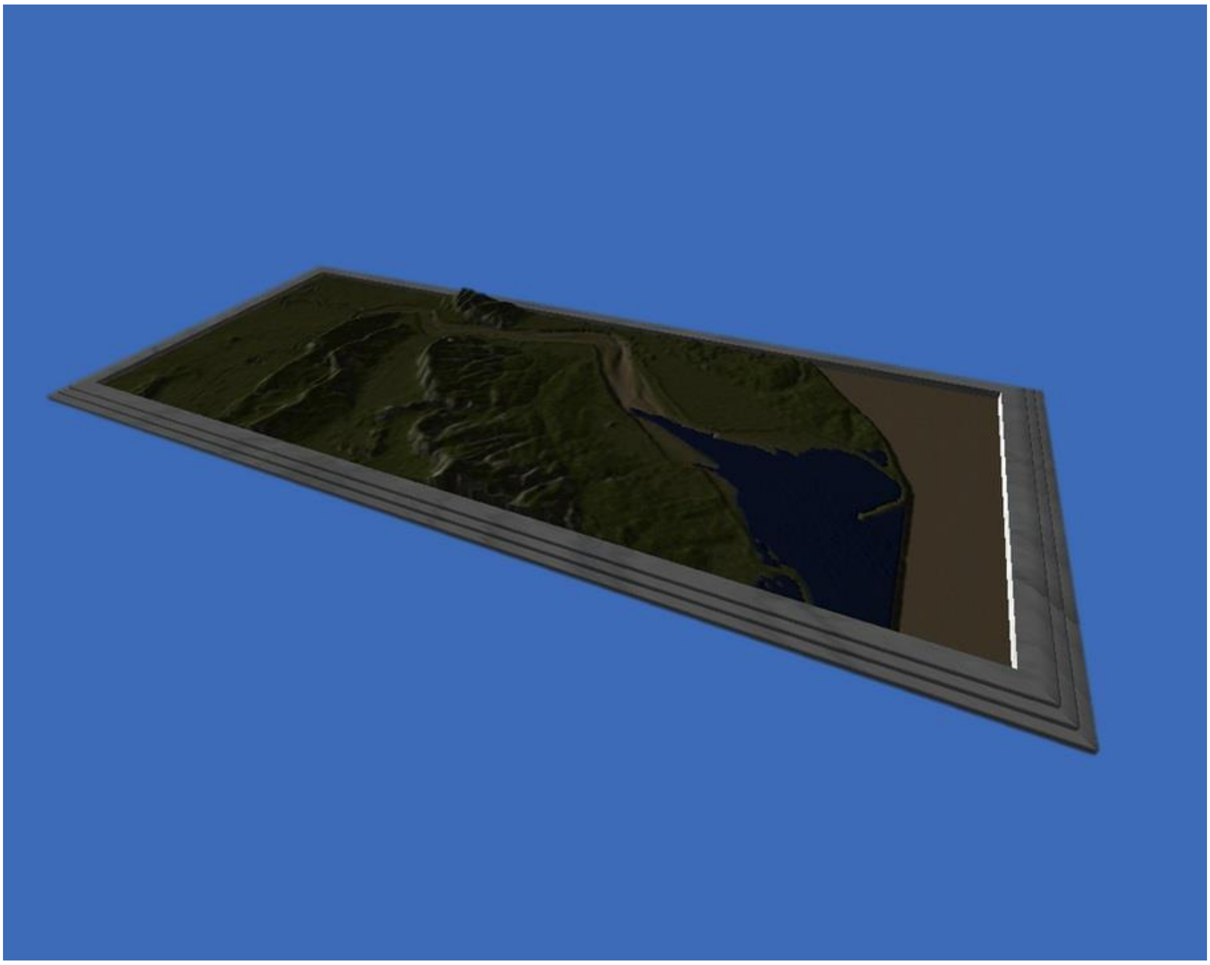
Work Package 4.5 - Testlab: proof of concept tests for short-listed measures in the Humber



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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 4. Measures: Assessments, tests and pilots and presents the results of activity 4.5 - Testlab: proof of concept tests for short-listed measures in the Humber. The aim of this work package is to identify the most suitable option(s) for flood risk management while maintaining /enhancing environmental protection. This activity builds on activity 3.5 - Design measures for flood risk management while maintaining/enhancing environmental protection measures in the Humber, which aimed to assess the flood risk benefits of a series of conceptual flood protection measures for the Humber. Following that activity, five potential measures have been short-listed for further exploration within the present report:

- Measure 6 – Managed Realignment at Keyingham and Goxhill, plus raised defences in high priority areas to keep pace with sea level rise. This is effectively a "Do nothing" approach with minimum intervention to address worst case flood issues.
- Measure 8 – Managed Realignment at Keyingham, Goxhill and Winteringham Ings, plus raise all Estuary defences by 1 m. This is effectively as a "Maintain the current strategy" approach that incorporates a small number of already identified managed realignment sites and defences raised by 1m.
- 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. This can be considered as a moderate interventionist approach incorporating some managed realignment and flood storage sites and defences raised by 2m.

- Measure 14 – 2014 ‘Realistic’ Measure, plus Estuary defences raised 1 m in line with post-2032 designation. This can be considered as a more interventionist approach with additional managed realignment and flood storage schemes and defences raised by 2m.
- Measure 16 – Sunk Island (Outer estuary) Barrier, seaward defences raised 1 m. This can be considered as a “Maximum intervention” approach on the basis of a potential worst case tidal surge scenario.

To enhance clarity of reporting, results are compared against those for Measure 1, which reflects the 2021 Baseline flood defences.

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.

