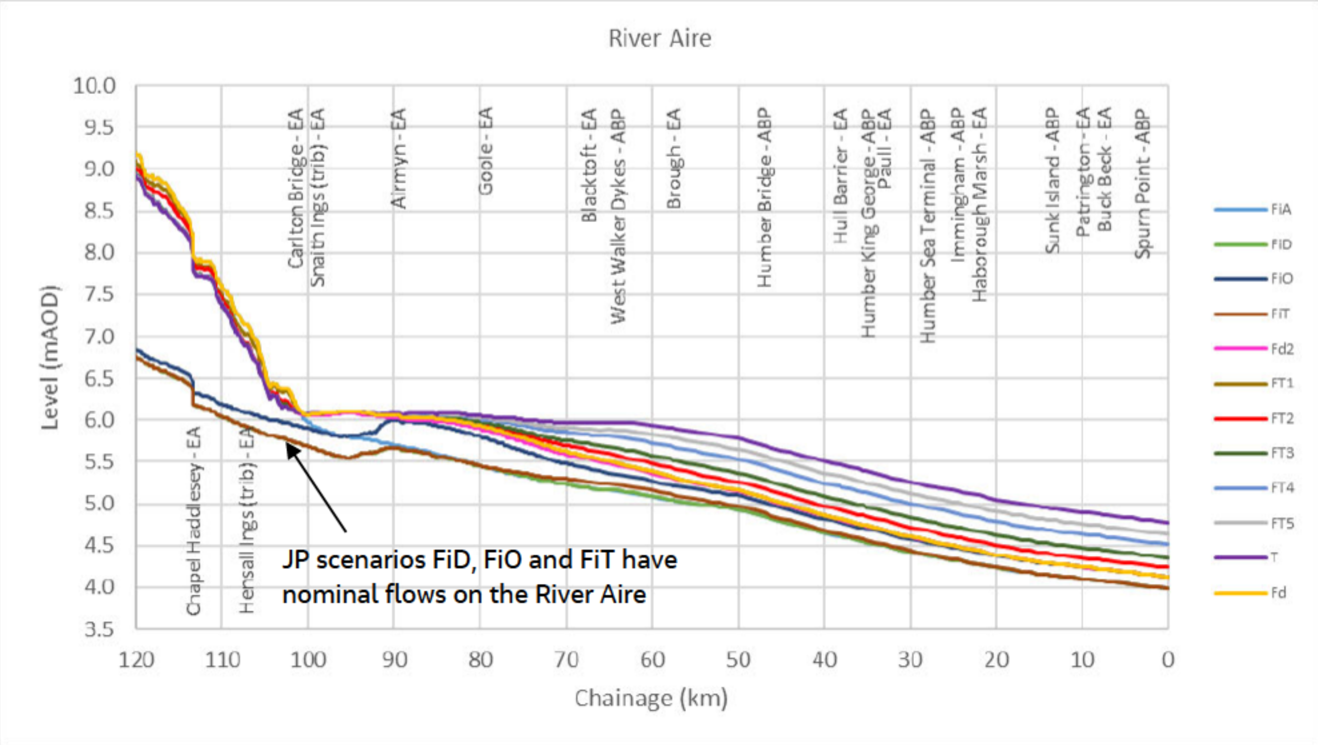


Figure 5.20: River Ouse 0.5% AEP JP events – 2021 H (upper chart) and 2121H (lower chart)



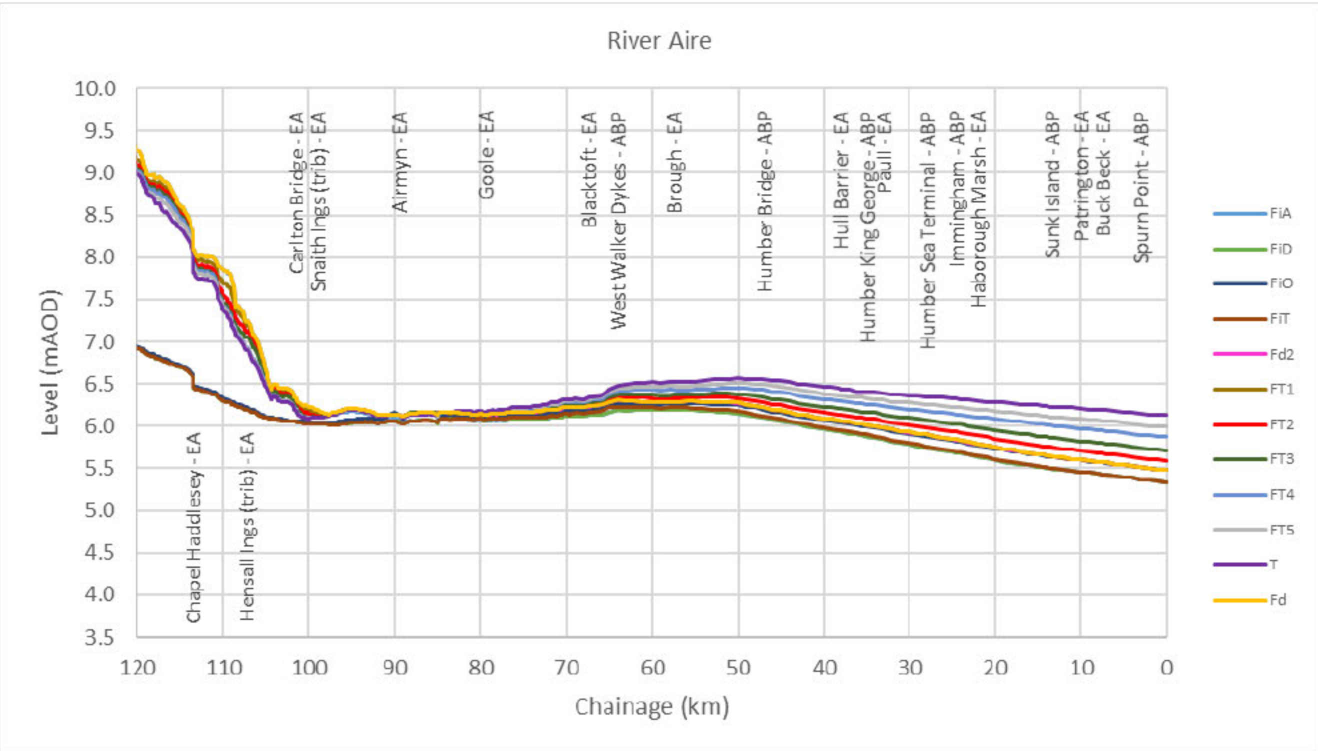
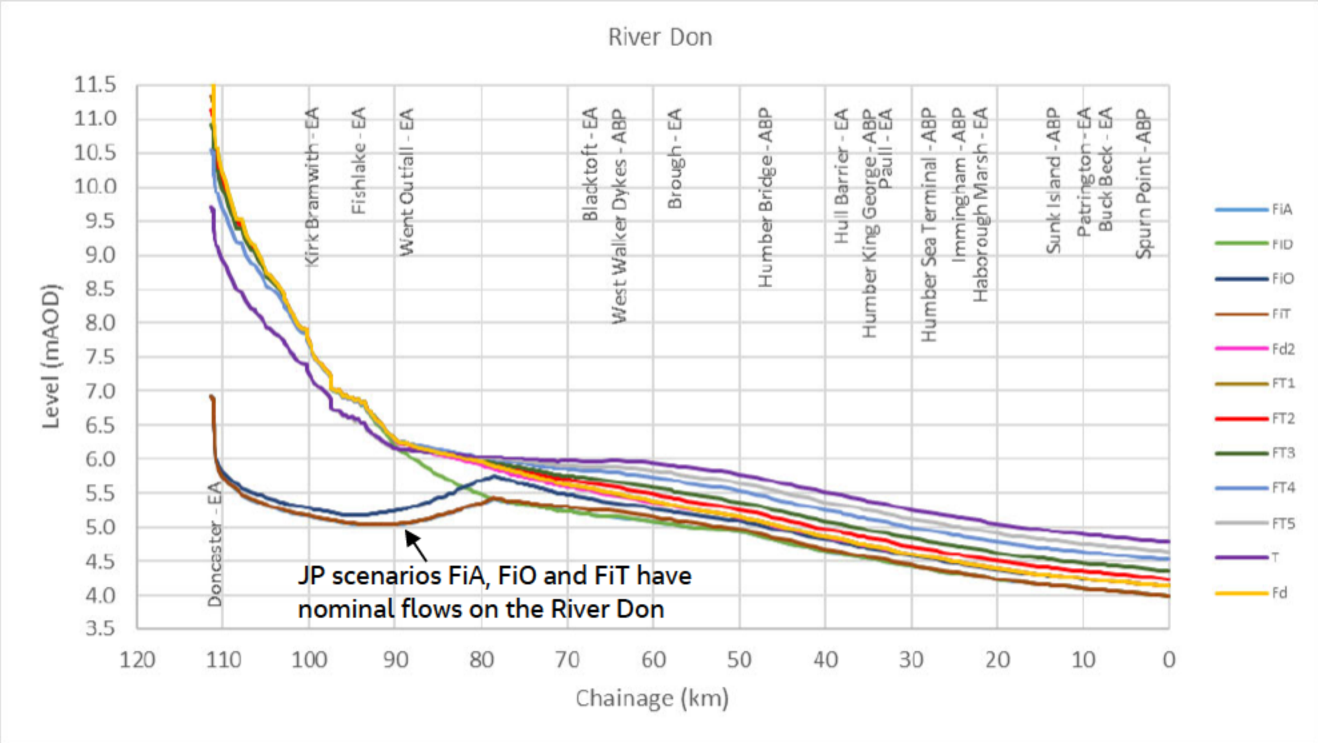


Figure 5.21: River Aire 0.5% AEP JP events – 2021 H (upper chart) and 2121H (lower chart)



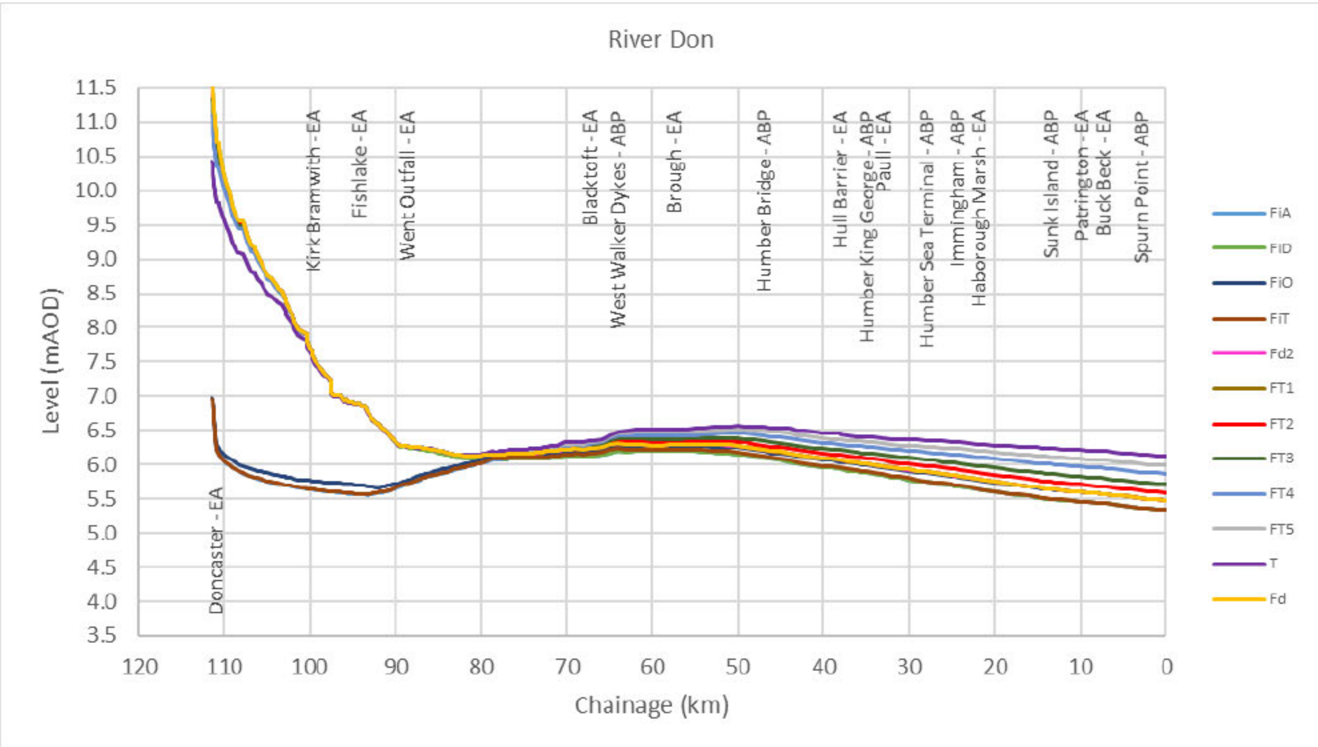
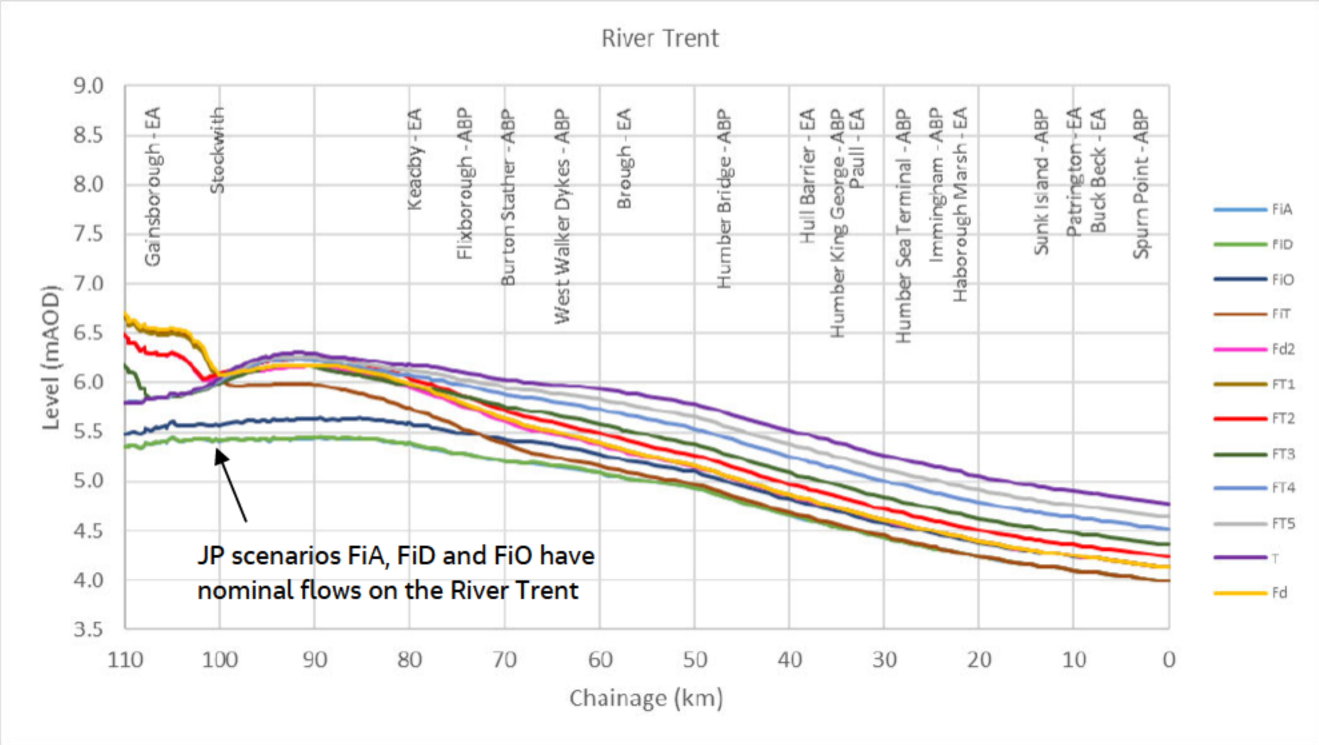


Figure 5.22: River Don 0.5% AEP JP events – 2021 H (upper chart) and 2121H (lower chart)



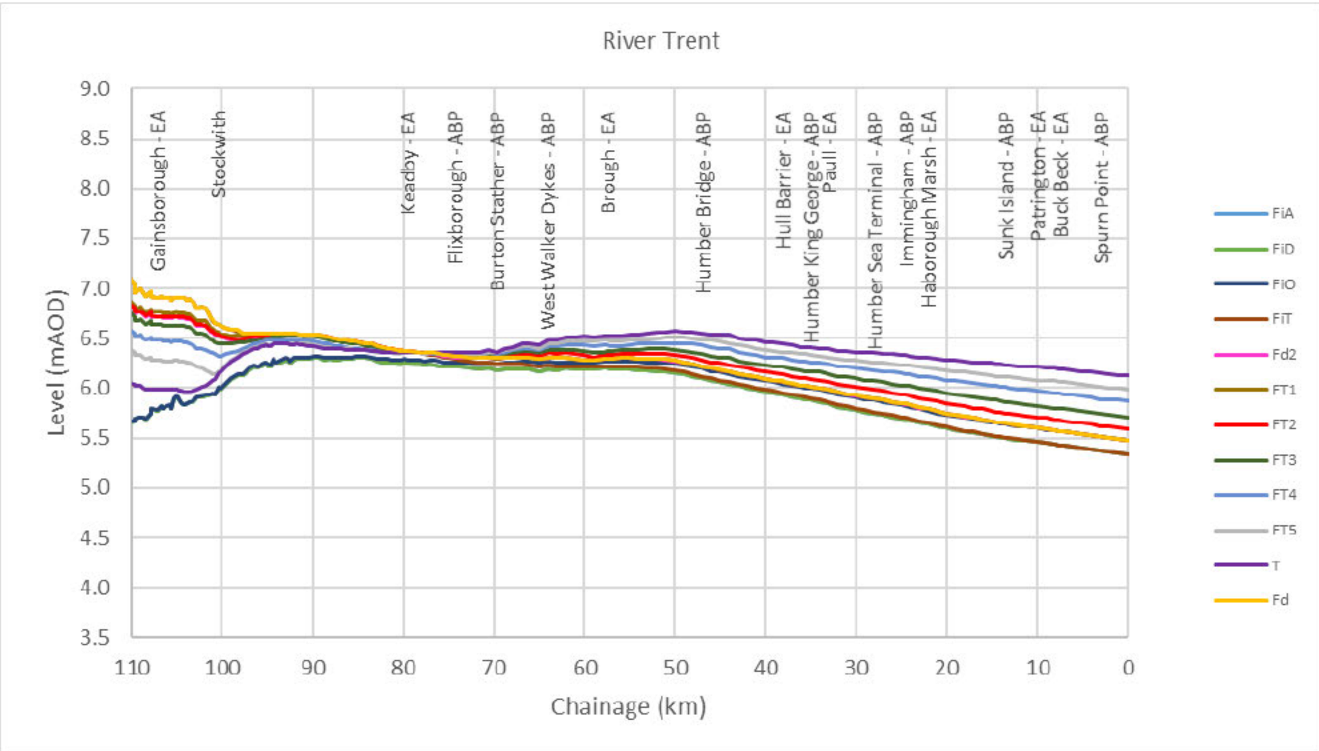


Figure 5.23: River Trent 0.5% AEP JP events – 2021 H (upper chart) and 2121H (lower chart)

6. Accuracy and Sensitivity to modelling assumptions

The approach adopted for the joint probability assessment does not allow uncertainty in boundary conditions to be propagated through the calculations to provide confidence bands for the extremes. This is one of the compromises that had to be accepted when the approach was selected. However, uncertainty and confidence information has been generated based on an understanding of the uncertainty in the boundary conditions and uncertainty in the hydrodynamic model, together with 'softer' information derived from the verification process (as reported in chapter 5.3).

Contributions to uncertainty in simulated extreme water levels include uncertainty in:

- Model boundary conditions (tidal boundaries and fluvial inflows)
- Assumed level of dependence between extreme fluvial and tidal boundary conditions
- Hydraulic model calibration performance
- Hydraulic model schematisation
- Assumed hydraulic model structure/spill coefficients
- Hydraulic model topographic / structure datasets / flood defence crest levels

The accuracy and confidence of the modelling can be assessed using:

- CFB2018 confidence levels
- Confidence in fluvial inflows (e.g. +/-25%)
- Sensitivity of simulated extreme water levels to different climate change scenarios
- Comparisons of results of joint probability method and full dependency simulations
- Model calibration statistics
- Comparing the project 1D in channel results with those of more detailed 2D models
- Comparison to 2014 Interim Water Level upper/lower bands

The impact of the timing of the high tide compared to the peak of the hydrographs was identified as a potential factor but not investigated in the sensitivity testing. It was considered of lower importance than other factors due to long duration of the hydrographs.

The impact of offshore waves has not been considered in this study but was tested during the HEWL Study[6]. The sensitivity test indicated a small increase in EWL of around 0.1 m at the estuary mouth for a northerly wave scenario which is propagated up the estuary and through into the tidal Trent. For an easterly scenario, there is a similar 0.1m increase at the estuary mouth, but this does not translate to an increase up the estuary.

The scale of uncertainty in simulated extreme water levels will vary at different model locations. E.g. where extreme water levels are tidally dominated, uncertainty will be dominated by the uncertainty in CB2018 boundary conditions, hydraulic model schematisation/calibration and assumed future sea level rise. In the fluvial dominated areas uncertainty will be dominated by the uncertainty in fluvial boundary conditions, hydraulic model schematisation/calibration and assumed future uplift to peak river flows. In locations where the defences are overtopped the impacts can be widespread and not just at the location of the overtopping, so uncertainty in crest levels may dominate other uncertainties.

[6] Jacobs & ABPmer, (2020). Humber Extreme Water Levels, Interim Final Report.
A report produced by Jacobs and ABPmer for Environment Agency, March 2020

6.1 Sensitivity to assumed dependency between fluvial and tidal extreme events

To provide an indication of the differences between the fluvial and tidal events the 2021 0.5% AEP event was compared the 0.5% full dependency (0.5% fluvial with 0.5% tide boundary). The full dependency would give the highest water levels when compared to the maximums from the joint probability. The differences in peak water level are detailed in Figure 6.1, the maximum differences of 0.21m are located on the River Trent.

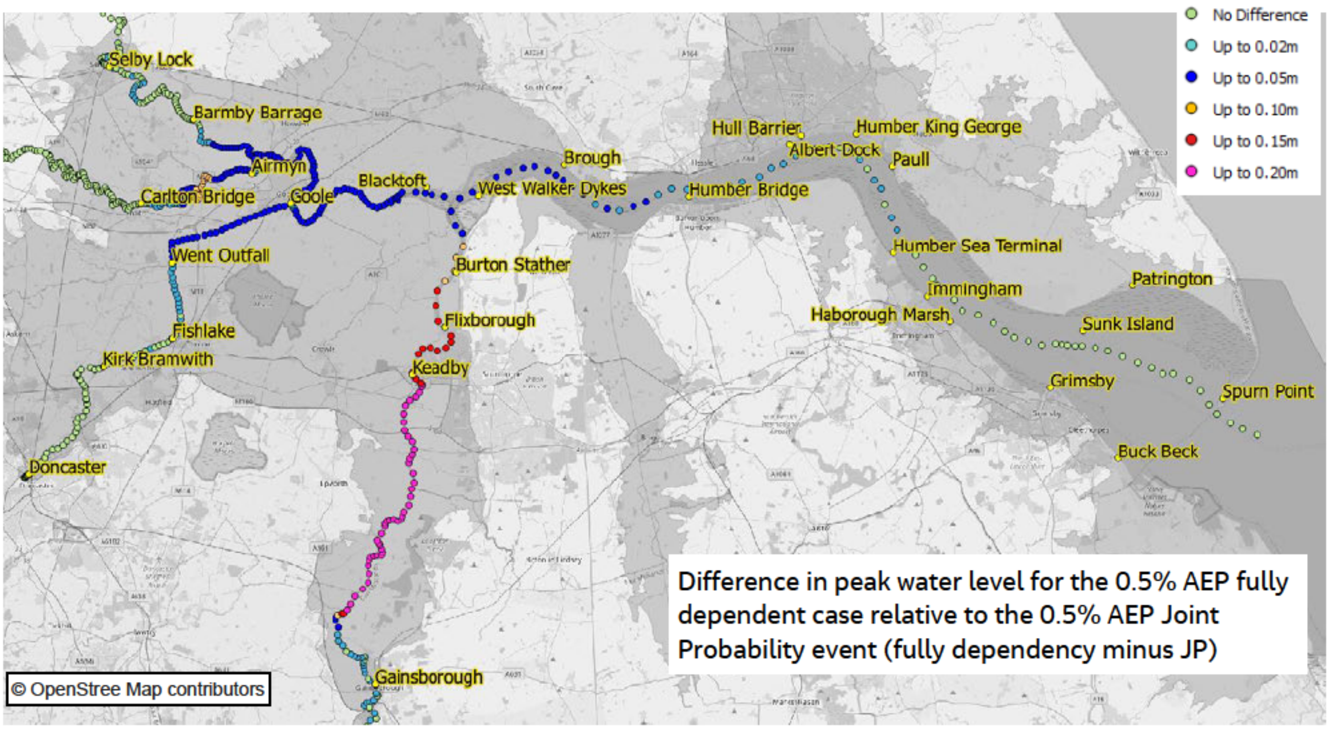


Figure 6.1: 0.5% AEP Full Dependency compared to 0.5% AEP Joint Probability

6.2 Model boundaries

6.2.1 Fluvial inflows

To test the sensitivity of simulated extreme water levels in the fluvial dominated areas, scaling fluvial inflows by a factor e.g. +/- 25% could be applied for the 1% AEP event. Equivalently, reuse of model results can be used e.g. 1% AEP results can be compared against AEP events with inflows approximately 25% higher/lower than those of the 1% AEP event.

For the test, the fluvial dependant (Fd) results for 5% and 0.5% have been used to test the flow sensitivity against the 1% AEP (initial JP simulations used as the tidal boundaries are all set to nominal). The differences in water levels are detailed in Figure 6.2 and Figure 6.3.

It is also noted that the climate change uplifts for the fluvial boundaries are applied directly to the present day boundaries. This potentially does not account for storage in the floodplains upstream of the model boundary and could therefore, overestimate the future epoch flows.

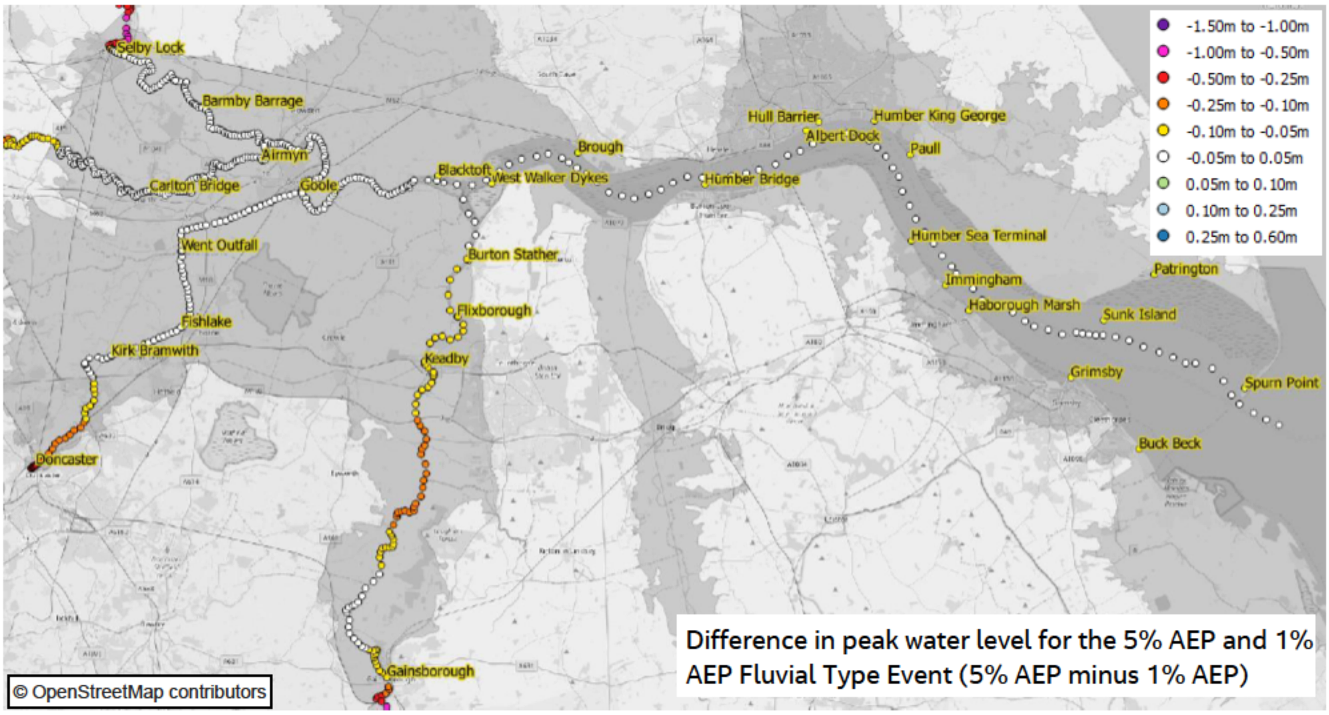


Figure 6.2: Fluvial Sensitivity 5% AEP minus 1% AEP (fluvial event)

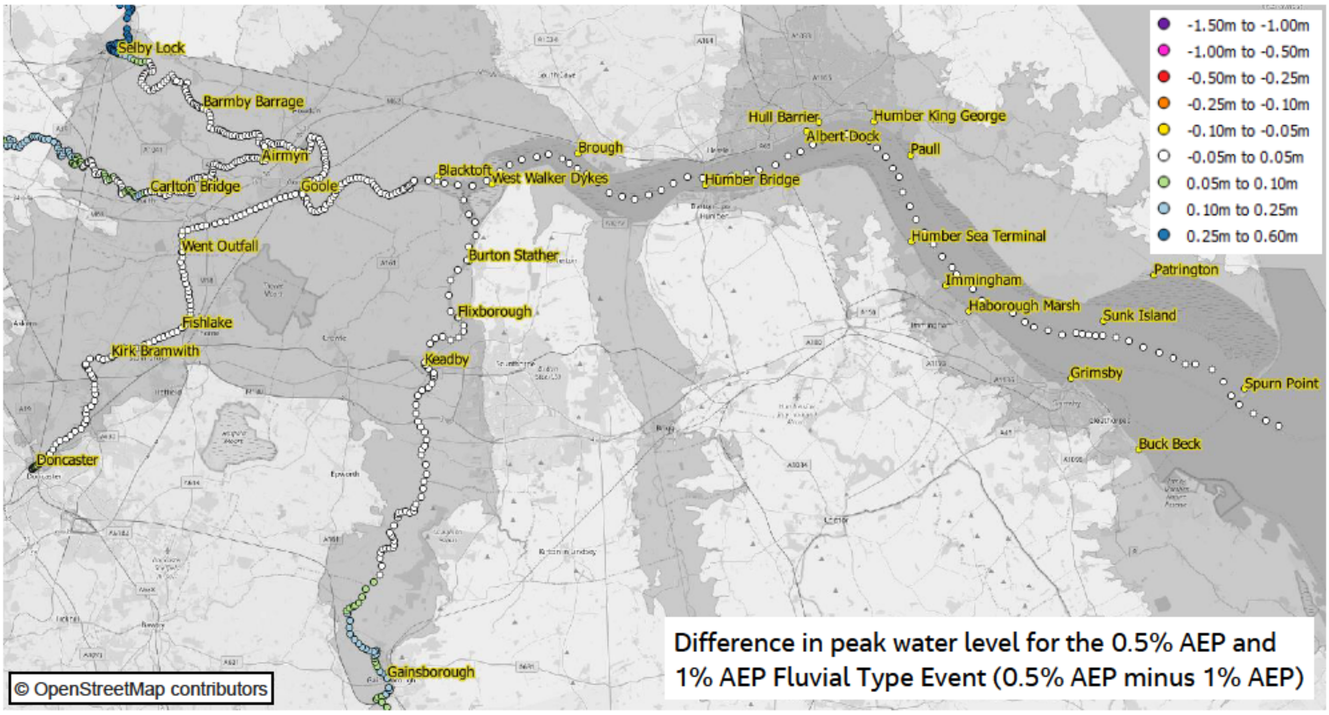


Figure 6.3: Fluvial Sensitivity 0.5% AEP minus 1% AEP (fluvial event)

6.2.2 CFB2018 uncertainties

The confidence levels at the model CFB2018 chainage point used for the model boundary are detailed in Table 6.1. For the 0.5% AEP, the confidence levels are -0.16m to 0.51m.

Table 6.1: CFB2018 Extreme tidal estimates confidence levels

AEP (%)	RP (1 in X year)	Selected Chainage and confidence levels (%)			Level Difference (m)	
		_3912	2.5%	97.5%	2.5%	97.5%
100	1	3.85	3.84	3.87	-0.01	0.03
50	2	3.96	3.94	4.00	-0.02	0.06
20	5	4.10	4.06	4.15	-0.04	0.09
10	10	4.21	4.16	4.29	-0.05	0.13
5	20	4.33	4.27	4.45	-0.06	0.18
4	25	4.37	4.30	4.50	-0.07	0.20
2	50	4.49	4.39	4.66	-0.10	0.27
1.33	75	4.56	4.46	4.78	-0.10	0.32
1	100	4.61	4.49	4.86	-0.12	0.37
0.67	150	4.69	4.55	4.99	-0.14	0.44
0.5	200	4.75	4.59	5.10	-0.16	0.51
0.4	250	4.78	4.60	5.15	-0.18	0.55
0.33	300	4.82	4.62	5.21	-0.20	0.59
0.2	500	4.93	4.71	5.40	-0.22	0.69
0.1	1000	5.07	4.80	5.66	-0.27	0.86

To test the impact of the boundary, the tidal dependant (T) model results for the 1% and 0.1% were used to test the tide sensitivity against the 0.5% AEP event. The reason for choosing the 1% and the 0.1% for this test is that these give similar upper and lower confidence levels to the 0.5% event (1% was -0.14m lower and 0.1% AEP was +0.32m higher in relation to the 0.5% AEP modelled tidal boundary)

The initial joint probability simulations have been used as the 1% and 0.5% have the same nominal fluvial conditions. The 0.1% shows differences beyond the tidal limit as the scenario includes a fluvial component of the Aire/Trent (50% AEP) and Ouse (20% AEP). The differences in water levels are detailed in Figure 6.4 and Figure 6.5.

End users could undertake their own uncertainty analysis by comparing the outputs for different return periods which have been modelled (similar approach as detailed above).

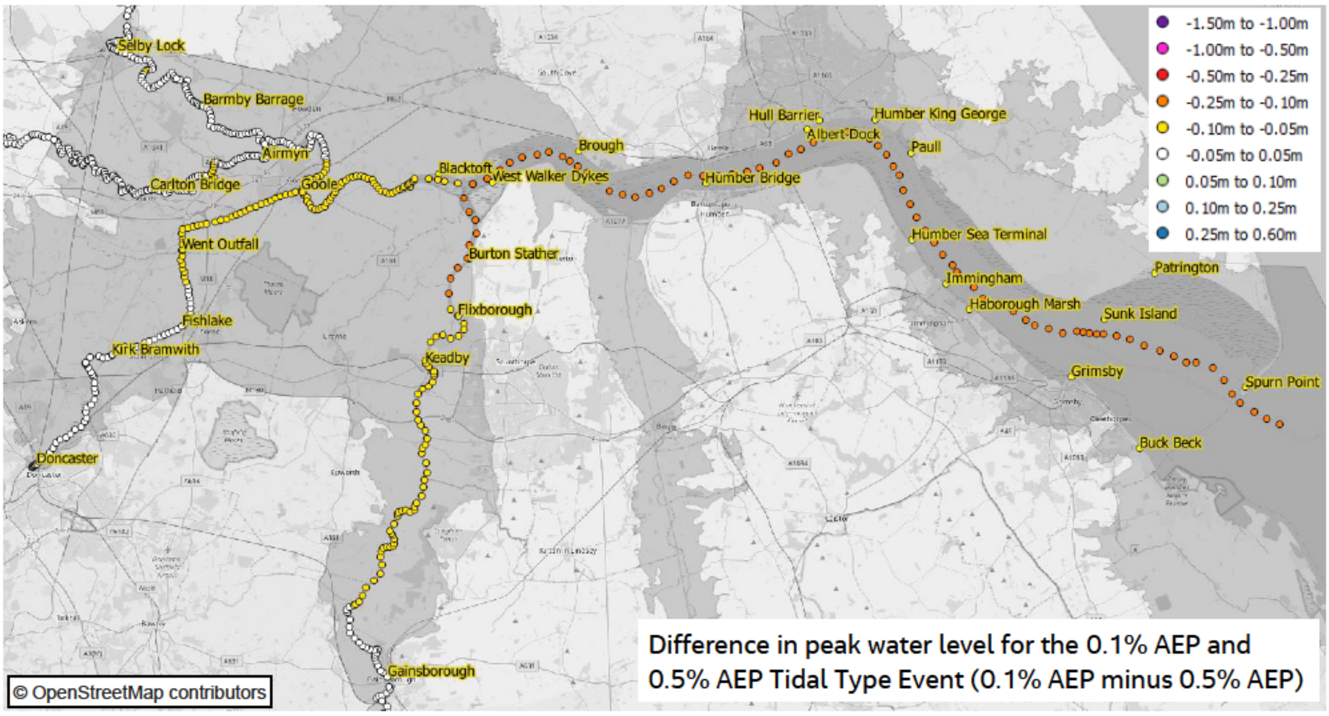


Figure 6.4: Tidal Sensitivity 0.1% AEP minus 0.5% AEP (tidal event)

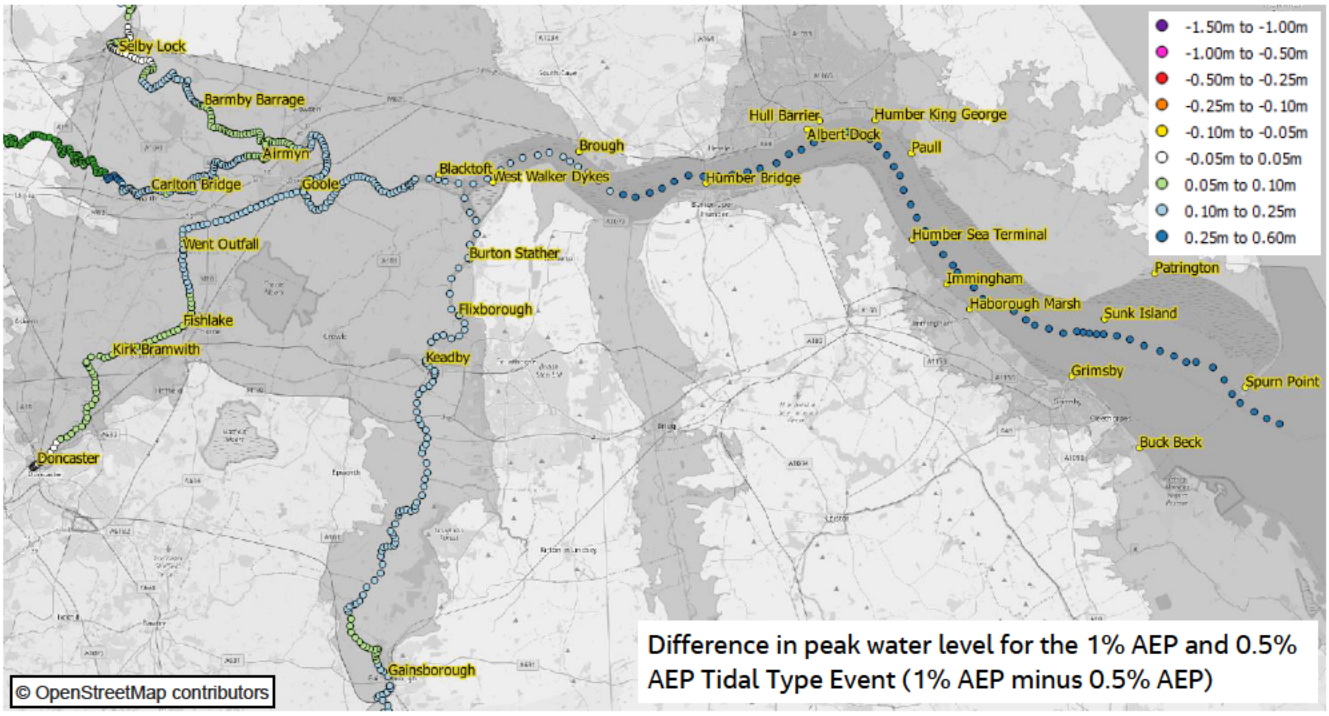


Figure 6.5: Tidal Sensitivity 1% AEP minus 0.5% AEP (tidal event)

6.3 Calibration accuracy

The 1D model used for the extreme water levels was calibrated/verified against seven events, three fluvial type events and four tidal events which includes the extreme tidal event of December 2013. The modelled water levels were compared to recorded data at 46 gauges stations. The model achieves a good overall calibration over the seven events in terms of generally matching peak values to within +/- 0.15m (EA specified target accuracy). The final technical reports covering the model build and initial calibration[7] and final calibration[8] should be referenced for details on the calibration.

Table 6.2 provides a summary of the model calibration accuracy for ±0.15m (preferred standard) and ±0.20m, ±0.25m and ±0.30m across the seven events. The November 2019 event which was assessed during the EWL study is not included in the Table 6.2 summary. The November 2019 event focused on the River Don and model results were within the +/- 0.15m (EA specified target accuracy), details are provided in Appendix N.

If the Environment Agency Spurn Point gauge is excluded, the model is predicting peak levels within ±0.15m accuracy for 74% of the comparable values, which increases to 87% for ±0.20m and up to 97% for the ±0.30m accuracy band. In the predominantly tidal areas, the standard of the calibration results is higher. If gauges on the upper extents of the four main tributaries are excluded, the model achieves 78% within the ±0.15m target accuracy, 95% at ±0.20m and 100% at ±0.30m.

Table 6.2: Summary of calibration results (percentage of gauges where predicted levels are within target accuracy)

Calibration accuracy	Final Calibration	
	All gauges (1)	Tidal/surge dominated gauges (2)
≤ ± 0.15 m	74%	78%
≤ ± 0.20 m	87%	95%
≤ ± 0.25 m	93%	99%
≤ ± 0.30 m	97%	100%

(1) excludes Environment Agency Spurn Point – considered suspect

(2) excludes Environment Agency Spurn Point + excludes Gainsborough, Selby Lock, Went Outfall and Carlton Bridge and all gauges upstream.

6.4 Comparison with detailed 1D/2D modelling

The comparison to detailed 1D/2D modelling highlighted a limitation of the 1D floodplain representation (reservoir unit which calculates a single water level) when compared to 2D floodplains (water level varies).

Figure 6.6 compares the 0.5% AEP event with the 1D/2D modelled output from the Tidal Trent[9]. The difference in the water level profile near Stockwith (chainage 100km) is due to the floodplain interaction as flows spill back to the channel. The location is also an area where a different JP can provide the peak level.

The comparison of the extremes at Gainsborough and Stockwith to the detailed 1D/2D modelling outputs show good agreement with the shape. At Gainsborough the new extremes are higher (expected as flows are higher than the 1D/2D modelling), with the exception of the 0.5% AEP where the new extremes are slightly lower (0.05m). At Stockwith, the largest uncertainty is associated for the 0.5% AEP event (0.22m), but there is a good match for all other AEPs.

