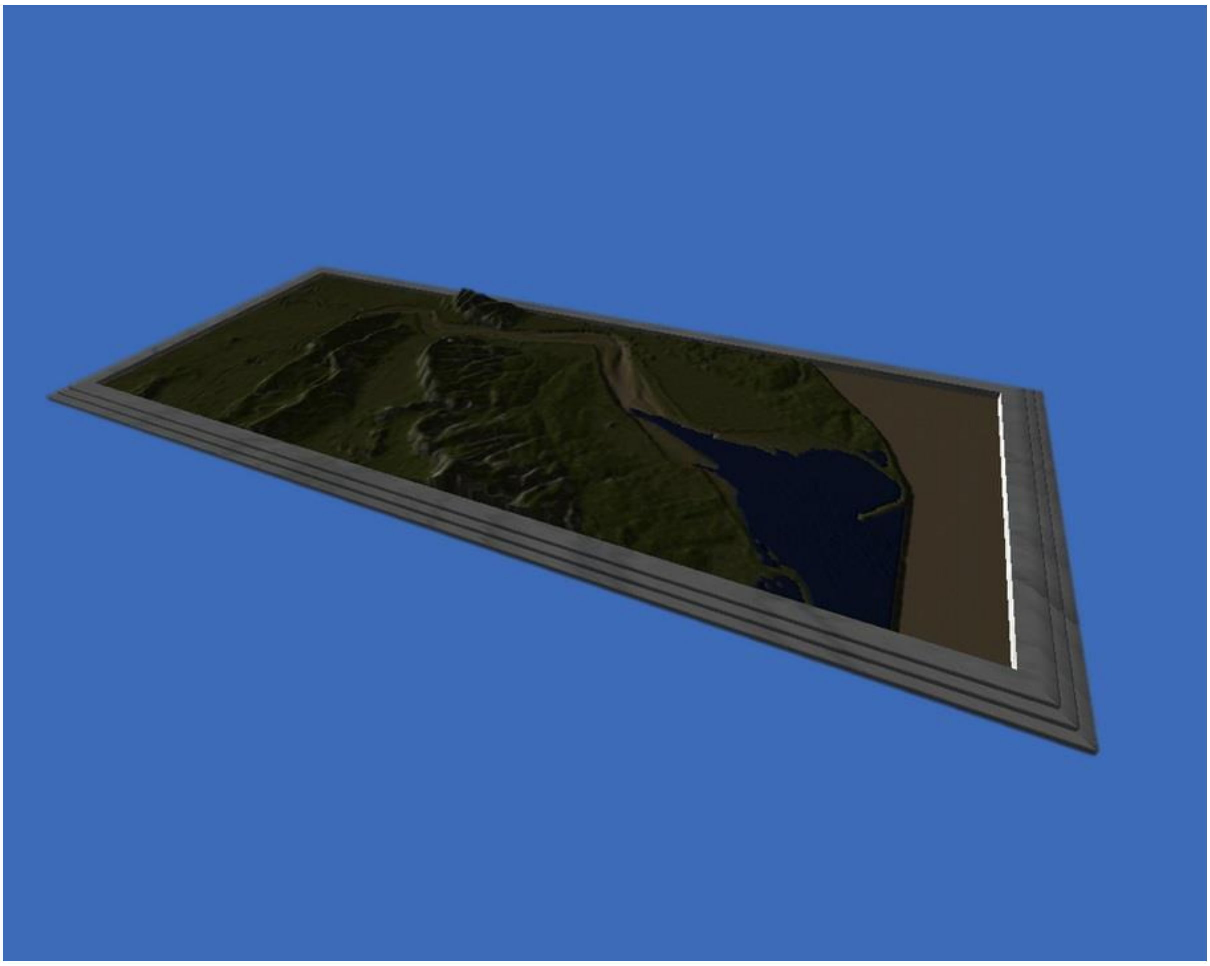
Work Package 3.5 - Design measures for flood risk management in the Humber



Dr Chris Skinner, Dr Lisa Harrison and Dr Robert E Thomas

Energy and Environment Institute, University of Hull

Interreg North Sea Region IMMERSE
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1 Introduction

The IMplementing MEasuREs for Sustainable Estuaries (IMMERSE) project focuses on international cooperation to address the challenges and threats faced by North Sea estuaries. To address these pressures, a three-step approach is used:

1. pressures are investigated and potential solutions, or measures, are explored;
2. measures are assessed, tested, and recommendations are provided; and
3. preparations are made to implement measures.

Not all individual measures will pass through all three steps during the lifetime of the IMMERSE project, because measure development and implementation is a long-term process, and because some partners are not legally mandated to implement measures.

The IMMERSE project consists of seven work packages:

- WP1. Project management
- WP2. Communication activities
- WP3. Measures: Defining pressures and solutions
- WP4. Measures: Assessments, tests and pilots
- WP5. Measures: Preparing for implementation
- WP6. Horizontal: Stakeholder integration
- WP7. Horizontal: Transnationality

This report is part of the different actions foreseen in Work Package 3. Measures: Defining pressures and solutions and presents the results of activity 3.5 - Design measures for flood risk management while maintaining/enhancing environmental protection measures in the Humber. The aim of this work package is to describe a series of conceptual flood protection measures for the Humber and assess them in terms of their flood risk benefits. Raw data is available in a shared cloud storage drive and can be made available on request.

1.1 The Humber

The Humber estuary drains one fifth of England (24,472 km^2), and provides the largest single input of freshwater to the North Sea from the English coastline. It is home to 500,000 people, 120,000 ha of agricultural land, and industries worth over £17.5bn GVA. These include the second largest chemical cluster in the UK, two of the country's six oil refineries, and five power stations. More than 25% of the UK's primary energy supply flows through the region, and its ports handle 14% of UK trade. However, the low-lying nature of the floodplains surrounding the Humber (Fig. 1) mean that the region is at severe risk of flooding during storm surges, which is expected to be exacerbated by forecast sea level rise of 0.26 – 1.45 m by 2100.

The wide, shallow, macrotidal estuary (Fig. 1.1) provides extensive wildlife habitat in its large intertidal zones and salt marshes and is thus of ecological importance for a number of habitats and species. The entire Estuary and parts of the tidal river tributaries have therefore been given a number of nature conservation designations under UK, European, and international law: it is a Natura 2000 site, designated as a Special Area of Conservation (SAC), a Special Protection Area (SPA), and a Ramsar site, together forming the Humber Estuary European Marine Site.

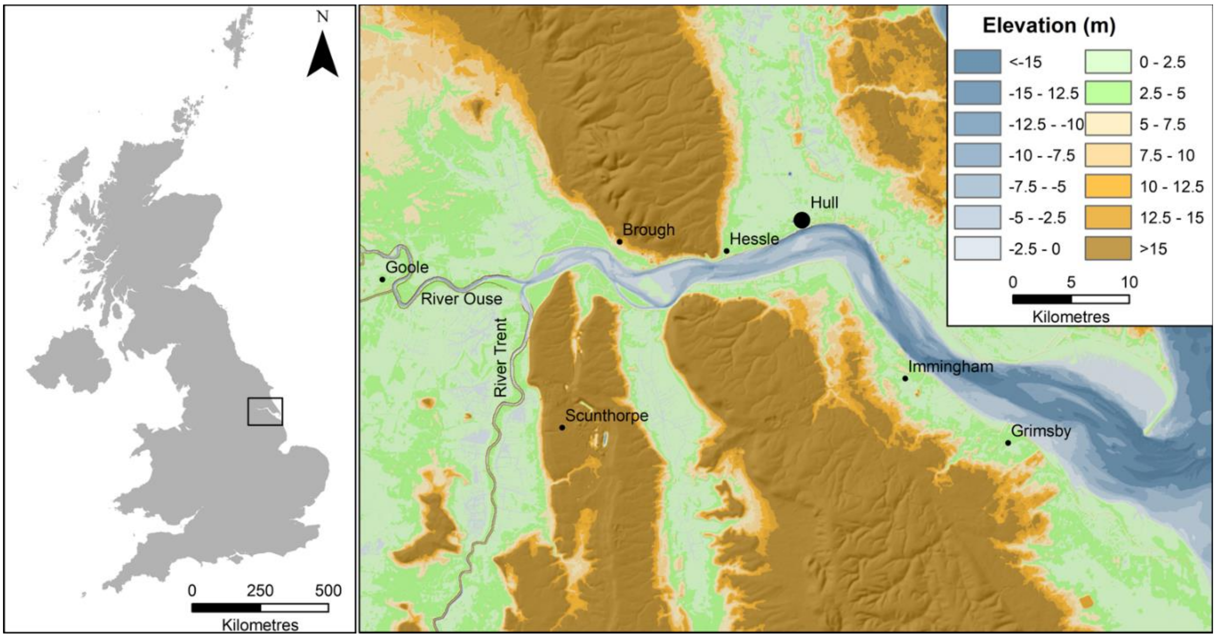

Figure 1.1 Map of the Humber estuary, indicating the position of the Humber within the UK (inset) and the bathymetric and topographic characteristics of the estuary and surrounding region. Note the extensive areas of land with elevation <2.5m above mean sea level.

Flood risk management in the Humber needs to be designed and implemented to provide cost effective, longer-term resilience to flooding without compromising ecosystems and causing damage to natural habitats along the estuary. A satisfactory solution requires co-development with estuary stakeholders. The University of Hull (UoH) has engaged with the Environment Agency, 12 local authorities and key stakeholders including Associated British Ports (ABP), Natural England and Internal Drainage Boards- to develop the Humber 2100+ flood risk strategy that aims to simultaneously address tidal flood risk while reinforcing the long-term ambition for a prosperous Humber, which is a safe and sustainable place to live, work and visit.

2 Methodology: The CAESAR-Lisflood model and set-up

This report adopts a numerical modelling methodology to assess a range of conceptual flood alleviation measures for the Humber in terms of their flood risk benefits. The numerical model employed for this purpose was CAESAR-Lisflood v1.92, a reduced complexity, cellular automata, Landscape Evolution Model (LEM). It was conceived and developed to simulate long-term (>100 years), large-scale, landscape change in response to processes such as climate and tectonics. Since its initial formulation, it has been extensively developed in order to exploit incremental improvements in both the numerical efficiency of the code, and the computational resource available.

Although the full CAESAR-Lisflood model includes options to simulate geomorphic and sediment transport processes, this functionality was not utilised for this work and the model effectively performs as the Lisflood-FP hydrodynamic model (Bates *et al*, 2010). For a full description of the CAESAR-Lisflood model, please refer to Coulthard *et al* (2013). CAESAR-Lisflood has been applied successfully to the simulation of tidal, estuarine and storm surge dynamics previously (Skinner *et al*, 2015; Ramirez *et al*, 2016). The advantages of CAESAR-Lisflood for strategic modelling of a large number of potential flood alleviation measures include its computational efficiency, its ability to rapidly simulate multiple scenarios, and its ability to simulate the over-topping of flood defences on to floodplains.

2.1 Model inputs

As inputs, CAESAR-Lisflood requires a spatial map of topographic or bathymetric values, a spatial map of roughness values and inlet and outlet boundary conditions, in the form of stages and/or discharges and stages, respectively.

2.2 Model domain

Figure 2.1 shows a hillshade of the full modelling domain. This will be henceforth referred to as the 'extended domain', with 'model domain' referring to a smaller area covering the extent of the available bathymetric and defence crest level data. The inland limits of the model domain along the fluvial inputs is indicated by the red dots in Figure 2.1. Changes to water levels and flood volumes are only considered within the model domain, or where overtopping has occurred in the model domain.

2.2.1 Topographic or bathymetric values

The base Digital Elevation Model (DEM) was constructed using multiple sources of data. These were:

- Bathymetry for the North Sea downloaded from DigiMap
- Bathymetry from 2010 bathymetric surveys provided by Associated British Ports (ABP)
- Bathymetry from 2016 bathymetric surveys provided by the Environment Agency
- LiDAR 1 m Surface Composite product downloaded from data.gov.uk
- OS5 Topography data downloaded from DigiMap

All data was resampled separately and converted into point clouds with a 50 m resolution. The LiDAR data was resampled based on the minimum elevation within each 50 m pixel. In order to merge datasets, the boundary between the bathymetric and topographic surfaces was distinguished manually using a hillshade of the LiDAR 1 m composite and marking the water level in the data. Bathymetric data were then retained based on subjective judgement of their quality: the 2016 survey was given priority, then the 2010 survey, and finally the North Sea data. Similarly, topographic data were retained based on subjective judgement of their quality: LiDAR data was given priority followed by the OS5 topography data. A final point cloud was constructed utilising points from all data sources, defined by the two zones and the priorities, so that there were no overlapping points. This final point cloud was interpolated using the Topo-to-Raster tool of ArcGIS 9.3, with hydro enforce enabled.

2.2.2 Adding defences

Surveys of crest levels for the Humber's defences were provided by the Environment Agency, reflecting the conditions during the 5th December 2013 storm surge. These were provided as, or processed into, polyline data. The polyline file was converted into a 50 m raster file by using the maximum elevation within each 50 m pixel. The base DEM (as described in 2.2.1) was merged with the resulting flood defence raster, selecting the highest elevation for each pixel. Owing to resolution issues or the absence of defence crest levels, three areas were manually added:

- The breach in the Alkborough Managed Realignment site
- Defences east of the River Ancholme
- Sand banks at Humberston Fitties

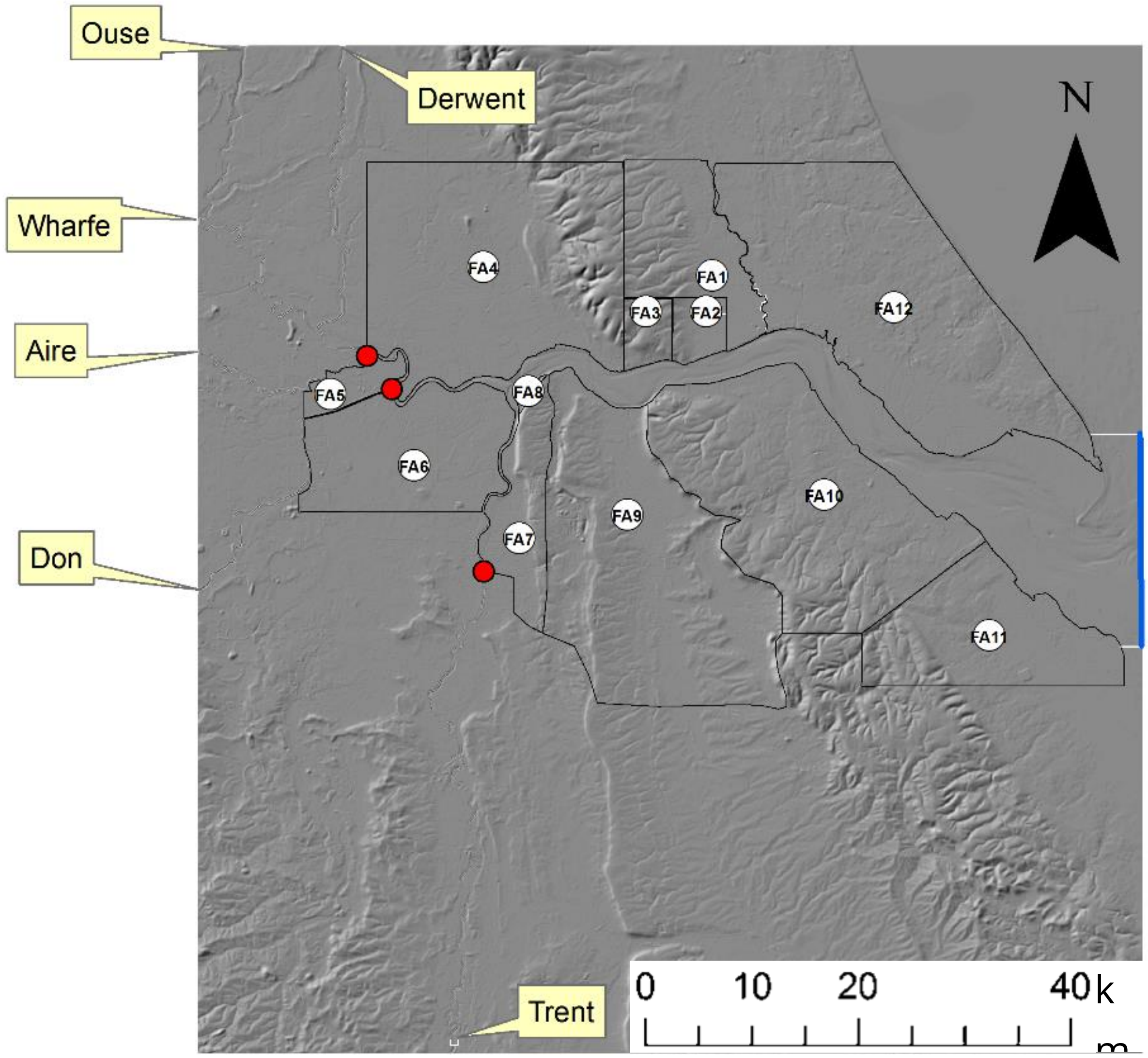

Figure 2.1 – The extended model domain, showing the limits of the model domain (red dots), the location of the tidal/stage mode input (blue line), and the locations of the reach model fluvial inputs (call out boxes, labelled with fluvial input). The zones of the Flood Action Areas (FA) are shown. Background imagery is a hillshade of the 2013 DEM with original bathymetry at 50 m grid cell size.

Since 2013, numerous sites have had defences improved. Data for these changes were provided by the Environment Agency in 2016, and have been incorporated manually into a separate DEM to represent present-day conditions.

2.2.3 Incorporating the location of fluvial inputs

There are several fluvial inputs into the Humber, with the most prominent being the Rivers Ouse and Trent. A representation of these inputs to beyond the influence of tides is important to reduce the boundary conditions related to the fluvial inputs and tidal storage. However, bathymetry and defence crest level data are currently not available for these areas. The fluvial inputs not covered by the extent of the 2016 bathymetric survey were therefore incorporated manually into the DEM. All channels were edited to be 1 pixel (50 m) wide, to an elevation of −3 m, and the pixels representing the banks edited to an elevation of 10 m to produce 'glass walls'. These are not intended to be accurate, but rather to deliver fluvial flows to the model domain and to allow tidal flows to propagate upstream.

2.2.4 The Adapted Model

During the modelling it was clear that due to the coarse resolution being used, the bathymetry landward of the confluence of the Rivers Ouse and Trent, known as Trent Falls, was not represented in sufficient detail, and this was inhibiting the tidal flows to Goole – this was evident in the simulated water levels and high error at Goole. To overcome this, the DEM was modified to create a 3-4 pixel wide, 6.5 m deep channel for the River Ouse landward of Trent Falls.

2.2.5 Flood Action and Draft Flood Areas

The Environment Agency defined 12 hydraulic-based Flood Action Areas, and the model domain was sub-divided into zones based on these (Figure 2.1). These were used to calculate changes in flood volumes around the Estuary. In order to avoid spill over between areas, zones of 'no data' (elevation = −9999) were applied between FA1 and FA2, FA1 and FA12, and FA3 and FA4. In order to extend the model domain to cover the Draft Flood Areas shown in Figure 2.2, fluvial defences were updated by replacing the default 'glass walled' elevations with surveyed crest levels. The bathymetry in these areas was not updated, and results in this extended zone should be considered less reliable than those within the estuary area.

2.3 Hydraulic boundary conditions

The hydraulic boundary conditions were prescribed using both tidal/stage mode and reach mode inputs. The tidal/stage mode input was the 28-day time series "designed flood curve" with a 10-minute timestep. Mean sea levels were estimated using mean 2014 stages for Spurn Point adjusted for sea level rise between 2014 and 2021 and supplemented with sea level rise values of +0.5 m, +1.0 m and +2 m. The 1-, 200- and 1000-year return period storm surge events were derived using the methodology set out in Environment Agency (2011). This used the donor surge shape for Immingham and high water of 5th December 2013 18:50 as the centre point for the applied surge shape since the astronomical high water for that tide was between Mean High Water (Springs) and Highest Astronomical Tide as per Environment Agency (2011). Note that not all sea level rise scenarios were simulated for all measures, since it was observed that some measures had minimal impact on resulting estuarine water levels. Tidal/stage mode inputs were applied to a one-pixel wide line of cells across the eastern edge of the model domain. Reach mode inputs were applied as discharge values (m^3s^{-1}) emerging from a set pixel. The model has six reach mode inputs introducing the mean annual discharges of the Ouse, Trent, Derwent, Wharfe, Aire and Don. Discharges were added to the model at the edge of the extended model domain at the locations labelled in Figure 2.1.

2.4 Roughness values

The model was run using a global value of Manning's n roughness of 0.015 s $m^{-1/3}$, as suggested by McCutcheon et al. (1990) for wide, deep, channelled estuaries with a high level of sediment transport and high turbidity and determined for the Humber by Skinner et al. (2015). This value is unusually low and was justified by McCutcheon et al. (1990) and King and Wolanski (1996) through the influence of very high sediment concentrations held in a turbulent area just above the estuary bed as a basal liquid mud layer, which acts to significantly reduce the friction between the flow and the bed. Nevertheless, Manning's n roughness values for vegetated or urbanised overbank areas are normally 4-5 times larger than this (e.g., Chow, 1959), which therefore may result in overestimation overbank velocities and floodplain inundation extents.

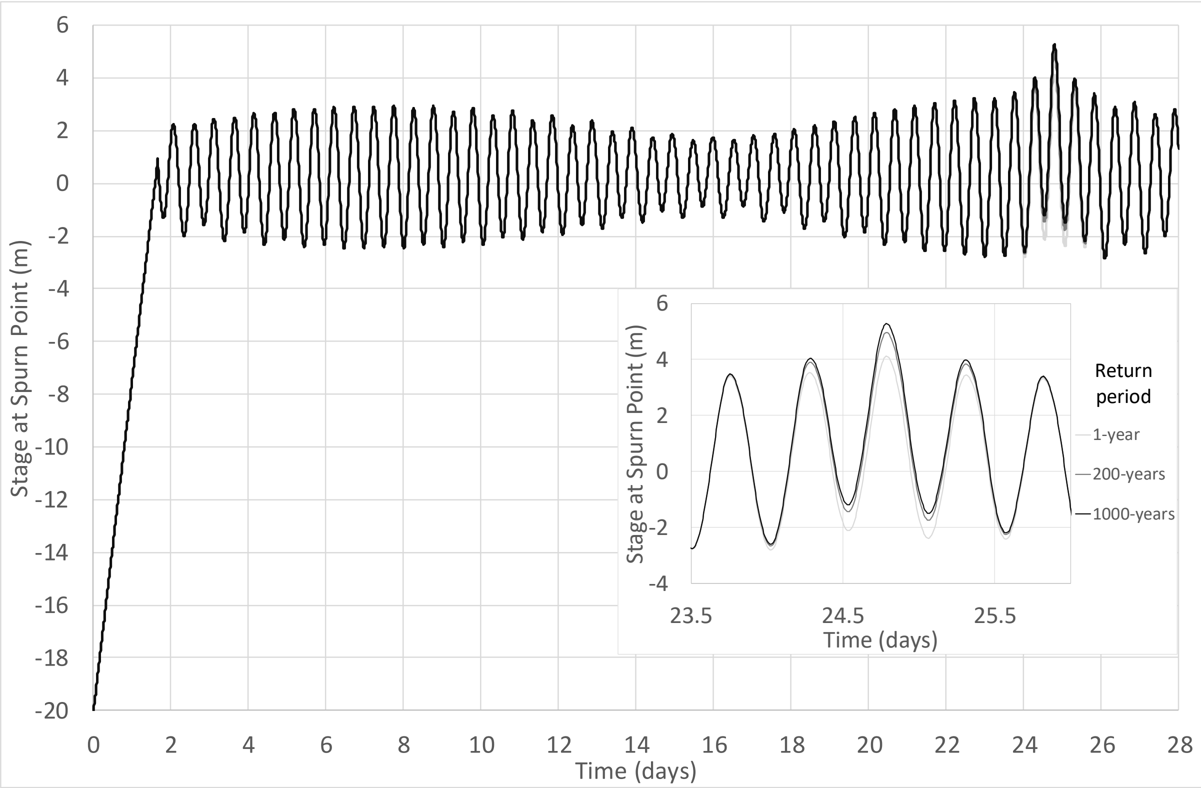

Figure 2.2 – Stage applied at the seaward boundary of the model. The first 40 hours of simulations linearly increase from a depth of zero to the estimated 28-day "designed flood curve". Inset shows a zoomed in region of the time series graph between days 23.5 and 26 of the time series. The peak of the storm surge occurs at 18:50 on day 24.

2.5 Model validation

The CAESAR-Lisflood model for the Humber Estuary was developed and rigorously tested to ascertain its suitability. The validation exercise is reported by Skinner et al. (2015). Errors were within the thresholds defined by the Foundation for Water Research (1993), which suggested that an operational model for estuarine environments should have an error of no more than 0.1 m at its mouth, and 0.3 m at its head.

2.6 Recorded Outputs

The model was set up to output the following information:

- Flood Area in each of the 33 HSRC Draft Flood Areas (Figure 2.3) at each timestep
  These were recorded at 10-minute intervals, and the maxima from each record used for comparison. For simulations that included either a Managed Realignment or Flood Storage site, the footprint of the site was excluded from the flood area containing it.
- Maximum water depth for each pixel
- Maximum water level for each pixel
- Maximum flow velocity for each pixel (no direction)
- Stage levels at each timestep for the Associated British Ports gauge locations
- Stage levels at each timestep for Environment Agency gauge locations

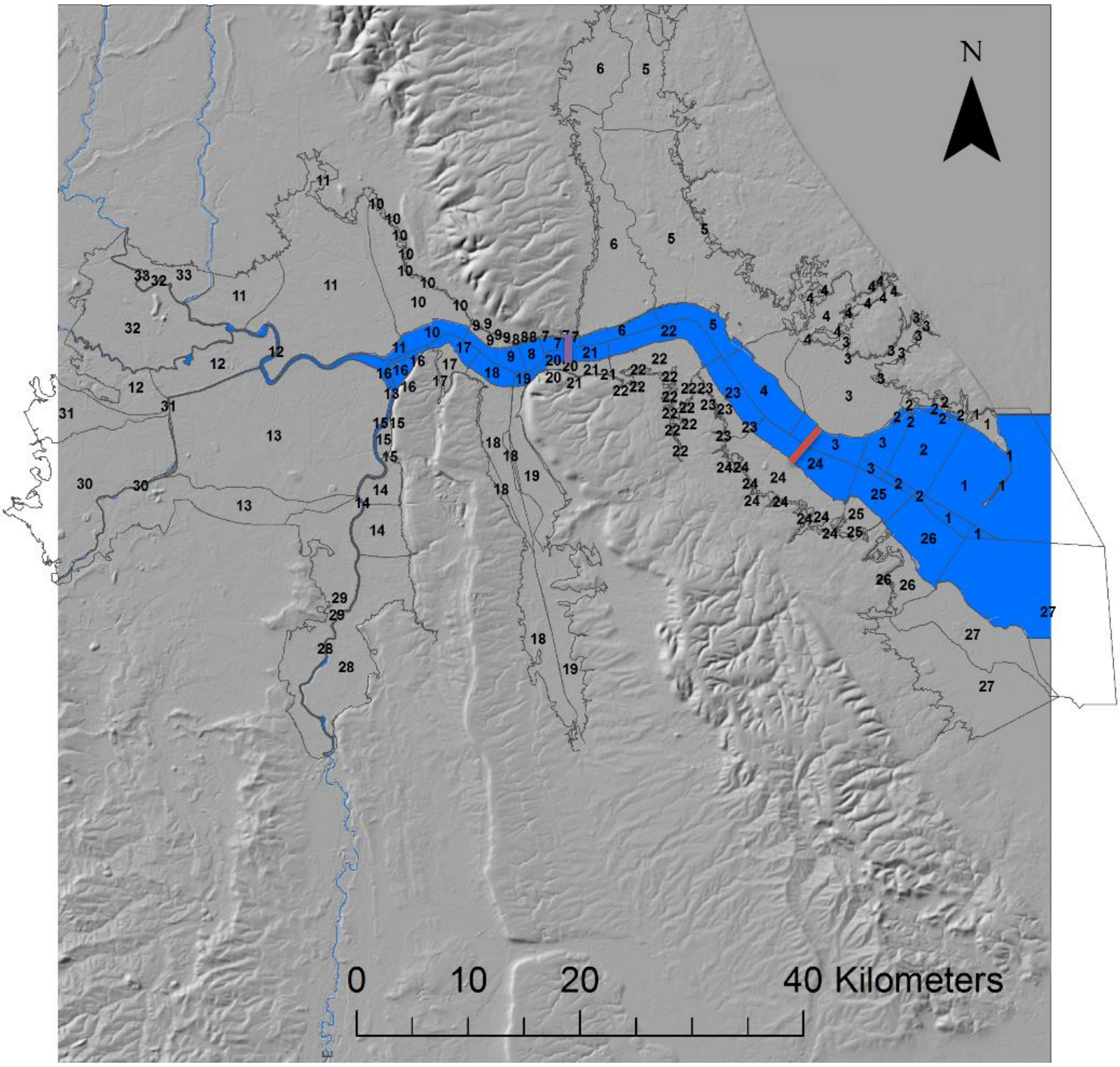

Figure 2.3 - Locations of the 33 HSCR Draft Flood Areas used for the calculation of flood volumes and flood areas. The yellow line indicates the approximate location of the Middle Estuary Barrier (Measures 31 and 32), and the orange line indicates the approximate location of the Sunk Island (outer estuary) Barrier (Measures 16, 16A and 33).

For each simulation, a flood inundation map was produced using the maximum water depth data; the flood extents shown are the areas that observed at least 0.01 m of flood depth during the simulation. To simplify spatial descriptions, the 33 HSCR Draft Flood Areas have been lumped into seven larger areas (Table 2.1). The flood alleviation strategies have been further grouped by measure type (Table 2.2): managed realignment (MR), hard defences, dredging, or compound, which includes any combination of measure types. Please note that the numbering convention of the different measures is as per the scoping document issued by the Environment Agency and is not necessarily sequential.

Table 2.1 - Grouping of the 33 HSRC Draft Flood Areas to simplify spatial descriptions

Area	Description	Zones
1	North Bank Outer	1,2,3,4
2	South Bank Outer	26,27
3	Hull	5,6,7
4	Grimsby	24,25
5	North Bank Inner	8,9,10
6	South Bank Inner	17,18,19,20,21,22,23
7	Ouse-Trent	11,12,13,14,15,28,29,30,31,32,33

2.7 Socio-economic impacts

In order to quantify the socio-economic impacts of flooding associated with each measure and each flood scenario, it was necessary to cross-reference flood inundation maps against census datasets describing the distribution of the population, residential property prices and sales, business properties, employment and the total gross value added to the economy at the local scale. Within England, these datasets are managed by the Office for National Statistics (ONS). In addition, data detailing residential property types are managed by the Valuation Office Agency.

2.7.1 Datasets and pre-processing

The datasets used and the geographical level at which they are available are shown in Table 2.3. The lowest geographical level at which census estimates are released are termed Output Areas (ONS, 2012), but data at this level are not available for analysis owing to the risk of disclosing information that could identify an individual person, household or business (ONS, 2012). Therefore, census data were initially sought for Lower Layer Super Output Areas (LSOAs), the boundaries for which were last defined in 2011. LSOAs have the properties that they have a minimum population of 1,000 residents and a maximum population of 3,000 residents within a minimum number of 400 households and a maximum number of 1,200 households (means 1,614 and 672, respectively) (ONS, 2012). When the desired data was not available at the LSOA level, they were obtained at the next level of the output area hierarchy, the Middle Layer Super Output Area (MSOA). MSOAs have the properties that they have a minimum population of 5,000 residents and a maximum population of 15,000 residents within a minimum number of 2,000 households and a maximum number of 6,000 households (means 7,787 and 3,245, respectively) (ONS, 2012). Boundaries for both LSOAs and MSOAs were obtained from the ONS (2021a; 2021b), generalised to a spatial resolution of 20 m and clipped to the mean high water mark.

At the LSOA level, population data categorised by gender and split into 5-yearly classes (i.e., 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75-79, 80-84, 85+) were available, but for the purpose of the present analysis, only the total resident population was considered. In addition, the number of people under employment by businesses within a LSOA, categorised into 18 employment sectors and rounded to the nearest 5 people, was available but again for the purpose of the present analysis, only the total number of people under employment was considered. Quantifying the value of residential properties within each LSOA required additional analysis since although the total number of properties categorised by property type (Bungalow, Flat/Maisonette, Terraced, Semi-Detached, Detached, Annexe, Other, UNKNOWN) was available and the mean price paid for all residential properties was available, the latter was not categorised by property type. Thus, there was a risk that estimates of the total value of residential properties in each LSOA could be biased if it was assumed that they were all worth the mean price paid. However, at MSOA level, the mean price paid was available for the Flat/Maisonette, Terraced, Semi-Detached, and Detached property types. For the present analysis, it was therefore assumed that Bungalows could be considered Detached and properties categorised as Annexe, Other, or UNKNOWN were assigned a value of zero. In order to estimate the total residential property value within each LSOA:

1. the ratios of the mean price paid for each property type relative to the mean price paid for all properties within each MSOA were calculated for each of the 10 years between 2009 and 2018. Years for which there were no property sales in a category were disregarded;
2. the mean ratios for each MSOA were computed;
3. since LSOAs are constituent parts of MSOAs, the mean ratio for each property type for the MSOA within which each LSOA was located was multiplied by the mean price paid for all residential properties in the LSOA to estimate the mean value of each property type within each LSOA;
4. the resulting mean value of each property type was multiplied by the number of properties of each property type within each LSOA to obtain an estimate of the total value of properties in each property type category; and
5. the total value of properties in the four property type categories were summed.

Both the number of businesses, categorised into 18 employment sectors and rounded to the nearest 5 businesses, and the total Gross Value Added (GVA) by economic activities were available for each MSOA. It was therefore necessary to apportion these data to the LSOAs of which they are composed. This was done by assuming that both the number of businesses and the GVA are proportional to the total number of people under employment by businesses within a LSOA.

2.7.2 Analysis within ArcGIS

Both the flood inundation maps and the census datasets are by their nature spatial datasets. This necessitates their analysis within a Geographical Information System (GIS). First, the inundation maps were converted into binary wet/dry maps and then converted into vector polygons using the Raster to Polygon tool within ArcGIS 10.8. Second, fields containing the total population, total residential property value, number of businesses, number of people under employment and the total gross value added were added to the attribute table of the LSOA boundaries. Third, flood inundation maps of each measure and scenario generated by CAESAR-Lisflood were intersected with the boundaries of the LSOAs. While this was undertaken, values of total population, total residential property values, number of businesses, number of people under employment and the total gross value added were scaled by the ratio of the area of each LSOA that was inundated by the total area of each LSOA. Fourth, the resulting intersected flood inundation-LSOA map was dissolved. While this was undertaken, values of total population, total residential property values, number of businesses, number of people under employment and the total gross value added within the inundated areas were summed, yielding an estimate of the total population, total residential property values, number of businesses, number of people under employment and the total gross value added directly impacted by flooding in each measure and scenario.

Table 2.2 - Description of modelled measures grouped by flood defence strategy type. The fluvial (landward) boundary condition was the long-term mean daily discharges for the Rivers Ouse and Trent.

Strategy Type	Measure number	Defence Description	Seaward boundary conditions: Event return period (years)	Seaward boundary conditions: Sea level rise (m)
Baseline	1	2021 Baseline	1, 200, 1000	0, 0.5, 1, 2
Managed Realignment	4	Managed Realignment at Keyingham and Goxhill	1, 200, 1000	0, 0.5, 1, 2
	6	Managed Realignment at Keyingham and Goxhill, plus raised defences in high priority areas to keep pace with sea level rise	1, 200, 1000	0, 0.5, 1, 2
	8	Managed Realignment at Keyingham, Goxhill and Winteringham Ings, plus raise all Estuary defences by 1 m	1, 200, 1000	0, 0.5, 1, 2
	9	Managed Realignment at Keyingham, Goxhill and Winteringham Ings, plus raise all Estuary defences by 2 m	1, 200, 1000	0, 0.5, 1, 2
	29	Managed Realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, and Cherry Cobb Sands	1, 200, 1000	0, 1, 2
	30	Managed Realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, Cherry Cobb Sands and Winteringham Ings	1, 200, 1000	0, 1, 2
	23	Managed Realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, Cherry Cobb Sands, Winteringham Ings and Goxhill	1, 200, 1000	0, 0.5, 1, 2
Hard defences	2	Degraded Defences	1, 200, 1000	0, 0.5, 1, 2
	31	Middle Estuary Barrier	1, 200, 1000	0
	32	Middle Estuary Barrier with seaward defences raised by 1 m	1, 200, 1000	0
	33	Sunk Island (Outer estuary) Barrier	1, 200, 1000	0, 1
	16	Sunk Island (Outer estuary) Barrier with seaward defences raised 1 m	1, 200, 1000	0, 0.5, 1, 2
	16a	Sunk Island (Outer estuary) Barrier with seaward defences raised 2 m	1, 200, 1000	0, 0.5, 1, 2
	20	Sunk Island Groyne	1, 200, 1000	0
	28	South Bank Peninsula	1, 200, 1000	0
Dredging	26	Dredging of the middle to inner estuary landward of the Humber Bridge	1, 200, 1000	0
	19	Estuary-wide dredging	1, 200, 1000	0

Table 2.2 (cont.) - Description of modelled measures grouped by flood defence strategy type. The fluvial (landward) boundary condition was the long-term mean daily discharges for the Rivers Ouse and Trent.

Strategy Type	Measure number	Defence Description	Seaward boundary conditions	
			Event return period (years)	Sea level rise (m)
Compound	12	Estuary defence levels raised to 2014 local 200-year return period water surface profile plus 1 m, plus Managed Realignment and Flood Storage sites	1, 200, 1000	0, 0.5, 1, 2
	13	Estuary defence levels raised to 2014 local 200-year return period water surface profile plus 2 m, plus Managed Realignment and Flood Storage sites	1, 200, 1000	0, 0.5, 1, 2
	14	2014 'Realistic' Measure, plus Estuary defences raised 1 m in line with post-2032 designation	1, 200, 1000	0, 0.5, 1, 2
	15	2014 'Realistic' Measure, plus Estuary defences raised 2 m in line with post-2032 designation	1, 200, 1000	0, 0.5, 1, 2
	17	Ouse and Trent (Inner estuary) Barriers, plus Keyingham and Goxhill Managed Realignment sites	1, 200, 1000	0, 0.5, 1, 2
	27	Ouse and Trent (Inner estuary) Barriers, raised downstream defences, plus Keyingham and Goxhill Managed Realignment sites	1, 200, 1000	0, 0.5, 1, 2
	18	Ouse and Trent (Inner estuary) Barriers, plus Keyingham and Goxhill Managed Realignment sites, and Broomfleet, Faxfleet and Adlingfleet Flood Storage sites	1, 200, 1000	0, 0.5, 1, 2
	34	Ouse and Trent (Inner estuary) Barriers operated for four hours, plus Keyingham and Goxhill Managed Realignment sites, and Broomfleet, Faxfleet and Adlingfleet Flood Storage sites	1, 200, 1000	0, 1, 2

Table 2.3 – Office for National Statistics and Valuation Office Agency datasets analysed as part of this work.

Data	Geographical level	Source
Population estimates - small area based by single year of age - England and Wales Mid-2018	LSOA	https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/lowersuperoutputareamidyearpopulationestimatesnationalstatistics
Business Register and Employment Survey 2018: open access (People under employment, including employees and directors, by sector)	LSOA	https://www.nomisweb.co.uk/query/construct/summary.asp?mode=construct&version=0&dataset=189
UK Business Counts - enterprises by industry and employment size band 2018	MSOA	https://www.nomisweb.co.uk/query/construct/summary.asp?mode=construct&version=0&dataset=142
UK small area GVA estimates 2018	MSOA	https://www.ons.gov.uk/economy/grossvalueaddedgva/datasets/uksmallareagvaestimates
Residential property sales by middle layer super output area: HPSSA dataset 1	MSOA	https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/hpssadataset1numberofresidentialpropertysalesbymsoaquarterlyrollingyear
Mean house prices by middle layer super output area: HPSSA dataset 3	MSOA	https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/hpssadataset3meanhousepricebymsoaquarterlyrollingyear
Mean house prices by lower layer super output area: HPSSA dataset 47	LSOA	https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/meanpricepaidbylowerlayersuperoutputareahpssadataset47
Property Type, LSOA (2014)	LSOA	http://ubdc.gla.ac.uk/dataset/property-type-lsoa

3 Model Simulations and Results

This section of the report will detail every measure simulated and the model results. Flood alleviation measures were broadly grouped based on flood defence types, such as managed realignment, hard defences, dredging, and compound (a mixture of different defence types) (Table 2.2). For better ease of comparison, results from each measure are compared to a Baseline (Measure 1, Section 3.1) to gauge their flood alleviation efficacy.

3.1 Measure 1 – 2021 Baseline

These simulations were intended to assess the performance of flood defences as they are in 2021. Results from these simulations will be used to assess the effectiveness of possible measures relative to the 'present day' situation.

The model set-up was as follows:

- Defences were uplifted to those expected by 2021, with defences as surveyed in 2017 plus planned schemes in the 6-year programme: Hull, Skeffling, South Ferriby, Paull Village, Immingham, and Able Logistics Park.
- The seaward boundary condition was set as the 28-day designed flood curve using the 2014 stages for Spurn Point with sea levels adjusted to forecast 2021 levels. Modelled scenarios were the 1-, 200- and 1000-year return period storm surge events, with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios.
- The landward boundary conditions were set as the long-term mean daily discharges for all fluvial inputs.

3.1.1 Results

The Baseline flood volumes for the 2021 defences vary from 0.07 × 10^6 m^3 to 2003 × 10^6 m^3 (Table 3.1). For the 1-year return period event, there is no flooding for present day sea levels, but defences are overtopped in the inner estuary, primarily the Ouse-Trent region for +0.5 m SLR. For +1 m and +2 m SLR, there is an increase in estuary-wide flooding, particularly in the South Bank Inner and Ouse-Trent regions, but the City of Hull experiences the least flooding (Figure 3.1). For a 200-year return period event, the only areas that escape flooding at present day sea levels are South Bank Outer and Grimsby, with a total mean flood volume of 8.5 × 10^6 m^3 that increases up to 1542 × 10^6 m^3 with +2 m SLR. The worst affected regions are South Bank Inner, Ouse-Trent and North Bank Outer (Figure 3.2). Hull is relatively well protected from the worst of the flooding up until +2 m SLR, where the flood volume reaches 203.5 × 10^6 m^3. A 1000-year return period event results in estuary wide flooding at present day sea levels apart from at Grimsby. Mean flood volumes increase from 37.38 × 10^6 m^3 at +0 m SLR up to 2003 × 10^6 m^3 with +2 m SLR. Hull has low flood volumes compared to the rest of the estuary regions for +0.5 m and +1 m SLR, but becomes inundated (346.7 × 10^6 m^3) with +2 m SLR and a 1000-year return period event (Figure 3.3). Locally, the worst hit areas are the Ouse-Trent region, South Bank Inner, and North Bank Outer, whereas North Bank Inner (and Hull and Grimsby for lower levels of sea level rise) floods significantly less. Table 3.2 shows stage levels for each event at various locations in the Humber Estuary. Mean stage levels increase from 4.63 m for a 1-year return period event at present day sea levels, up to 6.66 m for a 1000-year return period event with +2 m SLR. For present day sea levels, stage levels increase from the estuary mouth towards the inner estuary around Flixborough (also Brough and West Walker Dyke for the 1000-year return period event only). The location of the peak stage shifts from Flixborough to West Walker Dyke for the 1000-year return period event with +0.5 m SLR. For a +1 m SLR, the peak stage remains the same for the 1-year event but for the 200-year event, the peak stage moves towards Brough and the Humber Bridge, while the peak for the 1000-year event shifts again towards King George's Dock and Immingham. Finally, all peak stages shift for a +2 m SLR, with the peak for the 1-year event shifting to the Humber Bridge, and the peak for both 200- and 1000-year events shifting to Spurn Point.

Table 3.1 - Flood volumes by Area for Measure 1

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.81	53.89	0.18	6.45	32.19	234.84	2.74	22.85	68.51	349.19
South Bank Outer	0.00	0.00	0.01	38.17	0.00	1.46	21.87	165.58	0.19	11.70	53.21	215.30
Hull	0.00	0.00	0.01	5.98	0.01	0.28	2.54	203.49	0.04	1.38	9.87	346.66
Grimsby	0.00	0.00	0.00	86.70	0.00	0.02	18.49	163.27	0.00	0.90	60.52	199.76
North Bank Inner	0.00	0.22	2.47	45.64	1.17	6.30	13.39	68.29	3.94	10.47	19.49	79.25
South Bank Inner	0.00	0.06	8.93	257.46	3.28	33.67	111.96	362.08	18.71	75.88	176.11	403.00
Ouse-Trent	0.06	0.71	10.53	203.42	3.87	18.52	45.43	344.40	11.76	31.10	66.84	409.84
All	**0.07**	**0.99**	**22.76**	**691.25**	**8.50**	**66.70**	**245.87**	**1541.95**	**37.38**	**154.27**	**454.55**	**2002.99**

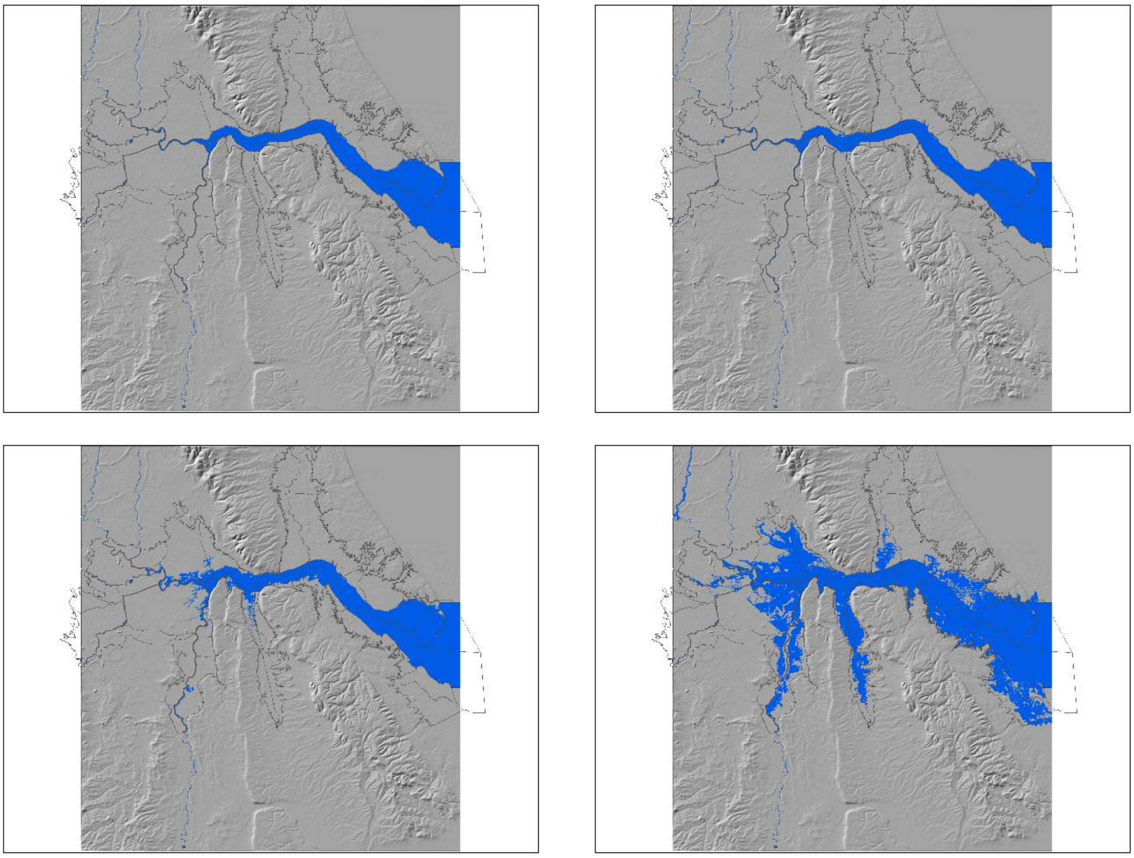

Figure 3.1 – Flood extents for Measure 1 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

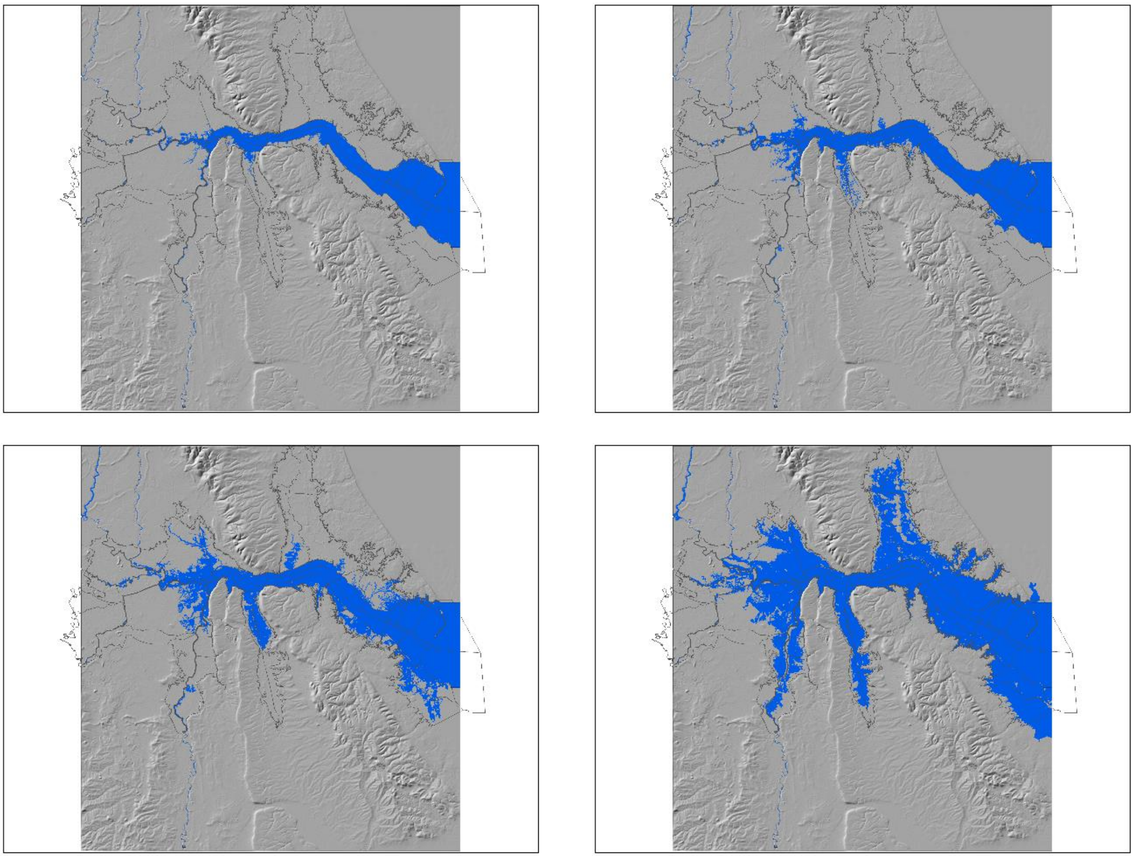

Figure 3.2 – Flood extents for Measure 1 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

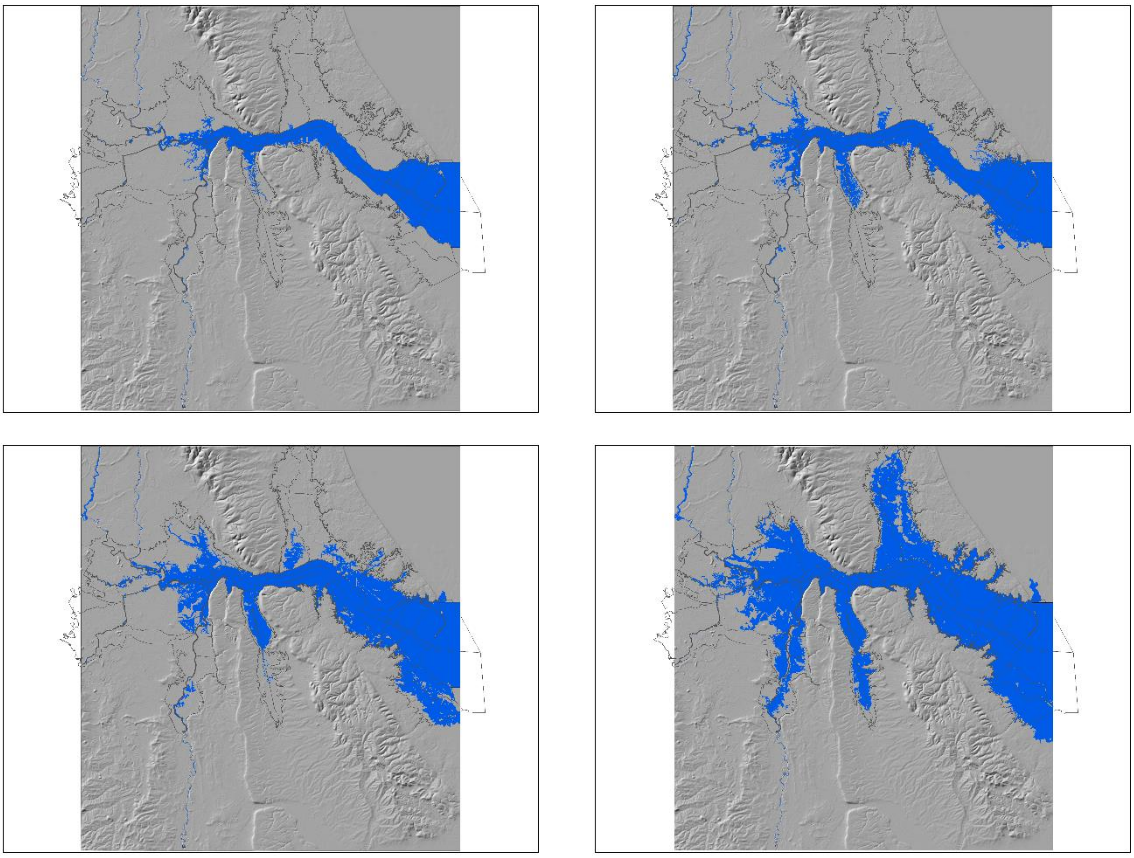

Figure 3.3 – Flood extents for Measure 1 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 3.2 – Maximum stages at tidal gauges throughout the Estuary for Measure 1.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.71	5.21	6.18	5.05	5.55	6.04	6.96	5.37	5.87	6.33	7.26
Grimsby	4.36	4.86	5.34	6.28	5.19	5.69	6.13	6.92	5.51	5.98	6.38	7.17
Immingham	4.50	5.00	5.48	6.33	5.33	5.81	6.22	6.91	5.64	6.09	6.42	7.12
Sunk Island	4.35	4.84	5.34	6.28	5.18	5.68	6.13	6.93	5.50	5.98	6.39	7.18
King George's Dock	4.63	5.15	5.64	6.36	5.48	5.94	6.28	6.92	5.78	6.17	6.42	7.09
Albert Dock	4.65	5.16	5.67	6.37	5.51	5.96	6.28	6.91	5.81	6.19	6.41	7.06
Humber Bridge	4.78	5.30	5.80	6.39	5.66	6.05	6.29	6.86	5.92	6.22	6.38	7.00
Brough	4.98	5.53	5.97	6.35	5.85	6.13	6.29	6.73	6.06	6.22	6.36	6.81
West Walker Dyke	5.10	5.64	5.99	6.31	5.91	6.10	6.27	6.58	6.06	6.23	6.32	6.64
Blacktoft Jetty	5.14	5.66	5.92	6.14	5.87	6.03	6.11	6.27	5.97	6.10	6.14	6.30
Flixborough	5.28	5.78	6.04	6.16	6.00	6.09	6.14	6.23	6.06	6.12	6.16	6.24
Goole	5.17	5.69	5.91	5.98	5.87	5.95	5.97	6.08	5.93	5.96	5.98	6.11
Ouse (upstream)	3.59	4.15	4.70	5.16	4.39	4.94	5.07	5.32	4.71	5.05	5.10	5.35
Trent (upstream)	4.12	4.63	5.09	5.78	4.79	5.23	5.62	5.84	5.03	5.46	5.77	5.84
Mean	**4.63**	**5.15**	**5.58**	**6.15**	**5.44**	**5.79**	**6.06**	**6.53**	**5.67**	**5.97**	**6.18**	**6.66**

Managed Realignment Measures

Managed Realignment has been used extensively in the Humber to compensate for habitat loss during development within saltmarshes and the estuarine floodplain. In practice, this means sacrificing land to flood by lowering or partially removing some defence lines and allowing water to enter and be stored in a specific area. The following seven measures model the impact of different managed realignment strategies on flood alleviation.

3.2 Measure 4 – Managed Realignment at Keyingham and Goxhill

Flood defences were set as per the Baseline (as they will be in 2021) with additional Managed Realignment sites at Keyingham and Goxhill. Details of the implementation is shown in Figure 4.1.

The boundary conditions were as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

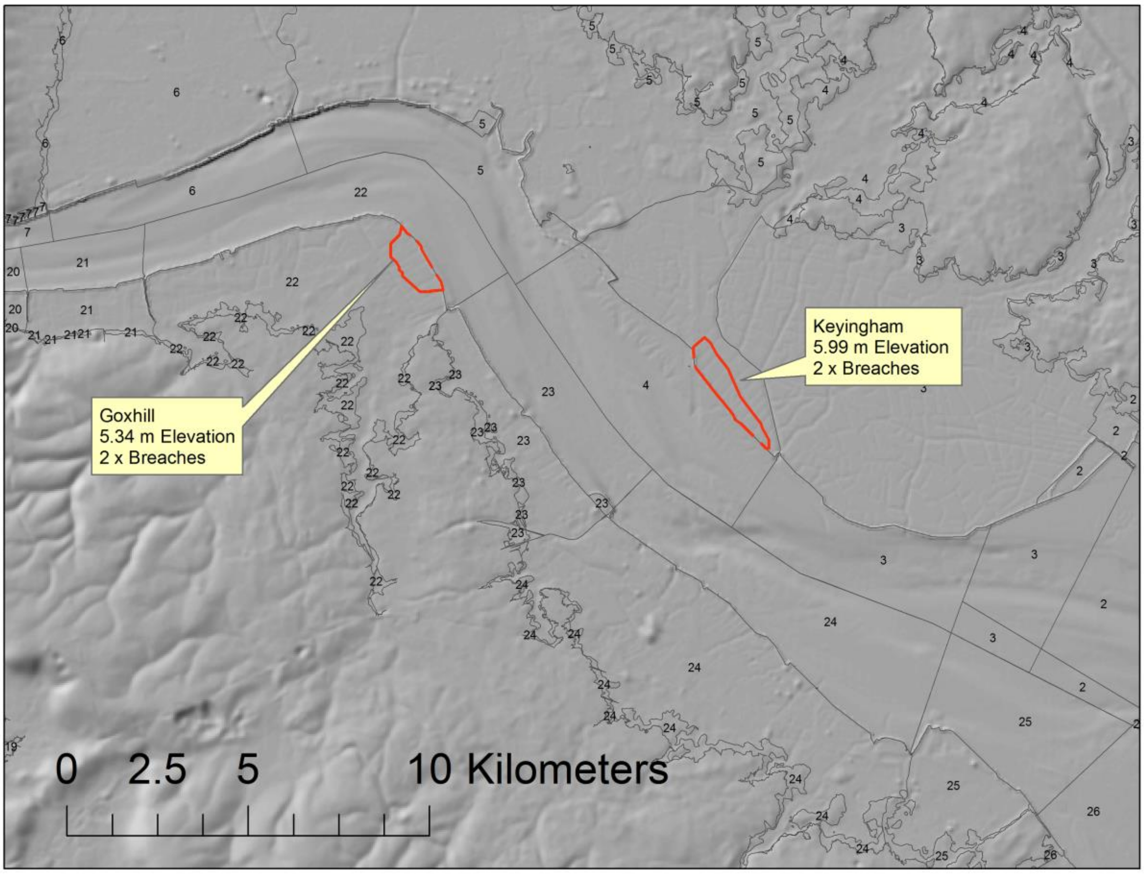

Figure 4.1 – Configuration of the Keyingham and Goxhill Managed Realignment sites (in red).

3.2.1 Results

In comparison to the Baseline, MR sites at Keyingham and Goxhill during a 1-year return period event did not reduce maximum flood volume at present-day sea level or +0.5 m SLR. For +1 m SLR, the mean estuary wide flood volume was reduced (most significantly at the south bank inner estuary by −0.55 × 10^6 m^3, Table 4.2). With +2 m SLR, MR resulted in an increase of mean flood volume by +2.62 × 10^6 m^3, but within this, flood volume was reduced locally at Grimsby and the south inner bank (−2.95 and −3.06 × 10^6 m^3, respectively) but increased significantly by +5.35 × 10^6 m^3 around the Ouse-Trent region (Figure 4.2).

For a 200-year event, MR reduced the present-day (i.e., +0 m SLR) mean flood volume (−0.29 × 10^6 m^3) but increased mean flood volume in comparison to the Baseline by +0.24, +3.83 and +14.67 × 10^6 m^3 for +0.5, 1 and 2 m SLR, respectively. The largest drop in volume locally relative to the Baseline occurred at the south bank inner estuary, while the largest increase to local volume for the SLR scenarios occurred in the mid estuary region around Grimsby and Hull (Figure 4.3).

MR slightly reduced the present-day 1000-year return period mean flood volume relative to the Baseline by −0.06 × 10^6 m^3 (mostly around the south bank inner estuary region). However, mean flood volumes were increased by +2.06, +3.79 and +14.41 × 10^6 m^3 for the +0.5, 1, and 2 m SLR scenarios, respectively (Figure 4.4).

Out of the 12 scenarios modelled, adding MR sites at Keyingham and Goxhill was only effective at reducing mean flood volumes in comparison to the Baseline for three scenarios (1-year +1 m SLR, 200-year +0 m SLR, and 1000-year +0 m SLR, Table 4.2). The two MR sites also had a negligible impact on stage heights throughout the estuary, shown by Tables 4.3 and 4.4.