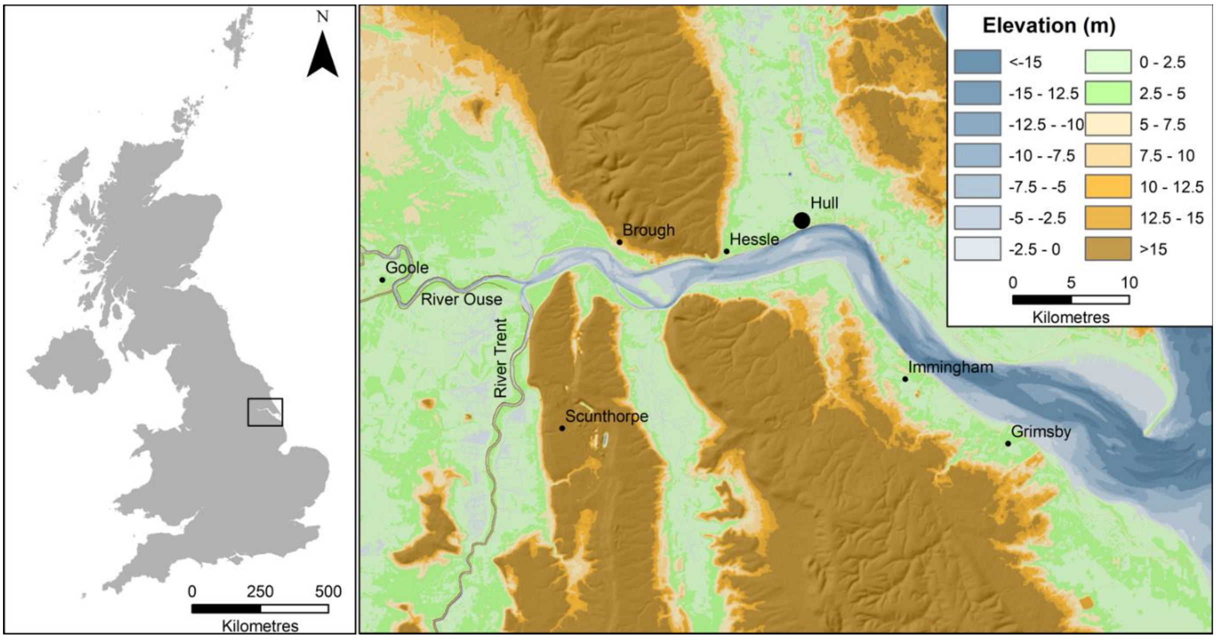

Figure 1.1 – Map of the Humber estuary, indicating the position of the Humber within the UK (inset) and the bathymetric and topographic characteristics of the estuary and surrounding region. Note the extensive areas of land with elevation <2.5m above mean sea level.

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 the short-listed 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. 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. Three areas were manually added:

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

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.

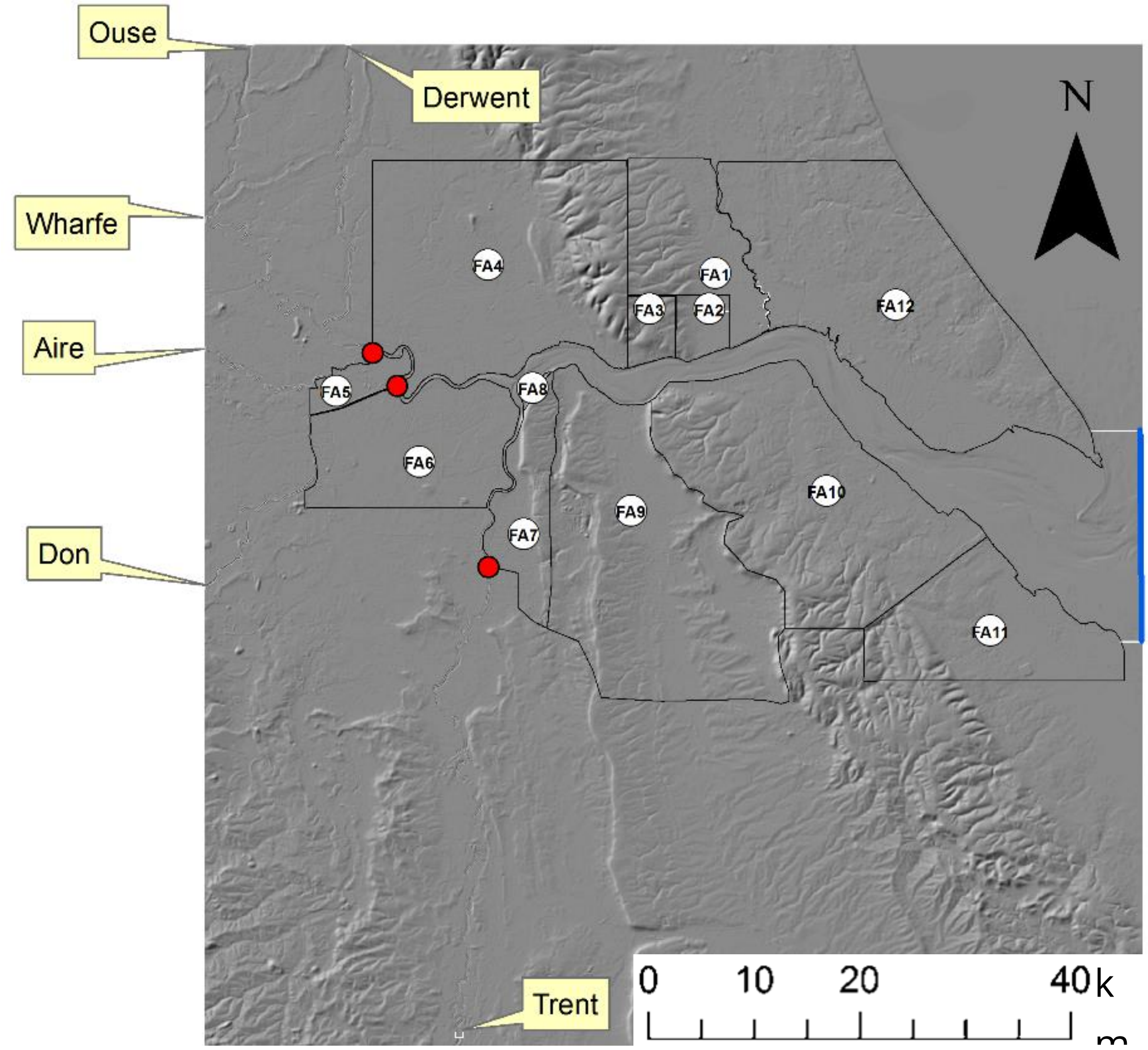

Figure 2.1 – The extended model domain, showing the limits of the domain (red dots), the location of the tidal input (blue line), and the locations of the fluvial inputs (call out boxes). Flood Action Areas (FA) are shown. Background imagery is a hillshade of the 2013 DEM with original bathymetry at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

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 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 the confluence.