[7] Model Proving and Calibration: ENV0000300C-CH2-ZZ-3A0-RP-HY-0003, 17th September 2019
[8] Model Update and Additional Calibration: ENV0000300C-CH2-ZZ-3A0-RP-HY-0005, 17th September 2019
[9] Tidal Trent Modelling and Mapping Study Addendum. Mott MacDonald, Jan 2015

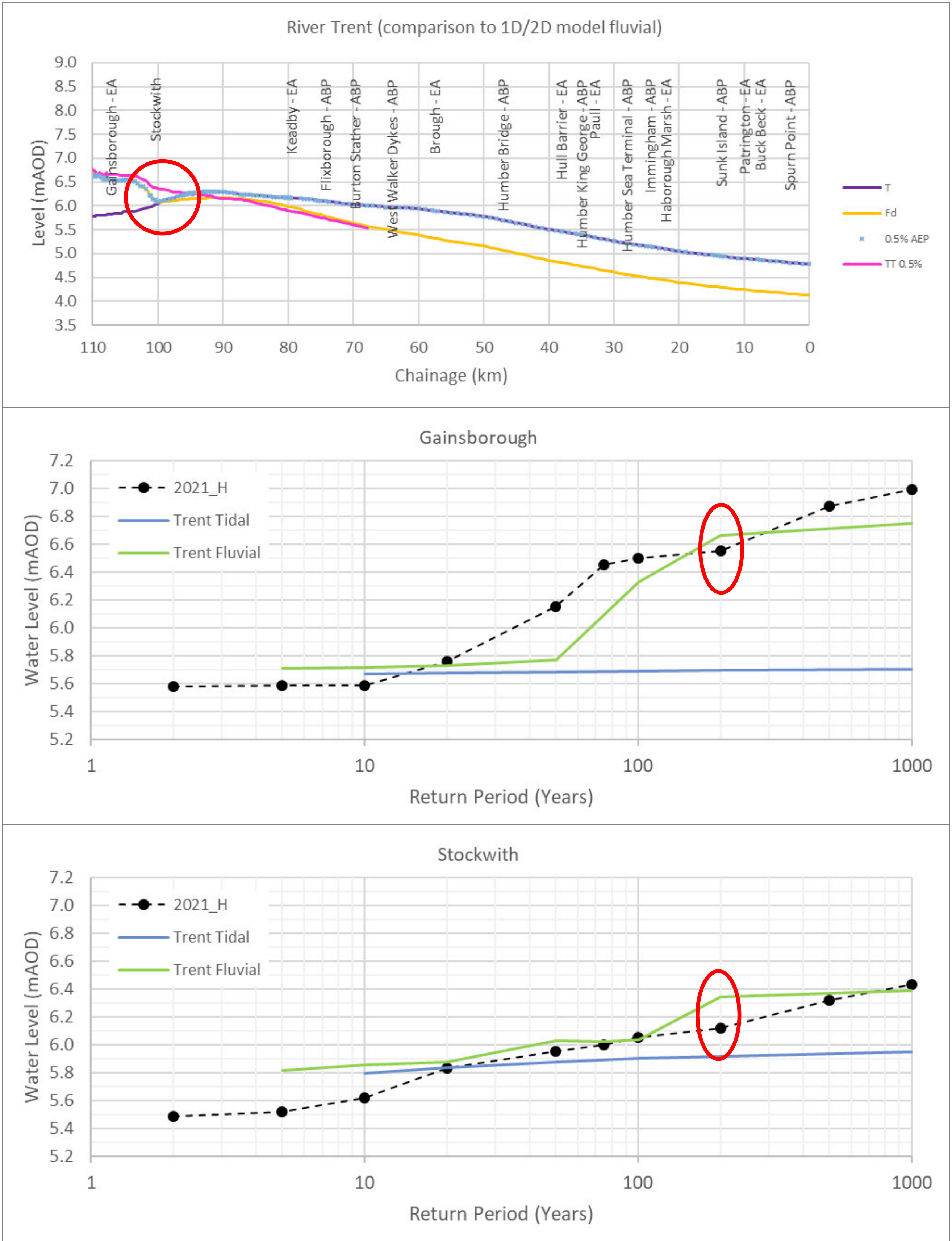


Figure 6.6: Comparison with detailed 1D/2D modelling (0.5% AEP event)

6.5 2014 Interim water levels

The confidence levels at Immingham from the 2014 interim water levels are detailed in Table 6.3. For the 0.5% AEP, the confidence levels are -0.18m to 0.23m.

Table 6.3: 2014 Interim water levels - at Immingham confidence levels

AEP (%)	RP (1 in X year)	Location and confidence levels (%)			Level Difference (m)		
		Immingham 2014 IWL	95% lower	95% Upper	95% lower	95% Upper	Immingham new EWL (2021_H)
100	1	4.26	4.25	4.27	-0.01	0.01	-
10	10	4.61	4.56	4.65	-0.05	0.04	4.58
2	50	4.88	4.79	5	-0.09	0.12	4.86
1	100	5.01	4.88	5.18	-0.13	0.17	4.99
0.5	200	5.14	4.96	5.37	-0.18	0.23	5.15
0.2	500	5.33	5.08	5.65	-0.25	0.32	5.33
0.1	1000	5.47	5.15	5.89	-0.32	0.42	5.47

6.6 Extreme water level dataset checks

The following checks were undertaken on the extreme water level datasets:

- Maximum extreme water levels from joint probability do not exceed the full dependency test, refer to Appendix K for details.
- Ensure peak water levels do not reduce as the AEP increases.

The 'peak water levels do not reduce as the AEP increases' check identified that this could occur in some locations for the higher flows/tide scenarios. Table 6.4 details the largest differences and the % of model nodes which are affected (out of 798 model nodes for 1815 model simulations). The differences do not occur until the future 2046 H++ scenario when flows/tides are higher and defence overtopping can result in small differences in water levels. Where differences occur, they are generally 0.01m, with some areas of 0.02m for the 2071 H++ at the 0.5% and 0.1% AEP. Differences up to 0.02m should be considered within the numerical accuracy of the model (the flood modeller default convergence criteria set at 0.01m, so comparison between 2 different simulations could show an absolute difference of +/-0.02m).

The locations of the model nodes where water levels are shown to reduce when AEP increases are detailed in Figure 6.7. The red dots represent the nodes which are generally grouped by locations on the Ouse (between Selby Lock and Barmby Barrage), Aire (around Carlton Bridge), lower reaches of the Don and Trent (between Keady to Flixborough). The charts within the figure show the results for all scenarios at a sample node within the locations highlighted, when a level reduction is shown it typically occurs at the flattening of the curve, which is due to defence overtopping controlling water levels. The charts also list the full set of nodes where the small level reduction is occurring.

It is recommended that end users review the water levels in these areas and select the appropriate results knowing that levels could be lower by 0.01m for a higher AEP.

Table 6.4: Peak level and AEP increase check - largest differences (m) and % of model nodes which are affected (out of 798 model nodes).

Scenario	Largest reduction (m) in peak water levels when moving up to the next AEP (negative value = level reduced)								
	50% to 20%	20% to 10%	10% to 5%	5% to 2%	2% to 1.33%	1.33% to 1%	1% to 0.5%	0.5% to 0.2%	0.2% to 0.1%
2021_M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2021_H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2021_H++	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2040_M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2040_H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2040_H++	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2046_M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2046_H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2046_H++	0.00	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00
	0.00%	0.38%	0.00%	0.00%	0.00%	0.13%	0.00%	0.00%	0.00%
2071_M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2071_H	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2071_H++	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.02
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.13%	0.88%
2121_M	-0.01	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	-0.01
	0.63%	0.00%	0.00%	0.00%	0.00%	0.00%	0.13%	0.00%	0.13%
2121_H	-0.01	0.00	0.00	0.00	-0.01	0.00	-0.01	0.00	0.00
	0.50%	0.00%	0.00%	0.00%	0.50%	0.00%	0.38%	0.00%	0.00%
2121_H++	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.88%	0.00%	0.00%

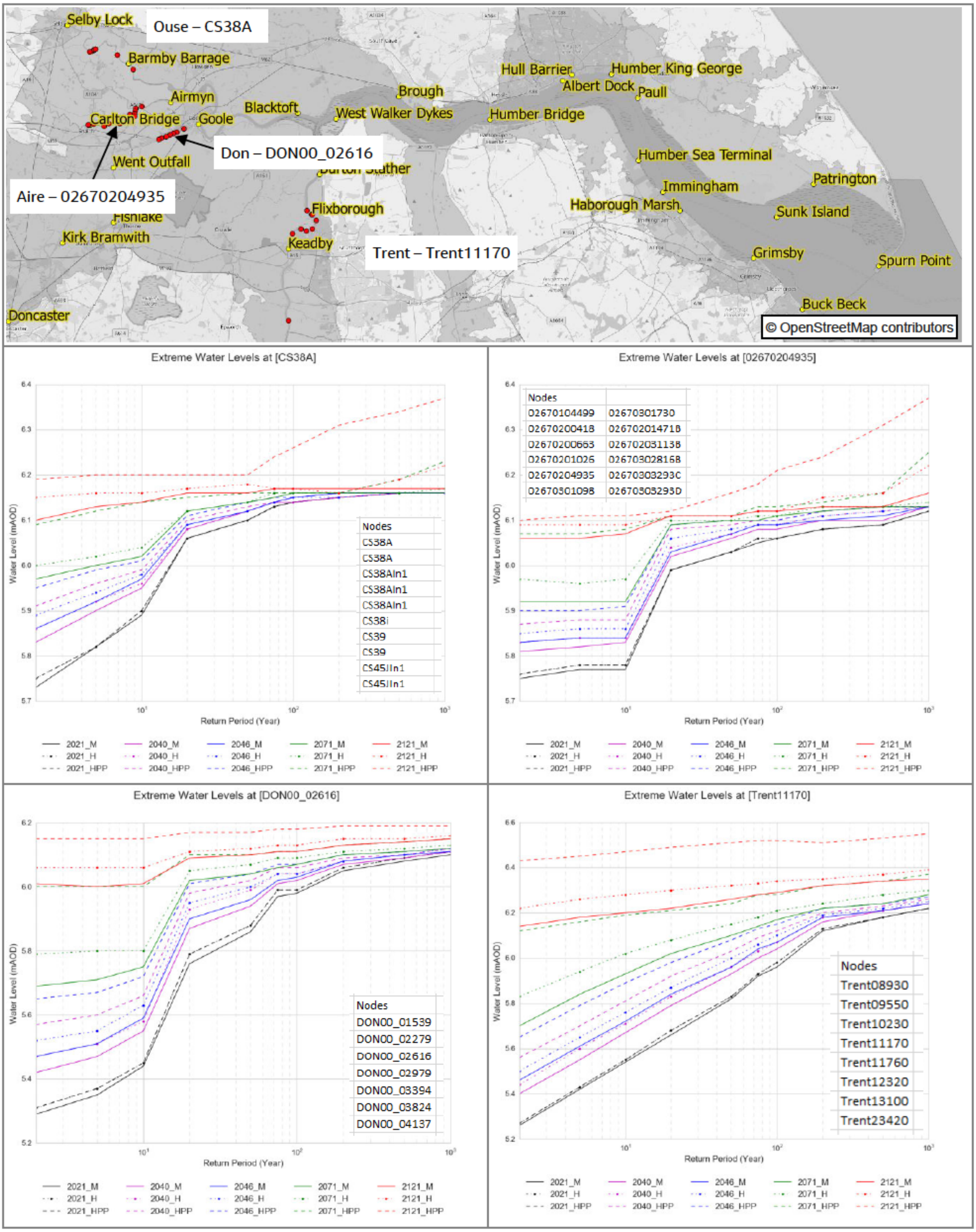


Figure 6.7: Model locations where water levels can reduce when AEP increases

7. Deliverables

7.1 Digital data

This chapter details the modelling deliverables. End users should take into consideration the uncertainty with the data as described in chapter 6, which investigates the accuracy and sensitivity to modelling assumptions.

Tabulated peak water levels are provided in spreadsheet and shapefile formats to accompany this report. Water level charts are also produced as 'png' images and 'csv' file for all model nodes. The digital files provided are detailed in Table 7.1 (spreadsheets) Table 7.2 (shapefiles) and Figure 7.1 (charts).

Table 7.1: Digital Files - Spreadsheets

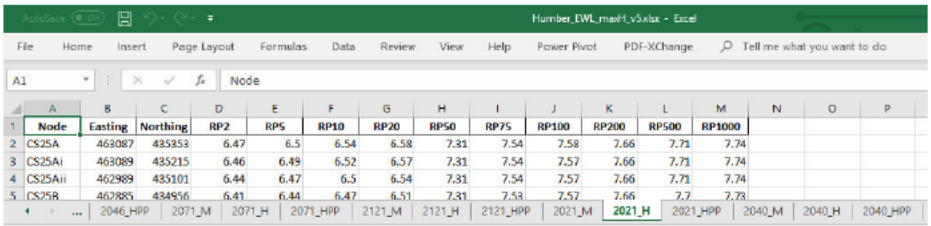
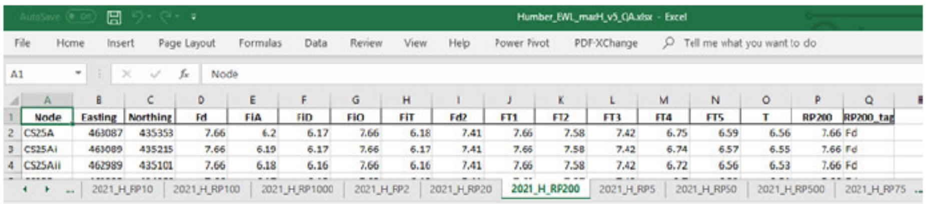
Filename	Comment
Humber_EWL_maxH_v5.xlsx	Maximum water level from full JP set (worksheet for each epoch/scenario) 
Humber_EWL_maxH_v5_QA.xlsx	Maximum water level for all JP (worksheet for each epoch/scenario/AEP) 
Humber_EWL_maxQ_v5.xlsx	Maximum flow from full JP set (worksheet for each epoch/scenario) positive flow – seaward direction
Humber_EWL_maxQ_v5_QA.xlsx	Maximum flow for all JP (worksheet for each epoch/scenario/AEP) positive flow – seaward direction
Humber_EWL_maxV_v5.xlsx	Maximum 'average' velocity from full JP set (worksheet for each epoch/scenario) positive velocity – seaward direction
Humber_EWL_maxV_v5_QA.xlsx	Maximum 'average' velocity for all JP (worksheet for each epoch/scenario/AEP) positive velocity – seaward direction
Humber_EWL_minQ_v5.xlsx	Minimum flow for all JP (worksheet for each epoch/scenario/AEP) negative velocity – inland direction
Humber_EWL_minQ_v5_QA.xlsx	Minimum 'average' velocity from full JP set (worksheet for each epoch/scenario) negative velocity – inland direction
Humber_EWL_minV_v5.xlsx	Minimum 'average' velocity for all JP (worksheet for each epoch/scenario/AEP) negative velocity – inland direction
Humber_EWL_minV_v5_QA.xlsx	Minimum flow for all JP (worksheet for each epoch/scenario/AEP) negative flow – inland direction

Table 7.2: Digital Files - Shapefiles

Filename for output value, variables include: **maxH - maximum water level (as shown below)** **maxQ - maximum flow (positive flow – seaward direction)** **maxV - maximum velocity [1] (positive velocity – seaward direction)** **minQ - minimum flow (negative flow – inland direction)** **minV - minimum velocity [1] (negative velocity – inland direction)**	**Filename for JP scenario which produces maximum/minimum value**
Humber_EWL_maxH_v5_2021_M.shp	Humber_EWL_maxH_v5_2021_M_maxTag.shp
Humber_EWL_maxH_v5_2021_H.shp	Humber_EWL_maxH_v5_2021_H_maxTag.shp
Humber_EWL_maxH_v5_2021_HPP.shp	Humber_EWL_maxH_v5_2021_HPP_maxTag.shp
Humber_EWL_maxH_v5_2040_M.shp	Humber_EWL_maxH_v5_2040_M_maxTag.shp
Humber_EWL_maxH_v5_2040_H.shp	Humber_EWL_maxH_v5_2040_H_maxTag.shp
Humber_EWL_maxH_v5_2040_HPP.shp	Humber_EWL_maxH_v5_2040_HPP_maxTag.shp
Humber_EWL_maxH_v5_2046_M.shp	Humber_EWL_maxH_v5_2046_M_maxTag.shp
Humber_EWL_maxH_v5_2046_H.shp	Humber_EWL_maxH_v5_2046_H_maxTag.shp
Humber_EWL_maxH_v5_2046_HPP.shp	Humber_EWL_maxH_v5_2046_HPP_maxTag.shp
Humber_EWL_maxH_v5_2071_M.shp	Humber_EWL_maxH_v5_2071_M_maxTag.shp
Humber_EWL_maxH_v5_2071_H.shp	Humber_EWL_maxH_v5_2071_H_maxTag.shp
Humber_EWL_maxH_v5_2071_HPP.shp	Humber_EWL_maxH_v5_2071_HPP_maxTag.shp
Humber_EWL_maxH_v5_2121_M.shp	Humber_EWL_maxH_v5_2121_M_maxTag.shp
Humber_EWL_maxH_v5_2121_H.shp	Humber_EWL_maxH_v5_2121_H_maxTag.shp
Humber_EWL_maxH_v5_2121_HPP.shp	Humber_EWL_maxH_v5_2121_HPP_maxTag.shp

[1] maximum/minimum velocity is the average velocity across the 1D cross section)

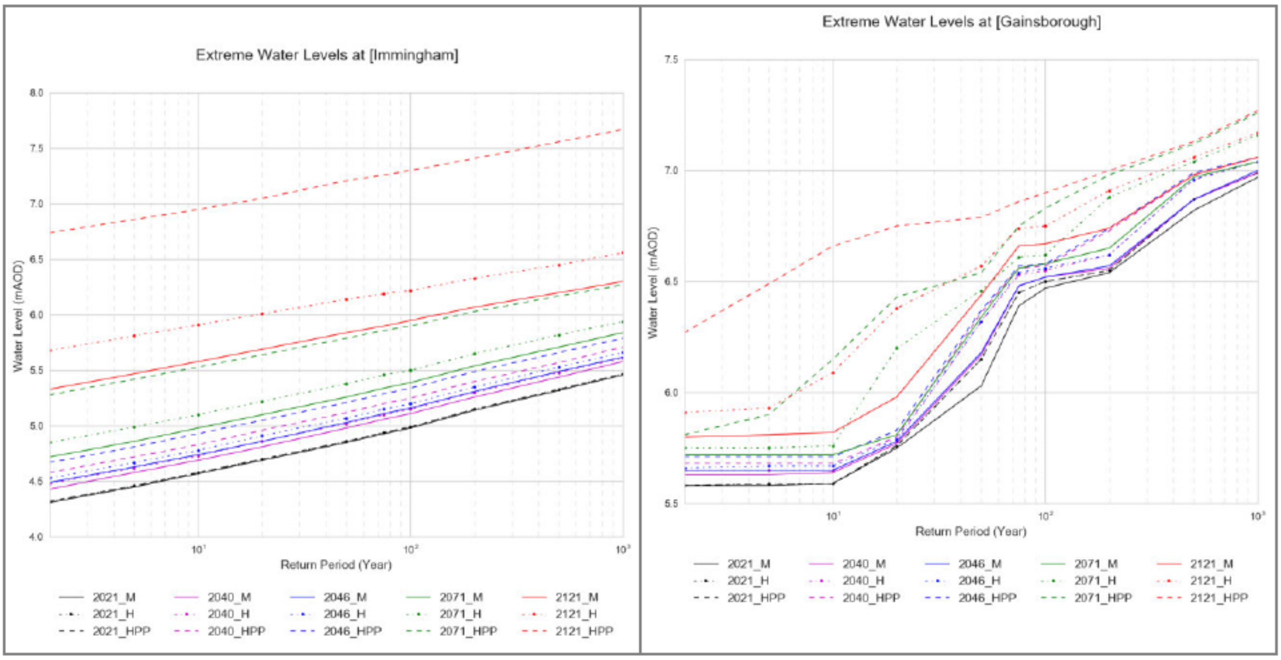


Figure 7.1: Water level charts

8. Conclusions and Recommendations

8.1 Conclusions

The extreme water level derivation method used defined joint probability combinations of sea level and fluvial flow for each AEP as boundary conditions to the hydraulic model. Following simulation of the joint probability combinations for each AEP worst-case results were extracted at each required location. This method was considered to be a well-established low-risk approach that used the FD2308 current practice desk-based methodology for defining joint probability boundary condition pairs. This method achieved all of the study requirements.

The fluvial model boundaries were extracted from the design simulation results of existing 1D/2D approved models for the Rivers Trent, Ouse and Aire. For the River Don, new design flows are based on an up to date flood frequency estimation and design hydrograph profile at Doncaster.

The seaward tidal boundary has been derived following the coastal flood boundary guidance (CFB18). This approach provided consistency with adjacent coastal studies.

The 1D hydrodynamic model developed and calibrated for this study was successfully used to derive extreme water levels for the present day scenario (2021) and future epochs (2040, 2046, 2071 and 2121), assuming the 2021 defence configuration remains. The Jacobs Global Flood Modeller platform was used to run and process 1815 simulations within a day.

This is the first time a consistent modelled set of extreme water levels has been developed for the study area. The approach allows for the extreme water levels to be easily updated to represent interventions e.g. defences and changes to official guidance (e.g. climate change).

The model will be used to test the impacts of the strategic flood risk management measures under the new Humber Strategy (currently being developed) and could also support future flood risk assessments and flood mapping projects.

8.2 Assumptions and limitations

There are a number of assumptions and limitations with the approach to deriving extreme water levels, which need to be considered when using the outputs. The key assumptions/limitations are discussed below:

- Only the main river flows for the Ouse, Aire, Don and Trent are considered, flow from tributaries which have control structures are assumed to be hydraulically isolated and not included (Rivers Derwent, Hull, Ancholme, Went, EA Beck).
- The joint probability dependency approach assumes that the dependence between the various fluvial and sea level inputs are well described by the pairwise dependence measure χ which focuses only on the dependence between extremes of sea level and the various fluvial inputs. The approach could be seen as slightly conservative as it assumes the worst case scenario of all rivers attaining their highest marginal flow values concurrently. Dependence analysis which examined extremal dependence between the flows themselves, carried out under HEWL, suggests that this assumption is liable to be slightly over cautious - whilst the river flows have high extremal dependence, they are not perfectly dependent at high levels.
- The primary consideration of the model schematisation was to be able to provide "in bank" extreme water levels and floodplain representation was only required in areas where the floodplain storage capacity could be filled and impacts the flows over the defences. The floodplain was represented by connecting overbank spills (bank/defence levels) to a 'Reservoir' unit, which uses terrain data to provide a stage/area relationship. The 'Reservoir' unit calculates a single water level over the area it covers, therefore spilling in and out of the reservoir can occur depending on the upstream/downstream water levels e.g. flows spill in at the upstream end of the reservoir and can flow back to the river downstream (depending on water and bank/defence levels). The defence crest levels are assumed to remain constant and no allowance is made

for breaches or erosion of the crest due to the flows over the defences. As the floodplain is represented at a "high level" approach, extracting floodplain water levels from the model simulations is not recommended.

- It is also noted that the climate change uplifts for the fluvial boundaries are applied directly to the present day boundaries. This potentially does not account for storage in the floodplains upstream of the model boundary and could therefore, overestimate the future epoch flows.
- In many locations, particularly with the future climate change simulations, the more extreme, lower probability, levels are controlled by the losses over the baseline 2021 flood defence crests.
- Sources of uncertainty, and sensitivity of simulated extreme water levels to sources of uncertainty, are discussed further in Chapter 6.
- The model used has a 1D representation so provides only a single extreme level on each cross-section. There may be some variation in level across wider cross-section in the main Humber estuary (as observed in the 2013 tidal surge).
- Wind and wave effects, which could result in changes to still water levels in the outer estuary have not been considered. Wave extremes are being considered as a separate piece of work as part of the H2100+ project, outputs will be available to use alongside the Humber still EWLs in the future.
- The model results are based on the planned 2021 defence representation. Therefore, results are only valid whilst defences on the ground align with the model. i.e. a change to planned defence schemes due for completion by 2021, or the construction of new defences will significantly reduce the accuracy of the outputs.

8.3 Recommendations

The following tasks are recommended:

- Review extreme water levels for the 2021 epoch against future notable flood events.
- Review extreme water levels following any future changes to underlying datasets and guidance e.g. coastal flood boundary dataset, climate change allowances, significant increase in fluvial flood records, updates to joint probability methodology.
- Any future use of the results derived in this study should take account of uncertainty and its implications for the intended end use.
- Confirm gauge datums e.g. gauges with zero datums and Airmyn Gauge datum.
- The model represents defences for 2021, if new interventions e.g. new defences are constructed the model should be re-run to generate a new valid set of extreme water levels.
- The finished crest levels and geometry of new interventions (e.g. defences) should be collected, collated and stored for easy access to allow for future updates to the model/EWL.

9. References

The following guidance documents and reports have been referenced:

- Tidal Trent Modelling and Mapping Study, Modelling and Mapping Report, Mott MacDonald, December 2013
- Tidal Trent Modelling and Mapping Study Addendum, Mott MacDonald, January 2015
- Upper Humber Flood Risk Mapping Study, Final Report, JBA, August 2016
- Humber Extreme Water Levels; Model development, calibration and validation report, CH2M and ABPmer, January 2017
- Humber Extreme Water Levels; Hydrodynamic Model Calibration Report, Jacobs and ABPmer, May 2018
- TN24 - Tidal rivers study – Review of floodplain influences on HEWL study area, Jacobs, September 2018
- Northern Forecasting Package: Lower Aire Model, JBA, July 2017
- Ouse and Wharfe Washlands Optimisation Study. Mott MacDonald, July 2018
- Don Catchment Model: Hydrology Report, JBA, February 2017
- ENV0000300C-CH2-ZZ-3A0-RP-HY-0003 | P03, HSCR, Flood Modeller Pro Model: Model Proving and Calibration, Jacobs, September 2019
- ENV0000300C-CH2-ZZ-3A0-RP-HY-0005 | P03, HSCR, Flood Modeller Pro Model: Model Update and Additional Calibration, Jacobs, September 2019
- ENV0000300C-CH2-ZZ-3A0-RP-HY-0006, River Don - Flood estimation audit trail, Jacobs December 2019
- ENV0000300C-CH2-ZZ-3A0-RP-HY-0008 | P02, HSCR, Fluvial flood hydrology review Jacobs, October 2020.
- Use of Joint Probability Methods in Flood Management: A guide to best practice. R&D Technical Report FD2308/TR2, Defra / Environment Agency, March 2005
- Coastal flood boundary conditions for the UK: update 2018 User guide: SC060064/TR7, Environment Agency
- Humber Estuary Extreme Water Levels, Draft Interim Final Report (Vol 1 and 2), Jacobs and ABPmer, March 2020
- HEWL review of river flow dependence, Janet Heffernan, September 2018
- Humber Extremes: Dependence Analysis, HSCR Extremes, J Heffernan Consulting Limited, May 2019

Appendix A. Hydrodynamic model updates undertaken prior to the final extreme water level production

Appendix A describes the changes made to the calibration model to develop the final model for the EWL production runs. The updates include the known changes (i.e. 2021 defences) and further improvements which were required following reviews of the initial EWL outputs.

A.1 2021 Defences

The calibration model was configured to represent conditions for the December 2013 event. The final model was updated to represent the design level for the schemes to be completed for 2021. Figure A.1 details the locations of the defences planned to be completed for 2021. The updates required changing elevations to the model spills units and for the Skeffling scheme, model cross sections were extended to allow for the setback defences. Table A.1 provides details the spills changed, the defence levels used and the data source.

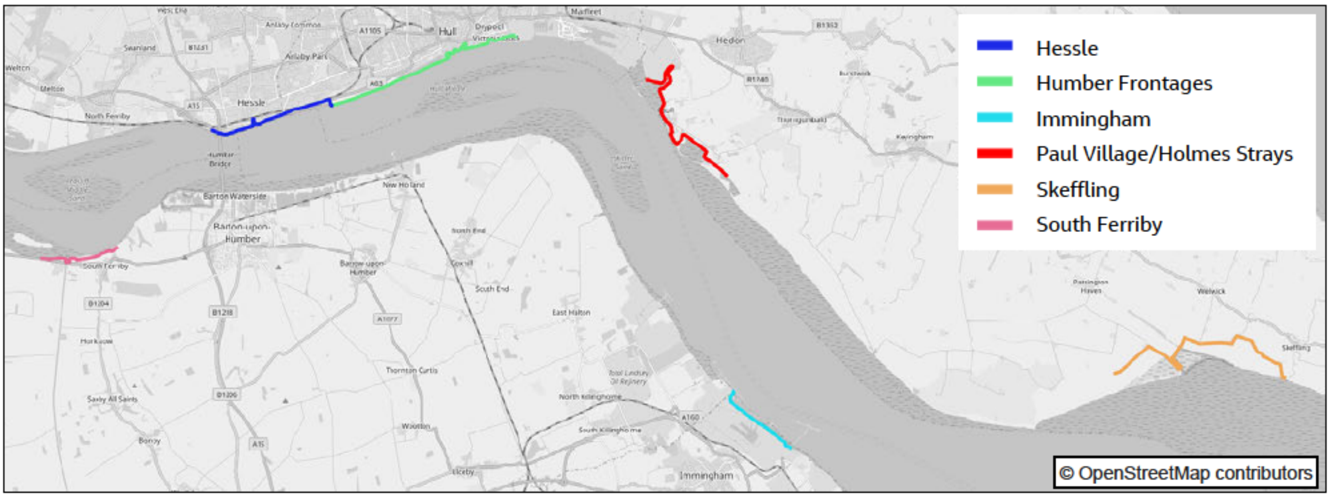


Figure A.1: 2021 Defence locations

Table A.1: 2021 Defences (model updates)

Scheme	Description of model schematisation		Source
	Node	Comment	
Hessle	IHU_0_022	6.90m defence levels added before and after existing high ground	D585 Hessle Foreshore Tidal Defences Supplemented with LiDAR for higher ground (Roads)
	IHU_0_023	6.90m defence levels added, then ties into existing high ground at Sullivan Way	
	IHU_0_024	Lower bank survey replaced with adjacent higher ground levels from LiDAR for Livingstone Road	
	IHU_0_025	Adjacent higher levels for Clive Sullivan Way used in preference to lower bank survey levels	
	IHU_0_026	Adjacent higher levels for Clive Sullivan Way used in preference to lower bank survey levels	
Humber Frontages	IHU_0_026	7.10m used for west of Makro defence	Humber Hull Frontage Improvements Scheme, FRA.
	IHU_0_027	7.25m for St Andrews Quay and Sailmakers Pub	
	IHU_0_028	6.55m, 6.25m, 6.325m for St Andrews and William Wright Dock	
	IHU_0_029	6.325m, 6.31m for William Wright and Albert Dock	

Scheme	Description of model schematisation		Source
	Node	Comment	
	lHU_0_030	6.65m, 6.42m, 6.40m, 6.55m for Albert Dock, Island Wharf, Humber Dock and Victoria Pier	Top of wall defence levels confirmed by EA 11/10/19
	lHU_0_030i	6.44m for Victoria Dock Village West	
	lHU_0_031	6.44m, for Victoria Dock Village West/East	
Immingham	rHU_0_044i	6.10m for phase 2 design level	Port of Immingham Scheme (ABP)
	rHU_0_045	6.10m for phase 2 design level, lock gates at 6.50m	
	rHU_0_046	6.10m for phase 2 design level	
Paul Village	lHU_0_035	6.80m defence level	Paull Village and Paul Holme Strays completed Oct 2019
	lHU_0_036	6.80m defence level	
	lHU_0_037	Varies 6.80m, 7.50m, 6.80m and 6.63m defence level	
	lHU_0_038	Varies 6.63m, 6.78m and 6.60m defence level	
Skeffling	lHU_0_057	Revised for setback defence at 5.40m and cross sections extended	Outstrays to Skeffling managed realignment overview
	lHU_0_058	Revised for setback defence at 5.40m/5.60m. Cross sections extended	
	lHU_0_059	Revised for setback defence at 5.60m. Cross sections extended	
	lHU_0_060	Revised for setback defence at 5.60m. Cross sections extended	
South Ferriby	rHU_0_016	Defence 6.20m, lower levels at structure retained	Humber South Bank Appraisal, Winteringham Ings to S Ferriby
	rHU_0_017	Defence 6.20m	

A.2 Bridge Overtopping

As part of the H2100+ project, the model has also been used for broadscale modelling work to assess the impacts of potential flood risk management measures, including defence raising. As part of this work, it was identified that several bridges in the upper reaches of the Ouse, Don and Trent which did not have a bypass spilling route after banks were raised. Overtopping spill units were added to the bridges listed in Table A.2, this has no impact on the calibration events tested as water levels do not reach the required level for overtopping of the bridge but added in advance of running future EWL epochs.

Table A.2: Bridge Spill update

Watercourse	Node	Comment
Ouse	SERAILbu	Selby Railway Bridge
Don	D1_10438u	Pipe Crossing
Don	DON01_3966bu	Fordstead Lane
Don	DON01_3175bu	Railway Bridge near Barnby Dun
Don	D00_21091bu	Low Lane
Don	D00_18858bu	Fishlake Nab, Stainforth
Don	D00_14253bu	Ferry Road, Thorne

A.3 Defence Level updates based on MDSF2

As part of the H2100+ project, MDSF2 modelling is being undertaken to assess floodplain risk and economic damages. The initial present day EWL (still water levels) highlighted areas where extensive flooding was occurring at high AEPs. The MDSF2 modellers undertook a crest level comparison between the MDSF2 model and the hydraulic model (averaged spill elevation between cross sections). Overall, there was reasonable agreement, however the model was checked where differences exceeded 0.5m.

The hydraulic model spills are taken between cross sections which can cover distances up to 2km (cross section spacing in the Humber estuary) and contain elevations at 10m to 20m intervals. The average hydraulic model spill lengths cover multiple features of FMP spills and are represented at a different scale in the MDSF2 defence line. So, although it is useful to compare these data there are limitations if there is a large variance in crest level along the length which impacts the average value.

Figure A.2 provides an example where the hydraulic model spill has an average elevation of 6.02m. The MDSF2 features (7 features over the model spill length) are colour coded so blues are when the average FMP spill is lower, greens within +/-0.2m and yellow/reds when the average FMP spill is higher. Comparison of the spill data over each MDSF2 segment, show similar levels (but shows differences when compared to the average spill). e.g. the MDSF2 red line elevation is 5.42m shows good agreement with the first 350m of the model spill but would be lower than the average.

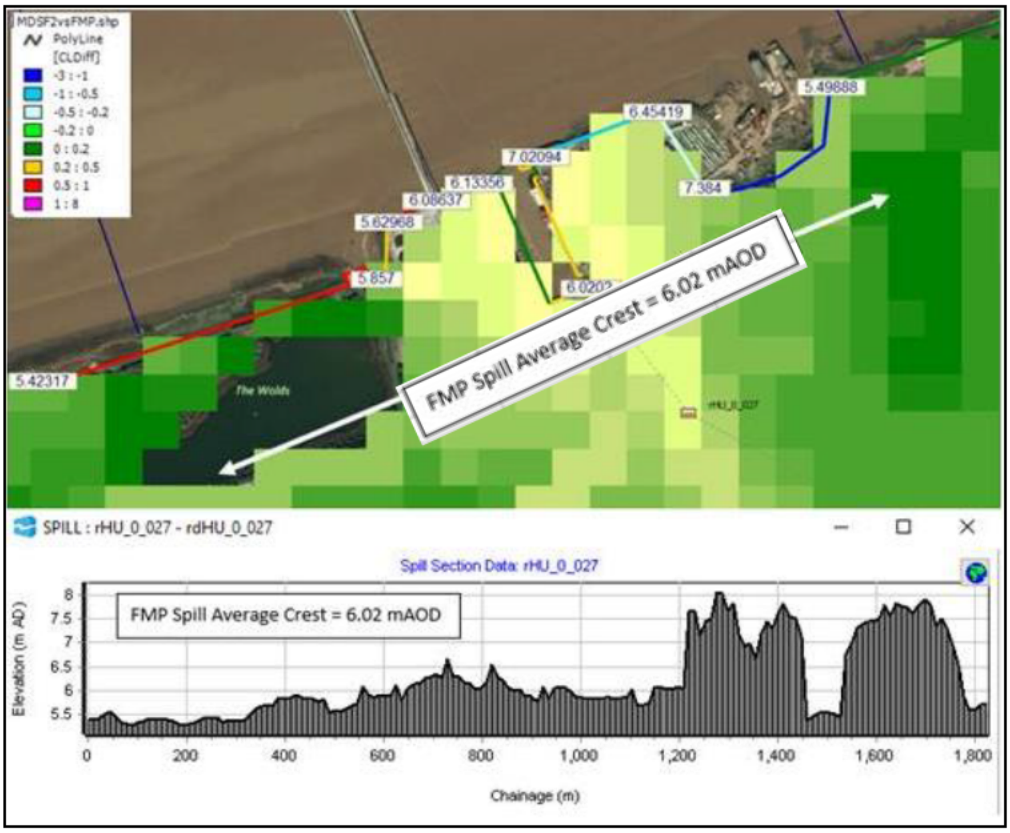


Figure A.2: MDSF2 and hydraulic model crest level comparison

Figure A.3 shows one location upstream of North Ferriby (near Byram Timber) where both the MDSF2 crest and hydraulic model spill (based on the HEWL bank top survey) were low and did not represent the actual defence level. This was identified from the MDSF2 work (flooding at low order events). In this location the LiDAR dataset (downloaded January 2020) was used to update the defence crest.

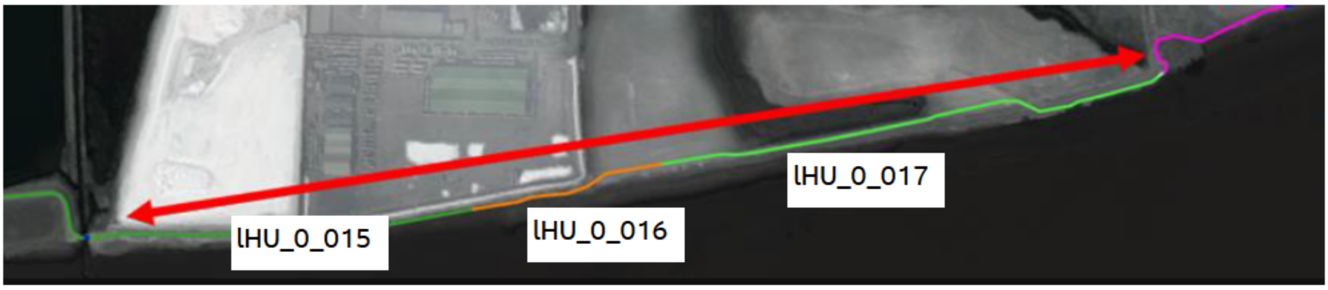


Figure A.3: Defence Crest updated following MDFS2 check

A.4 Floodplain volume check

The model was stress tested using the 2121 epoch 0.1% AEP H++ with full dependency (largest event simulated). One of the model assumptions was that floodplains were only schematised if floodplain feedback could occur (typically based on existing model outputs for the present day 0.1% AEP). A high level volume check was undertaken to prove the modelling assumption, this check highlighted two issues where the existing modelled floodplains could 'glass wall' and areas where the spilling volumes would exceed the floodplain volume.

Figure A.4 shows the locations where floodplain was added using 'reservoir' units (highlighted yellow nodes) and the impact on peak water levels (2121 epoch 0.1% AEP H++ with full dependency). For the mid reaches of the Ouse and Aire, peak levels reduce as the model was previously 'glass walled' within the schematised floodplain. The additional floodplain added to the model has increased the floodplain storage availability which reduces the in channel water levels.

Where the newly added floodplain impacts in channel levels (floodplain feedback now occurs when storage capacity is reached), the model is showing an increase up to 0.20m (around the confluence of the Ouse/Aire and right bank of the Trent).

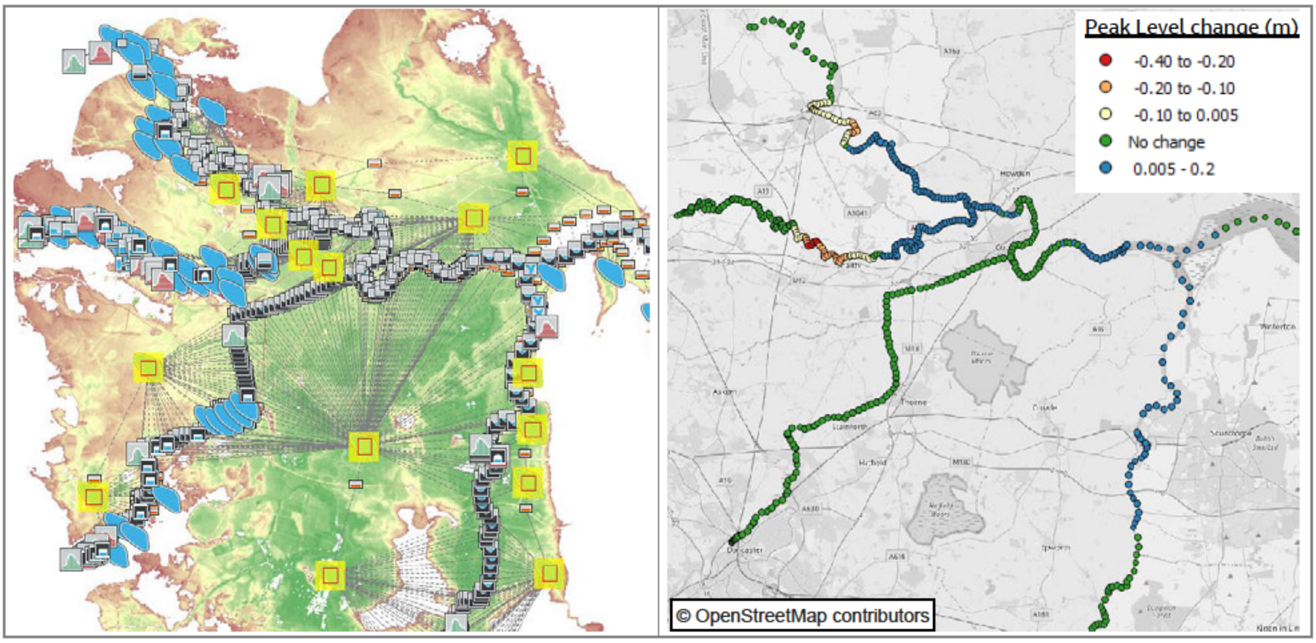


Figure A.4: Additional modelled floodplains

A.5 Bank/Defence spill coefficient

Following review of the initial set of results for the present day EWL, sensitivity tests were undertaken on the bank/defence spill coefficient using the December 2013 calibration event. The reason for the sensitivity test was due to recorded levels for the 2013 event being higher than the present day EWL (explained in Appendix B). The outcome of the test was to reduce the bank/defence coefficient by 20%, which is applied using an IED file which is referenced by the model. Sensitivity tests for the 0.5% and 0.1% AEP events tested for present day, indicated a maximum increase of 0.04m.

A.6 Trent Floodplain between Gainsborough and Stockwith

Additional resolution was added to the model to improve the water surface of the western floodplain between Gainsborough and Stockwith. The model schematisation update is detailed Figure A.5, which shows the original 1D reservoir split into 4 reservoirs, with floodplain/spill sections providing the connections. Data for the spills and reservoir units was extracted from composite LiDAR (downloaded July 2020).

At the 0.5% AEP event (fluvial), the floodplain update was shown to increase peak water levels at Gainsborough gauge by +0.11m. This level increase improves the comparison to detailed 1D2D modelling for events of a similar magnitude. The model update has negligible impacts downstream of the improved floodplain (e.g. at Stockwith) as floodplain flows still return to the Trent resulting in similar peak flows and water levels.