Table 4.1 – Flood volumes by Area for Measure 4.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.80	55.62	0.17	6.47	33.28	240.94	2.74	23.18	71.29	355.13
South Bank Outer	0.00	0.00	0.01	38.21	0.00	1.46	21.89	165.55	0.19	11.74	53.20	215.26
Hull	0.00	0.00	0.01	6.73	0.01	0.31	2.59	212.65	0.05	1.43	11.23	356.54
Grimsby	0.00	0.00	0.00	83.75	0.00	0.02	20.97	162.65	0.00	1.81	60.88	199.38
North Bank Inner	0.00	0.23	2.55	46.40	1.21	6.44	13.50	68.90	4.06	10.55	19.79	79.80
South Bank Inner	0.00	0.06	8.39	254.40	2.81	33.38	111.68	357.89	18.22	76.22	173.99	398.10
Ouse-Trent	0.06	0.73	10.83	208.06	4.01	18.86	45.79	348.03	12.07	31.40	67.96	413.18
All	**0.07**	**1.02**	**22.58**	**693.16**	**8.21**	**66.94**	**249.70**	**1556.62**	**37.32**	**156.33**	**458.34**	**2017.40**

Table 4.2 – Change in Flood volumes by Area for Measure 4 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.01	1.73	-0.01	0.02	1.08	6.10	0.00	0.33	2.78	5.94
South Bank Outer	0.00	0.00	0.00	0.04	0.00	0.01	0.02	-0.03	0.00	0.04	-0.01	-0.04
Hull	0.00	0.00	0.00	0.75	0.00	0.03	0.06	9.16	0.01	0.05	1.37	9.88
Grimsby	0.00	0.00	0.00	-2.95	0.00	0.00	2.48	-0.62	0.00	0.91	0.37	-0.38
North Bank Inner	0.00	0.01	0.08	0.76	0.04	0.14	0.11	0.62	0.11	0.08	0.30	0.56
South Bank Inner	0.00	0.00	-0.55	-3.06	-0.47	-0.30	-0.28	-4.20	-0.49	0.34	-2.12	-4.89
Ouse-Trent	0.00	0.02	0.30	4.64	0.15	0.34	0.36	3.63	0.31	0.30	1.11	3.35
All	**0.00**	**0.03**	**-0.17**	**1.91**	**-0.29**	**0.24**	**3.83**	**14.67**	**-0.06**	**2.06**	**3.79**	**14.41**

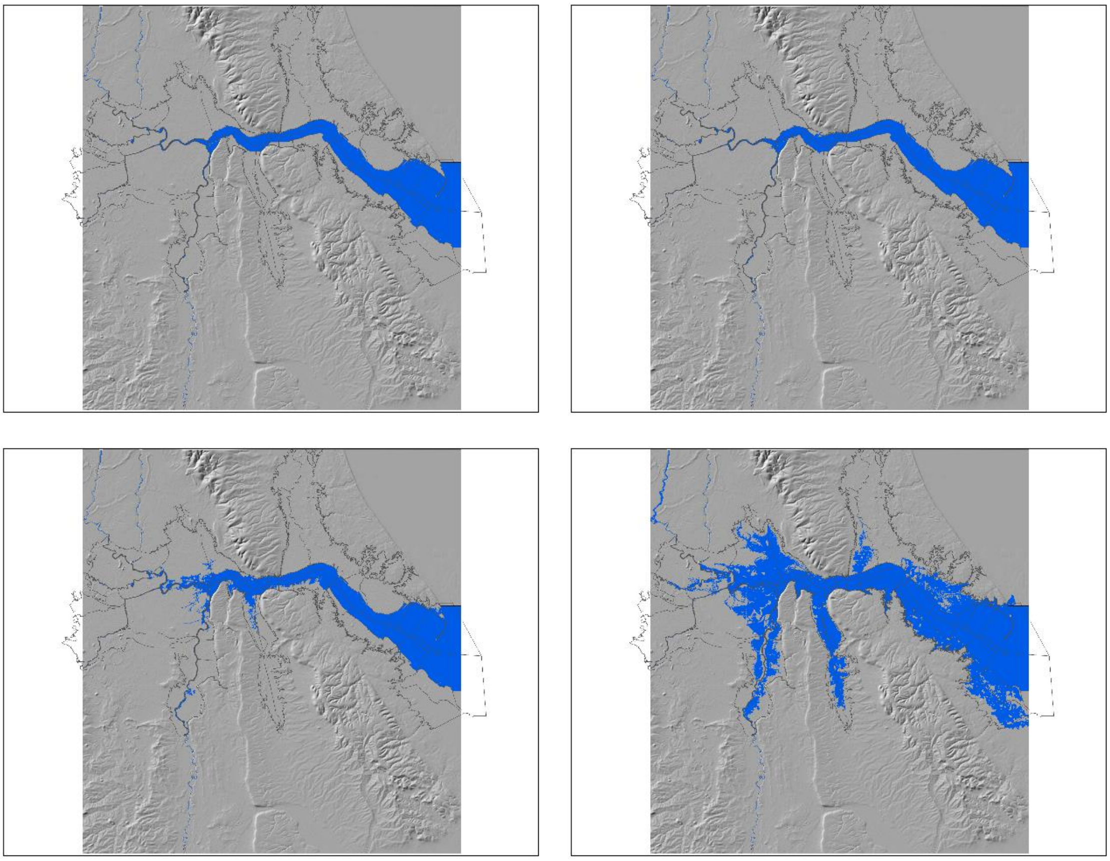

Figure 4.2 – Flood extents for Measure 4 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

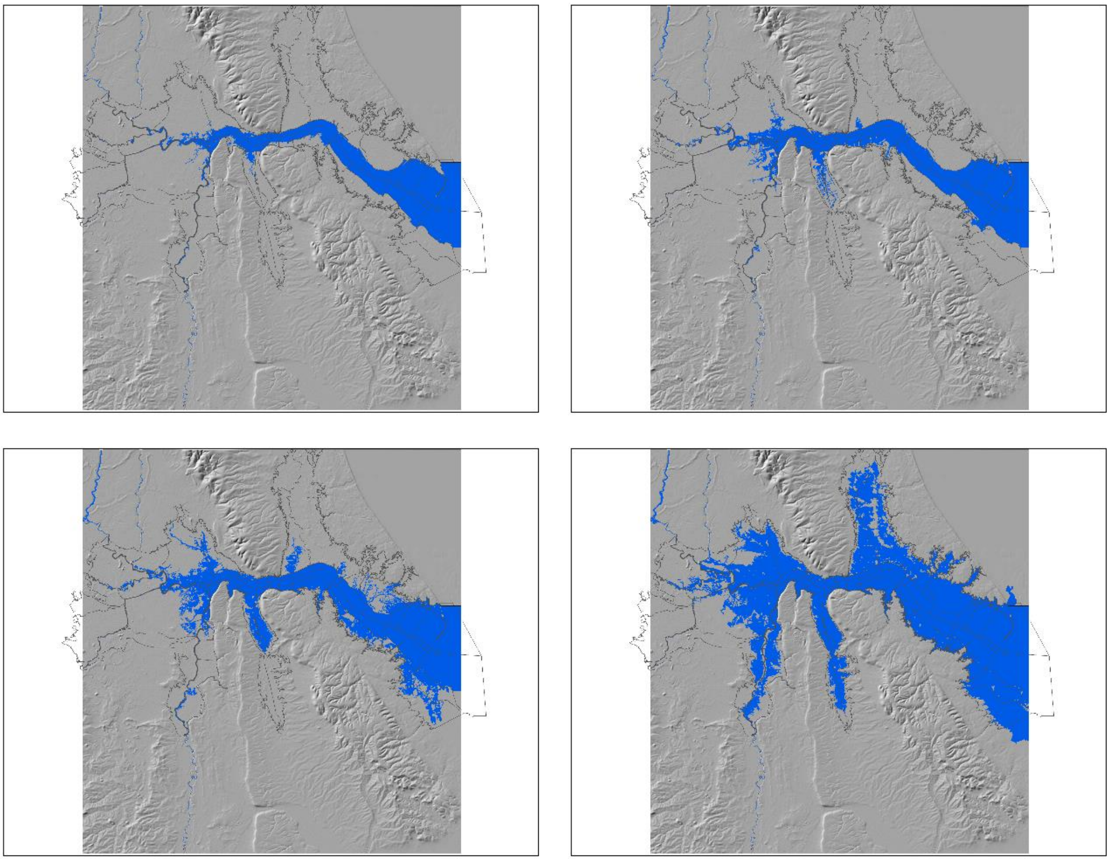

Figure 4.3 – Flood extents for Measure 4 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 4.3– Maximum stages at tidal gauges throughout the Estuary for Measure 4.

	Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	0	50	100	200	0	50	100	200	0	50	100	200
Spurn	4.20	4.70	5.20	6.19	5.05	5.55	6.04	6.96	5.37	5.87	6.33	7.26
Grimsby	4.35	4.85	5.34	6.29	5.19	5.69	6.14	6.92	5.51	5.99	6.39	7.17
Immingham	4.49	4.99	5.49	6.34	5.34	5.82	6.23	6.91	5.65	6.10	6.42	7.12
Sunk Island	4.35	4.83	5.34	6.29	5.18	5.68	6.14	6.93	5.50	5.99	6.39	7.18
King George's Dock	4.63	5.15	5.65	6.36	5.49	5.94	6.28	6.92	5.80	6.18	6.43	7.08
Albert Dock	4.66	5.17	5.68	6.38	5.53	5.96	6.28	6.91	5.82	6.19	6.42	7.06
Humber Bridge	4.78	5.31	5.81	6.40	5.67	6.05	6.29	6.86	5.93	6.22	6.38	6.99
Brough	4.98	5.54	5.98	6.36	5.86	6.13	6.30	6.74	6.06	6.23	6.36	6.81
West Walker Dyke	5.11	5.65	5.99	6.32	5.91	6.11	6.27	6.58	6.06	6.24	6.32	6.64
Blacktoft Jetty	5.15	5.66	5.92	6.14	5.88	6.04	6.11	6.27	5.97	6.10	6.14	6.30
Flixborough	5.27	5.78	6.04	6.16	6.00	6.09	6.14	6.23	6.06	6.12	6.16	6.24
Goole	5.17	5.69	5.91	5.98	5.87	5.94	5.97	6.08	5.93	5.96	5.98	6.11
Ouse (upstream)	3.60	4.16	4.71	5.15	4.40	4.94	5.07	5.33	4.71	5.05	5.10	5.35
Trent (upstream)	4.13	4.64	5.10	5.78	4.80	5.24	5.62	5.84	5.04	5.46	5.77	5.84
Mean	**4.63**	**5.15**	**5.58**	**6.15**	**5.44**	**5.80**	**6.06**	**6.53**	**5.67**	**5.98**	**6.19**	**6.65**

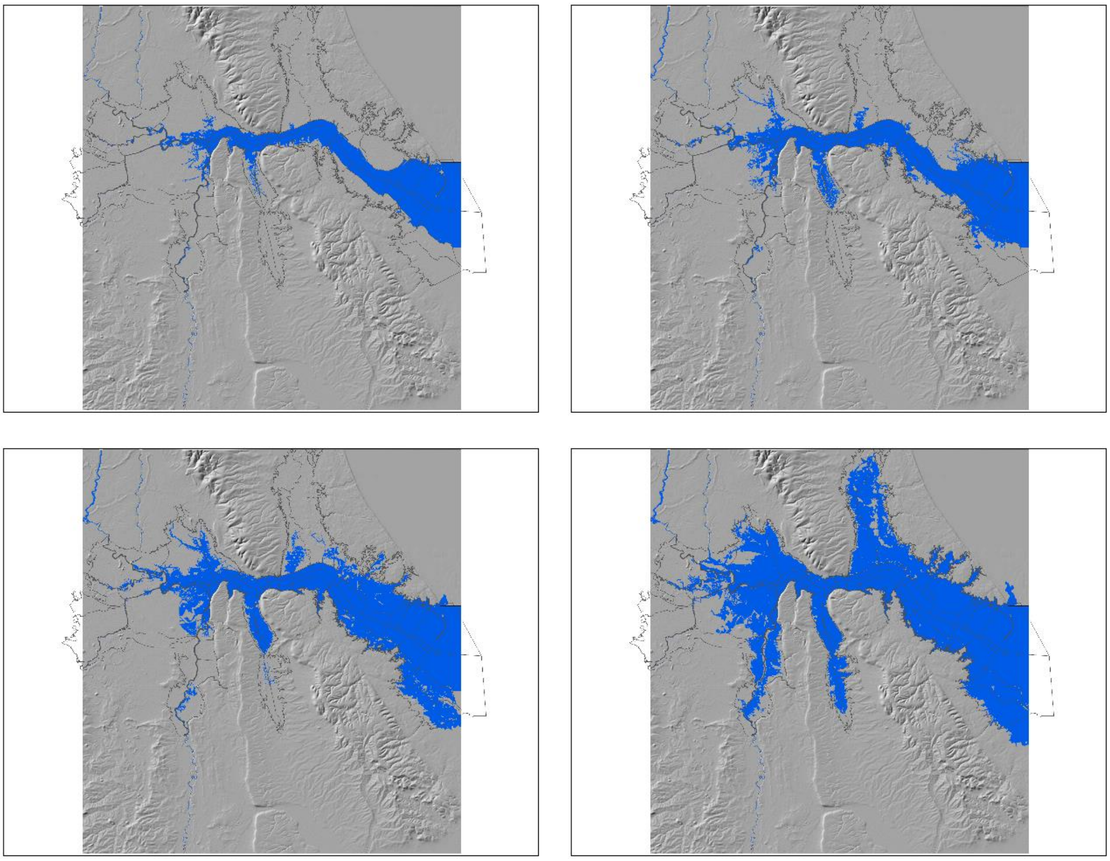

Figure 4.4 – Flood extents for Measure 4 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 4.4 – Change to the maximum stage for Measure 4 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grimsby	-0.01	-0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00
Immingham	-0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00
Sunk Island	-0.01	-0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00
King George's Dock	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	-0.01
Albert Dock	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	-0.01
Humber Bridge	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Brough	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00
West Walker Dyke	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Blacktoft Jetty	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Flixborough	-0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Goole	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ouse (upstream)	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trent (upstream)	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Mean	**0.00**	**0.00**	**0.01**	**0.00**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**

3.3 Measure 6 – Managed Realignment at Keyingham and Goxhill, plus raised defences in high priority areas to keep pace with sea level rise.

Flood defences were set as per the Baseline (as they will be in 2021) with additional Managed Realignment sites at Keyingham and Goxhill (as in Figure 4.1), and defences raised at High Priority areas by equivalent sea level rise. The High Priority areas are shown in Figure 5.1.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

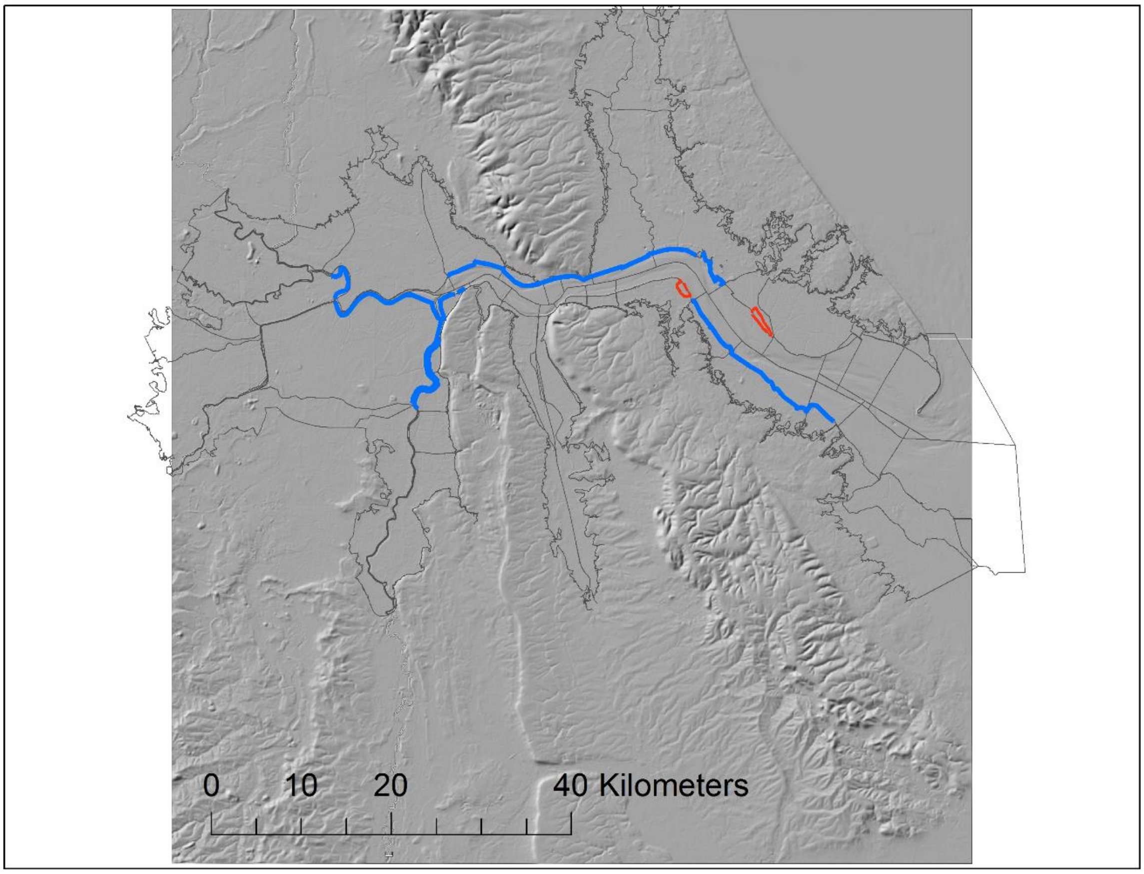

Figure 5.1 – Configuration of defence changes for Measure 6. Defences in High Priority Areas shown in blue raised in line with Sea Level Rise. Keyingham and Goxhill Managed Realignment sites shown in red, configured as in Figure 4.1.

3.3.1 Results

Adding defences at priority areas together with the two MR sites proved to be much more effective at reducing the mean flood volumes than model Measure 4. With the raised priority defences, 11 out of 12 of the scenarios were effective at reducing mean flood volume in comparison to the Baseline, and the remaining model run caused no change (Table 5.2).

Measure 6 resulted in lowering of mean flood volumes for all 1-year events in comparison to the Baseline, particularly with +2 m SLR, with the largest reduction of -21.29×10^6 m^3 (Table 5.2, Figure 5.2). For the 200-year event combined with +0.5 m SLR, mean flood volumes were increased from the Baseline by $+0.96 \times 10^6$ m^3. However, for the +0, +1 and +2 m SLRs, mean flood volumes reduced from -0.29 to -86.51×10^6 m^3 (Figure 5.3). For the 1000-year event, all mean flood volumes were reduced in comparison to the Baseline from -0.06×10^6 m^3 to -149.1×10^6 m^3. Local flood volumes show flood waters were redirected by the barriers to flood low priority areas such as the inner south bank and north outer bank (Figure 5.4), while flood waters were reduced in comparison to the Baseline locally up to -28.85×10^6 m^3 around Hull, -79.58×10^6 m^3 around Grimsby, and -89.85×10^6 m^3 around Ouse-Trent (all for the 1000-year return period event +2 m SLR). Stages do not increase during these events at present day sea levels but do steadily increase with the larger return period events (Table 5.4). The 1000-year events result in a jump in stage for each sea level increase increment.

Table 5.1 – Flood volumes by Area for Measure 6.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.80	56.48	0.17	6.47	33.63	259.54	2.74	23.24	73.89	373.10
South Bank Outer	0.00	0.00	0.01	38.38	0.00	1.47	21.95	167.12	0.19	11.75	53.54	218.15
Hull	0.00	0.00	0.00	1.17	0.01	0.01	0.02	192.33	0.05	0.01	6.76	317.81
Grimsby	0.00	0.00	0.00	81.22	0.00	0.00	21.42	116.25	0.00	2.27	45.08	121.18
North Bank Inner	0.00	0.00	0.60	46.79	1.21	3.03	8.56	69.25	4.06	6.34	16.28	80.85
South Bank Inner	0.00	0.07	9.69	278.36	2.81	37.05	124.68	390.51	18.22	84.81	183.62	434.65
Ouse-Trent	0.06	0.80	10.90	167.56	4.01	15.81	36.57	260.45	12.07	24.50	52.70	308.12
All	**0.07**	**0.87**	**22.00**	**669.96**	**8.21**	**63.84**	**246.83**	**1455.44**	**37.32**	**152.93**	**431.86**	**1853.86**

Table 5.2 – Change in Flood volumes by Area for Measure 6 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.01	2.60	-0.01	0.02	1.44	24.69	0.00	0.39	5.38	23.92
South Bank Outer	0.00	0.00	0.00	0.21	0.00	0.01	0.09	1.55	0.00	0.06	0.33	2.85
Hull	0.00	0.00	-0.01	-4.81	0.00	-0.27	-2.52	-11.16	0.01	-1.37	-3.11	-28.85
Grimsby	0.00	0.00	0.00	-5.48	0.00	-0.02	2.94	-47.02	0.00	1.37	-15.44	-78.58
North Bank Inner	0.00	-0.22	-1.87	1.15	0.04	-3.27	-4.84	0.96	0.11	-4.13	-3.21	1.60
South Bank Inner	0.00	0.01	0.76	20.90	-0.47	3.38	12.72	28.42	-0.49	8.93	7.50	31.65
Ouse-Trent	0.00	0.09	0.38	-35.86	0.15	-2.71	-8.86	-83.95	0.31	-6.60	-14.15	-101.72
All	**0.00**	**-0.12**	**-0.75**	**-21.29**	**-0.29**	**-2.86**	**0.96**	**-86.51**	**-0.06**	**-1.34**	**-22.69**	**-149.14**

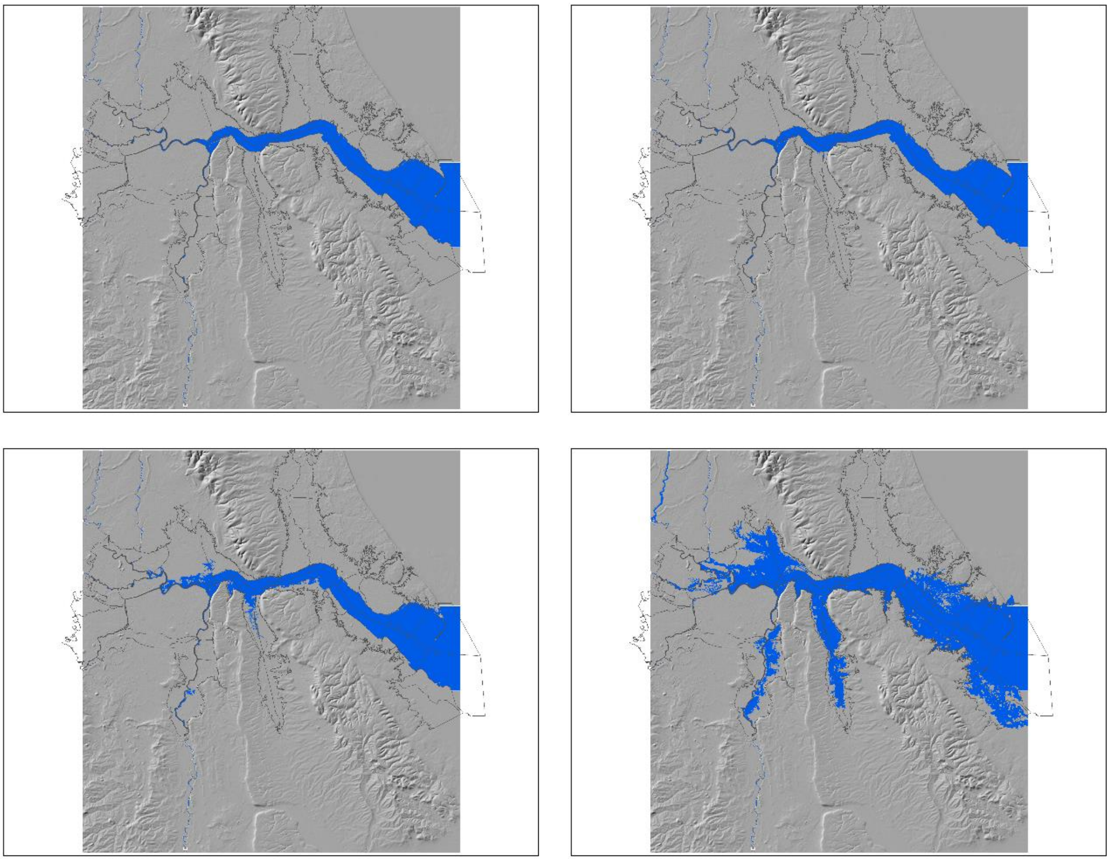

Figure 5.2 – Flood extents for Measure 6 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

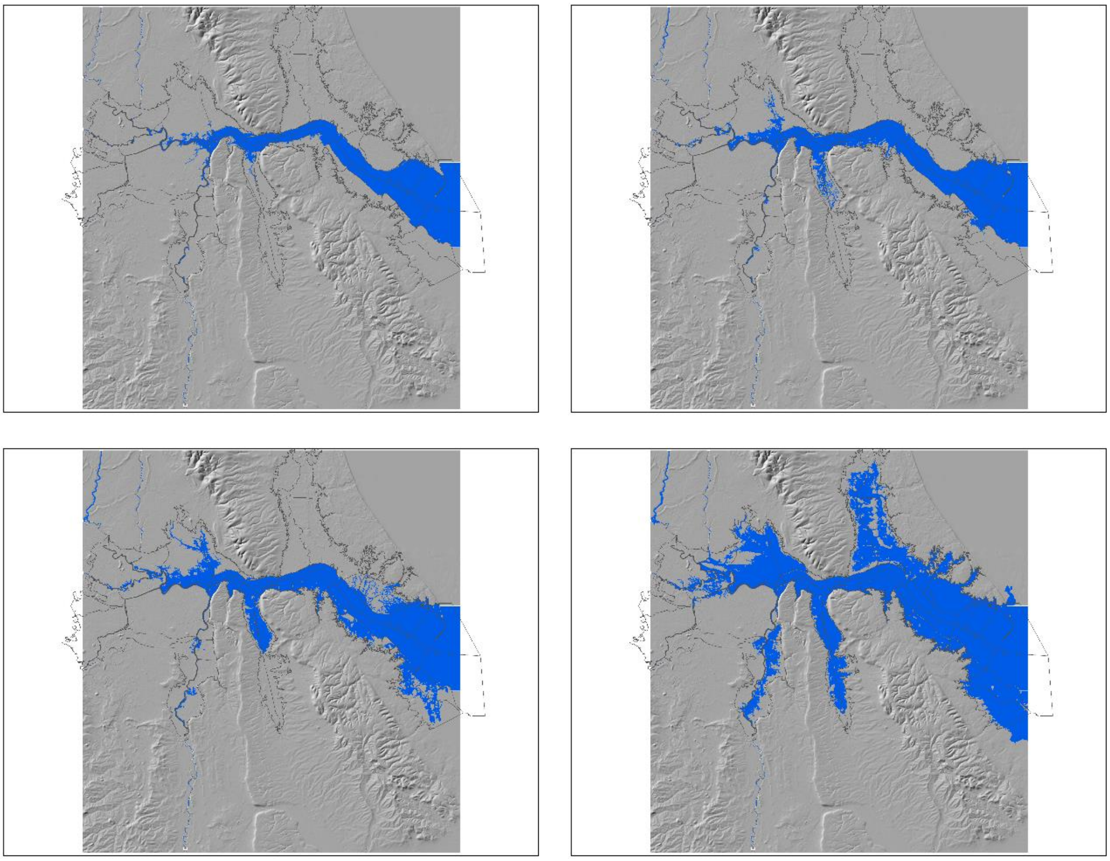

Figure 5.3 – Flood extents for Measure 6 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 5.3 – Maximum stages from tidal gauges throughout the Estuary for Measure 6.

	Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.19	5.05	5.55	6.04	6.98	5.37	5.87	6.33	7.28
Grimsby	4.35	4.85	5.34	6.30	5.19	5.69	6.14	6.98	5.51	5.99	6.41	7.27
Immingham	4.49	4.99	5.49	6.36	5.34	5.82	6.24	7.03	5.65	6.10	6.46	7.30
Sunk Island	4.35	4.83	5.34	6.30	5.18	5.68	6.15	6.98	5.50	5.99	6.41	7.26
King George's Dock	4.63	5.15	5.65	6.41	5.49	5.95	6.30	7.10	5.80	6.19	6.47	7.31
Albert Dock	4.66	5.17	5.68	6.44	5.53	5.97	6.30	7.09	5.82	6.20	6.47	7.31
Humber Bridge	4.78	5.31	5.82	6.48	5.67	6.07	6.35	7.07	5.93	6.26	6.47	7.27
Brough	4.98	5.54	6.03	6.45	5.86	6.20	6.38	6.98	6.06	6.31	6.45	7.13
West Walker Dyke	5.11	5.68	6.08	6.42	5.91	6.21	6.36	6.87	6.06	6.30	6.41	7.00
Blacktoft Jetty	5.15	5.69	6.00	6.24	5.88	6.09	6.20	6.49	5.97	6.15	6.23	6.56
Flixborough	5.27	5.82	6.25	6.51	6.00	6.35	6.48	6.80	6.06	6.41	6.51	6.88
Goole	5.17	5.72	5.96	6.05	5.87	6.00	6.04	6.16	5.93	6.02	6.05	6.19
Ouse (upstream)	3.60	4.16	4.70	5.15	4.40	4.93	5.07	5.32	4.71	5.05	5.10	5.35
Trent (upstream)	4.13	4.64	5.07	5.75	4.80	5.21	5.56	5.89	5.04	5.42	5.75	5.90
Mean	**4.63**	**5.16**	**5.62**	**6.22**	**5.44**	**5.84**	**6.12**	**6.70**	**5.67**	**6.02**	**6.25**	**6.86**

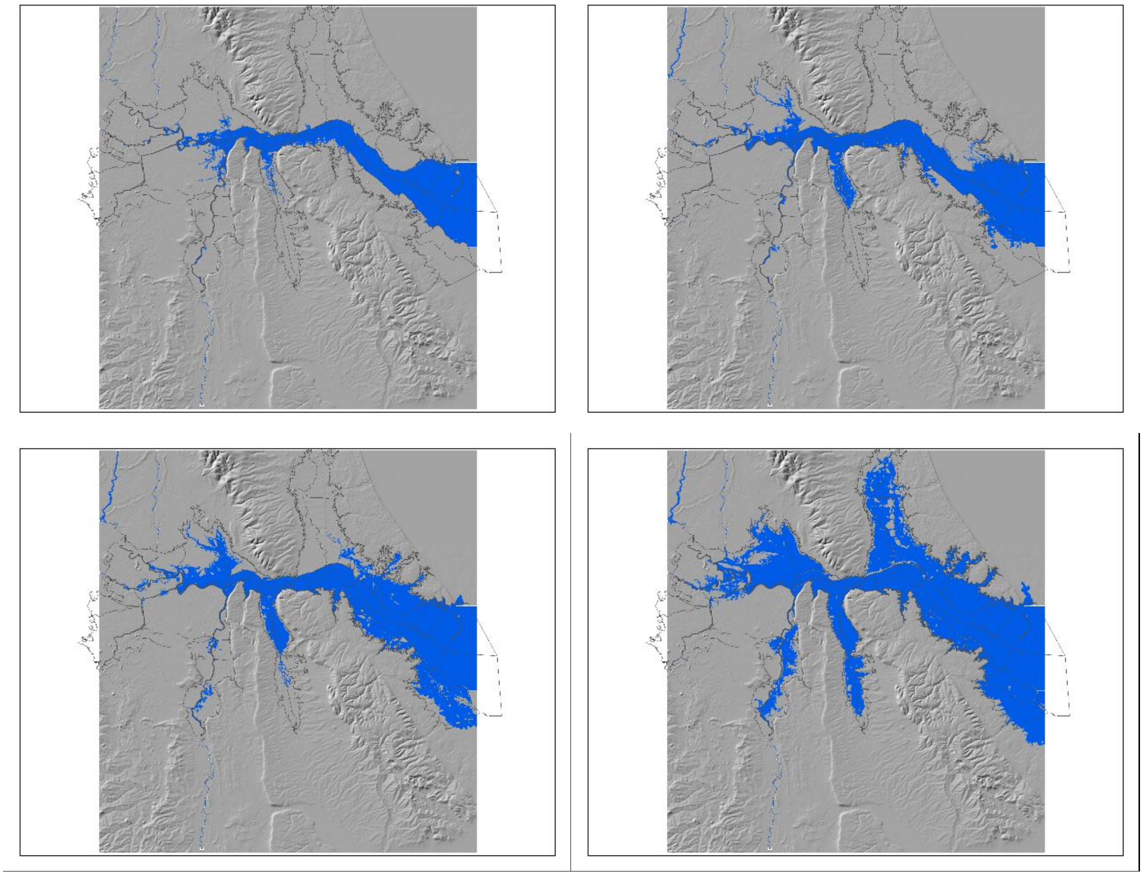

Figure 5.4 – Flood extents for Measure 6 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 5.4 – Change to the maximum stage for Measure 6 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.02
Grimsby	-0.01	-0.01	0.00	0.02	0.00	0.00	0.01	0.06	0.00	0.01	0.03	0.10
Immingham	-0.01	0.00	0.01	0.03	0.01	0.01	0.02	0.12	0.01	0.01	0.04	0.18
Sunk Island	-0.01	-0.01	0.00	0.02	0.00	0.00	0.02	0.05	0.00	0.01	0.02	0.08
King George's Dock	0.00	0.00	0.01	0.05	0.01	0.01	0.02	0.18	0.01	0.02	0.05	0.22
Albert Dock	0.01	0.01	0.01	0.07	0.01	0.01	0.03	0.18	0.01	0.02	0.05	0.24
Humber Bridge	0.00	0.01	0.02	0.09	0.01	0.03	0.06	0.21	0.01	0.04	0.09	0.27
Brough	0.00	0.01	0.07	0.09	0.01	0.08	0.09	0.24	0.01	0.09	0.09	0.32
West Walker Dyke	0.01	0.03	0.09	0.11	0.00	0.11	0.09	0.29	0.00	0.07	0.09	0.36
Blacktoft Jetty	0.01	0.04	0.09	0.11	0.00	0.06	0.08	0.23	0.01	0.05	0.09	0.26
Flixborough	-0.01	0.05	0.21	0.36	0.00	0.27	0.34	0.57	0.00	0.28	0.35	0.63
Goole	0.00	0.03	0.05	0.06	0.00	0.05	0.06	0.08	0.00	0.05	0.07	0.08
Ouse (upstream)	0.01	0.01	0.00	-0.01	0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Trent (upstream)	0.01	0.01	-0.01	-0.02	0.01	-0.02	-0.05	0.05	0.01	-0.04	-0.02	0.06
Mean	**0.00**	**0.01**	**0.04**	**0.07**	**0.01**	**0.04**	**0.06**	**0.16**	**0.00**	**0.04**	**0.07**	**0.20**

3.4 Measure 8 – Managed Realignment at Keyingham, Goxhill and Winteringham Ings, plus raise all Estuary defences by 1 m.

Flood defences were set as per the Baseline (2021 defences) with Managed Realignment sites at Keyingham, Goxhill and Winteringham Ings, plus all Estuary defences raised by 1 m. Keyingham and Goxhill sites as in Figure 4.1. Winteringham Ings site as in Figure 6.1. Raised defences are within the estuary only, and do not include the areas of the extended domain.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

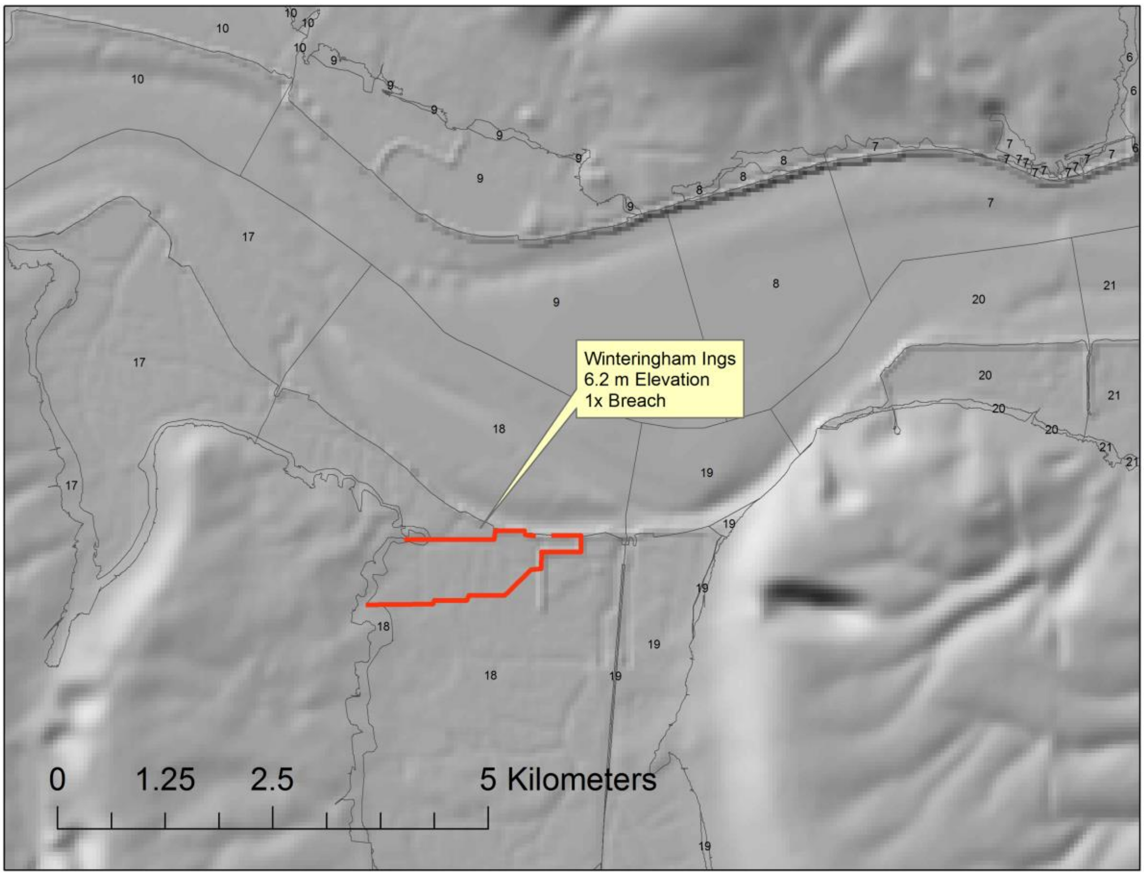

Figure 6.1 – Configuration of the Winteringham Ings Managed Realignment site (in red).

3.4.1 Results

Adding a third inner estuary MR site and increasing estuary wide defences (not just in high priority areas) resulted in a much larger reduction of mean flood volumes than Measure 6 in 11 out of the 12 scenarios (Table 6.2), while there was no change for the remaining scenario.

Measure 8 made no difference compared to the Baseline for a 1-year event at present day sea levels. However, when sea levels were increased the mean flood volume reduced by −0.33 to −567.6 × 10^6 m^3. Locally, these reductions were mainly found in the inner estuary and fluvial region (Figure 6.2). For a 200-year event, Measure 8 reduced mean flood volumes in comparison to the Baseline between −7.13 and −1107 × 10^6 m^3, which resulted in the highest local reductions around South Bank Inner, Hull, and North Bank Outer regions (Figure 6.3). The same local areas experienced the most benefit from mean flood volume reduction for a 1000-year event, between −33.13 and −1331 × 10^6 m^3 (Figure 6.4). Measure 8 impacted stage levels more than Measure 6 (Table 5.4), increasing the mean stage height in comparison to the Baseline by up to ~0.4 m, with the largest local increases in the inner estuary around Flixborough (Table 6.4).

Table 6.1 – Flood volumes by Area for Measure 8.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.14	2.39	0.08	0.43	1.00	55.02	0.25	0.73	4.48	91.97
South Bank Outer	0.00	0.00	0.01	4.65	0.00	0.24	1.74	37.24	0.08	1.00	5.35	69.31
Hull	0.00	0.00	0.00	0.03	0.00	0.00	0.02	4.70	0.00	0.02	0.23	20.25
Grimsby	0.00	0.00	0.00	1.05	0.00	0.00	0.45	38.28	0.00	0.07	2.06	85.76
North Bank Inner	0.00	0.00	0.00	6.06	0.00	0.14	1.74	25.62	0.01	0.82	4.91	34.08
South Bank Inner	0.00	0.00	0.01	10.83	0.01	0.10	4.11	107.37	0.04	0.78	19.57	165.74
Ouse-Trent	0.06	0.65	5.44	98.62	1.29	7.43	25.05	166.85	3.87	15.00	39.54	204.84
All	**0.07**	**0.66**	**5.60**	**123.64**	**1.38**	**8.34**	**34.10**	**435.08**	**4.25**	**18.42**	**76.14**	**671.94**

Table 6.2 – Change in Flood volumes by Area for Measure 8 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.67	-51.50	-0.10	-6.02	-31.19	-179.82	-2.48	-22.12	-64.02	-257.22
South Bank Outer	0.00	0.00	0.00	-33.52	0.00	-1.22	-20.13	-128.34	-0.12	-10.70	-47.87	-145.99
Hull	0.00	0.00	-0.01	-5.94	-0.01	-0.28	-2.52	-198.80	-0.04	-1.36	-9.63	-326.42
Grimsby	0.00	0.00	0.00	-85.64	0.00	-0.02	-18.04	-125.00	0.00	-0.83	-58.46	-114.01
North Bank Inner	0.00	-0.22	-2.47	-39.58	-1.17	-6.16	-11.66	-42.66	-3.94	-9.64	-14.58	-45.17
South Bank Inner	0.00	-0.05	-8.92	-246.63	-3.27	-33.57	-107.85	-254.71	-18.67	-75.10	-156.54	-237.26
Ouse-Trent	0.00	-0.06	-5.09	-104.80	-2.57	-11.09	-20.38	-177.55	-7.88	-16.10	-27.30	-205.00
All	**0.00**	**-0.33**	**-17.16**	**-567.62**	**-7.13**	**-58.36**	**-211.76**	**-1106.87**	**-33.13**	**-135.86**	**-378.41**	**-1331.06**

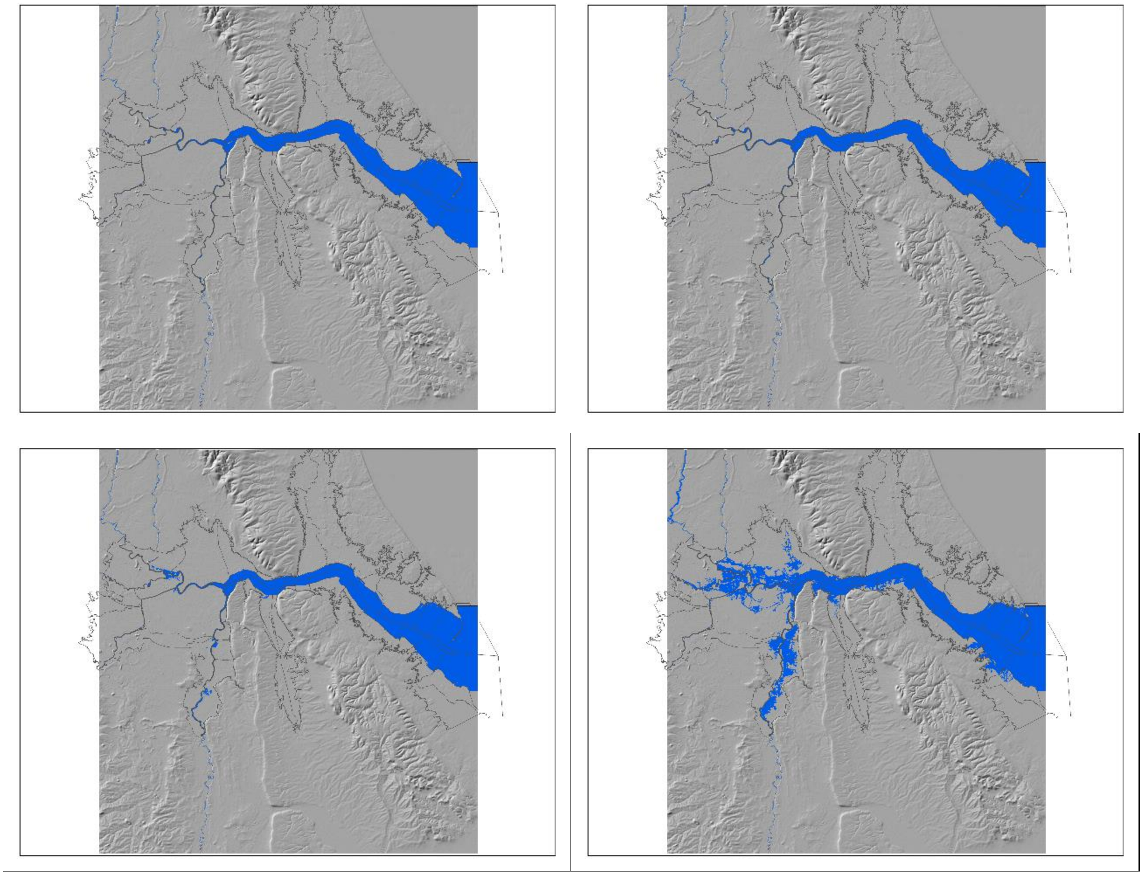

Figure 6.2 – Flood extents for Measure 8 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

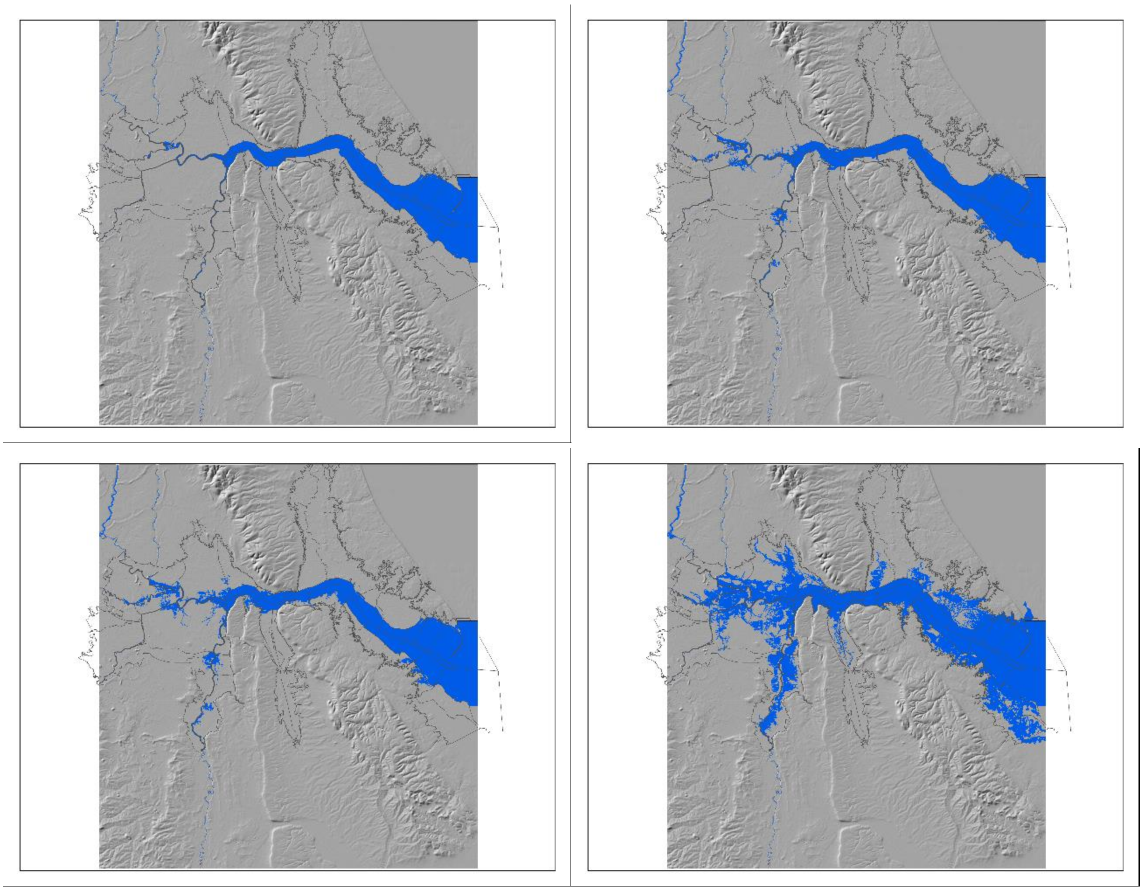

Figure 6.3– Flood extents for Measure 8 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 6.4 – Maximum stages at tidal gauges throughout the Estuary for Measure 8.

	Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	0	50	100	200	0	50	100	200	0	50	100	200
Spurn	4.20	4.71	5.20	6.20	5.05	5.55	6.06	7.03	5.37	5.88	6.36	7.32
Grimsby	4.35	4.85	5.35	6.34	5.19	5.70	6.19	7.13	5.52	6.01	6.51	7.38
Immingham	4.49	4.99	5.49	6.50	5.34	5.85	6.35	7.22	5.66	6.17	6.66	7.42
Sunk Island	4.35	4.84	5.33	6.34	5.18	5.69	6.19	7.13	5.51	6.01	6.51	7.39
King George's Dock	4.63	5.15	5.66	6.67	5.50	6.02	6.54	7.29	5.84	6.36	6.82	7.44
Albert Dock	4.66	5.18	5.70	6.72	5.53	6.07	6.57	7.30	5.87	6.40	6.86	7.43
Humber Bridge	4.78	5.31	5.85	6.88	5.69	6.25	6.75	7.31	6.04	6.58	6.99	7.39
Brough	4.98	5.54	6.12	7.02	5.94	6.48	6.94	7.28	6.28	6.80	7.10	7.38
West Walker Dyke	5.11	5.68	6.23	7.03	6.04	6.57	6.97	7.29	6.39	6.86	7.09	7.32
Blacktoft Jetty	5.15	5.70	6.25	6.95	6.06	6.59	6.91	7.11	6.42	6.84	6.98	7.14
Flixborough	5.27	5.83	6.36	6.98	6.22	6.69	6.96	7.06	6.52	6.90	7.01	7.07
Goole	5.17	5.73	6.21	6.61	6.08	6.44	6.60	6.66	6.34	6.56	6.63	6.67
Ouse (upstream)	3.60	4.16	4.73	5.13	4.41	4.93	5.06	5.31	4.73	5.03	5.08	5.35
Trent (upstream)	4.13	4.64	5.09	5.71	4.79	5.24	5.59	5.90	5.02	5.42	5.71	5.91
Mean	**4.63**	**5.16**	**5.68**	**6.51**	**5.50**	**6.01**	**6.41**	**6.93**	**5.82**	**6.27**	**6.59**	**7.04**

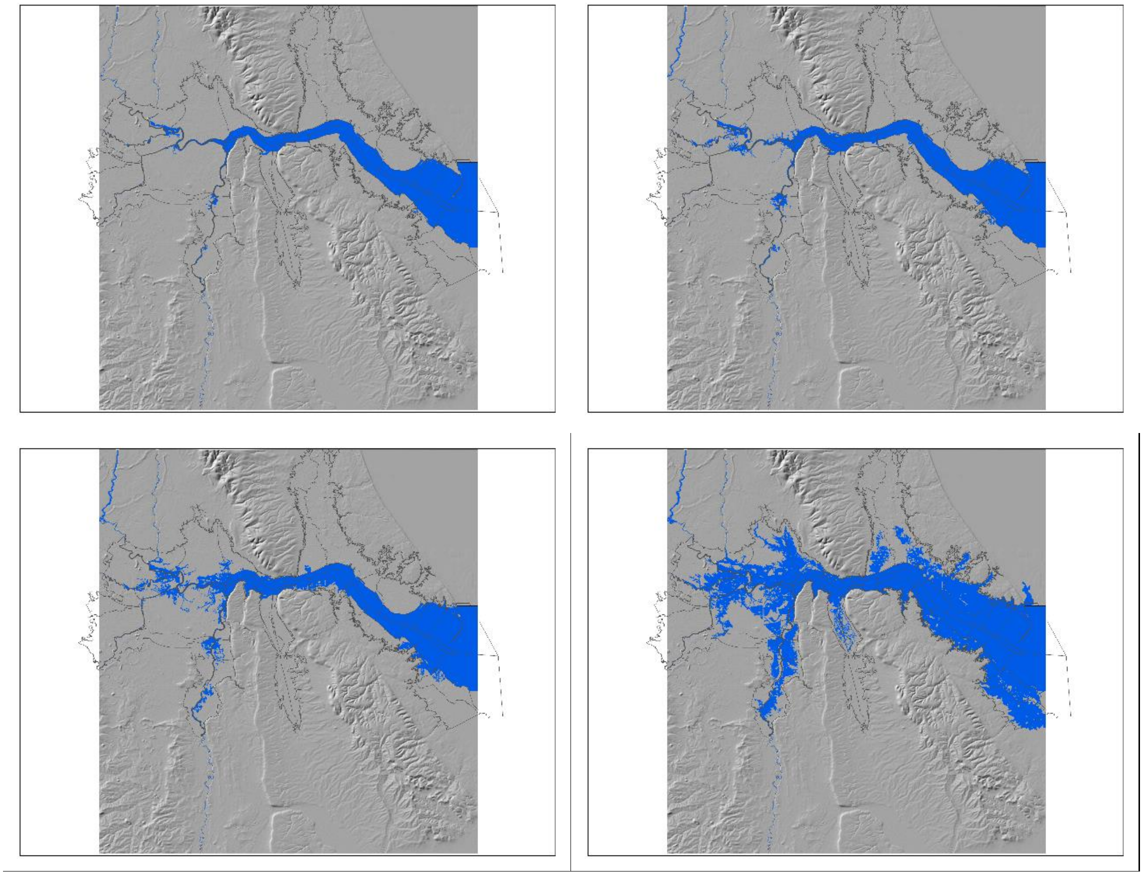

Figure 6.4 – Flood extents for Measure 8 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 6.4 – Change to the maximum stage for Measure 8 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.07	0.00	0.01	0.04	0.06
Grimsby	-0.01	-0.01	0.00	0.06	-0.01	0.01	0.06	0.21	0.01	0.03	0.13	0.22
Immingham	-0.01	0.00	0.01	0.17	0.01	0.04	0.13	0.30	0.02	0.08	0.24	0.30
Sunk Island	-0.01	-0.01	0.00	0.05	0.00	0.01	0.06	0.20	0.00	0.03	0.12	0.21
King George's Dock	0.00	0.00	0.03	0.32	0.02	0.09	0.27	0.37	0.05	0.19	0.40	0.35
Albert Dock	0.01	0.01	0.04	0.35	0.02	0.11	0.30	0.39	0.06	0.21	0.45	0.36
Humber Bridge	0.00	0.01	0.05	0.49	0.03	0.20	0.46	0.45	0.12	0.36	0.61	0.39
Brough	0.00	0.01	0.15	0.67	0.08	0.36	0.65	0.55	0.23	0.57	0.74	0.57
West Walker Dyke	0.01	0.03	0.24	0.72	0.13	0.47	0.70	0.71	0.34	0.63	0.77	0.69
Blacktoft Jetty	0.01	0.05	0.33	0.81	0.19	0.56	0.80	0.84	0.45	0.74	0.84	0.84
Flixborough	0.00	0.05	0.32	0.83	0.22	0.60	0.81	0.83	0.46	0.77	0.85	0.83
Goole	0.00	0.04	0.30	0.63	0.21	0.50	0.62	0.57	0.41	0.60	0.65	0.56
Ouse (upstream)	0.01	0.01	0.03	-0.03	0.03	-0.01	-0.02	-0.01	0.03	-0.01	-0.03	0.00
Trent (upstream)	0.01	0.01	0.00	-0.06	0.00	0.01	-0.03	0.06	-0.01	-0.03	-0.06	0.07
Mean	**0.00**	**0.02**	**0.11**	**0.36**	**0.07**	**0.21**	**0.35**	**0.40**	**0.15**	**0.30**	**0.41**	**0.39**

3.5 Measure 9 – Managed Realignment at Keyingham, Goxhill and Winteringham Ings, plus raise all Estuary defences by 2 m.

Flood defences were set as Baseline (2021 defences) with Managed Realignment sites at Keyingham, Goxhill and Winteringham Ings, plus all Estuary defences raised by 2 m. Keyingham and Goxhill sites as in Figure 4.1. Winteringham Ings site as in Figure 6.1. Raised defences are within the estuary only, and do not include the areas of the extended domain.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.5.1 Results

As for Measure 8, the largest reductions in mean flood volume locally occurred around the North Bank Outer, Hull, and South Bank Inner regions (Table 7.2). The defences did not dramatically decrease flood volumes for any of the events between +0 to 0.5 m SLR. However, for the larger events (200- and 1000-year return periods), the higher barriers decreased spatial inundation (Figures 7.1 - 7.3) and decreased mean flood volumes by up to a mean of -1677.17×10^6 m^3 in comparison to the Baseline for sea level rise values of between +1 and +2 m. Mean stages were increased in comparison to the Baseline by more than 0.7 m, with the highest local increases around Blacktoft Jetty (Table 7.4).