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 2.1, 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 and +1 m. These values were selected to approximate the most recent UK Climate Change Projections (Palmer et al., 2018), which suggest 50th percentile ± 95th percentile confidence interval sea level rise values of 0.492 ± 0.314 m to 2115 under RCP 2.6 and 50th percentile ± 95th percentile confidence interval sea level rise values of 0.925 ± 0.367 m to 2115 under RCP 8.5 (see Highways England, 2019 for Humber-specific values). The 1- 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). 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 confirmed 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 overestimated overbank velocities and floodplain inundation extents.

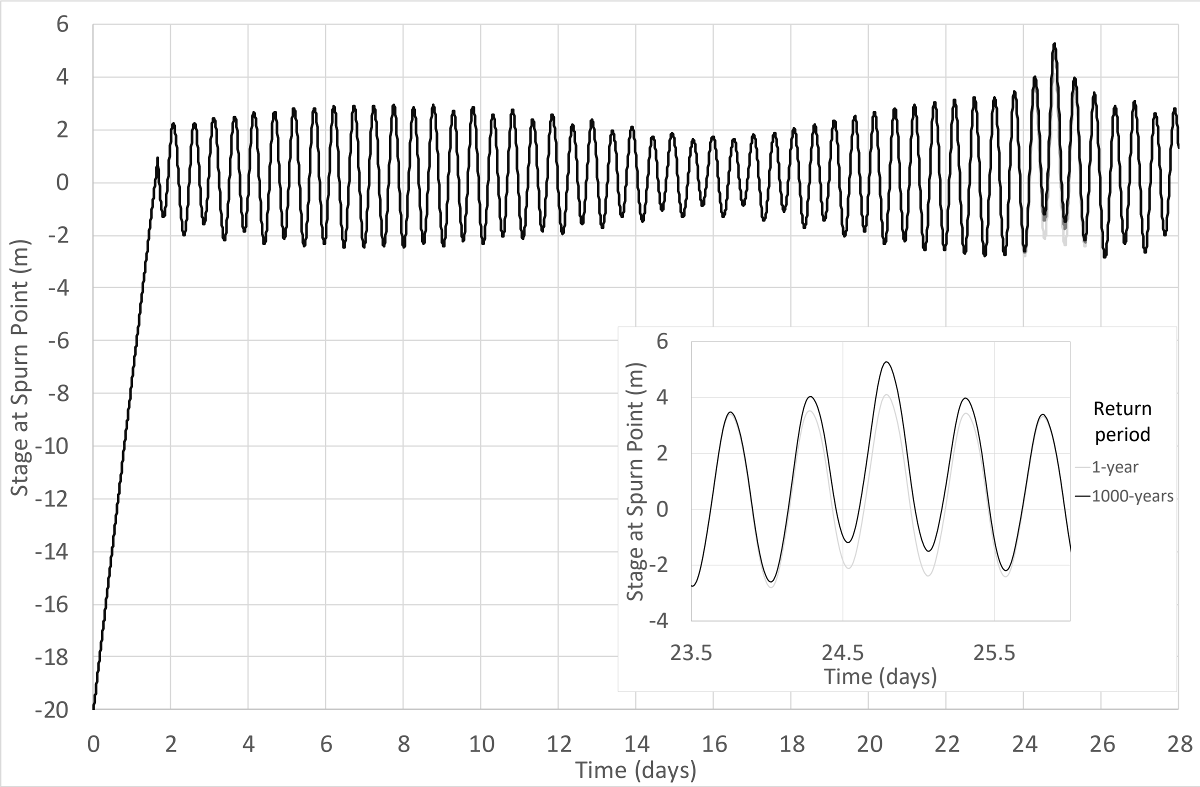

Figure 2.2 – Stage applied at the seaward boundary of the model. The first 40 hours of simulations linearly increase from a depth of zero to the estimated 28-day "designed flood curve". Inset shows a zoomed in region of the time series graph between days 23.5 and 26 of the time series. The peak of the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

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. 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.