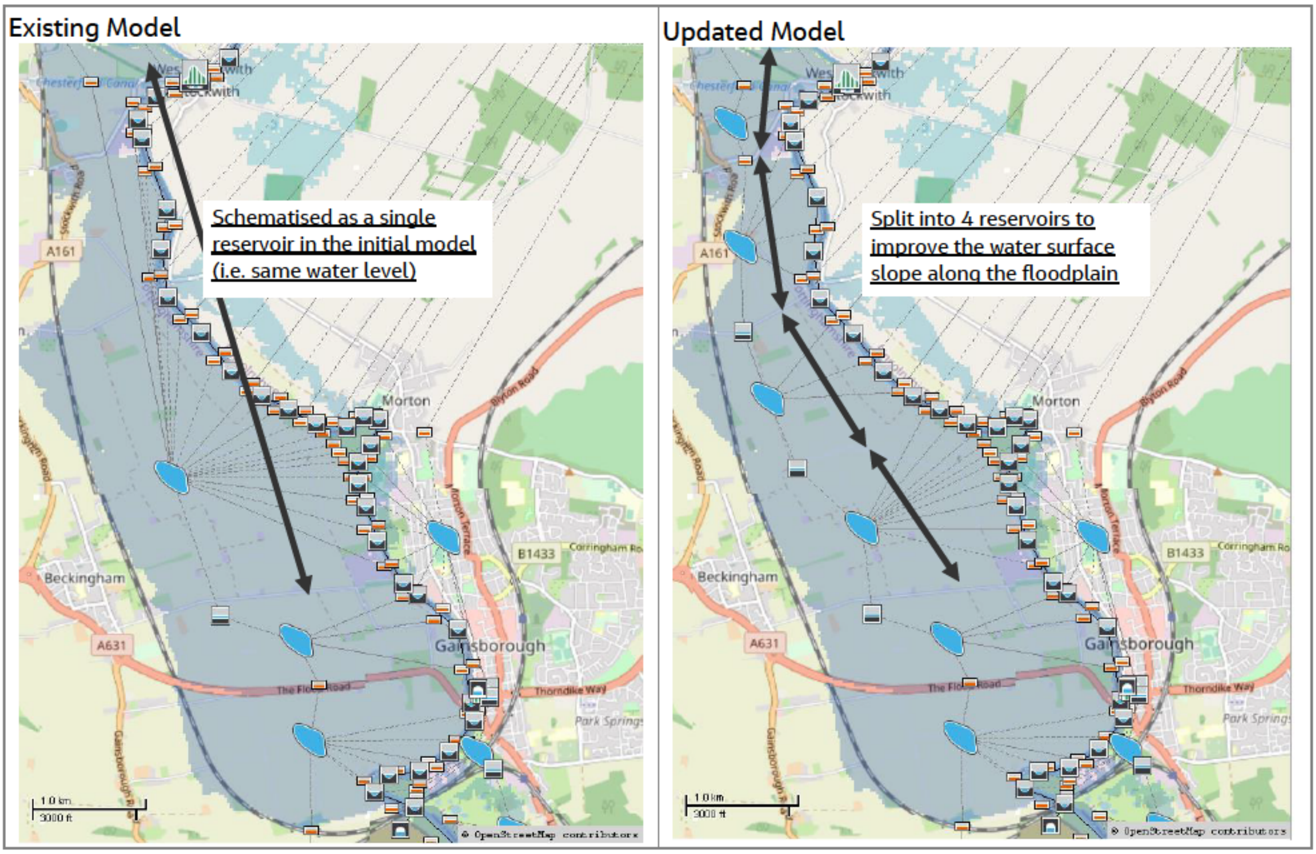


Figure A.5: Update to Trent Floodplain between Gainsborough and Stockwith

Appendix B. Spill Coefficient Sensitivity (calibration model)

The sensitivity results presented in Appendix B are based on the calibration version of the model using the December 2013 event. The calibration model/event was selected so the impacts on peak water levels due to reducing spill coefficients can be compared against real recorded data. i.e. to ensure that a coefficient selected would not have an adverse impact on the model accuracy. As described below, a 20% reduction to the original calibration model spill coefficient was adopted for the final version of the EWL model.

The first iteration of outputs for the extreme water levels highlighted gauges where the recorded December 2013 water level would exceed the 0.1% AEP EWL (1000-year). This includes the gauges at Humber Bridge (December 2013 0.08m higher), Brough (0.03m), Goole (0.03m) and Airmyn (0.05m). It is noted that there is potentially uncertainty with some of the estuary gauges which have datums of 0.0mAOD and impact the recorded data.

Sensitivity tests have been undertaken on the December 2013 event, to assess the impacts on peak water level by reducing the spill weir coefficient (originally set to 1.0) by 20% (adopted for the final EWL) and 50%. A lower coefficient will reduce spilling over banks/defences and increase in channel water levels. The results from the sensitivity tests are detailed in Table B.1 (estuary) and Table B.2 (tidal rivers) and long-sections for each watercourse (Figure B.1 to Figure B.4). The Key points are summarised below:

- No impact downstream of Immingham gauge
- Humber Bridge, level increase of 0.02m (-20% coefficient) and 0.05m (-50%), within calibration accuracy
- Brough, level increase of 0.03m (-20% coefficient) and 0.09m (-50%), within calibration accuracy
- West Walker Dykes, level increase of 0.04m (-20% coefficient) and 0.11m (-50%), within calibration accuracy for -20%, outside for -50%
- Goole, level increase of 0.01m (-20% coefficient) and 0.06m (-50%), within calibration accuracy for 50%
- Airmyn, level increase of 0.02m (-20% coefficient) and 0.08m (-50%), within calibration accuracy for 50%

Table B.1: December 2013 calibration and sensitivity tests on spill weir coefficient (estuary)

Station	Owner	December 2013								
		Rec	HEWL	Diff	FMP	Diff	-20%	Diff	-50%	Diff
Spurn Point	ABP	5.04	5.00	-0.04	5.07	0.02	5.07	0.02	5.07	0.02
Spurn Point [1]	*EA*	5.24	5.00	-0.24	5.07	-0.17	5.07	-0.17	5.07	-0.17
Buck Beck	EA	5.22	5.05	-0.17	5.12	-0.10	5.12	-0.10	5.12	-0.10
Patrington	EA		5.14		5.14		5.14		5.14	
Sunk Island	ABP	5.05	5.16	0.11	5.19	0.14	5.19	0.14	5.19	0.14
Grimsby	ABP		5.14		5.21		5.21		5.21	
Haborough M	EA		5.31		5.32		5.32		5.32	
Immingham	ABP		5.35		5.37		5.37		5.37	
Immingham	EA	5.31 [2]	5.34	0.02	5.33	0.02	5.33	0.02	5.34	0.03
Immingham	NTSLF	5.21	5.34	0.12	5.33	0.12	5.33	0.12	5.34	0.12
Humber Sea T	ABP	5.36	5.42	0.06	5.43	0.07	5.43	0.07	5.44	0.08
Paull	EA	5.69	5.56	-0.13	5.52	-0.17	5.53	-0.17	5.54	-0.15
Humber KG	ABP	5.48	5.62	0.14	5.57	0.09	5.58	0.10	5.60	0.11
Hull Barrier	EA		5.66		5.64		5.65		5.67	
Albert Dock	ABP		5.68		5.66		5.67		5.69	

Station	Owner	December 2013								
		Rec	HEWL	Diff	FMP	Diff	-20%	Diff	-50%	Diff
Humber Bridge	ABP	5.97	5.81	-0.16	5.85	-0.12	5.87	-0.10	5.90	-0.07
Brough	ABP		5.94		5.97		6.00		6.06	
Brough	EA	6.06	5.96	-0.10	5.97	-0.09	6.00	-0.06	6.06	0.00
West W Dykes	ABP	5.87	6.02	0.15	5.96	0.09	6.00	0.13	6.07	0.20
Alkborough	EA	5.87			5.83	-0.04	5.80	-0.07	5.46	-0.41

Table B.2: December 2013 calibration and sensitivity tests on spill weir coefficient (estuary)

Rive	Station	Owner	December 2013								
			Rec	HEWL	Diff	FMP	Diff	-20%	Diff	-50%	Diff
T	Burton Stather	ABP		5.92		5.90		5.93		6.00	
T	Flixborough	ABP		5.92		5.93		5.97		6.04	
T	Keadby	ABP		5.89		5.97		6.01		6.08	
T	Keadby	EA		5.89		5.97		6.01		6.08	
T	Gainsborough	EA	5.31	5.18	-0.14	5.36	0.05	5.37	0.06	5.40	0.09
T	Torksey	EA	4.57			4.17	-0.40	4.17	-0.40	4.17	-0.40
T	Carlton-on-Trent	EA				4.34		4.34		4.33	
T	North Muskham	EA	5.97			5.78	-0.19	5.78	-0.19	5.78	-0.19
O	Blacktoft	ABP		5.95		5.88		5.92		5.99	
O	Blacktoft	EA		5.95		5.88		5.92		5.99	
O	Goole	ABP		5.91		5.86		5.87		5.92	
O	Goole [1]	EA	6.04	5.91	-0.13	5.86	-0.18	5.87	-0.17	5.92	-0.12
O	Barmby Barrage	EA	5.96	5.91	-0.05	5.91	-0.05	5.93	-0.02	5.99	0.03
O	Selby Lock	EA	5.41	5.71	0.31	5.51	0.11	5.52	0.11	5.56	0.15
O	Selby Westmill	EA	5.50			5.41	-0.09	5.41	-0.09	5.41	-0.09
O	Cawood	EA	5.37			5.74	0.38	5.72	0.35	5.75	0.38
D	Went Outfall	EA	5.27	5.24	-0.03	5.15	-0.12	5.16	-0.11	5.18	-0.09
D	Fishlake	EA	4.82			4.72	-0.10	4.73	-0.09	4.74	-0.08
D	Kirk Bramwith [2]	EA	4.51			4.43	-0.08	4.43	-0.08	4.44	-0.07
D	Doncaster	EA	4.91			5.14	0.23	5.14	0.23	5.14	0.23
A	Airmyn	EA	6.11	5.96	-0.15	5.88	-0.22	5.91	-0.20	5.97	-0.14
A	Carlton Bridge	EA	4.95	5.16	0.20	5.07	0.12	5.08	0.12	5.08	0.13
A	Chapel Haddlesey	EA	5.26			5.26	0.00	5.26	0.00	5.27	0.00
A	Beale Weir	EA	5.75			5.74	-0.01	5.74	-0.01	5.74	-0.01

O = Ouse, A = Aire, D = Don, T =Trent. [1] Peak water level for 2013 taken from UH Study report

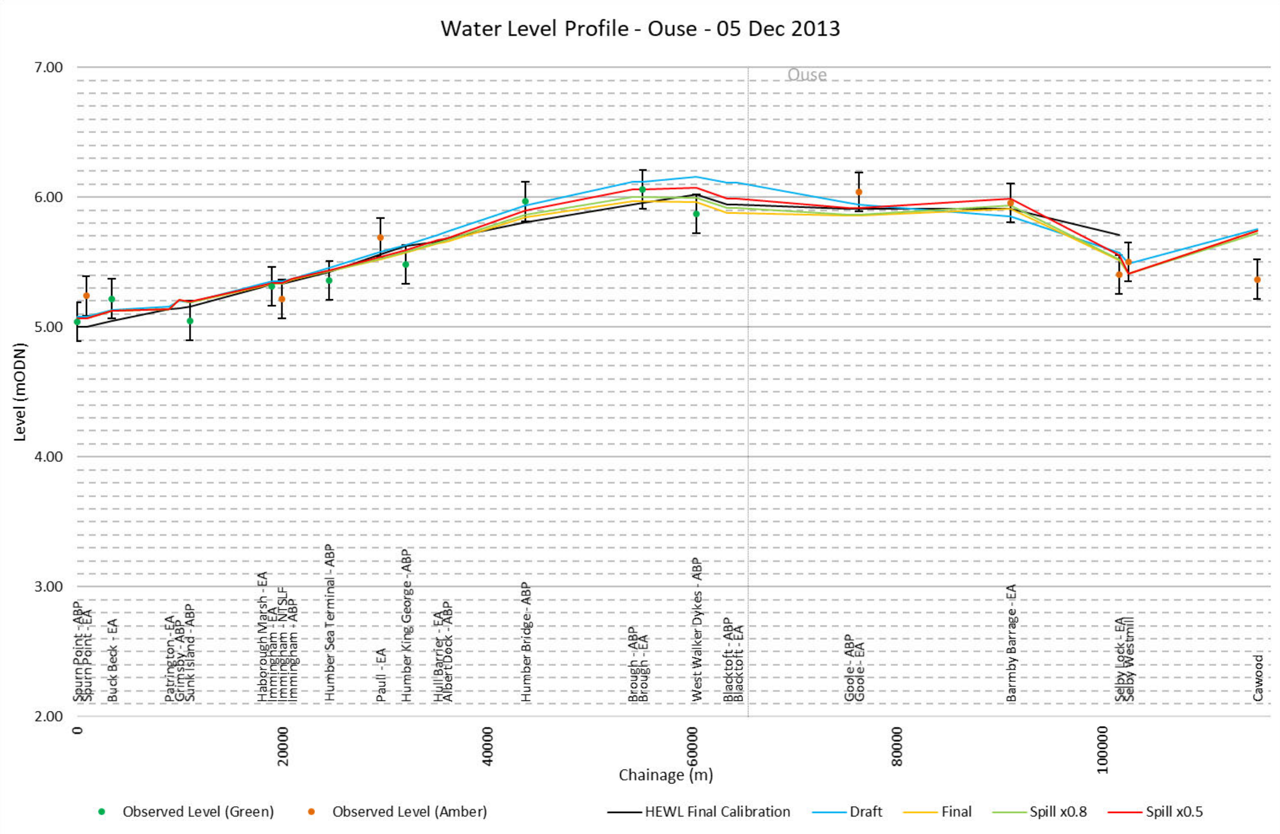


Figure B.1: Spill coefficient sensitivity test – December 2012, River Ouse

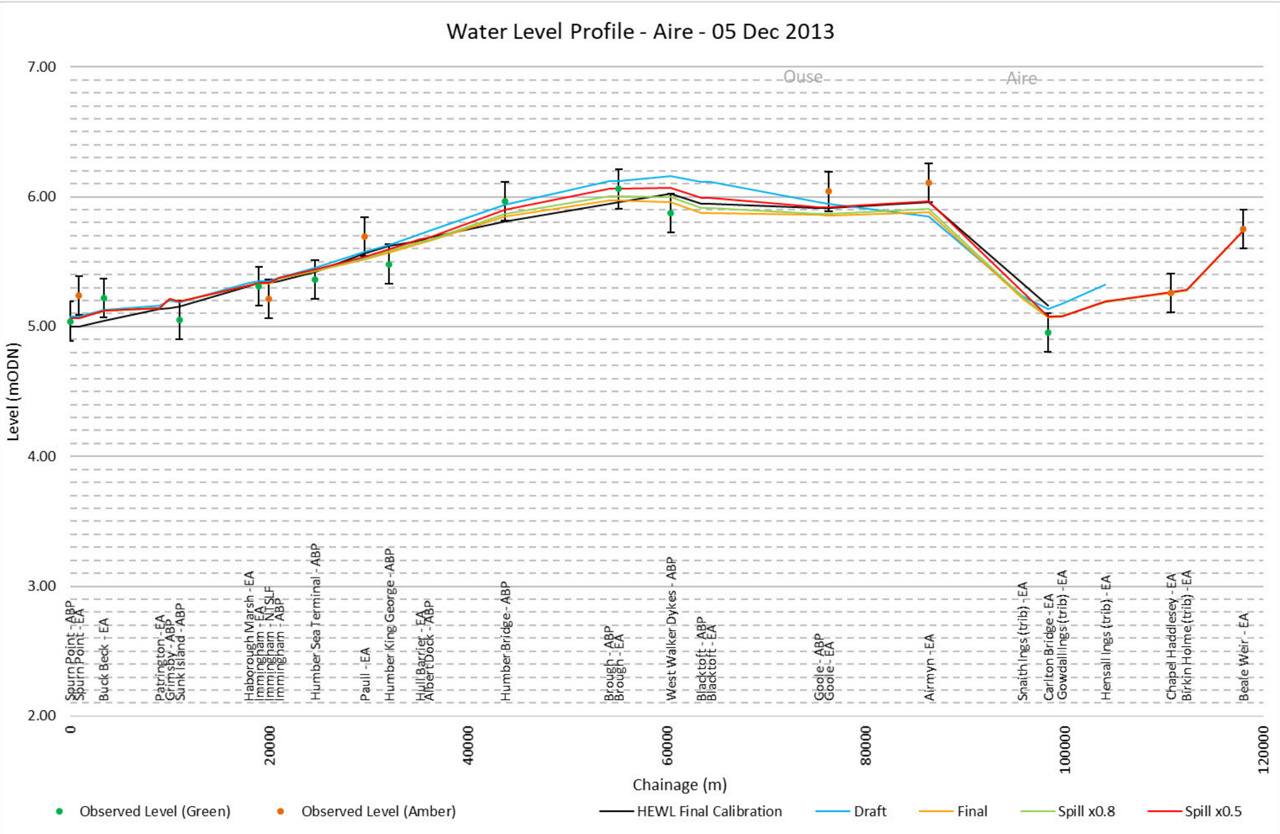


Figure B.2: Spill coefficient sensitivity test – December 2012, River Aire

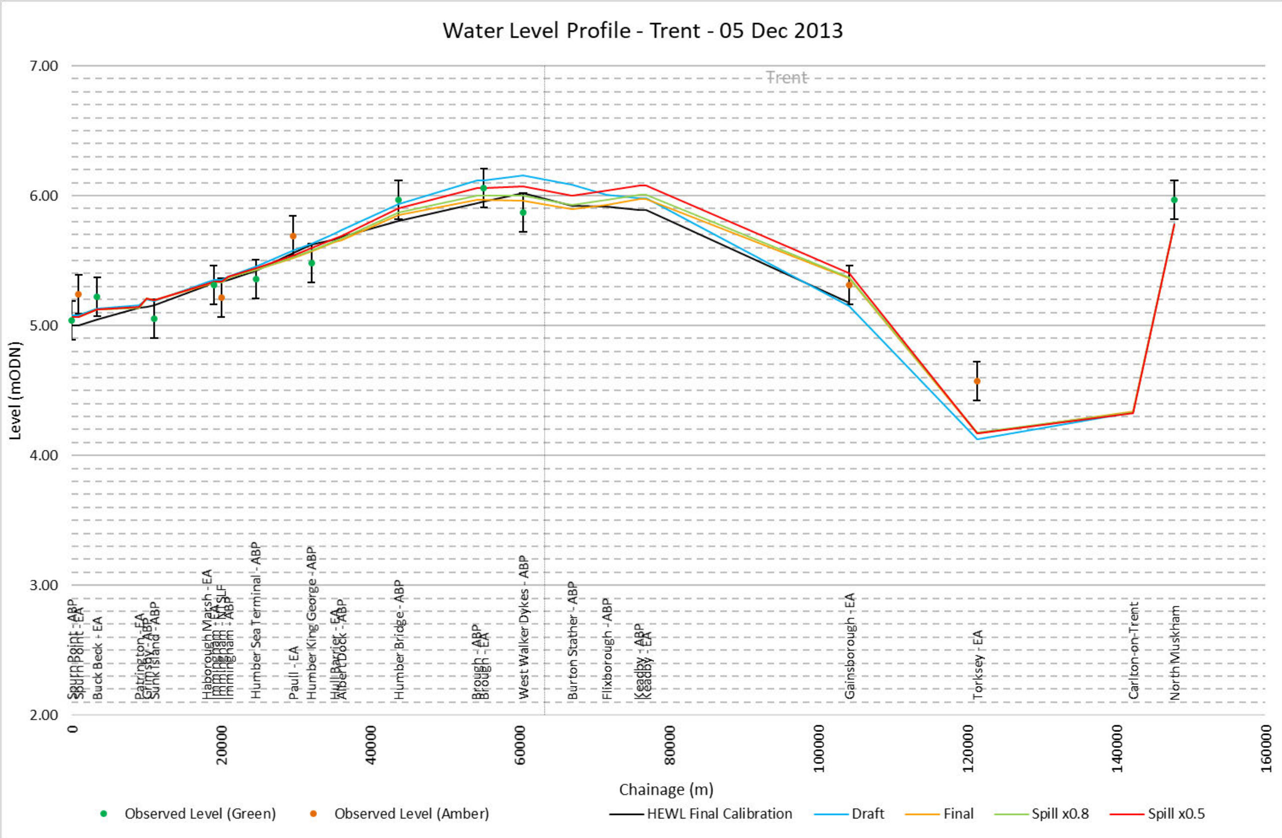


Figure B.3: Spill coefficient sensitivity test – December 2012, River Trent

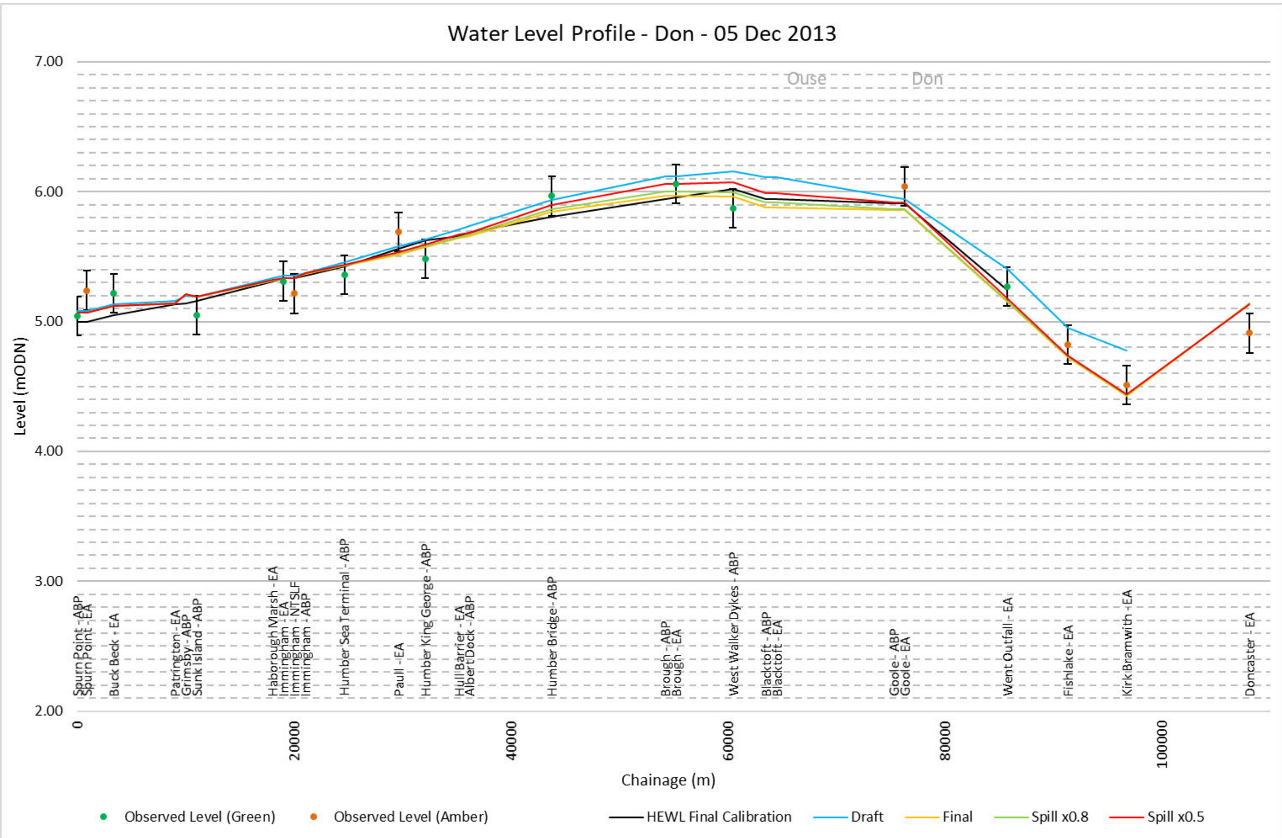
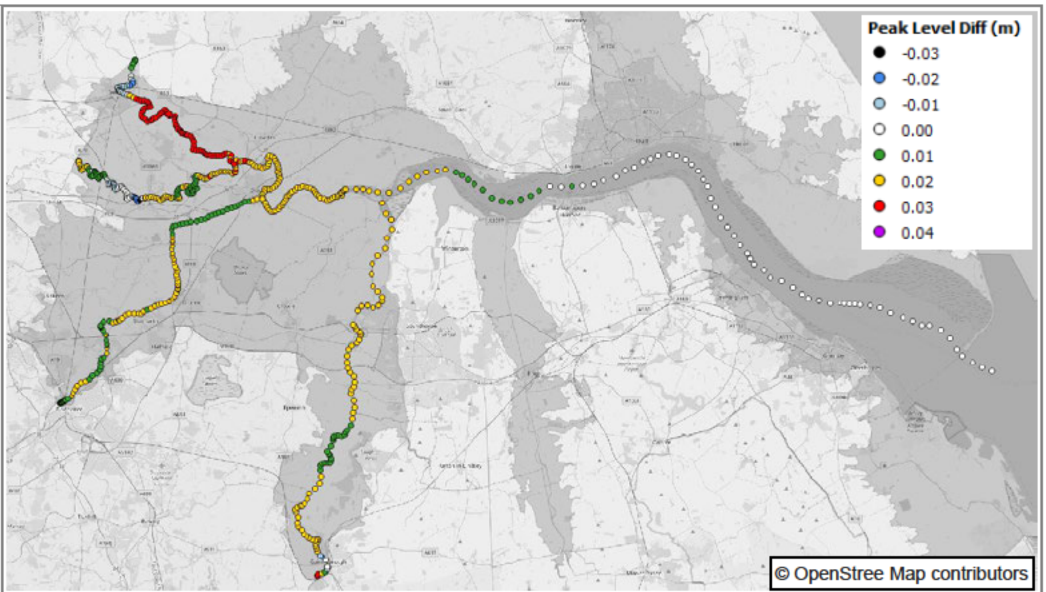


Figure B.4: Spill coefficient sensitivity test – December 2012, River Don

The full set of joint probability events for 0.5% and 0.1% AEP (200 and 1000-year) were tested using the 20% spill coefficient reductions. The change in peak water level is detailed in Figure B.5. For 0.5% AEP, the level rise is negligible downstream of Humber Bridge and then a 0.01m to 0.02m increase on the tidal rivers, with a 0.03m increase on the Ouse upstream of the Aire confluence. For the 0.1% AEP the highest peak water level increases of 0.03m to 0.04m in the lower reaches of the tidal rivers to Humber Bridge.

Water level difference for 0.5% AEP with spill coefficents globally reduced by 20%



Water level difference for 0.1% AEP with spill coefficents globally reduced by 20%

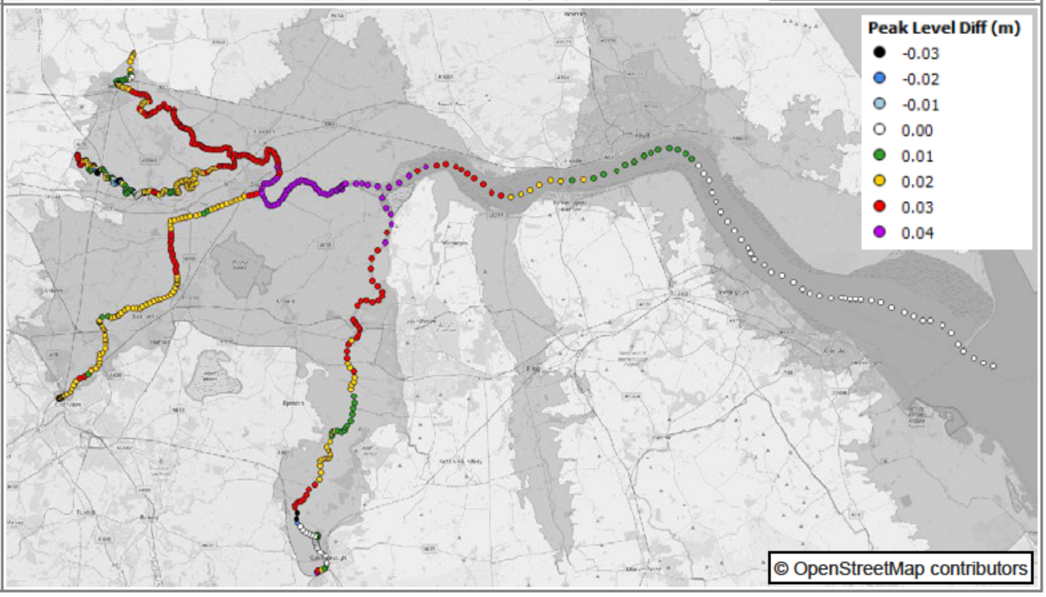


Figure B.5: Sensitivity to spill coefficient (0.5% and 0.1% AEP)

Appendix C. Design boundary: Peak flows and tides

C.1 Peak Design Flows

Table C.1: Peak Flows (+15%): 2021_M

Watercourse	Peak Flows (m^3/s) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
River Trent	540.5	679.7	774.0	913.1	1173.0	1306.4	1397.3	1648.0	2100.4	2442.6
River Ouse	547.2	619.3	702.3	826.4	993.1	1078.5	1125.6	1233.4	1329.6	1409.4
River Don	192.7	251.7	287.5	319.9	358.8	375.0	386.0	411.6	442.8	465.0
River Aire	337.0	344.1	348.0	363.7	416.8	459.7	483.9	613.8	870.1	1064.0

Table C.2: Peak Flows (+20%): 2021_H, 2021_H++, 2040_M and 2046_M

Watercourse	Peak Flows (m^3/s) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
River Trent	564.0	709.2	807.6	952.8	1224.0	1363.2	1458.0	1719.6	2191.7	2548.8
River Ouse	571.0	646.2	732.8	862.3	1036.3	1125.4	1174.5	1287.0	1387.4	1470.7
River Don	201.1	262.6	300.0	333.8	374.4	391.3	402.8	429.5	462.1	485.2
River Aire	351.7	359.0	363.1	379.5	434.9	479.6	504.9	640.5	908.0	1110.3

Table C.3: Peak Flows (+30%): 2040_H, 2046_H, 2071_M and 2121_M

Watercourse	Peak Flows (m^3/s) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
River Trent	611.0	768.3	874.9	1032.2	1326.0	1476.8	1579.5	1862.9	2374.3	2761.2
River Ouse	618.5	700.1	793.9	934.2	1122.6	1219.2	1272.4	1394.3	1503.0	1593.2
River Don	217.8	284.5	325.0	361.6	405.6	423.9	436.3	465.3	500.6	525.7
River Aire	381.0	388.9	393.4	411.1	471.1	519.6	547.0	693.9	983.6	1202.8

Table C.4: Peak Flows (+35%): 2040_H++ and 2046_H++

Watercourse	Peak Flows (m^3/s) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
River Trent	634.5	797.9	908.6	1071.9	1377.0	1533.6	1640.3	1934.6	2465.6	2867.4
River Ouse	642.3	727.0	824.4	970.1	1165.8	1266.1	1321.3	1447.9	1560.8	1654.5
River Don	226.2	295.4	337.5	375.5	421.2	440.2	453.1	483.2	519.9	545.9
River Aire	395.6	403.9	408.5	426.9	489.2	539.6	568.0	720.6	1021.5	1249.1

Table C.5: Peak Flows (+50%): 2046_H, 2071_H and 2121_H

Watercourse	Peak Flows (m^3/s) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
River Trent	705.0	886.5	1009.5	1191.0	1530.0	1704.0	1822.5	2149.5	2739.6	3186.0
River Ouse	713.7	807.8	916.0	1077.9	1295.3	1406.8	1468.2	1608.8	1734.2	1838.3
River Don	251.4	328.3	375.0	417.2	468.0	489.1	503.5	536.9	577.6	606.5
River Aire	439.6	448.8	453.9	474.3	543.6	599.5	631.1	800.6	1135.0	1387.9

Table C.6: Peak Flows (+65%): 2071_H++, 2071_H and 2121_H++

Watercourse	Peak Flows (m^3/s) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
River Trent	775.5	975.2	1110.5	1310.1	1683.0	1874.4	2004.8	2364.5	3013.6	3504.6
River Ouse	785.1	888.6	1007.6	1185.7	1424.9	1547.5	1615.0	1769.7	1907.6	2022.2
River Don	276.5	361.1	412.5	459.0	514.8	538.1	553.8	590.6	635.4	667.2
River Aire	483.6	493.7	499.3	521.8	598.0	659.5	694.3	880.7	1248.5	1526.7

C.2 Peak Design Tides

Table C.7: Tide Peaks (mAOD)

Sea Level Rise (SLR)	Tide Peak (mAOD) for Return Period 1 in X and Design AEP (%)									
	2	5	10	20	50	75	100	200	500	1000
	50	20	10	5	2	1.33	1	0.5	0.2	0.1
CFB2018	3.96	4.10	4.21	4.33	4.49	4.56	4.61	4.75	4.93	5.07
+ 0.02m SLR: 2021_M	3.98	4.12	4.23	4.35	4.51	4.58	4.63	4.77	4.95	5.09
+ 0.03m SLR: 2021_H_H++	3.99	4.13	4.24	4.36	4.52	4.59	4.64	4.78	4.96	5.10
+ 0.14m SLR: 2040_M	4.10	4.24	4.35	4.47	4.63	4.70	4.75	4.89	5.07	5.21
+ 0.18m SLR: 2040_H	4.14	4.28	4.39	4.51	4.67	4.74	4.79	4.93	5.11	5.25
+ 0.28m SLR: 2040_H++	4.24	4.38	4.49	4.61	4.77	4.84	4.89	5.03	5.21	5.35
+ 0.19m SLR: 2046_M	4.15	4.29	4.40	4.52	4.68	4.75	4.80	4.94	5.12	5.26
+ 0.23m SLR: 2046_H	4.19	4.33	4.44	4.56	4.72	4.79	4.84	4.98	5.16	5.30
+ 0.37m SLR: 2046_H++	4.33	4.47	4.58	4.70	4.86	4.93	4.98	5.12	5.30	5.44
+ 0.42m SLR: 2071_M	4.38	4.52	4.63	4.75	4.91	4.98	5.03	5.17	5.35	5.49
+ 0.54m SLR: 2071_H	4.50	4.64	4.75	4.87	5.03	5.10	5.15	5.29	5.47	5.61
+ 0.97m SLR: 2071_H++	4.93	5.07	5.18	5.30	5.46	5.53	5.58	5.72	5.90	6.04
+ 1.02m SLR: 2121_M	4.98	5.12	5.23	5.35	5.51	5.58	5.63	5.77	5.95	6.09
+ 1.38m SLR: 2121_H	5.34	5.48	5.59	5.71	5.87	5.94	5.99	6.13	6.31	6.45
+ 2.64m SLR: 2121_H++	6.60	6.74	6.85	6.97	7.13	7.20	7.25	7.39	7.57	7.71

Appendix D. Review of initial extreme water levels

The model was simulated to derive an initial set of present day extreme water levels for verification purposes. This task was undertaken prior to the confirmation of the uplifts for the epochs/scenarios, resulting in present day boundaries which do not include the SLR and fluvial uplifts (note that these results do not form part of the EWL deliverable, and are replaced by the final set following updates to the JP method and model).

Figure D.1 maps the event types which produce the maximum water level for the 0.5% AEP at each model calculation point. The maps categorise the peak level by fluvially dominated (red), tidally dominated (blue) and from the set of joint probabilities (green).

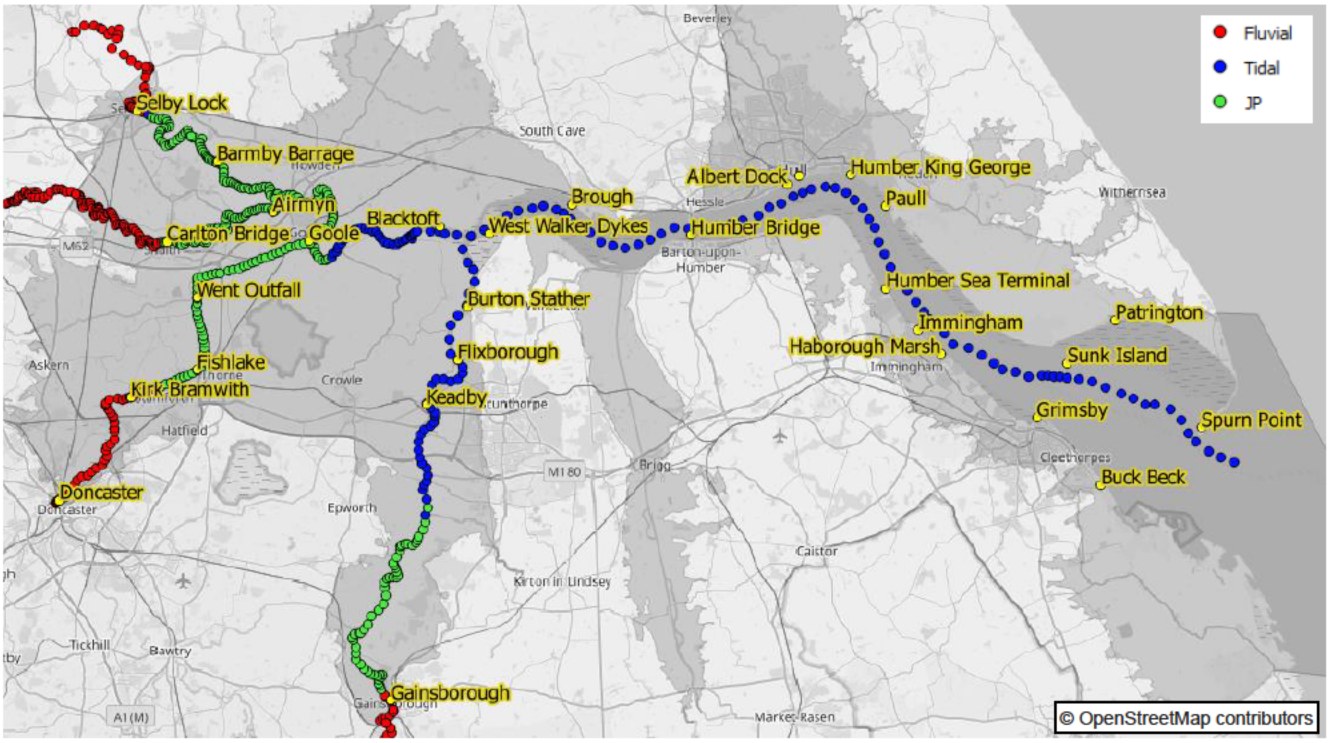


Figure D.1: Event type which produces peak water level – 0.5% AEP Initial results

D.1 Key findings from the verification process

The key findings from the verification process were lower EWL at Gainsborough when compared to previous modelling (1D/2D). Recorded water levels for December 2013 event at Airmyn, Goole, Brough and Humber Bridge gauges higher than the 0.1% EWL and to review the review joint probability method due to take account of the potential underestimation/bias of the simplified joint probability method.

D.1.1 Lower extreme water level at Gainsborough (compared to existing modelling)

At Gainsborough, the initial EWL was giving lower water levels when compared to the fluvial type events from the existing 1D/2D model (0.9m lower for the 0.5% AEP). During the calibration process a 'best overall calibration' channel roughness was selected, which slightly overestimate tidal event and underestimated fluvial events (but still within the specified the target accuracy of +/- 0.15m). Modelling has shown that water levels in Gainsborough are very sensitive to roughness, a 15% increase is predicted raise peak levels by 0.2m – 0.6m over the simulated range of present day events.

The JP approach was reviewed and updated to include 2 versions of the 1D model, the revised 'Trent fluvial' model included higher roughness values on the Trent (+15% between Gainsborough to the Ouse confluence). The 'Trent fluvial' model was used only for the JP simulations which had a high fluvial component on the Trent. Figure D.2 shows the verification chart at Gainsborough, the initial EWL (black line) is much lower than the fluvial events from the Tidal Trent 1D/2D model (orange line). The revised EWL (red line), shows much better agreement with the 1D/2D model results.

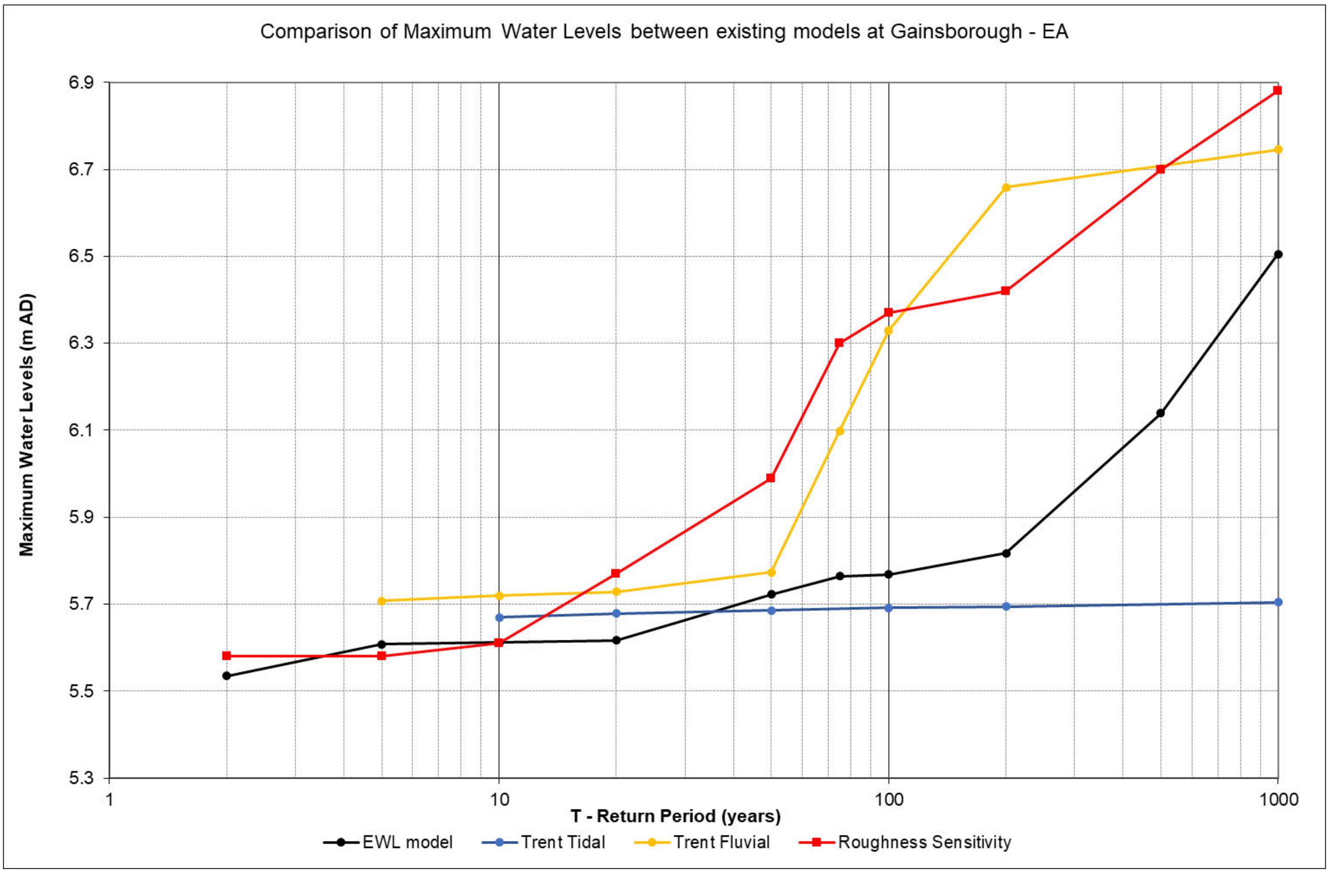


Figure D.2: Gainsborough EWL comparison to existing modelling results

D.1.2 Initial EWL lower than December 2013 event

The first iteration of outputs for the extreme water levels highlighted gauges where the recorded December 2013 water level would exceed the 0.1% AEP EWL (1000-year). This includes the gauges at Humber Bridge (December 2013 0.08m higher), Brough (0.03m), Goole (0.03m) and Airmyn (0.05m). The Environment Agency advised that there is potentially uncertainty with some of the estuary gauges which have datums of 0.0mAOD.

Figure D.3 charts the EWL against the indicative bank level near the gauge (red lines) and the December 2013 peak (blue line). The best fit model calibration showed the Brough and Humber Bridge gauges to be within the target accuracy, but the Airmyn and Goole gauges outside (-0.22m and -0.18m). Model sensitivity tests on bank/defence spills were undertaken on the December 2013 event (Full details and results to sensitivity tests are included in Appendix A).

The key findings were that a 50% reduction would be required to bring the modelled water levels to within the target accuracy at Airmyn and Goole, which is considered beyond the range of expected coefficients and not used for any further analysis. A 20% reduction was found to modelled water levels up to 0.02m at Airmyn and Goole. This was further explored using the 0.5% and 0.1% AEP EWL, which showed a 20% spill coefficient reduction would increase peak levels by up to 0.03m (0.5% AEP) and 0.04m (0.1% AEP).