Table 7.1 – Flood volumes by Area for Measure 9.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.14	1.63	0.08	0.43	0.92	23.00	0.25	0.73	2.52	46.82
South Bank Outer	0.00	0.00	0.01	4.67	0.00	0.24	1.74	22.04	0.08	1.00	5.22	29.67
Hull	0.00	0.00	0.00	0.01	0.00	0.00	0.00	2.78	0.00	0.00	0.15	5.25
Grimsby	0.00	0.00	0.00	1.06	0.00	0.00	0.45	13.69	0.00	0.07	2.08	23.93
North Bank Inner	0.00	0.00	0.00	1.40	0.00	0.00	0.00	8.04	0.00	0.00	0.05	13.93
South Bank Inner	0.00	0.00	0.01	1.28	0.01	0.09	0.46	10.08	0.04	0.28	0.80	27.59
Ouse-Trent	0.06	0.65	5.47	97.69	1.30	7.67	24.01	152.32	3.96	14.94	35.53	178.63
All	**0.07**	**0.66**	**5.63**	**107.74**	**1.38**	**8.42**	**27.59**	**231.95**	**4.32**	**17.01**	**46.36**	**325.83**

Table 7.2 – Change in Flood volumes by Area for Measure 9 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.67	-52.26	-0.10	-6.02	-31.27	-211.84	-2.48	-22.12	-65.98	-302.37
South Bank Outer	0.00	0.00	0.00	-33.50	0.00	-1.22	-20.13	-143.53	-0.12	-10.70	-47.99	-185.63
Hull	0.00	0.00	-0.01	-5.97	-0.01	-0.28	-2.54	-200.71	-0.04	-1.38	-9.71	-341.41
Grimsby	0.00	0.00	0.00	-85.64	0.00	-0.02	-18.04	-149.59	0.00	-0.83	-58.43	-175.83
North Bank Inner	0.00	-0.22	-2.47	-44.24	-1.17	-6.30	-13.39	-60.25	-3.94	-10.47	-19.44	-65.31
South Bank Inner	0.00	-0.05	-8.92	-256.18	-3.27	-33.58	-111.49	-352.00	-18.67	-75.60	-175.32	-375.40
Ouse-Trent	0.00	-0.06	-5.06	-105.73	-2.57	-10.85	-21.42	-192.08	-7.80	-16.16	-31.31	-231.21
All	**0.00**	**-0.33**	**-17.13**	**-583.51**	**-7.12**	**-58.28**	**-218.28**	**-1310.00**	**-33.06**	**-137.26**	**-408.19**	**-1677.17**

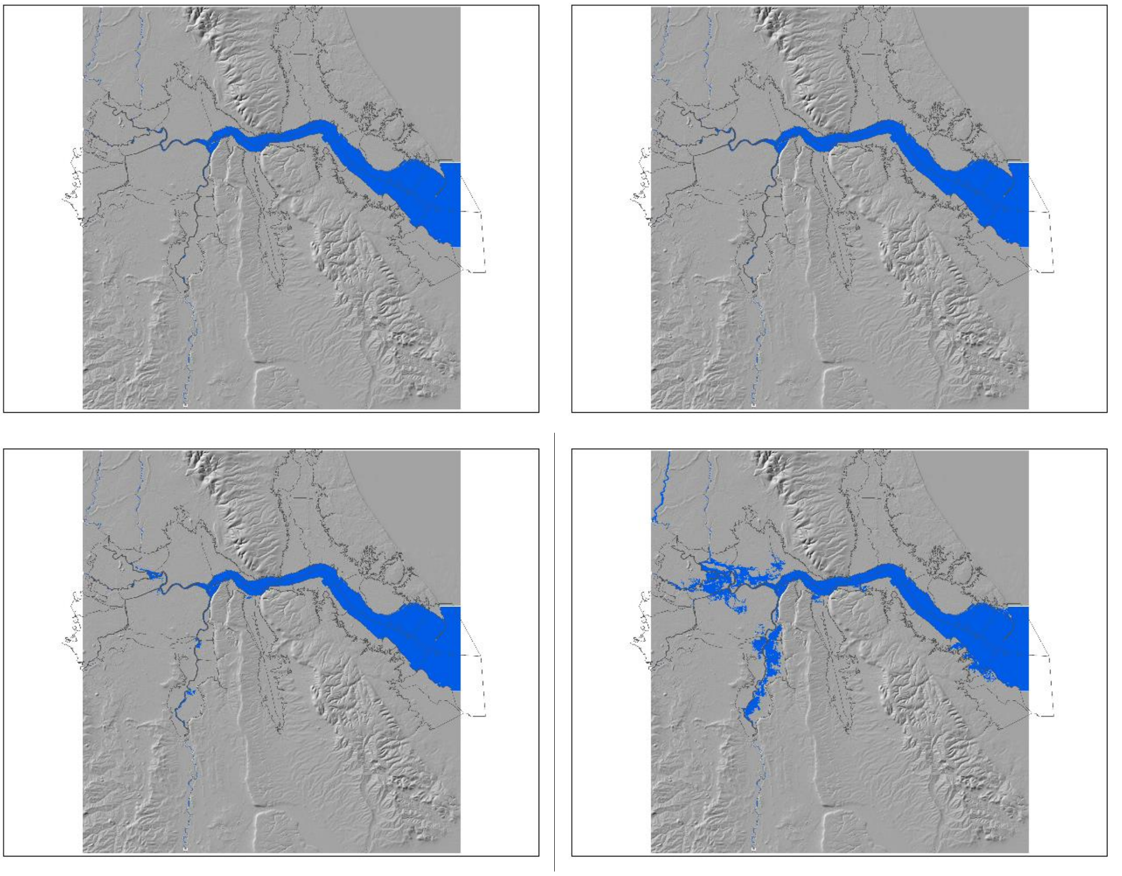

Figure 7.1 – Flood extents for Measure 9 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

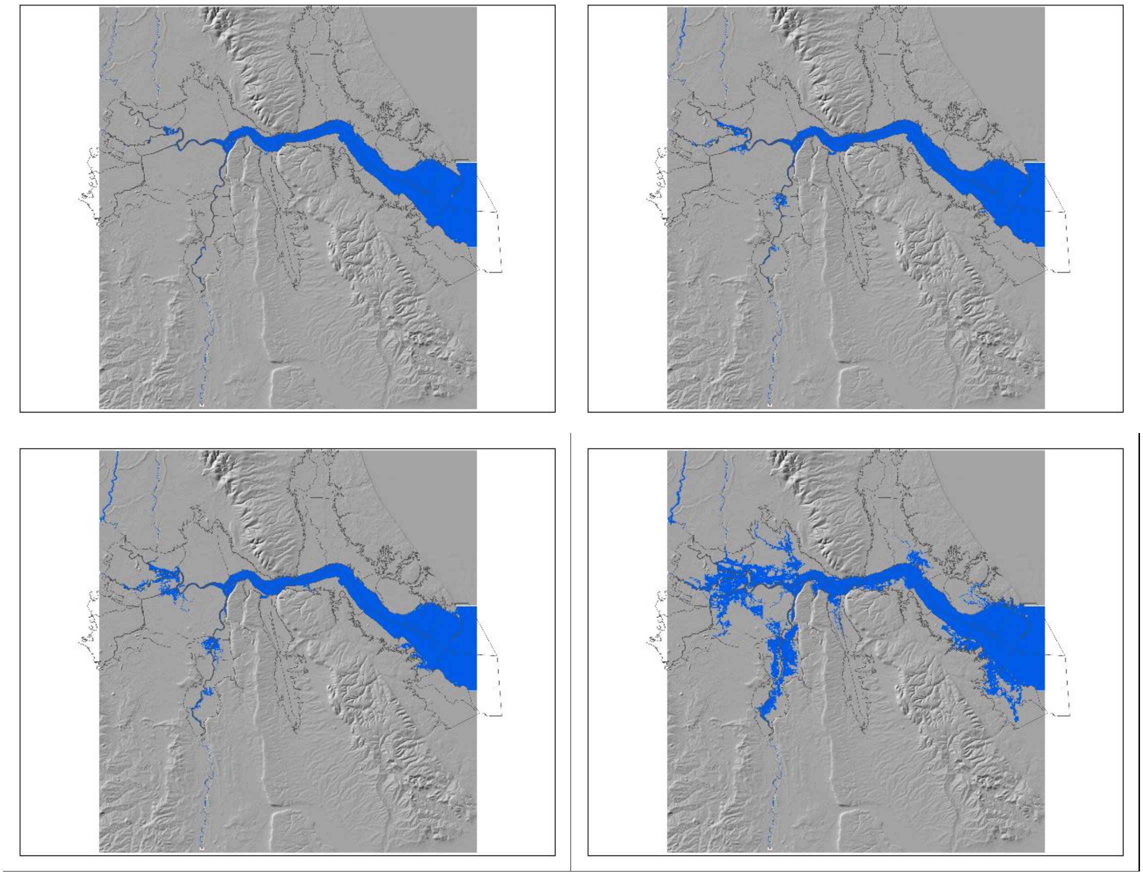

Figure 7.2 – Flood extents for Measure 9 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 7.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 9.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.71	5.20	6.20	5.05	5.55	6.06	7.04	5.37	5.87	6.37	7.36
Grimsby	4.35	4.85	5.35	6.34	5.19	5.70	6.19	7.18	5.52	6.01	6.51	7.50
Immingham	4.49	4.99	5.49	6.50	5.34	5.85	6.35	7.34	5.66	6.17	6.67	7.65
Sunk Island	4.35	4.84	5.33	6.34	5.18	5.69	6.18	7.17	5.51	6.01	6.51	7.49
King George's Dock	4.63	5.15	5.66	6.70	5.50	6.02	6.55	7.56	5.84	6.36	6.88	7.84
Albert Dock	4.66	5.18	5.70	6.75	5.53	6.07	6.58	7.61	5.87	6.40	6.93	7.89
Humber Bridge	4.78	5.31	5.85	6.96	5.69	6.25	6.79	7.79	6.04	6.59	7.14	8.01
Brough	4.98	5.54	6.12	7.19	5.94	6.50	7.04	7.94	6.29	6.84	7.37	8.09
West Walker Dyke	5.11	5.68	6.24	7.28	6.04	6.59	7.14	7.95	6.40	6.95	7.45	8.06
Blacktoft Jetty	5.15	5.71	6.25	7.28	6.06	6.62	7.14	7.81	6.43	6.98	7.41	7.90
Flixborough	5.27	5.83	6.36	7.18	6.22	6.71	7.09	7.71	6.53	6.97	7.31	7.79
Goole	5.17	5.73	6.22	6.76	6.08	6.46	6.70	7.07	6.35	6.63	6.83	7.12
Ouse (upstream)	3.60	4.16	4.73	5.12	4.41	4.93	5.05	5.30	4.73	5.03	5.07	5.33
Trent (upstream)	4.13	4.64	5.09	5.70	4.79	5.24	5.57	5.90	5.02	5.42	5.69	5.91
Mean	**4.63**	**5.17**	**5.69**	**6.59**	**5.50**	**6.01**	**6.46**	**7.24**	**5.83**	**6.30**	**6.72**	**7.42**

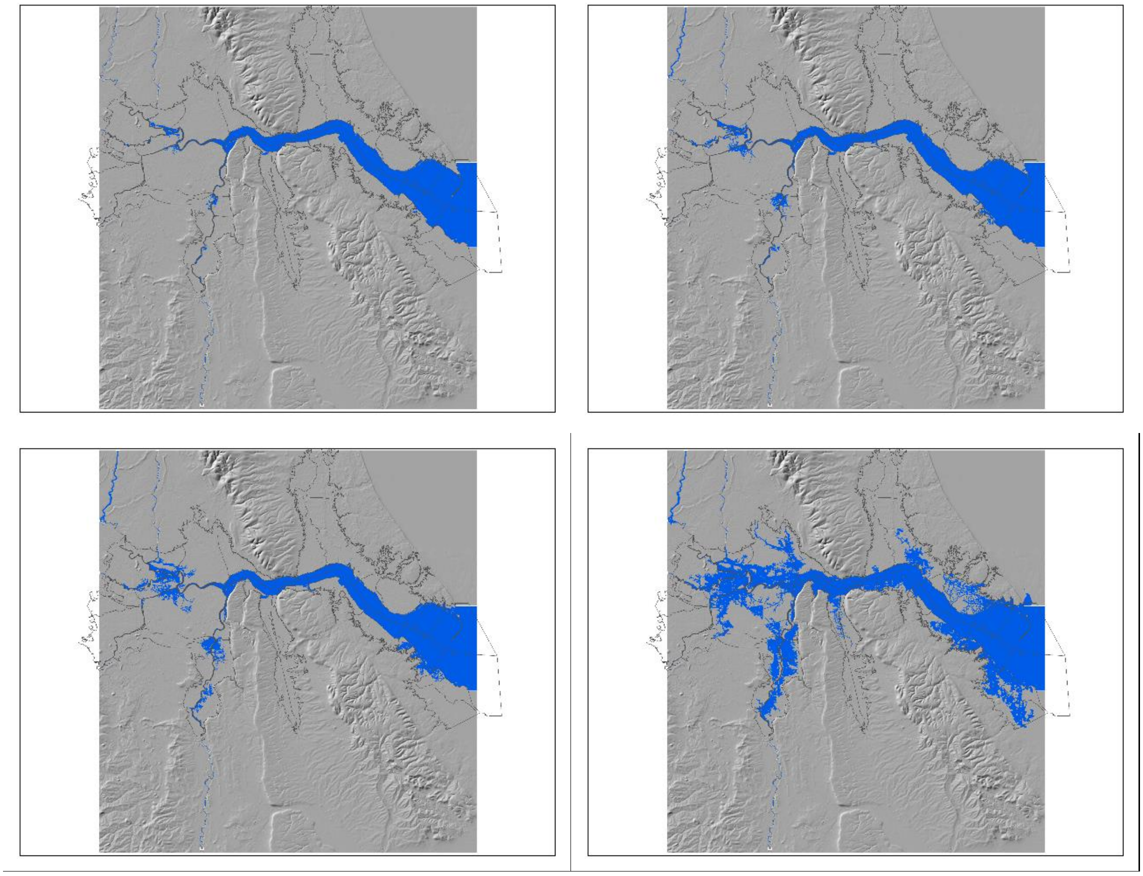

Figure 7.3 – Flood extents for Measure 9 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 7.4 – Change to the maximum stage for Measure 9 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.08	0.00	0.01	0.04	0.09
Grimsby	-0.01	-0.01	0.00	0.06	-0.01	0.01	0.06	0.27	0.01	0.03	0.13	0.33
Immingham	-0.01	0.00	0.01	0.17	0.01	0.04	0.13	0.43	0.02	0.08	0.25	0.53
Sunk Island	-0.01	-0.01	0.00	0.06	0.00	0.01	0.05	0.24	0.00	0.03	0.13	0.31
King George's Dock	0.00	0.00	0.03	0.34	0.02	0.09	0.27	0.64	0.05	0.19	0.45	0.76
Albert Dock	0.01	0.01	0.04	0.38	0.02	0.11	0.31	0.71	0.06	0.21	0.52	0.83
Humber Bridge	0.00	0.01	0.05	0.57	0.03	0.20	0.50	0.93	0.12	0.37	0.76	1.01
Brough	0.00	0.01	0.15	0.84	0.09	0.37	0.75	1.21	0.23	0.62	1.00	1.28
West Walker Dyke	0.01	0.04	0.25	0.97	0.13	0.49	0.87	1.37	0.35	0.71	1.12	1.43
Blacktoft Jetty	0.01	0.05	0.34	1.14	0.19	0.59	1.03	1.54	0.46	0.87	1.27	1.60
Flixborough	0.00	0.05	0.32	1.03	0.22	0.63	0.94	1.48	0.47	0.85	1.15	1.54
Goole	0.01	0.04	0.31	0.78	0.21	0.51	0.73	0.98	0.42	0.67	0.85	1.01
Ouse (upstream)	0.01	0.01	0.03	-0.03	0.03	-0.01	-0.02	-0.03	0.02	-0.02	-0.03	-0.02
Trent (upstream)	0.01	0.01	0.00	-0.07	0.00	0.00	-0.05	0.06	-0.01	-0.04	-0.08	0.07
Mean	**0.00**	**0.02**	**0.11**	**0.45**	**0.07**	**0.22**	**0.40**	**0.71**	**0.16**	**0.33**	**0.54**	**0.77**

3.6 Measure 29 – Managed Realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, and Cherry Cobb Sands

Flood defences were set as Baseline (2021 defences), but with large-scale managed realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, Cherry Cobb Sands. The Adlingfleet, Broomfleet, and Faxfleet Managed Realignment sites are as specified in Figure 8.1. The Sunk Island and Cherry Cobb Sands Managed Realignment sites are as specified in Figure 8.2, with estuary facing defences degraded by setting elevations to the mean of the surrounding pixels.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 1 and 2 m sea level rise (SLR), resulting in nine scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

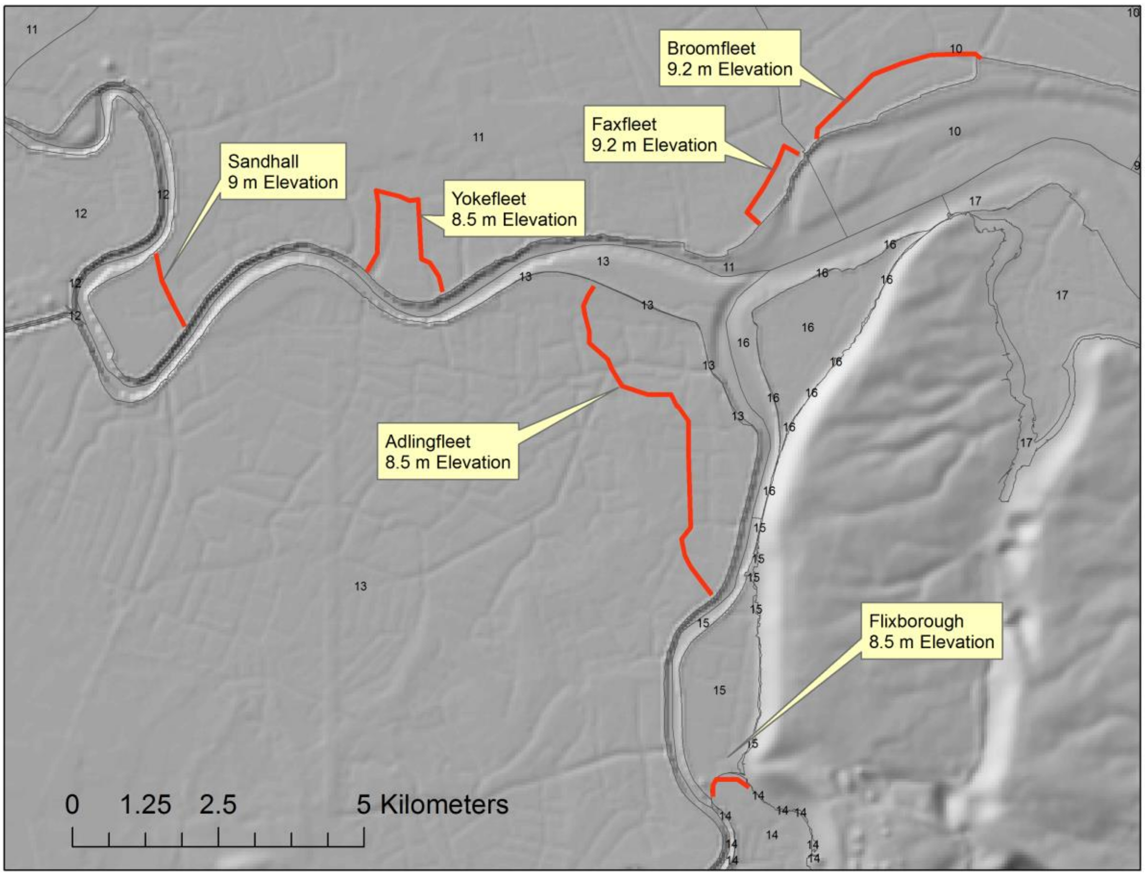

Figure 8.1 – Configuration of Flood Storage sites at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet and Flixborough. Elevations were raised along the red lines. Estuary facing defences kept as Baseline level.

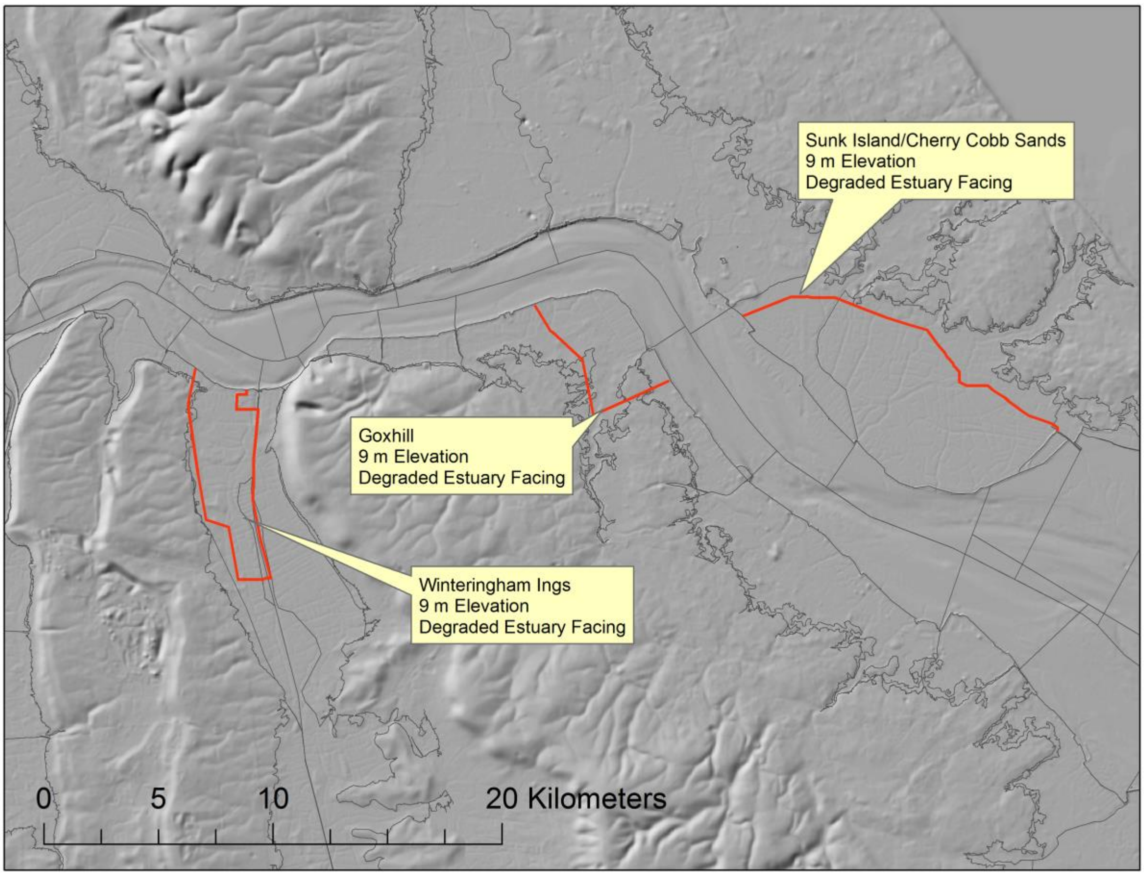

Figure 8.2 – Configuration of the large-scale Managed Realignment sites at Goxhill, Sunk Island/Cherry Cobb Sands and Winteringham Ings.

3.6.1 Results

Three out of the nine scenarios reduced mean flood volume in comparison to the Baseline (Tables 8.1 and 8.2). The largest reductions, of −250.0 × 10^6 m^3 and −415.5 × 10^6 m^3, occurred for the 200- and 1000-year return period events with +2 m SLR. The largest increase in mean flood volume relative to the Baseline was +15.12 × 10^6 m^3 for the 200-year return period event with +1 m SLR. Locally, the largest reductions in flood volumes occurred around the North Bank Inner, Hull, and Ouse-Trent regions, whereas Grimsby and South Bank Inner suffered from the largest increases (Figures 8.3 to 8.5). Tables 8.3 and 8.4 show that mean stages increased by between 0.07 and 0.15 m above the Baseline in eight of the nine scenarios, with the largest increases occurring during the +2m SLR scenarios. The Brough and Humber Bridge gauges exhibited lower stages than the surrounding gauges at 0 to +1 m SLR scenarios.

Table 8.1 – Flood volumes by Area for Measure 29.

	Flood Volumes (10^6 m^3)								
Return Period (yrs)	**1**	**1**	**1**	**200**	**200**	**200**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
North Bank Outer	0.00	1.04	44.86	0.19	28.97	84.79	3.23	44.93	110.41
South Bank Outer	0.00	0.02	41.28	0.00	23.50	168.22	0.28	55.32	219.26
Hull	0.00	0.01	8.38	0.01	3.44	96.56	0.13	8.24	176.10
Grimsby	0.00	0.00	108.17	0.00	31.15	186.25	0.01	71.36	212.94
North Bank Inner	0.00	1.90	45.70	0.95	11.86	67.19	3.27	17.94	77.21
South Bank Inner	0.00	10.65	257.09	3.87	119.67	373.02	21.92	183.00	417.91
Ouse-Trent	1.21	11.22	189.37	4.70	42.41	315.95	12.13	63.11	373.66
All	**1.22**	**24.85**	**694.85**	**9.72**	**260.99**	**1291.98**	**40.97**	**443.90**	**1587.49**

Table 8.2 – Change in Flood volumes by Area for Measure 29 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)									
Return Period (yrs)	**1**	**1**	**1**	**200**	**200**	**200**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
North Bank Outer	0.00	0.23	-9.02	0.02	-3.22	-150.05	0.49	-23.58	-238.78
South Bank Outer	0.00	0.01	3.11	0.00	1.63	2.64	0.09	2.10	3.96
Hull	0.00	0.00	2.40	0.00	0.90	-106.93	0.08	-1.63	-170.56
Grimsby	0.00	0.00	21.48	0.00	12.66	22.98	0.01	10.84	13.18
North Bank Inner	0.00	-0.57	0.05	-0.23	-1.54	-1.09	-0.67	-1.55	-2.03
South Bank Inner	0.00	1.72	-0.37	0.59	7.71	10.93	3.21	6.89	14.91
Ouse-Trent	1.15	0.70	-14.05	0.83	-3.03	-28.45	0.37	-3.73	-36.18
All	**1.15**	**2.09**	**3.60**	**1.22**	**15.12**	**-249.97**	**3.59**	**-10.65**	**-415.50**

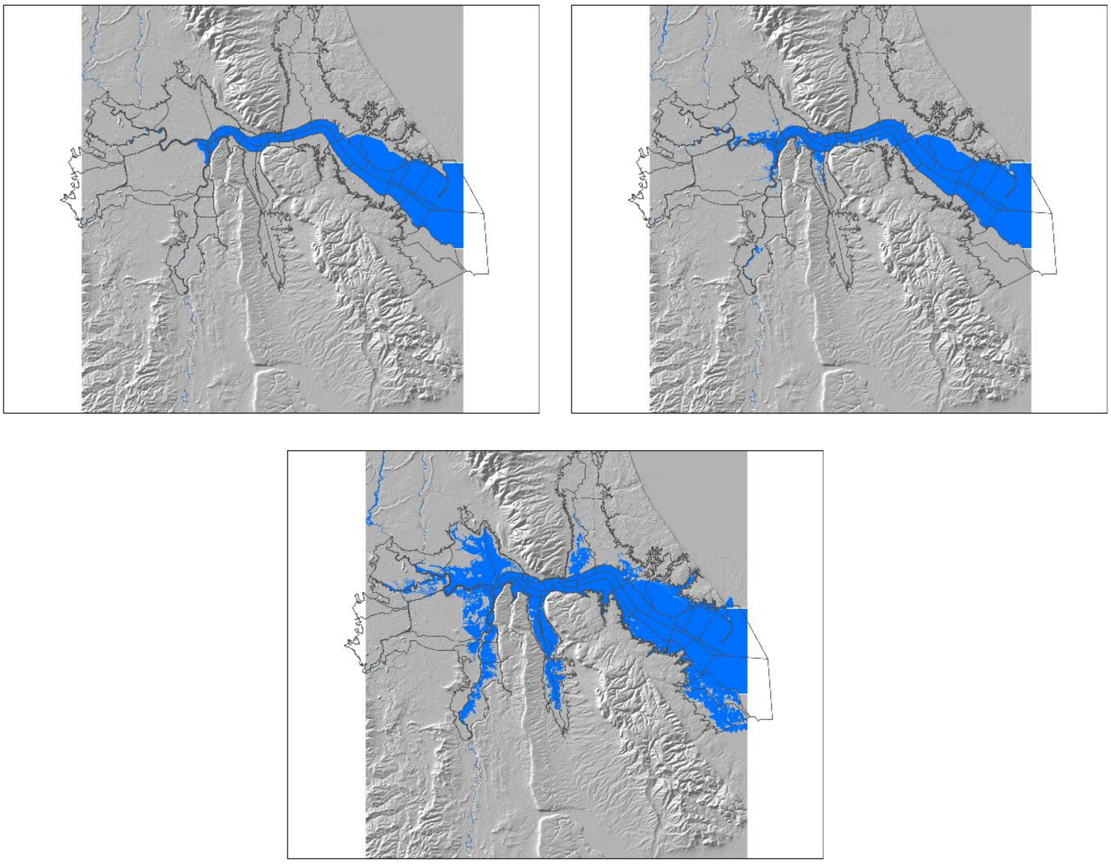

Figure 8.3– Flood extents for Measure 29 with a 1-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

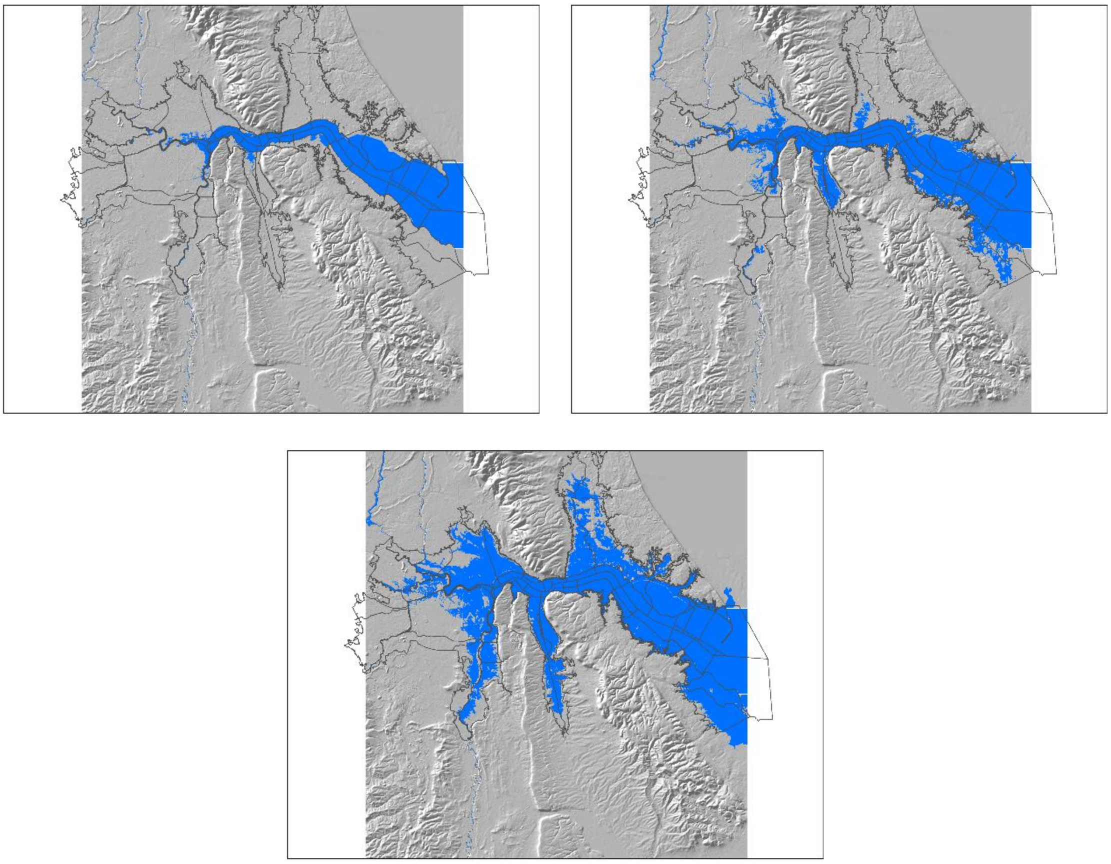

Figure 8.4 – Flood extents for Measure 29 with a 200-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

Table 8.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 29.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**		**in 1**	**in 1**	**in 200**		**in 200**	**in 200**	**in 1000**		**in 1000**	**in 1000**
SLR (cm)	**0**		**100**	**200**	**0**		**100**	**200**	**0**		**100**	**200**
Spurn	4.17		5.20	6.25	5.03		6.12	7.00	5.40		6.39	7.29
Grimsby	4.28		5.47	6.45	5.31		6.31	7.04	5.66		6.57	7.34
Immingham	4.47		5.61	6.53	5.47		6.43	7.03	5.78		6.65	7.38
Sunk Island	4.28		5.46	6.44	5.31		6.31	7.04	5.64		6.56	7.29
King George's Dock	4.63		5.77	6.49	5.62		6.41	7.07	5.91		6.57	7.30
Albert Dock	4.66		5.77	6.48	5.64		6.38	7.05	5.90		6.53	7.28
Humber Bridge	4.74		5.80	6.51	5.68		6.32	6.98	5.93		6.43	7.19
Brough	4.83		5.92	6.51	5.79		6.35	6.96	6.02		6.45	7.05
West Walker Dyke	4.92		6.01	6.46	5.90		6.36	6.83	6.09		6.44	6.92
Blacktoft Jetty	5.01		5.99	6.26	5.92		6.20	6.46	6.03		6.25	6.50
Flixborough	5.12		6.10	6.27	6.05		6.24	6.40	6.14		6.27	6.41
Goole	4.97		5.92	6.04	5.87		6.01	6.13	5.95		6.03	6.16
Ouse (upstream)	3.75		4.86	5.19	4.55		5.07	5.33	4.82		5.10	5.35
Trent (upstream)	4.34		5.25	5.77	4.97		5.63	5.85	5.18		5.77	5.85
Mean	**4.58**		**5.65**	**6.26**	**5.51**		**6.15**	**6.65**	**5.75**		**6.29**	**6.81**

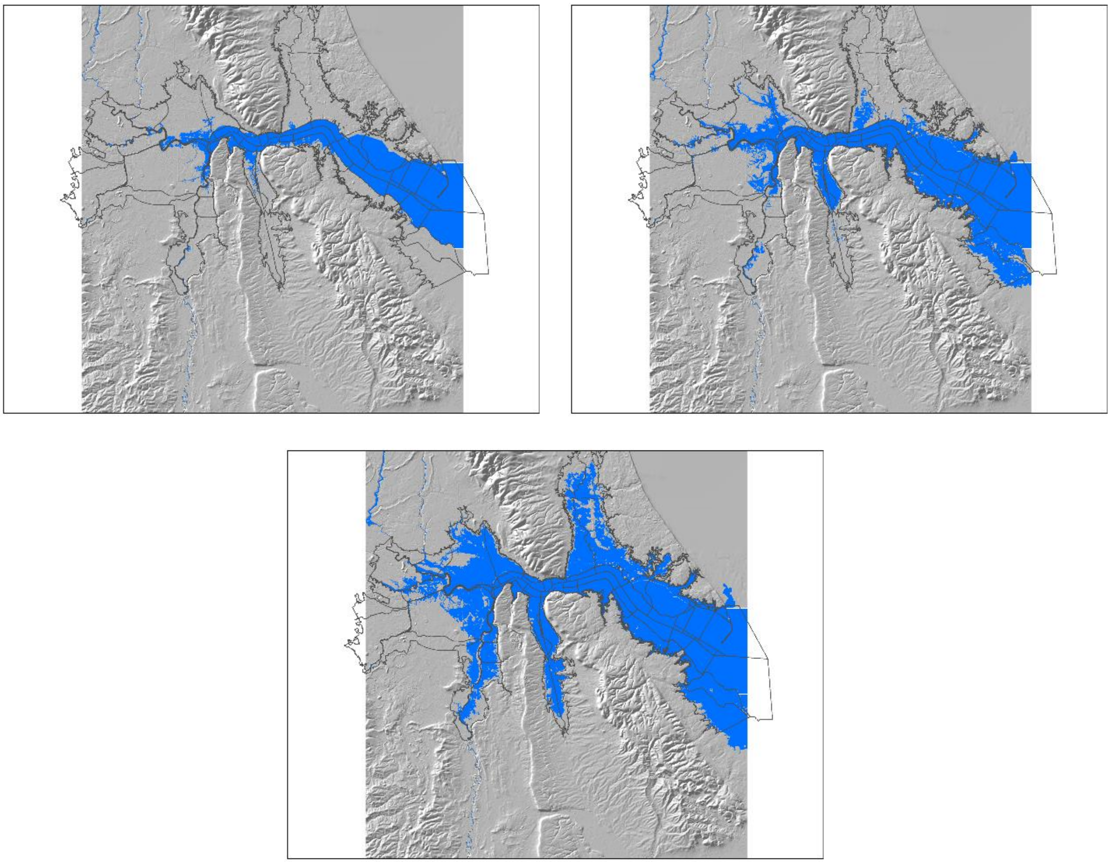

Figure 8.5 – Flood extents for Measure 29 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

Table 8.4 – Change Maximum Stages for Measure 29 relative to the Baseline (Measure 1).

Change from Baseline Equivalent Maximum Stage Height (m OSN)									
Return Period	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
Spurn	-0.03	-0.01	0.07	-0.02	0.08	0.04	0.03	0.06	0.03
Grimsby	-0.08	0.13	0.17	0.12	0.18	0.12	0.15	0.18	0.17
Immingham	-0.03	0.13	0.20	0.14	0.21	0.11	0.14	0.23	0.26
Sunk Island	-0.07	0.13	0.16	0.13	0.18	0.11	0.14	0.18	0.11
King George's Dock	-0.01	0.13	0.13	0.14	0.13	0.14	0.12	0.15	0.21
Albert Dock	0.01	0.10	0.11	0.12	0.11	0.14	0.09	0.12	0.22
Humber Bridge	-0.03	0.00	0.11	0.02	0.03	0.12	0.01	0.05	0.20
Brough	-0.15	-0.05	0.16	-0.07	0.06	0.22	-0.03	0.08	0.24
West Walker Dyke	-0.18	0.02	0.15	-0.01	0.09	0.25	0.03	0.12	0.28
Blacktoft Jetty	-0.13	0.07	0.12	0.05	0.09	0.19	0.06	0.11	0.20
Flixborough	-0.16	0.06	0.12	0.05	0.10	0.17	0.07	0.10	0.17
Goole	-0.20	0.01	0.06	0.00	0.04	0.05	0.02	0.04	0.05
Ouse (upstream)	0.16	0.16	0.04	0.17	0.00	0.01	0.11	0.00	0.00
Trent (upstream)	0.23	0.16	0.00	0.18	0.02	0.01	0.16	0.01	0.01
Mean	**-0.05**	**0.07**	**0.11**	**0.07**	**0.09**	**0.12**	**0.08**	**0.10**	**0.15**

3.7 Measure 30 – Managed Realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, Cherry Cobb Sands and Winteringham Ings

Flood defences are as described in Measure 29, but with the addition of the Winteringham Ings site (see Figures 8.1 and 8.2).

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 1 and 2 m sea level rise (SLR), resulting in nine scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.7.1 Results

Eight out of the nine scenarios reduced mean flood volume in comparison to the Baseline (Tables 9.1 and 9.2). The largest reductions, of −511.1 × 10^6 m^3 and −673.7 × 10^6 m^3, occurred for the 200- and 1000-year return period events with +2 m SLR. The only increase in mean flood volume relative to the Baseline was +1.04 × 10^6 m^3 for the 1-year return period event at present day sea levels. Locally the North Bank Outer, Hull, and South Bank Inner regions benefitted the most from a reduction in flood volumes compared to the Baseline, particularly for the larger events and sea levels (Figures 9.1 to 9.3).

Table 9.1 – Flood volumes by Area for Measure 30.

	Flood Volumes (10^6 m^3)								
Return Period (yrs)	**1**	**1**	**1**	**200**	**200**	**200**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
North Bank Outer	0.00	1.03	44.54	0.19	28.75	83.81	3.21	44.55	109.69
South Bank Outer	0.00	0.02	40.98	0.00	23.32	167.81	0.28	55.02	218.06
Hull	0.00	0.01	5.28	0.01	2.45	86.29	0.02	6.54	170.44
Grimsby	0.00	0.00	88.30	0.00	19.28	177.31	0.01	68.61	209.64
North Bank Inner	0.00	0.71	27.71	0.30	10.29	55.78	1.30	14.37	68.24
South Bank Inner	0.00	4.62	149.96	1.86	79.74	208.76	10.43	134.19	230.24
Ouse-Trent	1.11	4.98	112.22	1.99	34.50	251.05	5.26	53.06	323.01
All	**1.11**	**11.37**	**468.99**	**4.35**	**198.32**	**1030.80**	**20.50**	**376.36**	**1329.32**

Table 9.2 – Change in Flood volumes by Area for Measure 30 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)									
Return Period (yrs)	**1**	**1**	**1**	**200**	**200**	**200**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
North Bank Outer	0.00	0.23	-9.34	0.02	-3.44	-151.03	0.47	-23.95	-239.50
South Bank Outer	0.00	0.01	2.81	0.00	1.45	2.23	0.09	1.81	2.76
Hull	0.00	0.00	-0.70	0.00	-0.09	-117.21	-0.02	-3.32	-176.22
Grimsby	0.00	0.00	1.60	0.00	0.79	14.04	0.01	8.10	9.87
North Bank Inner	0.00	-1.75	-17.93	-0.87	-3.11	-12.51	-2.65	-5.12	-11.01
South Bank Inner	0.00	-4.32	-107.50	-1.41	-32.22	-153.32	-8.28	-41.92	-172.75
Ouse-Trent	1.04	-5.55	-91.20	-1.88	-10.93	-93.35	-6.50	-13.78	-86.83
All	**1.04**	**-11.39**	**-222.27**	**-4.15**	**-47.54**	**-511.14**	**-16.88**	**-78.19**	**-673.68**

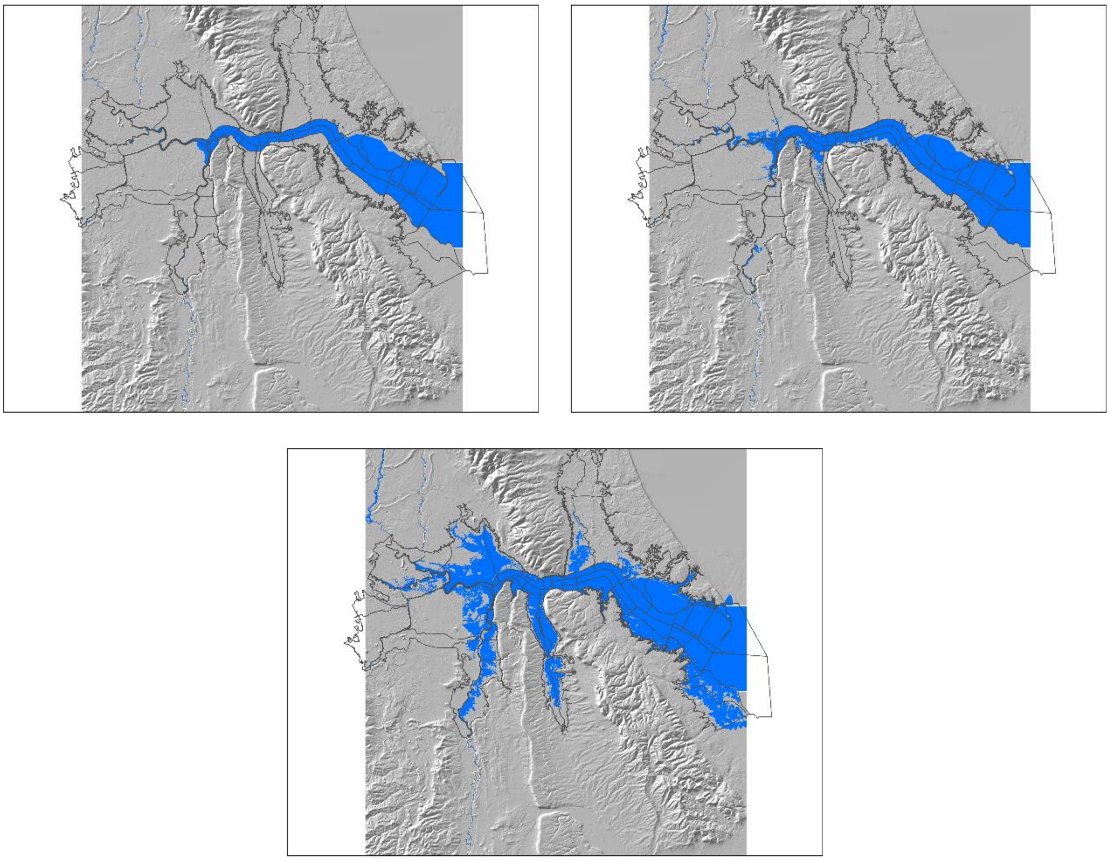

Figure 9.1 – Flood extents for Measure 30 with a 1-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

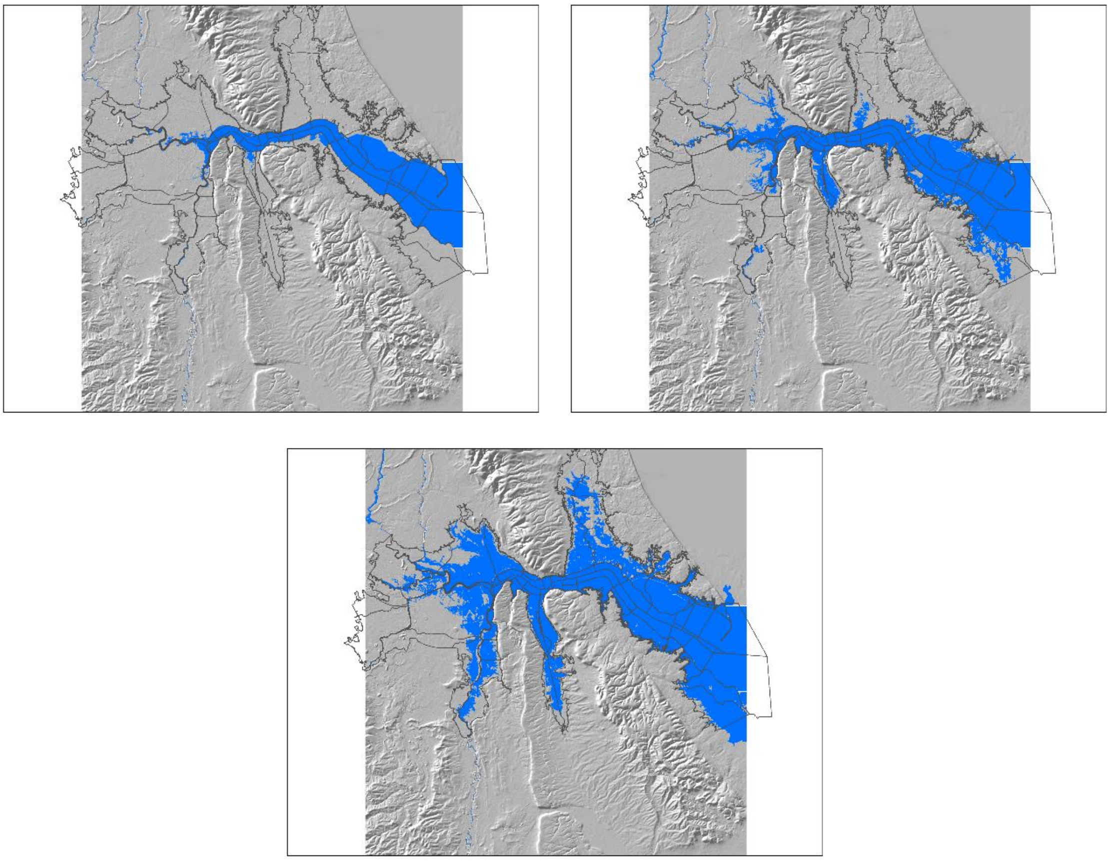

Figure 9.2 – Flood extents for Measure 30 with a 200-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

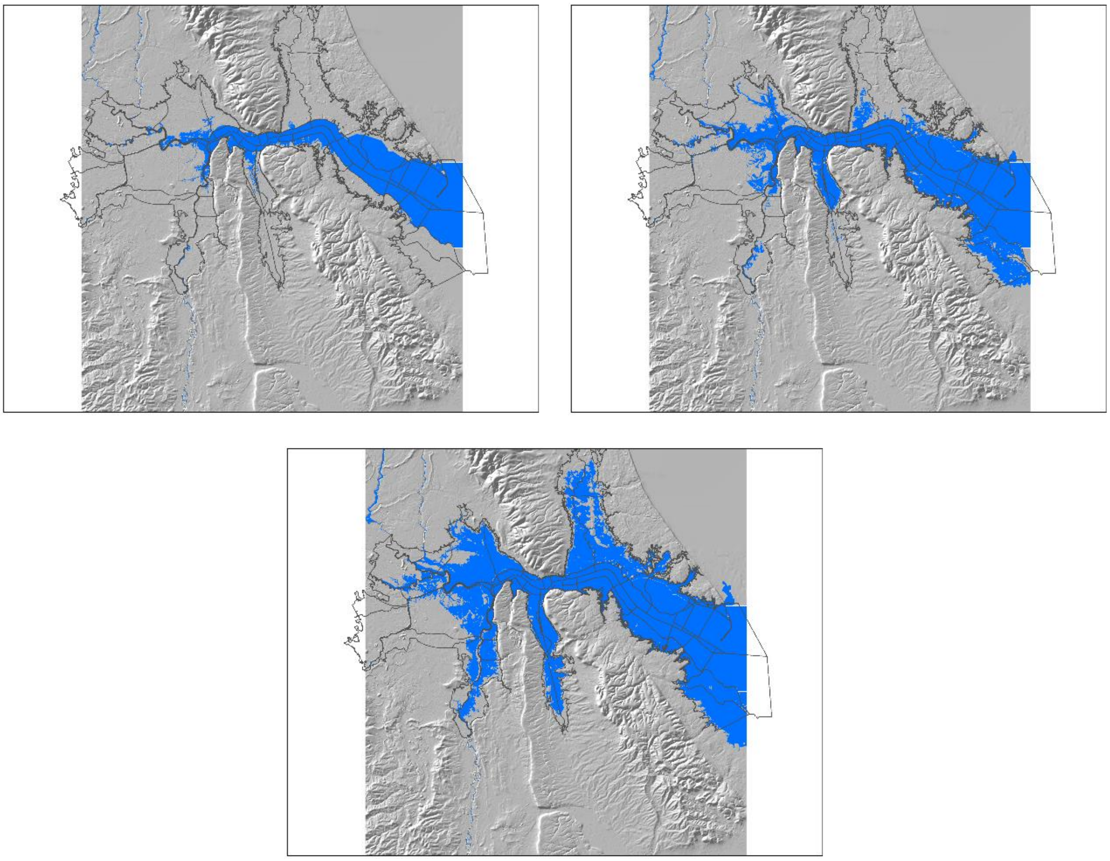

Figure 9.3 – Flood extents for Measure 30 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

3.8 Measure 23 – Managed Realignment at Adlingfleet, Broomfleet, Faxfleet and Sunk Island, Cherry Cobb Sands, Winteringham Ings and Goxhill

Flood defences are as described in Measure 30, but with the addition of the Goxhill site (see Figures 8.1 and 8.2). Estuary facing defences were degraded by setting elevations to the mean of the surrounding pixels.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.8.1 Results

Ten out of the 12 model scenarios reduced the mean flood volume in comparison to the Baseline, while two (1-year return period event with +0 and +0.5 m SLR) resulted in an increase in mean flood volumes above the Baseline (Tables 10.1 and 10.2). In comparison to the Baseline, the largest decreases of mean flood volume occurred for the +2 m SLR model scenarios, with decreases of −718.4 × 10^6 m^3 (1000-year return period), −573.0 × 10^6 m^3 (200-year return period) and −349.0 × 10^6 m^3 (1-year return period). The largest decreases in mean flood volume in comparison to the Baseline occurred locally at South Bank Inner, Hull, and North Bank Outer (Figures 10.1 to 10.3). Tables 10.3 and 10.4 show that changes to mean stages varied strongly with sea level rise, with values varying from −0.16 m at present day sea levels to +0.12 m for +2.0 m SLR for the 1-year return period flood and from +0.02 m at present day sea levels to +0.16 m for +2.0 m SLR for the 1000-year return period event.

Table 10.1 – Flood volumes by Area for Measure 23.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.83	44.68	0.13	6.84	28.55	91.97	2.88	21.90	46.64	123.01
South Bank Outer	0.00	0.00	0.01	40.53	0.00	1.70	23.11	168.64	0.21	12.55	55.21	218.86
Hull	0.00	0.00	0.01	7.43	0.01	0.36	3.67	99.60	0.05	1.97	10.12	182.70
Grimsby	0.00	0.00	0.00	16.18	0.00	0.08	7.43	152.43	0.01	2.37	31.40	202.41
North Bank Inner	0.00	0.00	0.78	30.62	0.32	3.36	11.02	57.88	1.45	8.75	16.31	69.84
South Bank Inner	0.00	0.00	0.47	78.99	0.07	7.51	42.56	135.41	2.24	25.25	80.61	153.66
Ouse-Trent	1.10	1.70	5.33	123.87	2.03	12.87	38.65	263.06	6.09	26.57	58.23	334.09
All	**1.10**	**1.71**	**7.43**	**342.29**	**2.56**	**32.74**	**154.99**	**969.00**	**12.92**	**99.36**	**298.52**	**1284.57**

Table 10.2 – Change in Flood volumes by Area for Measure 23 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.03	-9.21	-0.04	0.40	-3.64	-142.87	0.14	-0.95	-21.86	-226.18
South Bank Outer	0.00	0.00	0.00	2.36	0.00	0.25	1.25	3.06	0.02	0.85	1.99	3.57
Hull	0.00	0.00	0.00	1.45	0.00	0.08	1.13	-103.89	0.01	0.59	0.26	-163.96
Grimsby	0.00	0.00	0.00	-70.52	0.00	0.06	-11.05	-10.84	0.00	1.47	-29.12	2.64
North Bank Inner	0.00	-0.22	-1.69	-15.03	-0.85	-2.94	-2.38	-10.40	-2.49	-1.72	-3.18	-9.41
South Bank Inner	0.00	-0.05	-8.46	-178.47	-3.21	-26.16	-69.40	-226.68	-16.47	-50.63	-95.51	-249.34
Ouse-Trent	1.04	0.99	-5.20	-79.55	-1.83	-5.65	-6.78	-81.33	-5.67	-4.53	-8.62	-75.75
All	**1.03**	**0.72**	**-15.32**	**-348.96**	**-5.94**	**-33.96**	**-90.88**	**-572.95**	**-24.46**	**-54.92**	**-156.04**	**-718.42**

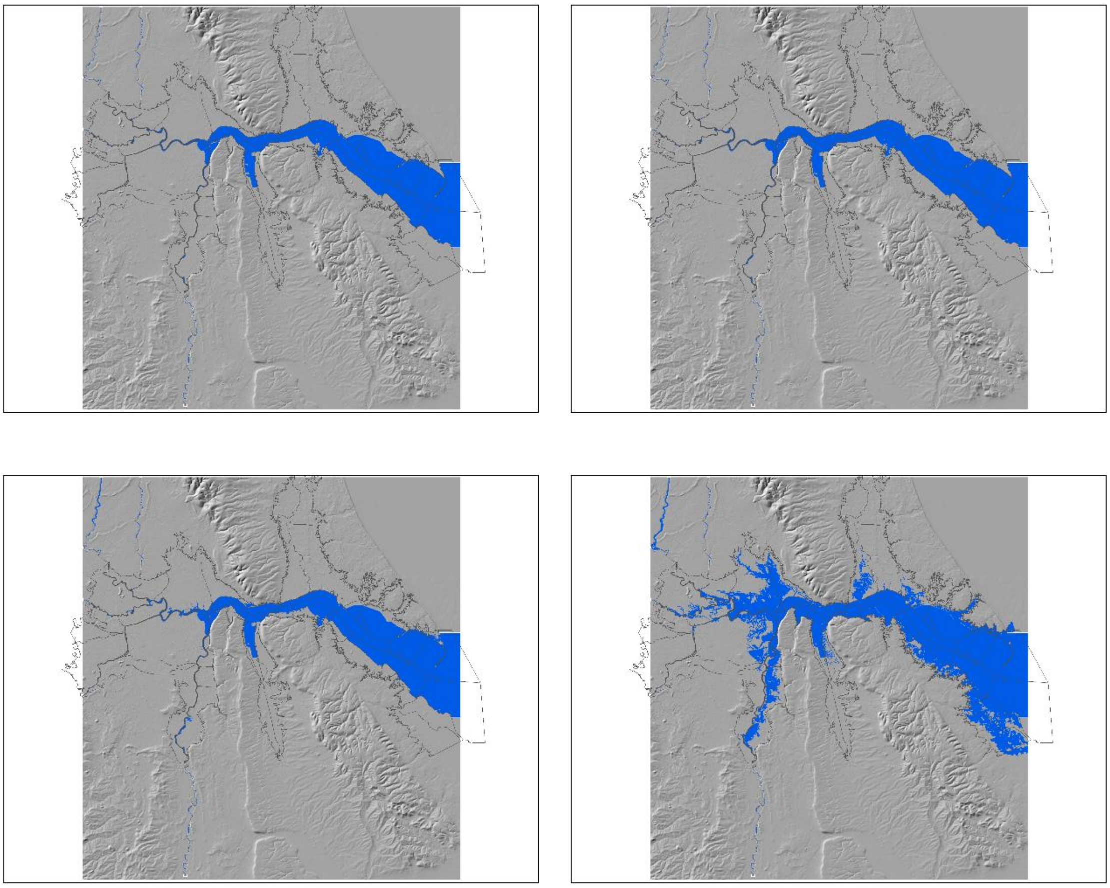

Figure 10.1 – Flood extents for Measure 23 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

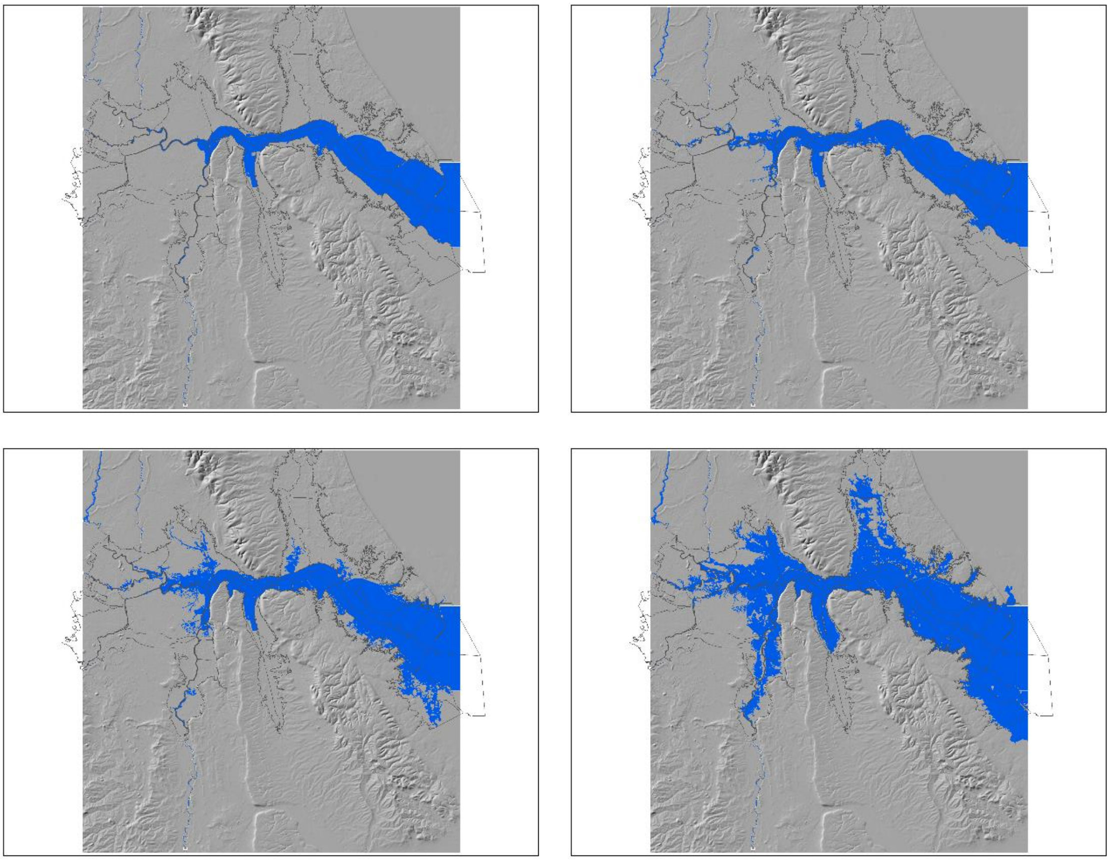

Figure 10.2 – Flood extents for Measure 23 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 10.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 23.

	Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	0	50	100	200	0	50	100	200	0	50	100	200
Spurn	4.16	4.67	5.18	6.25	5.01	5.58	6.11	7.01	5.38	5.92	6.39	7.31
Grimsby	4.23	4.86	5.44	6.43	5.26	5.77	6.27	7.08	5.59	6.10	6.54	7.31
Immingham	4.42	5.01	5.57	6.58	5.40	5.96	6.44	7.11	5.76	6.28	6.67	7.27
Sunk Island	4.24	4.85	5.43	6.43	5.26	5.77	6.28	7.08	5.59	6.11	6.54	7.33
King George's Dock	4.55	5.17	5.72	6.57	5.57	6.06	6.48	7.03	5.89	6.35	6.67	7.21
Albert Dock	4.56	5.18	5.71	6.53	5.56	6.04	6.43	7.01	5.87	6.32	6.62	7.20
Humber Bridge	4.58	5.14	5.62	6.37	5.49	5.92	6.26	7.07	5.78	6.14	6.44	7.23
Brough	4.61	5.16	5.69	6.50	5.51	6.05	6.40	7.06	5.86	6.26	6.58	7.16
West Walker Dyke	4.71	5.29	5.78	6.46	5.62	6.05	6.37	6.93	5.91	6.29	6.49	7.02
Blacktoft Jetty	4.76	5.35	5.80	6.26	5.69	6.02	6.21	6.51	5.90	6.16	6.28	6.54
Flixborough	4.88	5.46	5.92	6.27	5.82	6.07	6.23	6.42	6.01	6.20	6.29	6.43
Goole	4.73	5.34	5.81	6.05	5.68	5.92	6.02	6.15	5.87	5.98	6.06	6.16
Ouse (upstream)	3.80	4.42	4.97	5.23	4.67	5.04	5.07	5.34	4.94	5.06	5.10	5.36
Trent (upstream)	4.32	4.83	5.30	5.80	5.04	5.44	5.72	5.85	5.26	5.60	5.79	5.85
Mean	**4.47**	**5.05**	**5.57**	**6.27**	**5.40**	**5.84**	**6.16**	**6.69**	**5.69**	**6.06**	**6.32**	**6.81**

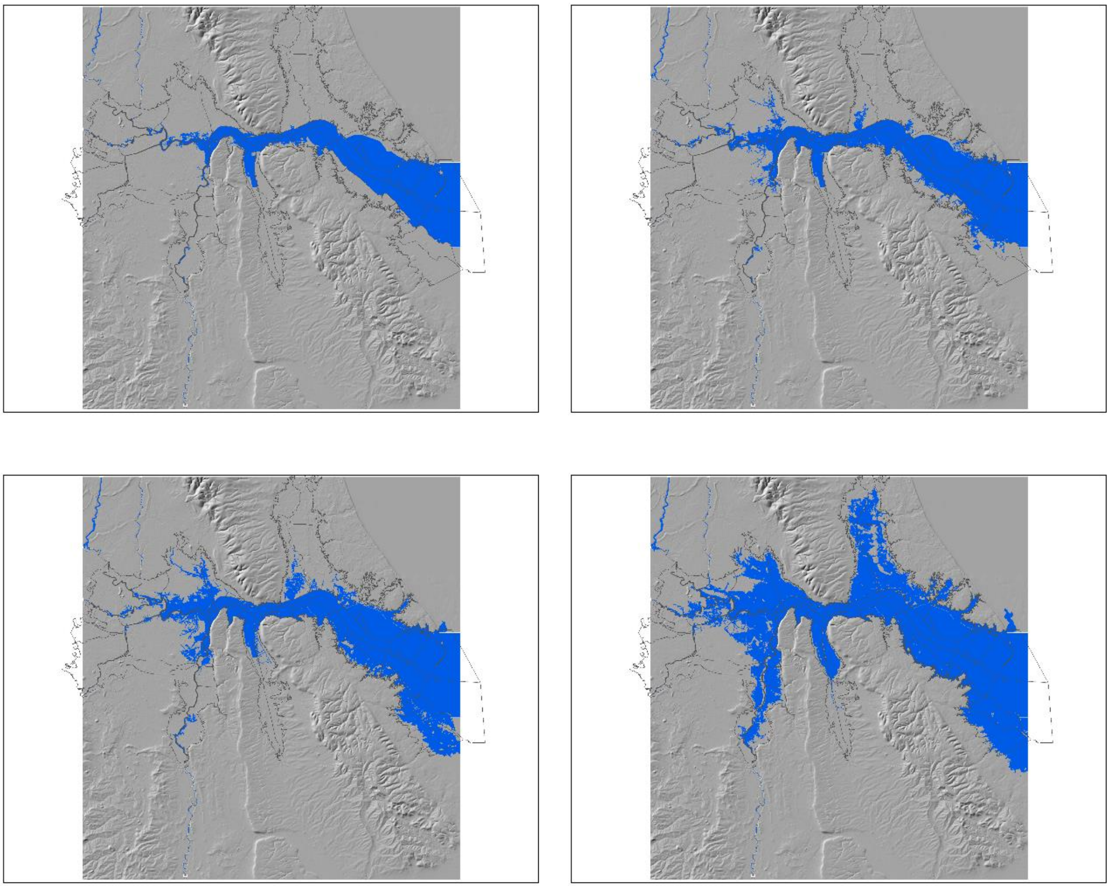

Figure 10.3 – Flood extents for Measure 23 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 10.4 – Change to the maximum stage for Measure 23 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	-0.03	-0.04	-0.03	0.07	-0.04	0.04	0.08	0.05	0.01	0.05	0.06	0.05
Grimsby	-0.13	0.00	0.10	0.15	0.07	0.08	0.14	0.16	0.08	0.13	0.16	0.14
Immingham	-0.08	0.01	0.09	0.24	0.07	0.15	0.22	0.19	0.12	0.19	0.25	0.15
Sunk Island	-0.11	0.01	0.10	0.15	0.07	0.10	0.14	0.16	0.09	0.13	0.16	0.15
King George's Dock	-0.09	0.02	0.08	0.21	0.09	0.13	0.21	0.10	0.10	0.18	0.25	0.12
Albert Dock	-0.09	0.01	0.04	0.15	0.04	0.09	0.16	0.11	0.06	0.13	0.20	0.14
Humber Bridge	-0.20	-0.17	-0.18	-0.02	-0.17	-0.12	-0.03	0.21	-0.14	-0.08	0.07	0.24
Brough	-0.37	-0.37	-0.28	0.14	-0.34	-0.08	0.11	0.33	-0.20	0.03	0.22	0.35
West Walker Dyke	-0.39	-0.36	-0.21	0.15	-0.29	-0.05	0.10	0.35	-0.14	0.05	0.17	0.38
Blacktoft Jetty	-0.38	-0.30	-0.12	0.13	-0.19	-0.01	0.10	0.25	-0.07	0.06	0.14	0.24
Flixborough	-0.39	-0.32	-0.12	0.12	-0.19	-0.01	0.09	0.19	-0.05	0.07	0.13	0.19
Goole	-0.44	-0.35	-0.10	0.07	-0.20	-0.03	0.05	0.06	-0.06	0.02	0.08	0.05
Ouse (upstream)	0.22	0.27	0.26	0.07	0.28	0.10	0.00	0.01	0.24	0.02	0.00	0.01
Trent (upstream)	0.21	0.21	0.21	0.02	0.25	0.21	0.10	0.01	0.24	0.15	0.02	0.01
Mean	**-0.16**	**-0.10**	**-0.01**	**0.12**	**-0.04**	**0.04**	**0.10**	**0.16**	**0.02**	**0.08**	**0.14**	**0.16**

Hard Defence Measures

The following eight measures all model the use of flood defence barriers to keep out flood waters, thereby protecting specific areas. This includes the construction of hard engineering structures such as flood walls, tidal barriers, and groynes to keep out the tide.