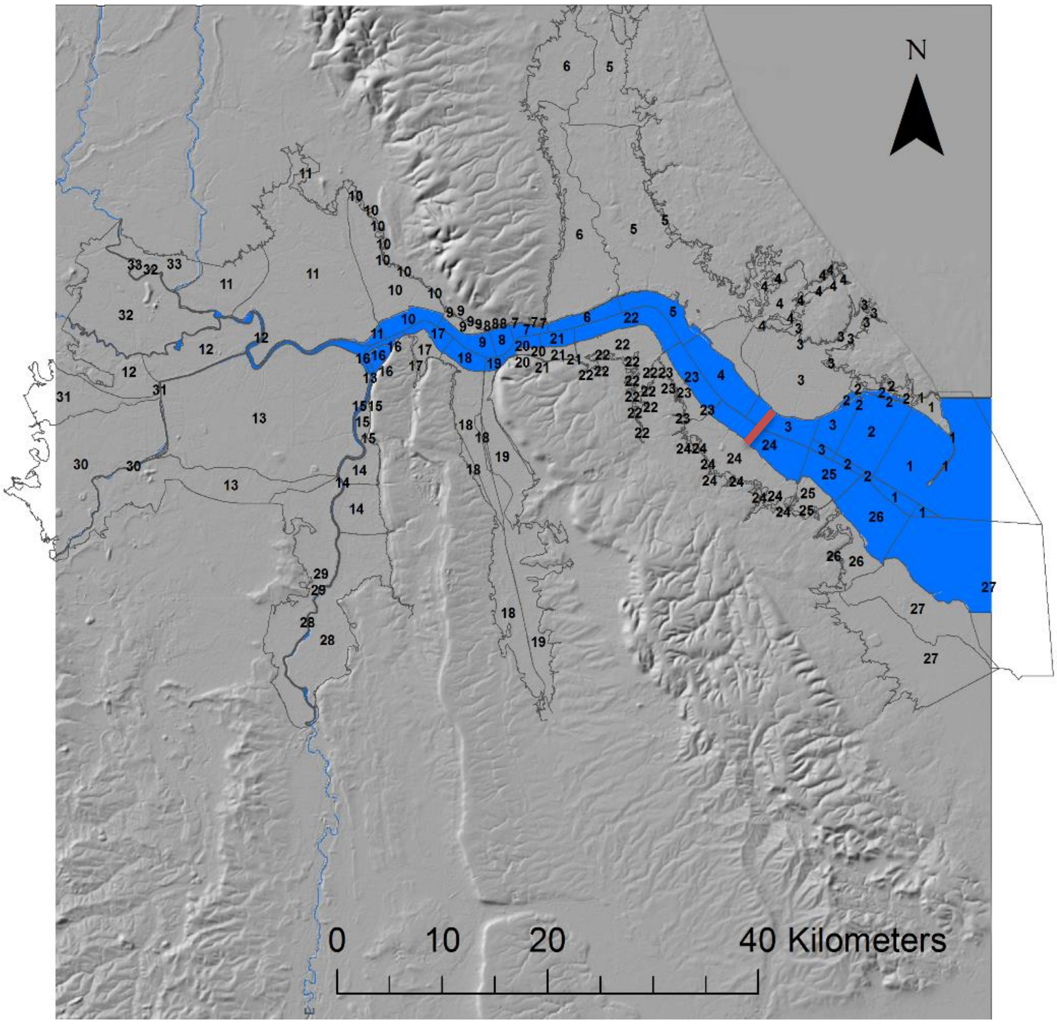

Figure 2.3 – Locations of the 33 HSCR Draft Flood Areas used for the calculation of flood volumes and flood areas. The orange line indicates the approximate location of the Sunk Island (outer estuary) Barrier (Measure 16).

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 2.1. 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;

Table 2.1 – 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

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.

2.8 Construction costs

In order to assess the construction costs of the different measures, it was necessary to:

1. extract linear lengths of embankments and walls that were to be raised in measures 6, 8, 13, 14 and 16 and estimate a representative height, crest width, and side slope of a typical embankment within the Humber. Using as-built plans for recently-constructed managed realignment sites, these were selected as 3 m, 4 m and 1 in 3, respectively. Using Environment Agency (2015a), the mean unit cost to construct embankments is £188 per m^3 (20^{th} percentile £118 per m^3, 80^{th} percentile £238 per m^3) for an embankment with volume <500 m^3, £94 per m^3 (20^{th} percentile £39 per m^3, 80^{th} percentile £122 per m^3) for an embankment with volume 500 to 5,000 m^3, £64 per m^3 (20^{th} percentile £55 per m^3, 80^{th} percentile £71 per m^3) for an embankment with volume 5,000 to 15,000 m^3, and £33 per m^3 (20^{th} percentile £19 per m^3, 80^{th} percentile £50 per

m^3) for an embankment with volume >15,000 m^3. The product of the linear length of embankment and the cross-sectional area needed to raise existing embankments (Figure 2.4) was then used to select the appropriate unit cost and multiplied to estimate the expected construction cost. In addition, the mean unit cost to raise walls by 0 to 1.2 m is £1,029 per m, and to raise walls by 1.2 to 2.1 m is £2,177 per m (Environment Agency, 2015a). Uncertainty bounds are not available for these values. These values were multiplied by the linear length of walls to estimate the expected cost to raise walls;

2. extract linear lengths of embankments that were to be removed in measure 14 and estimate a representative height, crest width, and side slope of a typical embankment within the Humber. Using as built plans for recently-constructed managed realignment sites, these were selected as 3 m, 4 m and 1 in 3, respectively (Figure 2.4). Using SNIFFER (2005 cited in Environment Agency, 2015b) and accounting for inflation between 2005 and 2015 (Bank of England, 2023), cost of removal ranges from £19.20 per m^3 to £25.60 per m^3. These values were then multiplied by the product of the linear length of embankment and the cross-sectional area for a typical embankment (39 m^2) to estimate the minimum and maximum expected construction cost, respectively, and their mean (£22.40 per m^3) was used as the best estimate of the expected construction cost;
3. extract the surface area of managed realignment and flood storage sites that were to be installed in measures 6, 8, 13 and 14. Using ABPmer (2015), four recently constructed managed realignment and flood storage sites within the Humber have incurred a mean unit cost per hectare of £62,091, with a range of £29,754 to £115,360 per hectare and a standard deviation of £32,161 per hectare. The mean ± 1 standard deviation unit costs were then multiplied by the surface area of each proposed site to estimate the minimum, mean and maximum expected construction costs.

In addition, Measure 16 involves the construction of a 3.89 km-long tidal surge barrier across the Humber. Very few tidal barriers have been constructed at this scale; for example, the Thames barrier in London is only 0.52 km long and cost £461 million in 1984 (£1.087 billion when accounting for inflation between 1984 and 2015 (Bank of England, 2023)) and the 9 km-long Oosterscheldekering cost fl. 8.5 billion in 1994 (Leeuwdrent, 2012), which equates to €5.79 billion (£4.2 billion) when accounting for inflation between 1994 and 2015 (International Institute of Social History, 2021). In the absence of better information, the inflated cost of the Thames barrier, the cost of the Oosterscheldekering, and a linear extrapolation of the inflated cost of the Thames barrier to the length of the Humber barrier (i.e., multiplying £1.087 by 3.89 / 0.52) were used to estimate likely minimum, mean and maximum costs, respectively.