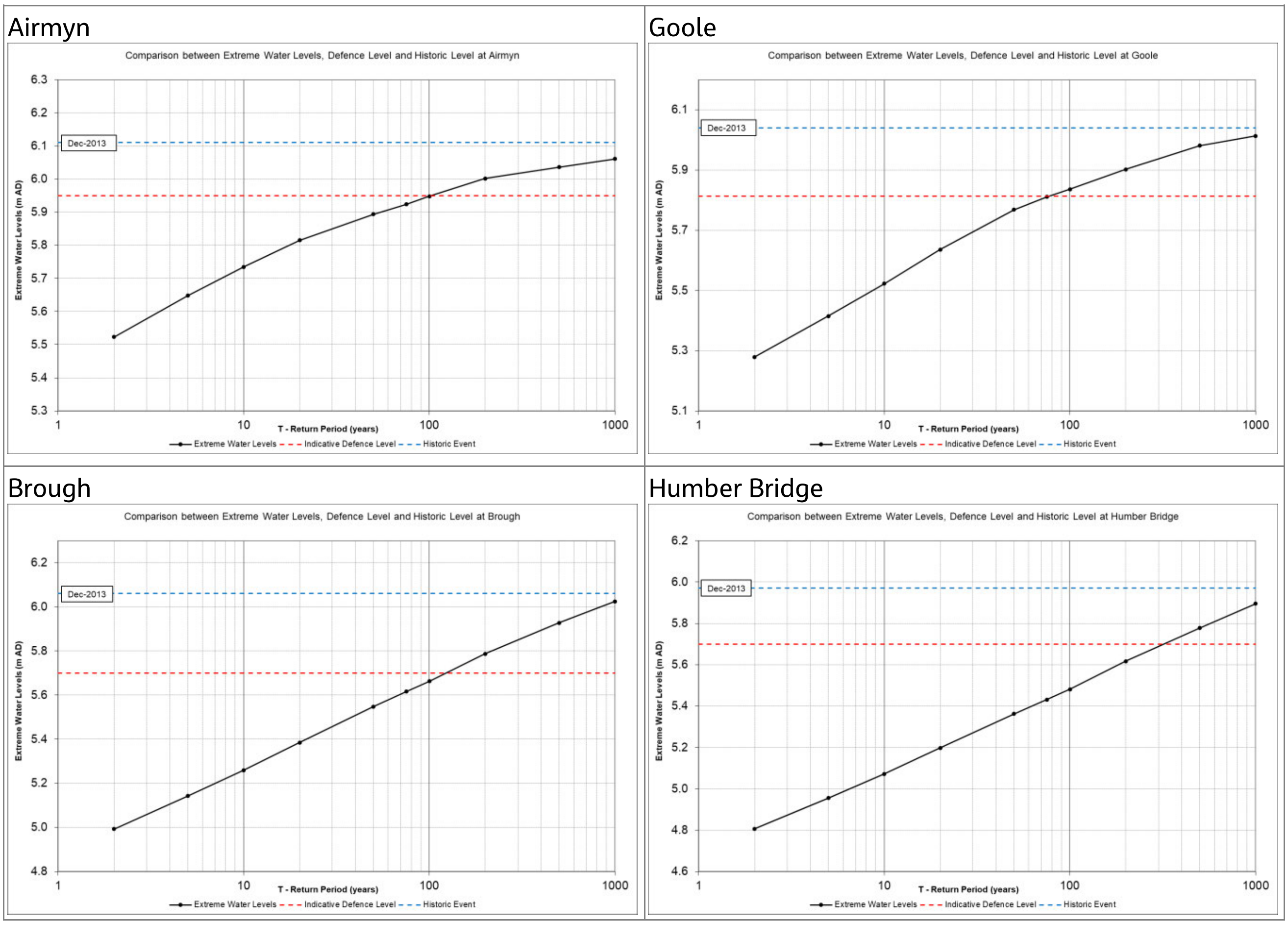


Figure D.3: Initial EWL compared to December 2013 peaks

D.1.3 Joint probability sensitivity test

Sensitivity tests were undertaken to assess the potential changes in water level for the joint probability. The initial results were compared to full dependency (worst case) and adjustments due to the potential tendency for the FD2308 simplified approach to result in an underestimate of EWLs. This was applied to the mixed tidal/fluvial events by adjusting joint probability combinations such that the calculated event exceedance probabilities are doubled (compared to the unadjusted probabilities).

Long sections presenting the 0.5% AEP peak water levels for the River Aire and Trent are detailed in Figure D.4 (River Trent) Figure D.5 (River Aire). The figures show the initial results (orange line) and the full dependency (blue line), the adjusted JP results (green line) sits in between the other results. The zone where the range is greatest is where peak water levels are determined by the joint probability combinations.

D.2 Summary and updates for final EWL

Changes were made to the model and joint probability matrix following the review of the initial extreme water levels (which included the verification tasks and subsequent sensitivity tests). The changes included:

- Additional 1D model ('Trent fluvial' model with +15% roughness between Gainsborough and confluence with the River Ouse) to be used only for the JP simulations which had a high fluvial component on the Trent.
- 20% spill coefficient reduction was adopted for the final set of EWL, based on the findings of the initial EWL and roughness sensitivity test (applied to the 1D models using an IED file).

- Adjusted joint probability matrix adopted for the final set of EWL, showed small increases in peak level at the gauge sites where the December 2013 event recorded water levels exceeded the initial present day EWL.

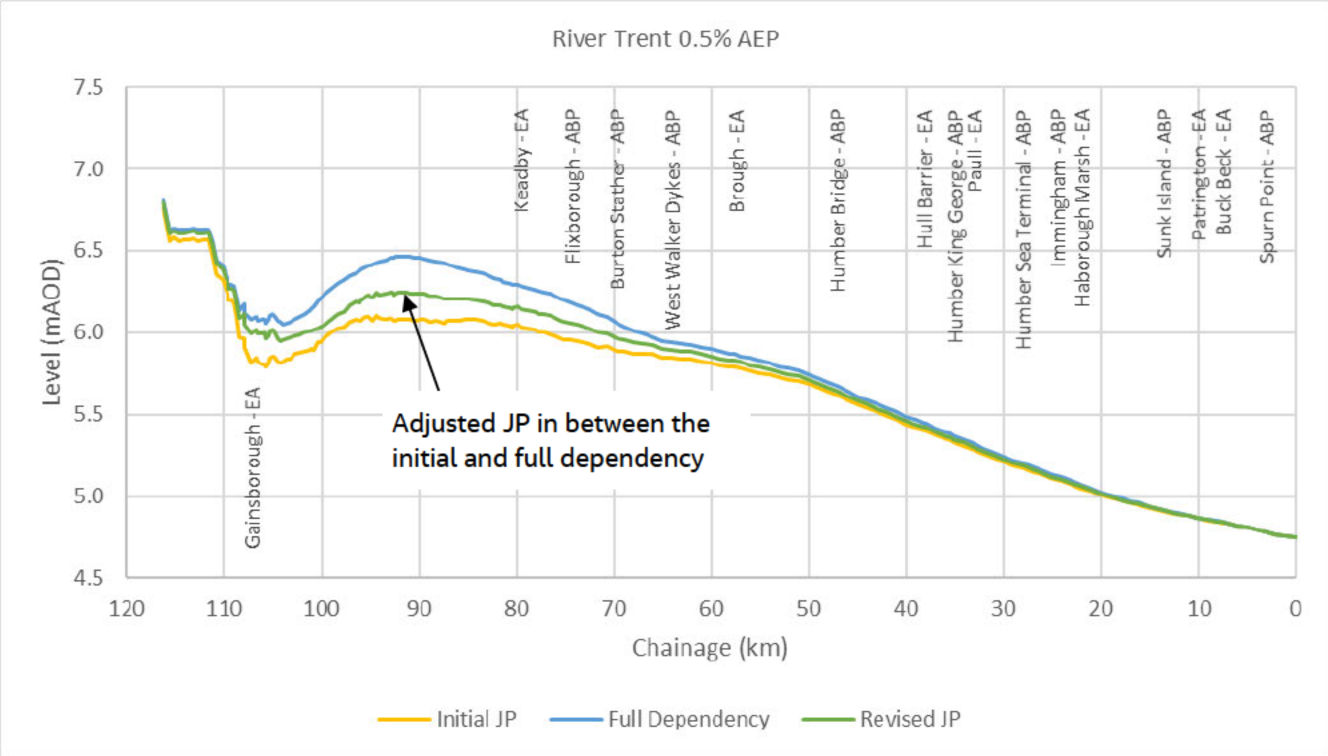


Figure D.4: River Trent comparison between full dependency, initial and adjusted JP – 0.5% AEP

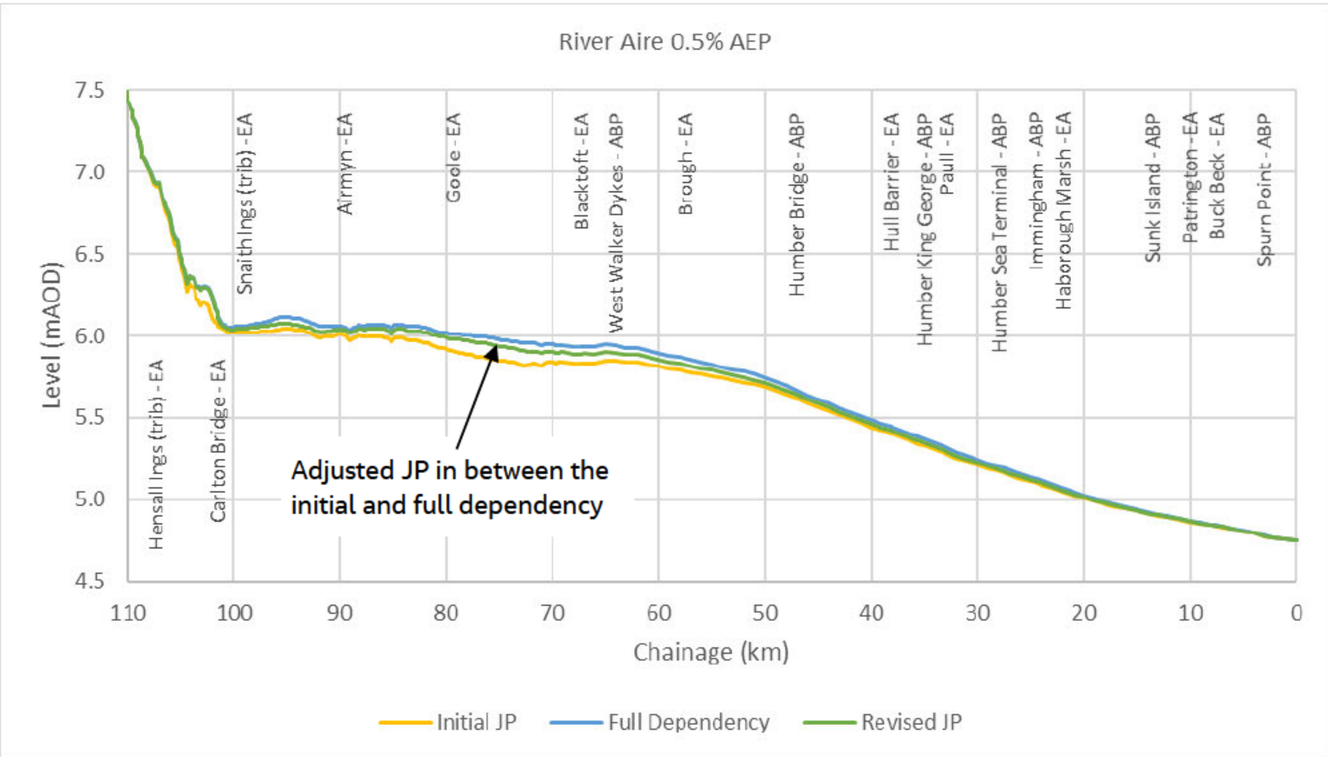


Figure D.5: River Aire comparison between full dependency, initial and adjusted JP – 0.5% AEP

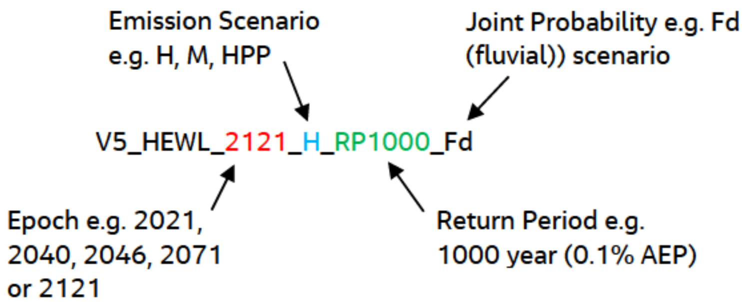
Appendix E. Hydrodynamic model details

The 1D model datafiles used for calibration, initial EWL and the final deliverable of EWL (highlighted green) are listed in Table E.1.

Table E.1: 1D Model datafile

1D Model Name	Comment
UH_TT_Estuary_v17_DON_Spills_2013_v3.DAT	Calibration model
UH_TT_Estuary_v21_2021.dat	Initial 2021 EWL model
v9_Humber_2021.dat with v3_lower_spill_coef.ied	Final 2021 EWL model (Trent roughness set for tidal events)
V9_Humber_2021.dat with v3_lower_spill_coef.ied and Trent_fluvial_roughness.ied	Final 2021 EWL model (Trent roughness set for fluvial events)

The final, full set of extreme water levels required 1,815 model simulations from which results are extracted and the maximum water levels collated. The models are set up using standard flood modeller events files (IEF file) which reference boundary conditions (IED file). The simulations and results use a standard filename approach which defines the scenarios and boundary conditions within name. An example of the 2121 epoch for the upper scenario for the 1000-year event and fluvial scenario is detailed below:



Each simulation is run for 200 model hours (full hydrograph) which takes approximately 25-minutes to complete using Flood Modeller Version 4.6 (latest version in September 2020 when the final simulations were undertaken).

The model uses a 30 second timestep, with the minimum iteration set to 4 (to force the model to undertake additional calculations) and maximum iterations set to 17 (to ensure model convergence). The save interval was to 300 seconds to adequately capture the shape of the tidal curves, given the model size (3995 nodes) this this results in a large output file 224MB.

The converge information for a sample of events (2021 and 2121) are detailed in Figure E.1 (all models show similar convergence patterns).

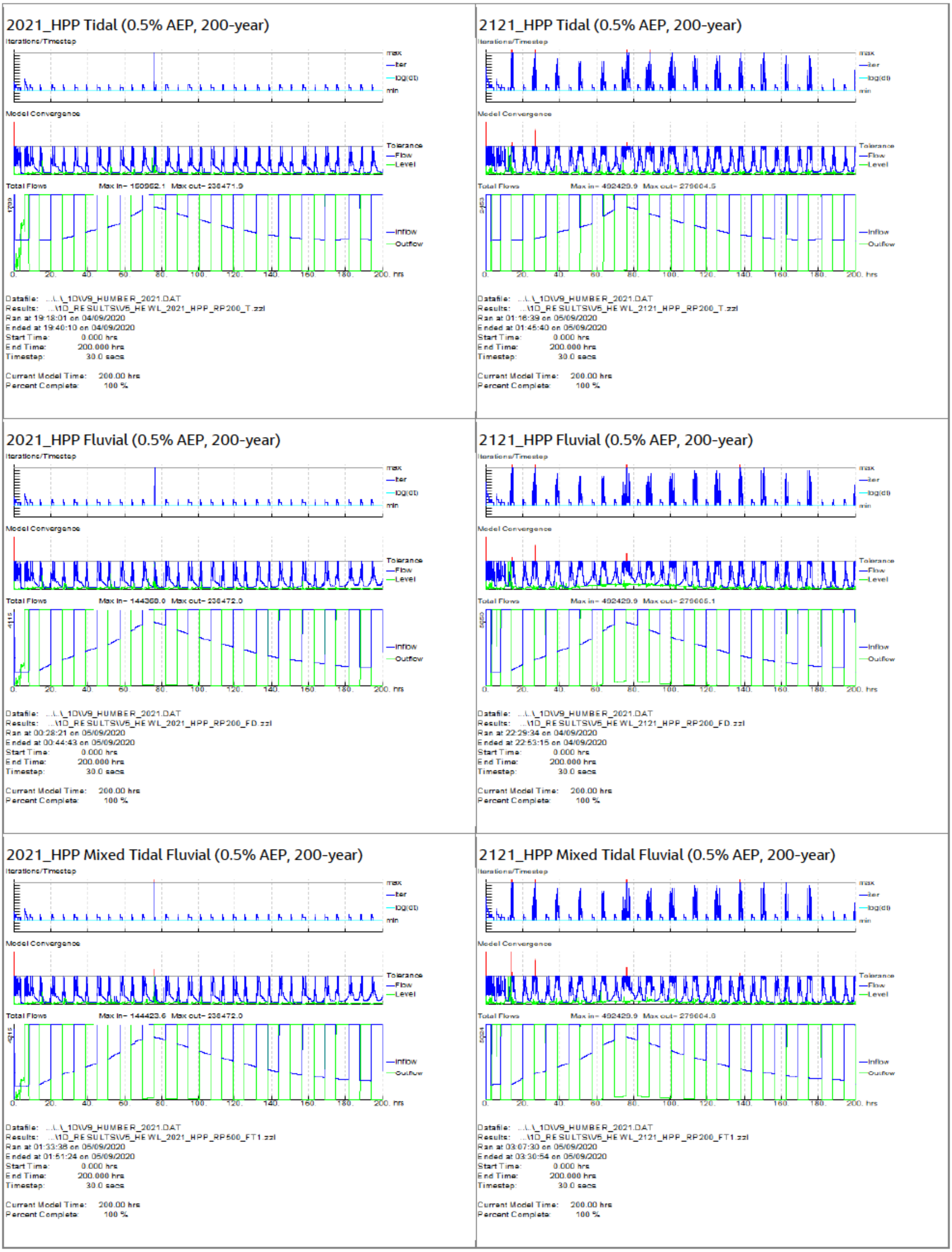


Figure E.1: Model Convergence

Appendix F. Initial JP combinations

Table F.1: JP matrix 2-year to 50-year

RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
2	2	2	2	2	<1	Fluvial - complete fluvial dependence	Fd
2	2	<1	<1	<1	<1	Fluvial - independent	FiA
2	<1	2	<1	<1	<1	Fluvial - independent	FiD
2	<1	<1	2	<1	<1	Fluvial - independent	FiO
2	<1	<1	<1	2	<1	Fluvial - independent	FiT
2	<1	<1	<1	<1	2	Tidal	T
5	5	5	5	5	<1	Fluvial - complete fluvial dependence	Fd
5	5	<1	<1	<1	<1	Fluvial - independent	FiA
5	<1	5	<1	<1	<1	Fluvial - independent	FiD
5	<1	<1	5	<1	<1	Fluvial - independent	FiO
5	<1	<1	<1	5	<1	Fluvial - independent	FiT
5	<1	<1	<1	<1	5	Tidal	T
10	10	10	10	10	<1	Fluvial - complete fluvial dependence	Fd
10	10	<1	<1	<1	<1	Fluvial - independent	FiA
10	<1	10	<1	<1	<1	Fluvial - independent	FiD
10	<1	<1	10	<1	<1	Fluvial - independent	FiO
10	<1	<1	<1	10	<1	Fluvial - independent	FiT
10	2	2	2	2	<1	Fluvial - less dependence	Fd2
10	<1	<1	<1	<1	10	Tidal	T
20	20	20	20	20	<1	Fluvial - complete fluvial dependence	Fd
20	20	<1	<1	<1	<1	Fluvial - independent	FiA
20	<1	20	<1	<1	<1	Fluvial - independent	FiD
20	<1	<1	20	<1	<1	Fluvial - independent	FiO
20	<1	<1	<1	20	<1	Fluvial - independent	FiT
20	5	5	5	5	<1	Fluvial - less dependence	Fd2
20	<1	<1	<1	<1	20	Tidal	T
50	50	50	50	50	<1	Fluvial - complete fluvial dependence	Fd
50	50	<1	<1	<1	<1	Fluvial - independent	FiA
50	<1	50	<1	<1	<1	Fluvial - independent	FiD
50	<1	<1	50	<1	<1	Fluvial - independent	FiO
50	<1	<1	<1	50	<1	Fluvial - independent	FiT
50	10	10	10	10	<1	Fluvial - less dependence	Fd2
50	2	2	5	2	2	Mixed tidal/fluvial	FT1
50	<1	<1	2	<1	5	Mixed tidal/fluvial	FT2
50	<1	<1	<1	<1	50	Tidal	T

Table F.2: JP matrix 75-year to 200-year

RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
75	75	75	75	75	<1	Fluvial - complete fluvial dependence	Fd
75	75	<1	<1	<1	<1	Fluvial - independent	FiA
75	<1	75	<1	<1	<1	Fluvial - independent	FiD
75	<1	<1	75	<1	<1	Fluvial - independent	FiO
75	<1	<1	<1	75	<1	Fluvial - independent	FiT
75	20	20	20	20	<1	Fluvial - less dependence	Fd2
75	5	2	10	5	2	Mixed tidal/fluvial	FT1
75	2	2	5	2	5	Mixed tidal/fluvial	FT2
75	<1	<1	2	<1	10	Mixed tidal/fluvial	FT3
75	<1	<1	<1	<1	75	Tidal	T
100	100	100	100	100	<1	Fluvial - complete fluvial dependence	Fd
100	100	<1	<1	<1	<1	Fluvial - independent	FiA
100	<1	100	<1	<1	<1	Fluvial - independent	FiD
100	<1	<1	100	<1	<1	Fluvial - independent	FiO
100	<1	<1	<1	100	<1	Fluvial - independent	FiT
100	20	20	20	20	<1	Fluvial - less dependence	Fd2
100	10	5	20	10	2	Mixed tidal/fluvial	FT1
100	2	2	5	2	5	Mixed tidal/fluvial	FT2
100	2	<1	5	2	10	Mixed tidal/fluvial	FT3
100	<1	<1	2	<1	20	Mixed tidal/fluvial	FT4
100	<1	<1	<1	<1	100	Tidal	T
200	200	200	200	200	<1	Fluvial - complete fluvial dependence	Fd
200	200	<1	<1	<1	<1	Fluvial - independent	FiA
200	<1	200	<1	<1	<1	Fluvial - independent	FiD
200	<1	<1	200	<1	<1	Fluvial - independent	FiO
200	<1	<1	<1	200	<1	Fluvial - independent	FiT
200	50	50	50	50	<1	Fluvial - less dependence	Fd2
200	20	20	50	20	2	Mixed tidal/fluvial	FT1
200	10	5	20	10	5	Mixed tidal/fluvial	FT2
200	5	5	10	5	10	Mixed tidal/fluvial	FT3
200	2	2	5	2	20	Mixed tidal/fluvial	FT4
200	2	<1	2	2	50	Mixed tidal/fluvial	FT5
200	<1	<1	2	<1	100	Mixed tidal/fluvial	FT6
200	<1	<1	<1	<1	200	Tidal	T

Table F.3: JP matrix 500-year to 1000-year

RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
500	500	500	500	500	2	Fluvial - complete fluvial dependence	Fd
500	500	<1	<1	<1	<1	Fluvial - independent	FiA
500	<1	500	<1	<1	<1	Fluvial - independent	FiD
500	<1	<1	500	<1	2	Fluvial - independent	FiO
500	<1	<1	<1	500	<1	Fluvial - independent	FiT
500	100	100	100	100	2	Fluvial - less dependence	Fd2
500	500	500	500	500	<1	Fluvial - less dependence	Fd3
500	200	200	500	200	1	Mixed tidal/fluvial	FT1
500	200	100	500	200	2	Mixed tidal/fluvial	FT2
500	100	50	200	100	5	Mixed tidal/fluvial	FT3
500	50	20	100	50	10	Mixed tidal/fluvial	FT4
500	20	10	50	20	20	Mixed tidal/fluvial	FT5
500	10	5	20	10	50	Mixed tidal/fluvial	FT6
500	5	2	10	5	100	Mixed tidal/fluvial	FT7
500	2	2	5	2	200	Mixed tidal/fluvial	FT8
500	<1	<1	2	<1	500	Tidal	T
1000	1000	1000	1000	1000	5	Fluvial - complete fluvial dependence	Fd
1000	1000	<1	<1	<1	2	Fluvial - independent	FiA
1000	<1	1000	<1	<1	<1	Fluvial - independent	FiD
1000	<1	<1	1000	<1	5	Fluvial - independent	FiO
1000	<1	<1	<1	1000	2	Fluvial - independent	FiT
1000	200	200	200	200	5	Fluvial - less dependence	Fd2
1000	1000	1000	1000	1000	<1	Fluvial - less dependence	Fd3
1000	1000	500	1000	1000	2	Mixed tidal/fluvial	FT1
1000	200	200	500	200	5	Mixed tidal/fluvial	FT2
1000	200	100	500	200	10	Mixed tidal/fluvial	FT3
1000	100	50	200	100	20	Mixed tidal/fluvial	FT4
1000	20	20	50	20	50	Mixed tidal/fluvial	FT5
1000	20	10	50	20	100	Mixed tidal/fluvial	FT6
1000	10	5	20	10	200	Mixed tidal/fluvial	FT7
1000	2	2	5	2	500	Mixed tidal/fluvial	FT8
1000	2	<1	5	2	1000	Tidal	T

Appendix G. Final JP combinations

Table G.1: JP matrix 2-year to 50-year

RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
2	2	2	2	2	<1	Fluvial - complete fluvial dependence	Fd
2	2	<1	<1	<1	<1	Fluvial - independent	FiA
2	<1	2	<1	<1	<1	Fluvial - independent	FiD
2	<1	<1	2	<1	<1	Fluvial - independent	FiO
2	<1	<1	<1	2	<1	Fluvial - independent	FiT
2	<1	<1	<1	<1	2	Tidal	T
5	5	5	5	5	<1	Fluvial - complete fluvial dependence	Fd
5	5	<1	<1	<1	<1	Fluvial - independent	FiA
5	<1	5	<1	<1	<1	Fluvial - independent	FiD
5	<1	<1	5	<1	<1	Fluvial - independent	FiO
5	<1	<1	<1	5	<1	Fluvial - independent	FiT
5	<1	<1	<1	<1	5	Tidal	T
10	10	10	10	10	<1	Fluvial - complete fluvial dependence	Fd
10	10	<1	<1	<1	<1	Fluvial - independent	FiA
10	<1	10	<1	<1	<1	Fluvial - independent	FiD
10	<1	<1	10	<1	<1	Fluvial - independent	FiO
10	<1	<1	<1	10	<1	Fluvial - independent	FiT
10	2	2	2	2	<1	Fluvial - less dependence	Fd2
10	<1	<1	<1	<1	10	Tidal	T
20	20	20	20	20	<1	Fluvial - complete fluvial dependence	Fd
20	20	<1	<1	<1	<1	Fluvial - independent	FiA
20	<1	20	<1	<1	<1	Fluvial - independent	FiD
20	<1	<1	20	<1	<1	Fluvial - independent	FiO
20	<1	<1	<1	20	<1	Fluvial - independent	FiT
20	5	5	5	5	<1	Fluvial - less dependence	Fd2
20	2	2	5	2	2	Mixed tidal/fluvial	FT1
20	<1	<1	2	<1	5	Mixed tidal/fluvial	FT2
20	<1	<1	<1	<1	20	Tidal	T
50	50	50	50	50	<1	Fluvial - complete fluvial dependence	Fd
50	50	<1	<1	<1	<1	Fluvial - independent	FiA
50	<1	50	<1	<1	<1	Fluvial - independent	FiD
50	<1	<1	50	<1	<1	Fluvial - independent	FiO
50	<1	<1	<1	50	<1	Fluvial - independent	FiT
50	10	10	10	10	<1	Fluvial - less dependence	Fd2
50	10	5	20	10	2	Mixed tidal/fluvial	FT1
50	2	2	5	2	5	Mixed tidal/fluvial	FT2
50	2	<1	5	2	10	Mixed tidal/fluvial	FT3
50	<1	<1	2	<1	20	Mixed tidal/fluvial	FT4
50	<1	<1	<1	<1	50	Tidal	T

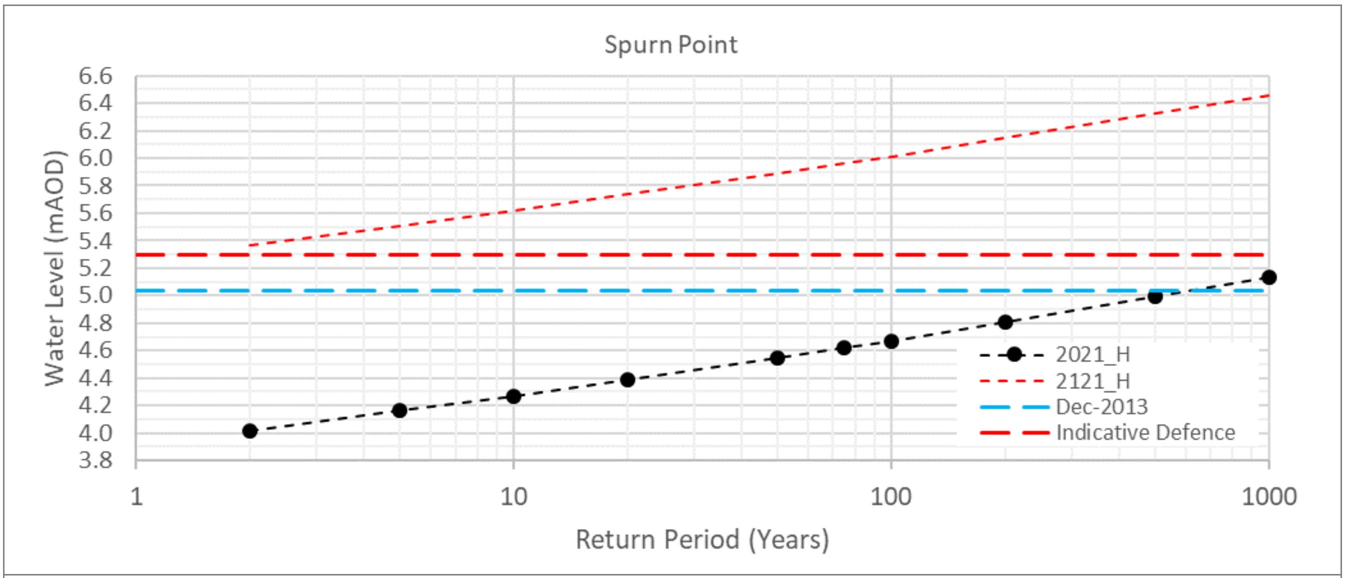
Table G.2: JP matrix 75-year to 200-year

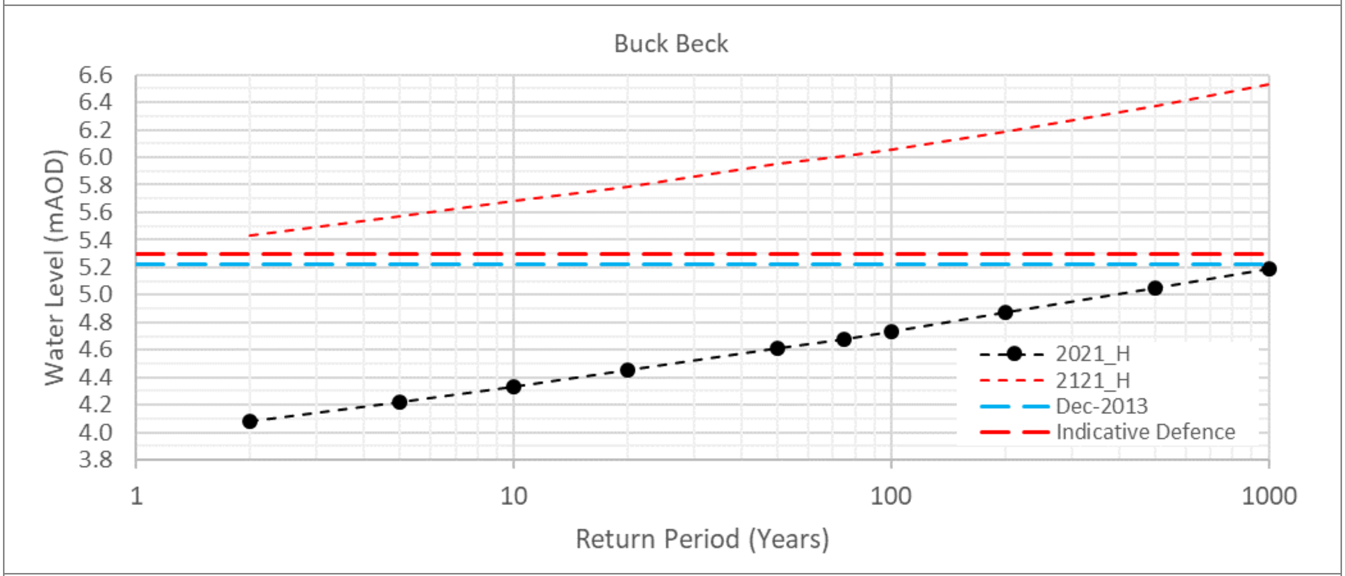
RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
75	75	75	75	75	2	Fluvial - complete fluvial dependence	Fd
75	75	<1	<1	<1	<1	Fluvial - independent	FiA
75	<1	75	<1	<1	<1	Fluvial - independent	FiD
75	<1	<1	75	<1	2	Fluvial - independent	FiO
75	<1	<1	<1	75	<1	Fluvial - independent	FiT
75	20	20	20	20	<1	Fluvial - less dependence	Fd2
75	5	2	10	5	10	Mixed tidal/fluvial	FT1
75	2	2	5	2	20	Mixed tidal/fluvial	FT2
75	<1	<1	2	<1	50	Mixed tidal/fluvial	FT3
75	<1	<1	2	<1	75	Tidal	T
100	100	100	100	100	2	Fluvial - complete fluvial dependence	Fd
100	100	<1	<1	<1	<1	Fluvial - independent	FiA
100	<1	100	<1	<1	<1	Fluvial - independent	FiD
100	<1	<1	100	<1	2	Fluvial - independent	FiO
100	<1	<1	<1	100	<1	Fluvial - independent	FiT
100	20	20	20	20	<1	Fluvial - less dependence	Fd2
100	20	20	50	20	2	Mixed tidal/fluvial	FT1
100	10	5	20	10	5	Mixed tidal/fluvial	FT2
100	5	5	10	5	10	Mixed tidal/fluvial	FT3
100	2	2	5	2	20	Mixed tidal/fluvial	FT4
100	2	<1	2	2	50	Mixed tidal/fluvial	FT5
100	<1	<1	2	<1	100	Tidal	T
200	200	200	200	200	5	Fluvial - complete fluvial dependence	Fd
200	200	<1	<1	<1	2	Fluvial - independent	FiA
200	<1	200	<1	<1	2	Fluvial - independent	FiD
200	<1	<1	200	<1	5	Fluvial - independent	FiO
200	<1	<1	<1	200	2	Fluvial - independent	FiT
200	50	50	50	50	5	Fluvial - less dependence	Fd2
200	100	50	200	100	5	Mixed tidal/fluvial	FT1
200	50	20	100	50	10	Mixed tidal/fluvial	FT2
200	20	10	50	20	20	Mixed tidal/fluvial	FT3
200	10	5	20	10	50	Mixed tidal/fluvial	FT4
200	5	2	10	5	100	Mixed tidal/fluvial	FT5
200	2	2	5	2	200	Tidal	T

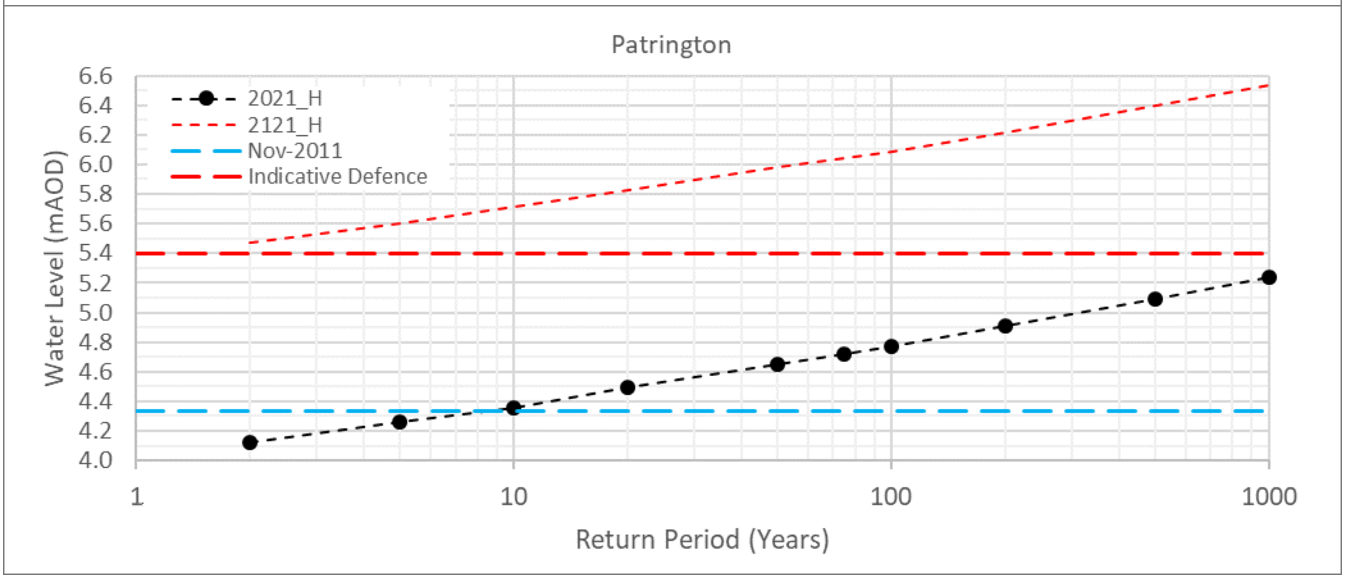
Table G.3: JP matrix 500-year to 1000-year

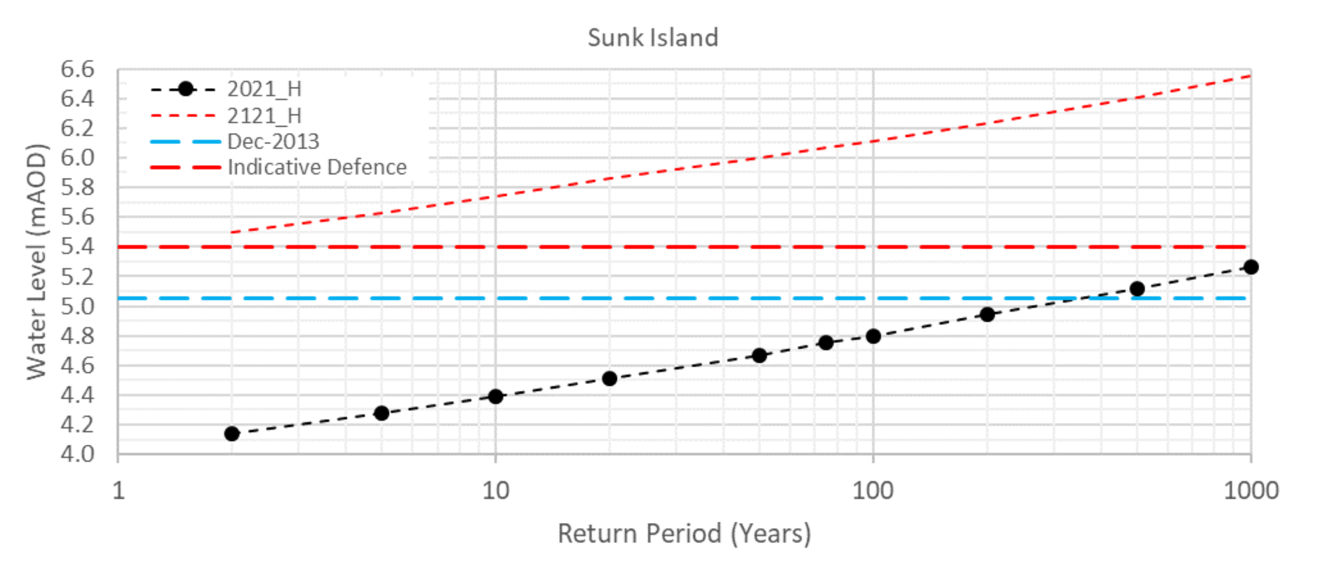
RP	Aire	Don	Ouse	Trent	Tidal	Event Type	ID
500	500	500	500	500	5	Fluvial - complete fluvial dependence	Fd
500	500	<1	<1	<1	2	Fluvial - independent	FiA
500	<1	500	<1	<1	2	Fluvial - independent	FiD
500	<1	<1	500	<1	5	Fluvial - independent	FiO
500	<1	<1	<1	500	2	Fluvial - independent	FiT
500	100	100	100	100	5	Fluvial - less dependence	Fd2
500	500	500	500	500	<1	Fluvial - less dependence	Fd3
500	200	200	500	200	5	Mixed tidal/fluvial	FT1
500	200	100	500	200	10	Mixed tidal/fluvial	FT2
500	100	50	200	100	20	Mixed tidal/fluvial	FT3
500	20	20	50	20	50	Mixed tidal/fluvial	FT4
500	20	10	50	20	100	Mixed tidal/fluvial	FT5
500	10	5	20	10	200	Mixed tidal/fluvial	FT6
500	2	2	5	2	500	Tidal	T
1000	1000	1000	1000	1000	20	Fluvial - complete fluvial dependence	Fd
1000	1000	<1	<1	<1	10	Fluvial - independent	FiA
1000	<1	1000	<1	<1	5	Fluvial - independent	FiD
1000	<1	<1	1000	<1	20	Fluvial - independent	FiO
1000	<1	<1	<1	1000	10	Fluvial - independent	FiT
1000	200	200	200	200	20	Fluvial - less dependence	Fd2
1000	1000	1000	1000	1000	5	Fluvial - less dependence	Fd3
1000	1000	500	1000	1000	10	Mixed tidal/fluvial	FT1
1000	200	200	500	200	20	Mixed tidal/fluvial	FT2
1000	200	100	500	200	50	Mixed tidal/fluvial	FT3
1000	100	50	200	100	100	Mixed tidal/fluvial	FT4
1000	20	20	50	20	200	Mixed tidal/fluvial	FT5
1000	20	10	50	20	500	Mixed tidal/fluvial	FT6
1000	10	5	20	10	1000	Tidal	T

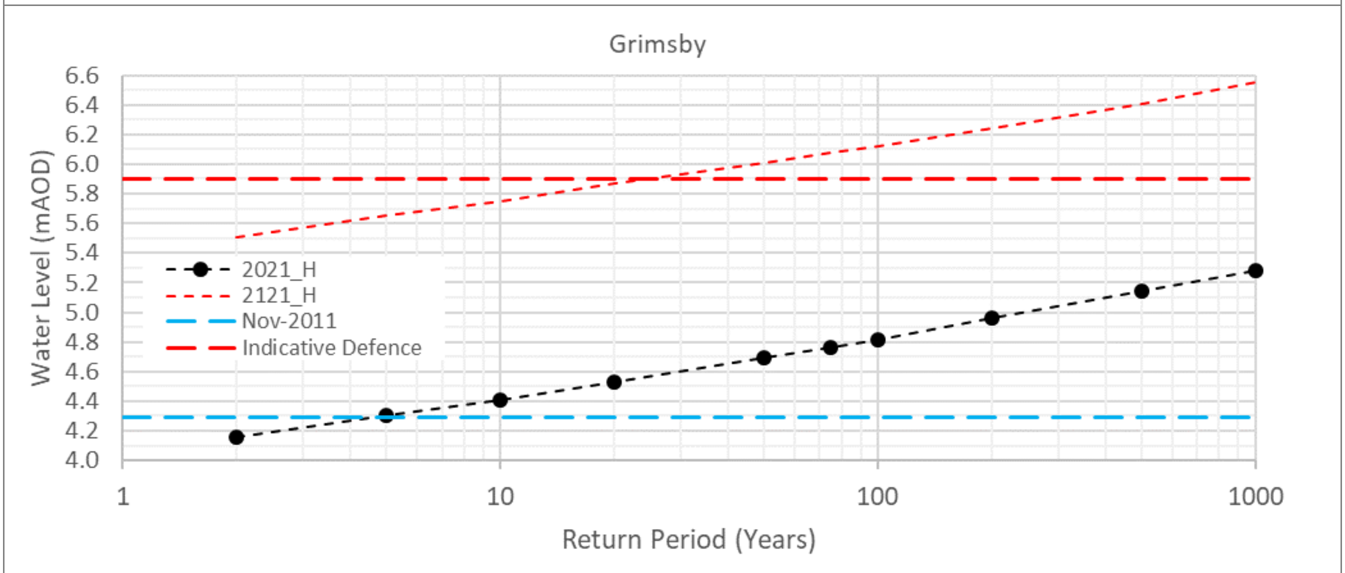
Appendix H. Comparison with recorded data