3.9 Measure 2 – Degraded Defences

This scenario is intended to assess what would happen if current defences were left to degrade and undergo no maintenance. This is an extreme, worst-case-scenario, effectively leaving the Estuary with little or no defences.

The Baseline 2021 defences were degraded by manually reducing the elevation of each pixel with a defence crest by setting the elevation to the mean of the surrounding pixels. This still left an imprint of the defence in situ, but significantly reduced the elevation. This was done for Estuary-only defences, and not the defences within the extended domain.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.9.1 Results

As expected, the degraded defences left the estuary more exposed and increased mean flood volumes above the Baseline (Tables 11.1 and 11.2) estuary-wide for all 12 model scenarios. Relative to the Baseline, mean flood volume increases varied from 1139 × 10^6 m^3 (1-year return period, +0 m SLR scenario) to 2651 × 10^6 m^3 (1000-year return period, +1 m SLR scenario). The worst hit areas locally for all the model scenarios were the Ouse-Trent area and Hull, followed by the south bank inner and north bank outer regions (Figures 11.1 to 11.3). Degraded defences throughout the estuary resulted in mean stage heights decreasing for every model scenario by between −0.75 and −1.26 m, with the largest drops (greater than −3 m) recorded at Flixborough for present day sea levels (Tables 11.3 and 11.4).

Table 11.1 – Flood volumes by Area for Measure 2.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	204.92	262.05	319.24	428.88	294.28	353.50	409.81	522.02	330.38	388.11	443.79	557.70
South Bank Outer	75.84	128.79	181.80	279.68	164.30	216.37	265.04	355.91	197.20	247.77	294.72	385.60
Hull	268.78	427.70	554.09	834.44	381.62	576.52	740.36	1064.99	439.74	649.74	822.50	1160.81
Grimsby	58.14	84.96	107.62	150.98	100.52	121.35	144.13	186.81	114.71	135.73	158.26	201.52
North Bank Inner	40.81	50.86	61.24	87.75	54.29	64.33	75.85	104.45	59.40	69.69	82.10	110.96
South Bank Inner	202.55	273.52	334.71	446.73	275.57	349.31	410.52	533.21	306.08	378.36	441.07	570.33
Ouse-Trent	287.64	422.57	621.37	1190.33	386.95	567.76	789.74	1423.92	436.41	631.71	863.13	1522.08
All	**1138.69**	**1650.45**	**2180.06**	**3418.78**	**1657.55**	**2249.14**	**2835.46**	**4191.30**	**1883.91**	**2501.11**	**3105.58**	**4508.99**

Table 11.2 – Change in Flood volumes by Area for Measure 2 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	204.92	262.04	318.43	374.99	294.10	347.06	377.62	287.18	327.64	365.26	375.29	208.51
South Bank Outer	75.84	128.79	181.78	241.51	164.30	214.91	243.18	190.34	197.01	236.08	241.51	170.30
Hull	268.78	427.70	554.08	828.47	381.61	576.24	737.82	861.49	439.69	648.36	812.64	814.15
Grimsby	58.14	84.96	107.62	64.29	100.52	121.33	125.64	23.54	114.71	134.83	97.75	1.76
North Bank Inner	40.81	50.64	58.77	42.10	53.12	58.03	62.46	36.17	55.46	59.22	62.61	31.71
South Bank Inner	202.55	273.47	325.78	189.27	272.30	315.64	298.56	171.12	287.37	302.48	264.96	167.33
Ouse-Trent	287.58	421.86	610.84	986.90	383.09	549.24	744.31	1079.52	424.65	600.61	796.29	1112.24
All	**1138.63**	**1649.46**	**2157.31**	**2727.53**	**1649.04**	**2182.44**	**2589.59**	**2649.35**	**1846.53**	**2346.84**	**2651.03**	**2506.00**

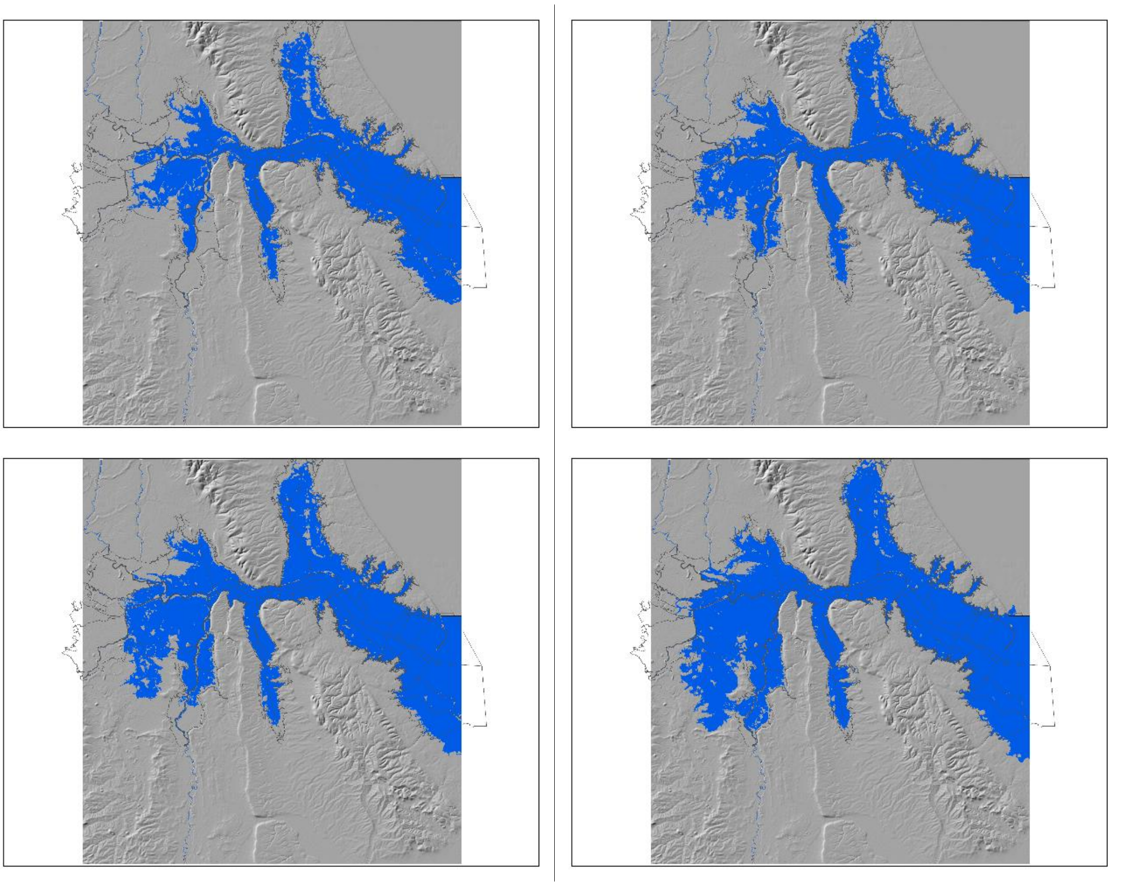

Figure 11.1 – Flood extents for Measure 2 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

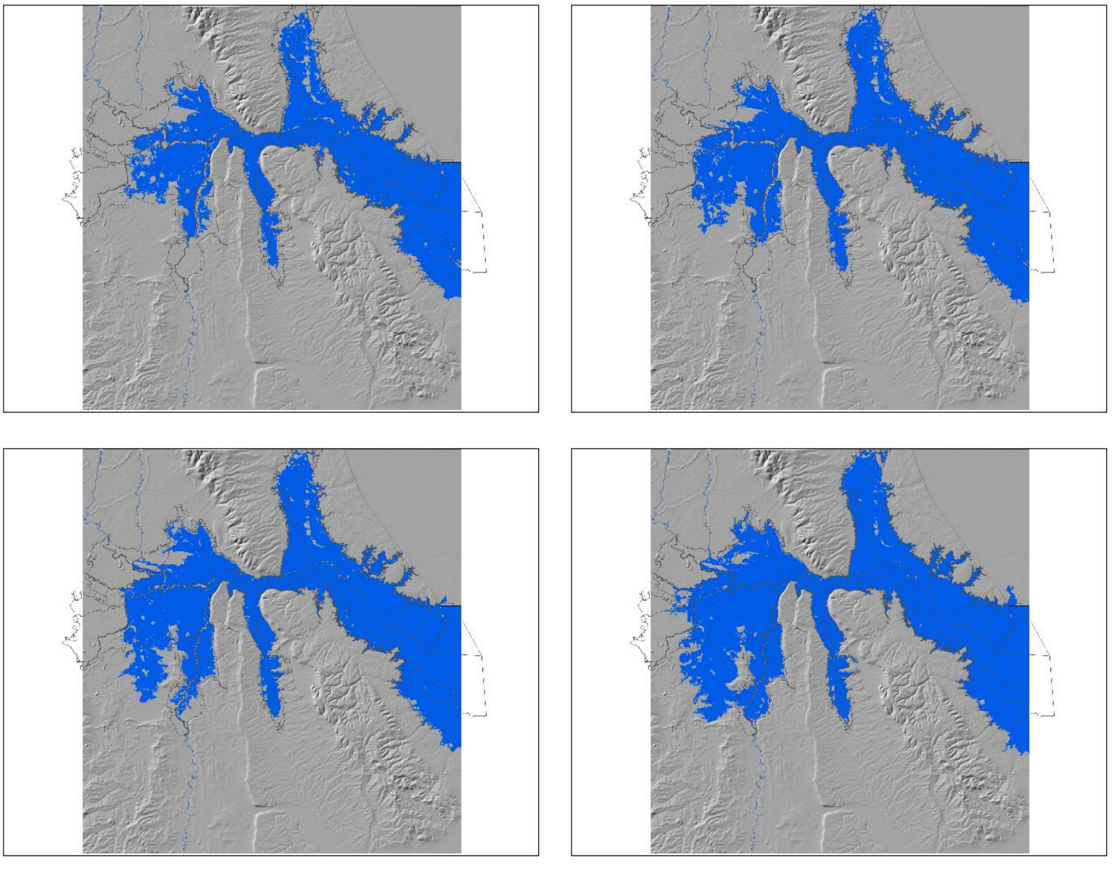

Figure 11.2 – Flood extents for Measure 2 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 11.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 2.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.15	4.65	5.13	6.16	4.98	5.49	6.00	6.97	5.28	5.81	6.33	7.29
Grimsby	4.19	4.69	5.24	6.21	5.04	5.57	6.06	6.97	5.39	5.87	6.36	7.26
Immingham	4.24	4.76	5.27	6.17	5.07	5.59	6.04	6.89	5.42	5.88	6.32	7.16
Sunk Island	4.20	4.69	5.24	6.22	5.03	5.58	6.07	6.99	5.40	5.89	6.37	7.28
King George's Dock	4.24	4.71	5.16	5.92	5.00	5.43	5.80	6.52	5.28	5.67	6.04	6.78
Albert Dock	4.23	4.68	5.10	5.82	4.95	5.36	5.71	6.42	5.22	5.59	5.92	6.68
Humber Bridge	4.12	4.53	4.90	5.53	4.77	5.12	5.41	6.08	5.00	5.30	5.60	6.32
Brough	3.91	4.25	4.55	5.06	4.43	4.74	4.96	5.48	4.59	4.88	5.09	5.66
West Walker Dyke	3.59	3.86	4.11	4.57	3.99	4.23	4.41	4.92	4.13	4.33	4.51	5.06
Blacktoft Jetty	2.88	3.15	3.44	4.14	3.22	3.48	3.78	4.49	3.34	3.60	3.92	4.62
Flixborough	2.61	2.80	3.15	3.95	2.80	3.12	3.46	4.29	2.90	3.25	3.58	4.42
Goole	2.68	2.94	3.23	3.99	2.97	3.23	3.54	4.33	3.09	3.35	3.66	4.46
Ouse (upstream)	2.95	3.23	3.55	4.33	3.25	3.54	3.87	4.69	3.35	3.67	4.00	4.83
Trent (upstream)	2.76	3.08	3.54	4.35	3.10	3.52	3.89	4.71	3.26	3.67	4.01	4.84
Mean	**3.63**	**4.00**	**4.40**	**5.17**	**4.19**	**4.57**	**4.93**	**5.70**	**4.40**	**4.77**	**5.12**	**5.90**

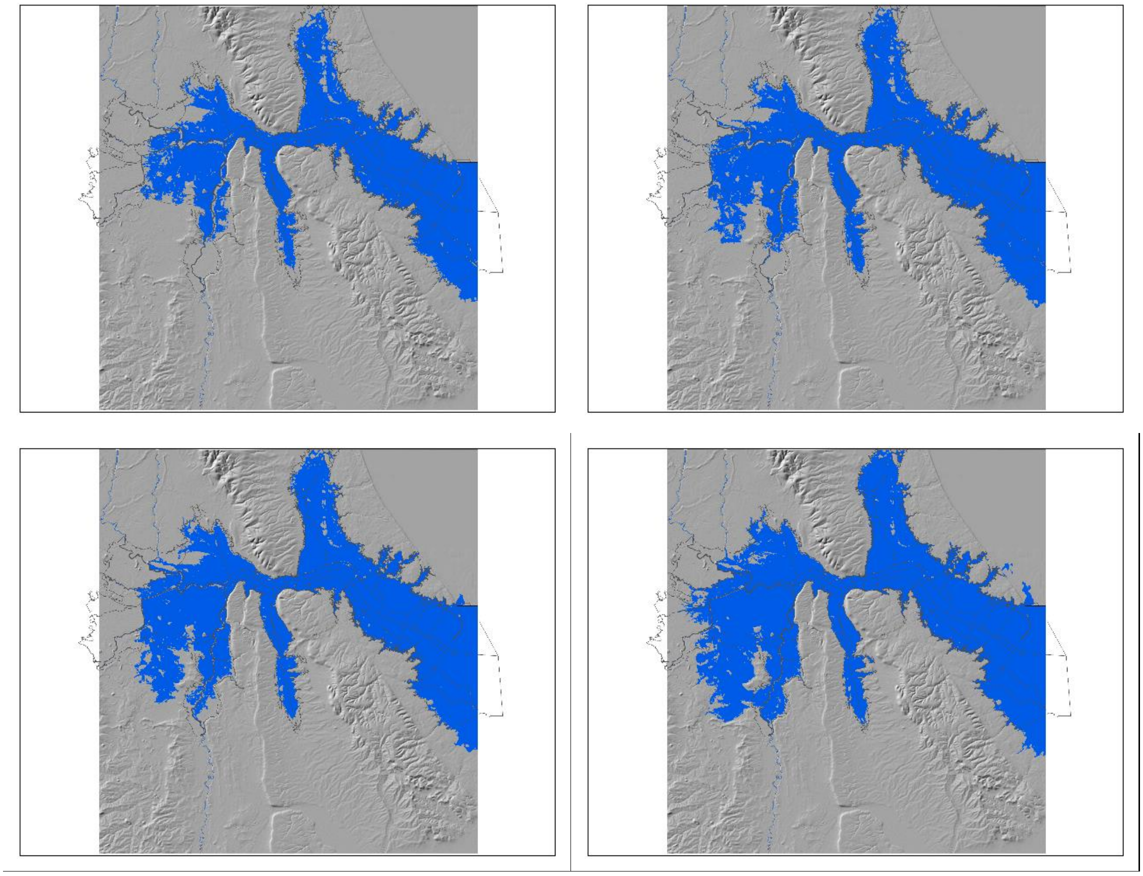

Figure 11.3 – Flood extents for Measure 2 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 11.4 – Change to the maximum stage for Measure 2 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	-0.05	-0.06	-0.08	-0.02	-0.07	-0.06	-0.04	0.01	-0.09	-0.05	0.00	0.02
Grimsby	-0.17	-0.17	-0.10	-0.08	-0.15	-0.12	-0.07	0.05	-0.11	-0.10	-0.02	0.10
Immingham	-0.26	-0.23	-0.22	-0.16	-0.26	-0.22	-0.18	-0.02	-0.22	-0.21	-0.10	0.04
Sunk Island	-0.15	-0.15	-0.09	-0.07	-0.15	-0.10	-0.06	0.06	-0.11	-0.09	-0.02	0.10
King George's Dock	-0.39	-0.43	-0.48	-0.44	-0.48	-0.50	-0.47	-0.40	-0.50	-0.50	-0.39	-0.31
Albert Dock	-0.43	-0.49	-0.57	-0.55	-0.56	-0.60	-0.57	-0.49	-0.59	-0.60	-0.49	-0.39
Humber Bridge	-0.65	-0.77	-0.90	-0.87	-0.88	-0.93	-0.88	-0.78	-0.92	-0.92	-0.78	-0.68
Brough	-1.07	-1.28	-1.42	-1.30	-1.42	-1.39	-1.33	-1.25	-1.47	-1.34	-1.28	-1.15
West Walker Dyke	-1.51	-1.78	-1.88	-1.74	-1.93	-1.87	-1.86	-1.66	-1.93	-1.90	-1.81	-1.58
Blacktoft Jetty	-2.26	-2.51	-2.48	-1.99	-2.66	-2.56	-2.33	-1.78	-2.63	-2.50	-2.22	-1.68
Flixborough	-2.66	-2.98	-2.89	-2.21	-3.20	-2.97	-2.68	-1.94	-3.16	-2.87	-2.58	-1.82
Goole	-2.49	-2.75	-2.68	-1.99	-2.90	-2.71	-2.43	-1.76	-2.84	-2.62	-2.32	-1.65
Ouse (upstream)	-0.63	-0.92	-1.16	-0.83	-1.14	-1.40	-1.20	-0.63	-1.35	-1.38	-1.11	-0.52
Trent (upstream)	-1.35	-1.54	-1.55	-1.43	-1.69	-1.71	-1.73	-1.13	-1.77	-1.78	-1.76	-1.01
Mean	**-1.01**	**-1.15**	**-1.18**	**-0.98**	**-1.25**	**-1.22**	**-1.13**	**-0.84**	**-1.26**	**-1.20**	**-1.06**	**-0.75**

3.10 Measure 31 – Middle Estuary Barrier

Measure 31 inserted a tidal barrier in the Middle Estuary, in the vicinity of the Humber Bridge (Figure 12.1). All flood defences were set as per the Baseline (2021 defences). The barrier was raised at the lowest tidal height prior to the storm surge and lowered at the following lowest tidal height.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1- , 200- and 1000-year return period events and with 0 m sea level rise (SLR), resulting in three scenarios.
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

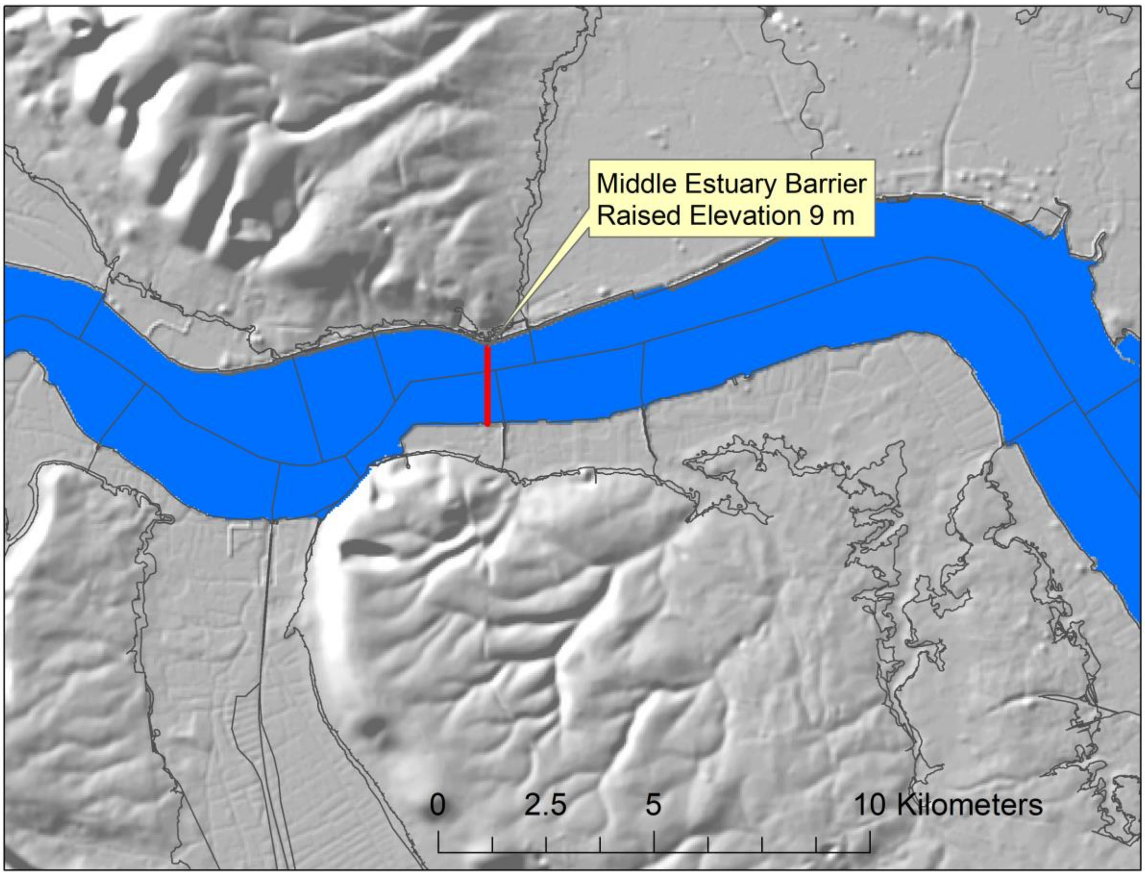

Figure 12.1 – The configuration of measure 31.

3.10.1 Results

For present day sea levels, Measure 31 reduced mean flood volumes relative to the Baseline by −0.07 × 10^6 m^3, −0.89 × 10^6 m^3, and −14.33 × 10^6 m^3 for the 1-, 200-, and 1000-year events, respectively (Table 12.1). The 1-year event resulted in no overbank flooding, whereas flooding occurred locally during the 200- and 1000-year events primarily in the South Bank Inner region, and to a lesser extent in the North Bank Outer region (Figure 12.2). Table 12.2 shows that mean stages were reduced in each flood scenario relative to the Baseline by −0.23 m, −0.5 m, and −0.55 m for the 1-, 200-, and 1000-year events, respectively. Stages increased from the estuary mouth to a peak at Albert Dock with a sharp decrease at the Humber bridge.

Table 12.1 – Flood volumes by Area for Measure 31.

	Flood Volumes (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.33	3.41
South Bank Outer	0.00	0.00	0.31
Hull	0.00	0.04	0.35
Grimsby	0.00	0.00	0.01
North Bank Inner	0.00	0.00	0.00
South Bank Inner	0.00	7.22	18.92
Ouse-Trent	0.00	0.02	0.04
All	**0.00**	**7.61**	**23.05**

Table 12.2 – Maximum stages at tidal gauges throughout the Estuary for Measure 31.

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	4.24	5.10	5.40
Grimsby	4.51	5.31	5.62
Immingham	4.80	5.56	5.81
Sunk Island	4.50	5.30	5.60
King George's Dock	5.10	5.80	5.98
Albert Dock	5.15	5.83	6.01
Humber Bridge	4.14	4.52	4.67
Brough	4.35	4.74	4.87
West Walker Dyke	4.43	4.83	4.98
Blacktoft Jetty	4.48	4.88	5.02
Flixborough	4.61	5.02	5.16
Goole	4.55	4.92	5.06
Ouse (upstream)	3.12	3.40	3.51
Trent (upstream)	3.66	3.91	4.01
Mean	**4.40**	**4.94**	**5.12**

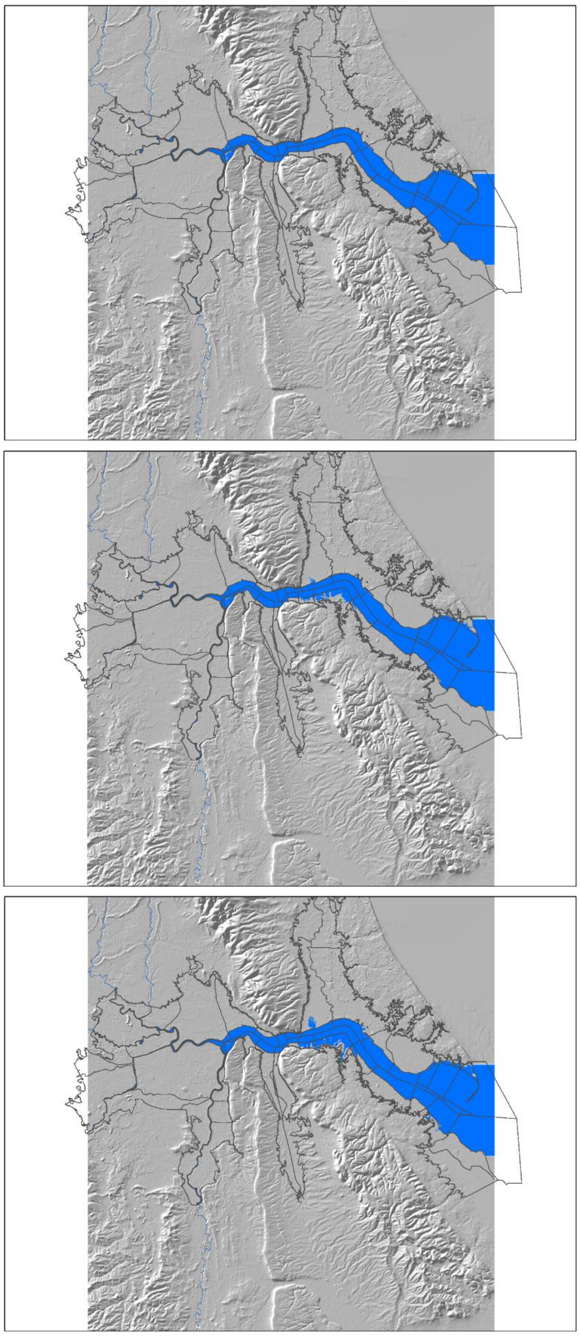

Figure 12.2 – Flood extents for Measure 31. Top with a 1-year return period, middle with a 200-year return period and bottom with a 1000-year return period.

3.11 Measure 32 – Middle Estuary Barrier with seaward defences raised by 1 m

Flood defences were set as per the Baseline (2021 defences), but all defences seaward (east) of the barrier installed in the middle estuary near Humber Bridge were raised by 1 m. The location of the barrier and the area of raised defences is shown in Figure 12.1. The barrier was raised at the lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0 m sea level rise (SLR), resulting in three scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.11.1 Results

As might be expected, improving the seaward defences by raising them by 1 m made no difference to flood volumes for a 1-year return period event (Table 13.1). However, for the larger 200- and 1000-year events, mean flood volumes were reduced by -8.35×10^6 m^3 and -36.85×10^6 m^3, respectively, in comparison to the Baseline. Locally, the South Bank Inner region had much reduced flood volumes in comparison to Measure 31 with the Baseline defences (Table 13.1), resulting in the North Bank Outer region having the highest local flood volumes (but still reduced from Measure 31) (Figure 13.1). Table 13.2 shows that mean stages did not change for the 1-year event between Measures 31 and 32 but increased slightly (between +0.01 and +0.03 m) for the larger events. Seaward of the barrier, stages were increased relative to the Baseline with only small increases in comparison to the present-day defences case, but stages landward of the barrier did not change relative to Measure 31 (compare with Table 12.2).

Table 13.1 – Flood volumes by Area for Measure 32.

	Flood Volumes (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.09	0.27
South Bank Outer	0.00	0.00	0.11
Hull	0.00	0.00	0.00
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	0.00	0.00
South Bank Inner	0.00	0.04	0.11
Ouse-Trent	0.00	0.02	0.04
All	**0.00**	**0.15**	**0.53**

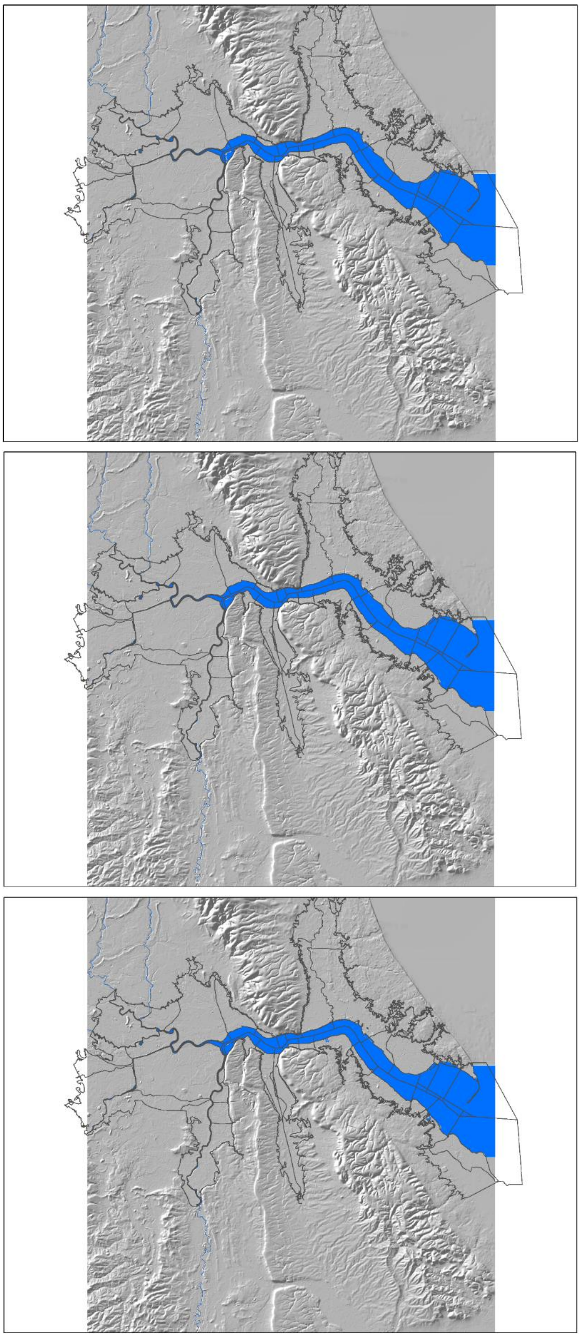

Figure 13.1 – Flood extents for Measure 32. Top with a 1-year return period, middle with a 200-year return period and bottom with a 1000-year return period.

Table 13.2 – Maximum stages at tidal gauges throughout the Estuary for Measure 32.

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	4.24	5.10	5.41
Grimsby	4.51	5.32	5.64
Immingham	4.80	5.58	5.87
Sunk Island	4.50	5.30	5.62
King George's Dock	5.10	5.84	6.11
Albert Dock	5.15	5.88	6.14
Humber Bridge	4.14	4.52	4.67
Brough	4.35	4.74	4.87
West Walker Dyke	4.43	4.83	4.98
Blacktoft Jetty	4.48	4.88	5.02
Flixborough	4.61	5.02	5.16
Goole	4.55	4.92	5.06
Ouse (upstream)	3.12	3.40	3.51
Trent (upstream)	3.66	3.91	4.01
Mean	**4.40**	**4.95**	**5.15**

3.12 Measure 33 – Sunk Island (Outer estuary) Barrier

The main flood defence for this scenario was a barrier installed at Sunk Island in the Outer estuary (Figure 14.1). The barrier was raised to an elevation of 8.5 m at the point of lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide. There were no further changes to defences.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0 and 1 m sea level rise (SLR), resulting in six scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

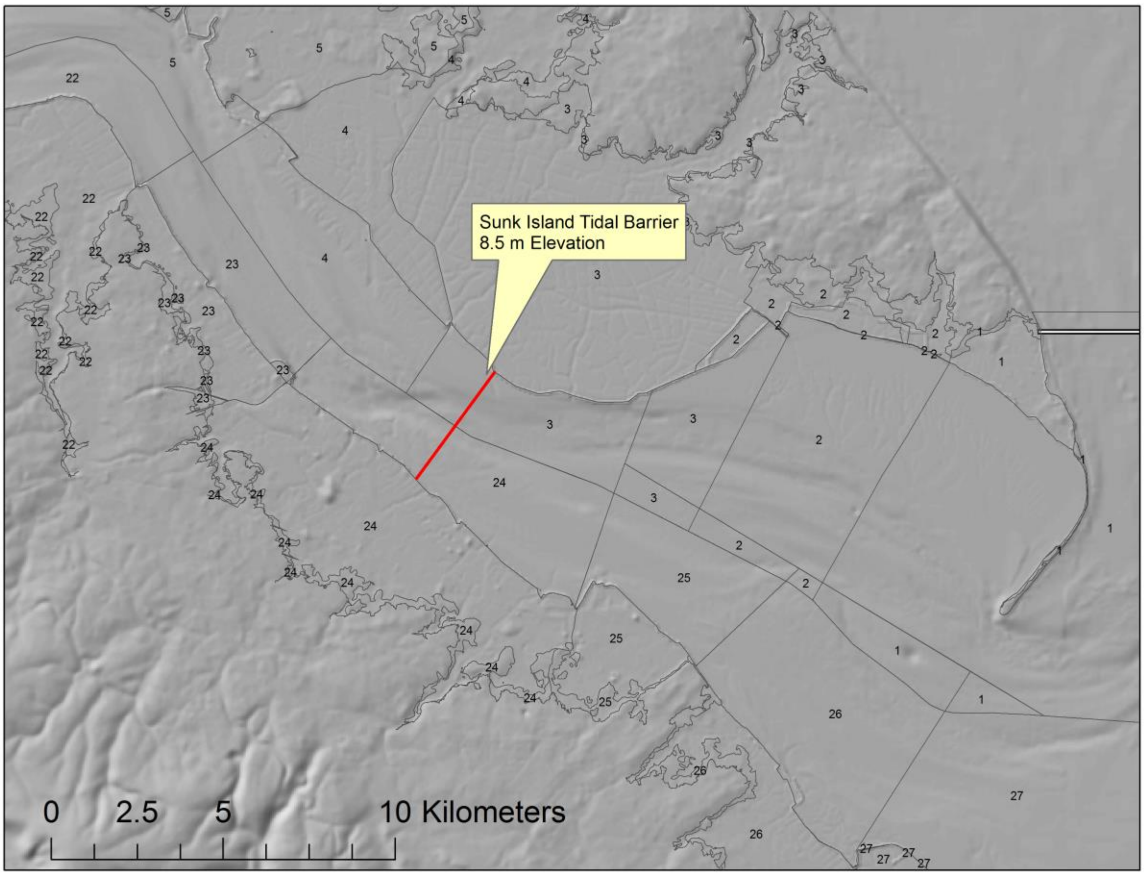

Figure 14.1 – Configuration of the Sunk Island Tidal Barrier in the Outer estuary.

3.12.1 Results

The addition of the Sunk Island barrier reduced mean flood volume relative to the Baseline in all six scenarios (Tables 14.1 and 14.2). For present day sea levels, flood volume was reduced by −0.06, −8.37, and −34.96 × 10^6 m^3 in comparison to the Baseline for a 1-, 200-, and 1000-year event, respectively, and −19.53, −185.5, and −313.4 × 10^6 m^3 for +1 m of SLR. The barrier resulted in the largest flood volume reductions relative to the Baseline landward of Grimsby (Table 14.2) but the North and South Bank Outer regions suffered the highest flood volumes, particularly for +1 m SLR scenarios (Table 14.1, Figures 14.2 to 14.4). Maximum stage levels (Table 14.3) were reduced in comparison to the Baseline throughout the estuary for every scenario modelled (Table 14.4). Locally, the impact of the barrier on stages was felt most strongly immediately landward (upstream) of the barrier, between the tidal gauges at Albert Dock and King George's Dock in Hull and Immingham.

Table 14.1 – Flood volumes by Area for Measure 33.

	Flood Volumes (10^6 m^3)					
Return Period (yrs)	**1**	**1**	**200**	**200**	**1000**	**1000**
SLR (cm)	**0**	**100**	**0**	**100**	**0**	**100**
North Bank Outer	0.00	0.58	0.11	28.34	2.26	55.83
South Bank Outer	0.00	0.00	0.00	20.56	0.12	52.21
Hull	0.00	0.00	0.00	0.01	0.00	0.16
Grimsby	0.00	0.00	0.00	1.14	0.00	10.69
North Bank Inner	0.00	0.13	0.00	1.63	0.00	3.01
South Bank Inner	0.00	0.01	0.00	2.58	0.00	8.68
Ouse-Trent	0.00	2.50	0.02	6.07	0.03	10.58
All	**0.00**	**3.23**	**0.13**	**60.33**	**2.42**	**141.16**

Table 14.2 – Change in Flood volumes by Area for Measure 33 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)					
Return Period (yrs)	**1**	**1**	**200**	**200**	**1000**	**1000**
SLR (cm)	**0**	**100**	**0**	**100**	**0**	**100**
North Bank Outer	0.00	-0.23	-0.06	-3.86	-0.47	-12.67
South Bank Outer	0.00	-0.01	0.00	-1.31	-0.07	-1.01
Hull	0.00	-0.01	-0.01	-2.53	-0.04	-9.71
Grimsby	0.00	0.00	0.00	-17.34	0.00	-49.82
North Bank Inner	0.00	-2.33	-1.17	-11.76	-3.94	-16.48
South Bank Inner	0.00	-8.92	-3.27	-109.38	-18.71	-167.44
Ouse-Trent	-0.06	-8.03	-3.85	-39.36	-11.72	-56.27
All	**-0.06**	**-19.53**	**-8.37**	**-185.54**	**-34.96**	**-313.39**

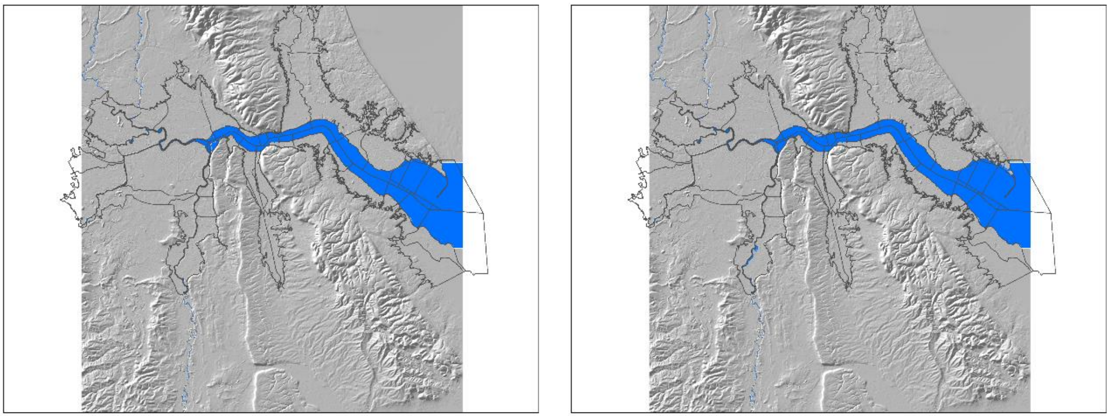

Figure 14.2 – Flood extents for Measure 33 with a 1-year return period. Left with 0 m SLR, right with 1 m SLR.

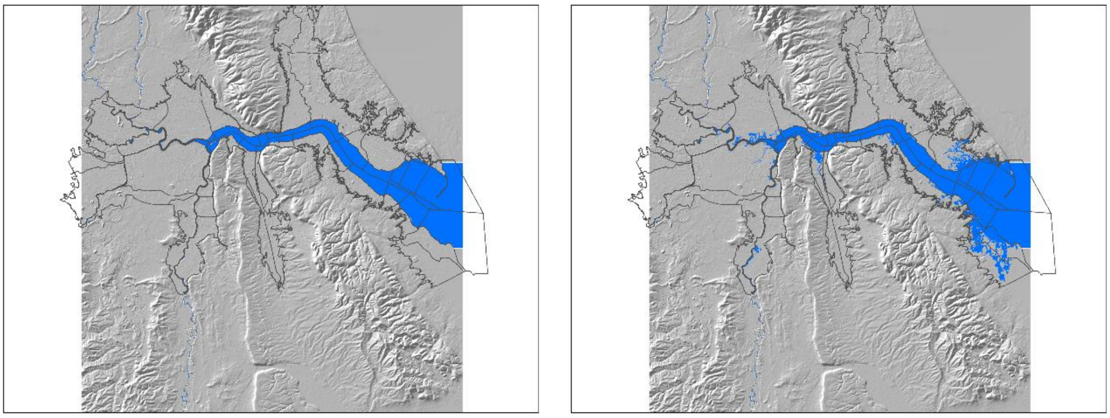

Figure 14.3 – Flood extents for Measure 33 with a 200-year return period. Left with 0 m SLR, right with 1 m SLR.

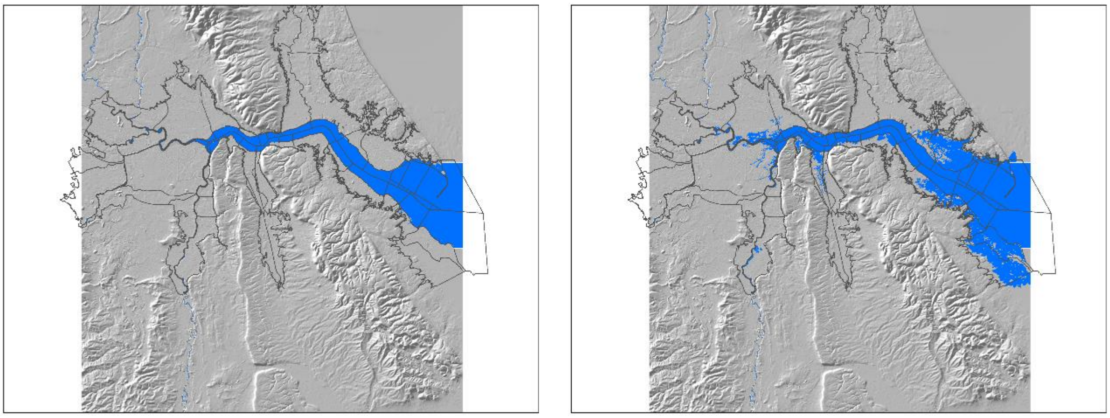

Figure 14.4 – Flood extents for Measure 33 with a 1000-year return period. Left with 0 m SLR, right with 1 m SLR.

Table 14.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 33.

	Maximum Stage Height (m OSN)					
Return Period	**in 1**	**in 1**	**in 200**	**in 200**	**in 1000**	**in 1000**
SLR (cm)	**0**	**100**	**0**	**100**	**0**	**100**
Spurn	4.17	5.20	5.03	6.01	5.35	6.31
Grimsby	4.25	5.23	5.06	6.12	5.42	6.37
Immingham	3.90	4.90	4.27	5.24	4.40	5.38
Sunk Island	4.23	5.26	5.11	6.11	5.42	6.40
King George's Dock	4.02	5.04	4.39	5.40	4.52	5.54
Albert Dock	4.03	5.06	4.40	5.43	4.55	5.57
Humber Bridge	4.14	5.21	4.52	5.59	4.67	5.71
Brough	4.35	5.44	4.74	5.78	4.87	5.90
West Walker Dyke	4.43	5.55	4.83	5.85	4.98	5.94
Blacktoft Jetty	4.48	5.57	4.88	5.83	5.02	5.89
Flixborough	4.61	5.68	5.02	5.97	5.16	6.01
Goole	4.55	5.62	4.92	5.85	5.06	5.89
Ouse (upstream)	3.12	4.18	3.40	4.51	3.51	4.65
Trent (upstream)	3.66	4.64	3.91	4.89	4.01	4.98
Mean	**4.14**	**5.18**	**4.61**	**5.61**	**4.78**	**5.75**

Table 14.4 – Change to the maximum stage for Measure 33 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)					
Return Period	**in 1**	**in 1**	**in 200**	**in 200**	**in 1000**	**in 1000**
SLR (cm)	**0**	**100**	**0**	**100**	**0**	**100**
Spurn	-0.03	-0.01	-0.03	-0.03	-0.02	-0.01
Grimsby	-0.11	-0.11	-0.13	-0.01	-0.09	-0.01
Immingham	-0.60	-0.58	-1.05	-0.97	-1.24	-1.04
Sunk Island	-0.12	-0.08	-0.08	-0.02	-0.09	0.02
King George's Dock	-0.61	-0.59	-1.09	-0.88	-1.26	-0.89
Albert Dock	-0.62	-0.61	-1.11	-0.84	-1.26	-0.84
Humber Bridge	-0.64	-0.59	-1.14	-0.70	-1.25	-0.67
Brough	-0.63	-0.53	-1.12	-0.51	-1.18	-0.46
West Walker Dyke	-0.67	-0.44	-1.08	-0.42	-1.08	-0.38
Blacktoft Jetty	-0.66	-0.35	-0.99	-0.28	-0.95	-0.25
Flixborough	-0.67	-0.36	-0.98	-0.18	-0.91	-0.15
Goole	-0.62	-0.29	-0.95	-0.12	-0.87	-0.09
Ouse (upstream)	-0.46	-0.52	-0.99	-0.57	-1.19	-0.45
Trent (upstream)	-0.45	-0.44	-0.88	-0.73	-1.02	-0.79
Mean	**-0.49**	**-0.39**	**-0.83**	**-0.45**	**-0.89**	**-0.43**

3.13 Measure 16 – Sunk Island (Outer estuary) Barrier, seaward defences raised 1 m

Flood defences were set as per the Baseline (2021 defences), but all defences seaward of the barrier installed at Sunk Island were raised by 1 m. The location of the barrier and the area of raised defences is shown in Figure 14.1. The barrier was raised to an elevation of 8.5 m at the point of lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.13.1 Results

The Sunk Island Tidal barrier was effective at reducing mean flood volumes in comparison to the Baseline in all 12 scenarios. For a 1-year return period event, the barrier resulted in only a small reduction of mean flood volumes, which were confined to the inner estuary (Tables 15.1 and 15.2). Only with a sea level rise of +2 m was the barrier more effective, reducing mean flood volumes by −293 × 10^6 m^3 relative to the Baseline. For 200- and 1000-year return period events, mean flood volumes were reduced by −903 × 10^6 m^3 and −1226 × 10^6 m^3, respectively, for a +2 m sea level rise. For these larger events, Hull only saw significant flood volume reductions with a +2 m sea level rise. Spatial inundation of flooding remained mostly estuary confined for all events until SLR reached +2 m, when the barriers were breached (Figures 15.1 to 15.3). Mean stages were reduced relative to the Baseline in all model scenarios (Tables 15.3 and 15.4) between −0.17 to −0.89 m, however stage levels up-estuary of the barrier at Sunk Island were reduced more than those situated towards to the mouth.

Table 15.1 – Flood volumes by Area for Measure 16.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.13	2.23	0.07	0.41	0.96	51.54	0.24	0.72	4.04	81.49
South Bank Outer	0.00	0.00	0.00	3.98	0.00	0.17	1.48	35.48	0.05	0.82	4.60	68.15
Hull	0.00	0.00	0.00	0.92	0.00	0.00	0.01	4.47	0.00	0.00	0.01	12.33
Grimsby	0.00	0.00	0.00	51.35	0.00	0.00	0.29	89.71	0.00	0.02	1.62	103.85
North Bank Inner	0.00	0.00	0.13	34.75	0.00	0.01	1.63	41.98	0.00	0.14	3.01	45.89
South Bank Inner	0.00	0.00	0.01	165.86	0.00	0.00	2.57	234.76	0.00	0.01	8.68	260.02
Ouse-Trent	0.00	0.17	2.50	139.64	0.02	0.35	6.07	181.39	0.03	0.49	10.58	205.11
All	**0.00**	**0.18**	**2.78**	**398.73**	**0.09**	**0.94**	**13.01**	**639.33**	**0.32**	**2.20**	**32.55**	**776.83**

Table 15.2 – Change in Flood volumes by Area for Measure 16 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.68	-51.66	-0.11	-6.04	-31.24	-183.31	-2.50	-22.13	-64.46	-267.70
South Bank Outer	0.00	0.00	-0.01	-34.19	0.00	-1.28	-20.38	-130.10	-0.14	-10.87	-48.61	-147.15
Hull	0.00	0.00	-0.01	-5.06	-0.01	-0.28	-2.53	-199.02	-0.04	-1.38	-9.86	-334.33
Grimsby	0.00	0.00	0.00	-35.35	0.00	-0.02	-18.20	-73.56	0.00	-0.88	-58.90	-95.92
North Bank Inner	0.00	-0.22	-2.33	-10.89	-1.17	-6.30	-11.76	-26.30	-3.94	-10.33	-16.48	-33.36
South Bank Inner	0.00	-0.06	-8.92	-91.60	-3.27	-33.67	-109.38	-127.33	-18.71	-75.87	-167.43	-142.98
Ouse-Trent	-0.06	-0.54	-8.03	-63.78	-3.85	-18.17	-39.36	-163.01	-11.72	-30.61	-56.26	-204.73
All	**-0.06**	**-0.81**	**-19.98**	**-292.52**	**-8.42**	**-65.76**	**-232.85**	**-902.62**	**-37.06**	**-152.07**	**-422.00**	**-1226.16**

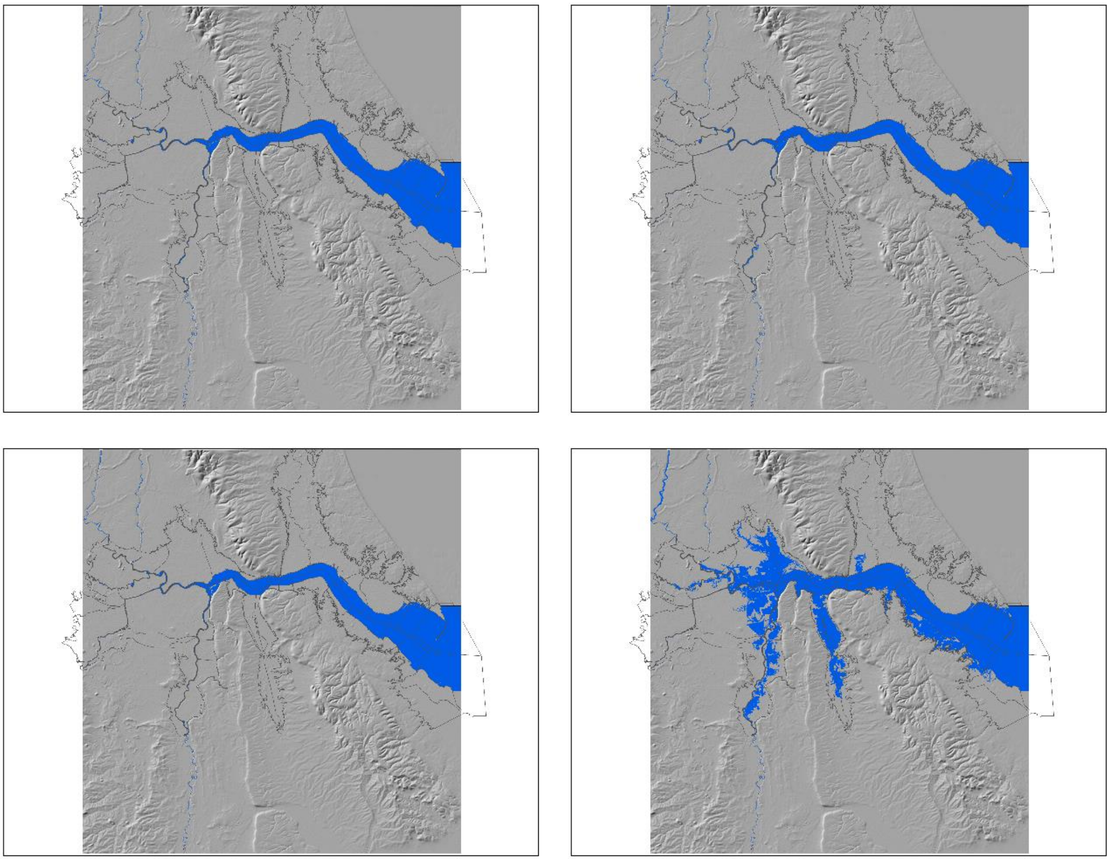

Figure 15.1 – Flood extents for Measure 16 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

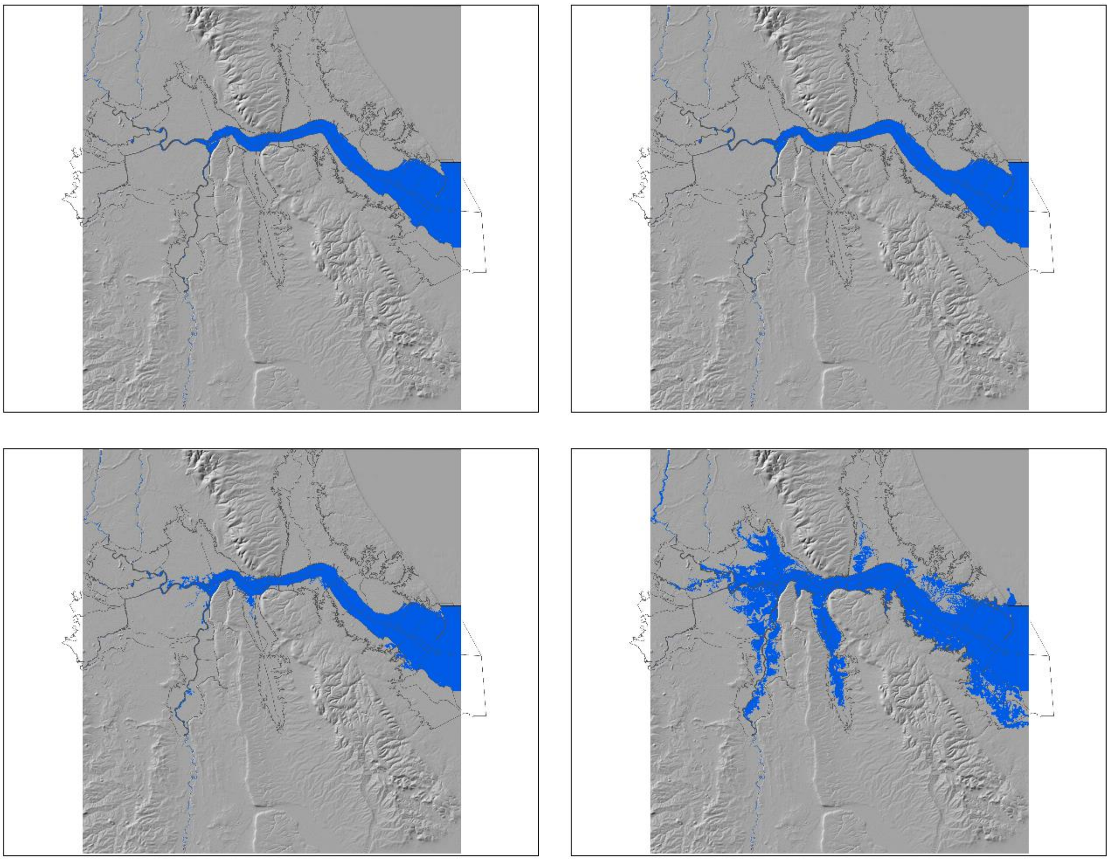

Figure 15.2 – Flood extents for Measure 16 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 15.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 16.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.17	4.69	5.20	6.18	5.03	5.54	6.03	7.02	5.35	5.85	6.36	7.31
Grimsby	4.25	4.73	5.24	6.27	5.07	5.62	6.12	7.10	5.42	5.96	6.45	7.37
Immingham	3.90	4.41	4.90	5.86	4.27	4.76	5.24	6.17	4.40	4.90	5.38	6.27
Sunk Island	4.23	4.73	5.26	6.29	5.11	5.61	6.12	7.11	5.42	5.98	6.41	7.36
King George's Dock	4.02	4.53	5.04	5.99	4.39	4.90	5.40	6.24	4.52	5.03	5.54	6.32
Albert Dock	4.03	4.55	5.06	6.01	4.40	4.92	5.43	6.24	4.55	5.06	5.57	6.32
Humber Bridge	4.14	4.67	5.21	6.08	4.52	5.07	5.59	6.27	4.67	5.21	5.71	6.34
Brough	4.35	4.88	5.44	6.16	4.74	5.29	5.78	6.29	4.87	5.43	5.90	6.31
West Walker Dyke	4.43	5.00	5.55	6.17	4.83	5.40	5.85	6.28	4.98	5.54	5.94	6.31
Blacktoft Jetty	4.48	5.04	5.57	6.07	4.88	5.42	5.83	6.12	5.02	5.57	5.89	6.13
Flixborough	4.61	5.17	5.68	6.11	5.02	5.53	5.97	6.15	5.16	5.67	6.01	6.16
Goole	4.55	5.08	5.62	5.95	4.92	5.47	5.85	5.97	5.06	5.62	5.89	5.98
Ouse (upstream)	3.12	3.63	4.18	5.04	3.40	3.94	4.51	5.10	3.51	4.07	4.65	5.12
Trent (upstream)	3.66	4.16	4.64	5.46	3.91	4.42	4.89	5.65	4.01	4.51	4.98	5.74
Mean	**4.14**	**4.66**	**5.18**	**5.97**	**4.61**	**5.13**	**5.62**	**6.26**	**4.78**	**5.31**	**5.76**	**6.36**

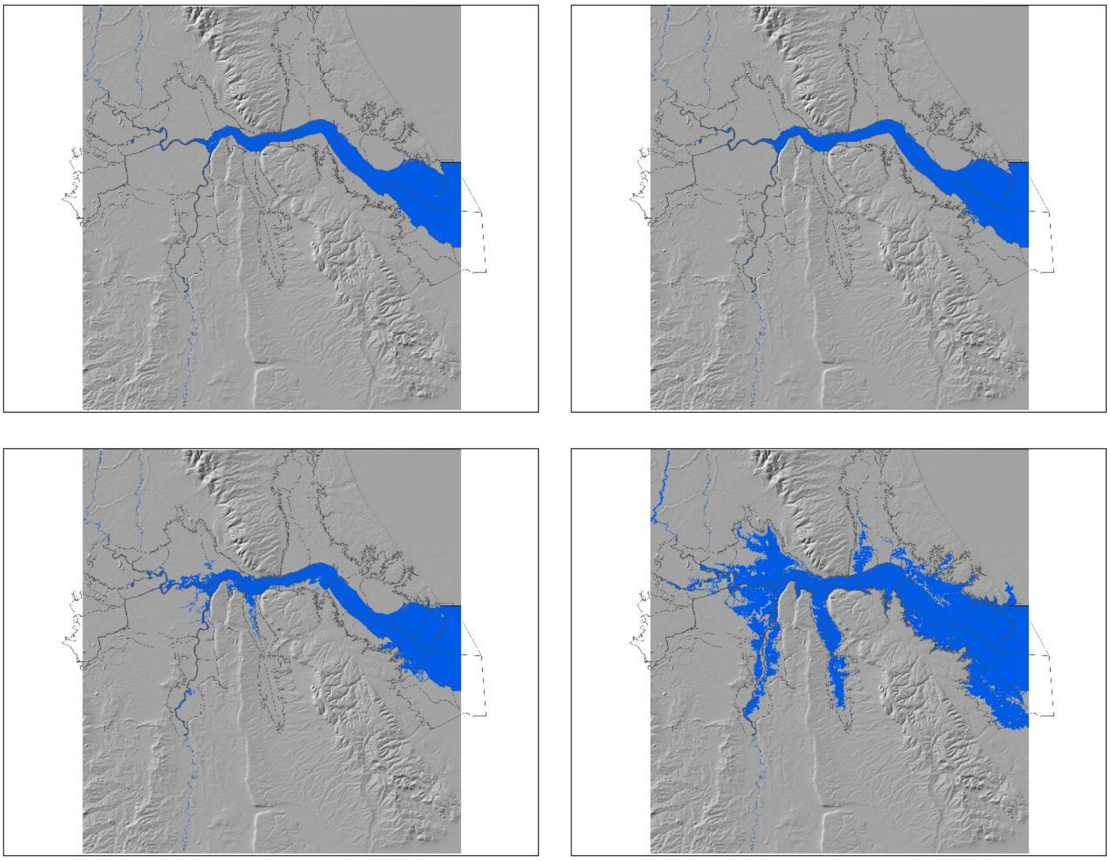

Figure 15.3 – Flood extents for Measure 16 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 15.4 – Change to the maximum stage for Measure 16 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	-0.03	-0.02	0.00	0.00	-0.03	-0.01	-0.01	0.06	-0.02	-0.02	0.03	0.05
Grimsby	-0.11	-0.14	-0.10	-0.01	-0.13	-0.07	-0.01	0.19	-0.09	-0.02	0.07	0.20
Immingham	-0.60	-0.59	-0.58	-0.47	-1.05	-1.05	-0.97	-0.75	-1.24	-1.19	-1.04	-0.85
Sunk Island	-0.12	-0.12	-0.08	0.00	-0.07	-0.07	-0.01	0.18	-0.09	0.00	0.03	0.18
King George's Dock	-0.61	-0.61	-0.59	-0.37	-1.09	-1.04	-0.88	-0.68	-1.26	-1.14	-0.89	-0.77
Albert Dock	-0.62	-0.62	-0.61	-0.36	-1.11	-1.04	-0.84	-0.67	-1.26	-1.12	-0.84	-0.75
Humber Bridge	-0.64	-0.63	-0.59	-0.31	-1.14	-0.98	-0.70	-0.59	-1.25	-1.02	-0.67	-0.66
Brough	-0.63	-0.66	-0.53	-0.20	-1.12	-0.84	-0.51	-0.45	-1.18	-0.79	-0.46	-0.50
West Walker Dyke	-0.67	-0.65	-0.44	-0.14	-1.08	-0.70	-0.41	-0.30	-1.08	-0.70	-0.38	-0.33
Blacktoft Jetty	-0.66	-0.62	-0.35	-0.06	-0.99	-0.61	-0.28	-0.15	-0.95	-0.53	-0.25	-0.17
Flixborough	-0.67	-0.61	-0.36	-0.04	-0.98	-0.55	-0.18	-0.08	-0.91	-0.45	-0.15	-0.09
Goole	-0.62	-0.61	-0.29	-0.03	-0.95	-0.48	-0.12	-0.11	-0.87	-0.35	-0.09	-0.13
Ouse (upstream)	-0.46	-0.52	-0.52	-0.11	-0.99	-0.99	-0.57	-0.23	-1.19	-0.98	-0.45	-0.23
Trent (upstream)	-0.45	-0.47	-0.44	-0.32	-0.88	-0.82	-0.73	-0.19	-1.02	-0.95	-0.79	-0.10
Mean	**-0.49**	**-0.49**	**-0.39**	**-0.17**	**-0.83**	**-0.66**	**-0.44**	**-0.27**	**-0.89**	**-0.66**	**-0.42**	**-0.30**

3.14 Measure 16A – Sunk Island (Outer estuary) Barrier, seaward defences raised 2 m

Flood defences were set as per the Baseline (2021 defences), but all defences seaward of the barrier installed at Sunk Island were raised by 2 m. The location of the barrier and the area of raised defences is shown in Figure 14.1. The barrier was raised to an elevation of 8.5 m at the point of lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.14.1 Results

Relative to the Baseline, Measure 16A resulted in a reduction of mean flood volume for every scenario between -0.06×10^6 m^3 (0 m SLR, 1-year return period) to -1304.40×10^6 m^3 (+2 m SLR, 1000-year return period) in comparison to the Baseline (Tables 16.1 and 16.2). However, comparing results to those of Measure 16 (Tables 15.2 and Table 16.2) indicates that raising of the defences seaward of the outer estuary barrier by 2 m only makes a significant difference to mean flood volumes for the 1000-year return period +1 m SLR event and +2 m sea level rise scenarios. Nevertheless, defences were still breached (Figures 16.1 to 16.3). For the largest flood event (1000-year return period +2 m SLR scenario), Measure 16A was 6% more effective at reducing the mean flood volume than the same event in Measure 16. Stages were very similar for both Measure 16 and measure 16A (Tables 15.4 and 16.4).