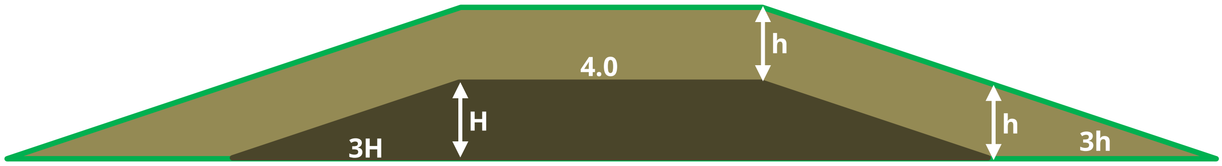

Figure 2.4 – Cross-section through typical embankment within the Humber. Existing embankment shown in dark brown, raised embankment profile shown in light brown. H has a typical value of 3.0 m, but h varies according to measure (0.5 m or 1.0 m to keep pace with SLR for Measure 6, 1.0 m for Measures 8, 14 and 16 and the difference between the existing defence crest elevation and the 2014 local 200-year return period water surface profile + 2.0 m for Measure 13). The typical cross-sectional area of existing embankments is therefore 4H + 3H = 39 m^2. The typical cross-sectional area needed to raise existing embankments by height h is therefore h ($2\sqrt{10}$ H + 3h + 4) = h ($6\sqrt{10}$ + 3h + 4), which is 12.24 m^2 for an increase of 0.5 m or 25.97 m^2 for an increase of 1.0 m.

3 Measure description and model setup

For all model simulations, the seaward boundary condition was set as the 28-day design flood curve using the 2014 stages for Spurn Point with sea levels adjusted to forecast 2021 levels. Modelled scenarios were the 1- and 1000-year return period storm surge events, with 0, 0.5 and 1.0 m sea level rise (SLR), resulting in six scenarios. The landward boundary conditions were set as the long-term mean daily discharges for all fluvial inputs.

3.1 Measure 1 – 2021 Baseline

For Measure 1, defences were uplifted to those in 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.

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

For Measure 6, flood defences were set as per Measure 1, with additional Managed Realignment sites at Keyingham and Goxhill (see Figure 3.1), and defences raised at High Priority areas by equivalent sea level rise. The High Priority areas are shown in Figure 3.1.

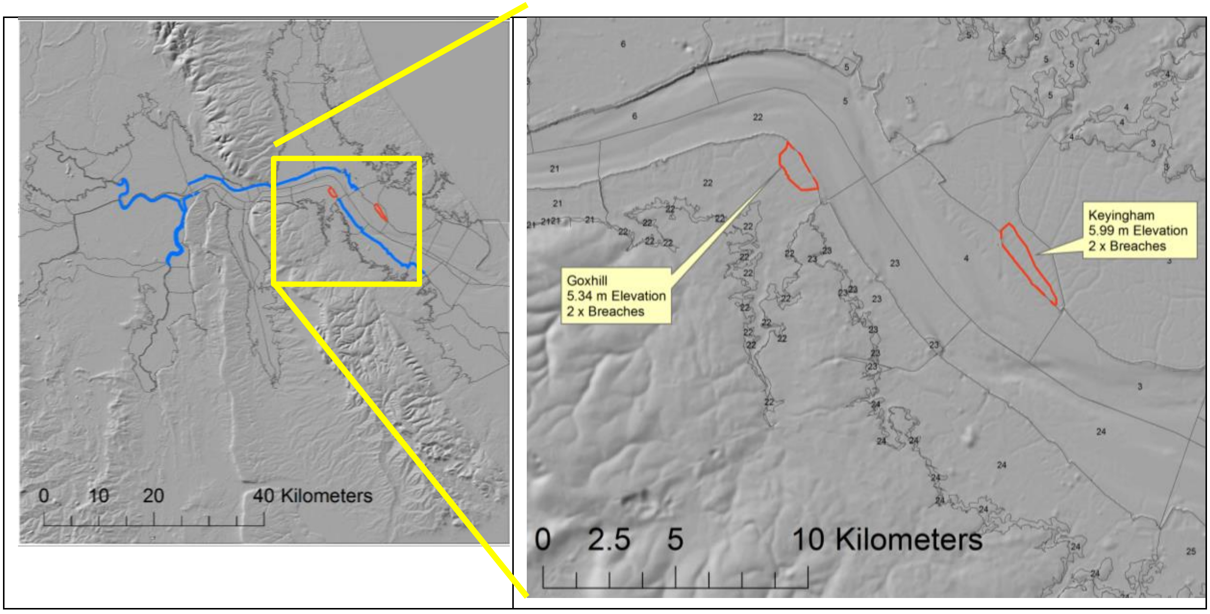

Figure 3.1 – Configuration of defence changes for Measure 6. Defences in High Priority Areas shown in blue raised in line with Sea Level Rise. Keyingham and Goxhill Managed Realignment sites shown in red.

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

For Measure 8, flood defences were set as per Measure 1, with additional Managed Realignment sites at Keyingham, Goxhill and Winteringham Ings, plus all Estuary defences raised by 1 m. Keyingham and Goxhill sites as in Figure 3.1. Winteringham Ings site as in Figure 3.2. Raised defences are within the estuary only, and do not include the areas of the extended domain.