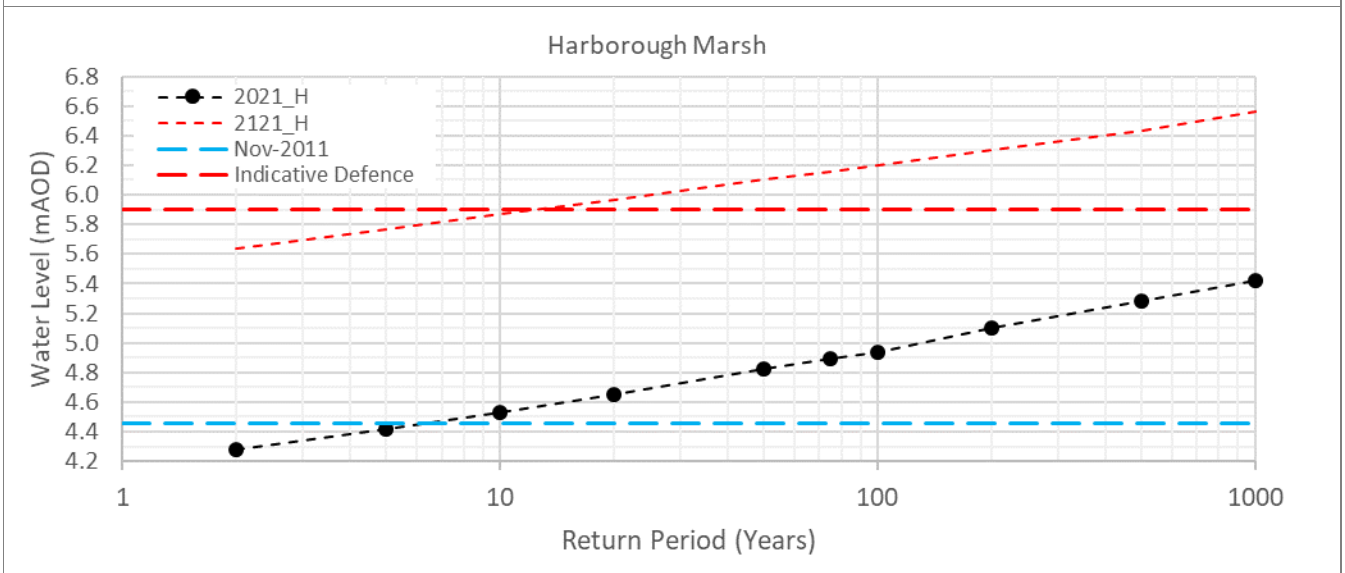


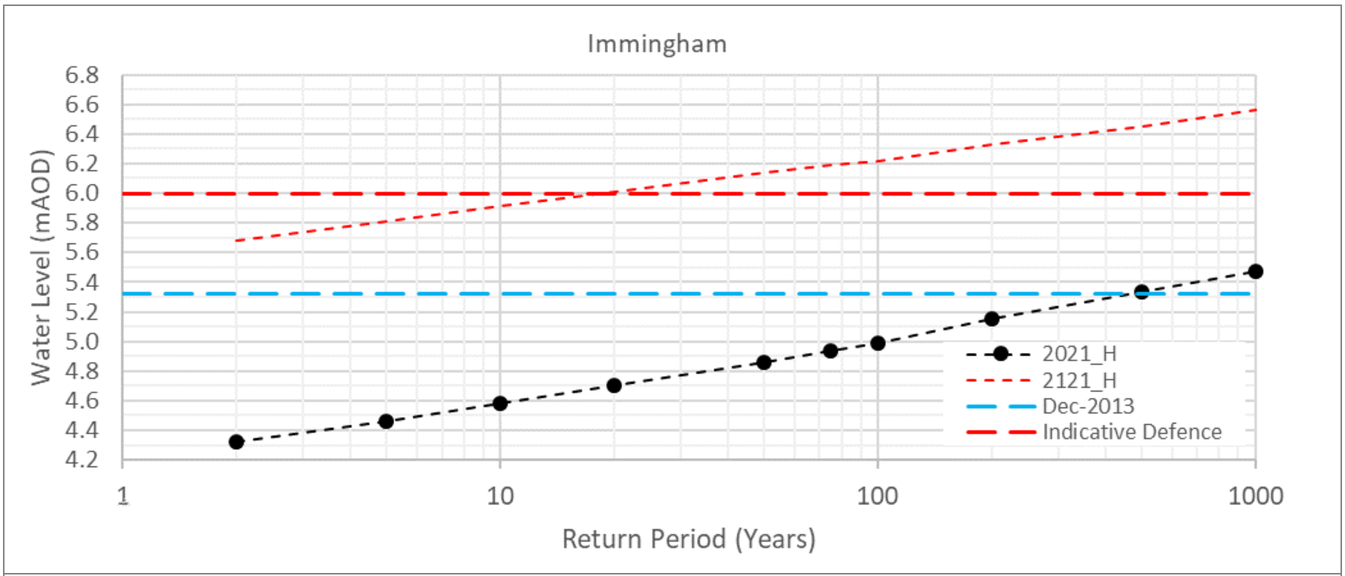


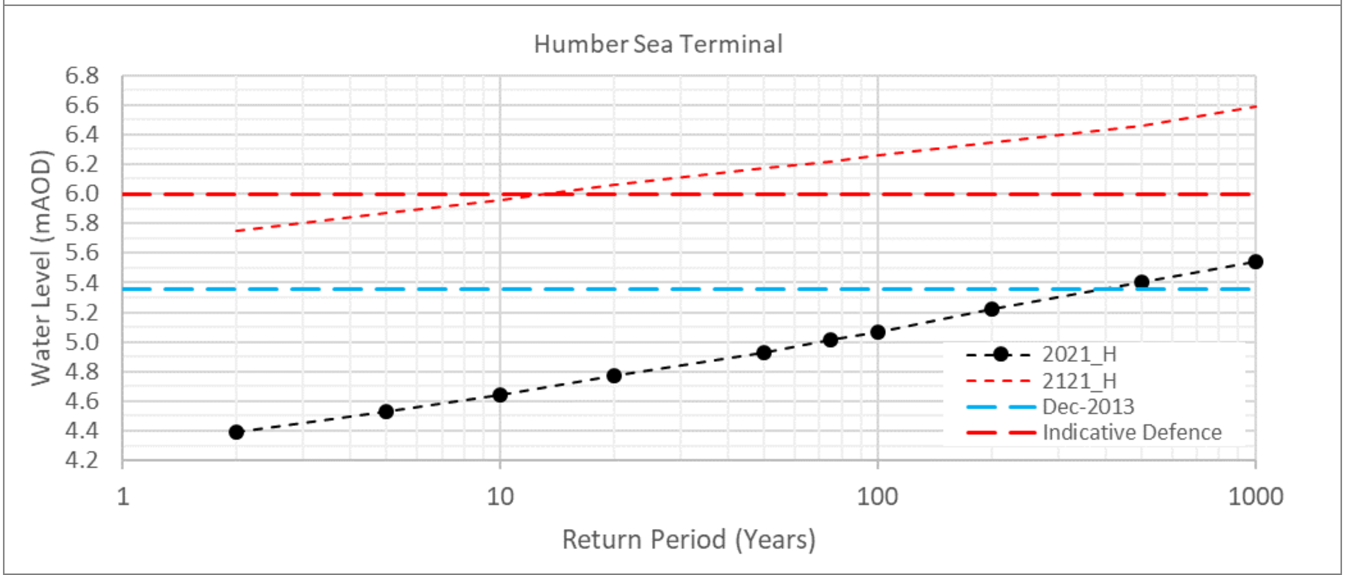


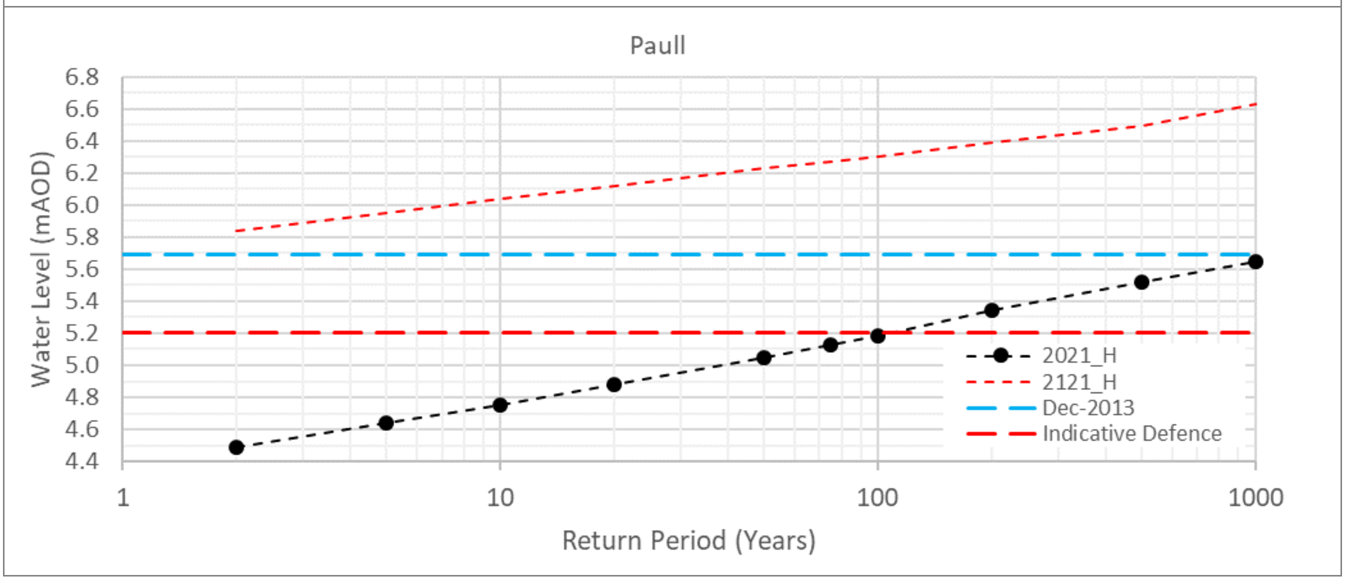

Sunk Island
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
2021_H
2121_H
Dec-2013
Indicative Defence
1
10
100
1000
Return Period (Years)

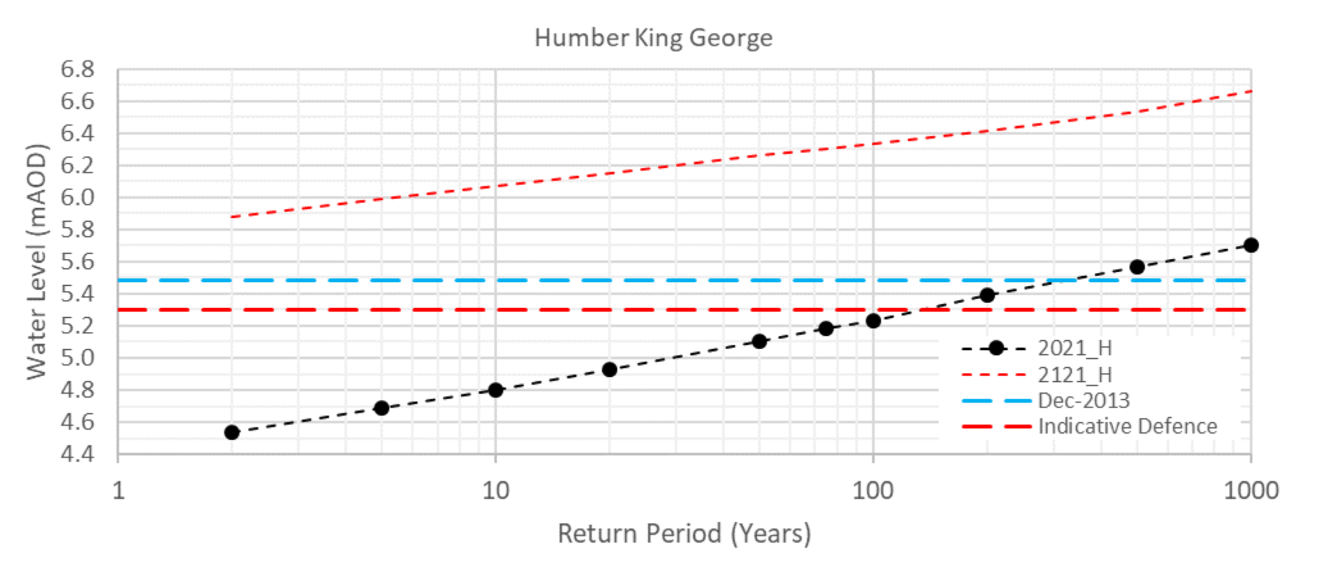

Grimsby
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
2021_H
2121_H
Nov-2011
Indicative Defence
1
10
100
1000
Return Period (Years)

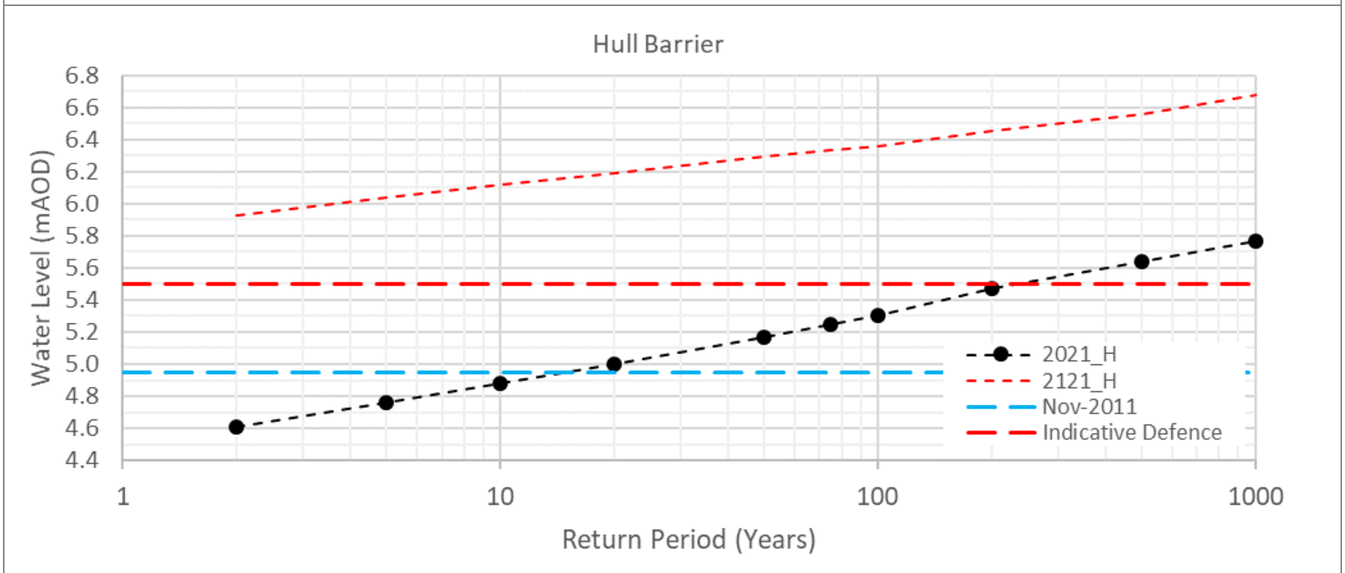

Harborough Marsh
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
2021_H
2121_H
Nov-2011
Indicative Defence
1
10
100
1000
Return Period (Years)

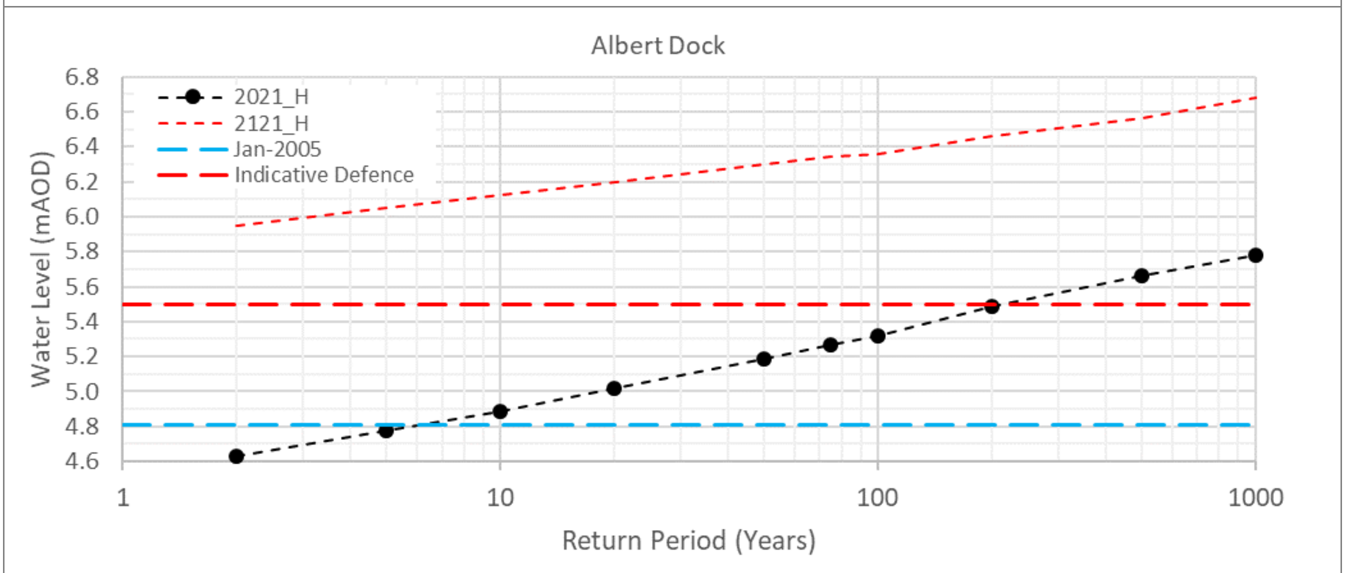

Immingham
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

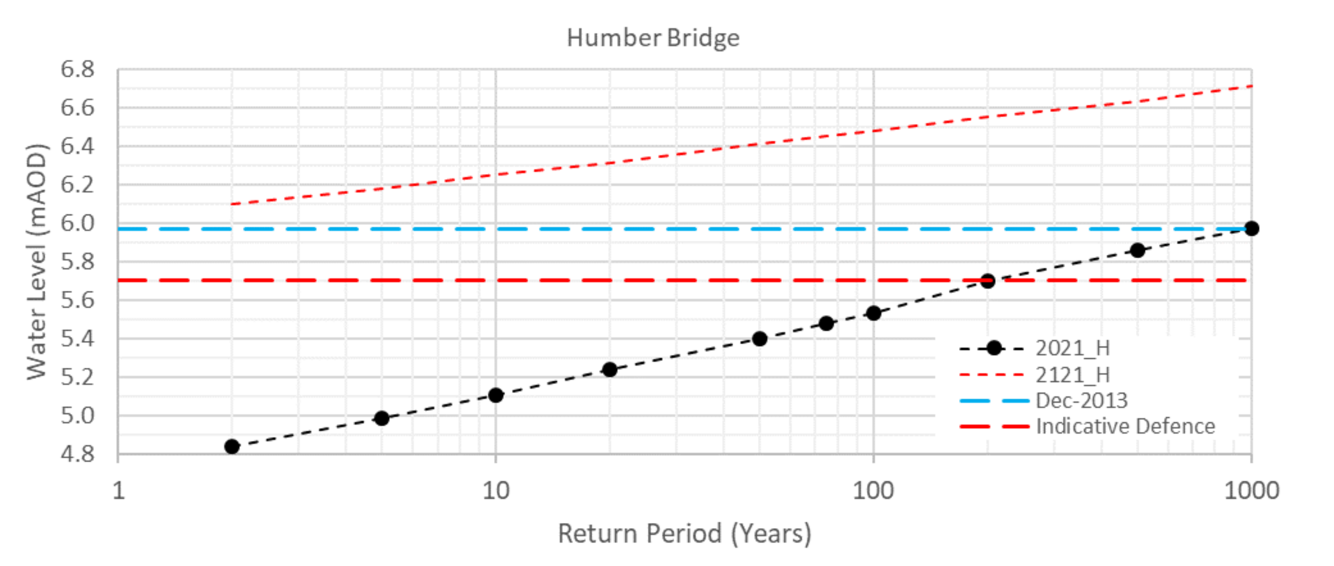

Humber Sea Terminal
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

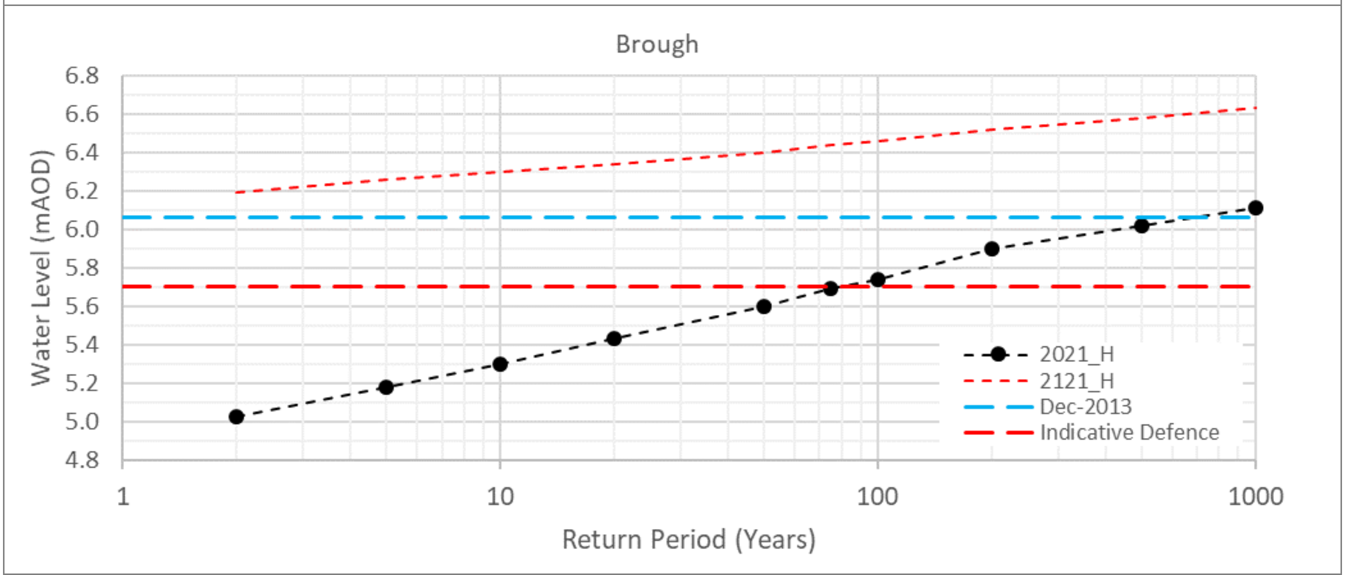

Paull
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

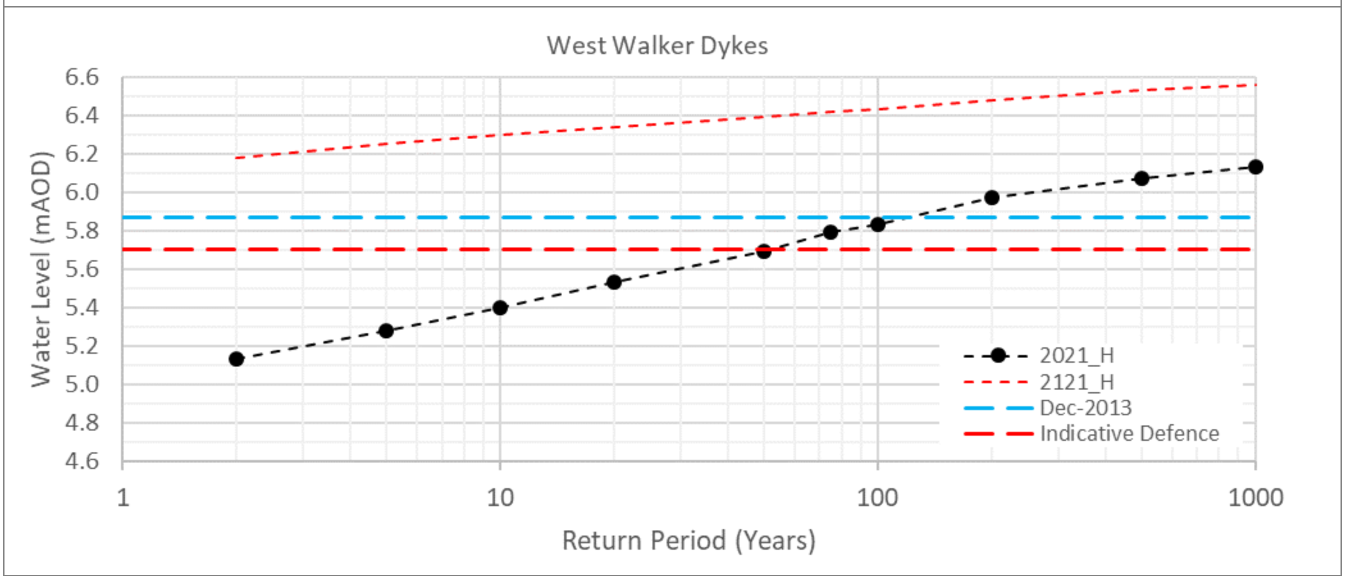

Humber King George
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

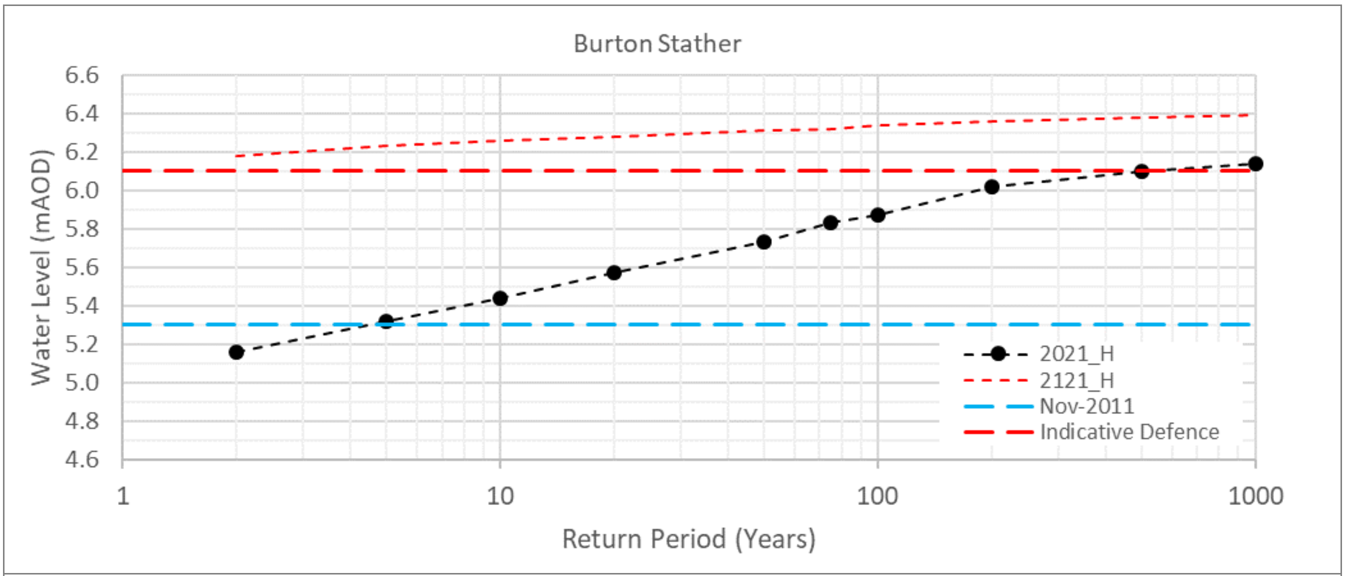

Hull Barrier
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Nov-2011
Indicative Defence

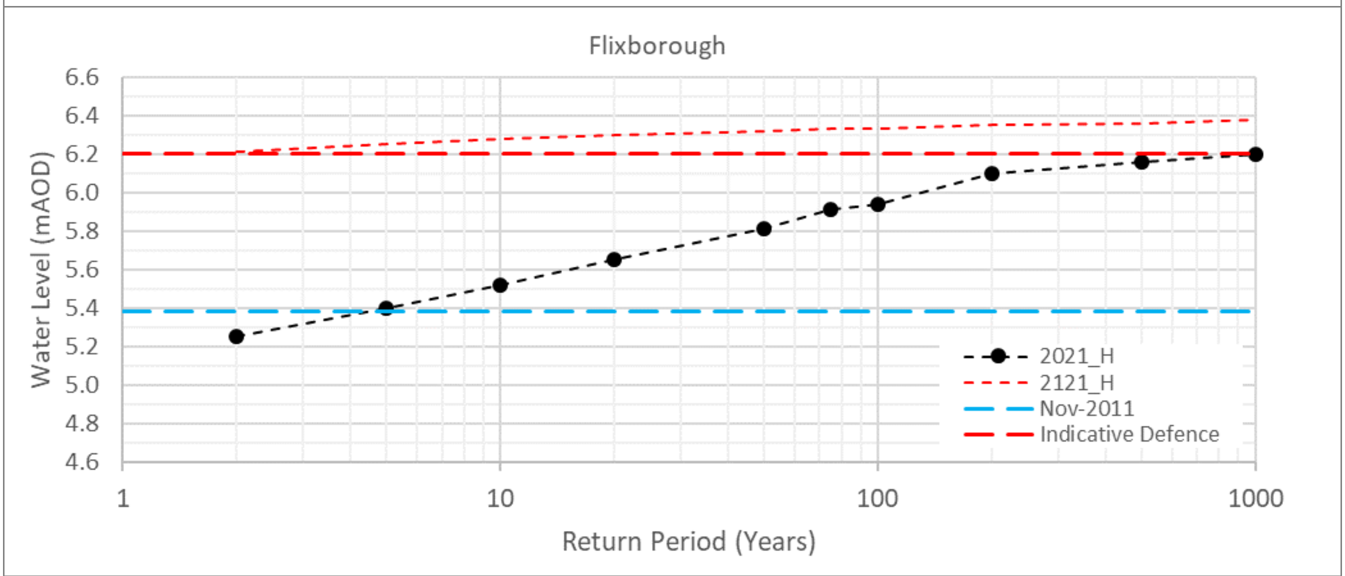

Albert Dock
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Jan-2005
Indicative Defence

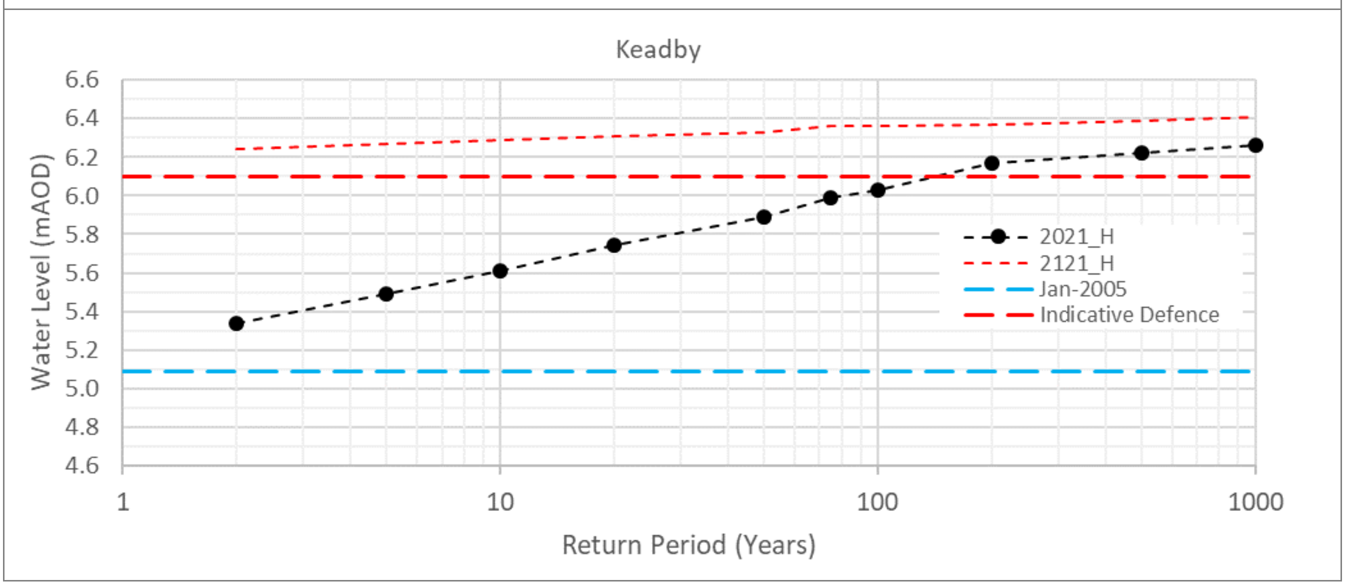

Humber Bridge
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

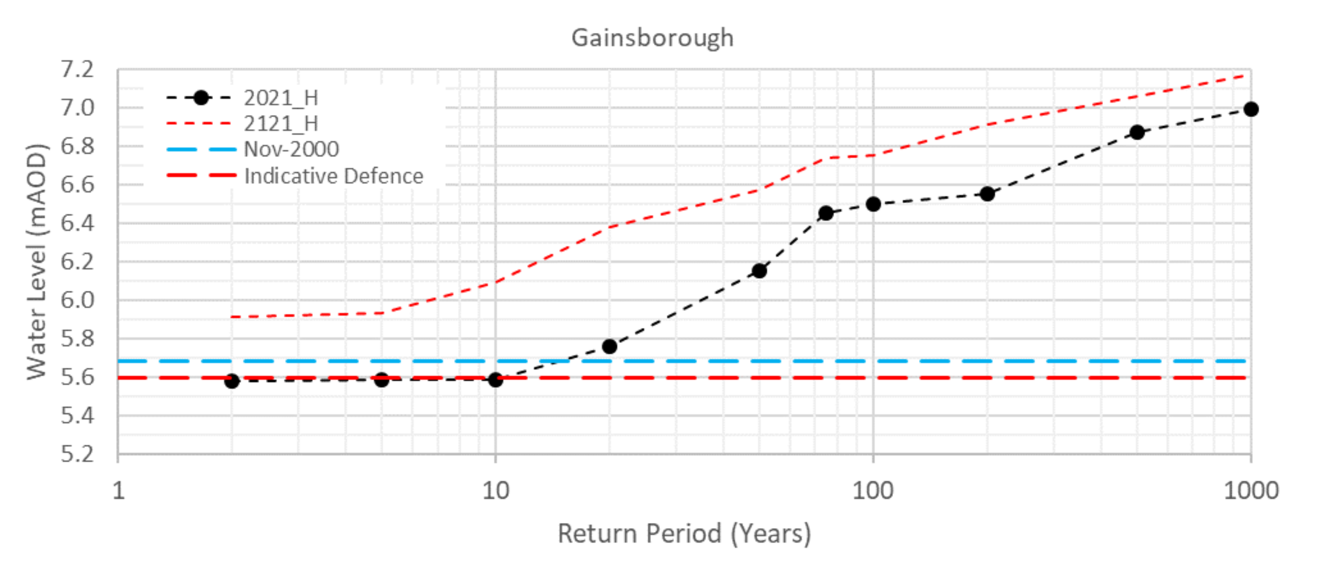

Brough
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

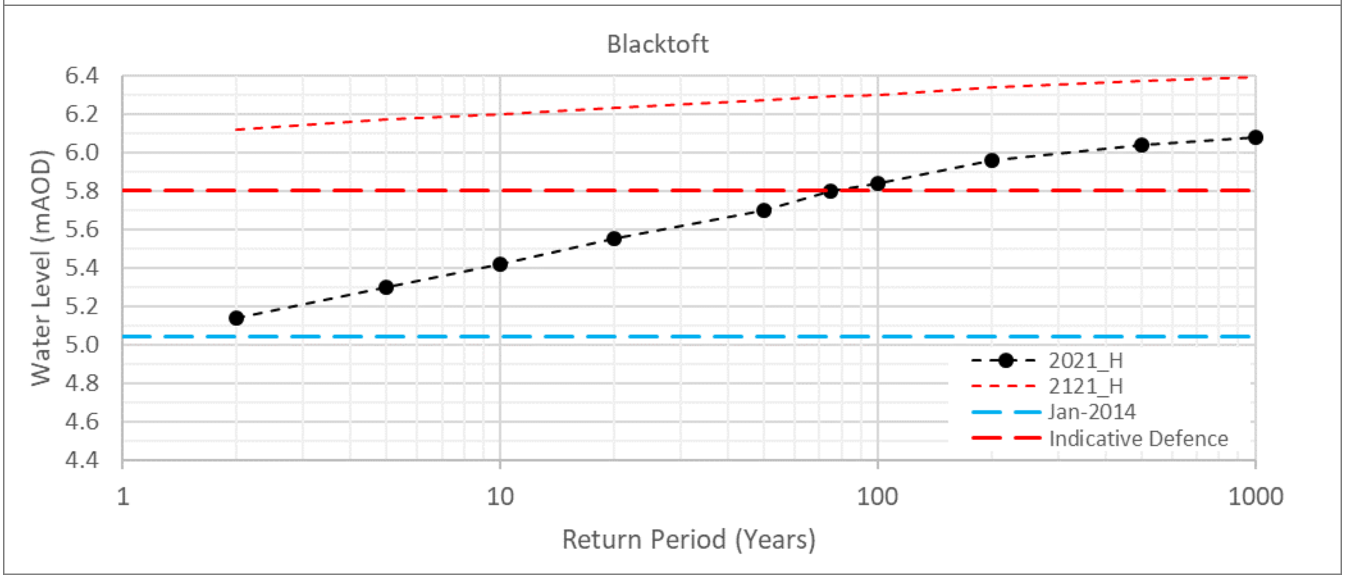

West Walker Dykes
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

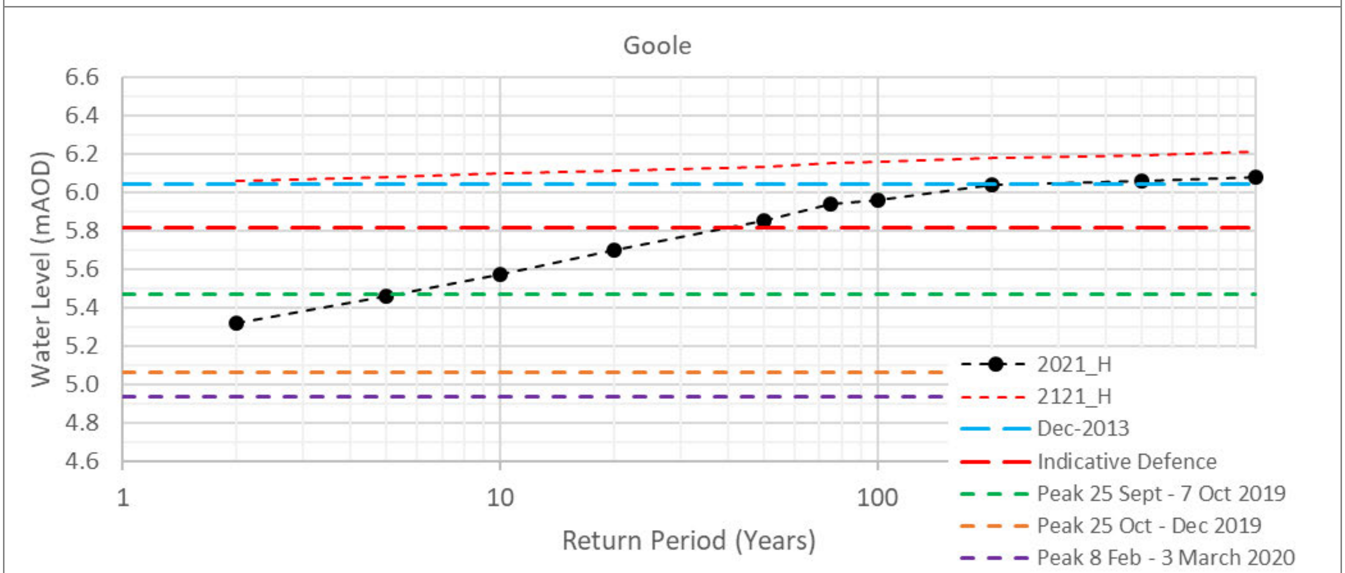

Burton Stather
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Nov-2011
Indicative Defence

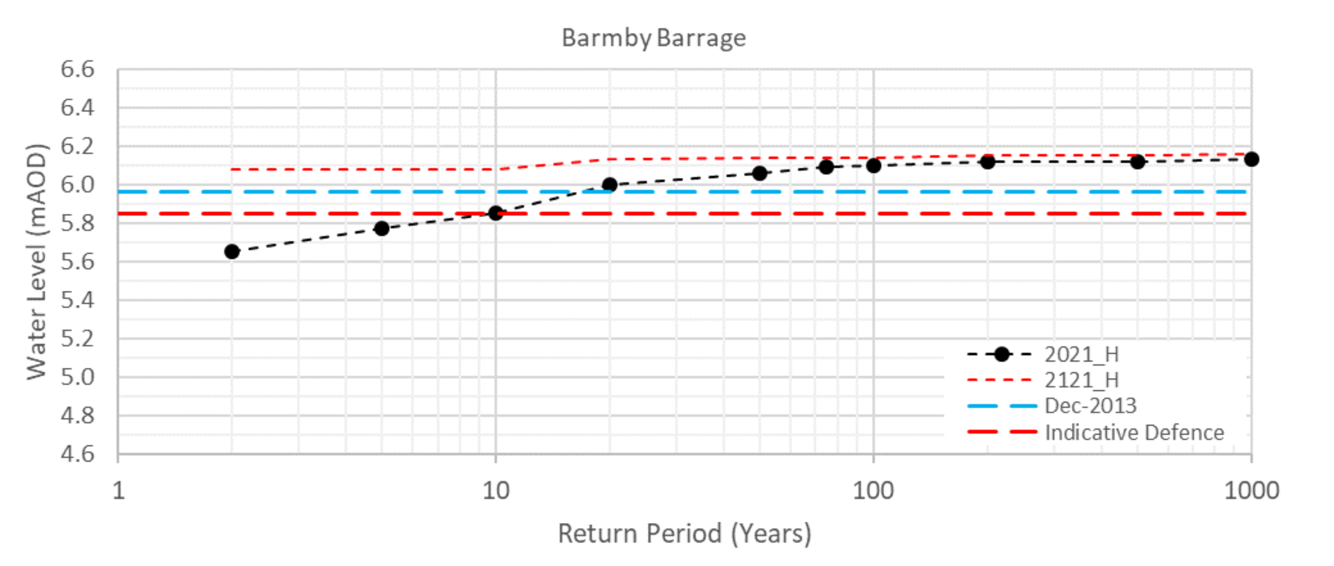

Flixborough
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Nov-2011
Indicative Defence

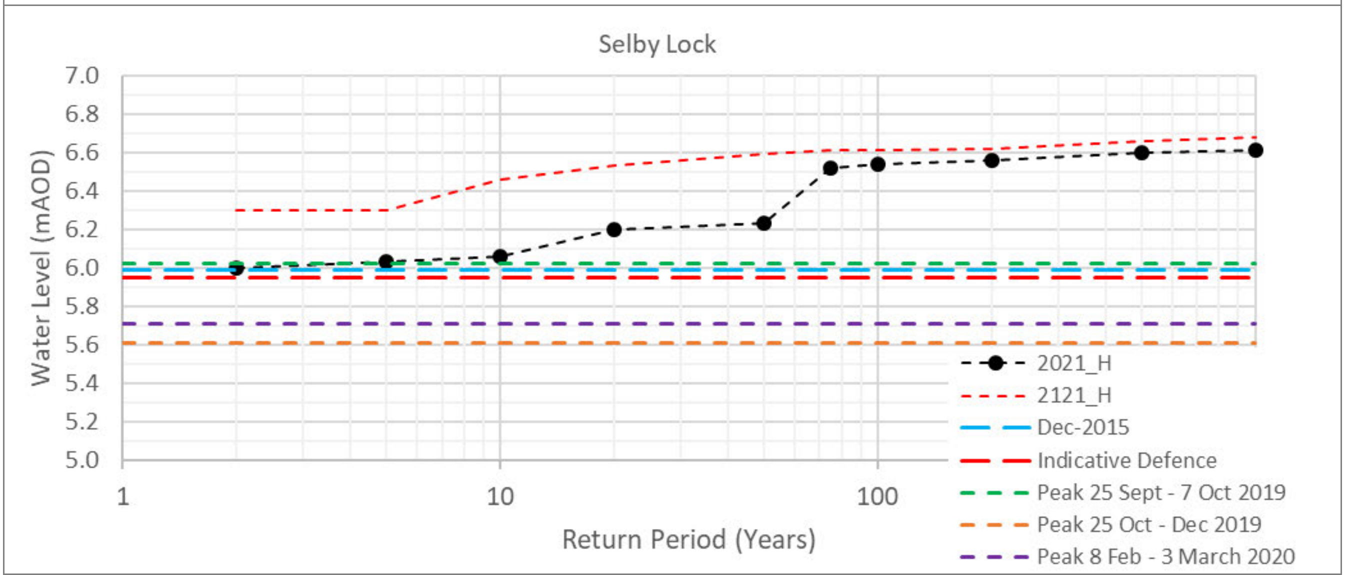

Keadby
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Jan-2005
Indicative Defence