Table 16.1 – Flood volumes by Area for Measure 16A.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.13	1.57	0.07	0.41	0.91	24.33	0.24	0.72	2.46	51.93
South Bank Outer	0.00	0.00	0.00	3.98	0.00	0.17	1.48	20.80	0.05	0.82	4.46	28.52
Hull	0.00	0.00	0.00	0.92	0.00	0.00	0.01	4.47	0.00	0.00	0.01	7.50
Grimsby	0.00	0.00	0.00	51.35	0.00	0.00	0.29	89.28	0.00	0.02	1.62	99.66
North Bank Inner	0.00	0.00	0.13	34.75	0.00	0.01	1.63	41.98	0.00	0.14	3.01	45.89
South Bank Inner	0.00	0.00	0.01	165.86	0.00	0.00	2.57	234.75	0.00	0.01	8.68	259.99
Ouse-Trent	0.00	0.17	2.50	139.64	0.02	0.35	6.07	181.39	0.03	0.49	10.58	205.11
All	**0.00**	**0.18**	**2.78**	**398.08**	**0.09**	**0.94**	**12.97**	**597.01**	**0.32**	**2.20**	**30.83**	**698.59**

Table 16.2 – Change in Flood volumes by Area for Measure 16A in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.68	-52.31	-0.11	-6.04	-31.28	-210.51	-2.50	-22.13	-66.05	-297.26
South Bank Outer	0.00	0.00	-0.01	-34.19	0.00	-1.28	-20.38	-144.78	-0.14	-10.87	-48.75	-186.78
Hull	0.00	0.00	-0.01	-5.06	-0.01	-0.28	-2.53	-199.02	-0.04	-1.38	-9.86	-339.16
Grimsby	0.00	0.00	0.00	-35.35	0.00	-0.02	-18.20	-73.99	0.00	-0.88	-58.90	-100.10
North Bank Inner	0.00	-0.22	-2.33	-10.89	-1.17	-6.30	-11.76	-26.30	-3.94	-10.33	-16.48	-33.36
South Bank Inner	0.00	-0.06	-8.92	-91.60	-3.27	-33.67	-109.38	-127.33	-18.71	-75.87	-167.43	-143.01
Ouse-Trent	-0.06	-0.54	-8.03	-63.78	-3.85	-18.17	-39.36	-163.01	-11.72	-30.61	-56.26	-204.73
All	**-0.06**	**-0.81**	**-19.98**	**-293.17**	**-8.42**	**-65.76**	**-232.90**	**-944.94**	**-37.06**	**-152.07**	**-423.72**	**-1304.40**

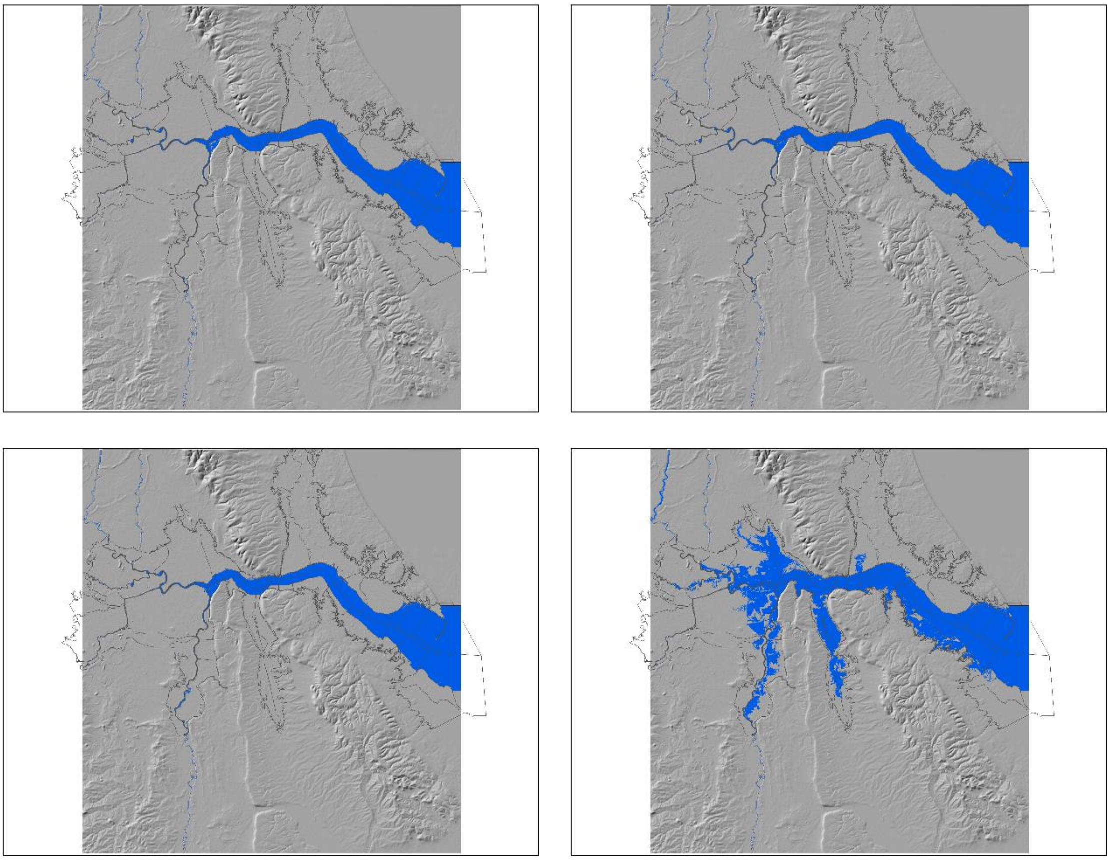

Figure 16.1 – Flood extents for Measure 16A with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

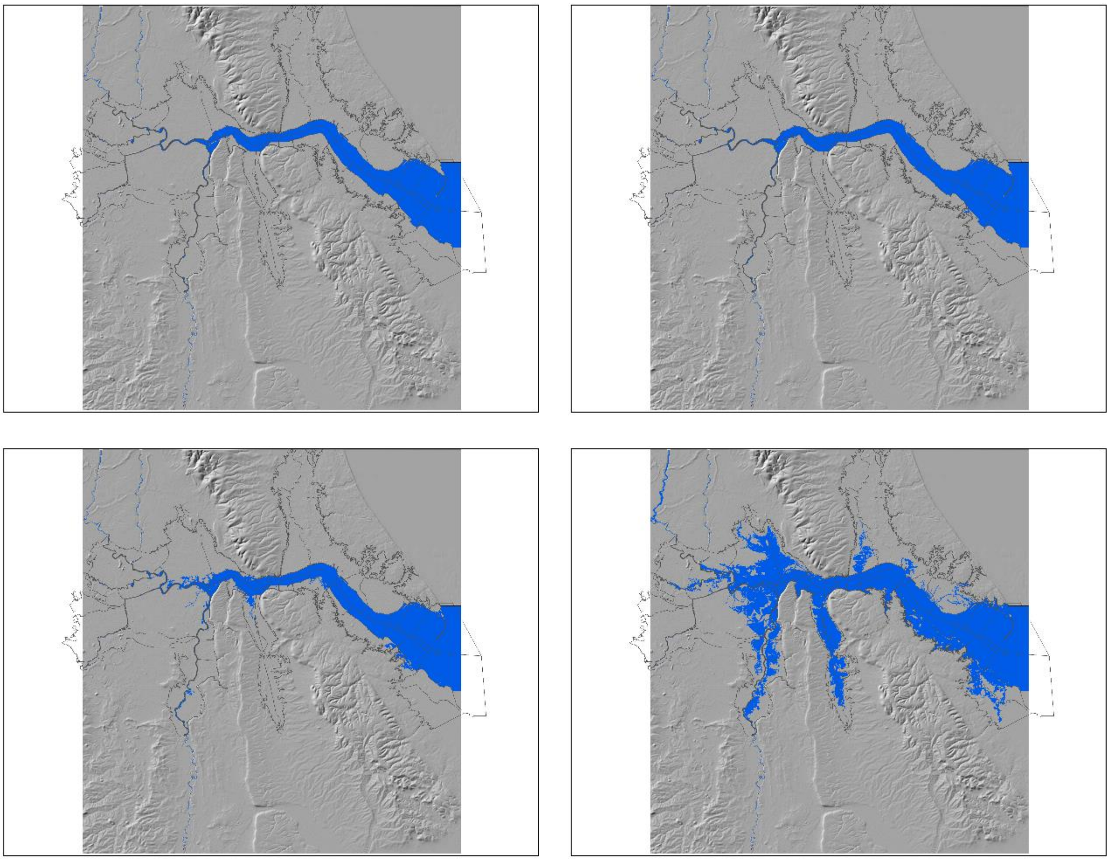

Figure 16.2 – Flood extents for Measure 16A with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 16.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 16A.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.17	4.69	5.20	6.18	5.03	5.54	6.03	7.03	5.35	5.85	6.36	7.36
Grimsby	4.25	4.73	5.24	6.27	5.07	5.62	6.12	7.14	5.42	5.96	6.46	7.46
Immingham	3.90	4.41	4.90	5.86	4.27	4.76	5.24	6.17	4.40	4.90	5.38	6.27
Sunk Island	4.23	4.73	5.26	6.28	5.11	5.61	6.12	7.13	5.42	5.98	6.42	7.45
King George's Dock	4.02	4.53	5.04	5.99	4.39	4.90	5.40	6.24	4.52	5.03	5.54	6.32
Albert Dock	4.03	4.55	5.06	6.01	4.40	4.92	5.43	6.24	4.55	5.06	5.57	6.32
Humber Bridge	4.14	4.67	5.21	6.08	4.52	5.07	5.59	6.27	4.67	5.21	5.71	6.34
Brough	4.35	4.88	5.44	6.16	4.74	5.29	5.78	6.29	4.87	5.43	5.90	6.31
West Walker Dyke	4.43	5.00	5.55	6.17	4.83	5.40	5.85	6.28	4.98	5.54	5.94	6.31
Blacktoft Jetty	4.48	5.04	5.57	6.07	4.88	5.42	5.83	6.12	5.02	5.57	5.89	6.13
Flixborough	4.61	5.17	5.68	6.11	5.02	5.53	5.97	6.15	5.16	5.67	6.01	6.16
Goole	4.55	5.08	5.62	5.95	4.92	5.47	5.85	5.97	5.06	5.62	5.89	5.98
Ouse (upstream)	3.12	3.63	4.18	5.04	3.40	3.94	4.51	5.10	3.51	4.07	4.65	5.12
Trent (upstream)	3.66	4.16	4.64	5.46	3.91	4.42	4.89	5.65	4.01	4.51	4.98	5.74
Mean	**4.14**	**4.66**	**5.18**	**5.97**	**4.61**	**5.13**	**5.62**	**6.27**	**4.78**	**5.31**	**5.76**	**6.38**

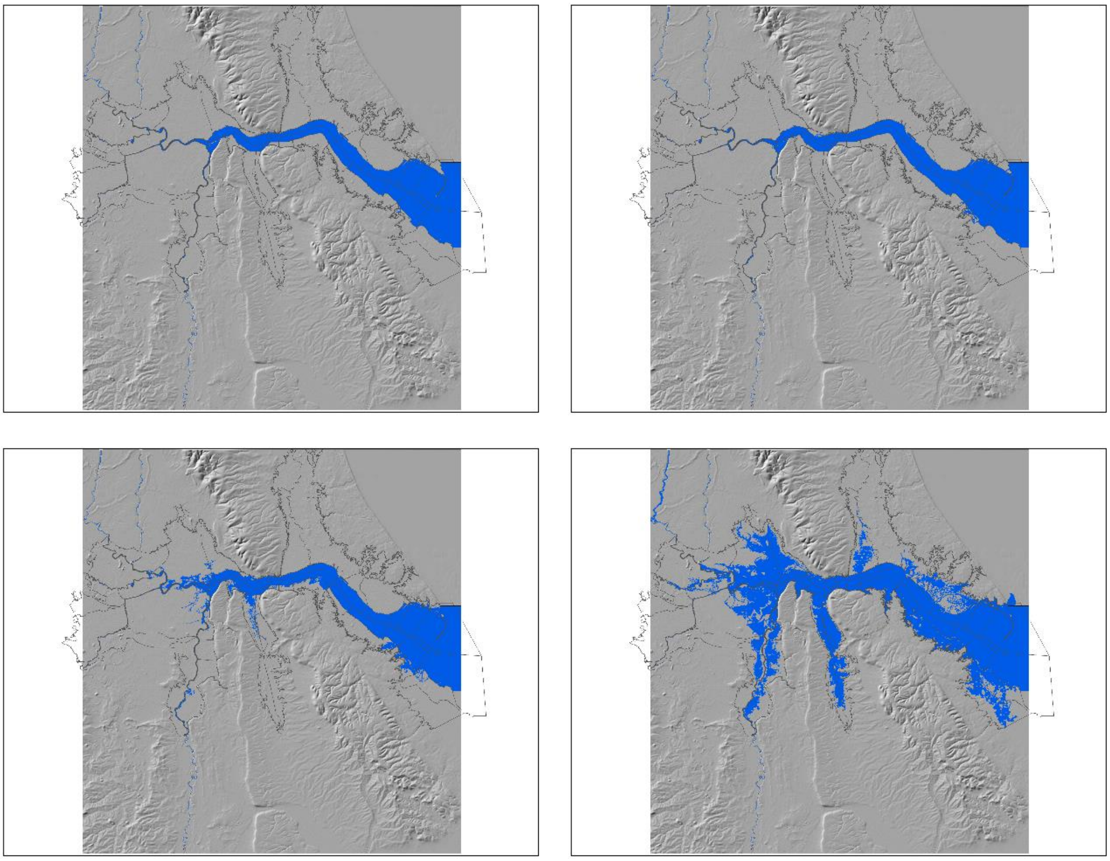

Figure 16.3 – Flood extents for Measure 16A with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 16.4 – Change to the maximum stage for Measure 16A relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	0	50	100	200	0	50	100	200	0	50	100	200
Spurn	-0.03	-0.02	0.00	0.00	-0.03	-0.01	-0.01	0.07	-0.02	-0.02	0.03	0.09
Grimsby	-0.11	-0.14	-0.10	-0.01	-0.13	-0.07	-0.01	0.22	-0.09	-0.02	0.08	0.29
Immingham	-0.60	-0.59	-0.58	-0.47	-1.05	-1.05	-0.97	-0.75	-1.24	-1.19	-1.04	-0.85
Sunk Island	-0.12	-0.12	-0.08	0.00	-0.07	-0.07	-0.02	0.20	-0.09	0.00	0.03	0.27
King George's Dock	-0.61	-0.61	-0.59	-0.37	-1.09	-1.04	-0.88	-0.68	-1.26	-1.14	-0.89	-0.77
Albert Dock	-0.62	-0.62	-0.61	-0.36	-1.11	-1.04	-0.84	-0.67	-1.26	-1.12	-0.84	-0.75
Humber Bridge	-0.64	-0.63	-0.59	-0.31	-1.14	-0.98	-0.70	-0.59	-1.25	-1.02	-0.67	-0.66
Brough	-0.63	-0.66	-0.53	-0.20	-1.12	-0.84	-0.51	-0.45	-1.18	-0.79	-0.46	-0.50
West Walker Dyke	-0.67	-0.65	-0.44	-0.14	-1.08	-0.70	-0.41	-0.30	-1.08	-0.70	-0.38	-0.33
Blacktoft Jetty	-0.66	-0.62	-0.35	-0.06	-0.99	-0.61	-0.28	-0.15	-0.95	-0.53	-0.25	-0.17
Flixborough	-0.67	-0.61	-0.36	-0.04	-0.98	-0.55	-0.18	-0.08	-0.91	-0.45	-0.15	-0.09
Goole	-0.62	-0.61	-0.29	-0.03	-0.95	-0.48	-0.12	-0.11	-0.87	-0.35	-0.09	-0.13
Ouse (upstream)	-0.46	-0.52	-0.52	-0.11	-0.99	-0.99	-0.57	-0.23	-1.19	-0.98	-0.45	-0.23
Trent (upstream)	-0.45	-0.47	-0.44	-0.32	-0.88	-0.82	-0.73	-0.19	-1.02	-0.95	-0.79	-0.10
Mean	**-0.49**	**-0.49**	**-0.39**	**-0.17**	**-0.83**	**-0.66**	**-0.44**	**-0.26**	**-0.89**	**-0.66**	**-0.42**	**-0.28**

3.15 Measure 20 – Sunk Island Groyne

Flood defences were set as per the Baseline (2021 defences) but with raised elevation across Sunk Island intertidal area to reduce the cross-sectional area of the Estuary. The intertidal area of Sunk Island, as specified in Figure 17.1, was raised by 2 m elevation.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0 m sea level rise (SLR), resulting in three scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

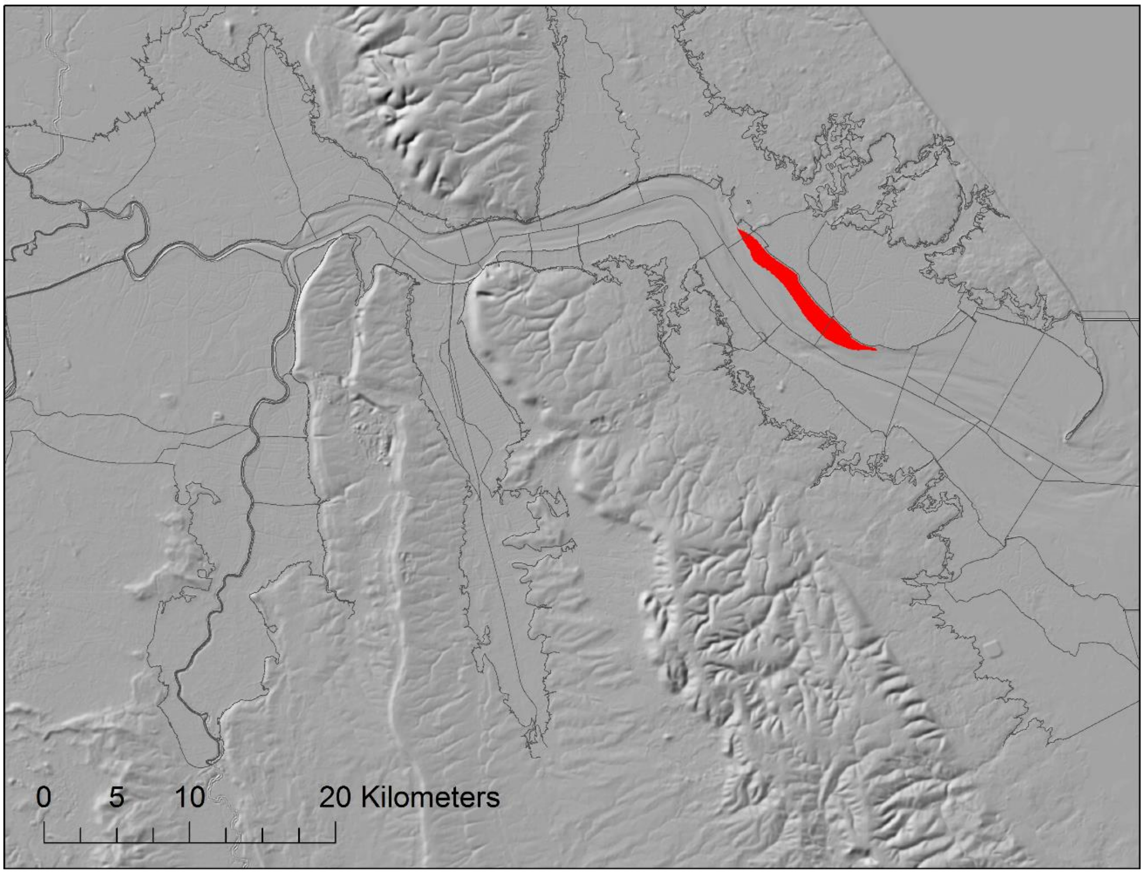

Figure 17.1 – Specification of the Sunk Island Groyne. Red are shows area with raised elevations.

3.15.1 Results

The Sunk Island groyne made no difference to either the mean or the local flood volumes in comparison to the Baseline for the smallest 1-year return period (Table 17.2, Figure 17.2). The 200- and 1000-year event return period scenarios do have reduced flood volumes in comparison to the Baseline by −0.38 × 10^6 m^3 and −0.40 × 10^6 m^3, respectively. Locally, the South Bank Inner and Ouse-Trent regions benefit the most from reduced flood volumes relative to the Baseline, however these areas were still inundated (Figure 17.2). Addition of the Sunk Island groyne did not impact stage heights relative to the Baseline (Table 17.4). It is not known how Measure 20 will impact flood volumes with SLR.

Table 17.1 – Flood volumes by Area for Measure 20.

	Flood Volumes (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.16	2.68
South Bank Outer	0.00	0.00	0.18
Hull	0.00	0.01	0.04
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	1.15	3.91
South Bank Inner	0.00	3.12	18.54
Ouse-Trent	0.06	3.67	11.63
All	**0.06**	**8.12**	**36.98**

Table 17.2 – Change in Flood volumes by Area for Measure 20 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	-0.01	-0.05
South Bank Outer	0.00	0.00	-0.01
Hull	0.00	0.00	0.00
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	-0.02	-0.04
South Bank Inner	0.00	-0.15	-0.17
Ouse-Trent	0.00	-0.19	-0.12
All	**0.00**	**-0.38**	**-0.40**

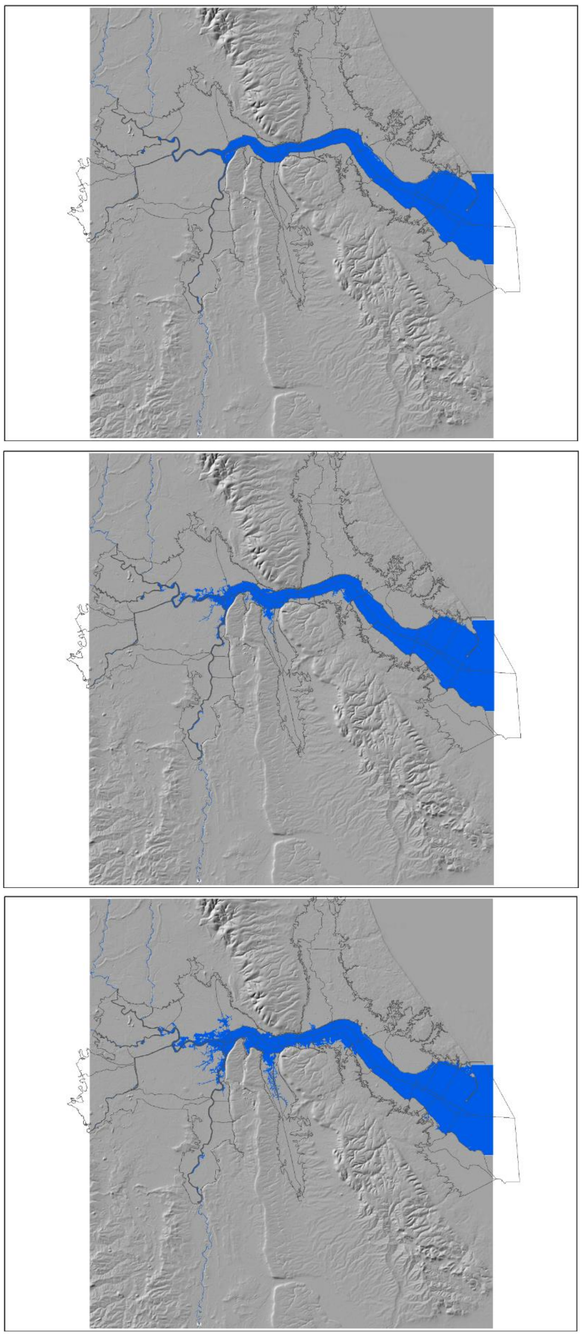

Figure 17.2 – Flood extents for Measure 20. Top with a 1-year return period, middle with a 200-year return period and bottom with a 1000-year return period.

Table 17.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 20.

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	4.19	5.05	5.37
Grimsby	4.34	5.18	5.51
Immingham	4.47	5.32	5.64
Sunk Island	4.34	5.17	5.49
King George's Dock	4.61	5.47	5.78
Albert Dock	4.64	5.51	5.81
Humber Bridge	4.76	5.65	5.92
Brough	4.96	5.85	6.05
West Walker Dyke	5.09	5.90	6.05
Blacktoft Jetty	5.12	5.86	5.97
Flixborough	5.24	5.99	6.06
Goole	5.15	5.87	5.92
Ouse (upstream)	3.60	4.41	4.73
Trent (upstream)	4.13	4.81	5.05
Mean	**4.62**	**5.43**	**5.67**

Table 17.4 – Change to the maximum stage for Measure 20 relative to the Baseline (Measure 1).

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	-0.01	-0.01	0.00
Grimsby	-0.02	-0.01	0.00
Immingham	-0.03	-0.01	0.00
Sunk Island	-0.02	-0.01	-0.01
King George's Dock	-0.02	-0.01	-0.01
Albert Dock	-0.01	0.00	0.00
Humber Bridge	-0.02	0.00	0.00
Brough	-0.02	-0.01	-0.01
West Walker Dyke	-0.02	-0.01	-0.01
Blacktoft Jetty	-0.02	-0.01	0.00
Flixborough	-0.03	-0.01	-0.01
Goole	-0.02	0.00	-0.01
Ouse (upstream)	0.01	0.02	0.02
Trent (upstream)	0.01	0.02	0.02
Mean	**-0.01**	**0.00**	**0.00**

3.16 Measure 28 – South Bank Peninsula

Measure 28 inserted an artificial peninsula, 10 m in elevation, on the south bank at the mouth of the estuary, opposite Spurn Point (Figure 18.1). All other flood defences were set as per the Baseline (2021 defences).

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1- , 200- and 1000-year return period events and with 0 m sea level rise (SLR), resulting in three scenarios.
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

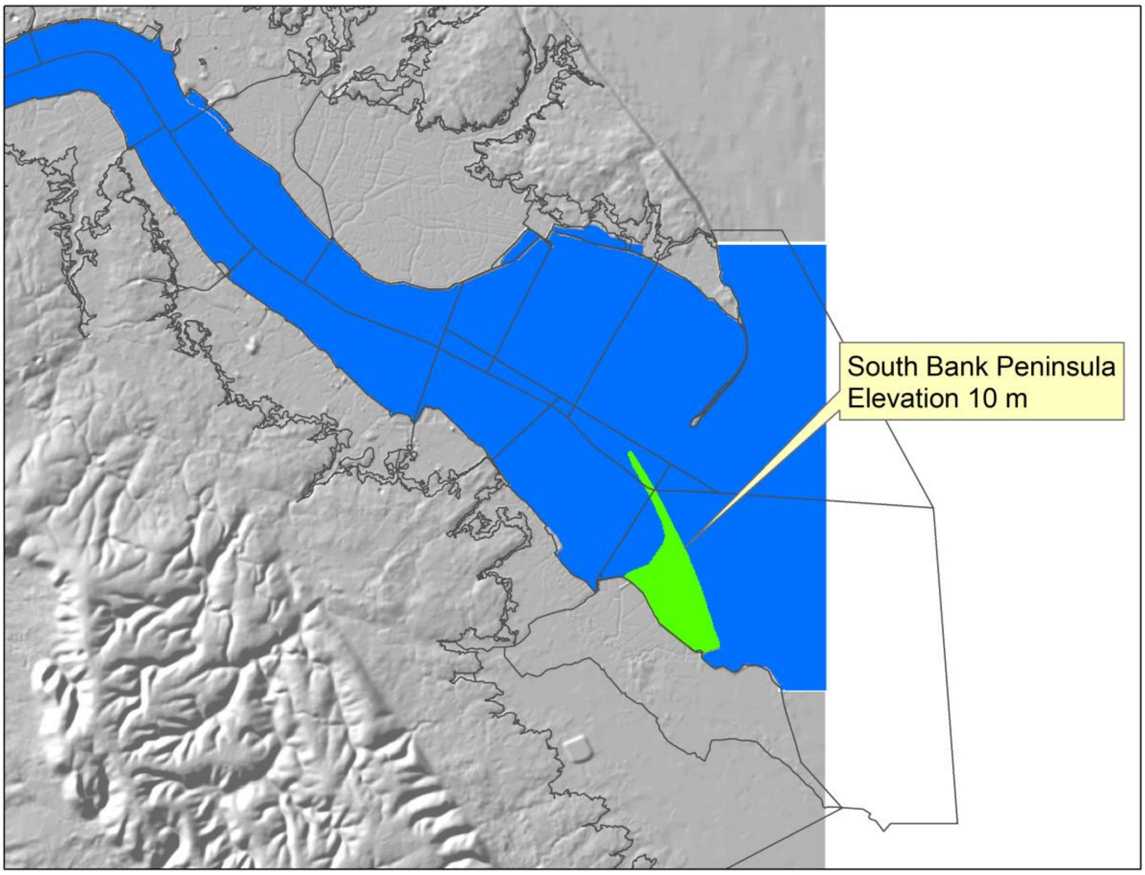

Figure 18.1 – The configuration of scenario 28. The area shaded green shows the location and extent of the south bank peninsula.

3.16.1 Results

Measure 28 did not change flood volume for the 1-year return period event, but increased mean flood volumes for the 200- and 1000-year events by $+1.99 \times 10^6$ m^3 and $+4.13 \times 10^6$ m^3, respectively, from the Baseline (Table 18.1). Locally, the flood volumes were increased primarily in the inner estuary, with the South Bank Inner, North Bank Inner and Ouse-Trent regions being the worst impacted by the peninsula (Figure 18.2). Table 18.2 shows that mean stage height levels only increased slightly, between +0.02 and +0.04 m, in comparison to the Baseline.

Table 18.1 – Flood volumes by Area for Measure 28.

	Flood Volumes (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.22	2.99
South Bank Outer	0.00	0.00	0.45
Hull	0.00	0.01	0.07
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	1.34	4.31
South Bank Inner	0.00	4.31	20.95
Ouse-Trent	0.07	4.61	12.75
All	**0.07**	**10.49**	**41.51**

Table 18.2 – Maximum stages at tidal gauges throughout the Estuary for Measure 28.

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	4.22	5.07	5.38
Grimsby	4.39	5.22	5.56
Immingham	4.54	5.37	5.68
Sunk Island	4.39	5.22	5.54
King George's Dock	4.67	5.52	5.82
Albert Dock	4.69	5.55	5.84
Humber Bridge	4.82	5.69	5.95
Brough	5.02	5.88	6.07
West Walker Dyke	5.15	5.94	6.07
Blacktoft Jetty	5.18	5.89	5.98
Flixborough	5.32	6.02	6.07
Goole	5.21	5.89	5.94
Ouse (upstream)	3.60	4.38	4.70
Trent (upstream)	4.12	4.79	5.02
Mean	**4.67**	**5.46**	**5.69**

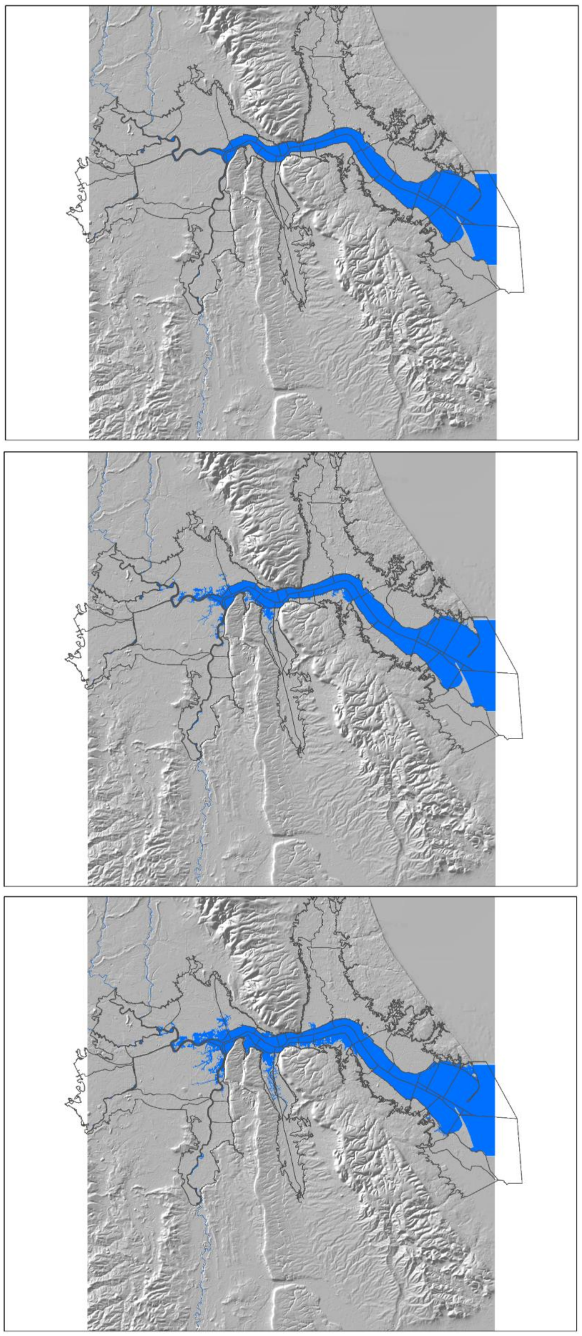

Figure 18.2 – Flood extents for Measure 28. Top with a 1-year return period, middle with a 200-year return period, and bottom with a 1000-year return period.

Dredging Measures

The following two measures model the use of dredging the estuary and part of the fluvial bathymetry to predict the impact on present-day sea-level flood volumes.

3.17 Measure 26 – Dredging of the middle and inner estuary landward of the Humber Bridge

Flood defences were set as per the Baseline (2021 defences), but with the bathymetry landward of the Humber Bridge (Figure 19.1) lowered by 1 m.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0 m sea level rise (SLR), resulting in three scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

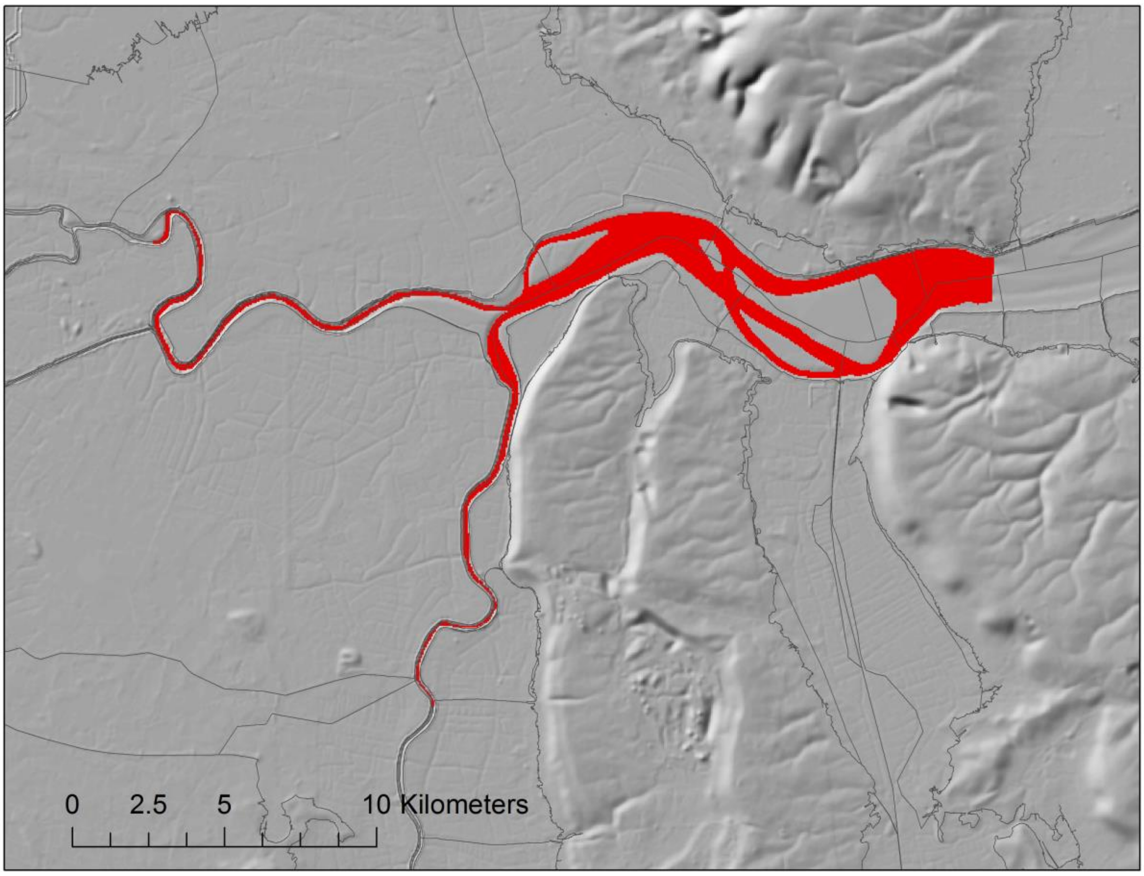

Figure 19.1 – Configuration of the large-scale dredging landward of the Humber Bridge. The area of reduced elevation is shown in red.

3.17.1 Results

Dredging the estuary upstream of the Humber bridge by −1 m resulted in an increase of mean flood volumes for every flood scenario at present day sea levels. Mean flood volumes were increased by +0.04 × 10^6 m^3 to +5.81 × 10^6 m^3 above the Baseline (Tables 19.1 and 19.2). Dredging resulted in the greatest local increase in stages and most flooding in the fluvial and inner estuary regions (Figure 19.2, Tables 19.3 and 19.4).

Table 19.1 – Flood volumes by Area for Measure 26.

	Flood Volumes (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.17	2.72
South Bank Outer	0.00	0.00	0.19
Hull	0.00	0.01	0.06
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	1.43	4.52
South Bank Inner	0.00	4.04	20.25
Ouse-Trent	0.10	5.86	15.45
All	**0.11**	**11.52**	**43.19**

Table 19.2 – Change in Flood volumes by Area for Measure 26 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)		
Return Period (yrs	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.00	-0.02
South Bank Outer	0.00	0.00	0.00
Hull	0.00	0.00	0.01
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	0.26	0.57
South Bank Inner	0.00	0.77	1.54
Ouse-Trent	0.04	2.00	3.70
All	**0.04**	**3.02**	**5.81**

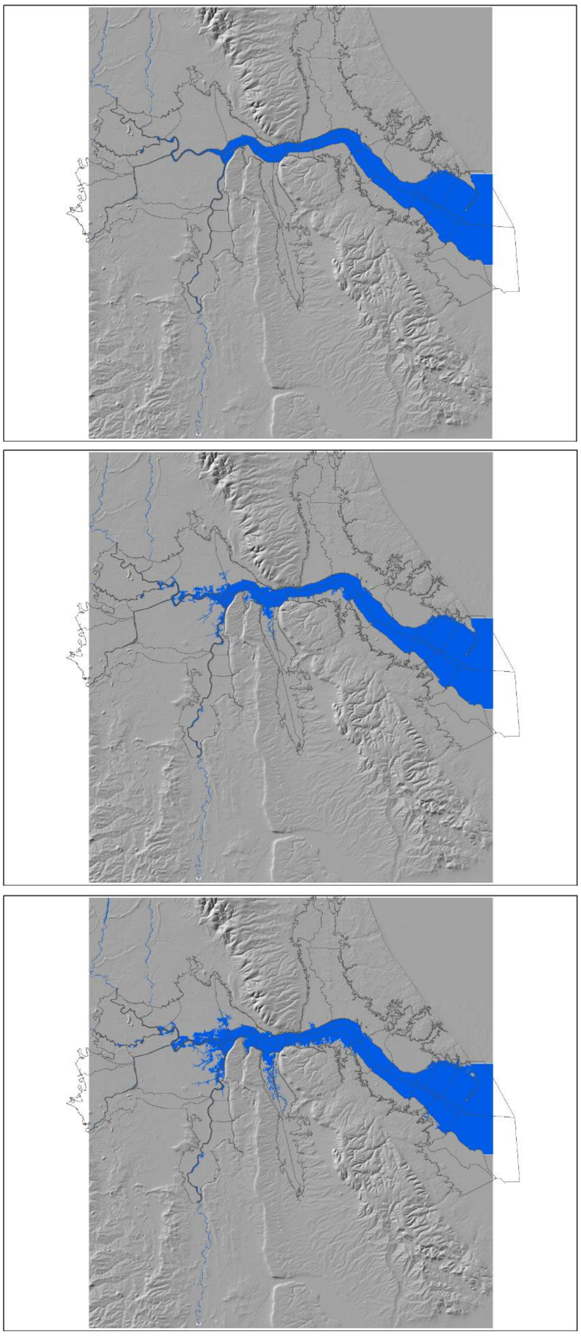

Figure 19.2 – Flood extents for Measure 26. Top with a 1-year return period, middle with a 200-year return period and bottom with a 1000-year return period.

Table 19.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 26.

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	4.20	5.05	5.37
Grimsby	4.35	5.18	5.51
Immingham	4.48	5.32	5.63
Sunk Island	4.34	5.18	5.50
King George's Dock	4.61	5.49	5.79
Albert Dock	4.63	5.53	5.82
Humber Bridge	4.81	5.69	5.95
Brough	5.04	5.90	6.08
West Walker Dyke	5.17	5.95	6.08
Blacktoft Jetty	5.22	5.91	6.00
Flixborough	5.34	6.03	6.09
Goole	5.28	5.92	5.97
Ouse (upstream)	3.69	4.48	4.79
Trent (upstream)	4.23	4.89	5.12
Mean	**4.67**	**5.47**	**5.69**

Table 19.4 – Change to the maximum stage for Measure 26 relative to the Baseline (Measure 1).

	Maximum Stage Height (m OSN)		
Return Period	**in 1**	**in 200**	**in 1000**
SLR (cm)	**0**	**0**	**0**
Spurn	0.00	0.00	0.00
Grimsby	-0.01	-0.01	0.00
Immingham	-0.02	-0.01	-0.01
Sunk Island	-0.01	0.00	0.00
King George's Dock	-0.03	0.01	0.01
Albert Dock	-0.02	0.01	0.01
Humber Bridge	0.03	0.03	0.03
Brough	0.06	0.04	0.02
West Walker Dyke	0.07	0.04	0.02
Blacktoft Jetty	0.08	0.04	0.03
Flixborough	0.06	0.02	0.02
Goole	0.11	0.05	0.04
Ouse (upstream)	0.10	0.09	0.08
Trent (upstream)	0.12	0.11	0.09
Mean	**0.04**	**0.03**	**0.03**

3.18 Measure 19 – Estuary-wide dredging

Flood defences were set as per the Baseline (2021 defences), but with the bathymetry of the estuary (Figure 20.1) lowered by 1 m.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0 m sea level rise (SLR), resulting in three scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

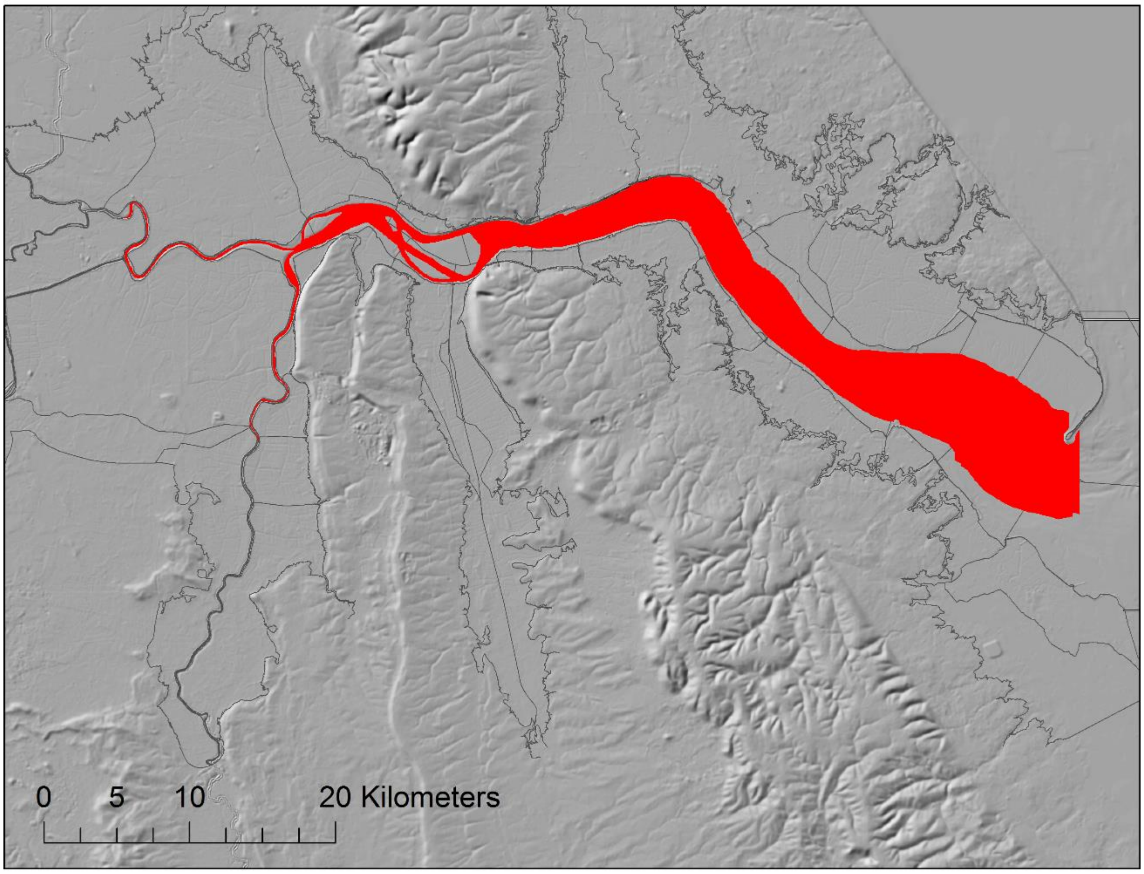

Figure 20.1 – Configuration of the large-scale, Estuary-wide dredge. Area of lowered elevation shown in red.

3.18.1 Results

Large scale estuary dredging, which lowered the bathymetry by −1 m, increased mean flood volumes by between +0.11 × 10^6 m^3 and +15.59 × 10^6 m^3 in comparison to the Baseline for all three return periods (Tables 20.1 and 20.2). Dredging did not prevent overbank flooding at present day sea levels, mostly impacting the inner estuary region (Figure 20.2). Mean stage heights were also increased for each event, but mostly for the smallest event (1-year) and locally in the inner estuary (Tables 20.3 and 20.4).

Table 20.1 – Flood volumes by Area for Measure 19.

	Flood Volumes (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.19	2.81
South Bank Outer	0.00	0.00	0.20
Hull	0.00	0.01	0.14
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	2.10	5.62
South Bank Inner	0.00	6.65	25.62
Ouse-Trent	0.18	8.24	18.58
All	**0.18**	**17.18**	**52.97**

Table 20.2 – Change in Flood volumes by Area for Measure 19 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)		
Return Period (yrs)	**1**	**200**	**1000**
SLR (cm)	**0**	**0**	**0**
North Bank Outer	0.00	0.01	0.07
South Bank Outer	0.00	0.00	0.01
Hull	0.00	0.00	0.09
Grimsby	0.00	0.00	0.00
North Bank Inner	0.00	0.93	1.68
South Bank Inner	0.00	3.37	6.91
Ouse-Trent	0.11	4.37	6.82
All	**0.11**	**8.68**	**15.59**

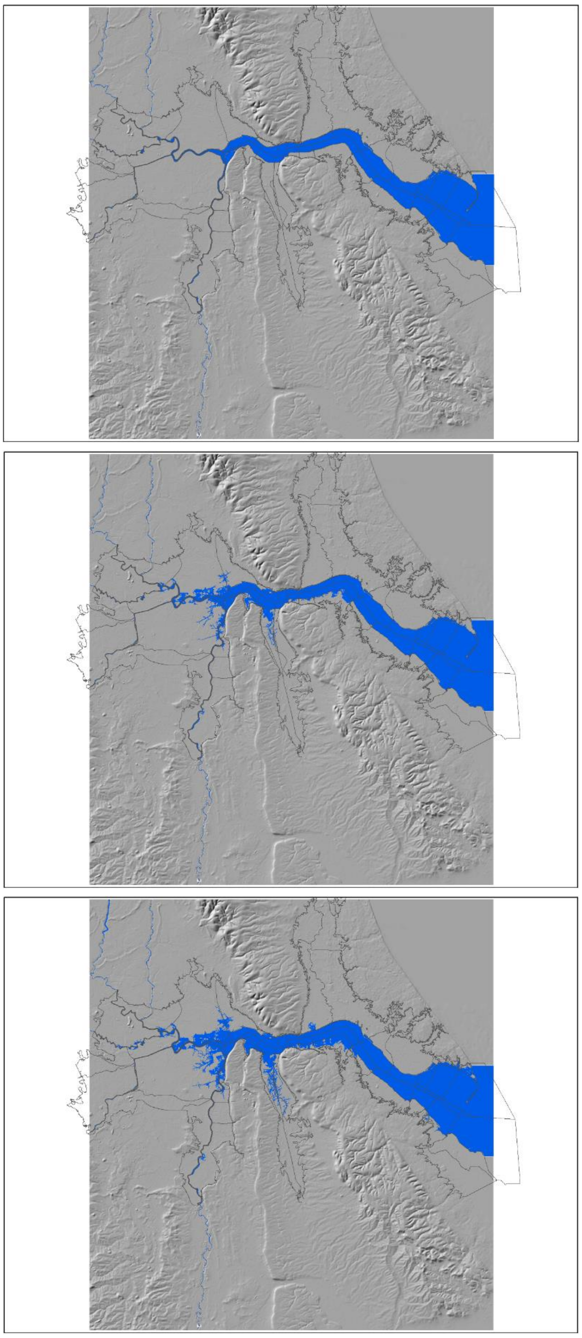

Figure 20.2 – Flood extents for Measure 19. Top with a 1-year return period, middle with a 200-year return period, and bottom with a 1000-year return period.

Table 20.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 19.

	Maximum Stage Height (m OSN)		
Return Period	in 1	in 200	in 1000
SLR (cm)	0	0	0
Spurn	4.20	5.06	5.38
Grimsby	4.36	5.21	5.52
Immingham	4.52	5.36	5.68
Sunk Island	4.35	5.19	5.51
King George's Dock	4.70	5.56	5.85
Albert Dock	4.74	5.61	5.89
Humber Bridge	4.91	5.77	6.01
Brough	5.17	5.95	6.11
West Walker Dyke	5.30	6.01	6.11
Blacktoft Jetty	5.36	5.93	6.05
Flixborough	5.46	6.05	6.10
Goole	5.42	5.94	5.97
Ouse (upstream)	3.78	4.56	4.85
Trent (upstream)	4.33	4.98	5.18
Mean	**4.76**	**5.51**	**5.73**

Table 20.4 – Change to the maximum stage for Measure 19 relative to the Baseline (Measure 1).

	Maximum Stage Height (m OSN)		
Return Period	in 1	in 200	in 1000
SLR (cm)	0	0	0
Spurn	0.00	0.00	0.01
Grimsby	0.00	0.02	0.01
Immingham	0.02	0.03	0.03
Sunk Island	0.00	0.01	0.01
King George's Dock	0.07	0.08	0.07
Albert Dock	0.09	0.10	0.08
Humber Bridge	0.14	0.11	0.09
Brough	0.19	0.10	0.06
West Walker Dyke	0.20	0.10	0.06
Blacktoft Jetty	0.22	0.06	0.08
Flixborough	0.19	0.05	0.03
Goole	0.25	0.07	0.04
Ouse (upstream)	0.20	0.17	0.15
Trent (upstream)	0.21	0.19	0.16
Mean	**0.13**	**0.08**	**0.06**

Compound Measures

The following eight measures simulate a compound approach to flood alleviation. This combines the use of hard engineering structures to keep out the tide in some areas, with soft engineering structures (e.g., managed realignment and flood storage areas) to adapt to the tide in other areas.

3.19 Measure 12 – Estuary defence levels raised to 2014 local 200-year return period water surface profile plus 1 m, plus Managed Realignment and Flood Storage sites

Estuary defences were raised to an elevation of +1 m above the 2014 local 200-year return period water surface profile. Managed realignment sites were installed at Keyingham, Goxhill, and Winteringham Ings. Flood Storage sites were installed at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet and Flixborough. Defence heights are shown in Figure 21.1, the Keyingham and Goxhill Managed Realignment schemes are shown in Figure 4.1, and the Winteringham Ings Managed Realignment scheme is shown in Figure 6.1. Flood Storage sites are shown in Figure 21.2.

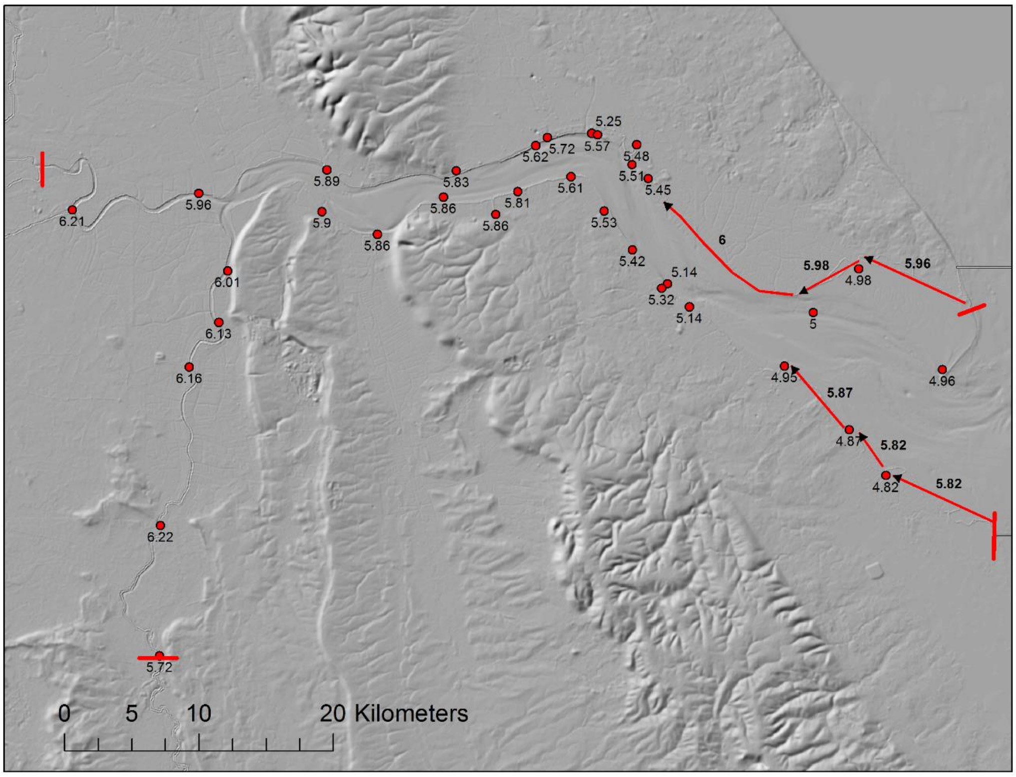

Figure 21.1 – Configuration of defence crest levels based on the local 1-in-200-year return period water surface elevations (red dots; labels show elevations in metres above OSN). Commencing from the most Easterly extent of defences (as shown by red arrows and values in bold) and marching Westwards, Baseline defence crest elevations were replaced with the elevation of the nearest local water surface elevation +1 m. The red lines show the maximum extents to which changes were applied. For the Rivers Ouse and Trent, the elevations were applied to both banks.

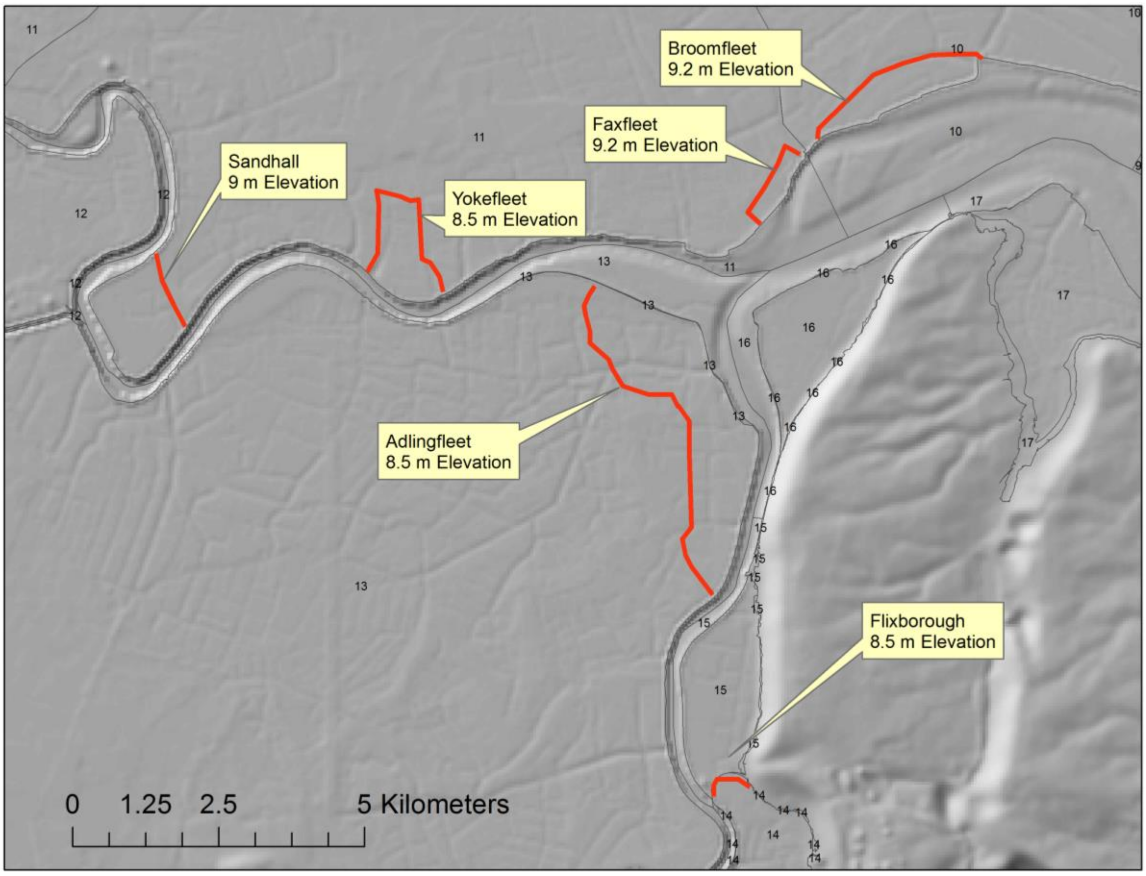

Figure 21.2 – Configuration of Flood Storage sites at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet and Flixborough. Elevations were raised along the red lines. Estuary facing defences were kept as Baseline level.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.19.1 Results

Measure 12 reduced mean flood volumes in every return period and sea level rise scenario to varying degrees, from -0.06×10^6 m^3 (1-year event, 0 m SLR) to -694.2×10^6 m^3 (1000-year event, +2 m SLR). The compound approach was most effective at reducing flood volumes relative to the Baseline for the longer return period events and larger sea level rise scenarios in the Ouse-Trent and Inner South bank areas. The areas which gained the least benefit were South Bank Outer, Hull and Grimsby (Figures 21.3 to 21.5). Mean stages increased above the Baseline in all scenarios except the 1-year return period, +0 m SLR scenario (Tables 21.3 and 21.4). Locally, stages were reduced by a small amount or remained the same in the outer estuary when compared to the

Baseline but stages increased by up to 1 m in the mid-upper estuary for the longer return period events and larger sea level rise scenarios. Interestingly, local stage heights show very different responses between the upstream Ouse and Trent gauges. For example, for a 200-year event with +2 m SLR, the upstream River Ouse stage height increased by +0.02 m, while the Upstream Trent increased by +1.28 m when compared with the Baseline (Table 21.4).

Table 21.1 – Flood volumes by Area for Measure 12.