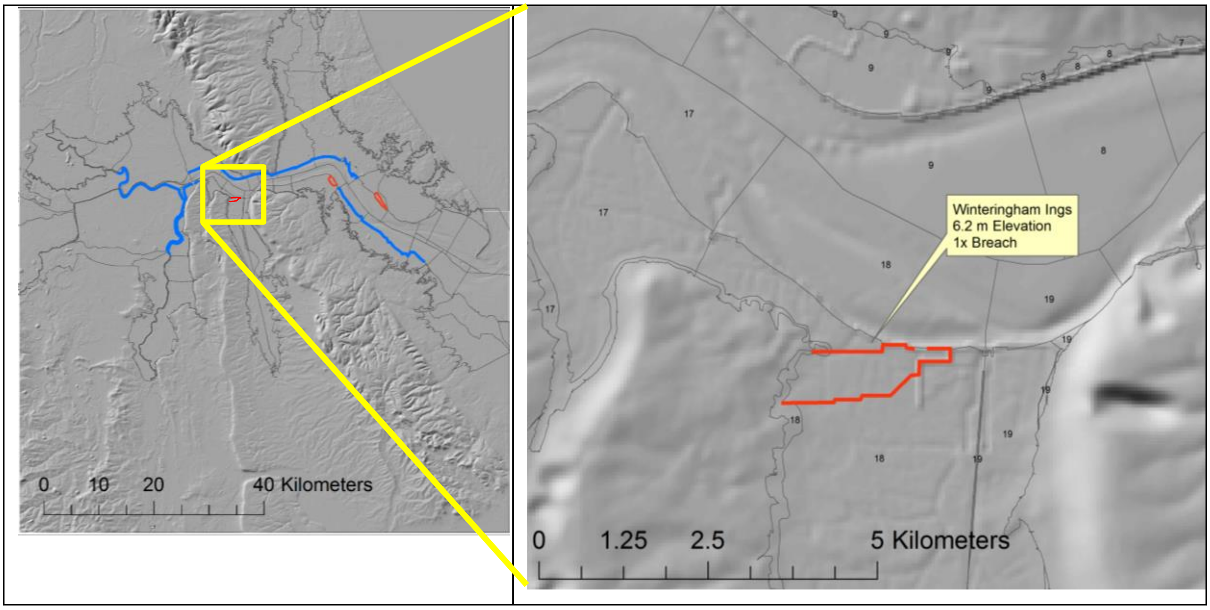

Figure 3.2 – Configuration of the Keyingham, Goxhill and Winteringham Ings Managed Realignment sites shown in red.

3.4 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

For Measure 13, 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 3.3, the Keyingham and Goxhill Managed Realignment schemes are shown in Figure 3.1, and the Winteringham Ings Managed Realignment scheme is shown in Figure 3.2. Flood Storage sites are shown in Figure 3.4.

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

For Measure 14, flood defence crest levels were set as per Measure 1 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 3.5, the Keyingham and Goxhill Managed Realignment schemes are shown in Figure 3.1, the Winteringham Ings Managed Realignment scheme is shown in Figure 3.2, and flood storage sites are shown in Figures 3.4 and 3.5.

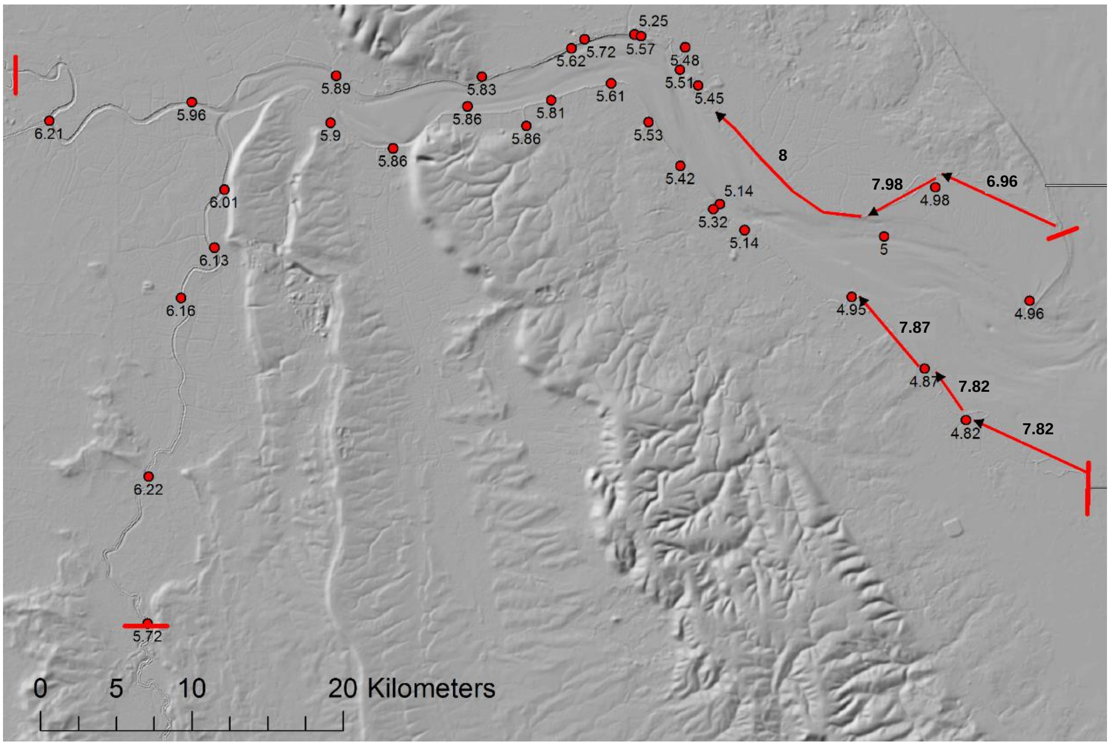

Figure 3.3 – Configuration of defence crest levels based on the local 1-in-200-year return period water surface elevations (red dots; labels show elevations in metres above OSN). Commencing from the most Easterly extent of defences (as shown by red arrows and values in bold) and marching Westwards, Baseline defence crest elevations were replaced with the elevation of the nearest local water surface elevation +2 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.