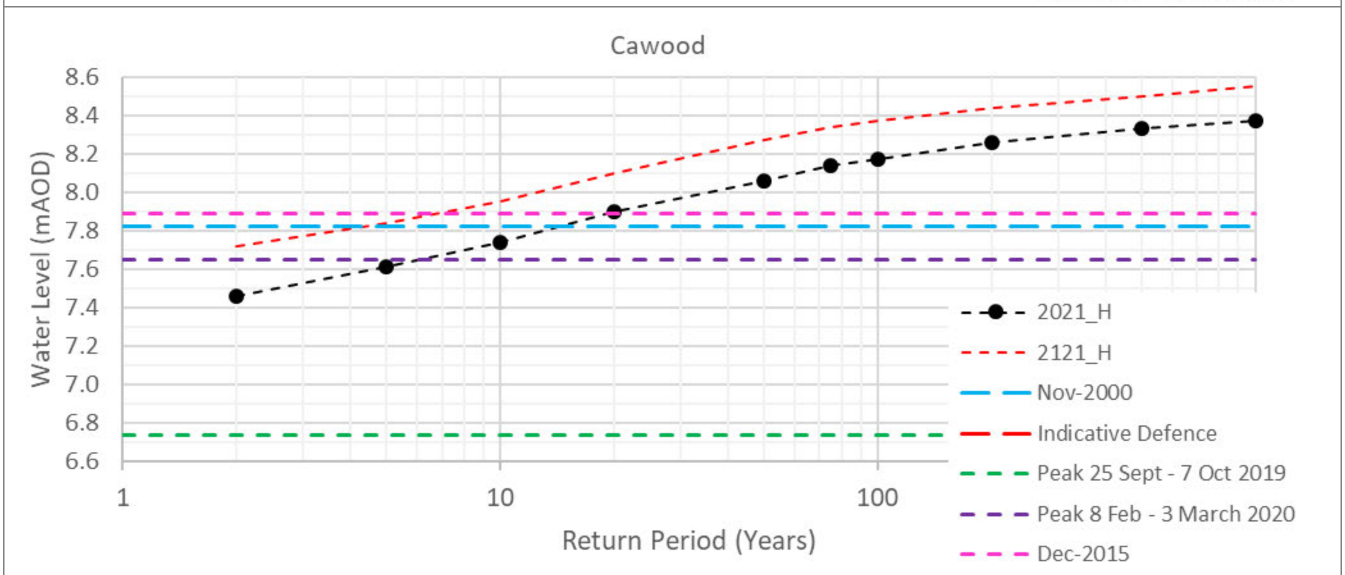

Gainsborough
Water Level (mAOD)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Nov-2000
Indicative Defence

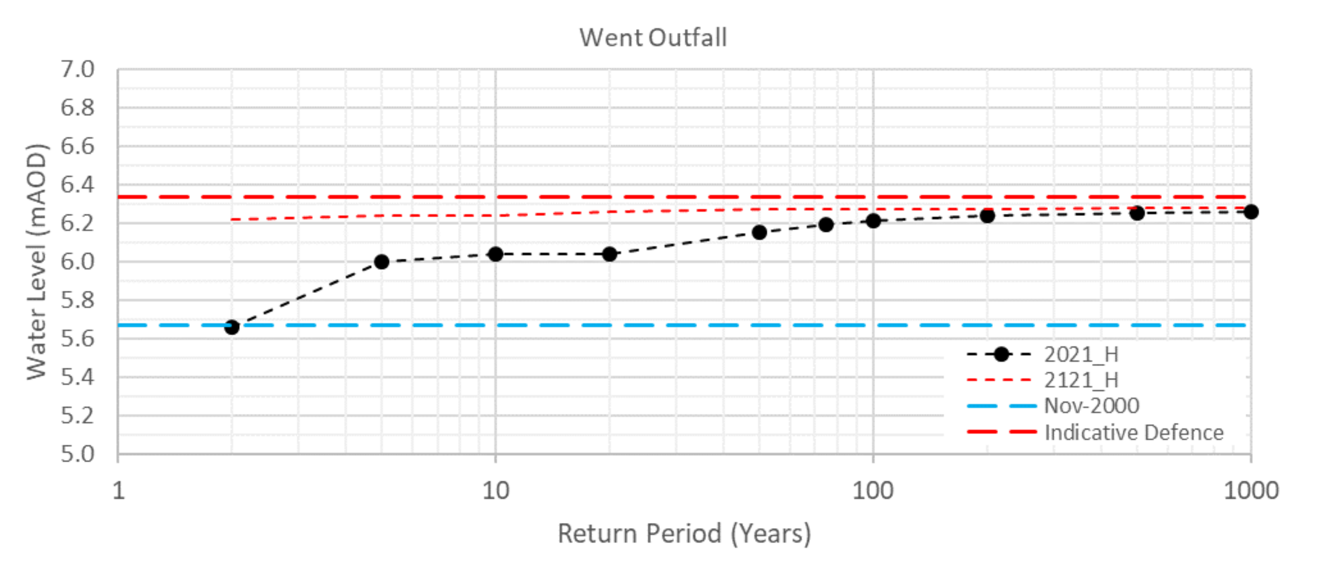

Blacktoft
Water Level (mAOD)
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Jan-2014
Indicative Defence

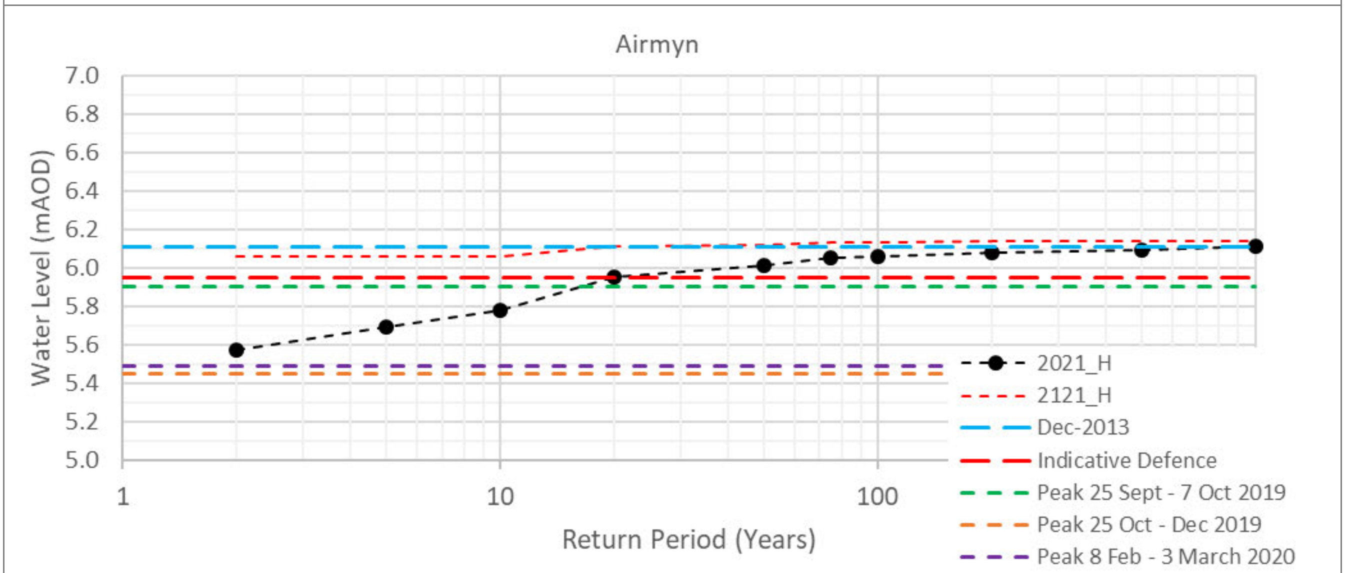

Goole
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020

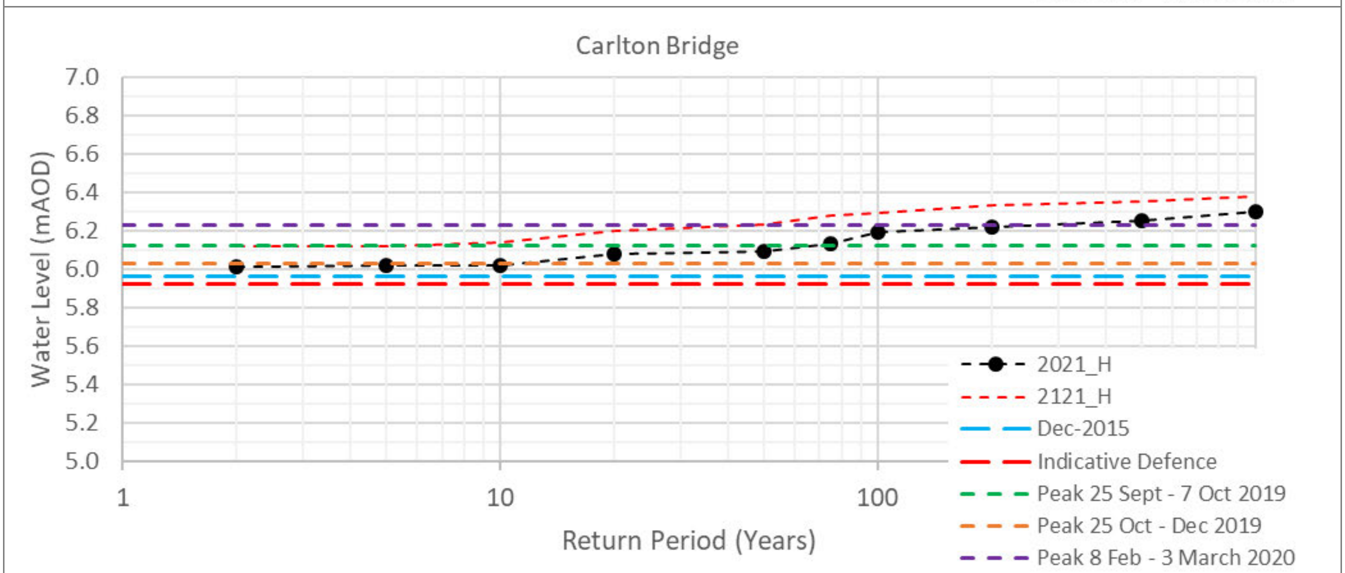

Barmby Barrage
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence

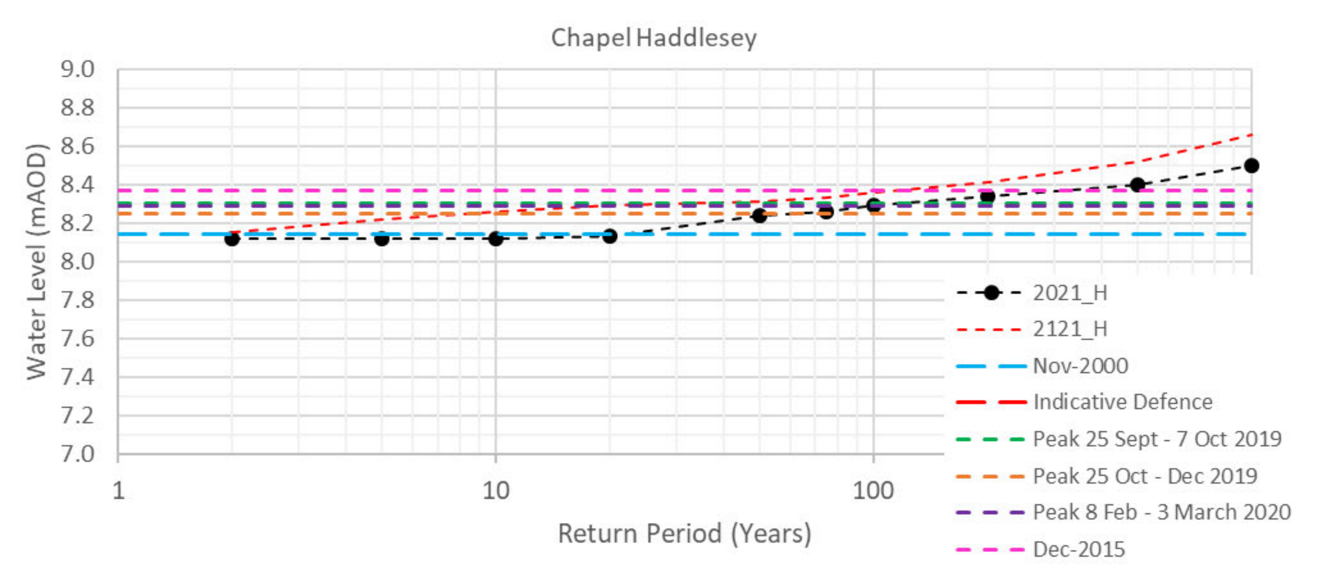

Selby Lock
Water Level (mAOD)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
Return Period (Years)
2021_H
2121_H
Dec-2015
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020

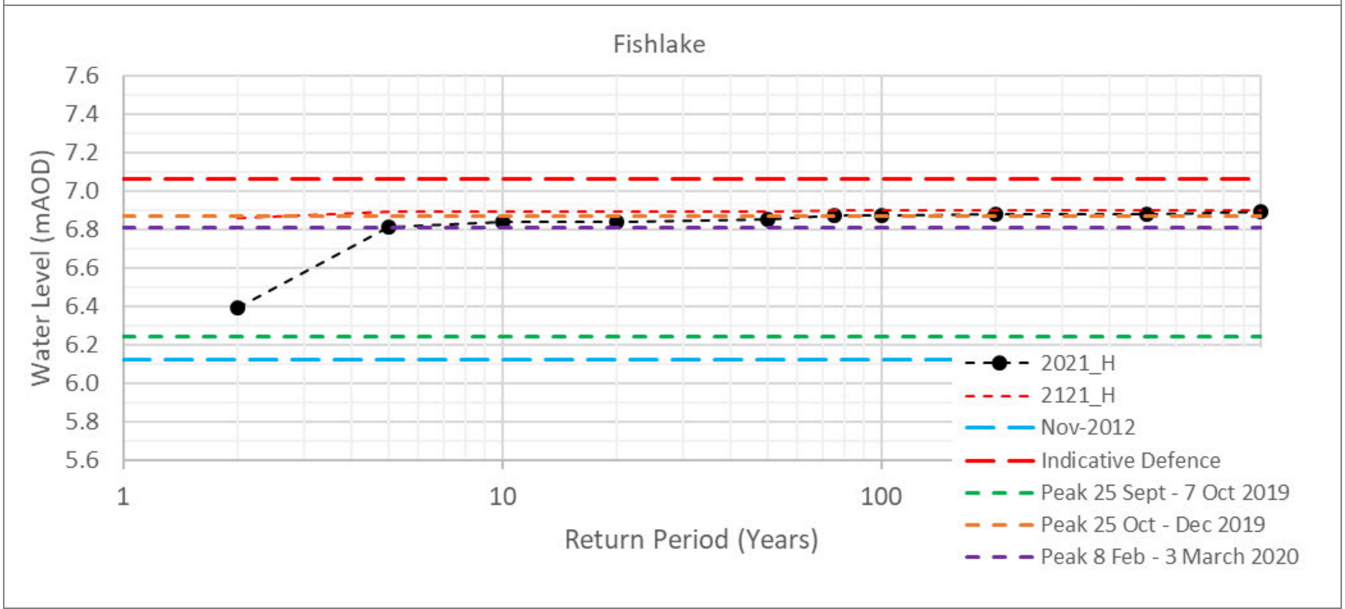

Cawood
Water Level (mAOD)
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
1
10
100
Return Period (Years)
2021_H
2121_H
Nov-2000
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 8 Feb - 3 March 2020
Dec-2015

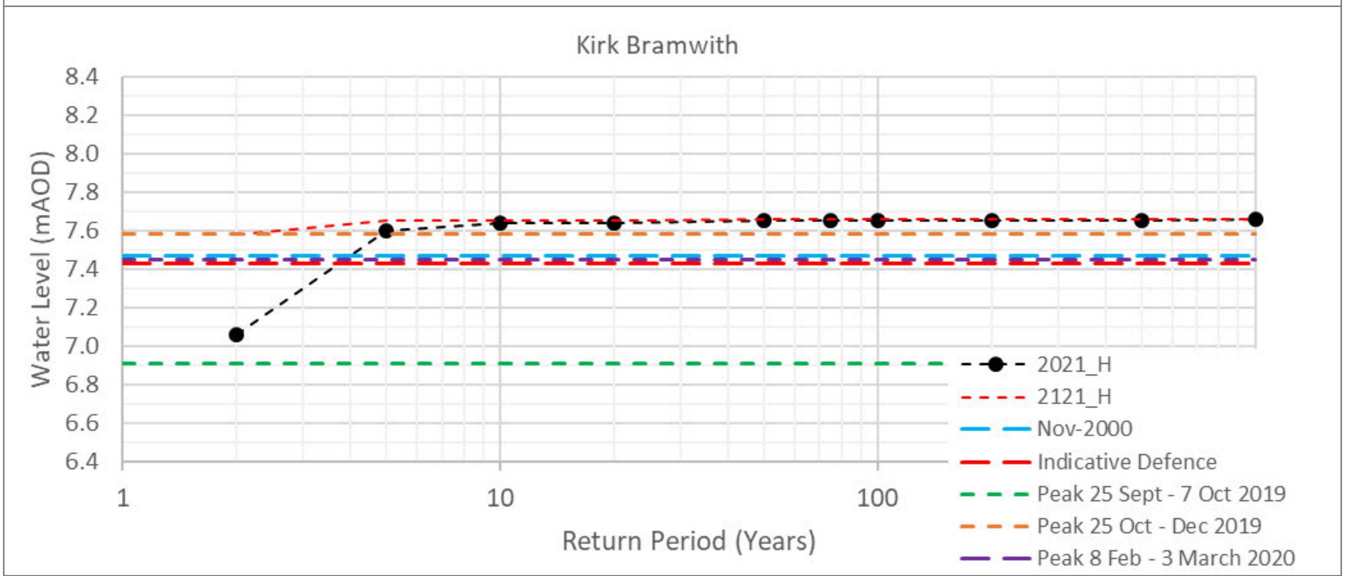

Went Outfall
Water Level (mAOD)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
2021_H
2121_H
Nov-2000
Indicative Defence

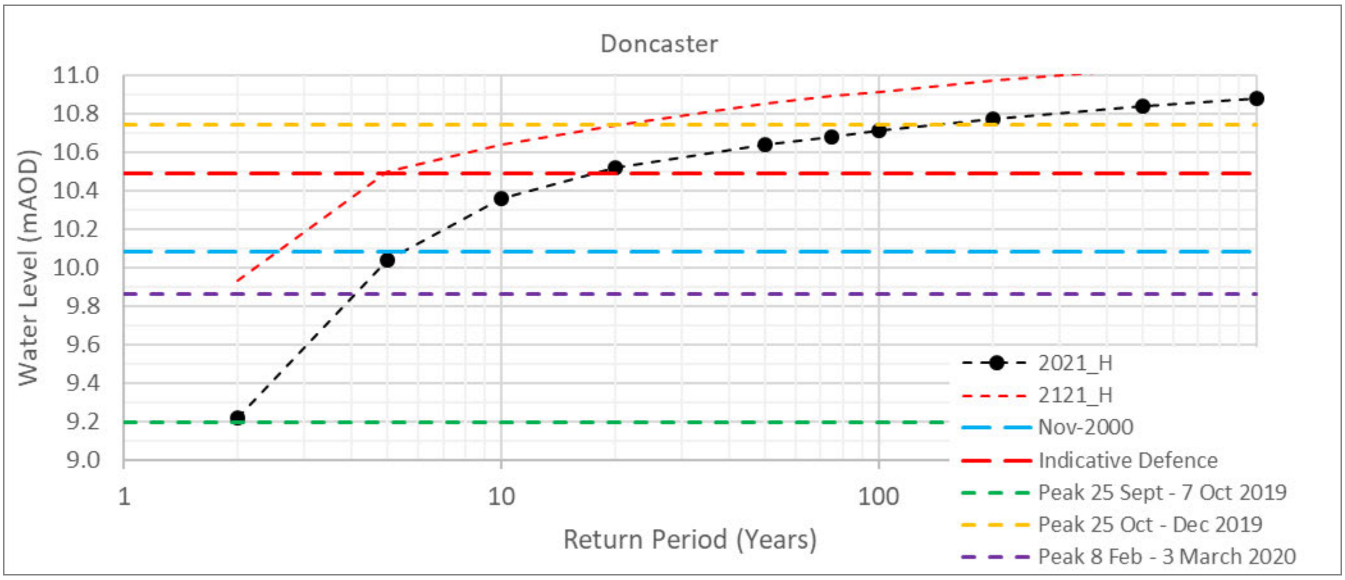

Airmyn
Water Level (mAOD)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
Return Period (Years)
2021_H
2121_H
Dec-2013
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020


Carlton Bridge
Water Level (mAOD)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
Return Period (Years)
2021_H
2121_H
Dec-2015
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020


Chapel Haddlesey
Water Level (mAOD)
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
1
10
100
Return Period (Years)
2021_H
2121_H
Nov-2000
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020
Dec-2015


Fishlake
Water Level (mAOD)
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
1
10
100
Return Period (Years)
2021_H
2121_H
Nov-2012
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020


Kirk Bramwith
Water Level (mAOD)
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
1
10
100
Return Period (Years)
2021_H
2121_H
Nov-2000
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020


Doncaster
Water Level (mAOD)
11.0
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
9.2
9.0
1
10
100
Return Period (Years)
2021_H
2121_H
Nov-2000
Indicative Defence
Peak 25 Sept - 7 Oct 2019
Peak 25 Oct - Dec 2019
Peak 8 Feb - 3 March 2020

Appendix I. Comparison with 2014 Interim Water Levels

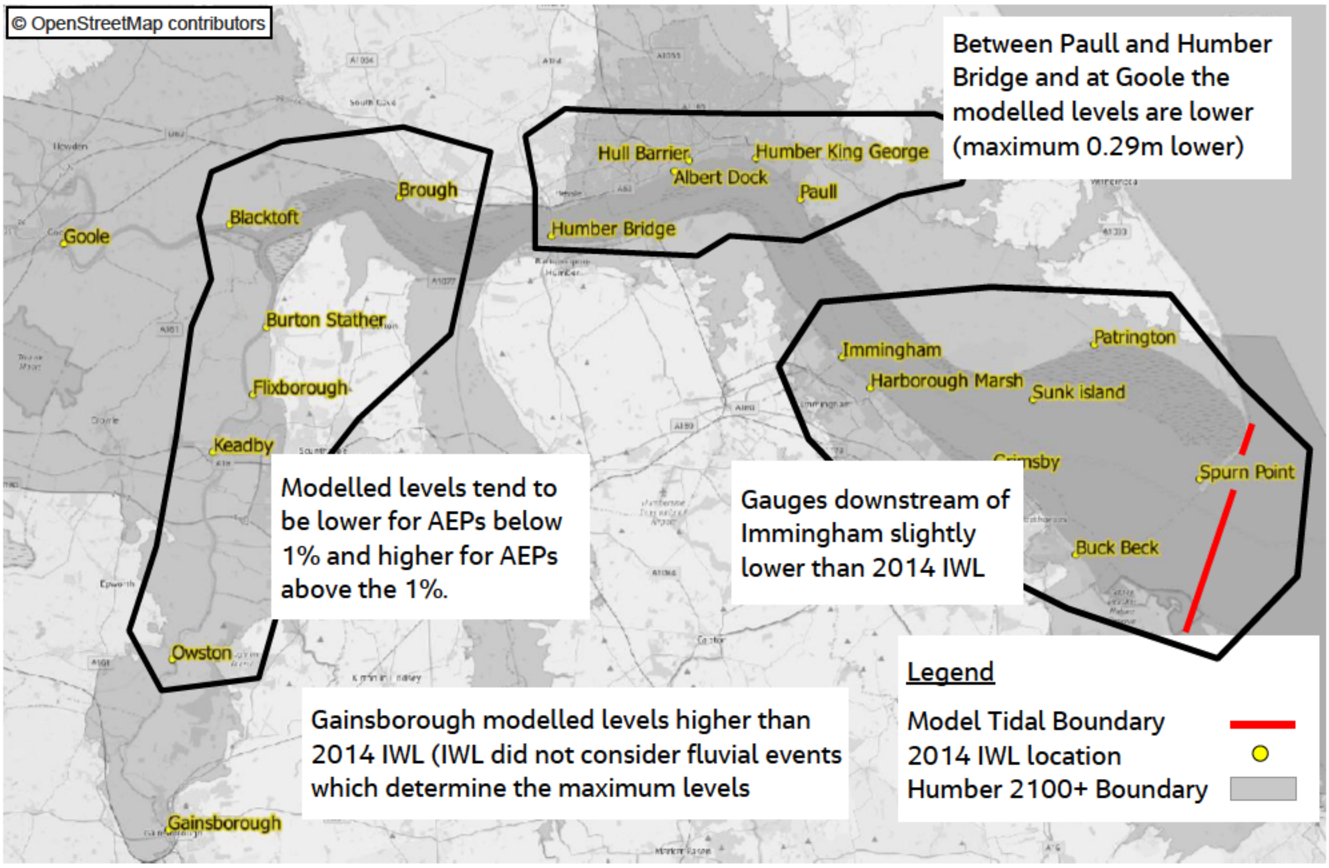
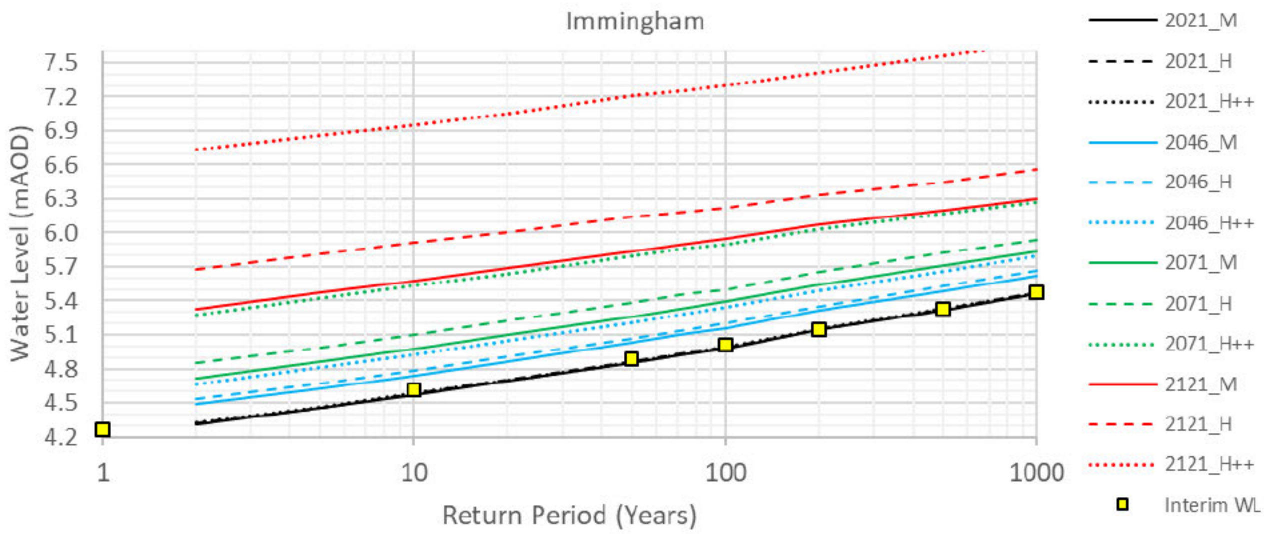
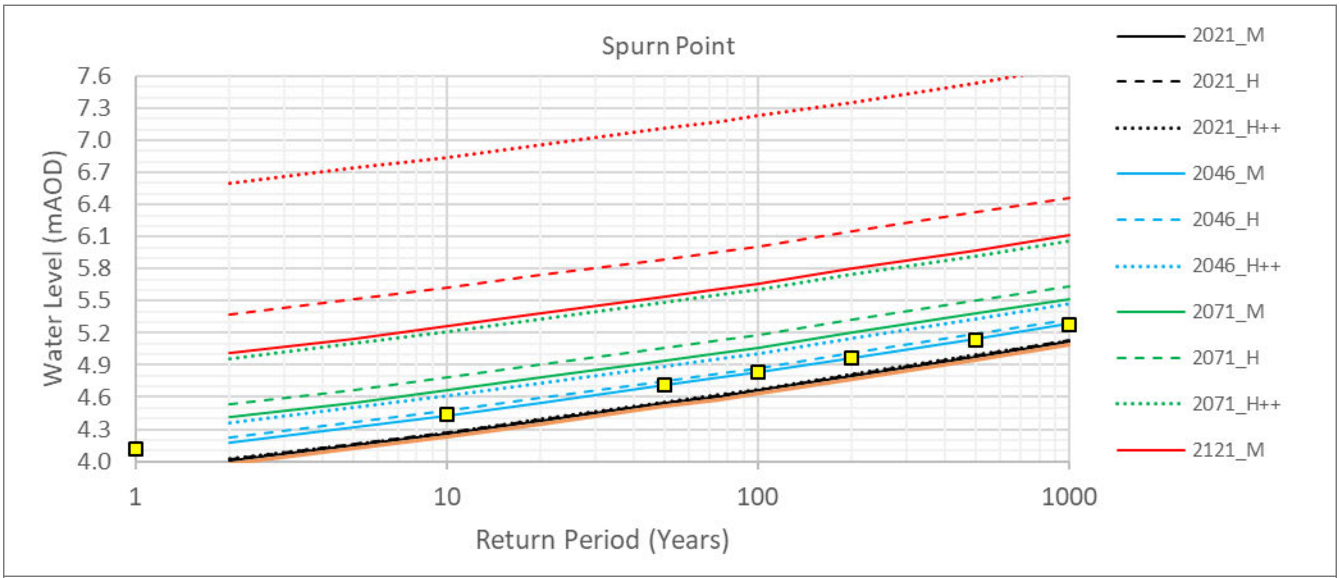
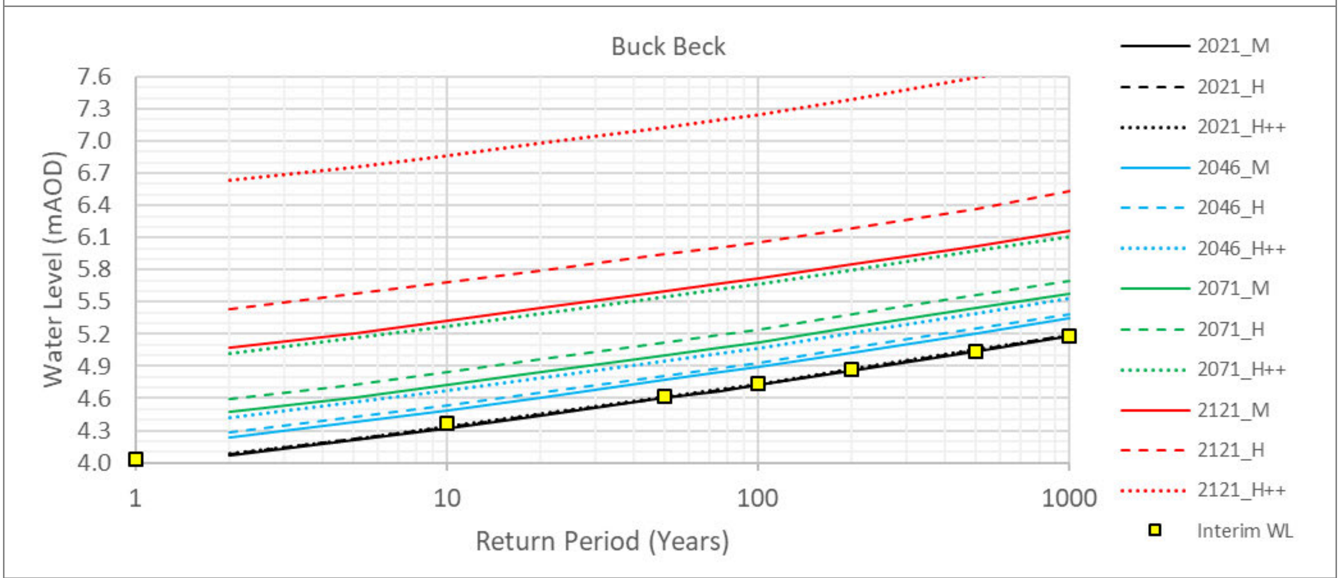
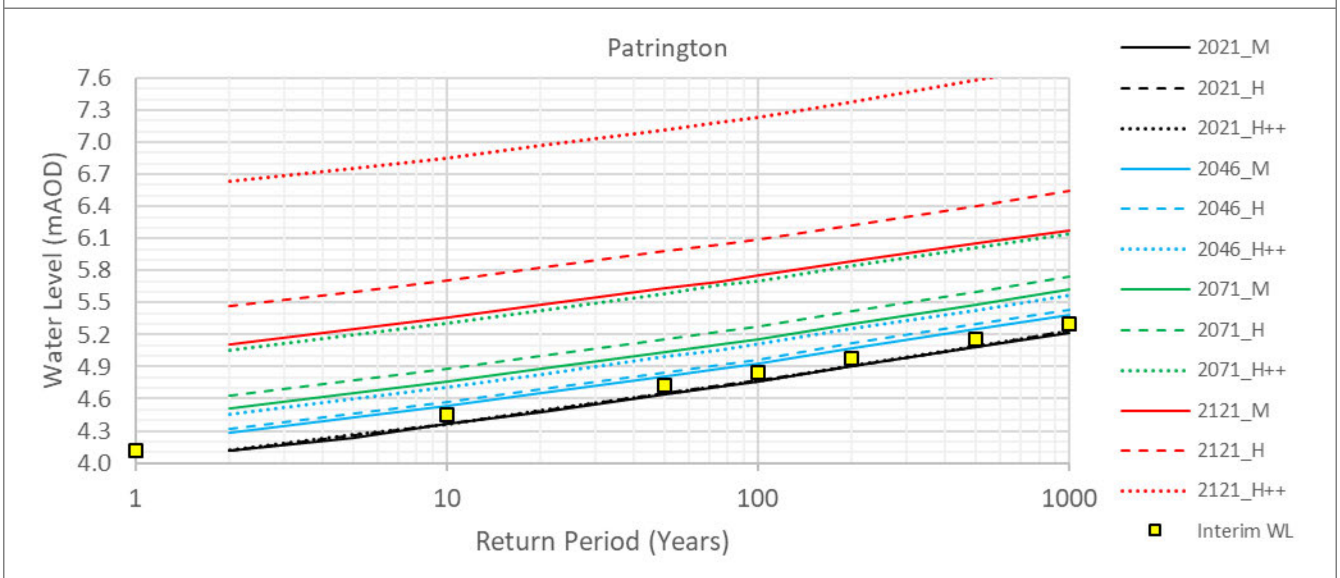


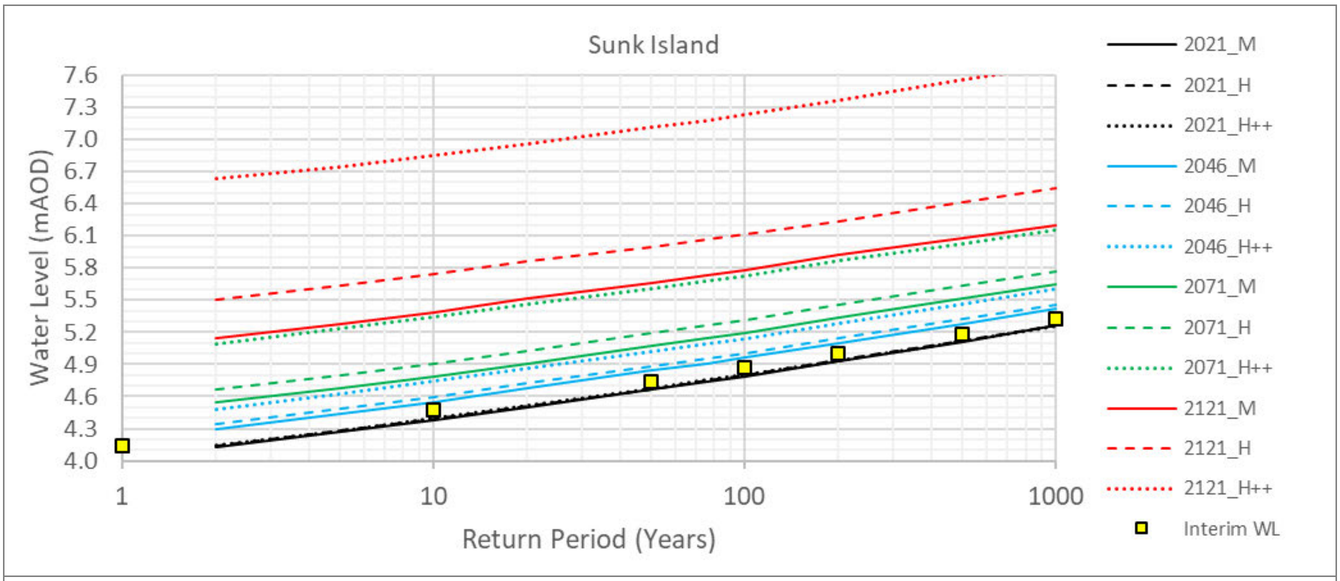
Figure I.1: 2014 Interim Water Level locations

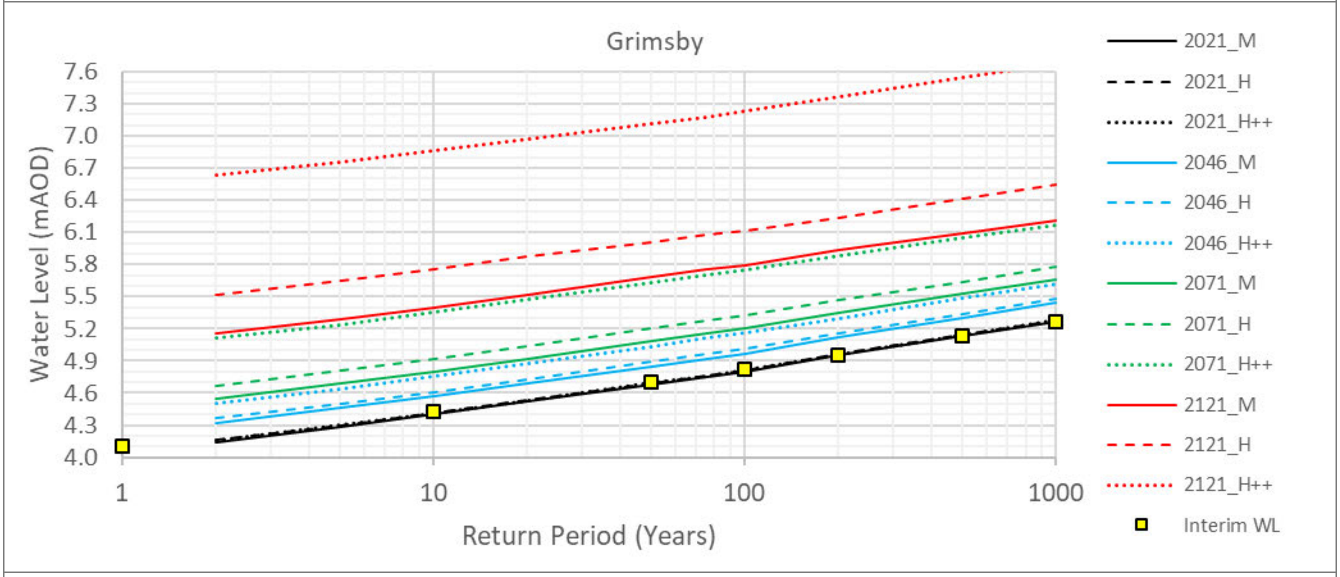


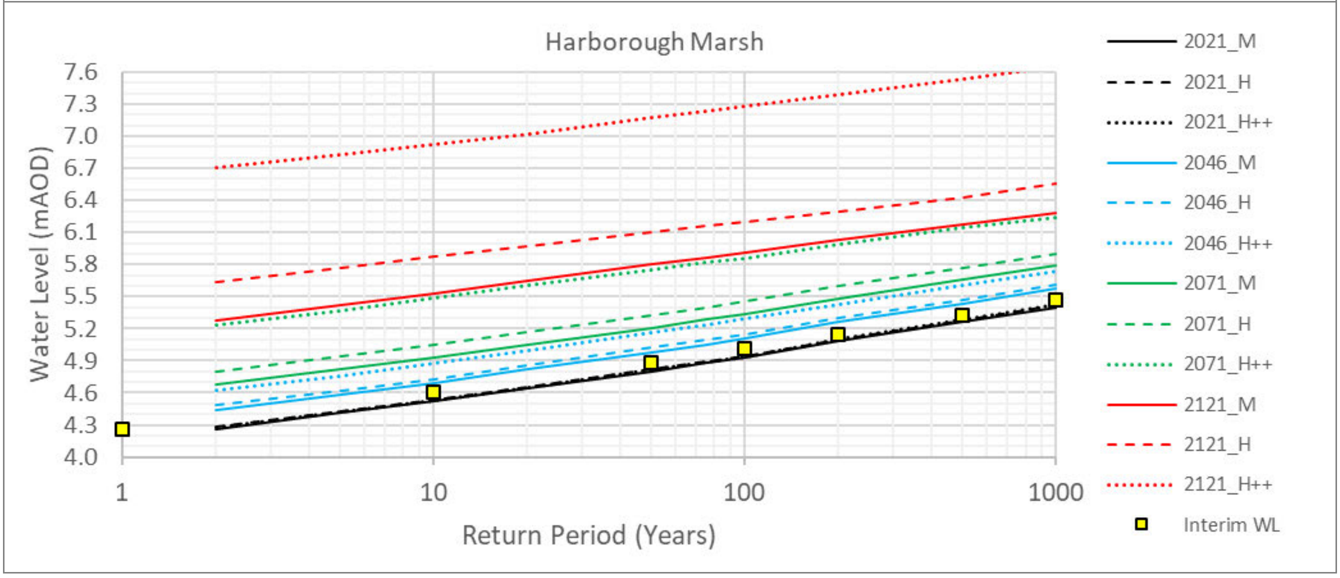

Spurn Point
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
4.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M

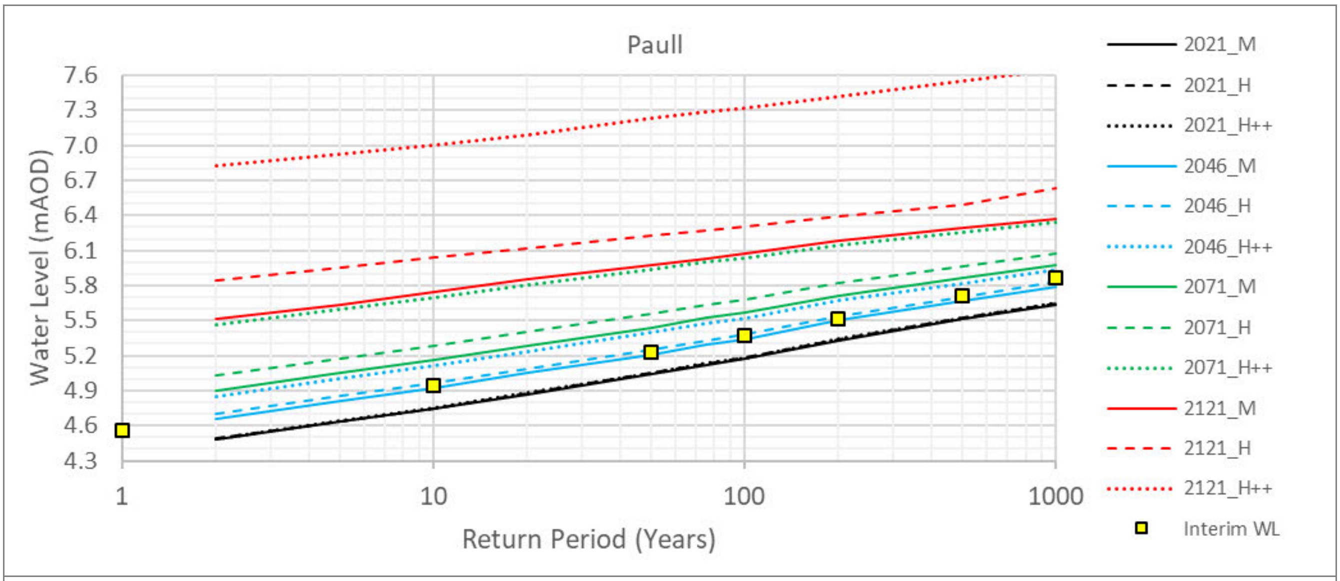

Buck Beck
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
4.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