Flood Volumes (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.14	23.34	0.08	0.43	8.82	210.79	0.25	1.82	51.91	314.68
South Bank Outer	0.00	0.00	0.01	25.28	0.00	0.24	9.77	187.94	0.08	1.29	49.77	247.76
Hull	0.00	0.00	0.00	3.36	0.00	0.00	1.19	182.87	0.00	0.11	10.47	324.11
Grimsby	0.00	0.00	0.00	18.85	0.00	0.00	7.52	170.30	0.00	1.02	44.65	202.73
North Bank Inner	0.00	0.00	0.00	0.01	0.00	0.00	0.00	6.64	0.00	0.00	0.02	13.97
South Bank Inner	0.00	0.01	0.14	10.63	0.05	0.68	3.54	127.88	0.33	1.80	12.96	166.75
Ouse-Trent	0.00	0.00	0.63	37.95	0.17	2.94	10.47	78.05	1.37	6.58	20.80	100.92
All	**0.00**	**0.01**	**0.92**	**119.42**	**0.30**	**4.28**	**41.30**	**964.46**	**2.02**	**12.62**	**190.58**	**1370.93**

Table 21.2 – Change in Flood volumes by Area for Measure 12 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.67	-30.54	-0.10	-6.02	-23.37	-24.06	-2.48	-21.03	-16.59	-34.51
South Bank Outer	0.00	0.00	0.00	-12.89	0.00	-1.22	-12.10	22.37	-0.12	-10.40	-3.44	32.46
Hull	0.00	0.00	-0.01	-2.62	-0.01	-0.28	-1.35	-20.63	-0.04	-1.27	0.60	-22.56
Grimsby	0.00	0.00	0.00	-67.85	0.00	-0.02	-10.97	7.03	0.00	0.12	-15.87	2.97
North Bank Inner	0.00	-0.22	-2.47	-45.64	-1.17	-6.30	-13.39	-61.64	-3.94	-10.47	-19.47	-65.28
South Bank Inner	0.00	-0.05	-8.79	-246.83	-3.23	-32.99	-108.42	-234.21	-18.38	-74.08	-163.15	-236.24
Ouse-Trent	-0.06	-0.71	-9.90	-165.47	-3.70	-15.58	-34.96	-266.35	-10.39	-24.52	-46.05	-308.92
All	**-0.06**	**-0.98**	**-21.84**	**-571.83**	**-8.21**	**-62.42**	**-204.56**	**-577.49**	**-35.36**	**-141.66**	**-263.97**	**-632.07**

Table 21.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 12.

Maximum Stage Height (m OSN)												
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.17	5.05	5.55	6.04	6.99	5.37	5.88	6.33	7.29
Grimsby	4.35	4.85	5.34	6.27	5.19	5.70	6.15	7.00	5.51	6.01	6.40	7.23
Immingham	4.49	4.99	5.49	6.39	5.33	5.84	6.29	6.97	5.66	6.15	6.50	7.23
Sunk Island	4.35	4.83	5.34	6.27	5.18	5.69	6.15	7.00	5.51	6.01	6.40	7.24
King George's Dock	4.63	5.14	5.65	6.57	5.49	6.00	6.45	7.00	5.82	6.33	6.67	7.19
Albert Dock	4.65	5.16	5.68	6.61	5.51	6.04	6.50	7.00	5.85	6.35	6.70	7.18
Humber Bridge	4.75	5.29	5.84	6.78	5.66	6.22	6.67	7.03	6.02	6.53	6.84	7.16
Brough	4.97	5.53	6.08	6.88	5.91	6.39	6.75	7.09	6.23	6.67	6.90	7.15
West Walker Dyke	5.08	5.65	6.14	6.93	6.01	6.43	6.68	7.13	6.27	6.65	6.79	7.16
Blacktoft Jetty	5.11	5.70	6.10	6.97	5.98	6.31	6.51	7.10	6.18	6.46	6.76	7.12
Flixborough	5.23	5.79	6.17	7.19	6.09	6.29	6.40	7.28	6.21	6.37	6.62	7.30
Goole	5.15	5.72	6.08	6.75	6.00	6.20	6.31	6.84	6.15	6.28	6.45	6.84
Ouse (upstream)	3.60	4.17	4.73	5.17	4.42	4.92	5.07	5.35	4.73	5.04	5.10	5.37
Trent (upstream)	4.15	4.72	5.30	6.54	4.92	5.53	6.10	7.12	5.23	5.82	6.50	7.40
Mean	**4.62**	**5.16**	**5.65**	**6.53**	**5.48**	**5.94**	**6.29**	**6.92**	**5.77**	**6.18**	**6.50**	**7.06**

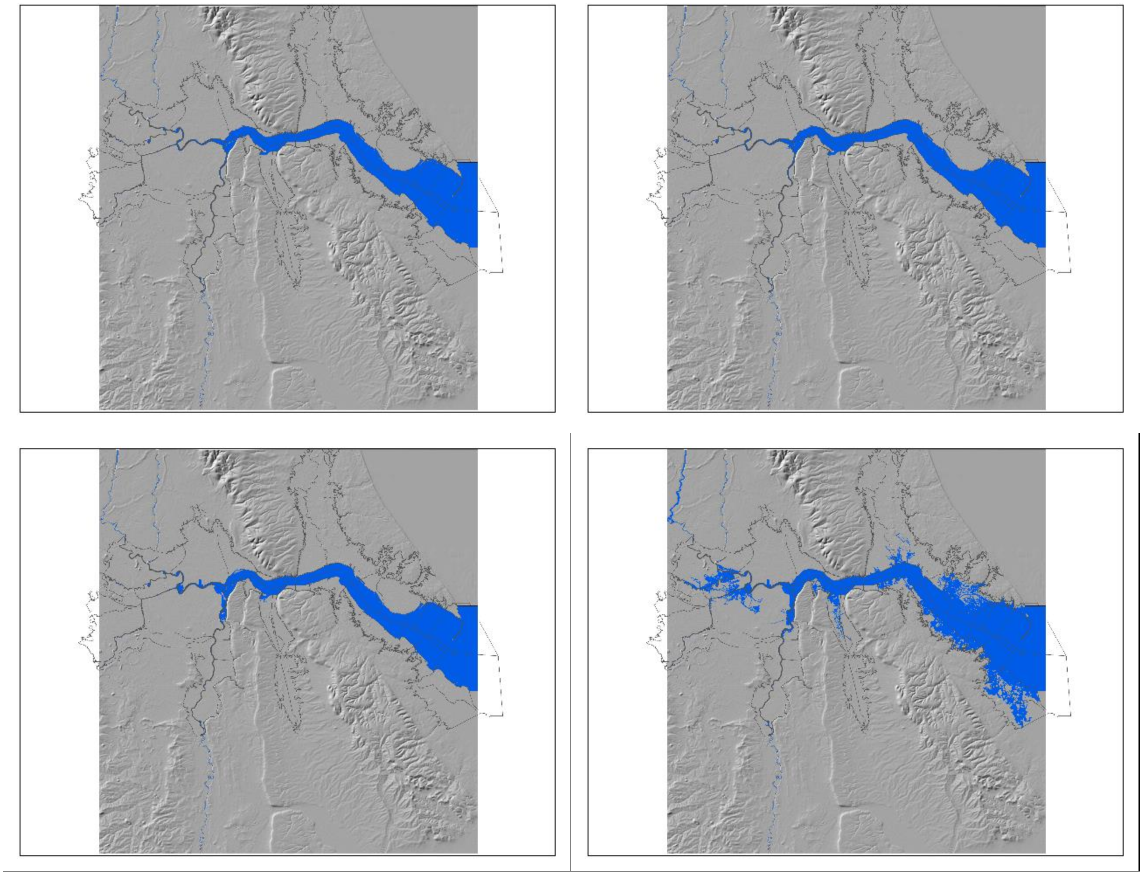

Figure 21.3 – Flood extents for Measure 12 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

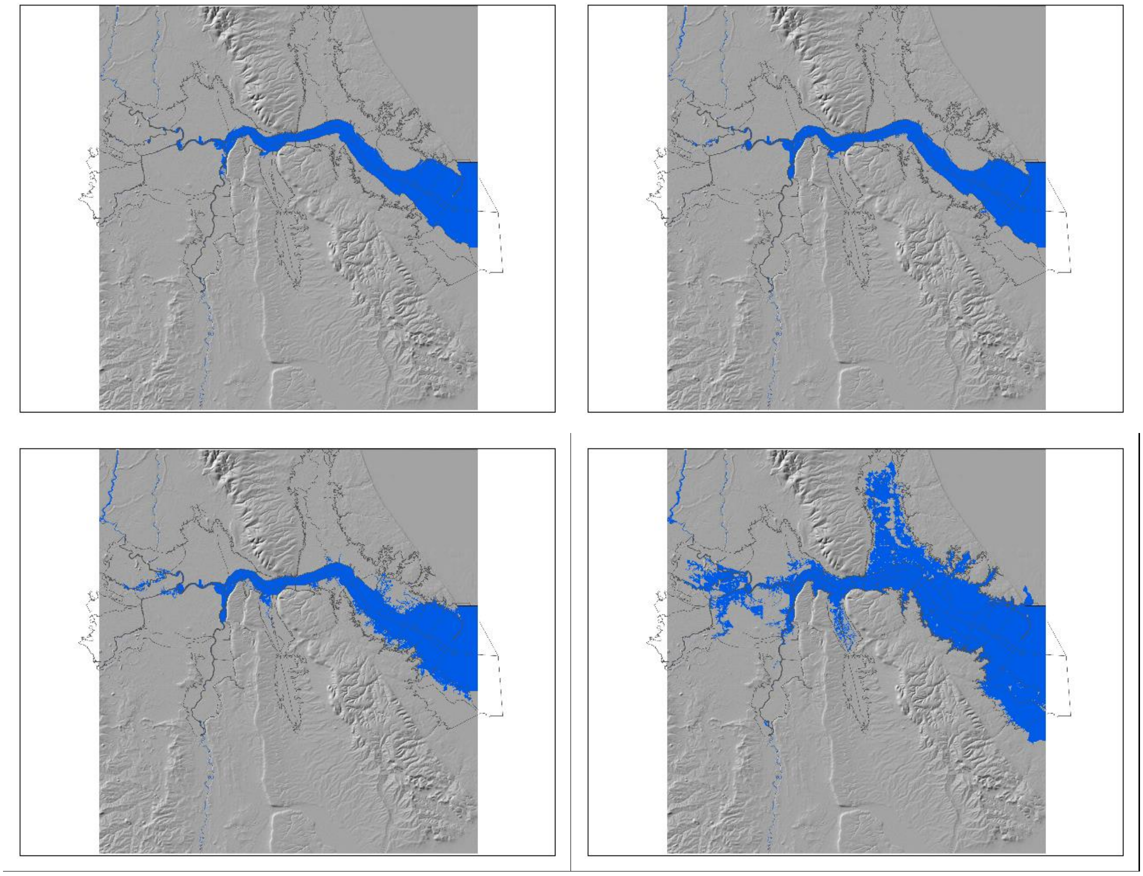

Figure 21.4 – Flood extents for Measure 12 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

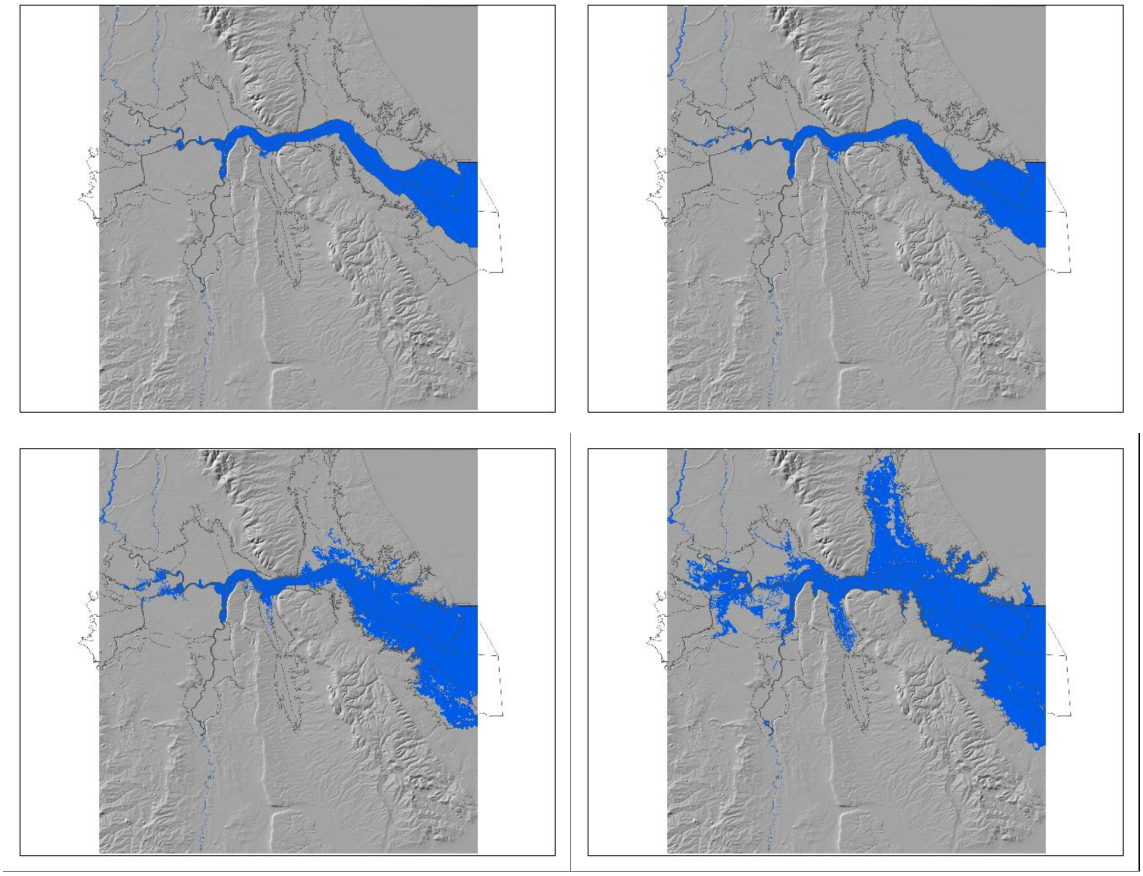

Figure 21.5 – Flood extents for Measure 12 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 21.4 – Change to the maximum stage for Measure 12 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.02
Grimsby	-0.01	-0.01	0.00	-0.01	0.00	0.01	0.02	0.08	0.00	0.03	0.02	0.07
Immingham	-0.01	0.00	0.01	0.06	0.01	0.03	0.07	0.06	0.02	0.07	0.08	0.11
Sunk Island	-0.01	-0.01	0.00	-0.02	0.00	0.01	0.02	0.07	0.00	0.03	0.01	0.06
King George's Dock	-0.01	-0.01	0.01	0.21	0.01	0.07	0.17	0.08	0.04	0.16	0.24	0.10
Albert Dock	0.00	0.00	0.01	0.24	0.00	0.08	0.23	0.09	0.04	0.17	0.29	0.11
Humber Bridge	-0.03	-0.01	0.04	0.38	0.01	0.17	0.38	0.17	0.10	0.31	0.46	0.16
Brough	-0.01	0.00	0.11	0.52	0.06	0.27	0.46	0.35	0.17	0.44	0.54	0.33
West Walker Dyke	-0.02	0.00	0.15	0.62	0.09	0.33	0.42	0.55	0.21	0.42	0.47	0.52
Blacktoft Jetty	-0.03	0.04	0.19	0.84	0.11	0.28	0.40	0.83	0.22	0.36	0.62	0.82
Flixborough	-0.05	0.02	0.13	1.03	0.09	0.20	0.26	1.05	0.15	0.25	0.46	1.06
Goole	-0.02	0.03	0.17	0.76	0.13	0.26	0.34	0.75	0.22	0.32	0.47	0.73
Ouse (upstream)	0.02	0.02	0.03	0.01	0.03	-0.02	-0.01	0.02	0.02	-0.01	0.00	0.02
Trent (upstream)	0.03	0.09	0.21	0.76	0.13	0.30	0.48	1.28	0.21	0.36	0.73	1.55
Mean	**-0.01**	**0.01**	**0.08**	**0.39**	**0.05**	**0.14**	**0.23**	**0.39**	**0.10**	**0.21**	**0.31**	**0.41**

3.20 Measure 13 – Estuary defence levels raised to 2014 local 200-year return period water surface profile plus 2 m, plus Managed Realignment and Flood Storage sites

Estuary defences were raised to an elevation of +2 m above the 2014 local 200-year return period water surface profile. Managed realignment sites were installed at Keyingham, Goxhill, and Winteringham Ings. Flood Storage sites were installed at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet and Flixborough. Defence heights are shown in Figure 21.1, the Keyingham and Goxhill Managed Realignment schemes are shown in Figure 4.1, and the Winteringham Ings Managed Realignment scheme is shown in Figure 6.1. Flood Storage sites are shown in Figure 21.2.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.20.1 Results

Increasing flood defences by an additional 1 m above those in Measure 12 resulted in little change to the mean flood volumes for the +0 m and +0.5 m SLR simulations (compare Tables 21.1 and 22.1). However, the added +1 m elevation makes a significant impact on reducing mean flood volumes in comparison to the Baseline under the +1 m and +2 m sea level rise scenarios. For example, Measure 13 reduced mean flood volumes for a 1000-year event by −419.0 × 10^6 m^3 for +1 m SLR, and −1631 × 10^6 m^3 for +2 m SLR (Table 22.2), meaning a +34 % and +50 % increase in efficacy, respectively, between Measures 12 to 13. Locally, the largest reductions in flood volume relative to the Baseline were found in the South Bank Inner, North Bank Outer, Hull and the Ouse-Trent regions (Figures 22.1 to 22.3). Mean stages were increased relative to the Baseline for all but the smallest event (−0.01 m for the 1-year return period, +0 m SLR scenario), up to +0.82 m for the largest event (1000-year return period, +2 m SLR scenario) (Table 22.4). Locally, stages were increased relative to the Baseline for the +1 m and +2 m SLR simulations throughout the estuary, but particularly at Blacktoft Jetty and Flixborough. As with Measure 12, this compound approach also worsens flooding in the upstream River Trent more so than the upstream River Ouse, with a stage increase above the Baseline of +0.01 m in the upstream River Ouse and +1.73 m for the upstream River Trent for the 1000-year return period event with +2 m SLR (Table 22.4).

Table 22.1 – Flood volumes by Area for Measure 13.

Flood Volumes (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.00	0.88	0.00	0.07	0.48	42.25	0.02	0.29	4.12	92.95
South Bank Outer	0.00	0.00	0.01	4.68	0.00	0.24	1.75	27.30	0.08	1.00	5.28	67.83
Hull	0.00	0.00	0.00	0.07	0.00	0.00	0.00	11.71	0.00	0.00	0.51	44.27
Grimsby	0.00	0.00	0.00	0.86	0.00	0.00	0.33	19.58	0.00	0.03	1.79	59.20
North Bank Inner	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
South Bank Inner	0.00	0.01	0.10	4.65	0.05	0.36	1.39	18.34	0.20	0.88	3.21	31.81
Ouse-Trent	0.00	0.00	0.66	32.20	0.18	3.06	11.03	61.23	1.41	6.72	20.70	76.12
All	**0.00**	**0.01**	**0.77**	**43.34**	**0.23**	**3.73**	**14.98**	**180.42**	**1.71**	**8.92**	**35.60**	**372.24**

Table 22.2 – Change in Flood volumes by Area for Measure 13 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.80	-53.01	-0.18	-6.37	-31.71	-192.59	-2.71	-22.56	-64.39	-256.24
South Bank Outer	0.00	0.00	0.00	-33.49	0.00	-1.22	-20.12	-138.27	-0.12	-10.70	-47.93	-147.47
Hull	0.00	0.00	-0.01	-5.91	-0.01	-0.28	-2.54	-191.78	-0.04	-1.38	-9.36	-302.39
Grimsby	0.00	0.00	0.00	-85.83	0.00	-0.02	-18.15	-143.69	0.00	-0.87	-58.73	-140.56
North Bank Inner	0.00	-0.22	-2.47	-45.64	-1.17	-6.30	-13.39	-68.28	-3.94	-10.47	-19.49	-79.19
South Bank Inner	0.00	-0.05	-8.83	-252.81	-3.23	-33.31	-110.57	-343.75	-18.51	-75.00	-172.91	-371.19
Ouse-Trent	-0.06	-0.71	-9.87	-171.23	-3.69	-15.46	-34.40	-283.16	-10.34	-24.38	-46.15	-333.72
All	**-0.06**	**-0.98**	**-21.98**	**-647.91**	**-8.28**	**-62.97**	**-230.89**	**-1361.53**	**-35.67**	**-145.36**	**-418.95**	**-1630.76**

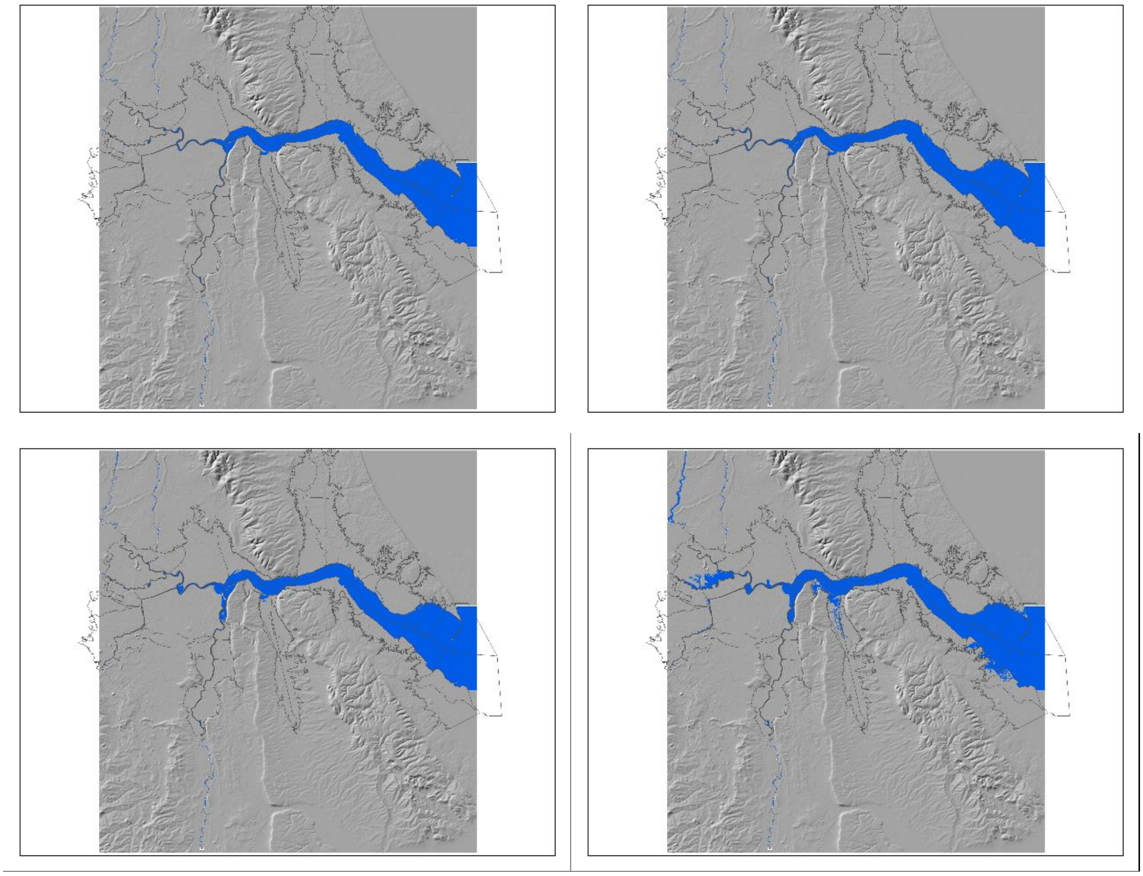

Figure 22.1 – Flood extents for Measure 13 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

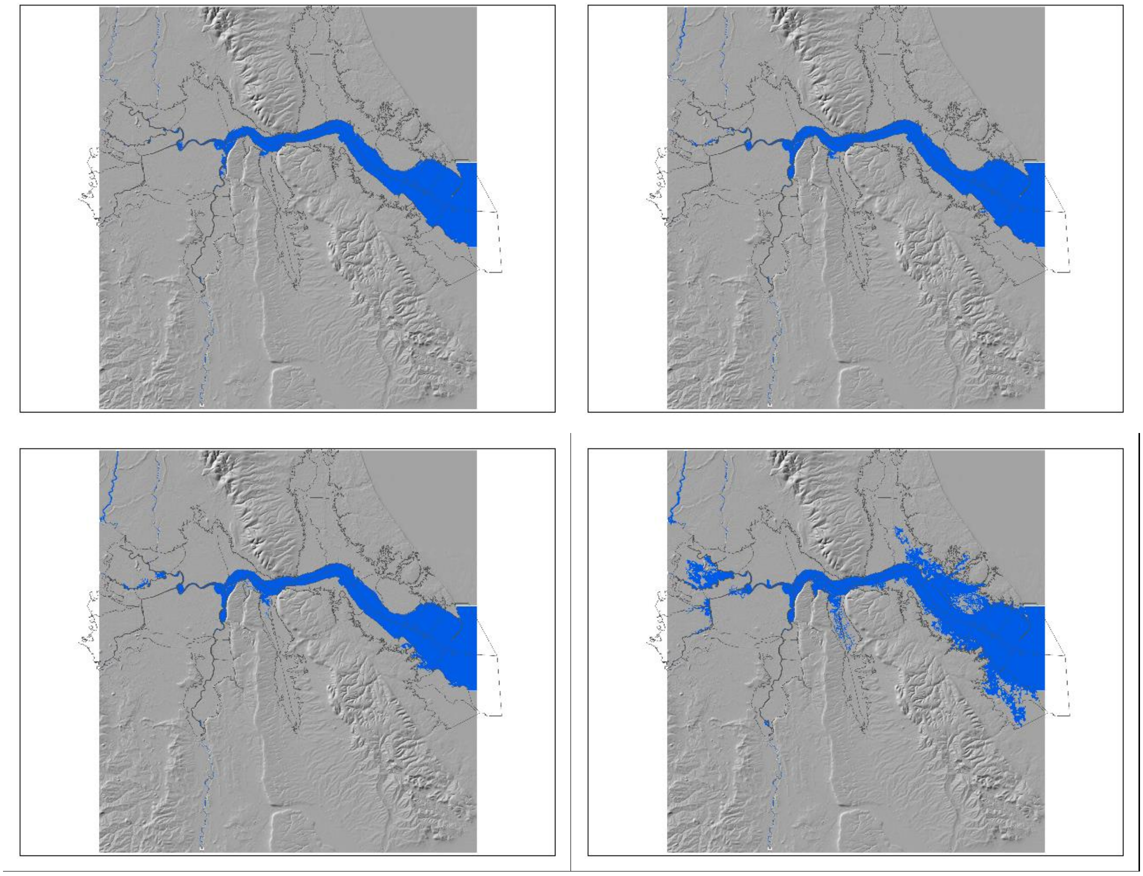

Figure 22.2 – Flood extents for Measure 13 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 22.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 13.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.20	5.05	5.55	6.06	7.04	5.37	5.88	6.36	7.33
Grimsby	4.35	4.85	5.34	6.33	5.19	5.70	6.19	7.14	5.51	6.02	6.51	7.38
Immingham	4.49	4.99	5.49	6.48	5.33	5.84	6.34	7.26	5.66	6.17	6.65	7.48
Sunk Island	4.35	4.83	5.34	6.34	5.18	5.69	6.18	7.13	5.51	6.01	6.50	7.38
King George's Dock	4.63	5.14	5.65	6.68	5.49	6.00	6.52	7.43	5.82	6.35	6.84	7.60
Albert Dock	4.65	5.16	5.68	6.73	5.51	6.04	6.56	7.45	5.85	6.37	6.88	7.62
Humber Bridge	4.75	5.29	5.84	6.88	5.66	6.22	6.72	7.54	6.02	6.55	7.01	7.68
Brough	4.97	5.53	6.09	7.00	5.91	6.39	6.82	7.63	6.23	6.69	7.03	7.81
West Walker Dyke	5.08	5.65	6.15	7.05	6.01	6.45	6.75	7.79	6.27	6.67	7.05	7.93
Blacktoft Jetty	5.11	5.70	6.13	7.09	6.00	6.35	6.61	7.72	6.23	6.53	7.00	7.91
Flixborough	5.23	5.79	6.17	7.36	6.09	6.30	6.49	7.84	6.22	6.39	6.90	8.04
Goole	5.15	5.72	6.12	6.97	6.02	6.26	6.41	7.36	6.19	6.37	6.70	7.56
Ouse (upstream)	3.60	4.17	4.73	5.16	4.42	4.93	5.06	5.33	4.73	5.04	5.09	5.36
Trent (upstream)	4.15	4.72	5.30	6.56	4.92	5.54	6.10	7.26	5.24	5.83	6.47	7.57
Mean	**4.62**	**5.16**	**5.66**	**6.63**	**5.48**	**5.95**	**6.34**	**7.28**	**5.78**	**6.20**	**6.64**	**7.48**

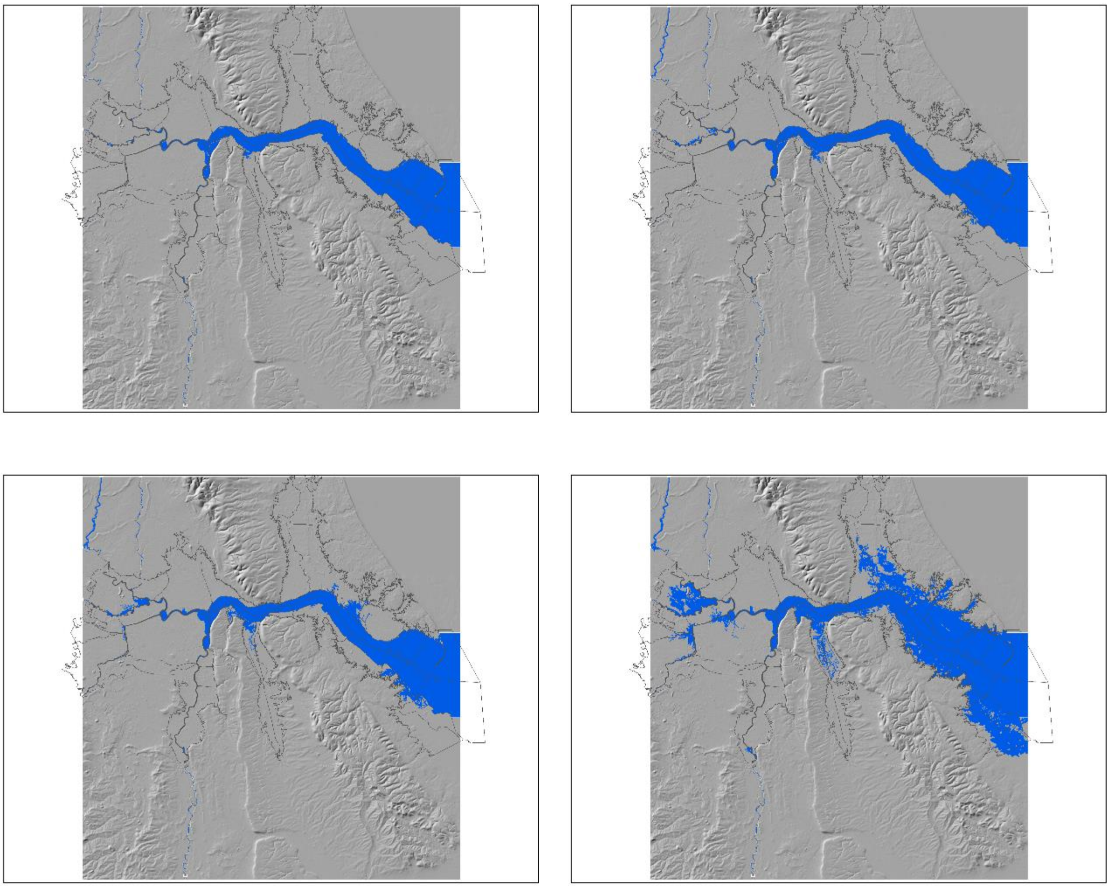

Figure 22.3 – Flood extents for Measure 13 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 22.4 – Change to the maximum stage for Measure 13 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.08	0.00	0.01	0.03	0.07
Grimsby	-0.01	-0.01	0.00	0.05	0.00	0.01	0.06	0.22	0.01	0.04	0.12	0.21
Immingham	-0.01	0.00	0.01	0.15	0.01	0.03	0.12	0.34	0.02	0.08	0.23	0.36
Sunk Island	-0.01	-0.01	0.00	0.05	0.00	0.01	0.05	0.20	0.00	0.03	0.11	0.20
King George's Dock	-0.01	0.00	0.01	0.32	0.01	0.07	0.24	0.50	0.04	0.18	0.41	0.52
Albert Dock	0.00	0.00	0.01	0.36	0.00	0.08	0.28	0.55	0.04	0.18	0.47	0.56
Humber Bridge	-0.03	-0.01	0.04	0.49	0.01	0.18	0.43	0.67	0.10	0.33	0.63	0.68
Brough	-0.01	0.00	0.12	0.64	0.06	0.27	0.53	0.89	0.17	0.47	0.67	0.99
West Walker Dyke	-0.02	0.00	0.16	0.74	0.09	0.35	0.48	1.21	0.21	0.44	0.73	1.29
Blacktoft Jetty	-0.03	0.04	0.22	0.96	0.13	0.32	0.50	1.45	0.26	0.43	0.86	1.61
Flixborough	-0.05	0.02	0.13	1.21	0.09	0.21	0.35	1.61	0.15	0.26	0.74	1.79
Goole	-0.02	0.03	0.21	0.99	0.15	0.31	0.43	1.27	0.26	0.40	0.72	1.45
Ouse (upstream)	0.02	0.02	0.03	0.01	0.03	-0.01	-0.01	0.01	0.03	-0.01	-0.02	0.01
Trent (upstream)	0.03	0.09	0.22	0.78	0.13	0.31	0.49	1.42	0.22	0.37	0.71	1.73
Mean	**-0.01**	**0.01**	**0.08**	**0.48**	**0.05**	**0.15**	**0.28**	**0.74**	**0.11**	**0.23**	**0.46**	**0.82**

3.21 Measure 14 – 2014 'Realistic' Measure, plus Estuary defences raised 1 m in line with post-2032 designation

Flood defence crest levels were set as per the Baseline (2021 defences) but adjusted according to the post-2032 designation, with areas of improved defence raised by 1 m, plus Managed Realignment and Flood Storage sites in the 2014 'realistic' scenario. Managed realignment sites were installed at Keyingham, Goxhill, and Winteringham Ings. Flood Storage sites were installed at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet, Flixborough, Patrington and Ryehill. The post-2032 designations are shown in Figure 23.1, the Keyingham and Goxhill Managed Realignment schemes are shown in Figure 4.1, the Winteringham Ings Managed Realignment scheme is shown in Figure 6.1, and flood storage sites are shown in Figures 21.2 and 23.2.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

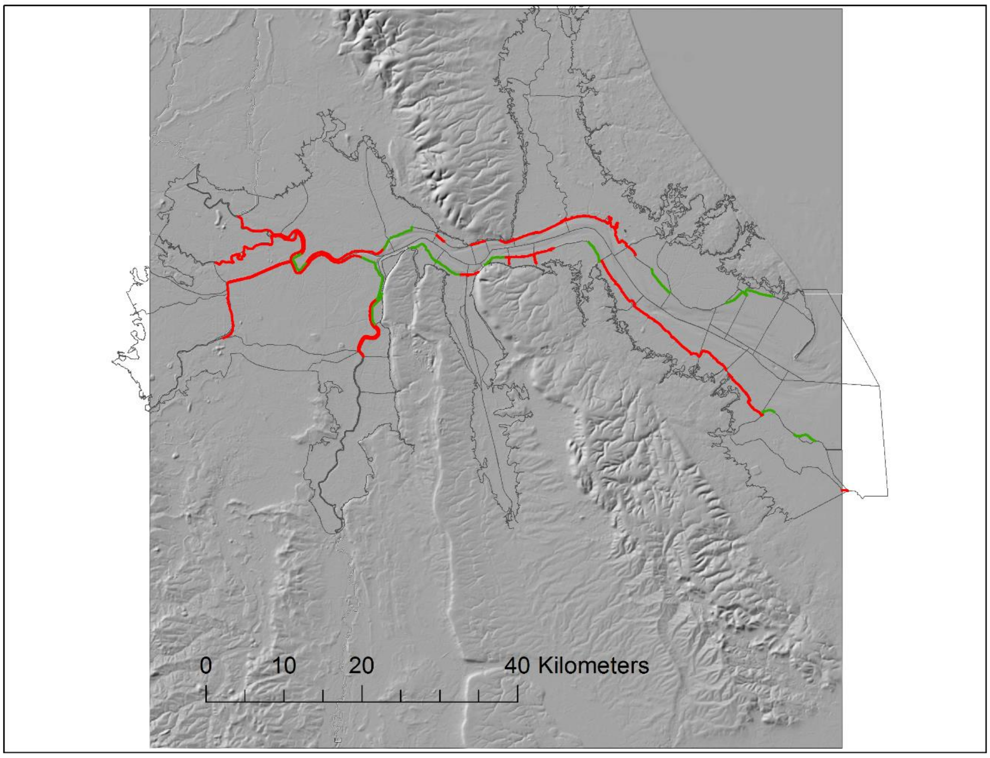

Figure 23.1 – Configuration of the post-2032 designations. Red lines show areas where defence assets are raised. Green areas show areas where defence assets are removed by setting their elevation to the mean of surrounding cells.

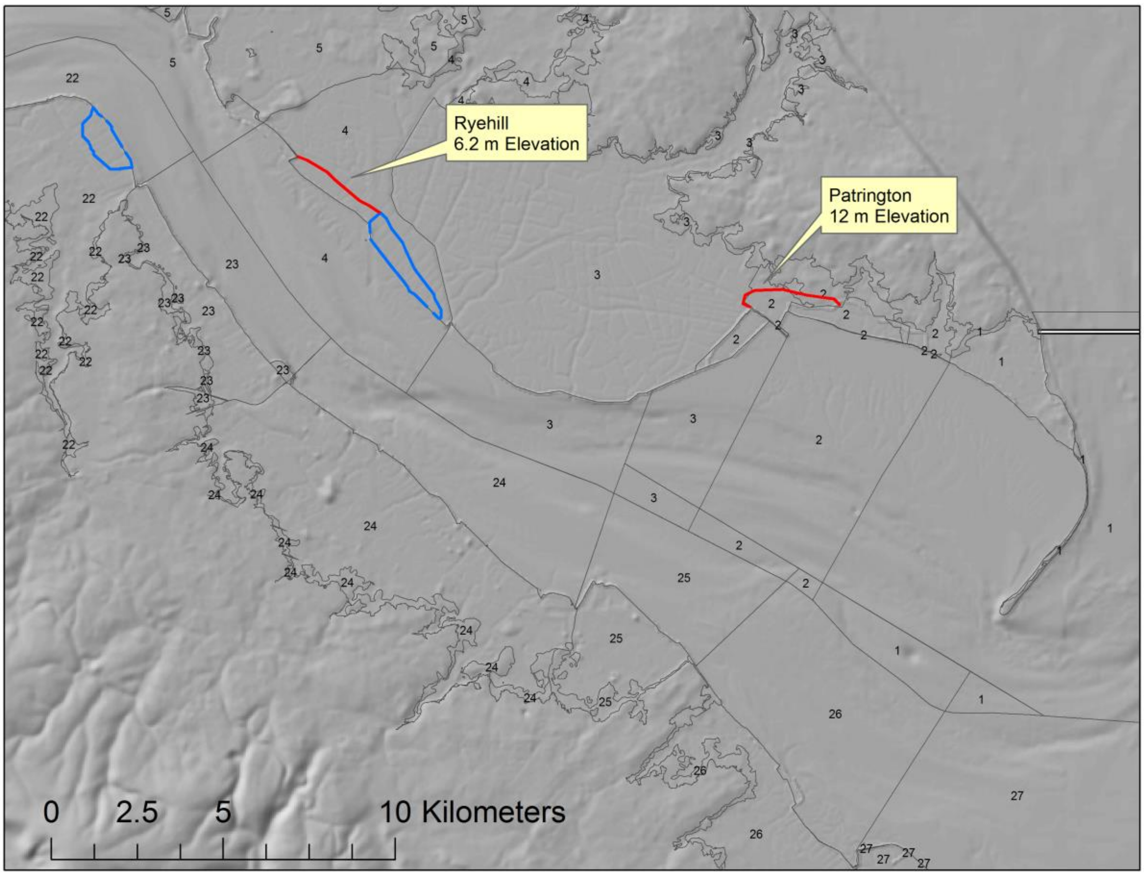

Figure 23.2 – Configuration of the Ryehill and Patrington Flood Storage sites. Estuary facing defences treated according to the post-2032 designations.

3.21.1 Results

In comparison to Measures 12 and 13, Measure 14 has declined efficacy of flood alleviation with only four out of the 12 model runs having reduced mean flood volumes relative to the Baseline (Tables 23.1 and 23.2), with the largest reduction of −667.30 × 10^6 m^3 (1000-year return period event, +2 m SLR scenario). Of the remaining eight scenarios, the mean flood volume was increased in comparison to the Baseline from +57.95 × 10^6 m^3 (1000-year return period event, +0.5 m SLR scenario) to +113.41 × 10^6 m^3 (1-year return period event, +1 m SLR scenario). Locally, the worst impacted area for flooding in every scenario was the South Bank Outer region, despite the defences there being raised (Figures 23.1, 23.3 to 23.5). Of the scenarios that did reduce mean flood volumes relative to the Baseline, the largest reductions occurred locally at the South Bank Inner and Ouse-Trent regions for the larger sea level rise scenarios (Table 23.2). In comparison to the Baseline, half the simulations resulted in reduced mean stages of between −0.02 and −0.14 m, while half resulted in increased mean stages of between +0.05 and +0.43 m, including every +2 m SLR scenario simulation (Table 23.4). Locally, when compared to the Baseline, stage heights varied the least in the outer estuary and increased the most in the inner estuary. Addition of the Ryehill and Patrington flood storage sites did not noticeably impact nearby stages.

Table 23.1 – Flood volumes by Area for Measure 14.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.78	43.79	0.17	6.34	29.49	214.76	2.70	20.72	61.91	316.80
South Bank Outer	36.25	60.37	80.66	121.95	70.56	92.28	113.14	198.02	82.98	104.45	131.52	237.05
Hull	0.00	0.00	0.00	0.02	0.00	0.00	0.01	134.83	0.00	0.00	2.06	258.41
Grimsby	0.00	0.00	0.00	77.77	0.00	0.00	9.79	112.92	0.00	0.08	34.88	127.23
North Bank Inner	0.00	0.00	0.65	9.00	0.29	2.25	6.59	20.83	1.18	5.84	7.87	28.48
South Bank Inner	17.81	24.94	41.37	142.78	27.37	48.20	94.52	186.82	37.17	68.60	132.52	203.85
Ouse-Trent	7.17	9.42	13.04	59.88	10.53	13.27	22.31	127.27	11.75	16.66	30.93	163.87
All	**61.24**	**94.73**	**136.50**	**455.20**	**108.92**	**162.34**	**275.86**	**995.44**	**135.78**	**216.35**	**401.68**	**1335.69**

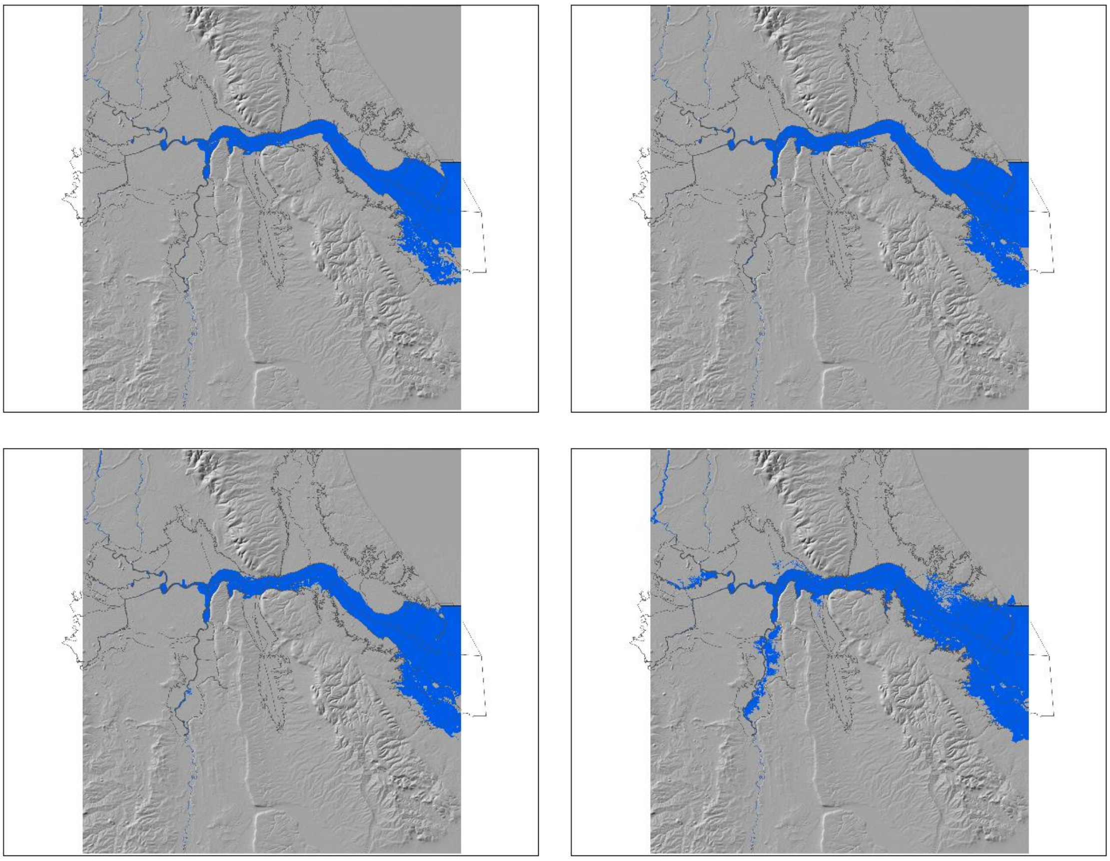

Figure 23.3 – Flood extents for Measure 14 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 23.2 – Change in Flood volumes by Area for Measure 14 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.02	-10.10	-0.01	-0.11	-2.70	-20.09	-0.04	-2.13	-6.59	-32.39
South Bank Outer	36.25	60.37	80.65	83.78	70.56	90.82	91.28	32.44	82.79	92.76	78.30	21.75
Hull	0.00	0.00	-0.01	-5.96	-0.01	-0.28	-2.53	-68.66	-0.04	-1.38	-7.81	-88.26
Grimsby	0.00	0.00	0.00	-8.92	0.00	-0.02	-8.70	-50.35	0.00	-0.82	-25.64	-72.53
North Bank Inner	0.00	-0.22	-1.82	-36.65	-0.88	-4.05	-6.80	-47.45	-2.77	-4.63	-11.62	-50.77
South Bank Inner	17.81	24.88	32.44	-114.68	24.10	14.52	-17.43	-175.27	18.46	-7.28	-43.60	-199.15
Ouse-Trent	7.11	8.71	2.51	-143.54	6.66	-5.25	-23.12	-217.13	0.00	-14.44	-35.91	-245.97
All	**61.17**	**93.74**	**113.74**	**-236.06**	**100.42**	**95.64**	**29.99**	**-546.51**	**98.40**	**62.07**	**-52.87**	**-667.30**

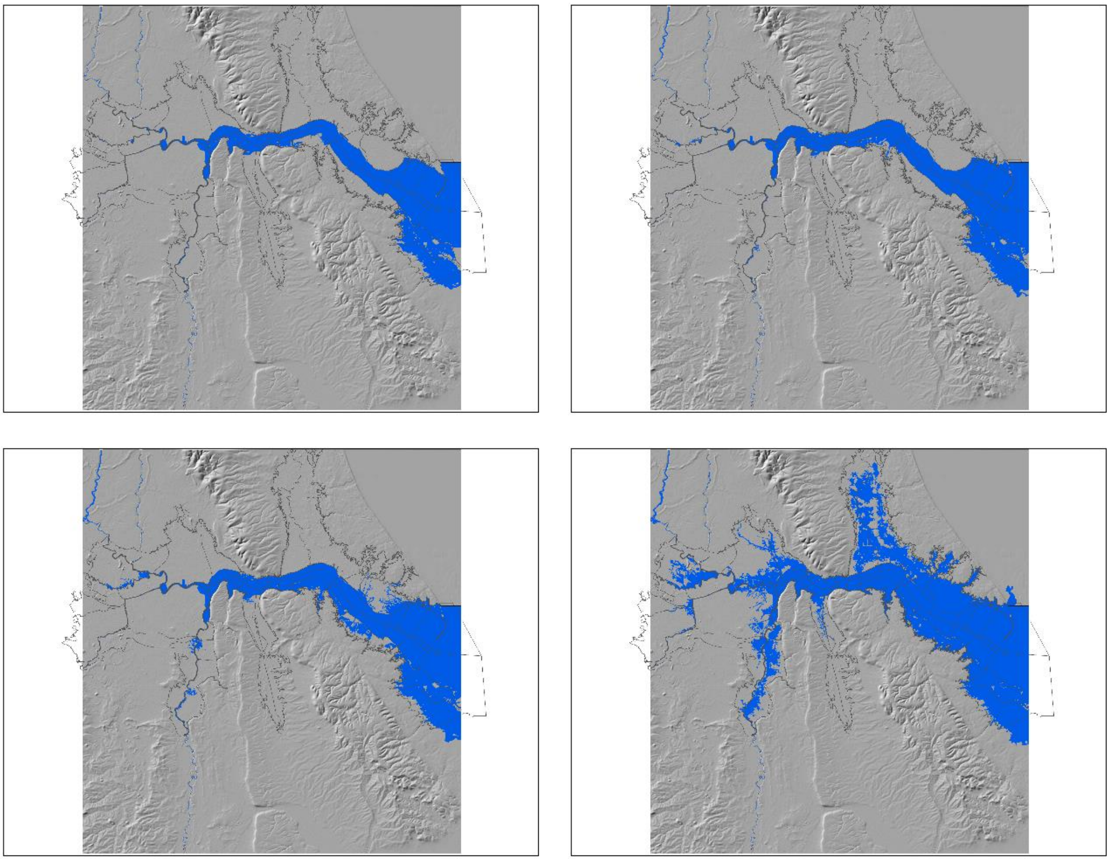

Figure 23.4 – Flood extents for Measure 14 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

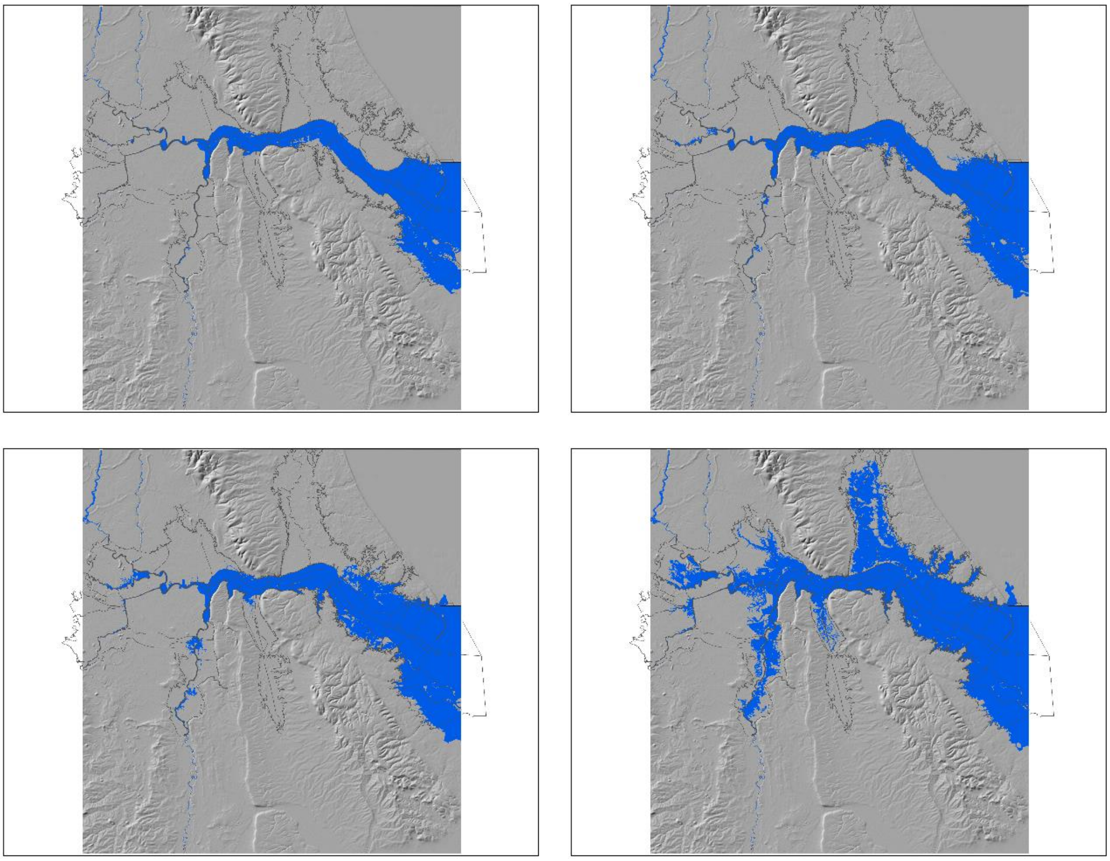

Figure 23.5 – Flood extents for Measure 14 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 23.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 14.

	Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.19	5.05	5.56	6.04	6.97	5.37	5.86	6.33	7.29
Grimsby	4.35	4.85	5.34	6.29	5.19	5.67	6.13	6.97	5.50	5.98	6.40	7.23
Immingham	4.49	4.98	5.47	6.34	5.32	5.80	6.21	6.97	5.63	6.07	6.44	7.27
Sunk Island	4.35	4.85	5.33	6.29	5.19	5.67	6.14	6.98	5.50	5.98	6.40	7.25
King George's Dock	4.61	5.10	5.59	6.33	5.45	5.87	6.22	7.10	5.73	6.10	6.42	7.36
Albert Dock	4.60	5.12	5.59	6.34	5.45	5.85	6.20	7.10	5.73	6.08	6.42	7.37
Humber Bridge	4.67	5.12	5.54	6.35	5.42	5.87	6.22	7.21	5.70	6.11	6.45	7.45
Brough	4.71	5.19	5.63	6.52	5.51	5.93	6.32	7.33	5.77	6.16	6.66	7.52
West Walker Dyke	4.66	5.21	5.69	6.62	5.52	5.98	6.45	7.33	5.83	6.27	6.73	7.49
Blacktoft Jetty	4.68	5.21	5.73	6.69	5.55	6.06	6.52	7.22	5.88	6.37	6.74	7.32
Flixborough	4.91	5.50	5.97	6.76	5.83	6.18	6.56	7.26	6.06	6.38	6.81	7.37
Goole	4.76	5.28	5.85	6.73	5.66	6.16	6.58	7.00	5.98	6.43	6.76	7.05
Ouse (upstream)	3.71	4.29	4.87	5.23	4.55	4.98	5.07	5.35	4.87	5.04	5.09	5.38
Trent (upstream)	4.27	4.73	5.13	5.81	4.88	5.32	5.68	5.89	5.10	5.50	5.81	5.89
Mean	**4.50**	**5.01**	**5.50**	**6.32**	**5.33**	**5.78**	**6.17**	**6.90**	**5.62**	**6.02**	**6.39**	**7.09**

Table 23.4 – Change to the maximum stage for Measure 14 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	-0.01	0.00	0.03
Grimsby	-0.01	-0.01	0.00	0.01	0.00	-0.02	0.00	0.05	-0.01	0.00	0.02	0.07
Immingham	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.06	-0.01	-0.02	0.02	0.15
Sunk Island	-0.01	0.00	-0.01	0.01	0.01	-0.01	0.01	0.05	-0.01	0.00	0.01	0.07
King George's Dock	-0.03	-0.05	-0.05	-0.03	-0.03	-0.07	-0.06	0.17	-0.06	-0.07	-0.01	0.27
Albert Dock	-0.05	-0.05	-0.08	-0.03	-0.06	-0.10	-0.07	0.19	-0.08	-0.10	0.01	0.30
Humber Bridge	-0.10	-0.18	-0.26	-0.04	-0.24	-0.18	-0.07	0.35	-0.22	-0.11	0.07	0.45
Brough	-0.27	-0.34	-0.34	0.17	-0.35	-0.19	0.03	0.60	-0.28	-0.06	0.30	0.70
West Walker Dyke	-0.44	-0.43	-0.30	0.31	-0.39	-0.12	0.18	0.75	-0.23	0.04	0.41	0.85
Blacktoft Jetty	-0.46	-0.45	-0.18	0.55	-0.32	0.02	0.41	0.95	-0.09	0.27	0.60	1.02
Flixborough	-0.37	-0.27	-0.07	0.61	-0.17	0.10	0.42	1.03	0.00	0.25	0.65	1.13
Goole	-0.41	-0.41	-0.06	0.74	-0.22	0.21	0.61	0.92	0.05	0.46	0.78	0.94
Ouse (upstream)	0.13	0.14	0.16	0.07	0.16	0.04	-0.01	0.03	0.16	0.00	-0.01	0.03
Trent (upstream)	0.15	0.11	0.04	0.04	0.09	0.09	0.07	0.05	0.07	0.05	0.04	0.05
Mean	**-0.13**	**-0.14**	**-0.08**	**0.17**	**-0.11**	**-0.02**	**0.11**	**0.37**	**-0.05**	**0.05**	**0.21**	**0.43**

3.22 Measure 15 – 2014 'Realistic' Measure, plus Estuary defences raised 2 m in line with post-2032 designation

Flood defence crest levels were set as per the Baseline (2021 defences) but adjusted according to the post-2032 designation, with areas of improved defence raised by 2 m, plus the Managed Realignment and Flood Storage sites in the 2014 'realistic' scenario. Managed realignment sites were installed at Keyingham, Goxhill, and Winteringham Ings. Flood Storage sites were installed at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet, Flixborough, Patrington and Ryehill.. The post-2032 designations are shown in Figure 23.1, the Keyingham and Goxhill Managed Realignment schemes are shown in Figure 4.1, the Winteringham Ings Managed Realignment scheme is shown in Figure 6.1, and flood storage sites are shown in Figures 21.2 and 23.2.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.22.1 Results

In comparison to the Baseline, Measure 15 resulted in increased mean flood volumes in eight of the 12 scenarios between +28.88 to +99.44 × 10^6 m^3. The remaining four scenarios resulted in decreased mean flood volumes of between −54.56 and −710.8 × 10^6 m^3, including every +2 m SLR scenario (Table 24.2). Locally, flood volumes were largest in the South Bank Inner region and reduced the most relative to the Baseline in the South Bank Inner and Ouse-Trent regions (Tables 24.1 and 24.2, Figures 24.1 to 24.3). Mean stages reduced by between −0.02 m and −0.13 m for six of the scenarios and increased by between +0.05 m and +0.56 m for six of the scenarios (Tables 24.3 and 24.4). For the most part, stages reduced for the +0m and +0.5 m sea level rise scenarios and increased for the +2 m SLR scenarios. As with Measure 14, local stages remained similar to the Baseline in the outer estuary region but were more varied upstream in the fluvial region.