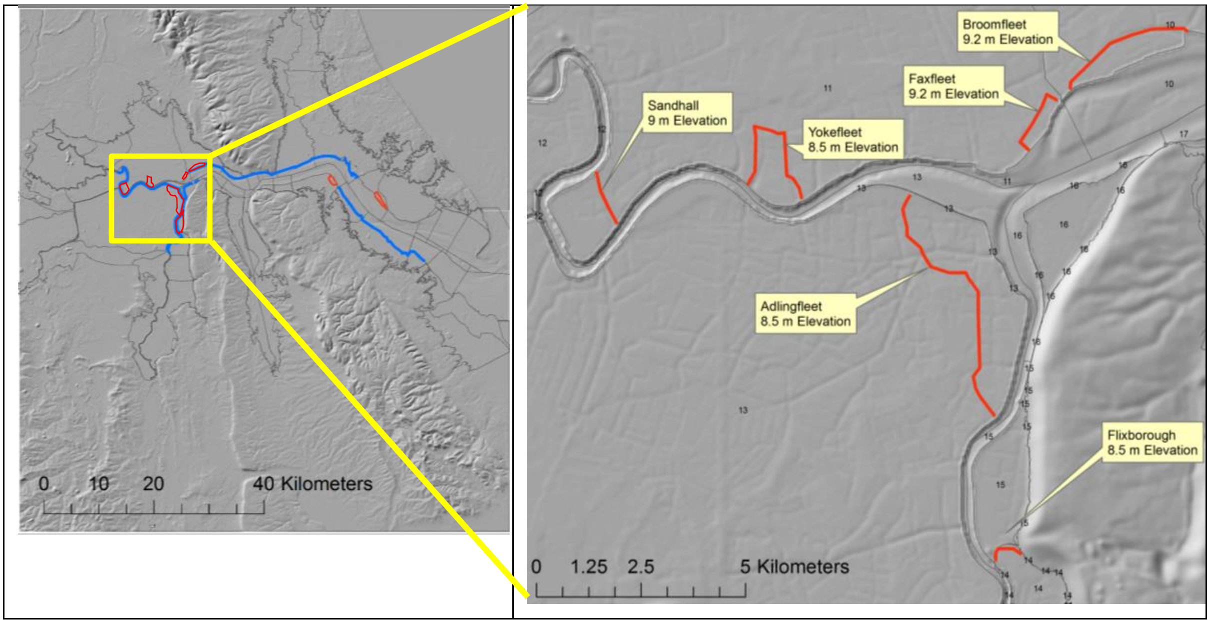

Figure 3.4 – Configuration of Flood Storage sites at Sandhall, Yokefleet, Adlingfleet, Broomfleet, Faxfleet and Flixborough. Elevations were raised along the red lines. Estuary facing defences were kept as Baseline level.

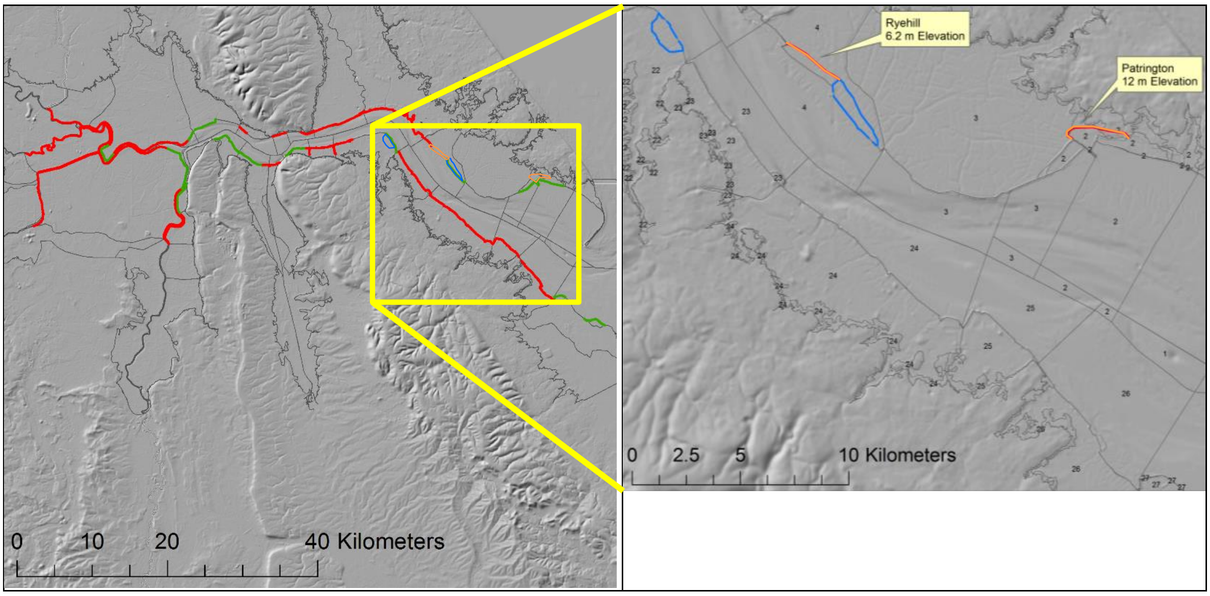

Figure 3.5 – Configuration of the post-2032 designations. Red lines show areas where defence assets are raised. Green areas show areas where defence assets are removed by setting their elevation to the mean of surrounding cells. Blue areas show Keyingham and Goxhill Managed Realignment sites (see also Figure 3.1), orange areas show the Ryehill and Patrington Flood Storage sites. Estuary facing defences treated according to the post-2032 designations.

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

The main flood defence for this scenario was a barrier installed at Sunk Island in the Outer estuary (Figure 2.3). 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. All defences seaward of the barrier were as per Measure 8.

4 Results

4.1 Flood volumes and water levels

Flood outlines for the five different measures, together with the baseline case (measure 1) are shown in Figures 4.1 to 4.6 for SLR scenarios of +0 m (i.e. present day), +0.5 m and +1.0 m. For completeness, flood outlines for the +2.0 m SLR scenario are shown in Appendix A. The impact of the different measures on total overbank flood volumes relative to Measure 1 is shown in Table 4.1.

Figures 4.1 to 4.6 and Table 4.1 show that, in terms of flood volumes, Measures 13 and 16 are most effective at limiting the volume of water on land, while Measure 14 is the least effective for all scenarios except the +1.0 m SLR and 1000-year return period storm surge scenario; Measure 6 is the least effective for the +1.0 m SLR and 1000-year return period storm surge scenario. Measure 8 is more effective for larger storm surge events, irrespective of the SLR scenario, but is still not as effective as Measures 13 and 16. For example, for a +1.0 m SLR and a 1000-year return period storm surge, Measure 16 reduced flood volume by 92.8% or 422.0 × 10^6 m^3, Measure 13 reduced flood volume by 92.2% or 419.0 × 10^6 m^3, Measure 8 reduced flood volume by 83.3% or 378.4 × 10^6 m^3, Measure 14 reduced flood volume by 11.6% or 52.87 × 10^6 m^3, and Measure 6 reduced flood volume by 4.99% or 22.69 × 10^6 m^3. Therefore, it can be concluded that the measure that incorporates 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 (Measure 8) reduces flood volumes more effectively than the measure that includes mid-outer estuary sites (e.g., Sunk Island/ Cherry Cobb sands, Goxhill and Keyingham) (Measure 6). Furthermore, partial removal of some estuarine flood defences alongside the addition of outer estuary flood storage sites (Ryehill and Patrington; Measure 14) was not beneficial for flood alleviation at present day to +0.5 SLR but was somewhat effective for the largest storm surges and +1.0 m SLR.