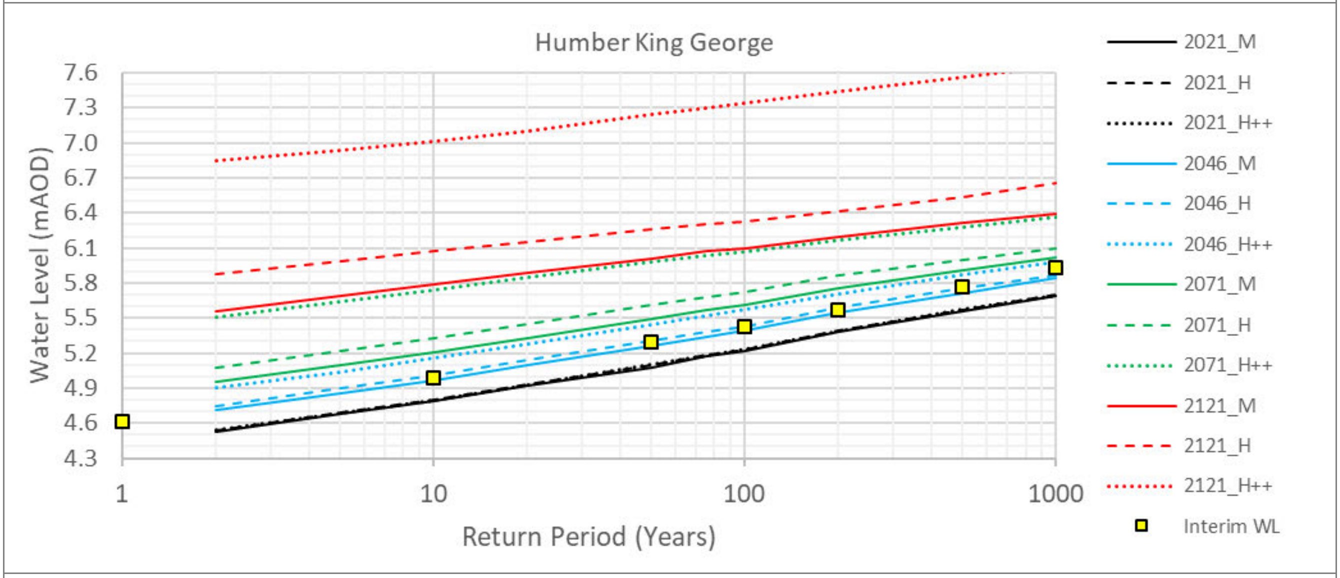

Patrington
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
4.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

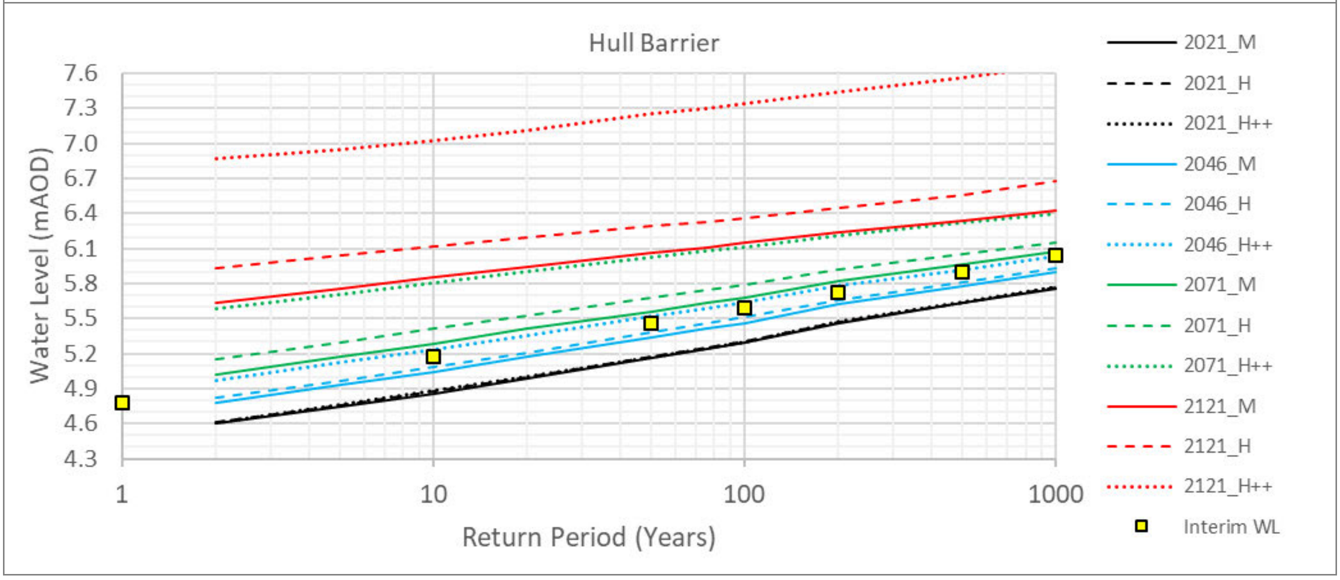

Sunk Island
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
4.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

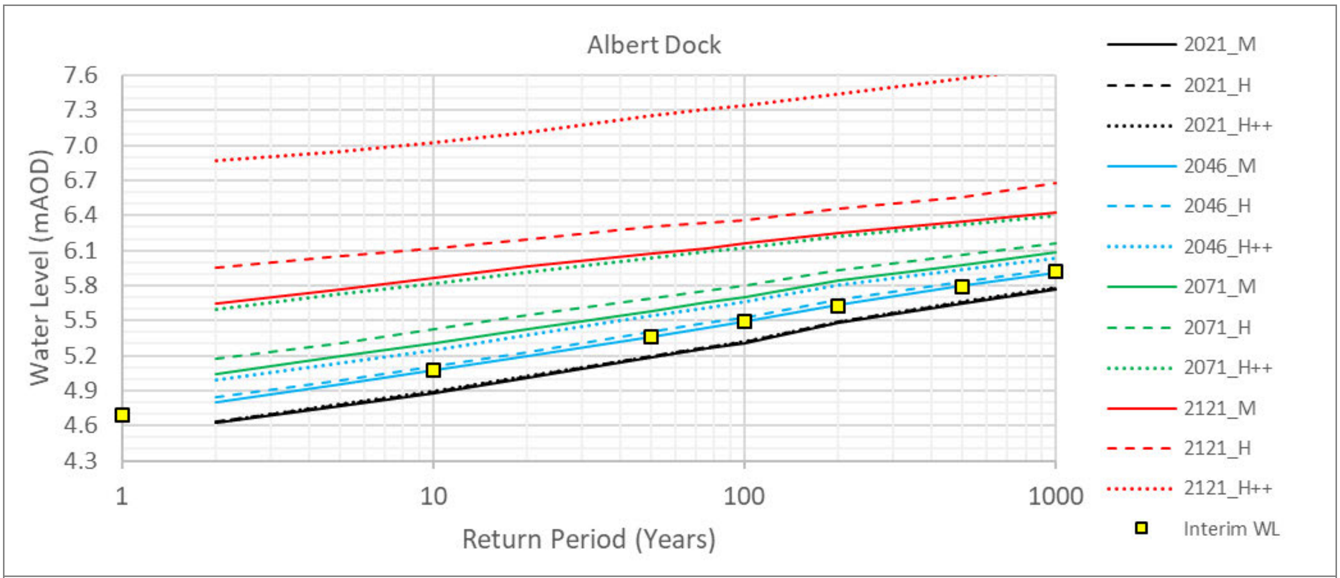

Grimsby
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
4.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

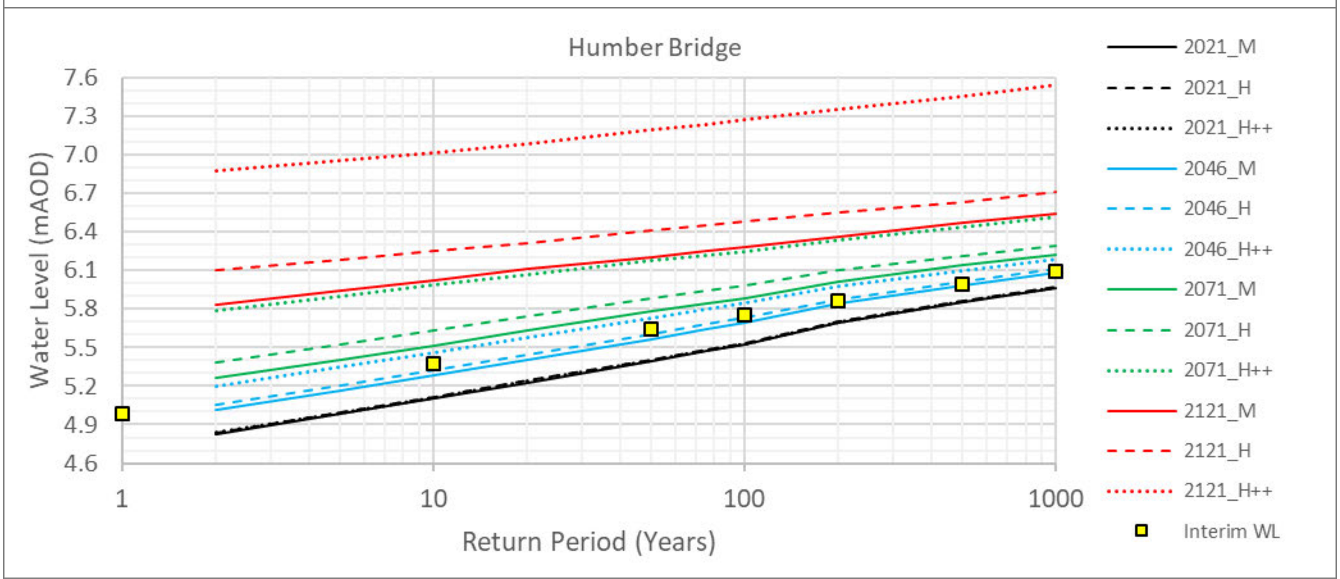

Harborough Marsh
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
4.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

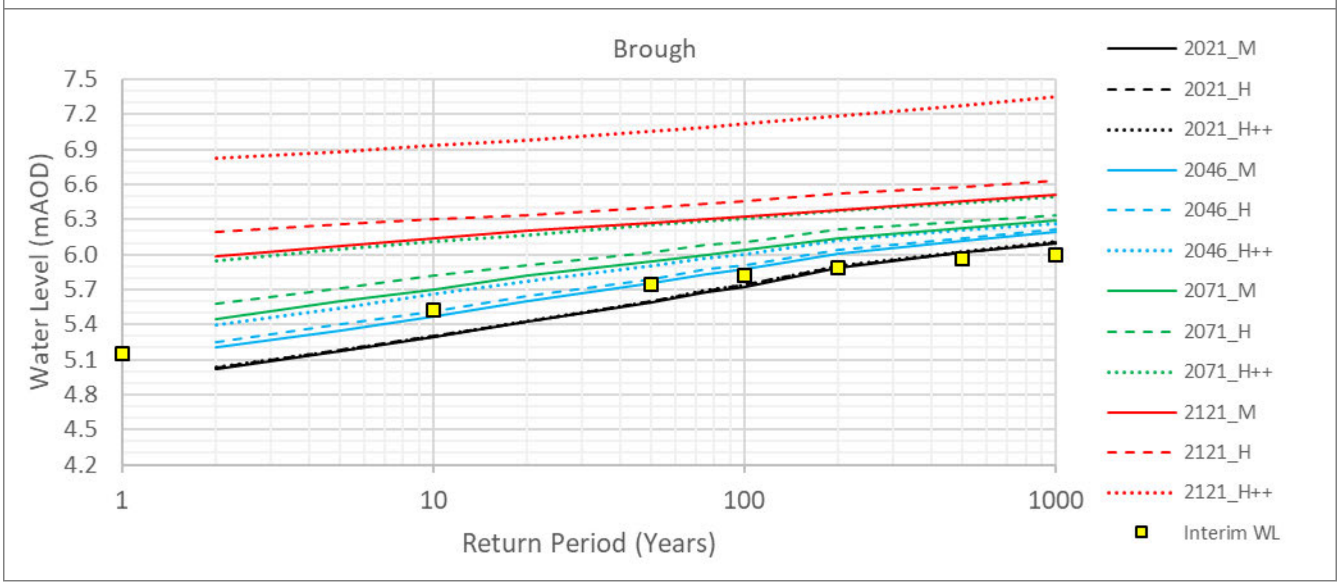

Paull
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

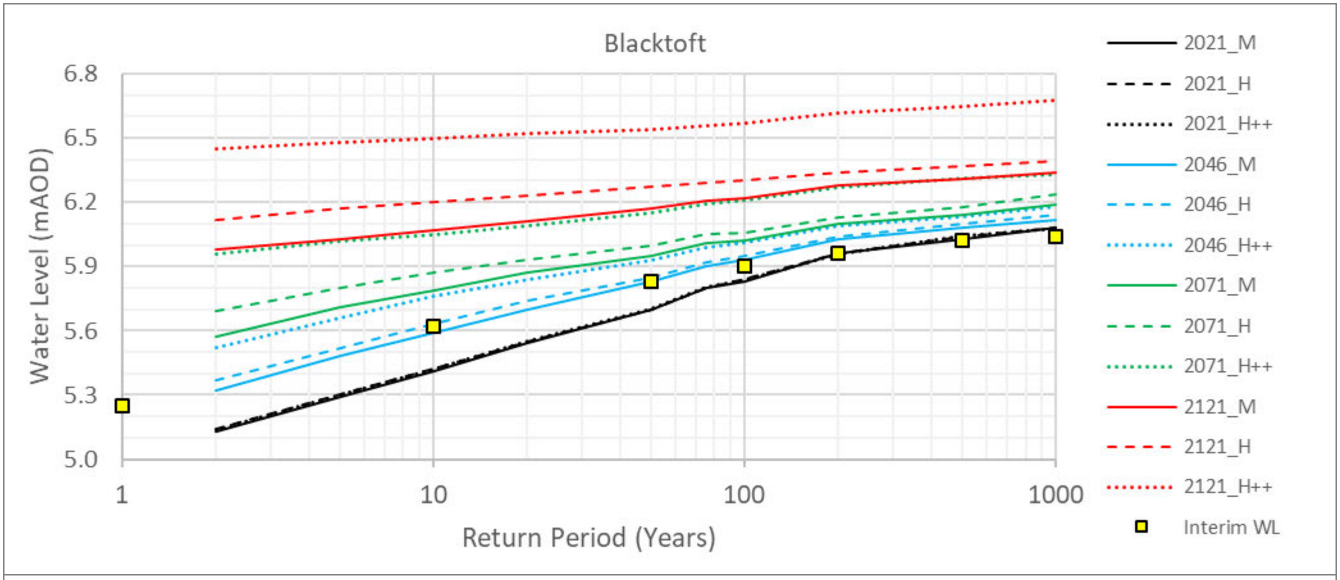

Humber King George
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

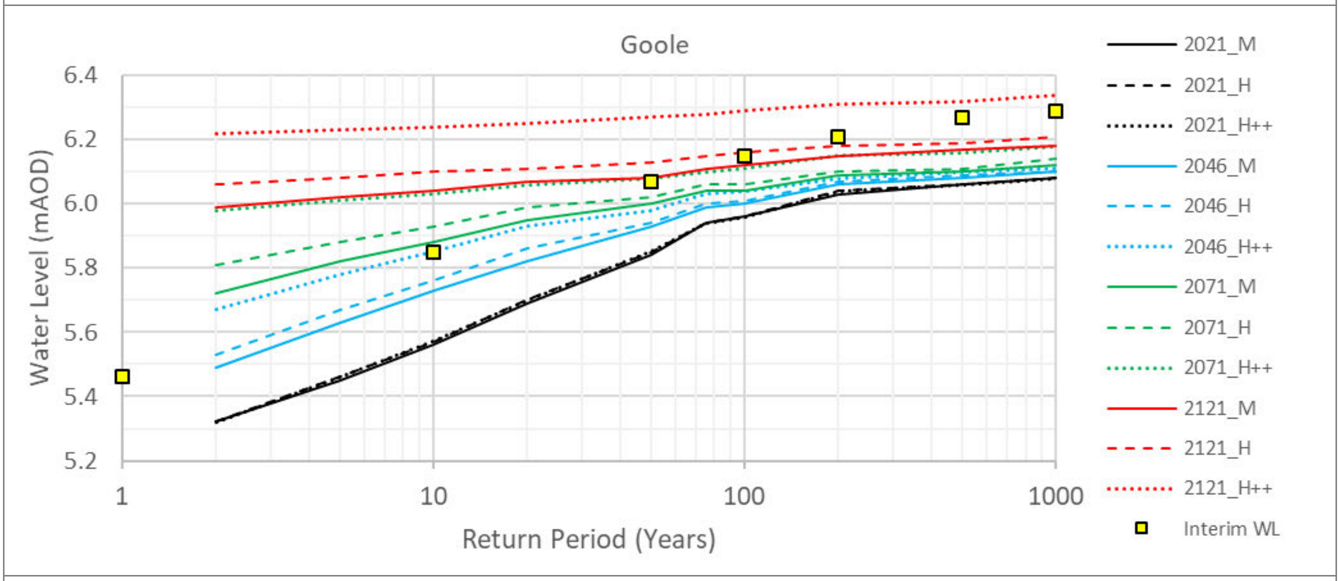

Hull Barrier
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL


Albert Dock
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
4.3
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

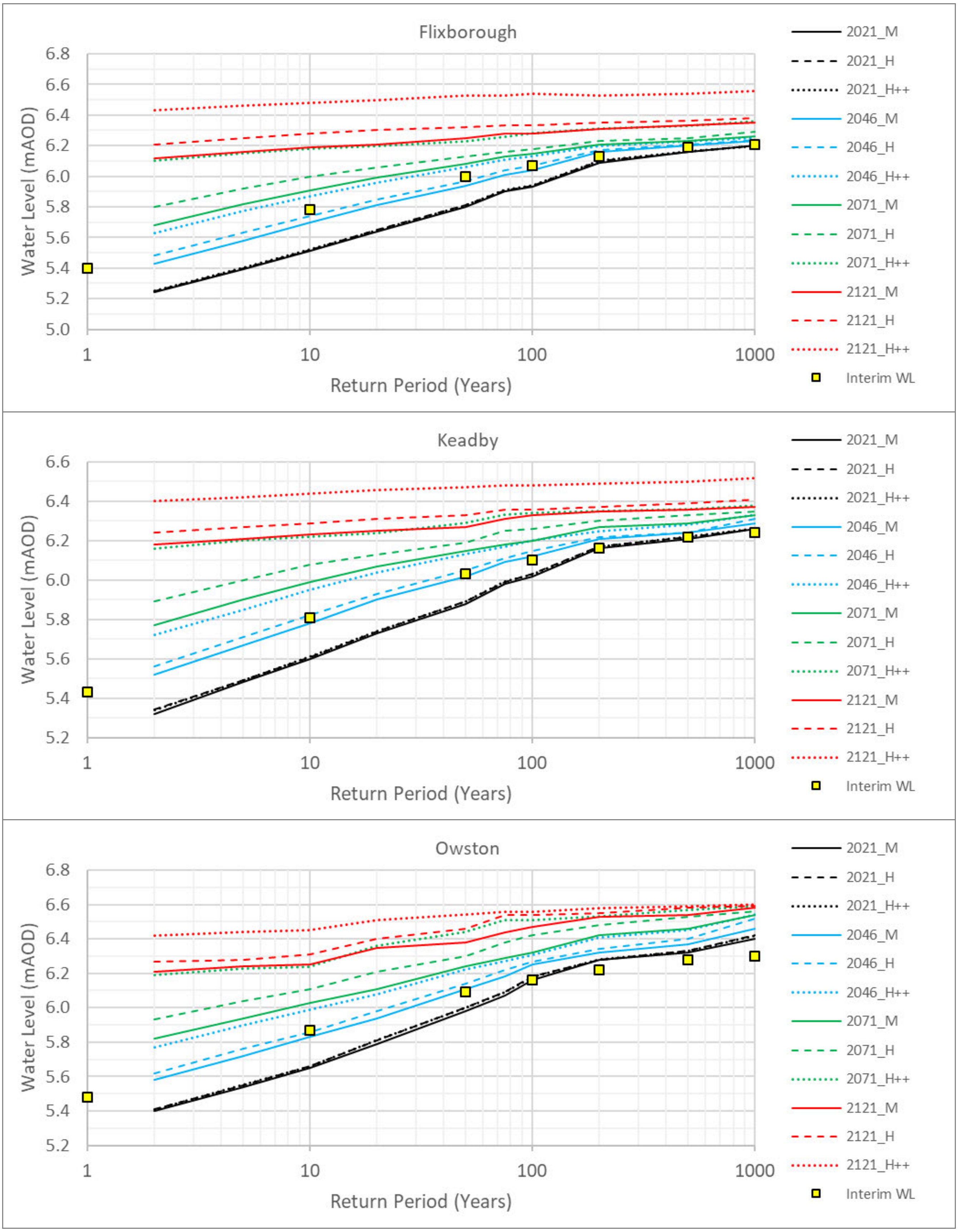

Humber Bridge
Water Level (mAOD)
7.6
7.3
7.0
6.7
6.4
6.1
5.8
5.5
5.2
4.9
4.6
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

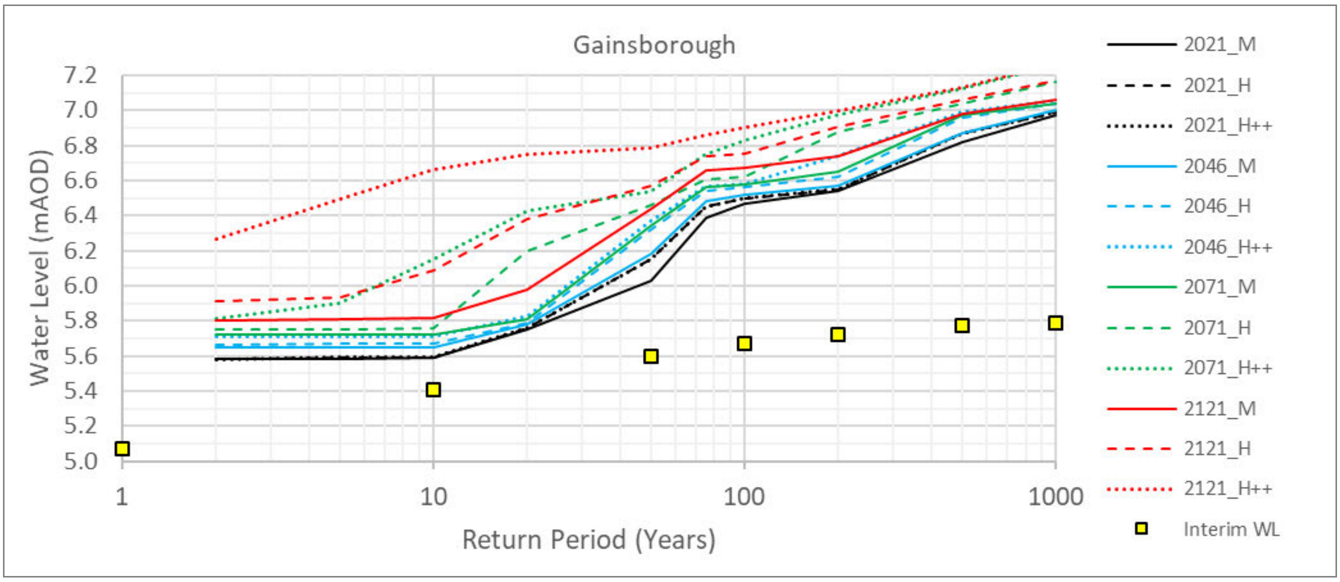

Brough
Water Level (mAOD)
7.5
7.2
6.9
6.6
6.3
6.0
5.7
5.4
5.1
4.8
4.5
4.2
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL


Blacktoft
Water Level (mAOD)
6.8
6.5
6.2
5.9
5.6
5.3
5.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL


Goole
Water Level (mAOD)
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL


Burton Stather
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

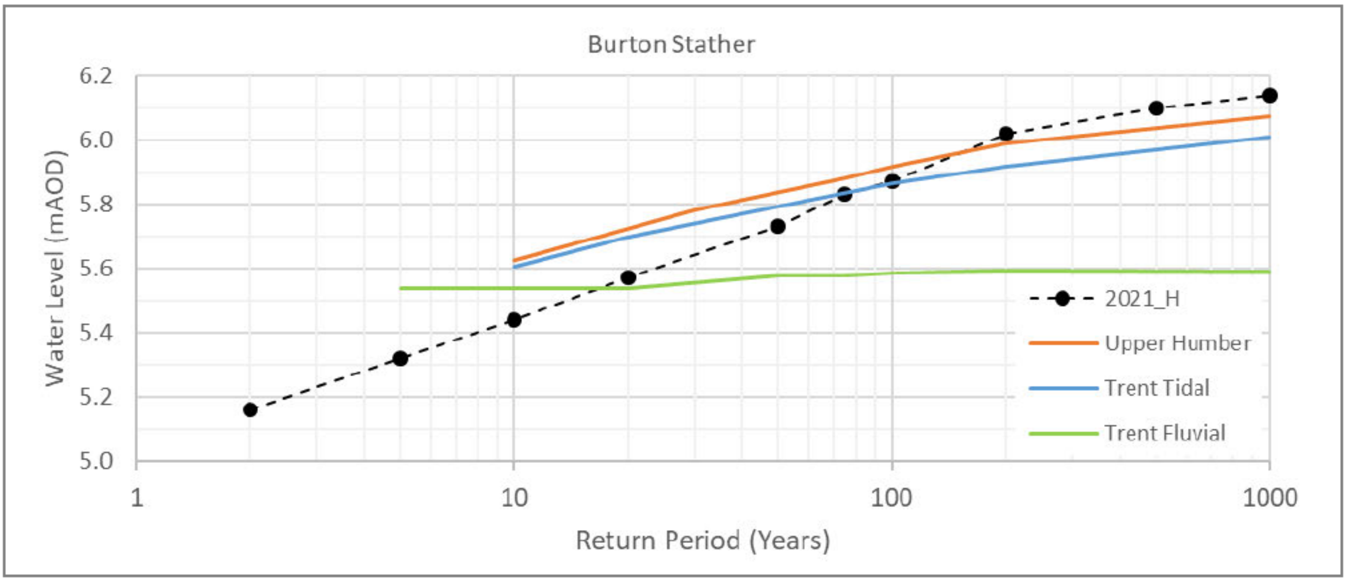

Flixborough
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL
Keadby
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL
Owston
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

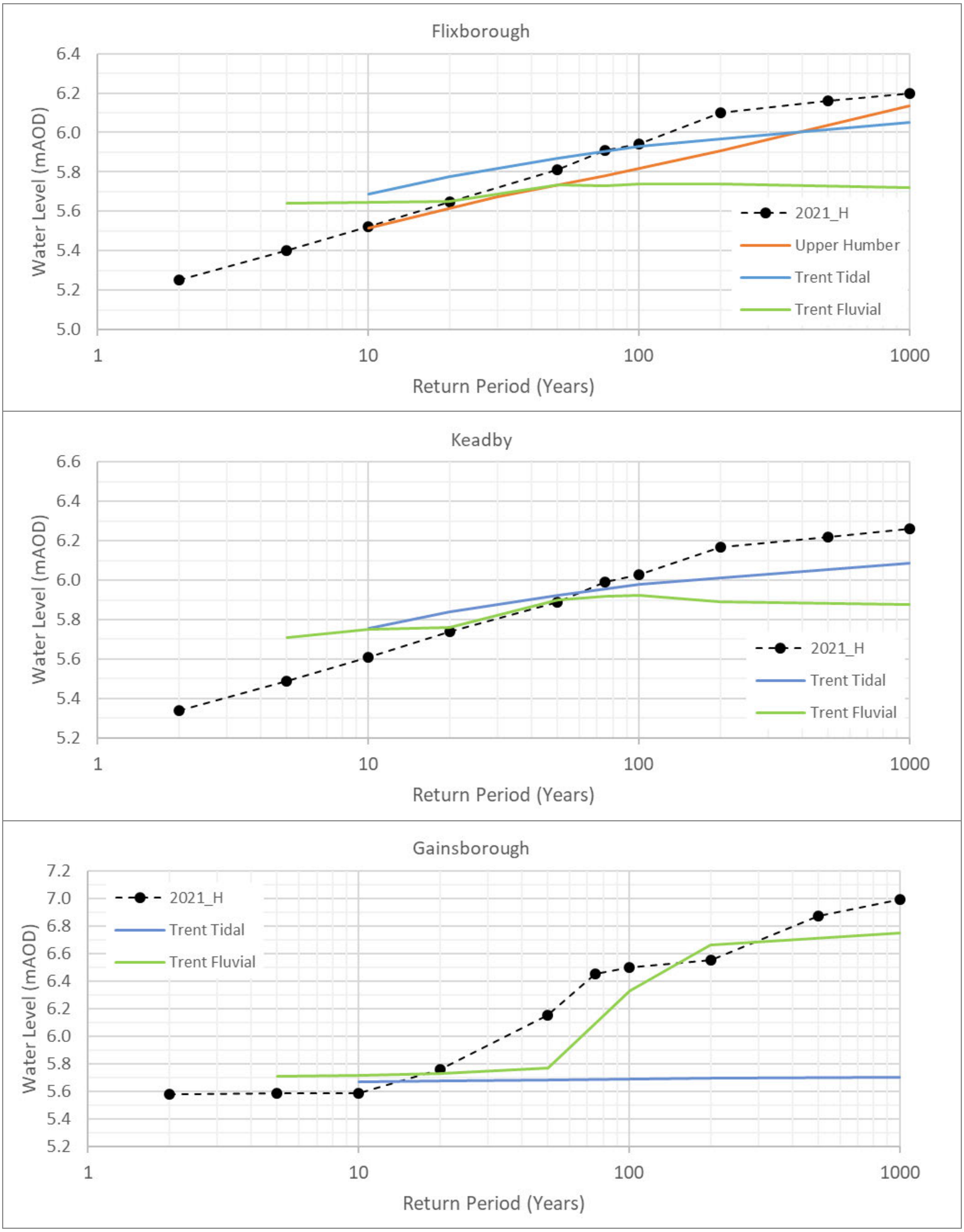

Gainsborough
Water Level (mAOD)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
2021_M
2021_H
2021_H++
2046_M
2046_H
2046_H++
2071_M
2071_H
2071_H++
2121_M
2121_H
2121_H++
Interim WL

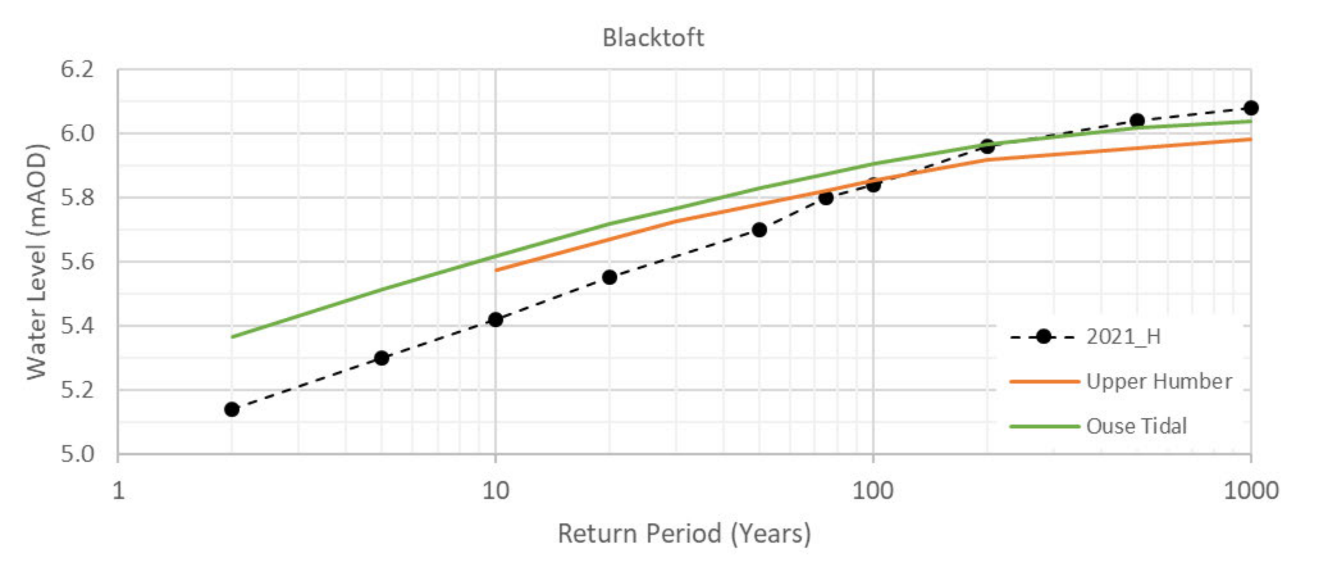
Appendix J. Comparison with existing modelling studies

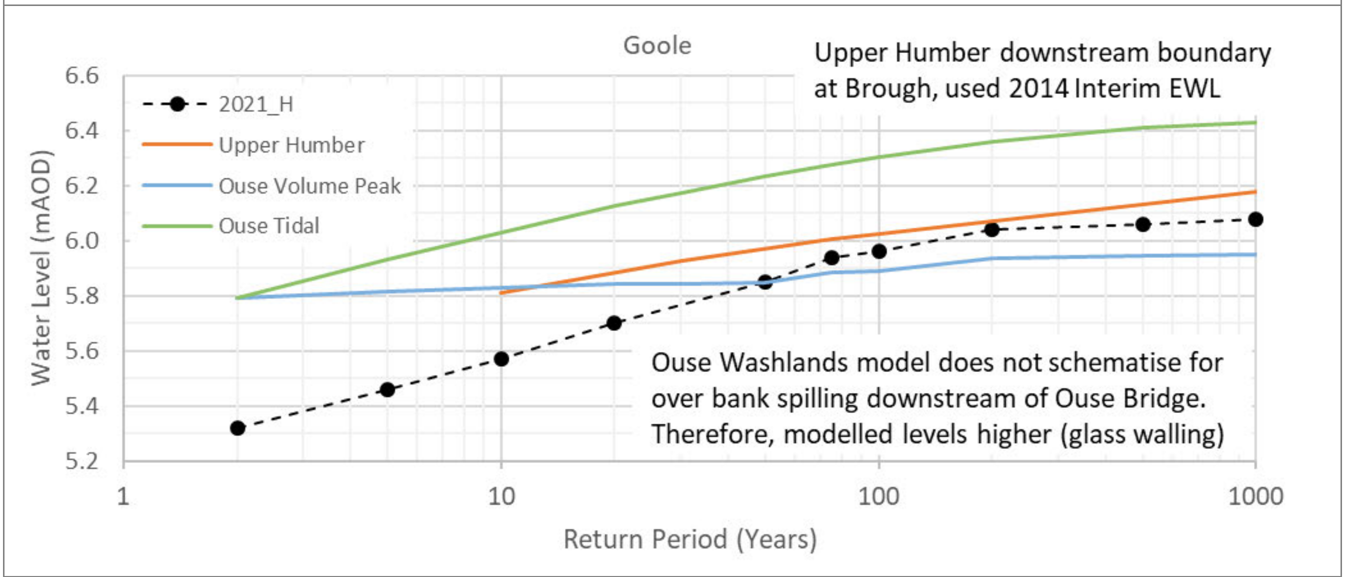
The 2021 extreme water levels are compared to existing modelling at gauges where comparisons could be made. The existing modelling studies used for the comparison are detailed in the table below.

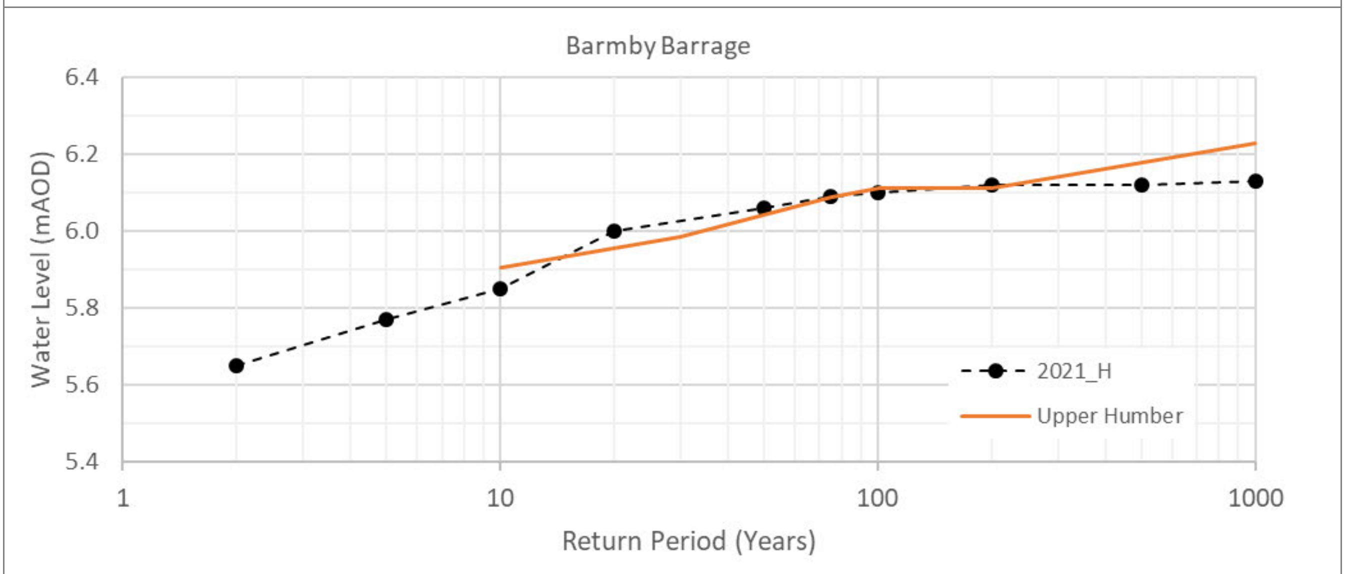
Existing Study	Gauges compared	Legend used level charts
Ouse and Wharfe Washlands Optimisation Study. Mott MacDonald, July 2018	Blacktoft, Goole, Selby Lock, Selby Westmill	Ouse Volume Peak Ouse Tidal
Northern Forecasting Package: Lower Aire Model. JBA, July 2017	Chapel Haddlesey	Aire Fluvial
Don Catchment Model: Hydrology Report. JBA, February 2017.	Fishlake, Kirk Bramwith, Doncaster, Went Outfall	Don Fluvial
Tidal Trent Modelling and Mapping Study. Addendum. Mott MacDonald, Jan 2015	Burton Stather, Flixborough, Keadby, Gainsborough	Trent Tidal Trent Fluvial
Upper Humber Flood Risk Mapping Study. JBA, August 2016	Burton Stather, Flixborough, Blacktoft, Goole, Barmby Barrage, Selby Lock, Went Outfall, Airmyn, Carton Bridge, Fishlake, Kirk Bramwith, Selby Westmill, and River Aire at Snaith/Gowdall/Hensall Ings	Upper Humber

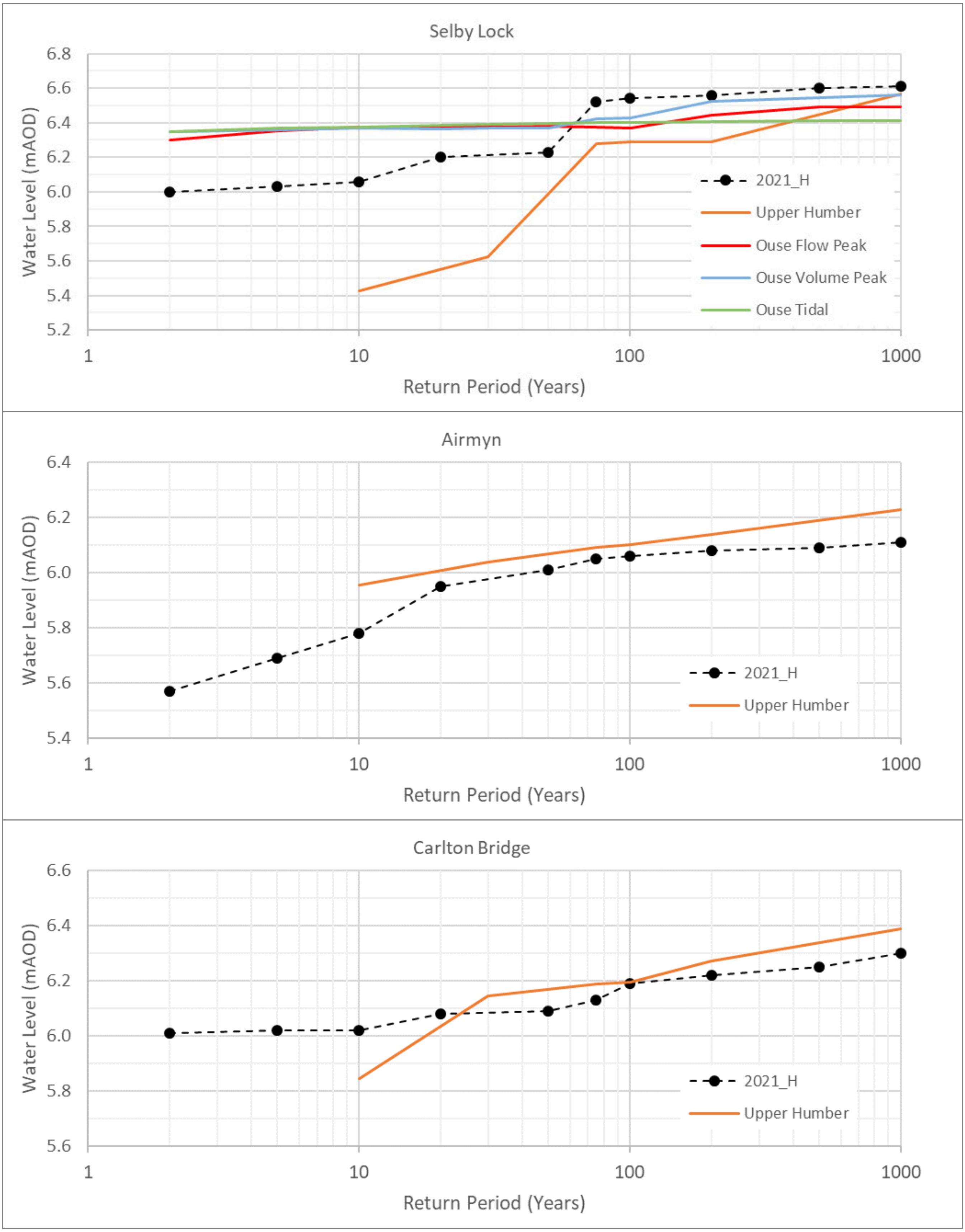


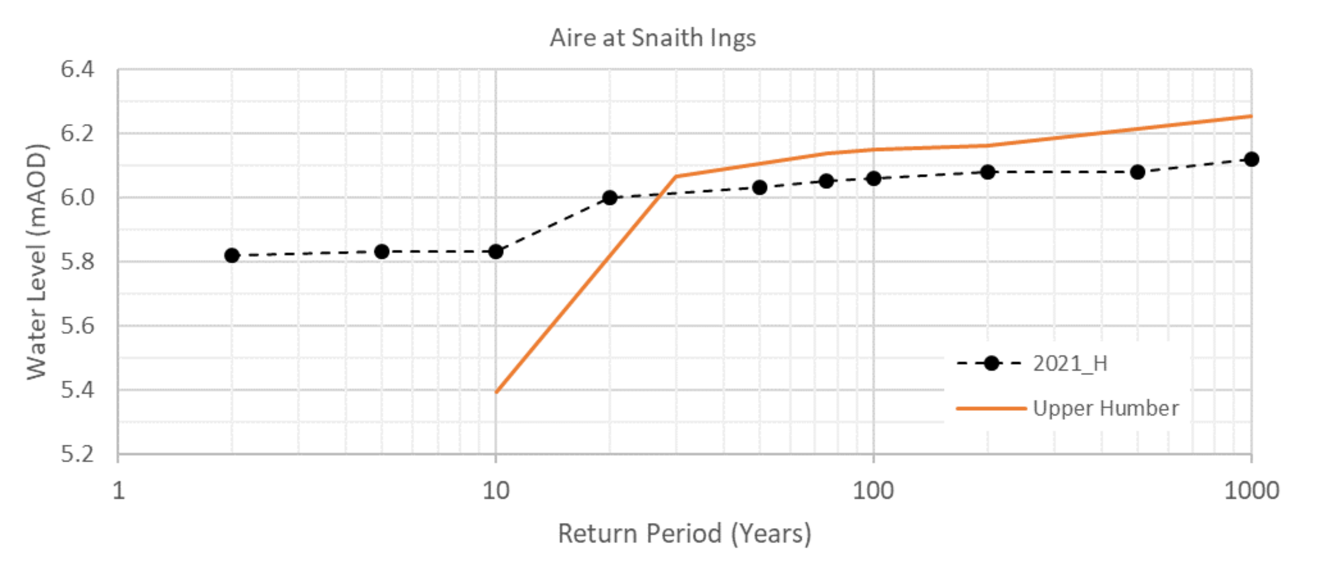

Flixborough
Water Level (mAOD)
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber
Trent Tidal
Trent Fluvial
Keadby
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_H
Trent Tidal
Trent Fluvial
Gainsborough
Water Level (mAOD)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_H
Trent Tidal
Trent Fluvial