Table 24.1 – Flood volumes by Area for Measure 15.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.78	43.82	0.17	6.34	29.50	215.24	2.70	20.73	61.98	318.72
South Bank Outer	35.98	59.57	79.39	120.25	69.42	90.78	111.48	189.28	81.57	102.82	129.73	221.66
Hull	0.00	0.00	0.00	0.00	0.00	0.00	0.00	134.23	0.00	0.00	2.06	256.70
Grimsby	0.00	0.00	0.00	78.04	0.00	0.00	9.95	113.23	0.00	0.08	34.98	125.94
North Bank Inner	0.00	0.00	0.66	9.03	0.30	2.29	6.63	21.02	1.20	5.87	7.88	28.57
South Bank Inner	17.91	25.06	41.48	142.88	27.47	48.29	94.80	187.04	37.22	68.82	132.73	201.61
Ouse-Trent	7.14	9.48	13.11	60.08	10.58	13.32	22.39	113.18	11.80	16.72	30.63	138.96
All	**61.03**	**94.11**	**135.43**	**454.10**	**107.94**	**161.01**	**274.75**	**973.22**	**134.49**	**215.02**	**399.99**	**1292.16**

Table 24.2 – Change in Flood volumes by Area for Measure 15 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.02	-10.06	-0.01	-0.10	-2.69	-19.60	-0.04	-2.12	-6.53	-30.47
South Bank Outer	35.98	59.57	79.38	82.08	69.42	89.33	89.61	23.70	81.38	91.12	76.52	6.36
Hull	0.00	0.00	-0.01	-5.98	-0.01	-0.28	-2.54	-69.26	-0.04	-1.38	-7.81	-89.96
Grimsby	0.00	0.00	0.00	-8.65	0.00	-0.02	-8.53	-50.04	0.00	-0.82	-25.53	-73.82
North Bank Inner	0.00	-0.22	-1.81	-36.62	-0.87	-4.02	-6.76	-47.26	-2.75	-4.60	-11.61	-50.67
South Bank Inner	17.90	25.00	32.55	-114.58	24.19	14.61	-17.16	-175.05	18.51	-7.07	-43.38	-201.38
Ouse-Trent	7.07	8.77	2.59	-143.34	6.71	-5.20	-23.04	-231.22	0.05	-14.38	-36.21	-270.88
All	**60.96**	**93.12**	**112.67**	**-237.15**	**99.44**	**94.31**	**28.88**	**-568.73**	**97.11**	**60.75**	**-54.56**	**-710.83**

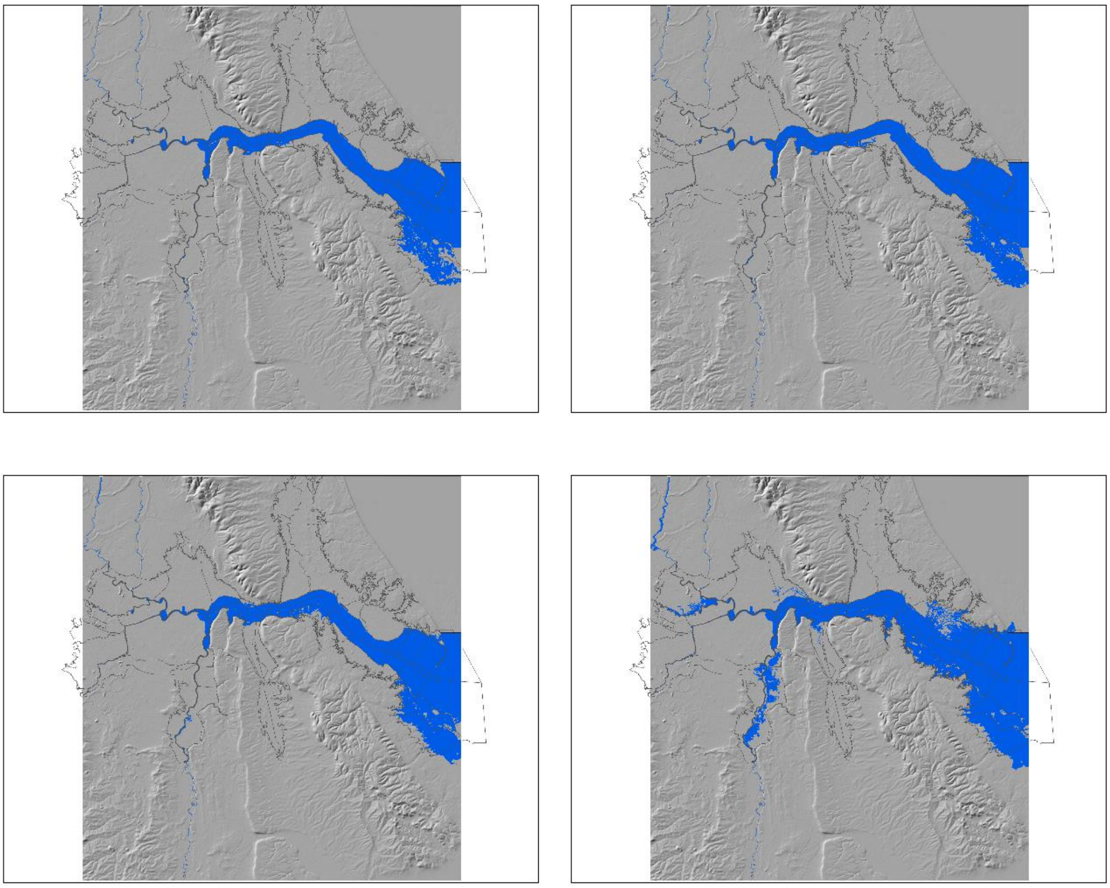

Figure 24.1 – Flood extents for Measure 15 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

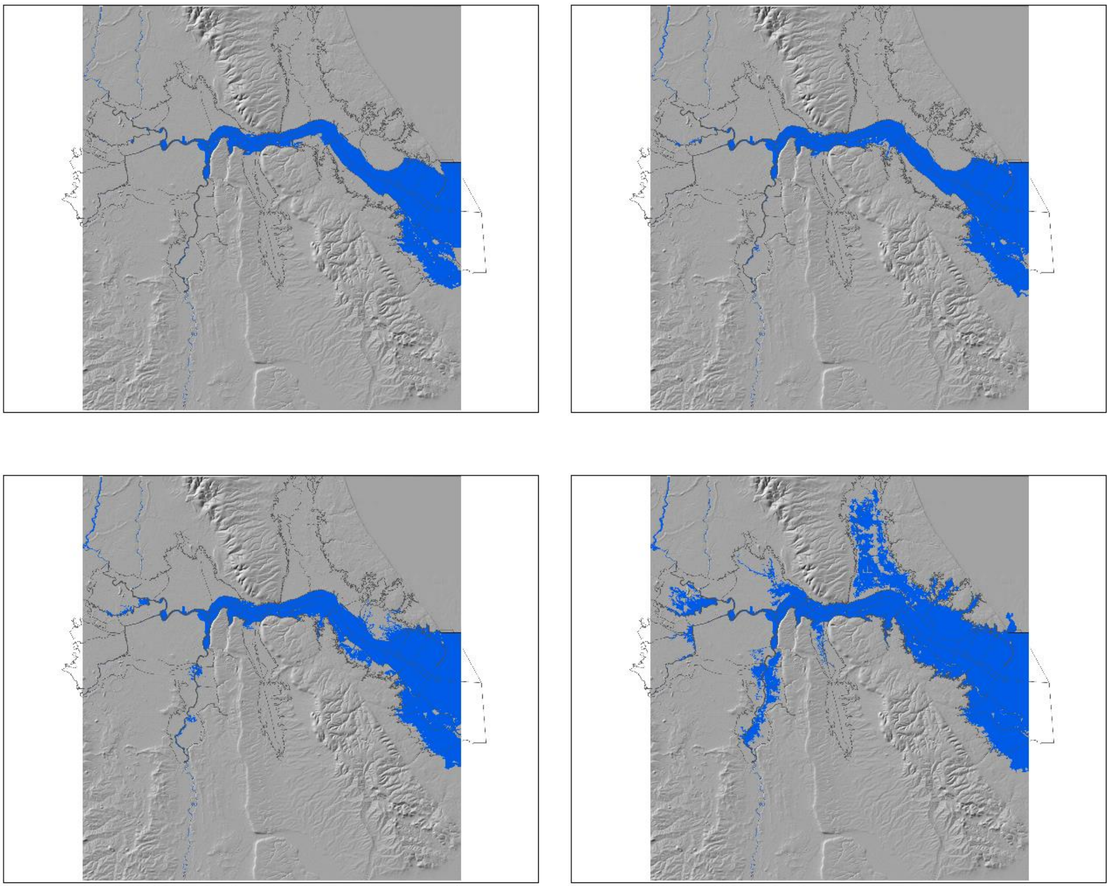

Figure 24.2 – Flood extents for Measure 15 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 24.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 15.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.19	5.05	5.56	6.04	6.98	5.37	5.86	6.33	7.29
Grimsby	4.35	4.85	5.34	6.29	5.19	5.67	6.13	6.97	5.50	5.98	6.40	7.24
Immingham	4.49	4.98	5.47	6.34	5.32	5.80	6.21	6.97	5.63	6.07	6.44	7.28
Sunk Island	4.35	4.85	5.33	6.29	5.19	5.67	6.14	6.98	5.50	5.98	6.40	7.26
King George's Dock	4.61	5.10	5.59	6.33	5.45	5.87	6.22	7.11	5.73	6.10	6.42	7.37
Albert Dock	4.60	5.12	5.59	6.34	5.45	5.85	6.21	7.11	5.73	6.08	6.43	7.40
Humber Bridge	4.68	5.12	5.55	6.35	5.42	5.87	6.22	7.24	5.71	6.12	6.46	7.51
Brough	4.72	5.19	5.63	6.52	5.52	5.94	6.33	7.37	5.78	6.16	6.66	7.65
West Walker Dyke	4.66	5.22	5.70	6.63	5.53	5.98	6.45	7.45	5.83	6.28	6.74	7.73
Blacktoft Jetty	4.70	5.22	5.74	6.70	5.56	6.05	6.51	7.45	5.88	6.38	6.74	7.71
Flixborough	4.90	5.52	5.99	6.76	5.85	6.19	6.56	7.48	6.07	6.38	6.82	7.74
Goole	4.74	5.29	5.84	6.73	5.66	6.15	6.58	7.30	5.98	6.43	6.77	7.55
Ouse (upstream)	3.72	4.30	4.86	5.24	4.56	4.99	5.07	5.35	4.88	5.04	5.09	5.38
Trent (upstream)	4.27	4.73	5.13	5.81	4.88	5.32	5.68	5.89	5.10	5.51	5.81	5.90
Mean	**4.50**	**5.01**	**5.50**	**6.32**	**5.33**	**5.78**	**6.17**	**6.98**	**5.62**	**6.03**	**6.39**	**7.21**

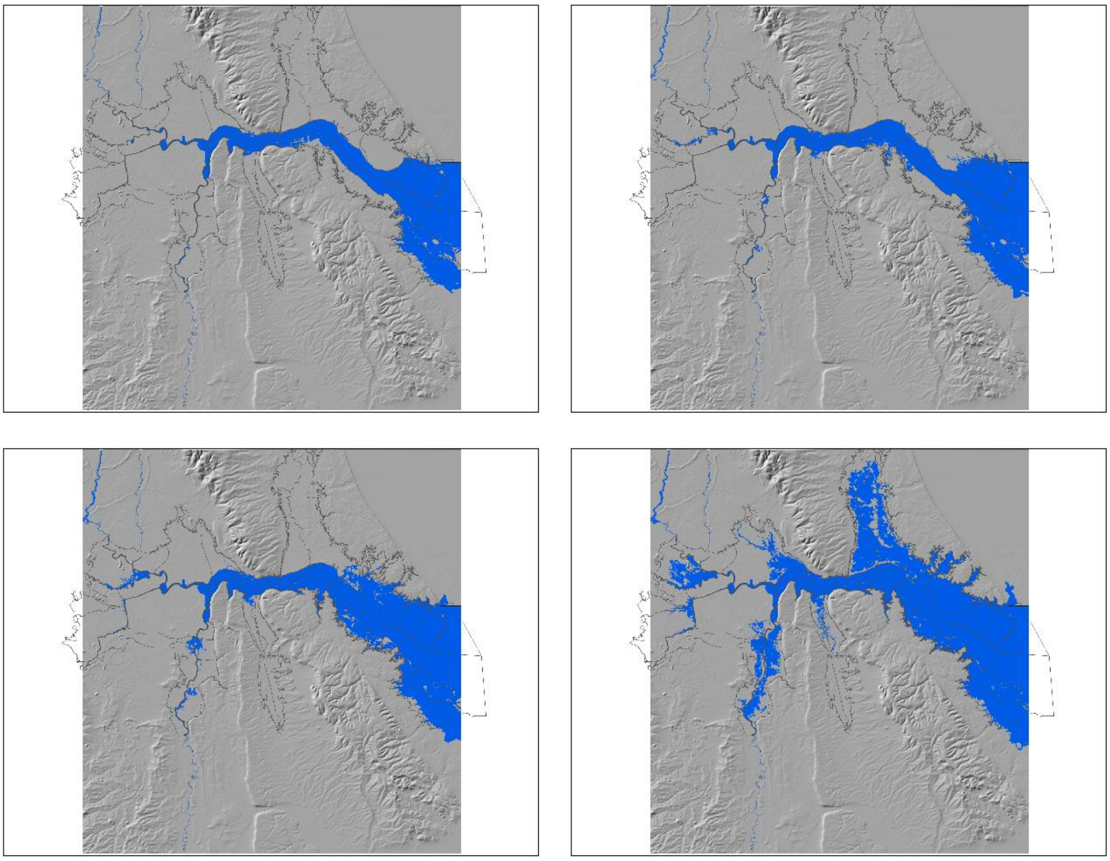

Figure 24.3 – Flood extents for Measure 15 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 24.4 – Change to the maximum stage for Measure 15 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	-0.01	0.00	0.03
Grimsby	-0.01	-0.01	0.00	0.01	0.00	-0.02	0.00	0.06	-0.01	0.00	0.02	0.07
Immingham	-0.01	-0.01	-0.01	0.01	0.00	-0.01	0.00	0.06	-0.01	-0.02	0.02	0.16
Sunk Island	-0.01	0.00	-0.01	0.01	0.01	-0.01	0.01	0.05	-0.01	0.00	0.01	0.08
King George's Dock	-0.03	-0.05	-0.05	-0.03	-0.03	-0.07	-0.06	0.19	-0.06	-0.07	0.00	0.28
Albert Dock	-0.05	-0.05	-0.08	-0.03	-0.06	-0.10	-0.07	0.20	-0.08	-0.10	0.01	0.33
Humber Bridge	-0.10	-0.18	-0.25	-0.04	-0.23	-0.17	-0.07	0.37	-0.21	-0.11	0.08	0.51
Brough	-0.27	-0.34	-0.34	0.17	-0.34	-0.19	0.04	0.64	-0.28	-0.06	0.30	0.83
West Walker Dyke	-0.45	-0.43	-0.29	0.32	-0.38	-0.13	0.18	0.87	-0.22	0.04	0.42	1.09
Blacktoft Jetty	-0.44	-0.44	-0.17	0.57	-0.32	0.02	0.40	1.18	-0.08	0.27	0.60	1.41
Flixborough	-0.38	-0.25	-0.05	0.61	-0.15	0.11	0.42	1.25	0.01	0.26	0.66	1.50
Goole	-0.43	-0.40	-0.07	0.75	-0.21	0.21	0.61	1.21	0.06	0.46	0.79	1.44
Ouse (upstream)	0.13	0.15	0.16	0.08	0.17	0.05	-0.01	0.03	0.17	0.00	-0.01	0.03
Trent (upstream)	0.15	0.11	0.04	0.04	0.09	0.09	0.07	0.05	0.07	0.05	0.04	0.05
Mean	**-0.13**	**-0.14**	**-0.08**	**0.18**	**-0.10**	**-0.02**	**0.11**	**0.44**	**-0.05**	**0.05**	**0.21**	**0.56**

3.23 Measure 17 – Ouse and Trent (Inner estuary) Barriers, plus Keyingham and Goxhill Managed Realignment sites

Flood defence crest levels were set as per the Baseline (2021 defences), but with Keyingham and Goxhill Managed Realignment sites and tidal barriers on the Ouse and Trent. The specification of the Keyingham and Goxhill Managed Realignment sites is as shown in Figure 4.1. The location of the Ouse and Trent tidal barriers in shown in Figure 25.1. The Ouse and Trent tidal barriers were raised at the point of lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

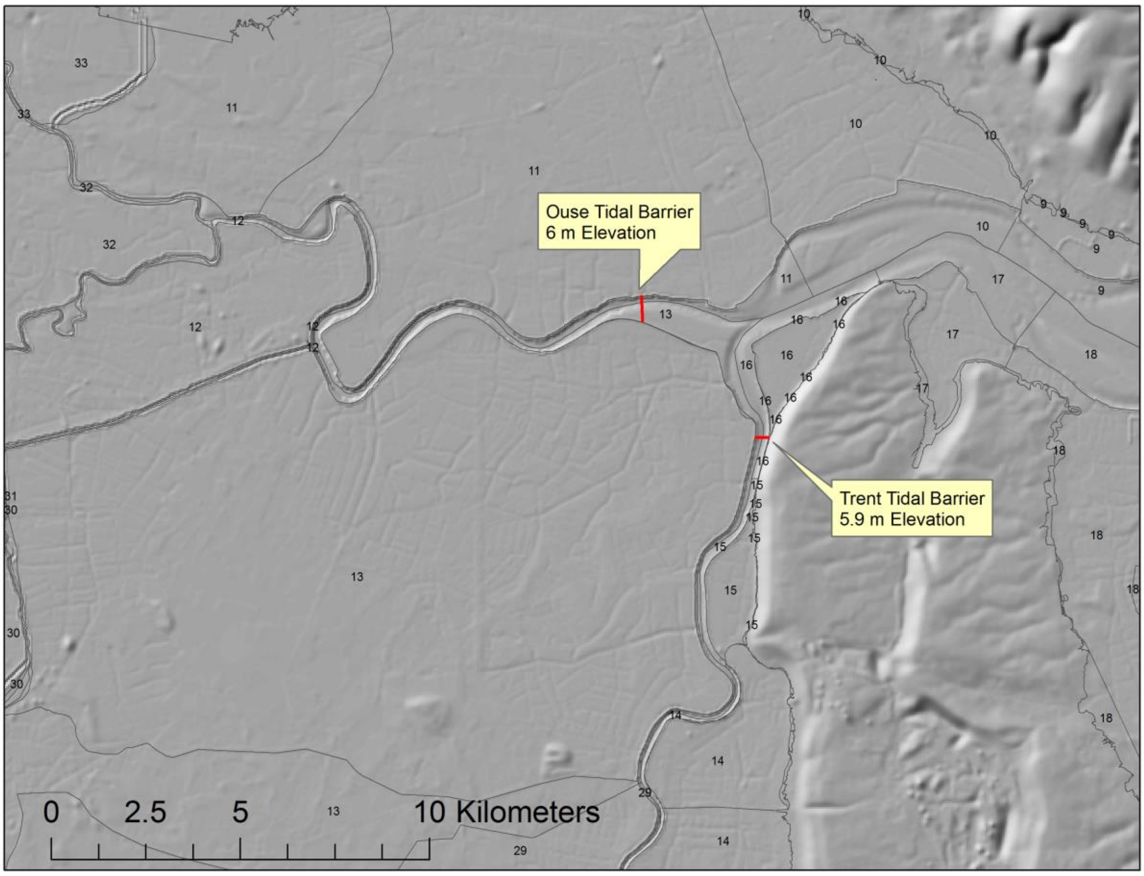

Figure 25.1 – Configuration of the Ouse and Trent tidal barriers.

3.23.1 Results

Measure 17 resulted in an increase of mean flood volumes of between +0.01 × 10^6 m^3 and 54.36 × 10^6 m^3 relative to the Baseline in all 12 of the model simulations (Tables 25.1 and 25.2). Locally, the South Bank Inner region is the worst affected by the increased flood volumes, followed by Hull during the +2 m SLR events (Figures 25.2 to 25.4). The Ouse-Trent region benefits the most from the tidal barriers, but only during the worst events (200- and 1000-year events with +1 m and- +2 m SLR). Importantly, the tidal barriers do not prevent upstream flooding without additional measures (i.e., raising hard defences). Mean stages were reduced by between −0.05 and −0.24 m relative to the Baseline in nine of the 12 simulations, with little to no change for the remaining three simulations all of which occurred with +2m sea level rise (Tables 25.3 and 25.4). Locally, most gauges in the outer estuary from Spurn to Sunk Island experienced little change relative to the Baseline, but there were increases in stages within the mid (King George's Dock) to inner (West Walker Dyke) estuary. From Blacktoft Jetty to the upstream reaches of the Ouse and the Trent, all stages decreased relative to the Baseline (Table 25.4).

Table 25.1 – Flood volumes by Area for Measure 17.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.80	58.05	0.17	6.62	35.20	247.03	2.77	24.35	74.85	361.79
South Bank Outer	0.00	0.00	0.01	38.59	0.00	1.50	22.20	165.96	0.19	11.98	53.58	215.70
Hull	0.00	0.00	0.11	9.77	0.01	0.84	4.02	226.61	0.36	2.47	14.71	370.46
Grimsby	0.00	0.00	0.00	86.08	0.00	0.03	34.72	166.09	0.00	11.66	65.35	201.15
North Bank Inner	0.06	1.51	8.19	47.75	5.68	12.24	17.87	68.62	10.32	15.51	24.18	79.45
South Bank Inner	0.01	2.67	23.84	270.79	13.81	60.66	149.77	374.70	39.11	114.43	195.96	415.47
Ouse-Trent	0.01	2.51	14.03	199.64	8.23	18.72	36.45	321.28	14.53	26.29	56.81	381.37
All	**0.07**	**6.70**	**46.99**	**710.67**	**27.90**	**100.61**	**300.23**	**1570.30**	**67.29**	**206.70**	**485.44**	**2025.39**

Table 25.2 – Change in Flood volumes by Area for Measure 17 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.00	4.16	-0.01	0.17	3.00	12.19	0.03	1.50	6.35	12.60
South Bank Outer	0.00	0.00	0.00	0.42	0.00	0.05	0.34	0.39	0.00	0.29	0.36	0.40
Hull	0.00	0.00	0.10	3.79	0.00	0.56	1.48	23.12	0.31	1.09	4.85	23.80
Grimsby	0.00	0.00	0.00	-0.62	0.00	0.01	16.24	2.81	0.00	10.76	4.83	1.38
North Bank Inner	0.06	1.29	5.73	2.11	4.51	5.93	4.47	0.34	6.38	5.05	4.69	0.20
South Bank Inner	0.00	2.62	14.91	13.34	10.54	26.99	37.82	12.62	20.40	38.55	19.85	12.47
Ouse-Trent	-0.06	1.80	3.50	-3.78	4.36	0.20	-8.99	-23.12	2.77	-4.80	-10.04	-28.47
All	**0.01**	**5.71**	**24.23**	**19.42**	**19.40**	**33.91**	**54.36**	**28.35**	**29.91**	**52.43**	**30.89**	**22.39**

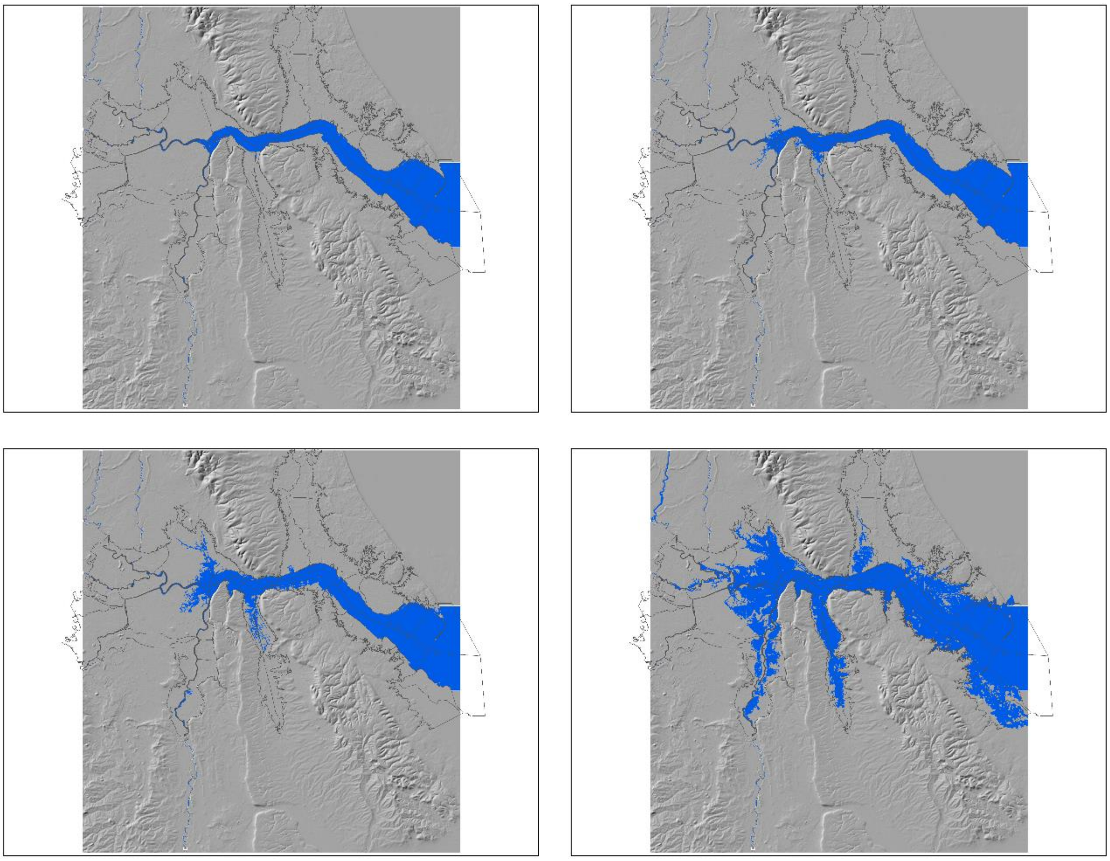

Figure 25.2 – Flood extents for Measure 17 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

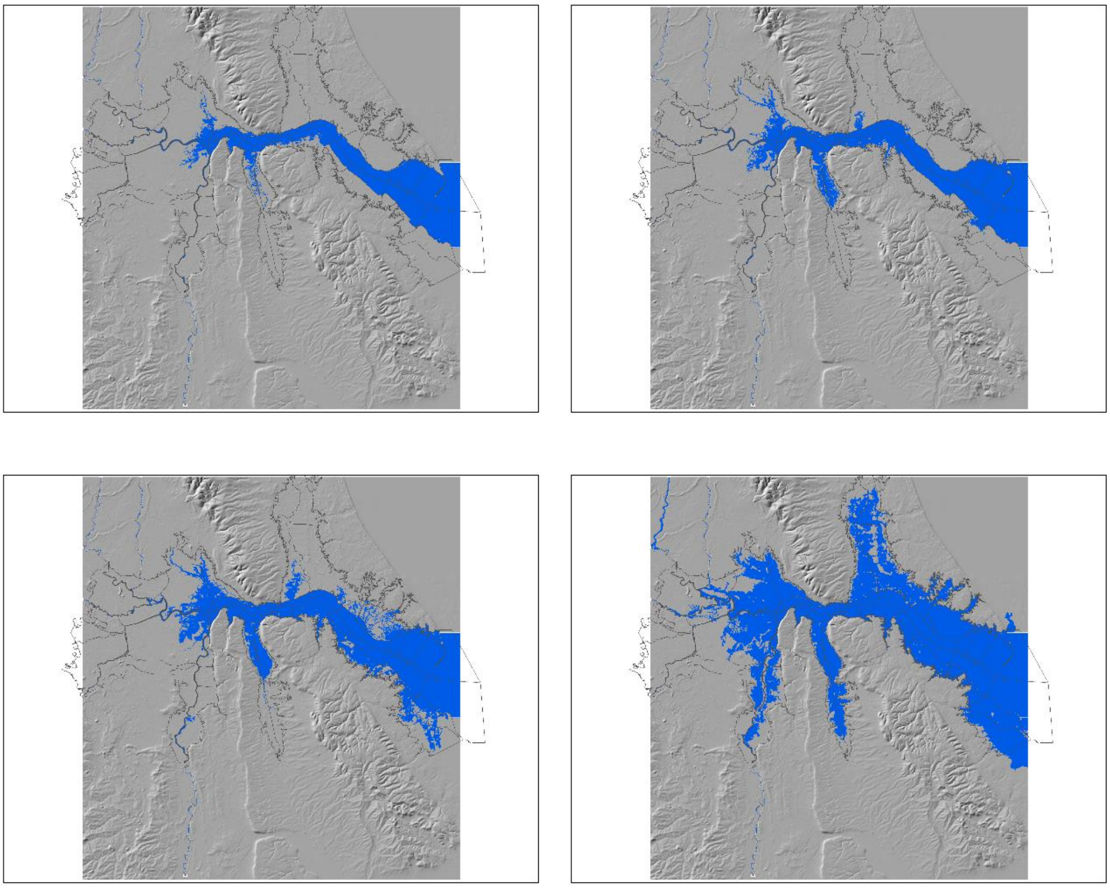

Figure 25.3 – Flood extents for Measure 17 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 25.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 17.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.19	5.05	5.55	6.05	6.97	5.37	5.88	6.33	7.26
Grimsby	4.35	4.85	5.35	6.31	5.18	5.70	6.16	6.93	5.52	6.01	6.41	7.19
Immingham	4.48	4.99	5.53	6.38	5.37	5.86	6.27	6.95	5.69	6.15	6.46	7.13
Sunk Island	4.34	4.83	5.34	6.31	5.18	5.69	6.16	6.94	5.51	6.00	6.41	7.20
King George's Dock	4.70	5.26	5.78	6.49	5.64	6.06	6.36	6.96	5.92	6.27	6.49	7.12
Albert Dock	4.78	5.33	5.84	6.49	5.70	6.09	6.38	6.95	5.96	6.29	6.49	7.11
Humber Bridge	5.09	5.65	6.06	6.51	5.95	6.24	6.41	6.94	6.15	6.37	6.48	7.05
Brough	5.48	5.93	6.19	6.55	6.14	6.29	6.45	6.84	6.25	6.39	6.52	6.92
West Walker Dyke	5.61	6.00	6.23	6.51	6.16	6.37	6.46	6.76	6.31	6.43	6.51	6.82
Blacktoft Jetty	4.45	5.04	5.57	6.07	4.87	5.43	5.83	6.12	5.02	5.58	5.89	6.14
Flixborough	4.60	5.15	5.69	6.11	5.00	5.54	5.97	6.14	5.15	5.67	6.01	6.16
Goole	4.53	5.08	5.61	5.95	4.91	5.47	5.84	5.97	5.07	5.61	5.89	6.00
Ouse (upstream)	3.15	3.66	4.21	5.05	3.57	4.12	4.68	5.22	3.74	4.30	4.86	5.25
Trent (upstream)	3.76	4.24	4.73	5.55	4.16	4.66	5.12	5.77	4.32	4.82	5.29	5.81
Mean	**4.54**	**5.05**	**5.52**	**6.18**	**5.21**	**5.65**	**6.01**	**6.53**	**5.43**	**5.84**	**6.15**	**6.65**

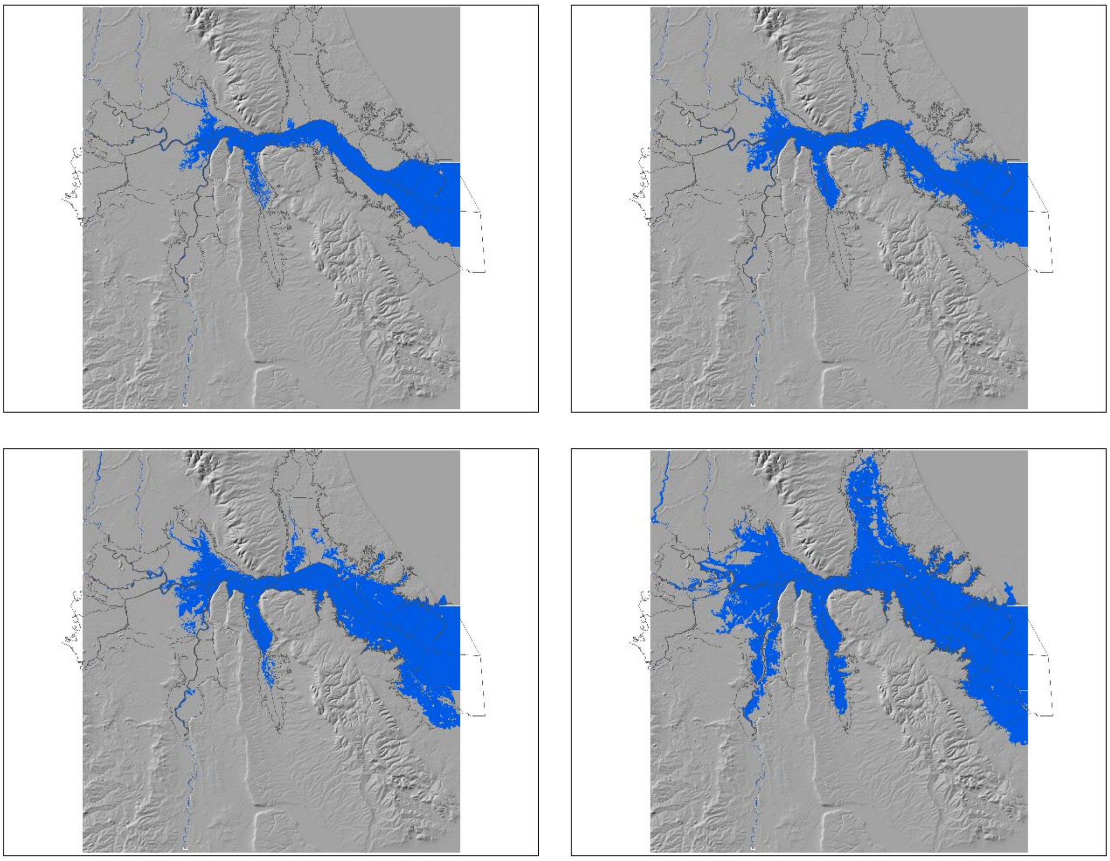

Figure 25.4 – Flood extents for Measure 17 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 25.4 – Change to the maximum stage for Measure 17 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.01	-0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00
Grimsby	-0.01	-0.02	0.01	0.02	-0.01	0.01	0.03	0.01	0.01	0.03	0.02	0.02
Immingham	-0.02	0.00	0.05	0.05	0.04	0.05	0.06	0.03	0.05	0.06	0.04	0.01
Sunk Island	-0.01	-0.01	0.00	0.02	-0.01	0.01	0.03	0.01	0.00	0.02	0.02	0.02
King George's Dock	0.06	0.11	0.14	0.13	0.16	0.12	0.09	0.03	0.14	0.10	0.07	0.03
Albert Dock	0.13	0.17	0.17	0.12	0.19	0.13	0.10	0.05	0.15	0.11	0.08	0.04
Humber Bridge	0.31	0.35	0.26	0.12	0.30	0.20	0.12	0.08	0.23	0.14	0.10	0.05
Brough	0.50	0.40	0.22	0.19	0.29	0.17	0.16	0.11	0.19	0.17	0.16	0.10
West Walker Dyke	0.51	0.36	0.24	0.20	0.25	0.26	0.19	0.18	0.26	0.20	0.19	0.18
Blacktoft Jetty	-0.69	-0.62	-0.35	-0.07	-1.00	-0.61	-0.28	-0.15	-0.94	-0.52	-0.25	-0.16
Flixborough	-0.68	-0.63	-0.35	-0.04	-1.00	-0.55	-0.17	-0.08	-0.92	-0.46	-0.15	-0.09
Goole	-0.64	-0.61	-0.30	-0.04	-0.96	-0.48	-0.13	-0.12	-0.86	-0.35	-0.10	-0.11
Ouse (upstream)	-0.43	-0.49	-0.50	-0.10	-0.82	-0.82	-0.39	-0.10	-0.97	-0.75	-0.24	-0.10
Trent (upstream)	-0.36	-0.38	-0.36	-0.23	-0.63	-0.58	-0.49	-0.07	-0.70	-0.63	-0.48	-0.04
Mean	**-0.10**	**-0.10**	**-0.06**	**0.03**	**-0.23**	**-0.15**	**-0.05**	**0.00**	**-0.24**	**-0.13**	**-0.04**	**0.00**

3.24 Measure 27 – Ouse and Trent (Inner estuary) Barriers, raised downstream defences, plus Keyingham and Goxhill Managed Realignment Sites

Flood defences were set as per the Baseline (2021 defences), but with Keyingham and Goxhill Managed Realignment sites, tidal barriers on the Ouse and Trent, and raised defences downstream of the tidal barriers. The locations of the Keyingham and Goxhill Managed Realignment sites are shown in Figure 4.1, and the locations of the Ouse and Trent tidal barriers and raised defences are shown in Figure 27.1. The Ouse and Trent tidal barriers were raised at the point of lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

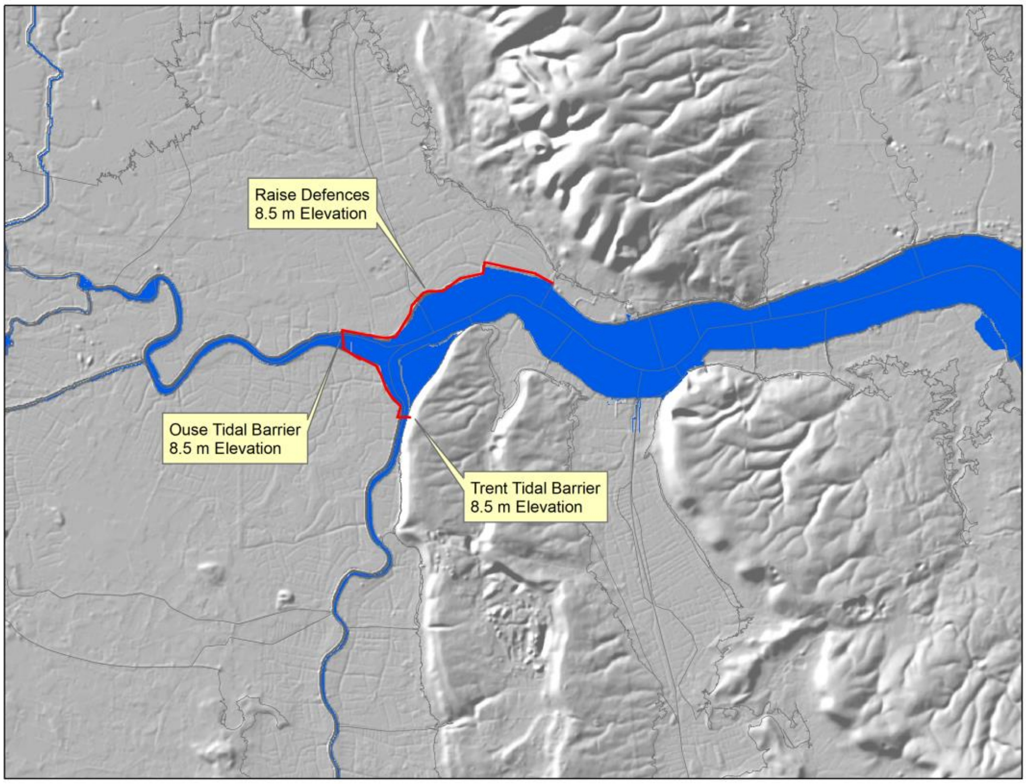

Figure 27.1 – Configuration of the Ouse and Trent Tidal Barriers and the raised downstream defences.

3.24.1 Results

Measure 27 reduced flood volumes by between −6.64 × 10^6 m^3 and −128.2 × 10^6 m^3 relative to the Baseline in four out of the 12 scenarios (Tables 27.1 and 27.2), which included all +2 m SLR scenarios and the 1000-year +1 m SLR scenario. The remaining eight simulations of the +0 m and + 1 m SLR scenarios saw increased flooding from +0.01 × 10^6 m^3 to +44.28 × 10^6 m^3. Locally, areas worse-off from Measure 27 relative to the Baseline were Hull, South Bank Inner and North Bank Outer, whereas the Ouse-Trent and North Bank Inner regions benefitted from the scheme (Figure 27.2 to 27.4). Mean stage heights were reduced by between −0.01 and −0.22 m relative to the Baseline in eight of the 12 scenarios (Tables 27.3 and 27.4). The remaining four simulations saw increased mean stages relative to the Baseline of between +0.01 and +0.12 m, which included all +2 m SLR simulations and the +1 m SLR 1000-year return period event. The spatial pattern of changed local stages relative to the Baseline mimics that of the other Ouse and Trent tidal barrier scenarios, with stages virtually unchanged relative to the Baseline in the outer estuary, increased in the mid-inner estuary, and sharply decreased upstream of the tidal barrier in the fluvial region (Table 27.4).

Table 27.1 – Flood volumes by Area for Measure 27.

	Flood Volumes (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.80	58.25	0.17	6.62	35.20	253.25	2.77	24.35	75.14	370.77
South Bank Outer	0.00	0.00	0.01	38.60	0.00	1.50	22.20	165.98	0.19	11.98	53.59	215.76
Hull	0.00	0.00	0.12	10.95	0.01	0.92	4.94	247.26	0.38	2.98	16.10	398.35
Grimsby	0.00	0.00	0.00	87.47	0.00	0.03	39.19	169.99	0.00	16.39	66.86	203.30
North Bank Inner	0.06	1.24	5.68	32.48	4.14	6.76	8.62	42.75	6.47	7.69	9.73	47.61
South Bank Inner	0.01	2.93	28.69	290.49	15.85	75.42	168.72	411.07	47.94	134.31	215.65	459.82
Ouse-Trent	0.00	0.27	2.90	119.20	0.06	0.61	6.66	157.08	0.12	0.84	10.84	179.23
All	**0.07**	**4.44**	**38.20**	**637.43**	**20.23**	**91.84**	**285.54**	**1447.39**	**57.87**	**198.56**	**447.91**	**1874.85**

Table 27.2 – Change in Flood volumes by Area for Measure 27 in comparison to the Baseline (Measure 1).

	Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)											
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.00	4.36	-0.01	0.17	3.00	18.41	0.03	1.50	6.63	21.58
South Bank Outer	0.00	0.00	0.00	0.43	0.00	0.05	0.34	0.41	0.00	0.29	0.38	0.46
Hull	0.00	0.00	0.10	4.97	0.00	0.63	2.41	43.77	0.33	1.60	6.23	51.69
Grimsby	0.00	0.00	0.00	0.77	0.00	0.01	20.70	6.72	0.00	15.49	6.34	3.54
North Bank Inner	0.06	1.02	3.21	-13.16	2.97	0.46	-4.78	-25.54	2.53	-2.77	-9.76	-31.64
South Bank Inner	0.00	2.87	19.75	33.03	12.57	41.74	56.77	48.99	29.23	58.43	39.54	56.83
Ouse-Trent	-0.06	-0.44	-7.63	-84.23	-3.80	-17.91	-38.77	-187.32	-11.64	-30.25	-56.00	-230.61
All	**0.01**	**3.45**	**15.44**	**-53.83**	**11.73**	**25.14**	**39.67**	**-94.56**	**20.49**	**44.28**	**-6.64**	**-128.15**

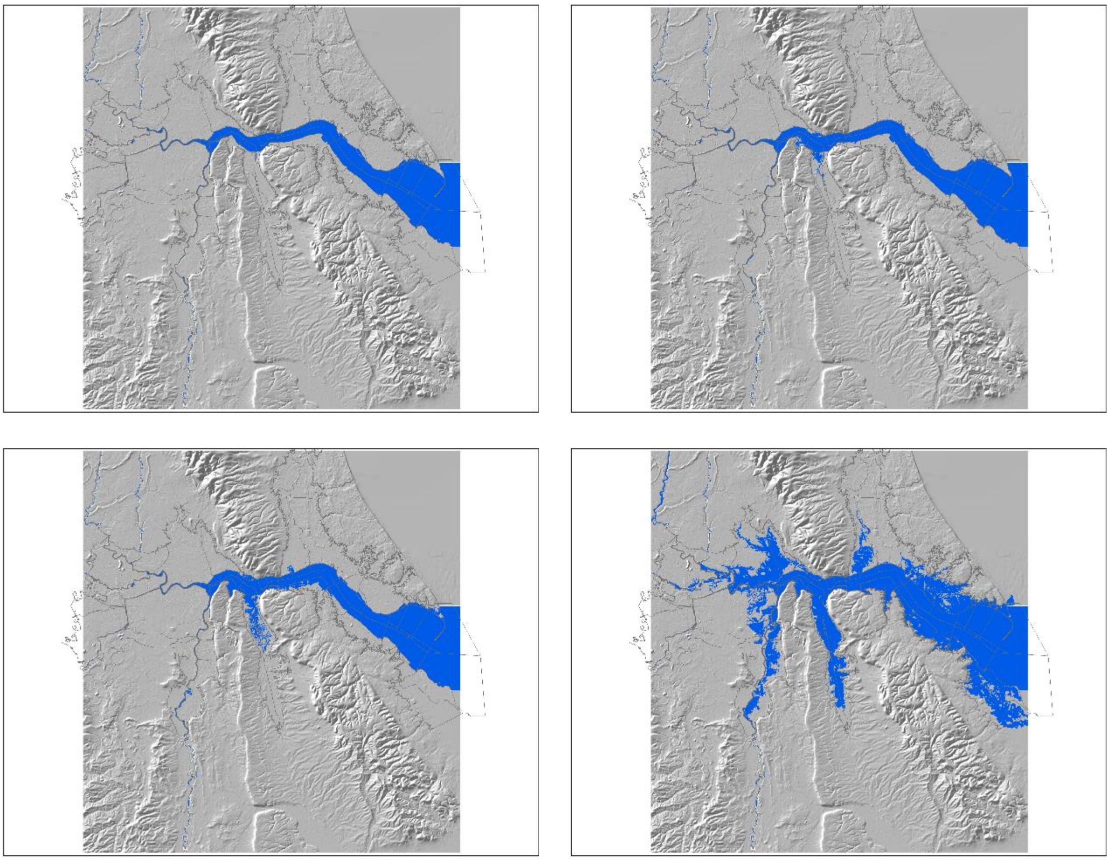

Figure 27.2 – Flood extents for Measure 27 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

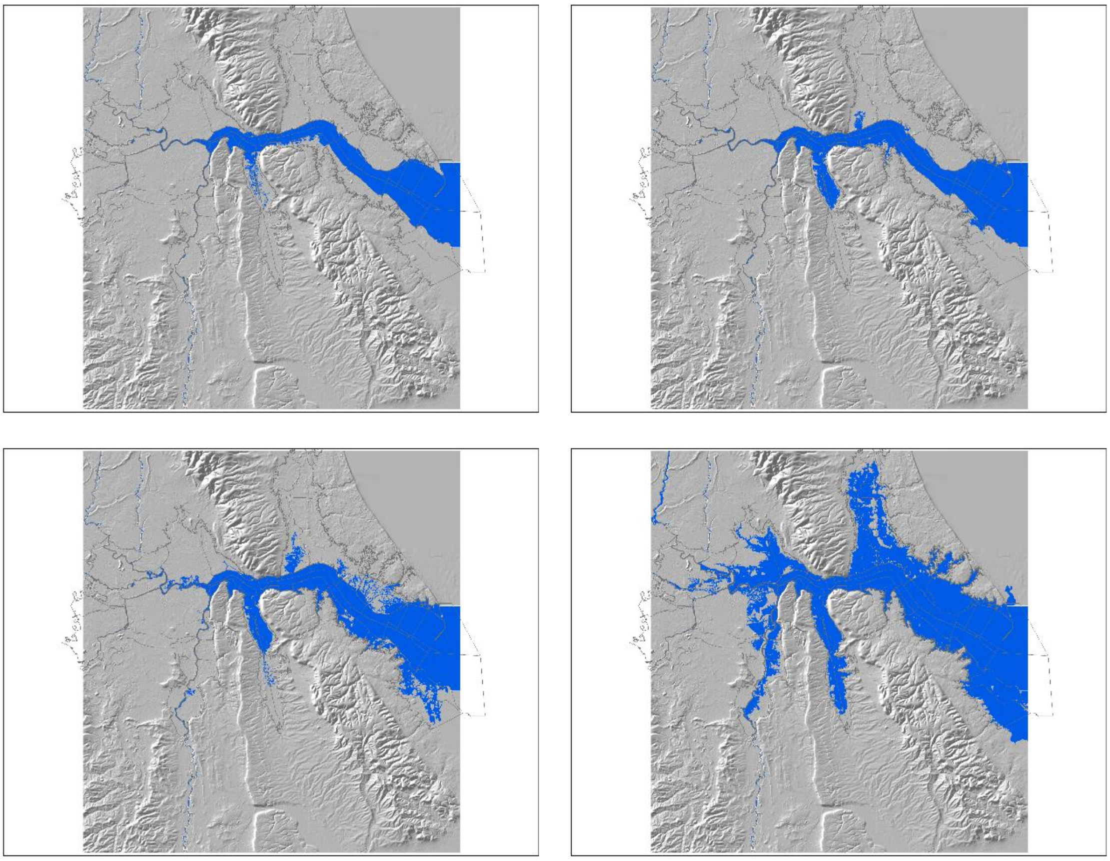

Figure 27.3 – Flood extents for Measure 27 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 27.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 27.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	4.20	4.70	5.20	6.19	5.05	5.55	6.05	6.97	5.37	5.88	6.33	7.26
Grimsby	4.35	4.85	5.35	6.31	5.18	5.70	6.16	6.93	5.52	6.01	6.41	7.19
Immingham	4.48	4.99	5.53	6.38	5.37	5.86	6.27	6.95	5.69	6.15	6.46	7.19
Sunk Island	4.34	4.83	5.34	6.31	5.18	5.69	6.16	6.94	5.51	6.00	6.41	7.20
King George's Dock	4.70	5.26	5.78	6.51	5.64	6.06	6.36	7.07	5.92	6.27	6.49	7.24
Albert Dock	4.78	5.33	5.84	6.53	5.70	6.09	6.38	7.09	5.96	6.29	6.49	7.24
Humber Bridge	5.09	5.65	6.07	6.66	5.96	6.25	6.46	7.15	6.16	6.38	6.62	7.27
Brough	5.48	5.95	6.23	6.80	6.16	6.42	6.69	7.23	6.31	6.63	6.72	7.33
West Walker Dyke	5.61	6.05	6.42	6.85	6.26	6.61	6.78	7.29	6.52	6.73	6.83	7.37
Blacktoft Jetty	4.45	5.04	5.57	6.14	4.87	5.43	5.85	6.20	5.02	5.58	5.92	6.23
Flixborough	4.60	5.15	5.69	6.16	5.00	5.54	5.99	6.22	5.15	5.67	6.03	6.23
Goole	4.53	5.08	5.61	5.97	4.91	5.47	5.85	6.00	5.07	5.61	5.90	6.03
Ouse (upstream)	3.15	3.66	4.20	5.05	3.57	4.10	4.66	5.20	3.73	4.28	4.82	5.24
Trent (upstream)	3.76	4.24	4.72	5.53	4.15	4.64	5.10	5.77	4.31	4.80	5.25	5.81
Mean	**4.54**	**5.06**	**5.54**	**6.24**	**5.21**	**5.67**	**6.05**	**6.64**	**5.45**	**5.88**	**6.19**	**6.77**

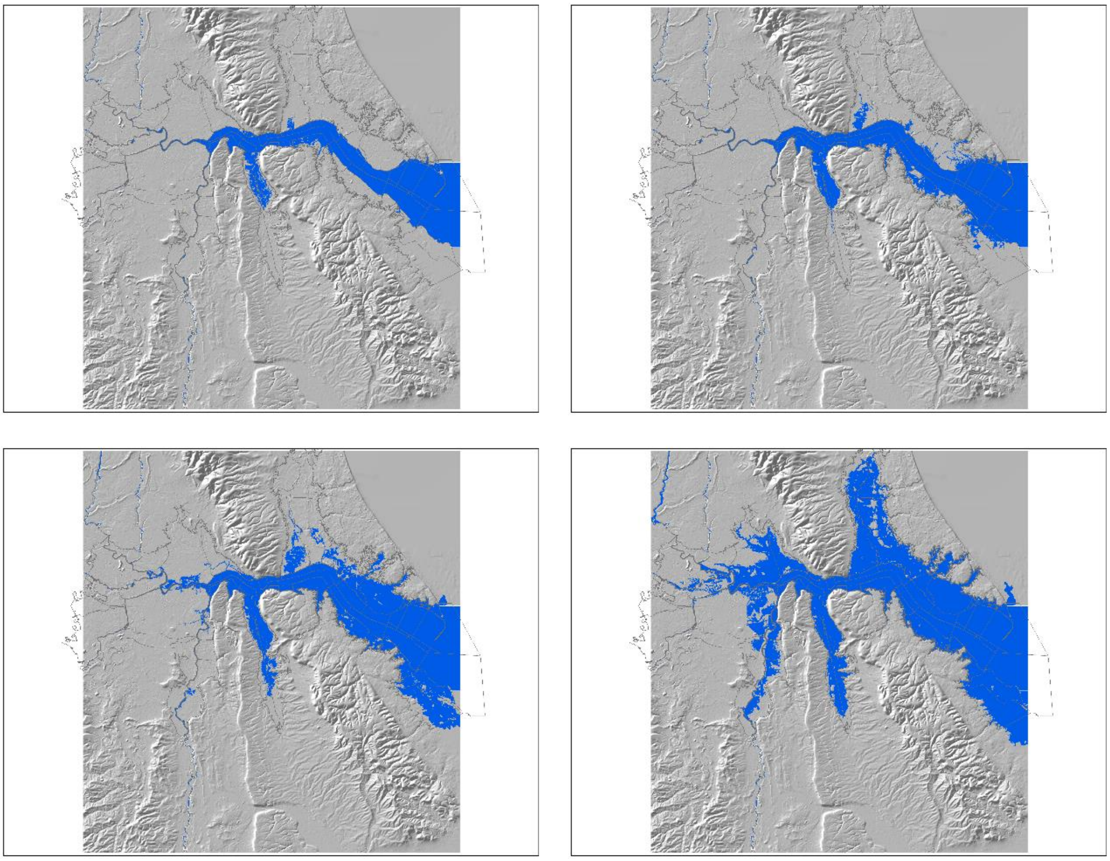

Figure 27.4 – Flood extents for Measure 27 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 27.4 – Change to the maximum stage for Measure 27 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.01	-0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00
Grimsby	-0.01	-0.02	0.01	0.02	-0.01	0.01	0.03	0.01	0.01	0.03	0.02	0.02
Immingham	-0.02	0.00	0.05	0.05	0.04	0.05	0.06	0.04	0.05	0.06	0.04	0.07
Sunk Island	-0.01	-0.01	0.00	0.02	-0.01	0.01	0.03	0.01	0.00	0.02	0.02	0.02
King George's Dock	0.06	0.11	0.14	0.15	0.16	0.12	0.09	0.15	0.14	0.10	0.07	0.15
Albert Dock	0.13	0.17	0.17	0.16	0.19	0.13	0.10	0.18	0.15	0.11	0.08	0.18
Humber Bridge	0.31	0.35	0.26	0.27	0.30	0.20	0.18	0.29	0.24	0.16	0.25	0.27
Brough	0.50	0.42	0.27	0.45	0.31	0.29	0.40	0.50	0.25	0.41	0.36	0.52
West Walker Dyke	0.51	0.40	0.43	0.54	0.35	0.51	0.51	0.71	0.46	0.50	0.51	0.73
Blacktoft Jetty	-0.69	-0.62	-0.35	0.01	-1.00	-0.61	-0.27	-0.06	-0.94	-0.52	-0.23	-0.07
Flixborough	-0.68	-0.63	-0.35	0.01	-1.00	-0.55	-0.16	-0.01	-0.92	-0.46	-0.13	-0.01
Goole	-0.64	-0.61	-0.30	-0.02	-0.96	-0.48	-0.12	-0.08	-0.86	-0.35	-0.08	-0.07
Ouse (upstream)	-0.43	-0.49	-0.50	-0.11	-0.82	-0.83	-0.41	-0.12	-0.98	-0.77	-0.28	-0.11
Trent (upstream)	-0.36	-0.39	-0.37	-0.24	-0.64	-0.60	-0.51	-0.07	-0.72	-0.66	-0.51	-0.03
Mean	**-0.10**	**-0.09**	**-0.04**	**0.09**	**-0.22**	**-0.12**	**-0.01**	**0.11**	**-0.22**	**-0.10**	**0.01**	**0.12**

3.25 Measure 18 – Ouse and Trent (Inner estuary) Barriers, plus Keyingham and Goxhill Managed Realignment sites, and Broomfleet, Faxfleet and Adlingfleet Flood Storage sites

Flood defences were set as per the Baseline (2021 defences), but with Keyingham and Goxhill Managed Realignment sites, Broomfleet, Faxfleet and Adlingfleet Flood Storage sites, and tidal barriers on the Ouse and Trent. The locations of the Keyingham and Goxhill Managed Realignment sites are shown in Figure 4.1, the locations of the Broomfleet, Faxfleet and Adlingfleet Flood Storage sites are shown in Figure 21.2 and the locations of the Ouse and Trent tidal barriers are shown in Figure 25.1. The Ouse and Trent tidal barriers were raised at the point of lowest water in the driving tidal data during the low tide preceding the surge tide, and lowered back down to the Baseline bathymetry at the lowest water level during the low tide immediately after the surge tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 0.5, 1 and 2 m sea level rise (SLR), resulting in 12 scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.25.1 Results

Measure 18 reduced mean flood volumes from between −49.79 and −235.04 × 10^6 m^3 relative to the Baseline in five of the 12 simulations. These simulations included the +1 m sea level rise scenarios for the 200- and 1000-year return period events and the +2 m sea level rise scenarios for all considered return periods. These reductions translated locally to the South Bank Inner and Ouse-Trent regions; however, flood volumes were higher in these regions relative to the Baseline for the smaller flood events (Tables 26.1 and 15.2). Flood inundation maps still show large scale flooding during Measure 18, particularly across Hull, South Bank Inner and the fluvial region (Figures 26.1 to 26.3). Mean stages were reduced by between −0.03 and −0.22 m relative to the Baseline in nine out of the 12 scenarios and were increased by +0.06 m for the three +2 m SLR simulations (Tables 26.3 and 26.4). Spatially, the same patterns of stages were seen in Measure 17, where stages were virtually unchanged relative to the Baseline in the outer estuary, increased in the mid-inner estuary, and sharply decreased upstream of the tidal barrier in the fluvial region (Table 26.4).

Table 26.1 – Flood volumes by Area for Measure 18.

Flood Volumes (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	0.80	49.36	0.17	6.60	32.56	225.07	2.76	22.24	69.64	330.93
South Bank Outer	0.00	0.00	0.01	38.54	0.00	1.49	22.15	166.51	0.19	11.94	53.57	216.39
Hull	0.00	0.00	0.08	8.40	0.01	0.76	3.82	197.75	0.30	2.31	11.03	336.23
Grimsby	0.00	0.00	0.00	84.97	0.00	0.02	33.43	167.44	0.00	10.05	65.11	202.58
North Bank Inner	0.03	0.93	6.12	46.76	4.02	9.84	14.35	70.54	8.22	12.35	19.89	82.25
South Bank Inner	4.08	5.34	22.56	171.71	14.23	51.64	120.77	232.51	34.82	94.46	156.42	259.24
Ouse-Trent	0.00	0.72	7.19	153.67	3.00	8.12	18.44	276.31	5.98	11.52	29.09	340.33
All	**4.11**	**7.00**	**36.76**	**553.40**	**21.42**	**78.48**	**245.51**	**1336.14**	**52.29**	**164.87**	**404.76**	**1767.95**

Table 26.2 – Change in Flood volumes by Area for Measure 18 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)												
Return Period (yrs)	**1**	**1**	**1**	**1**	**200**	**200**	**200**	**200**	**1000**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
North Bank Outer	0.00	0.00	-0.01	-4.52	-0.01	0.15	0.37	-9.77	0.03	-0.61	1.14	-18.26
South Bank Outer	0.00	0.00	0.00	0.37	0.00	0.04	0.28	0.94	0.00	0.25	0.36	1.09
Hull	0.00	0.00	0.07	2.42	0.00	0.48	1.28	-5.75	0.26	0.93	1.16	-10.43
Grimsby	0.00	0.00	0.00	-1.73	0.00	0.01	14.94	4.17	0.00	9.15	4.60	2.82
North Bank Inner	0.03	0.71	3.65	1.12	2.84	3.54	0.95	2.26	4.28	1.89	0.40	3.00
South Bank Inner	4.08	5.29	13.62	-85.75	10.96	17.97	8.81	-129.58	16.11	18.58	-19.69	-143.75
Ouse-Trent	-0.06	0.01	-3.33	-49.76	-0.87	-10.40	-26.99	-68.09	-5.77	-19.58	-37.75	-69.51
All	**4.05**	**6.01**	**14.00**	**-137.85**	**12.92**	**11.78**	**-0.35**	**-205.81**	**14.91**	**10.60**	**-49.79**	**-235.04**

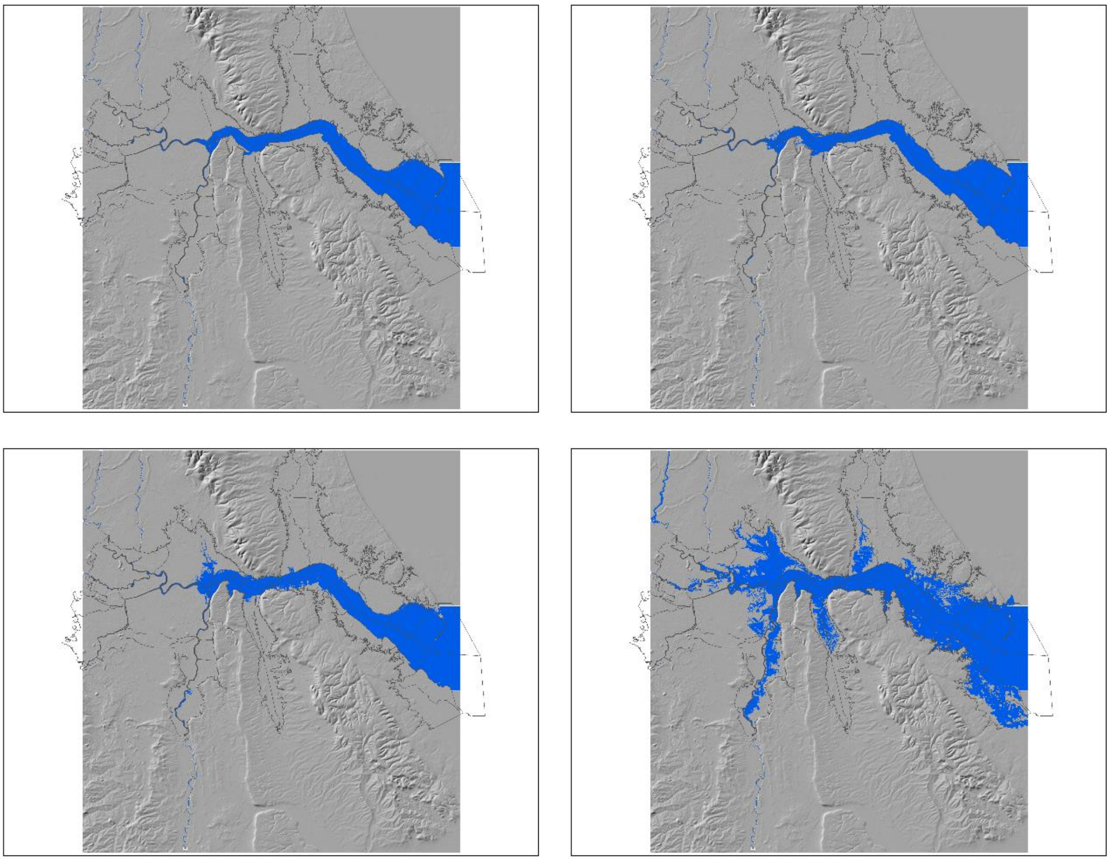

Figure 26.1 – Flood extents for Measure 18 with a 1-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

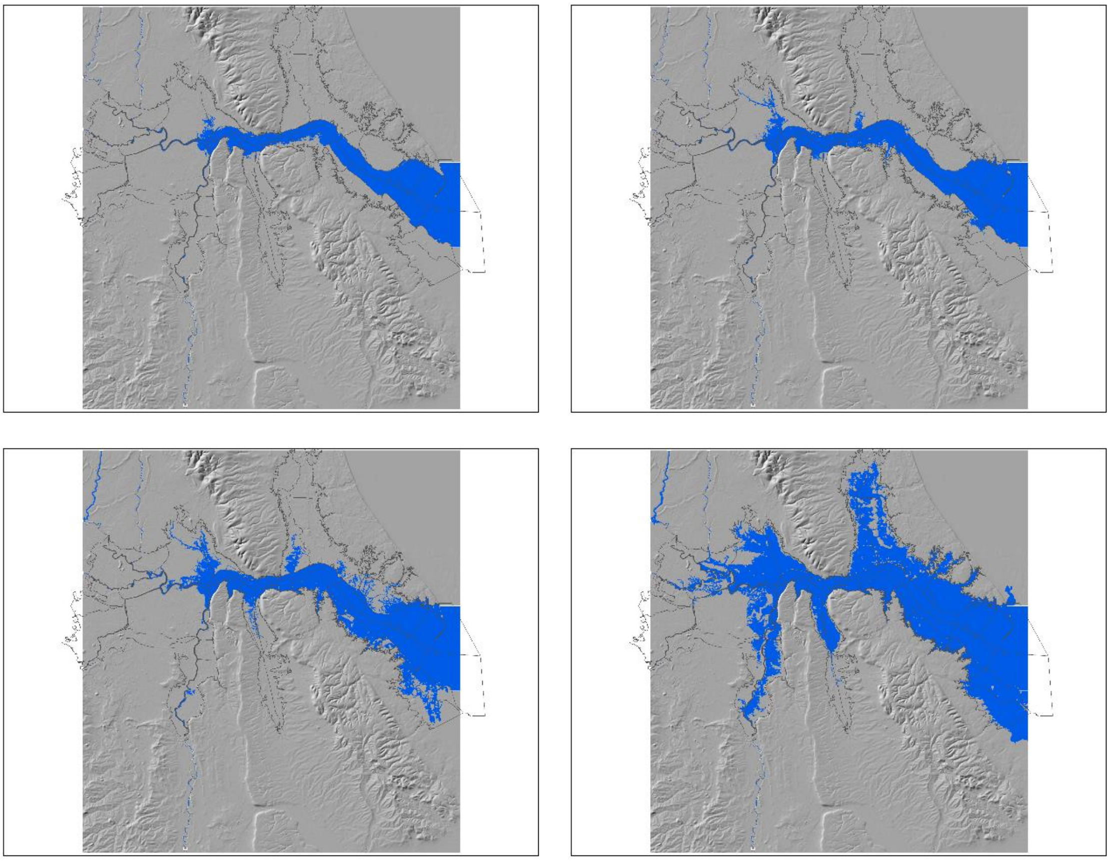

Figure 26.2 – Flood extents for Measure 18 with a 200-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 26.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 18.

	Maximum Stage Height (m OSN)											
Return Period	in 1	in 1	in 1	in 1	in 200	in 200	in 200	in 200	in 1000	in 1000	in 1000	in 1000
SLR (cm)	0	50	100	200	0	50	100	200	0	50	100	200
Spurn	4.20	4.70	5.20	6.19	5.05	5.55	6.05	6.98	5.37	5.88	6.33	7.26
Grimsby	4.35	4.85	5.35	6.30	5.18	5.70	6.16	6.93	5.52	6.00	6.40	7.19
Immingham	4.48	4.99	5.52	6.37	5.36	5.86	6.27	6.95	5.69	6.14	6.46	7.15
Sunk Island	4.34	4.83	5.34	6.31	5.18	5.69	6.16	6.95	5.51	6.00	6.41	7.21
King George's Dock	4.69	5.24	5.76	6.47	5.62	6.04	6.35	7.01	5.91	6.26	6.48	7.16
Albert Dock	4.76	5.31	5.82	6.51	5.68	6.07	6.37	7.00	5.94	6.27	6.48	7.14
Humber Bridge	5.05	5.59	6.03	6.59	5.92	6.22	6.41	7.00	6.14	6.36	6.47	7.10
Brough	5.38	5.87	6.16	6.60	6.09	6.27	6.44	6.94	6.22	6.37	6.50	7.02
West Walker Dyke	5.49	5.91	6.18	6.57	6.09	6.31	6.41	6.86	6.24	6.40	6.46	6.93
Blacktoft Jetty	4.42	5.01	5.55	6.09	4.84	5.40	5.83	6.22	5.02	5.56	5.89	6.26
Flixborough	4.57	5.12	5.66	6.14	4.96	5.50	5.95	6.29	5.12	5.66	6.00	6.32
Goole	4.51	5.05	5.59	5.95	4.89	5.44	5.85	6.03	5.05	5.60	5.88	6.06
Ouse (upstream)	3.33	3.92	4.53	5.20	3.94	4.65	5.03	5.33	4.28	5.00	5.07	5.35
Trent (upstream)	3.78	4.27	4.76	5.68	4.19	4.69	5.16	5.80	4.35	4.85	5.32	5.82
Mean	**4.53**	**5.05**	**5.53**	**6.21**	**5.21**	**5.67**	**6.03**	**6.59**	**5.45**	**5.88**	**6.16**	**6.71**

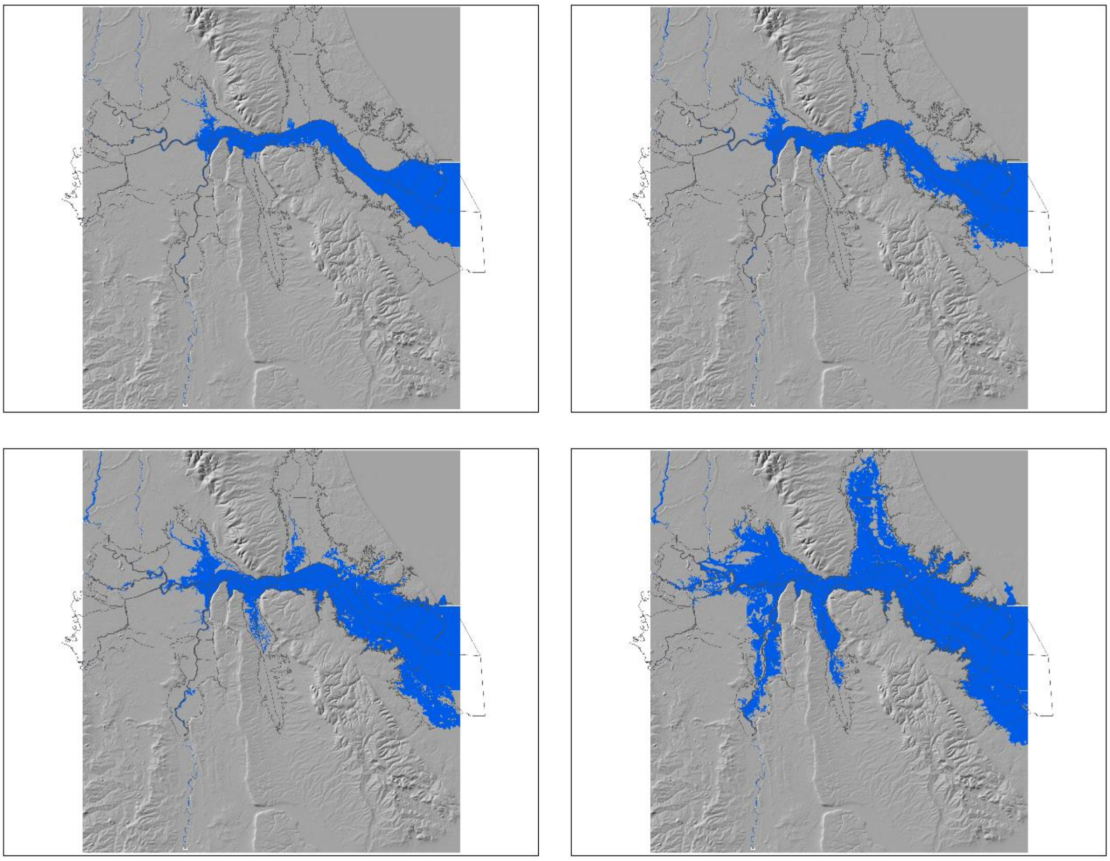

Figure 26.3 – Flood extents for Measure 18 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 0.5 m SLR, Bottom-left with 1 m SLR, and Bottom-right with 2 m SLR.

Table 26.4 – Change to the maximum stage for Measure 18 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)											
Return Period	**in 1**	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**	**0**	**50**	**100**	**200**
Spurn	0.00	0.00	0.00	0.01	-0.01	0.00	0.01	0.02	0.00	0.01	0.01	0.00
Grimsby	-0.01	-0.02	0.01	0.02	-0.01	0.01	0.03	0.01	0.01	0.03	0.02	0.02
Immingham	-0.02	0.00	0.04	0.04	0.03	0.05	0.05	0.04	0.05	0.05	0.04	0.03
Sunk Island	-0.01	-0.01	0.00	0.02	-0.01	0.01	0.03	0.03	0.00	0.02	0.02	0.02
King George's Dock	0.05	0.10	0.12	0.12	0.14	0.11	0.08	0.09	0.12	0.08	0.06	0.07
Albert Dock	0.11	0.15	0.15	0.13	0.17	0.11	0.09	0.10	0.14	0.09	0.07	0.08
Humber Bridge	0.28	0.28	0.22	0.20	0.26	0.18	0.12	0.13	0.22	0.13	0.09	0.10
Brough	0.40	0.34	0.19	0.24	0.24	0.14	0.15	0.20	0.16	0.14	0.14	0.21
West Walker Dyke	0.39	0.27	0.19	0.26	0.18	0.21	0.14	0.28	0.18	0.16	0.14	0.29
Blacktoft Jetty	-0.72	-0.64	-0.36	-0.05	-1.03	-0.63	-0.28	-0.05	-0.95	-0.54	-0.25	-0.04
Flixborough	-0.71	-0.66	-0.38	-0.02	-1.04	-0.58	-0.19	0.06	-0.95	-0.47	-0.16	0.08
Goole	-0.66	-0.64	-0.32	-0.03	-0.99	-0.50	-0.13	-0.05	-0.88	-0.36	-0.10	-0.05
Ouse (upstream)	-0.25	-0.23	-0.18	0.05	-0.45	-0.28	-0.04	0.00	-0.43	-0.04	-0.03	0.00
Trent (upstream)	-0.33	-0.36	-0.33	-0.10	-0.59	-0.55	-0.46	-0.04	-0.67	-0.60	-0.44	-0.02
Mean	**-0.11**	**-0.10**	**-0.05**	**0.06**	**-0.22**	**-0.12**	**-0.03**	**0.06**	**-0.21**	**-0.09**	**-0.03**	**0.06**

3.26 Measure 34 – Ouse and Trent (Inner estuary) Barriers operated for 4 hours, plus Keyingham and Goxhill Managed Realignment sites, and Broomfleet, Faxfleet and Adlingfleet Flood Storage sites

Flood defences were set as per the Baseline (2021 defences), but with Keyingham and Goxhill Managed Realignment sites, Broomfleet, Faxfleet and Adlingfleet Flood Storage sites, and tidal barriers on the Ouse and Trent. The locations of the Keyingham and Goxhill Managed Realignment sites are shown in Figure 4.1, the locations of the Broomfleet, Faxfleet and Adlingfleet Flood Storage sites are shown in Figure 21.2, and the location of the Ouse and Trent tidal barriers are shown in Figure 25.1. The Ouse and Trent tidal barriers were raised two hours before the peak tide and lowered again two hours after the peak tide.

The boundary conditions were set-up as follows:

- Seaward boundary condition: As Baseline – 1-, 200- and 1000-year return period events and with 0, 1 and 2 m sea level rise (SLR), resulting in nine scenarios
- Landward boundary conditions: As Baseline (long-term mean daily discharges for all fluvial inputs)

3.26.1 Results

Measure 34 reduced flood volumes by between -2.81×10^6 m^3 and -249.7×10^6 m^3 relative to the Baseline in five out of the nine scenarios (Tables 28.1 and 28.2). In the remaining four scenarios, which included every present-day sea level event and the 1-year return period event +1 m sea level rise scenario, mean flood volumes increased by between 4.02×10^6 m^3 and 14.78×10^6 m^3 relative to the Baseline. Measure 34 was therefore more effective than other compound measures that included barriers on the Ouse and Trent (Measures 17, 18 and 27), but not as effective as the compound measures that did not (Measures 12, 13, 14 and 15). Locally, the South Bank Inner and the Ouse-Trent regions benefitted most from Measure 34, with the highest reduction in flood volumes relative to the Baseline (Figures 28.1 to 28.3), while the South Bank Outer, Grimsby and North Bank Inner regions were slightly worse-off relative to the Baseline. Mean stages reduced relative to the Baseline by between −0.07 and −0.76 m in five of the nine scenarios and the 1- and 200-year return period events with +2 m sea level rise scenarios saw reduced stage levels at every gauge (Table 28.4). Conversely, mean stages increased relative to the Baseline by between +0.07 and 0.53 m for every 1000-year return period scenario and the 200-year return period +2 m sea level rise scenario. For all of the 1- and 200-year return period scenarios, stages significantly reduced relative to the Baseline (from Blacktoft Jetty upstream (Table 28.4).

Table 28.1 – Flood volumes by Area for Measure 34.

Flood Volumes (10^6 m^3)									
Return Period (yrs)	**1**	**1**	**1**	**200**	**200**	**200**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
North Bank Outer	0.00	0.82	49.21	0.17	32.53	224.64	2.80	69.43	330.37
South Bank Outer	0.00	0.01	38.53	0.00	22.15	166.49	0.20	53.55	216.33
Hull	0.00	0.08	8.30	0.01	3.77	197.02	0.31	10.93	335.49
Grimsby	0.00	0.00	84.43	0.00	33.19	167.16	0.00	64.91	202.45
North Bank Inner	0.03	5.99	45.69	3.98	13.57	69.43	8.15	17.94	81.12
South Bank Inner	4.05	22.53	171.19	14.33	120.31	232.26	34.83	156.16	258.42
Ouse-Trent	0.00	6.90	146.08	2.91	17.54	262.30	5.87	28.52	329.11
All	**4.08**	**36.34**	**543.43**	**21.40**	**243.06**	**1319.29**	**52.16**	**401.44**	**1753.30**

Table 28.2 – Change in Flood volumes by Area for Measure 34 in comparison to the Baseline (Measure 1).

Change in Flood Volume from Equivalent Baseline Return Period and Sea Level Rise (10^6 m^3)									
Return Period (yrs)	**1**	**1**	**1**	**200**	**200**	**200**	**1000**	**1000**	**1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
North Bank Outer	0.00	0.02	-4.67	0.00	0.34	-10.21	0.07	0.93	-18.82
South Bank Outer	0.00	0.00	0.36	0.00	0.28	0.92	0.01	0.33	1.03
Hull	0.00	0.07	2.32	0.00	1.23	-6.47	0.26	1.07	-11.17
Grimsby	0.00	0.00	-2.27	0.00	14.70	3.89	0.00	4.40	2.69
North Bank Inner	0.03	3.53	0.05	2.81	0.17	1.14	4.20	-1.55	1.88
South Bank Inner	4.05	13.60	-86.27	11.05	8.35	-129.82	16.12	-19.95	-144.58
Ouse-Trent	-0.06	-3.62	-57.34	-0.96	-27.89	-82.10	-5.88	-38.32	-80.73
All	**4.02**	**13.58**	**-147.83**	**12.90**	**-2.81**	**-222.65**	**14.78**	**-53.11**	**-249.70**

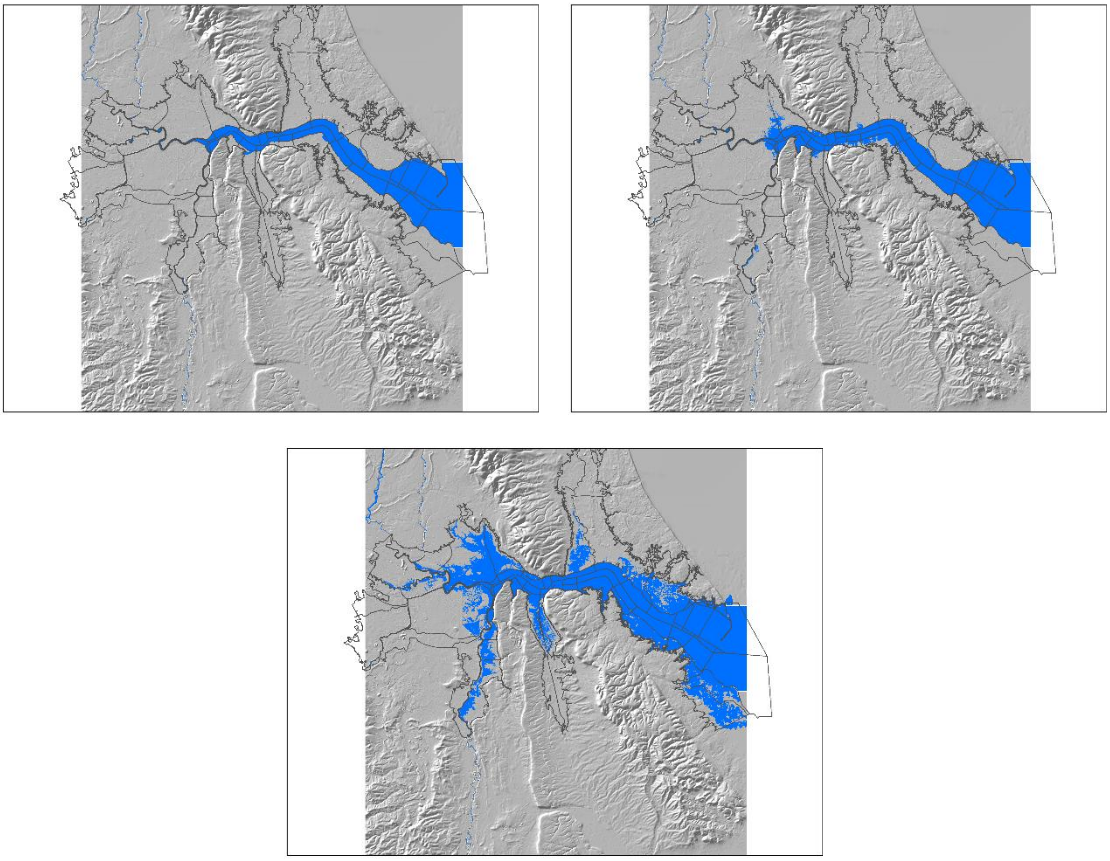

Figure 28.1 – Flood extents for Measure 34 with a 1-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

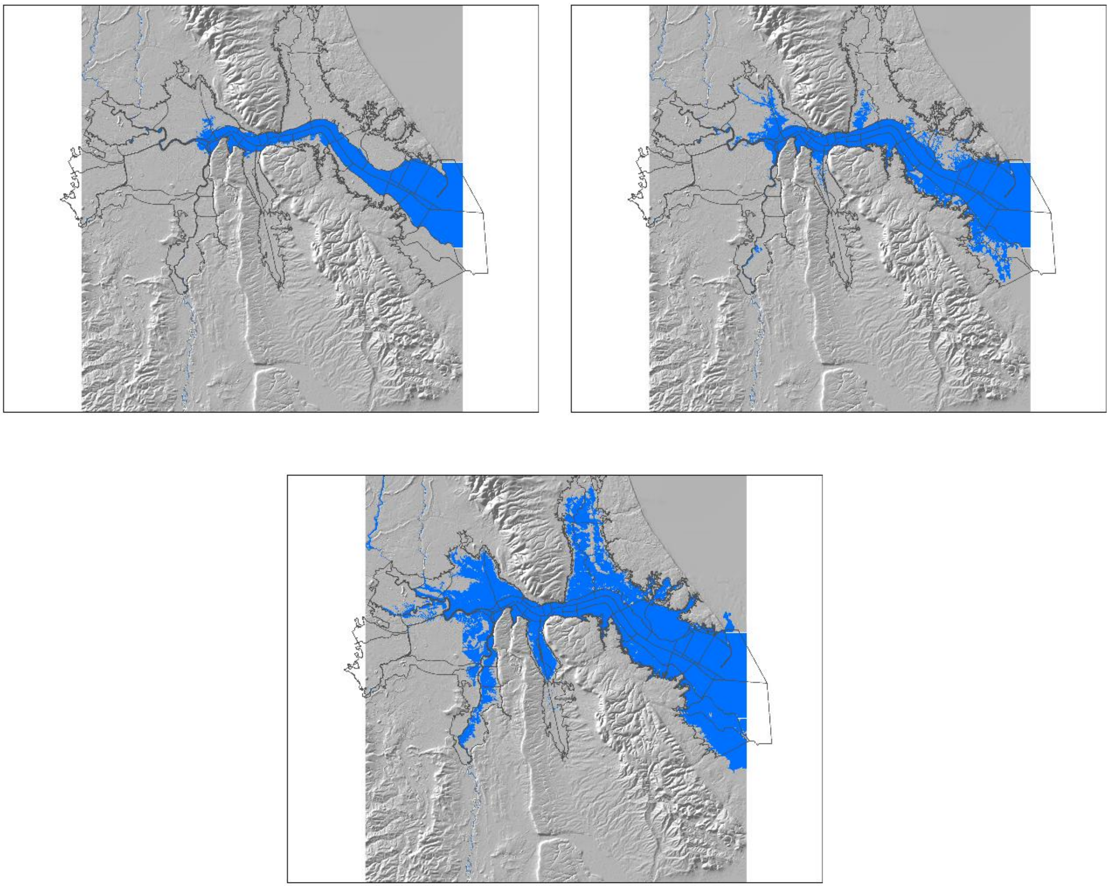

Figure 28.2 – Flood extents for Measure 34 with a 200-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

Table 28.3 – Maximum stages at tidal gauges throughout the Estuary for Measure 34.

	Maximum Stage Height (m OSN)											
Return Period	**in 1**		**in 1**	**in 1**	**in 200**		**in 200**	**in 200**	**in 1000**		**in 1000**	**in 1000**
SLR (cm)	**0**		**100**	**200**	**0**		**100**	**200**	**0**		**100**	**200**
Spurn	4.20		5.05	5.37	5.21		6.05	6.33	6.19		6.98	7.26
Grimsby	4.35		5.19	5.52	5.36		6.16	6.40	6.30		6.93	7.19
Immingham	4.50		5.38	5.69	5.54		6.27	6.45	6.37		6.95	7.15
Sunk Island	4.34		5.19	5.51	5.35		6.16	6.40	6.30		6.96	7.20
King George's Dock	4.72		5.63	5.91	5.77		6.34	6.48	6.47		7.01	7.16
Albert Dock	4.79		5.69	5.95	5.82		6.36	6.48	6.50		7.00	7.15
Humber Bridge	5.06		5.93	6.14	6.04		6.40	6.47	6.58		7.00	7.10
Brough	5.38		6.09	6.21	6.16		6.43	6.50	6.60		6.94	7.03
West Walker Dyke	5.50		6.09	6.24	6.18		6.42	6.46	6.57		6.87	6.95
Blacktoft Jetty	4.42		4.84	4.99	5.55		5.93	5.94	6.27		6.48	6.49
Flixborough	4.57		4.96	5.11	5.66		5.96	6.16	6.17		6.33	6.38
Goole	4.51		4.89	5.04	5.59		5.85	6.00	5.96		6.07	6.10
Ouse (upstream)	3.13		3.46	3.66	4.19		4.63	4.86	5.05		5.23	5.26
Trent (upstream)	3.68		3.93	4.07	4.66		4.91	5.10	5.50		5.76	5.82
Mean	**4.51**		**5.17**	**5.39**	**5.50**		**5.99**	**6.15**	**6.20**		**6.61**	**6.73**

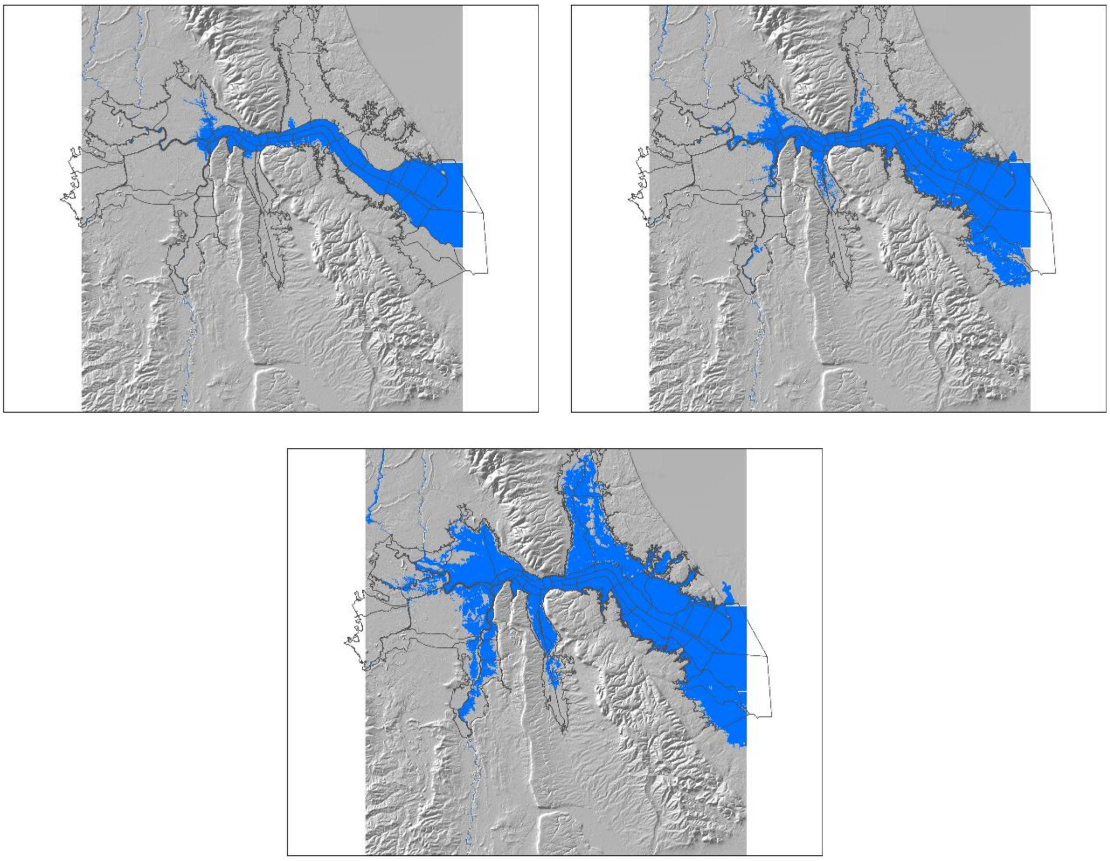

Figure 28.3 – Flood extents for Measure 34 with a 1000-year return period. Top-left with 0 m SLR, Top-right with 1 m SLR and Bottom with 2 m SLR.

Table 28.4 – Change to the maximum stage for Measure 34 relative to the Baseline (Measure 1).

	Change from Baseline Equivalent Maximum Stage Height (m OSN)								
Return Period	**in 1**	**in 1**	**in 1**	**in 200**	**in 200**	**in 200**	**in 1000**	**in 1000**	**in 1000**
SLR (cm)	**0**	**100**	**200**	**0**	**100**	**200**	**0**	**100**	**200**
Spurn	0.00	-0.16	-0.81	0.15	0.01	-0.63	0.82	0.66	0.00
Grimsby	-0.01	-0.15	-0.76	0.17	0.03	-0.52	0.79	0.55	0.02
Immingham	-0.01	-0.10	-0.64	0.21	0.05	-0.46	0.73	0.53	0.03
Sunk Island	-0.01	-0.15	-0.77	0.16	0.03	-0.52	0.80	0.57	0.02
King George's Dock	0.09	0.00	-0.45	0.29	0.07	-0.44	0.69	0.59	0.08
Albert Dock	0.13	0.02	-0.42	0.30	0.09	-0.43	0.69	0.59	0.08
Humber Bridge	0.28	0.12	-0.26	0.38	0.11	-0.39	0.66	0.62	0.10
Brough	0.40	0.12	-0.14	0.30	0.14	-0.23	0.54	0.58	0.21
West Walker Dyke	0.39	0.10	-0.07	0.27	0.15	-0.12	0.52	0.55	0.31
Blacktoft Jetty	-0.72	-1.07	-1.14	-0.32	-0.18	-0.32	0.30	0.34	0.19
Flixborough	-0.71	-1.08	-1.05	-0.34	-0.18	-0.06	0.10	0.17	0.13
Goole	-0.66	-1.02	-0.94	-0.28	-0.13	-0.08	0.03	0.09	-0.01
Ouse (upstream)	-0.45	-1.24	-1.50	-0.19	-0.44	-0.47	0.34	0.12	-0.10
Trent (upstream)	-0.43	-1.16	-1.71	-0.12	-0.71	-0.74	0.47	0.00	-0.03
Mean	**-0.12**	**-0.41**	**-0.76**	**0.07**	**-0.07**	**-0.39**	**0.53**	**0.43**	**0.08**

4 Summary of flood stage, area and volume results

4.1 Managed realignment

Seven different managed realignment (MR) strategies were presented: Measures 4, 6, 8, 9, 23, 29 and 30. Mean stages obtained from these simulations are summarised in Table 29.1 and the stage data from individual gauge stations for every simulation is summarised in Figure 29.1 (graphs denoted MR). MR resulted in a decrease in stages for the 1-year storm surge at present day sea levels, and mainly an increase for every other scenario.

Flood alleviation efficacy varied between each measure, with Measure 4 resulting in lower stages than Measures 8 and 9 (in some situations note that lower stages mean that more water has overtopped defences and spread out over the land surface, retaining less water within the boundary of the estuary (Table 29.1 and Figure 29.1). Figure 29.2 makes it apparent that certain scenarios can increase flood volume and flood area relative to the Baseline, particularly Measures 4, 6 and 29, and how this change can vary with increasing SLR. Measure 9, which produced the largest negative percentage change in flood volume relative to the Baseline (Table 29.2), was the best measure for flood alleviation within the MR strategies but this approach worked best for longer return period events and SLR increments. Measures that incorporated larger areas of managed realignment (i.e., Winteringham Ings) and flood storage (e.g., Broomfleet, Faxfleet and Adlingfleet) in the inner estuary and fluvial region (Measures 8 and 9) reduced flood volumes more effectively than measures that included mid-outer estuary sites (e.g., Sunk Island/ Cherry Cobb sands, Goxhill and Keyingham) (Measures 4, 6, 23, 29 and 30).

4.2 Hard defences

Eight different hard defence strategies were presented: Measures 2, 16, 16A, 20, 28, 31, 32, and 33 which, as with the MR Measures, produced very different results. Table 29.1 shows that the majority of the hard defence strategies reduced mean stages, and Figure 29.1 (middle column) shows the location where the largest reductions in stages occurred (e.g. Measures 16 and 16A reduced stages upstream of the Sunk Island (outer estuary) barrier). Flood volume and flood area data (Figure 29.2) and percentage changes in flood volume relative to the Baseline (Table 29.2) show that Measure 2 (degraded defences) is by far the worst option in terms of flood alleviation, but Measures 16 and 16A (Sunk Island (outer estuary) barrier and raised downstream defences) produce some of the best results for flood alleviation up until +2m SLR. Building a middle estuary barrier (Measures 31 and 32), a south bank peninsula (Measure 28), and groyne at Sunk Island (Measure 20) all proved to be less effective hard engineering strategies for flood alleviation.

4.3 Dredging

Only two dredging scenarios were modelled at present day sea levels. The results show that dredging is not a viable option for flood alleviation (especially when compared to other strategies) in terms of stages (Table 29.1 and Figure 29.3A), flood volumes and areas (Figure 29.3A) and percentage change in flood volume relative to the Baseline (Table 29.2).

4.4 Compound

The eight compound scenarios that were modelled showed very different levels of flood alleviation efficacy in the Humber Estuary. Table 29.1 shows mixed results in mean stages relative to the Baseline, whereas Figure 29.1 shows that for most measures, stages increase as one moves landwards. Figure 29.2 and Table 29.2 highlight the increasing disparity in flood alleviation efficacy between the different measures for the scenarios with SLR. Measures 17 and 27, which both employ tidal barriers in the inner estuary on the Rivers Ouse and Trent, stand out as the worst compound approaches for flood alleviation in the Humber. Measure 17 increases

Table 29.1: Summary table showing percentage change (%) in mean stage relative to the Baseline (Measure 1) for each scenario. Light blue columns identify scenarios with a 1-year return period storm surge event, mid-blue columns identify scenarios with a 200-year return period event, and dark blue columns identify scenarios with a 1000-year return period event. Unless greyed out, each storm surge event was run with present day sea levels (0), 0.5, 1.0 and 2.0 m sea level rise.

	Measure	1-year return period				200-year return period				1000-year return period			
		0	0.5	1.0	2.0	0	0.5	1.0	2.0	0	0.5	1.0	2.0
Managed Realignment	4	−0.04	0.01	0.10	0.09	0.09	0.09	0.10	0.00	0.09	0.10	0.04	−0.03
	6	−0.04	0.09	0.40	0.86	0.09	0.48	0.63	2.17	0.09	0.49	0.81	2.82
	8	−0.03	0.11	1.03	4.99	0.58	2.44	4.74	5.26	1.61	3.84	6.09	4.96
	9	−0.03	0.11	1.04	5.98	0.58	2.51	5.31	9.52	1.64	4.11	7.69	10.4
	29	−1.37		1.14	2.22	1.17		1.91	2.05	1.33		2.07	2.70
	30	−2.88		−0.57	1.54	−0.79		1.09	2.19	−0.10		1.73	2.71
	23	−3.59	−1.89	−0.56	2.19	−1.02	0.61	2.00	2.68	−0.05	1.49	2.68	2.71
Hard Defences	2	−11.3	−11.6	−11.4	−9.16	−12.0	−10.9	−9.75	−7.25	−11.5	−10.4	−8.50	−6.08
	31	−0.82				−4.45				−5.25			
	32	−0.81				−4.20				−4.51			
	33	−9.68		−7.03		−13.9		−7.82		−14.5		−7.46	
	16	−9.68	−8.71	−7.01	−3.28	−13.9	−11.0	−7.78	−4.87	−14.5	−10.9	−7.23	−5.41
	16A	−9.68	−8.71	−7.01	−3.27	−13.9	−11.0	−7.77	−4.76	−14.5	−10.9	−7.20	−5.06
	20	−0.38				−0.15				−0.07			
	28	0.82				0.58				0.49			
Dredging	26	0.17				0.25				0.17			
	19	1.70				1.12				0.81			
Compound	12	−0.25	−0.09	0.67	3.52	0.33	1.82	3.17	2.38	1.14	2.97	3.67	2.35
	13	−0.24	−0.09	0.68	4.96	0.33	1.89	3.94	7.55	1.15	3.20	5.93	7.71
	14	−2.21	−2.32	−2.08	0.70	−2.16	−1.32	0.04	3.61	−1.74	−0.62	1.47	4.56
	15	−2.19	−2.30	−2.04	0.73	−2.11	−1.30	0.06	3.98	−1.71	−0.59	1.50	5.34
	17	3.50	2.93	2.15	1.52	2.44	1.81	1.40	0.82	2.01	1.51	1.20	0.74
	27	3.51	3.06	2.62	2.94	2.70	2.52	2.50	3.05	2.54	2.53	2.37	3.09
	18	2.84	2.37	1.84	1.84	2.05	1.55	1.23	1.46	1.70	1.30	1.03	1.31
	34	3.05		−0.39	−7.58	4.53		1.18	−6.06	12.1		9.13	1.36

Table 29.2: Summary table showing the percentage change (%) in flood volume relative to the Baseline (Measure 1) for each scenario. Light blue columns identify scenarios with a 1-year return period storm surge event, mid-blue columns identify scenarios with a 200-year return period event, and dark blue columns identify scenarios with a 1000-year return period event. Unless greyed out, each storm surge event was run with present day sea levels (0), 0.5, 1.0 and 2.0 m sea level rise.

	Measure	1-year return period				200-year return period				1000-year return period			
		0	50	100	200	0	50	100	200	0	50	100	200
Managed Realignment	4	2.54	2.74	−0.76	0.28	−3.44	0.36	1.56	0.95	−0.16	1.33	0.83	0.72
	6	2.54	−12.4	−3.31	−3.08	−3.44	−4.29	0.39	−5.61	−0.16	−0.87	−4.99	−7.45
	8	2.32	−33.8	−75.4	−82.1	−83.8	−87.5	−86.1	−71.8	−88.6	−88.1	−83.3	−66.5
	9	2.50	−33.6	−75.3	−84.4	−83.7	−87.4	−88.8	−85.0	−88.4	−89.0	−89.8	−83.7
	29	1766		9.18	0.52	14.3		6.15	−16.2	9.61		−2.34	−20.7
	30	1602		−50.0	−32.2	−48.8		−19.3	−33.2	−45.2		−17.2	−33.6
	23	1589	72.3	−67.3	−50.5	−69.8	−50.9	−37.0	−37.2	−65.4	−35.6	−34.3	−35.9
Hard Defences	2	1.7×10^{6}	166532	9480	395	19394	3272	1053	172	4940	1521	583	125
	31	−98.2				−10.5				−38.4			
	32	−98.2				−98.3				−98.6			
	33	−99.7		−85.8		−98.5		−75.5		−93.5		−69.0	
	16	−99.7	−82.2	−87.8	−42.3	−99.0	−98.6	−94.7	−58.5	−99.1	−98.6	−92.8	−61.2
	16A	−99.7	−82.2	−87.8	−42.4	−99.0	−98.6	−94.7	−61.3	−99.1	−98.6	−93.2	−65.1
	20	−1.54				−4.47				−1.06			
	28	13.8				23.4				11.1			
Dredging	26	61.7				35.5				15.5			
	19	175				102				41.7			
Compound	12	−97.2	−98.5	−96.0	−82.7	−96.5	−93.6	−83.2	−37.5	−94.6	−91.8	−58.1	−31.6
	13	−97.2	−98.9	−96.6	−93.7	−97.3	−94.4	−93.9	−88.3	−95.4	−94.2	−92.2	−81.4
	14	93916	9464	500	−34.2	1181	143	12.2	−35.4	263	40.2	−11.6	−33.3
	15	93593	9402	495	−34.3	1169	141	11.8	−36.9	260	39.4	−12.0	−35.5
	17	13.8	577	106	2.81	228	50.8	22.1	1.84	80.0	34.0	6.79	1.12
	27	8.32	348	67.8	−7.79	138	37.7	16.1	−6.13	54.8	28.7	−1.46	−6.4
	18	6211	607	61.5	−19.9	152	17.7	−0.14	−13.4	39.9	6.87	−11.0	−11.7
	34	6169		59.7	−21.4	152		−1.14	−14.4	39.5		−11.7	−12.5

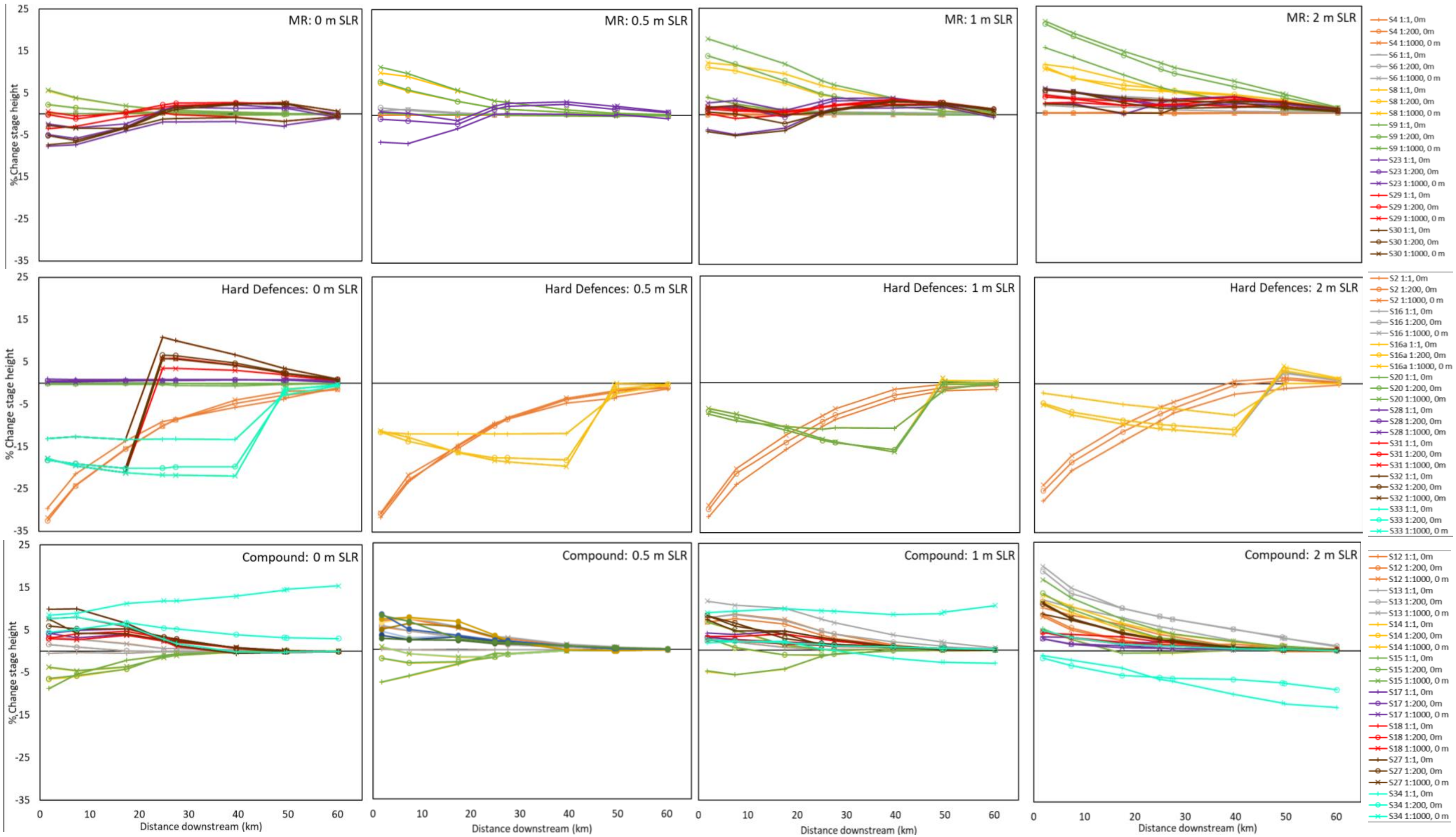

Figure 29.1: Percentage change (%) in stage relative to Baseline against distance downstream. Measure ID is represented by 'S' in the legend (e.g., S4 is Measure 4). Symbols represent the 1-year return period (vertical dash), 200-year return period (open circle) and 1000-year return period (cross) events. Each row shows results from one measure strategy (managed realignment (MR), hard defences, and compound) and each column shows results for one sea level rise scenario (0, +0.5, +1, and +2 m).

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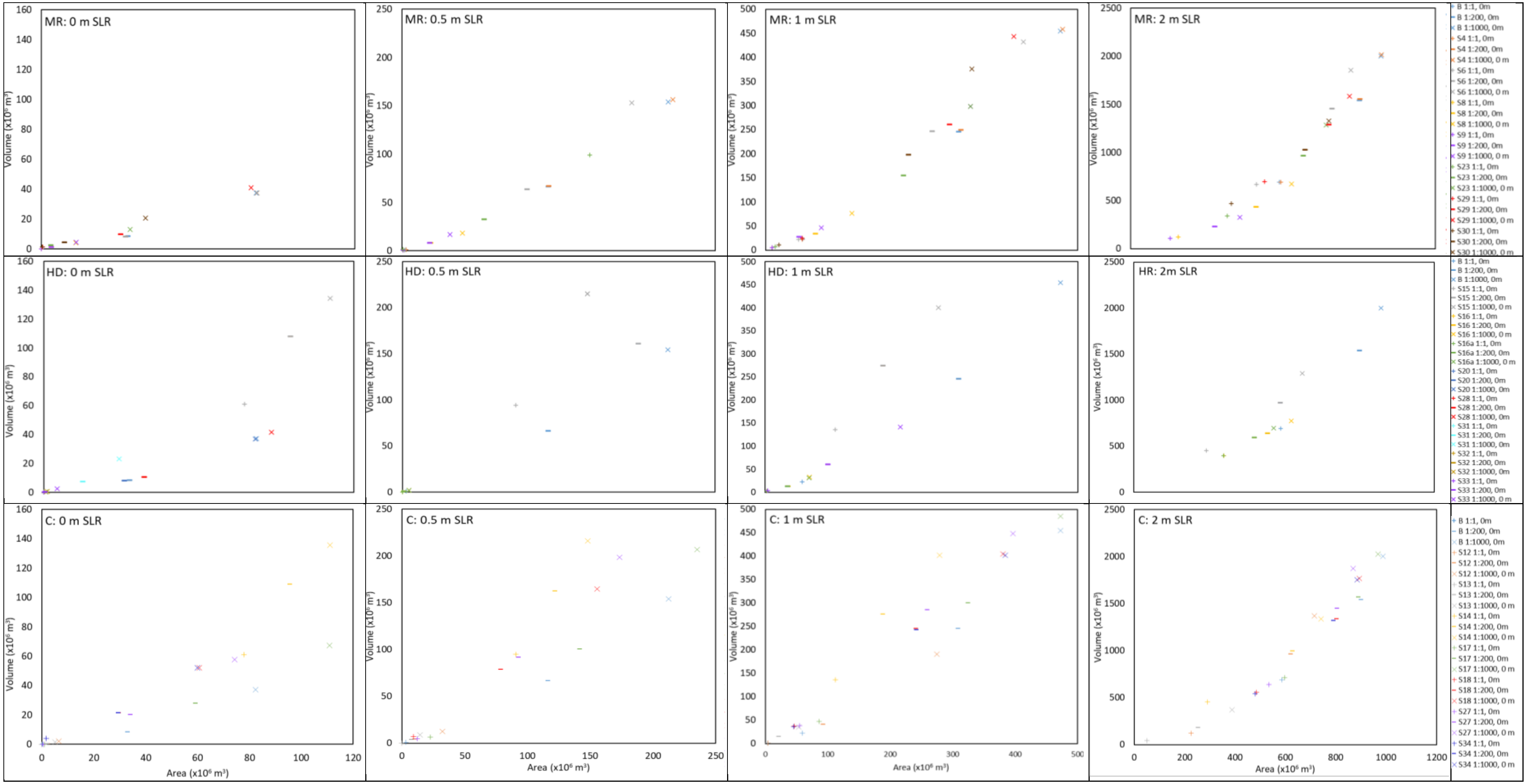

Figure 29.2: Flood volume against flood area for all measures. Measure 2 is omitted due to the extremely large areas and volumes observed. Measure ID is represented by 'S' in the legend (e.g., S4 is Measure 4), except for Measure 1, which is shown as 'B' (i.e., Baseline). Symbols represent the 1-year return period (+), 200-year return period (-) and 1000-year return period (x) events. Each row shows results from one measure strategy (managed realignment (MR), hard defences, and compound) and each column shows results for one sea level rise scenario (0, +0.5, +1, and +2 m). Note that x, y axes are consistent down columns but not across rows.

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flood volume relative to the Baseline for every storm surge return period and SLR scenario. Partial removal of some estuarine flood defences alongside the addition of outer estuary flood storage sites (Ryehill and Patrington) was not beneficial for flood alleviation at present day to +0.5 SLR but was somewhat effective for +1 and +2 m SLR (Measures 14 and 15). Measures 13 and 12 were the two best compound measures to include managed realignment and flood storage sites in the inner estuary and fluvial region. Measure 13 increased mean and local stages (Table 29.1 and Figure 29.1), but reduced the percentage change in flood volume (Table 29.2) and area of flood inundation in comparison to the Baseline (Figure 29.2).

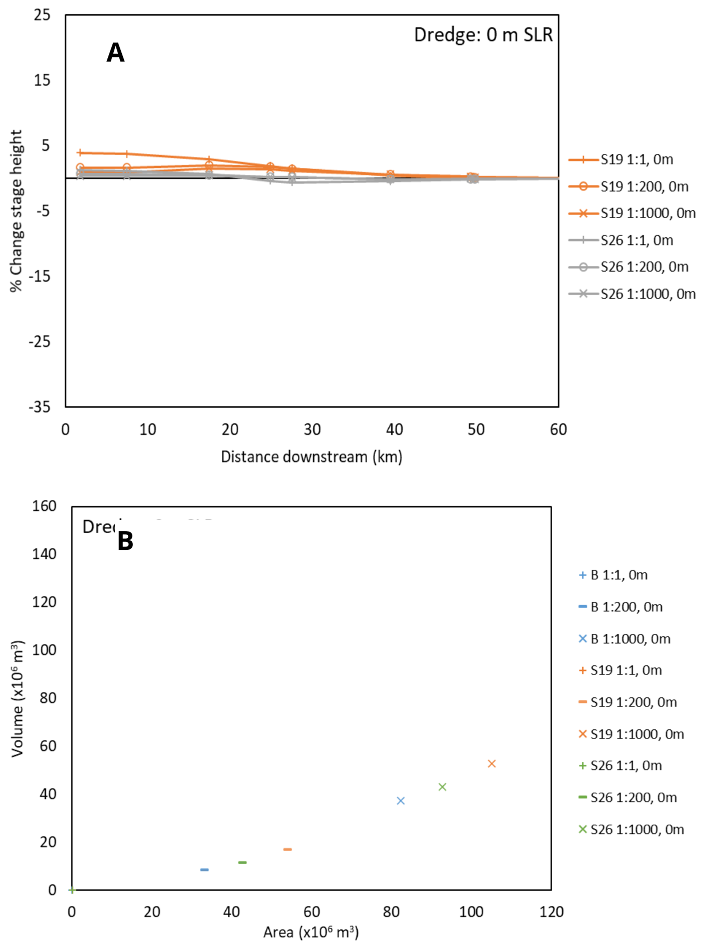

Figure 29.3: A. Percentage change (%) in stage relative to Baseline against distance downstream for the two dredging measures at present day sea levels. Measure ID is represented by 'S' in the legend (e.g., S19 is Measure 19). Symbols represent the 1-year return period (vertical dash), 200-year return period (open circle) and 1000-year return period (cross) events. B. Flood volume against flood area for the two dredging measures at present day sea levels. Measure ID is represented by 'S' in the legend (e.g., S4 is Measure 4), except for Measure 1, which is shown as 'B' (i.e., Baseline). Symbols represent the 1-year return period (+), 200-year return period (-) and 1000-year return period (x) events.

5 Discussion and Conclusions

This report has presented results of numerical modelling simulations of various flood alleviation measures for the Humber estuary with 1-, 200- and 1000-year return period storm surge events combined with up to four different sea level rise scenarios ranging from present day levels to a +2 m increase. Flood alleviation measures have been grouped into strategy types including managed realignment, hard defences, dredging, and compound approaches. Measures were compared against a Baseline, which was described as what the Humber estuary flood defences will be in the year 2021 after current ongoing improvement works by the Environment Agency.

5.1 Best and worst measures for minimising flood stages, areas and volumes

In terms of minimising flood stages, areas and volumes, the best type of measure was hard defences, closely followed by some compound measures. Measure 16A, the Sunk Island (outer estuary) barrier with seaward defences raised by 2 m, was the most effective measure for sea level rise (SLR) values less than +2m. However, Measure 16A lost some of its efficacy with +2 m of SLR, because the simulations reported herein were limited to a maximum increase of defence crest levels of 2 m. Thus, continued efficacy of hard defences relies on continued upgrades to the defences in the form of further elevation increase, and continued investment, to keep out the tide. Conversely, a middle estuary barrier (located near the Humber Bridge), a south bank peninsula, and a groyne at Sunk Island (Measures 31, 32, 28, and 20) were relatively ineffective. At SLR values of +2 m, Measure 9, Managed Realignment at Keyingham, Goxhill and Winteringham Ings and raise all Estuary defences by 2 m, and Measure 13, Estuary defence levels raised to 2014 local 200-year return period water surface profile plus 2 m and managed realignment at Keyingham, Goxhill, and Winteringham Ings and flood storage sites at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet and Flixborough, are the most effective measures for decreasing overbank flood volumes (Table 28.2).

The worst type of measure was Measure 2, doing nothing and allowing the 2021 barriers degrade over time and this consistently resulted in the largest flood volumes. The next worst was dredging, which increased the available estuary capacity to allow tidal ingress into the estuary and resulted in higher overbank flood volumes relative to the Baseline in each modelled scenario. Furthermore, dredging is very costly, needs to be repeated frequently to maintain lowered bed elevations and is damaging to the environment. Dredging is therefore not advised as a viable option for flood alleviation. Other measures that were relatively ineffective include Measure 4, Managed Realignment at Keyingham and Goxhill, which resulted in most scenarios exhibiting increased overbank flood volumes and Measures 17, 18 and 27, which resulted in inconsistent performance. The ineffectiveness of Measures 17, 18 and 27, which all inserted barriers on the Rivers Ouse and Trent in the inner estuary, suggests that barriers should be avoided at these locations, possibly because of reflection and amplification of the tidal wave.

5.2 Equifinality

Table 28.1 and Figure 28.1 show that very different strategies could result in similar outcomes, depending upon which dependent variable is considered. For example, Measure 2, Degraded Defences, which resulted in the largest overbank flood volume of any measure (Table 28.2), resulted in a reduction in stages relative to the Baseline because water overtopped the degraded defences, spread over the land and reduced the water within the bounds of the estuary. The consequence of adopting this measure would be increased tidal flood risk for all communities and infrastructure within the estuary, even present-day sea levels. This would necessarily require significant adaptation (e.g. raising or floating homes and infrastructure) or abandonment of estuarine communities and retreat to higher ground. Conversely, Measures 16 and 16A resulted in similar reductions of mean stages because the barrier at Sunk Island in the outer estuary, combined with raised flood defences, reduced the overall volume of water entering the estuary.

5.3 Sensitivity of results to managed realignment location

Results have highlighted the sensitivity of flood stages, areas and volumes to the relative of managed realignment and flood storage sites. In the Humber estuary, managed realignment and flood storage sites are more effective in the inner estuary (i.e., Winteringham Ings) than in the mid-outer estuary (i.e., Ryehill, Patrington, Goxhill, and Keyingham). Modelling of a generic funnel-shaped estuary, based on the dimensions of the Humber, indicate that this conclusion may be transferable to other macrotidal funnel-shaped estuaries (Harrison *et al*., in prep). Although flood storage and managed realignment sites (e.g., Winteringham Ings, Ryehill, and Patrington) have a small area relative to the size of the Humber estuary, available land is finite; site creation and total area is restricted because of the abundance of infrastructure and communities. Therefore, a suitable balance needs to be found between flood alleviation schemes and other requirements in the estuary (e.g. ecology, coastal squeeze, location of towns/cities which restrict sacrificing of land).

5.4 Economic analysis

In this section, the results of the socio-economic analyses described in section 2.7 are introduced into the assessment and used to help identify the optimal measures. Figure 30.1 plots three metrics of economic impact against the total flooded area: the total number of directly affected residents (i.e., residents whose homes lie within the flood outline), the value of directly affected residential properties (i.e., homes that lie within the flood outline), and the value of directly affected Gross Value Added (i.e., the value that would be added to the economy due to the production of goods and services if the area within the flood outline was not flooded). The impacts of the 1 m and 2 m sea level rise scenarios are shown within each row of plots; the impacts of the 1-, 200- and 1000-year return period storm surges are plotted separately within each subplot.

The rationale for the analysis presented in Figure 30.1 is that for a given return period event, the best flood risk management measures are those that result in both the smallest flooded areas and the smallest economic impacts. Furthermore, for a given flooded area, the most effective Measure is that which minimises the economic impact. That is, from an economic perspective, focus needs to be put on those Measures that protect assets that either have the greatest importance for the population or have the greatest economic value. Results indicate that the best measures in terms of both the smallest flooded areas and the smallest economic impacts for a sea level rise of 1 m are Measures 16, 16A, 33, 13, 8 and 9, with the most efficient (i.e., the least damage for a given flooded area) being Measure 13 (Figure 30.1 A-C). The best Measures in terms of both the smallest flooded areas and the smallest economic impacts for a sea level rise of 2 m are Measures 13, 9, 8, 14, 15, 16 and 16A, with the most efficient (i.e., the least damage for a given flooded area) generally being Measure 16, with Measure 9 being most efficient for 1000-year return period events (Figure 30.1 D-F). It should be noted that, owing to the interests of project partners, Measure 33 was not simulated for the 2 m sea level rise scenarios.

Measures can be categorised in terms of the scale and cost of intervention, with Measures 8 and 9 a basic 'continue the strategy' approach (i.e., small number of already identified MR sites plus defences raised by 1 m and 2 m, respectively), Measure 13 a moderate interventionist approach with additional MR sites and defences raised by 2m, Measures 14 and 15 a more interventionist strategy with a series of MR sites and defences raised by 1 m and 2 m, respectively, and Measures 33, 16 and 16A maximum intervention with an outer estuary barrier and seaward defences raised by 1 m for measure 16 and 2 m for measure 16A.

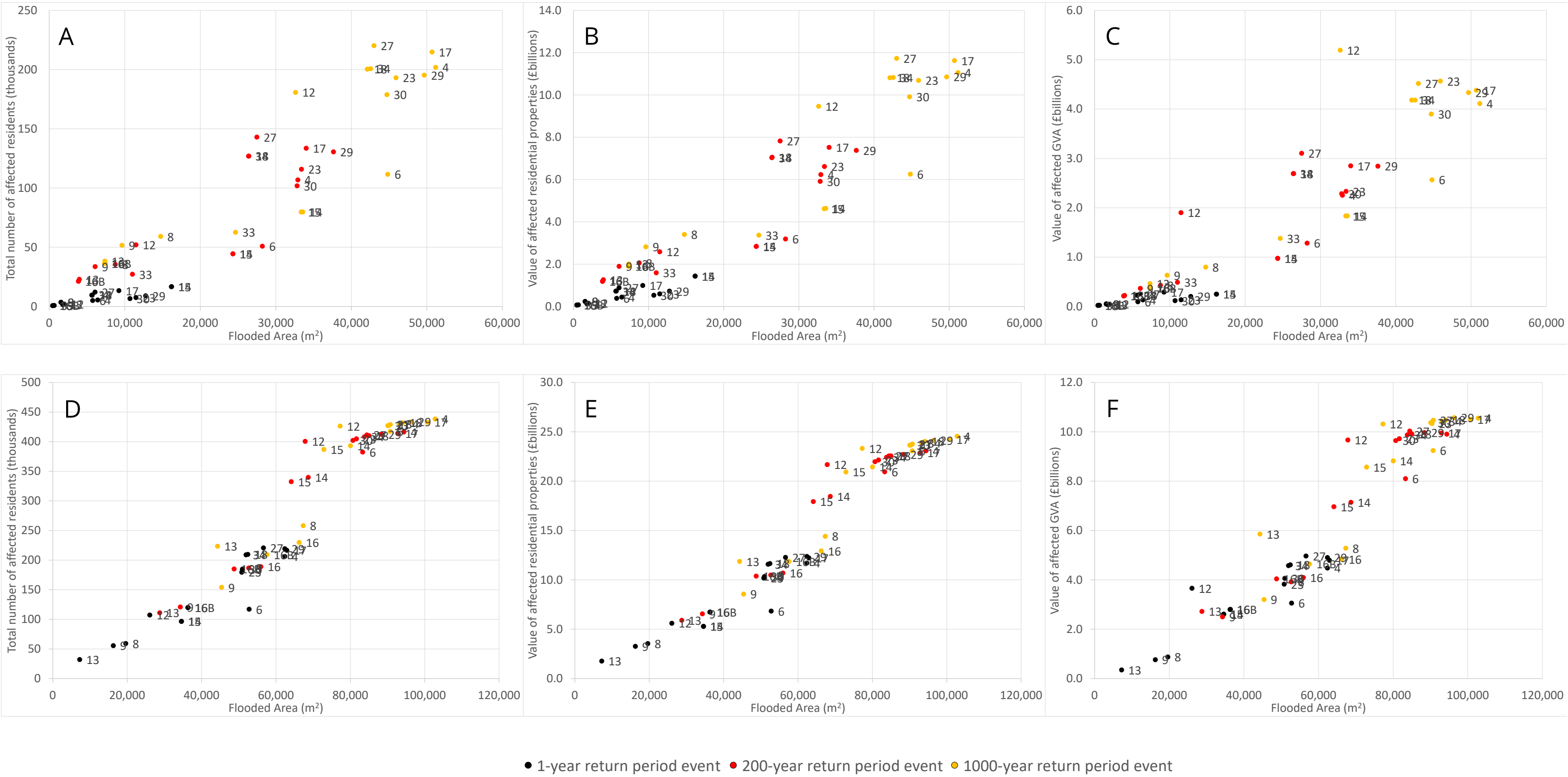

Figure 30.1. Economic impacts of flooding caused by 1- (black filled circles), 200- (red filled circles) and 1000- (gold filled circles) year return period storm surges for measures 1 to 34 under 1 m (A, B, and C) and 2 m (D, E, and F) sea level rise scenarios. Each circle is labelled with the relevant Measure ID. For a given return period, the best measures are those which cause the smallest flooded areas and economic impacts. For a given flooded area, the best measure is that which minimises the economic impact.

Measures 8 and 9 (managed realignment at Keyingham, Goxhill and Winteringham Ings, plus raise all estuary defences by 1 m and 2 m, respectively) and 13 (raise estuary defences to the 2014 200-year return period water surface profile plus 2 m, plus managed realignment and flood storage sites) are more sustainable flood alleviation options which help to create space to protect and preserve intertidal areas and their ecosystems. Such strategies need careful planning but can be some of the best options for longer-term (+1 to +2 m SLR) flood alleviation in the Humber Estuary.

Measures 16 and 16A (Sunk Island tidal barrier, seaward defences raised by 1 m and 2 m, respectively) lose efficacy for the largest 1000-year event with +2 m SLR (Table 28.2). This indicates the need for continuous maintenance and upgrades (increasing defence height to keep pace with SLR) of the Sunk Island barrier and the seaward defences, otherwise the defences would become obsolete and result in an increased risk of danger to lives. Such maintenance and upgrades would be costly. Furthermore, hard defences on the seaward side of the barrier could exacerbate coastal squeeze, damaging valuable ecosystems in the intertidal areas. For larger levels of SLR, the barrier would likely have to be increasingly in operation for every high tide, not just storm surge events. In this case, consideration would be needed on the implications of a tidal barrier combined with large fluvial flood events in the Rivers Ouse and Trent, and further modelling is recommended to understand potential geomorphological and sedimentological impacts. In addition, more detailed, complex, economic modelling may be needed to understand the impact on port operations within the Humber.

5.5 Limitations and Future work

It is important to remember when interpreting the results reported that CAESAR-Lisflood is a reduced complexity, or reduced physics, hydraulic model. The code employs careful approximations of physical processes in order to significantly increase the efficiency of the model, allowing for rapid calculation of scenarios while still yielding useful outputs.

It is suggested that the CAESAR-Lisflood model is suitable for use as a strategic model informing further work for the EA. The model errors are within the thresholds defined by the Foundation for Water Research (1993), which suggested that an operational model for estuarine environments should have an error of no more than 0.1 m at its mouth, and 0.3 m at its head – this model falls within those guidelines. The model has also been shown to produce the same behavioural response in water level changes as predicted by a far more complex model (Delft-3D).

Therefore, based on these tests and knowledge of the model, it is recommended that the useful information the model can confidently provide include:

- Relative water level changes – location, order of magnitude
- Relative flood volume changes – location, order of magnitude
- Indication of changes to areas at risk of flooding
- Relative flow velocity changes – location, order of magnitude

Information that should not be expected from this modelling work, and would require modelling using a more sophisticated modelling approach include:

- Detailed flood inundation mapping, especially in built up areas
- Precise predictions of water levels
- Precise predictions of flood volumes
- Precise predictions of flow velocities

This work has only utilised the hydraulic component of the CAESAR-Lisflood model. There is capability in the model to forecast changes in geomorphology over time, and the impacts of sea level rise on the Humber's sediment dynamics and bathymetry are unknown. Adding a geomorphic component may also help to predict how managed realignment sites in particular change in efficacy over time due to sedimentation. In addition, since this report focused solely on the hydraulic impacts of certain flood alleviation schemes, it is also recommended that habitat modelling be undertaken on the ecological impacts of Measures 8, 13, 14 and 16 and opportunities for habitat creation before construction works begin.

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