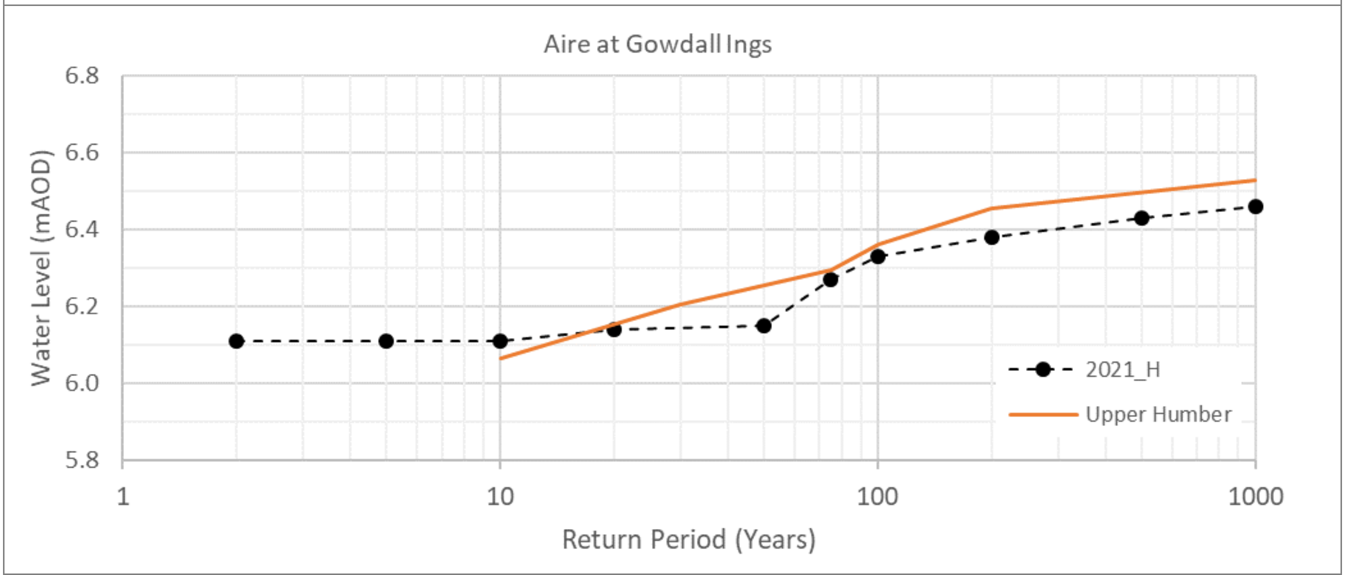

Blacktoft
Water Level (mAOD)
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber
Ouse Tidal

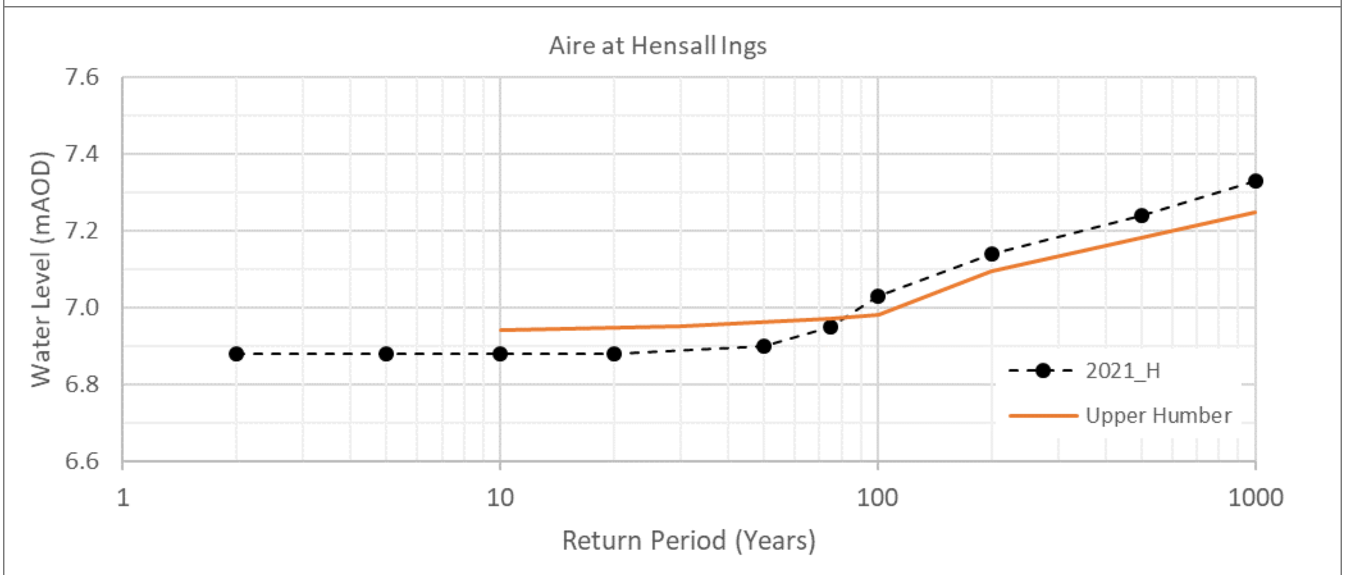

Goole
Upper Humber downstream boundary at Brough, used 2014 Interim EWL
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
2021_H
Upper Humber
Ouse Volume Peak
Ouse Tidal
Ouse Washlands model does not schematise for over bank spilling downstream of Ouse Bridge. Therefore, modelled levels higher (glass walling)
1
10
100
1000
Return Period (Years)

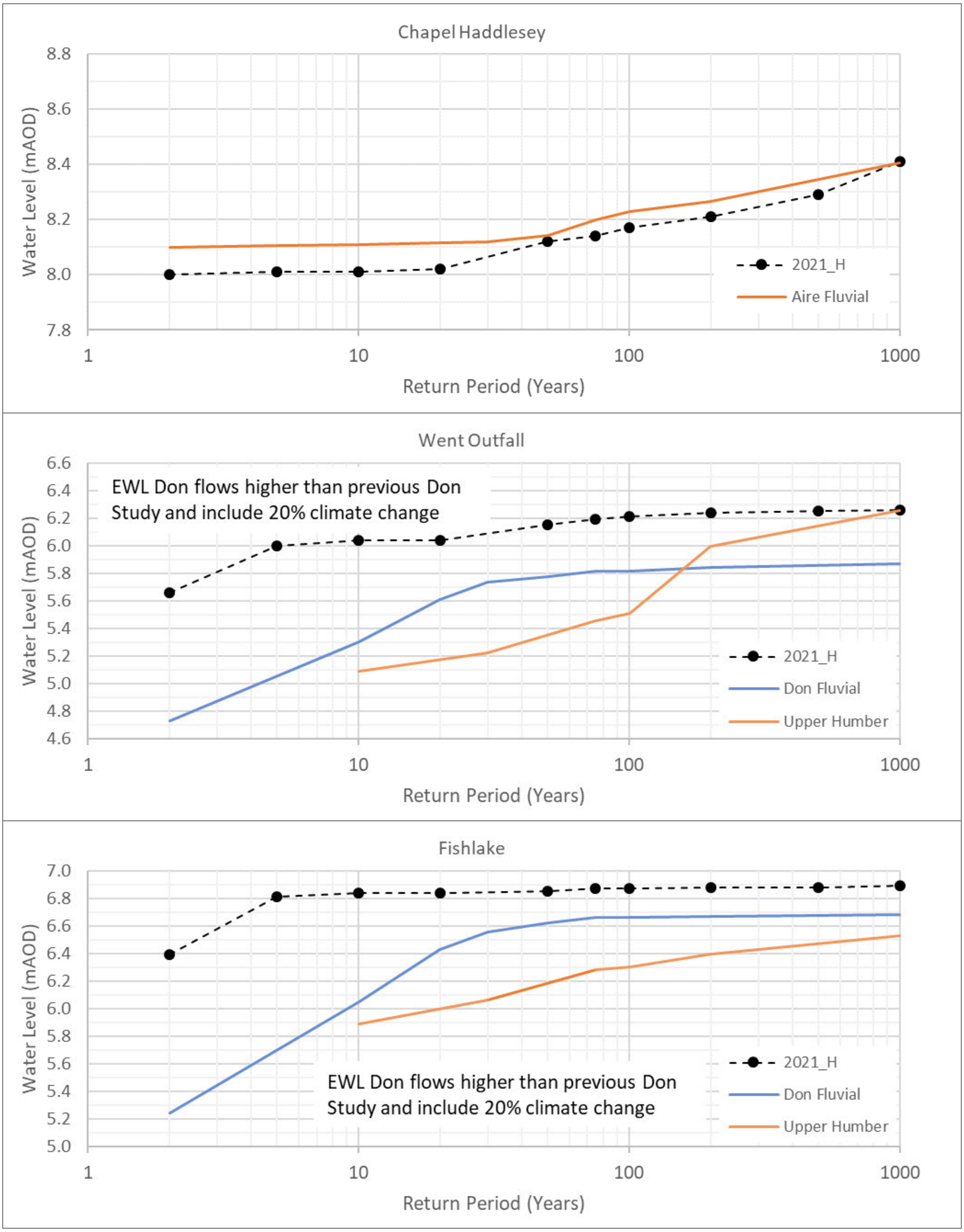

Barmby Barrage
Water Level (mAOD)
6.4
6.2
6.0
5.8
5.6
5.4
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber

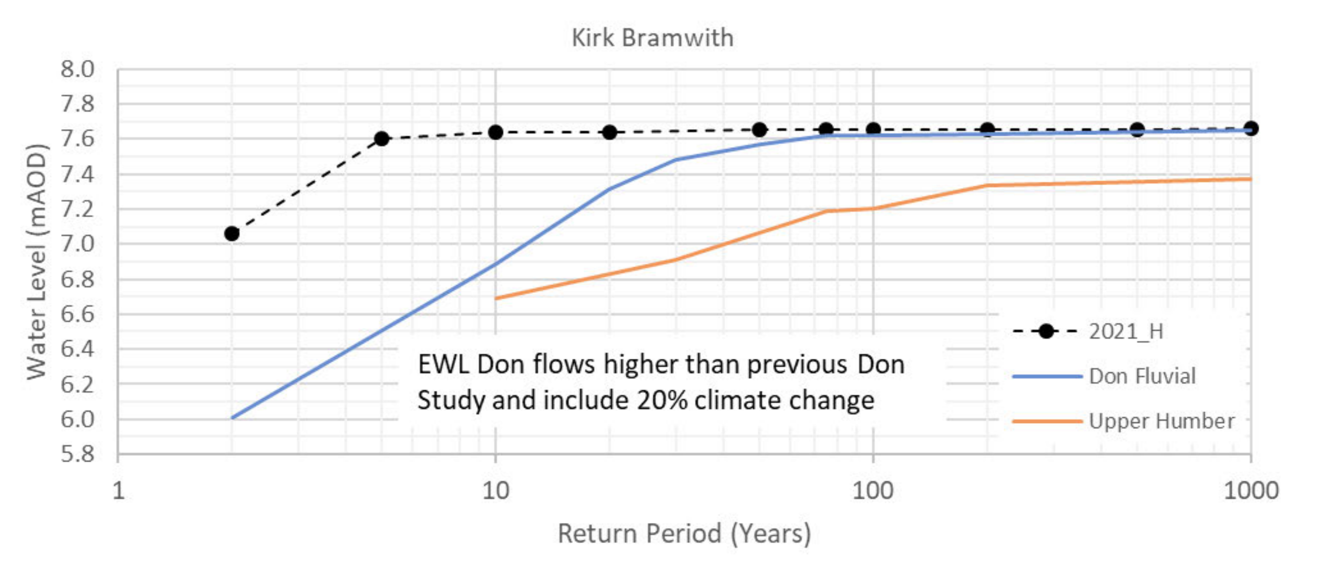

Selby Lock
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber
Ouse Flow Peak
Ouse Volume Peak
Ouse Tidal
Airmyn
Water Level (mAOD)
6.4
6.2
6.0
5.8
5.6
5.4
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber
Carlton Bridge
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber

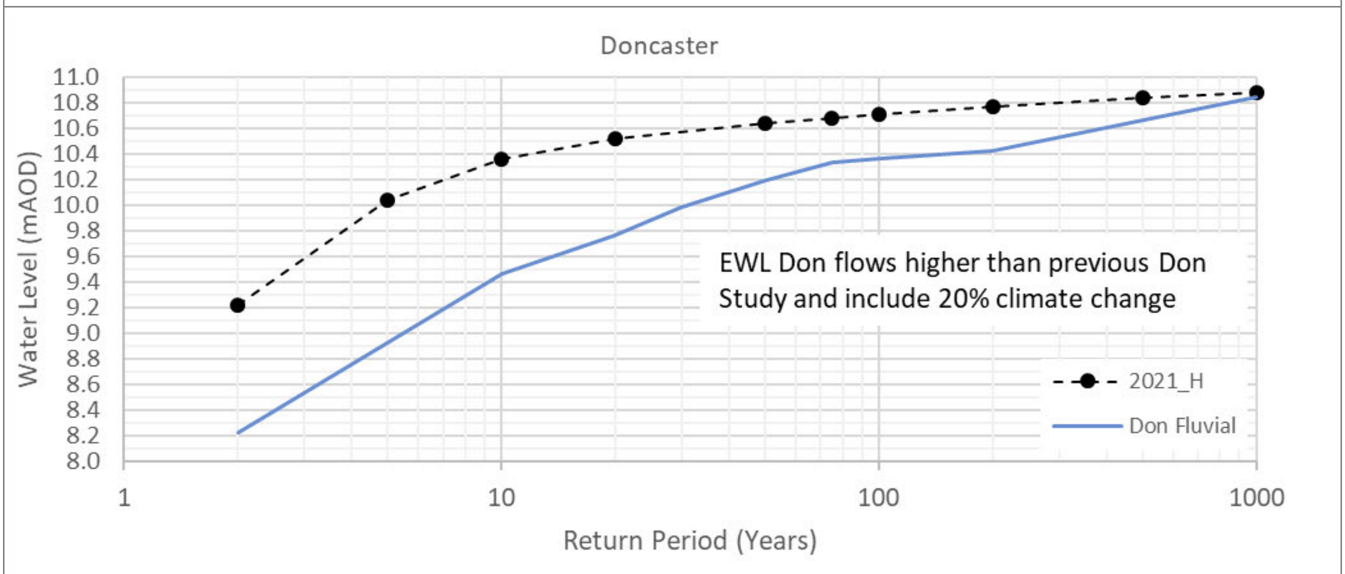

Aire at Snaith Ings
Water Level (mAOD)
6.4
6.2
6.0
5.8
5.6
5.4
5.2
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber


Aire at Gowdall Ings
Water Level (mAOD)
6.8
6.6
6.4
6.2
6.0
5.8
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber


Aire at Hensall Ings
Water Level (mAOD)
7.6
7.4
7.2
7.0
6.8
6.6
1
10
100
1000
Return Period (Years)
2021_H
Upper Humber


Chapel Haddlesey
Water Level (mAOD)
8.8
8.6
8.4
8.2
8.0
7.8
1
10
100
1000
Return Period (Years)
2021_H
Aire Fluvial
Went Outfall
EWL Don flows higher than previous Don Study and include 20% climate change
Water Level (mAOD)
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
1
10
100
1000
Return Period (Years)
2021_H
Don Fluvial
Upper Humber
Fishlake
Water Level (mAOD)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
1
10
100
1000
Return Period (Years)
EWL Don flows higher than previous Don Study and include 20% climate change
2021_H
Don Fluvial
Upper Humber


Kirk Bramwith
Water Level (mAOD)
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
1
10
100
1000
Return Period (Years)
EWL Don flows higher than previous Don Study and include 20% climate change
2021_H
Don Fluvial
Upper Humber


Doncaster
Water Level (mAOD)
11.0
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
9.2
9.0
8.8
8.6
8.4
8.2
8.0
1
10
100
1000
Return Period (Years)
EWL Don flows higher than previous Don Study and include 20% climate change
2021_H
Don Fluvial

Appendix K. Joint Probability vs Full Dependency review

Figure K.1 summarises the locations where the joint probability peak water levels exceeded the full dependency scenario. This overall summary is based on results from all scenarios/epochs (15 set of results). Differences up to 0.02m should be considered within the numerical accuracy of the model (the flood modeller default convergence criteria set at 0.01m, so comparison between 2 different simulations could show an absolute difference of 0.02m).

There is an area on the Ouse with differences up to 0.05m (joint probability – full dependency), the model boundaries (inflow, tides) are applied as per the joint probability matrix and model convergence is good. The differences could be explained by the complex hydraulics, i.e. the River Ouse location they are located within the zones where peak water levels are derived from either fully tidal, fully fluvial or joint probability scenarios. The hydraulics are further complicated with surcharge bridges predicting as the floodplain storage is full and peak water levels in the river and floodplain are at a similar level.

Table K.1 shows the differences between the joint probability and full dependency peak water levels at model node CS45J (which has the largest differences). The table shows results are as expected for the lower order events, the 500-year event starts to exceed +0.02m for the 2021 epoch, which reduces to a 50-year event for the 2121 epoch.

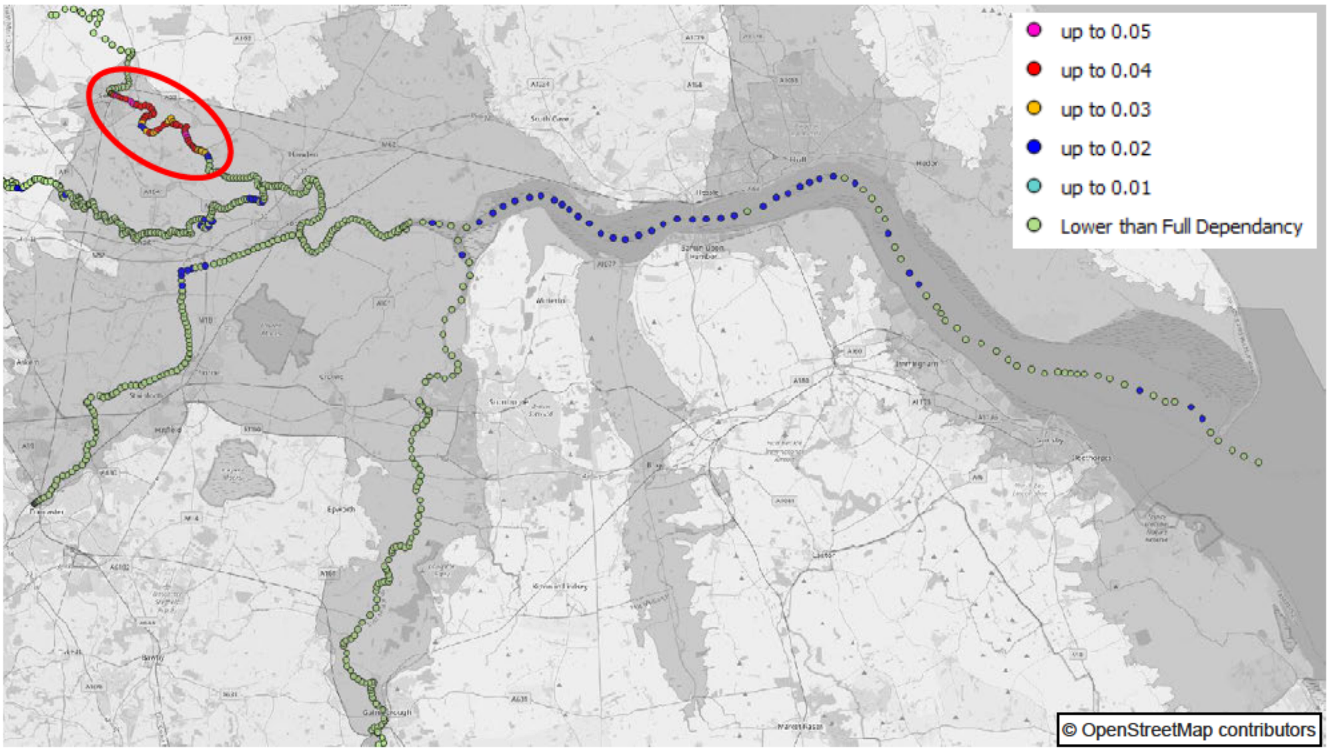


Figure K.1: Locations where Joint Probability exceeds Full Dependency

Table K.1: Differences between Joint Probability and Full Dependency at model Node "CS45J"

Epoch/Scenario	Difference in peak water level (m) for each design return period									
	2	5	10	20	50	75	100	200	500	1000
2021_M	-0.36	-0.28	-0.22	-0.08	-0.04	-0.02	-0.01	0.02	0.04	0.04
2021_H	-0.36	-0.27	-0.22	-0.07	-0.04	-0.01	-0.01	0.03	0.04	0.04
2021_H++	-0.36	-0.27	-0.22	-0.07	-0.04	-0.01	-0.01	0.03	0.04	0.04
2040_M	-0.29	-0.22	-0.18	-0.06	-0.03	-0.01	0.00	0.03	0.04	0.05
2040_H	-0.26	-0.20	-0.16	-0.06	-0.03	0.01	0.01	0.04	0.04	0.05
2040_ H++	-0.21	-0.17	-0.14	-0.04	-0.02	0.02	0.02	0.04	0.05	0.05
2046_M	-0.26	-0.20	-0.17	-0.06	-0.03	0.00	0.00	0.03	0.04	0.05
2046_H	-0.24	-0.18	-0.16	-0.05	-0.02	0.01	0.02	0.04	0.05	0.05
2046_ H++	-0.18	-0.15	-0.13	-0.04	-0.01	0.02	0.02	0.04	0.05	0.04
2071_M	-0.17	-0.15	-0.13	-0.03	-0.01	0.01	0.02	0.04	0.05	0.04
2071_H	-0.14	-0.13	-0.12	-0.03	0.02	0.04	0.04	0.05	0.05	0.05
2071_ H++	-0.09	-0.10	-0.08	0.01	0.04	0.04	0.04	0.03	0.04	-0.03
2121_M	-0.09	-0.09	-0.07	-0.02	-0.01	0.02	0.02	0.03	0.04	0.03
2121_H	-0.05	-0.05	-0.04	-0.01	0.02	0.02	0.03	0.03	0.02	-0.02
2121_ H++	0.00	0.00	-0.01	-0.01	-0.04	-0.01	-0.01	-0.02	-0.03	-0.07

Appendix L. Humber Extremes: Review of River Flow Dependence and Dependence Analysis

Refer to documents:

ENV0000300C-CH2-ZZ-3A0-TN-HY-0003 - HEWL review of river flow dependence, Janet Heffernan, September 2018

ENV0000300C-CH2-ZZ-3A0-TN-HY-0004 -Humber Extremes: Dependence Analysis, HSCR Extremes, J Heffernan Consulting Limited, May 2019

Appendix M. Hydrology Report and FEH calculation record

Refer to documents:

ENV0000300C-CH2-ZZ-3A0-RP-HY-0008 (Hydrology report)

ENV0000300C-CH2-ZZ-3A0-RP-HY-0006 (FEH calculation record – Appendix A to the hydrology Report)

Appendix N. November 2019 Calibration at Fishlake (Don)

N.1 Introduction

During and after the submission of the initial EWL's, the catchments of the Humber experienced flood events which resulted in some of the highest water levels recorded. At Fishlake gauge on the River Don, recorded water levels during November 2019 and February 2020 exceeded the modelled design EWL's as detailed in Figure N.1.

Based on this information, the November 2019 event was used as a calibration event and the model updated to give confidence in the results on the River Don, focusing on water levels at Fishlake. The following sections describe the model boundaries, updates and calibration results.

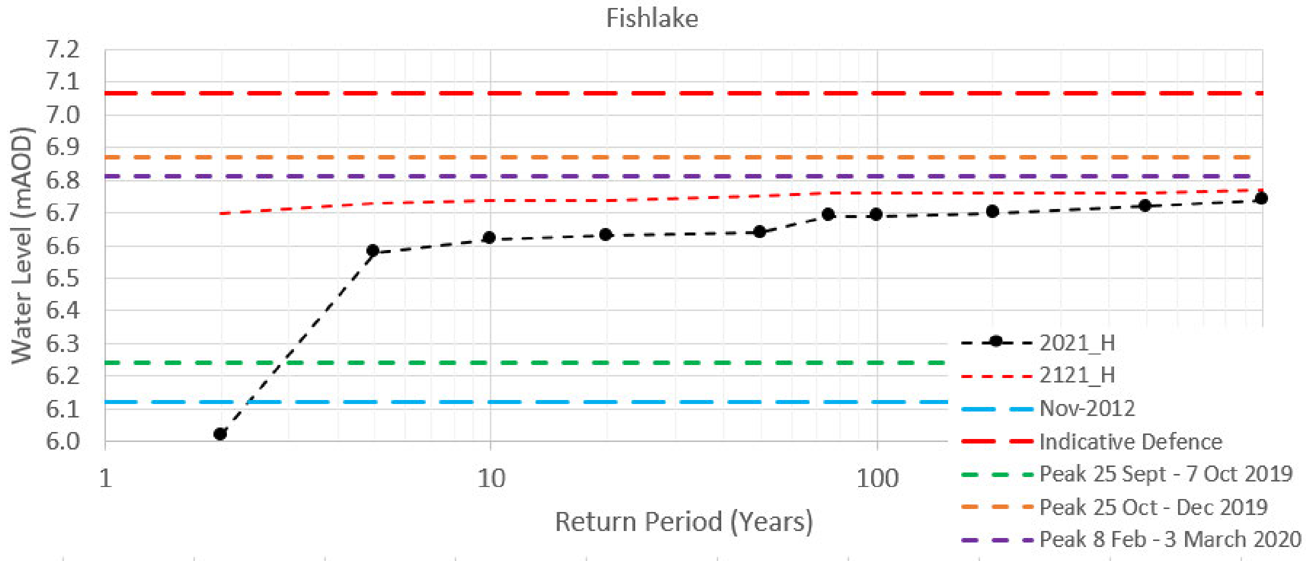


Figure N.1: Fishlake initial EWL comparison to recent flood events

N.2 November 2019 model boundary data

The model inflow and downstream tidal boundaries were taken from the recorded data from the stations detailed in Table N.1 and Figure N.2. The exact same approach was taken as used in the previous model calibration undertaken for this study, which included the following adjustments to the recorded data:

- The model inflow from the Ouse is based on the sum of flow at the gauging stations on the Ouse and Wharfe. Therefore, an adjustment of 11 hours was applied for travel time due to the location of the Ouse and Wharfe gauges which are located approximately 22 km and 18 km upstream of the model boundary.
- EA Spurn tidal data was lowered by 0.3m, based on the average offset between the ABP and EA gauges for previous calibration events.

Table N.1: Stations providing model boundaries for calibration

Stn. No	River	Stn. Name	Gauge Type	NGR
27009	Ouse	Skelton	Flow and Level	456845, 455373
27089	Wharfe	Tadcaster	Flow and Level	447709, 444121
27003	Aire	Beal	Flow and Level	453040, 425471
27021	Don	Doncaster	Flow and Level	456977, 403973
28022	Trent	North Muskham	Flow and Level	480435, 360565
L3370	Humber	Spurn (EA) (1)	Level	539856, 410943

(1) The Spurn data was supplied with the following comment "*Marked suspect as large correction could not be made on 27 Nov and PTX replaced at end of period - trace compares well however*"

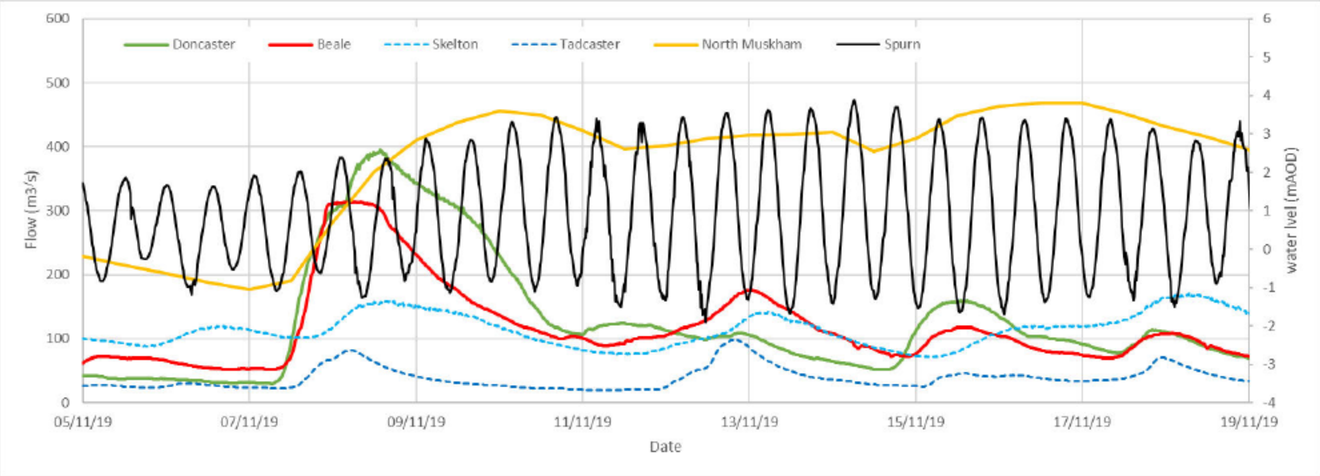


Figure N.2: November 2019 flow and level boundaries

N.3 Model updates

It was found that adjustments to channel roughness and bridge calibration coefficients were required to improve the model calibration at Fishlake. The changes to bridge coefficients were required to reduce the bridge afflux which allows more flow reach Fishake and increase levels. The model bank/defence elevations were checked against survey/LiDAR and found to be acceptable and not changed for the calibration.

The changes to the model are summarised in Figure N.3, changes were only applied to the River Don.

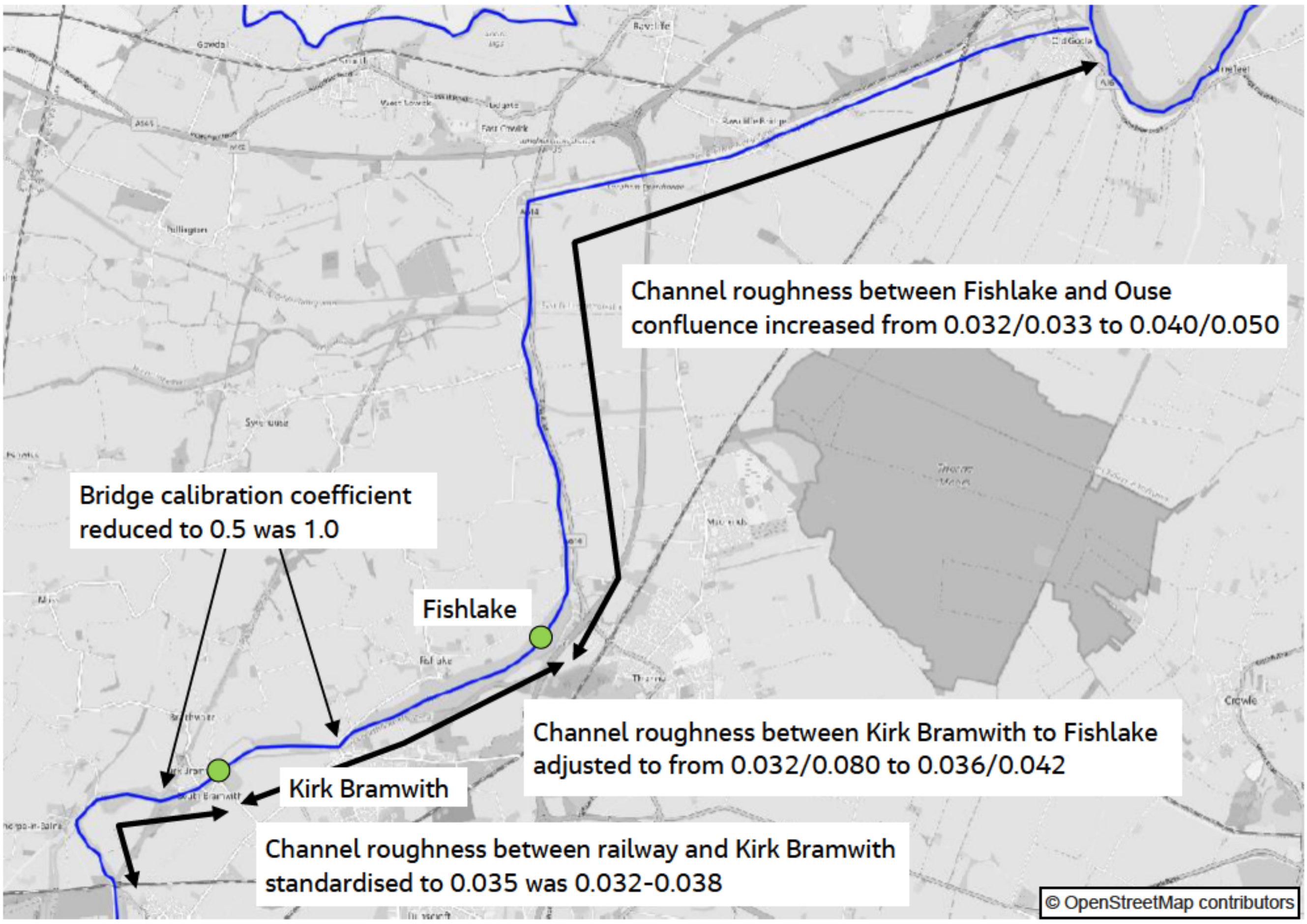


Figure N.3: Model Updates

N.4 Results

Comparison of the recorded and modelled maximum water levels are detailed in Table N.2. The updated model predicted maximum water levels to be within -0.07m of the recorded maximum at Fishlake (initial model was predicting a -0.30m difference). Peak water levels also increased at Kirk Bramwith by 0.11m, however, they are still within the +/-0.15m specified calibration accuracy (initial model was -0.5m lower, now +0.6m higher than recorded). The updates were shown to have a negligible impact at Doncaster gauge.

Time series comparison of the modelled and recorded water levels are detailed in Figure N.4 (Fishlake), Figure N.5 (Kirk Bramwith) and Figure N.6 (Doncaster).

Figure N.7 details the comparison at Immingham gauge, which was checked due to the uncertainty with the EA Spurn data. Using the 0.3m spurn offset the model was showing good agreement up until the 9th November after which the model over predicted the recorded data at Immingham. Noting, that the Spurn data was marked as suspect, a sensitivity test was undertaken by lowering the Spurn data a further 0.5m (total 0.8m), so the model would show good agreement at Immingham after the 9th November.

The sensitivity test showed that the water levels at Fishlake are not significantly impacted by the downstream boundary. Lowering the boundary by 0.5m, the model predicted a 0.01m difference for the peak level at Fishlake.

Table N.2: November 2019 calibration results

Gauge	Maximum Water Level (mAOD) and Difference to Recorded (m)			
	Recorded level	Initial model	Updated model	Sensitivity Test
Fishlake	**6.87**	6.57 (-0.30)	6.80 (-0.07)	6.79 (-0.08)
Kirk Bramwith	7.58	7.53 (-0.05)	7.64 (+0.06)	7.64 (+0.06)
Doncaster	10.74	10.69 (-0.05)	10.69 (-0.05)	10.69 (-0.05)

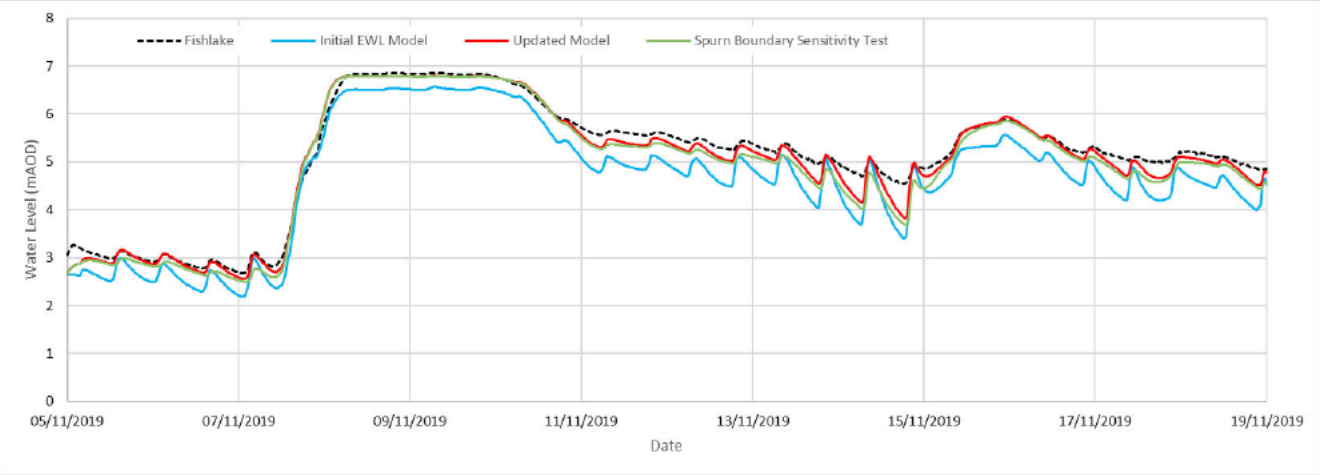


Figure N.4: November 2019 calibration: Fishlake

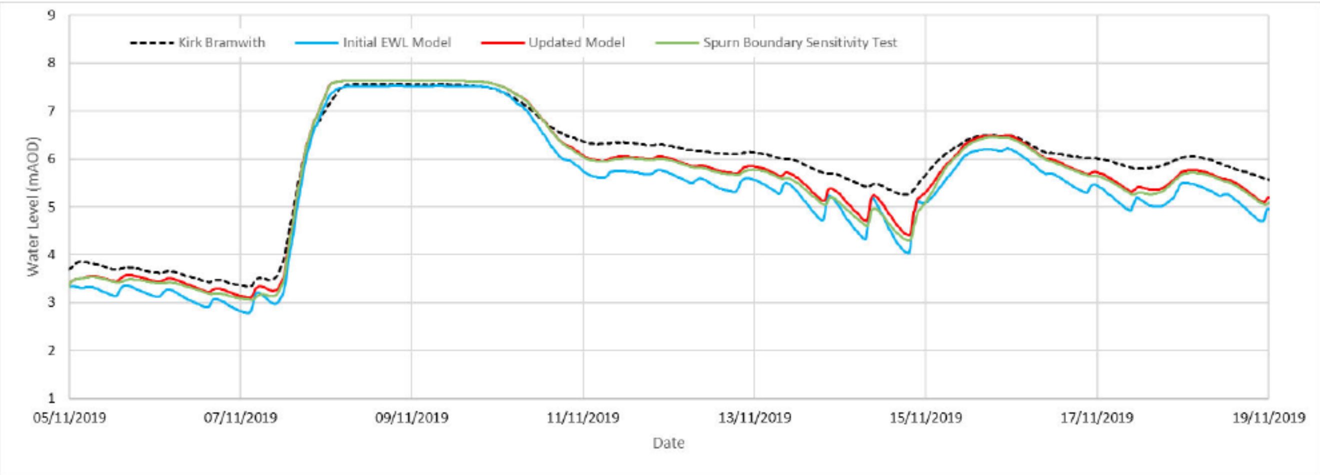


Figure N.5: November 2019 calibration: Kirk Bramwith

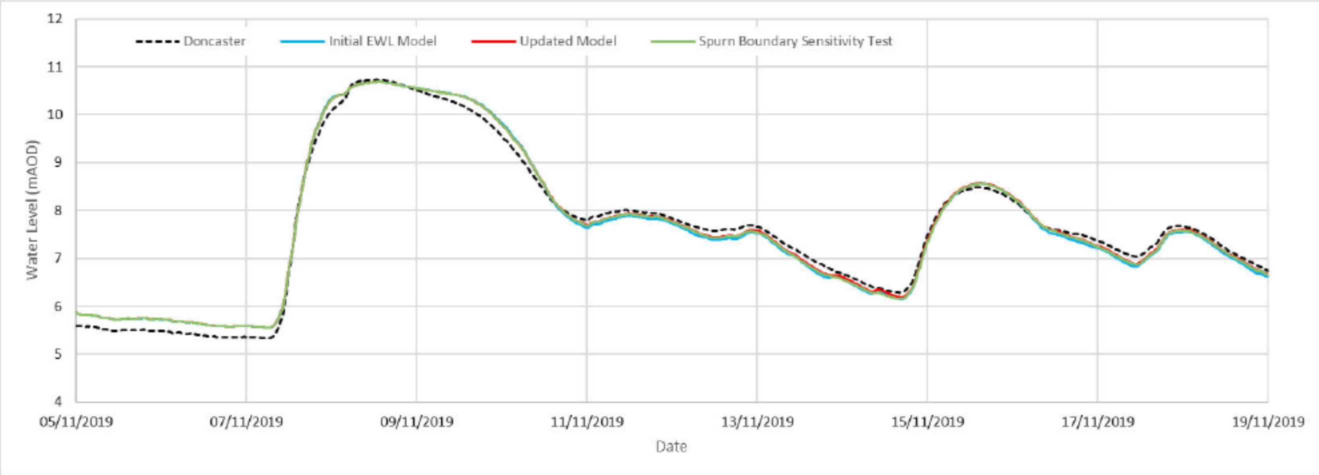


Figure N.6: November 2019 calibration: Doncaster

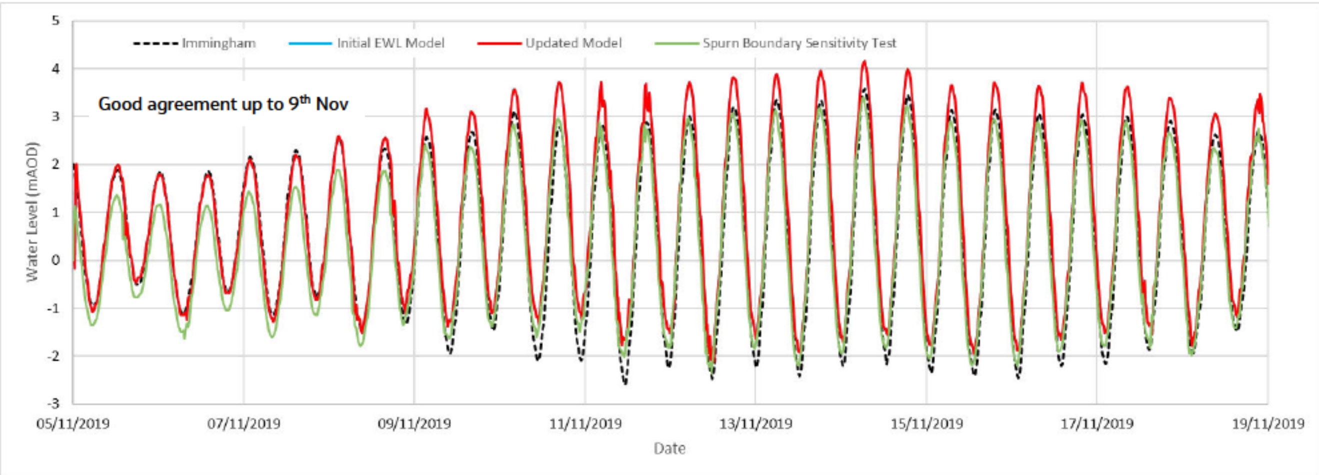


Figure N.7: November 2019 calibration: Immingham