Considering selected large and costly infrastructural assets around the estuary, very little water spilled onto the floodplain for the baseline scenario for the 1-year return period storm surge and sea level rise of 1.0 m (Figures 4.5 and 4.6). Of the selected measures, Measure 8 reduced flood volumes around the CEMEX plant at South Ferriby by 100% or −2.89 × 10^6 m^3, Measure 16 reduced flood volumes by 99.88% or −2.89 × 10^6 m^3, Measure 13 reduced flood volumes by 96.65% or −2.79 × 10^6 m^3, but Measure 14 (11.04% or +0.32 × 10^6 m^3) and Measure 6 (17.89% or +0.52 × 10^6 m^3) increased flood volumes in this area (Table 4.2). For the same flooding scenario, Measure 16 reduced flood volumes around the large power station at Drax by 100% or −2.62 × 10^3 m^3, Measure 14 reduced flood volumes by 99.9% or −2.62 × 10^3 m^3, but Measures 6, 8 and 13 increased flood volumes, with the worst performer being Measure 13, which increased flood volumes by 460% or +12.07 × 10^3 m^3 (Table 4.2).

Table 4.1 – 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 event and dark blue columns identify scenarios with a 1000-year return period event. Each storm surge event was run with 0.0, 0.5 and 1.0 m sea level rise. Table cells coloured from ±100%. Values outside this range are coloured with the value at ±100%.

Measure	1-year return period			1000-year return period		
	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR
6	2.54	−12.4	−3.31	−0.16	−0.87	−4.99
8	2.32	−33.8	−75.4	−88.6	−88.1	−83.3
13	−97.2	−98.9	−96.6	−95.4	−94.2	−92.2
14	93916	9464	500	263	40.2	−11.6
16	−99.7	−82.2	−87.8	−99.1	−98.6	−92.8

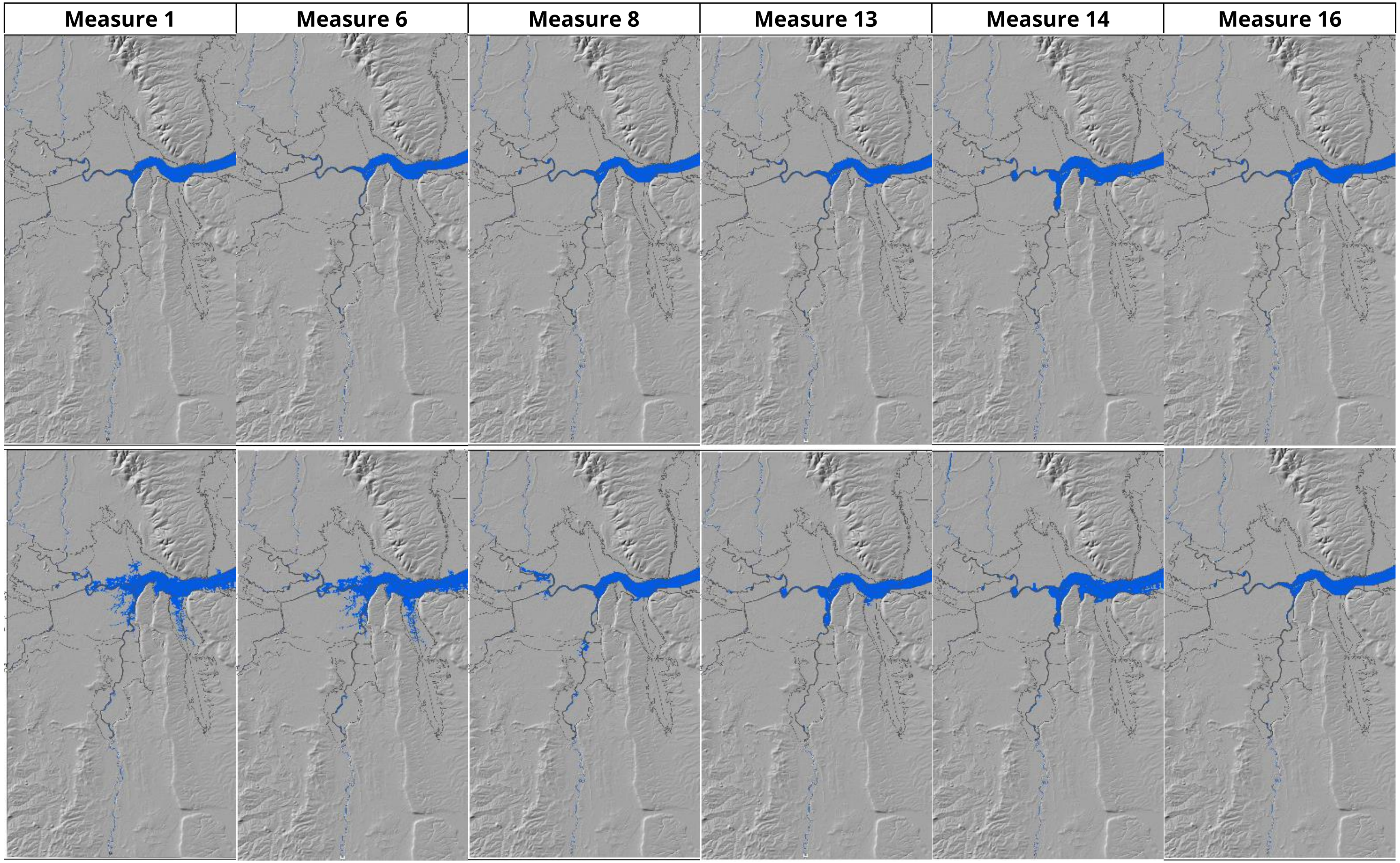

Figure 4.1 – Inner estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 0 m (i.e., present day).

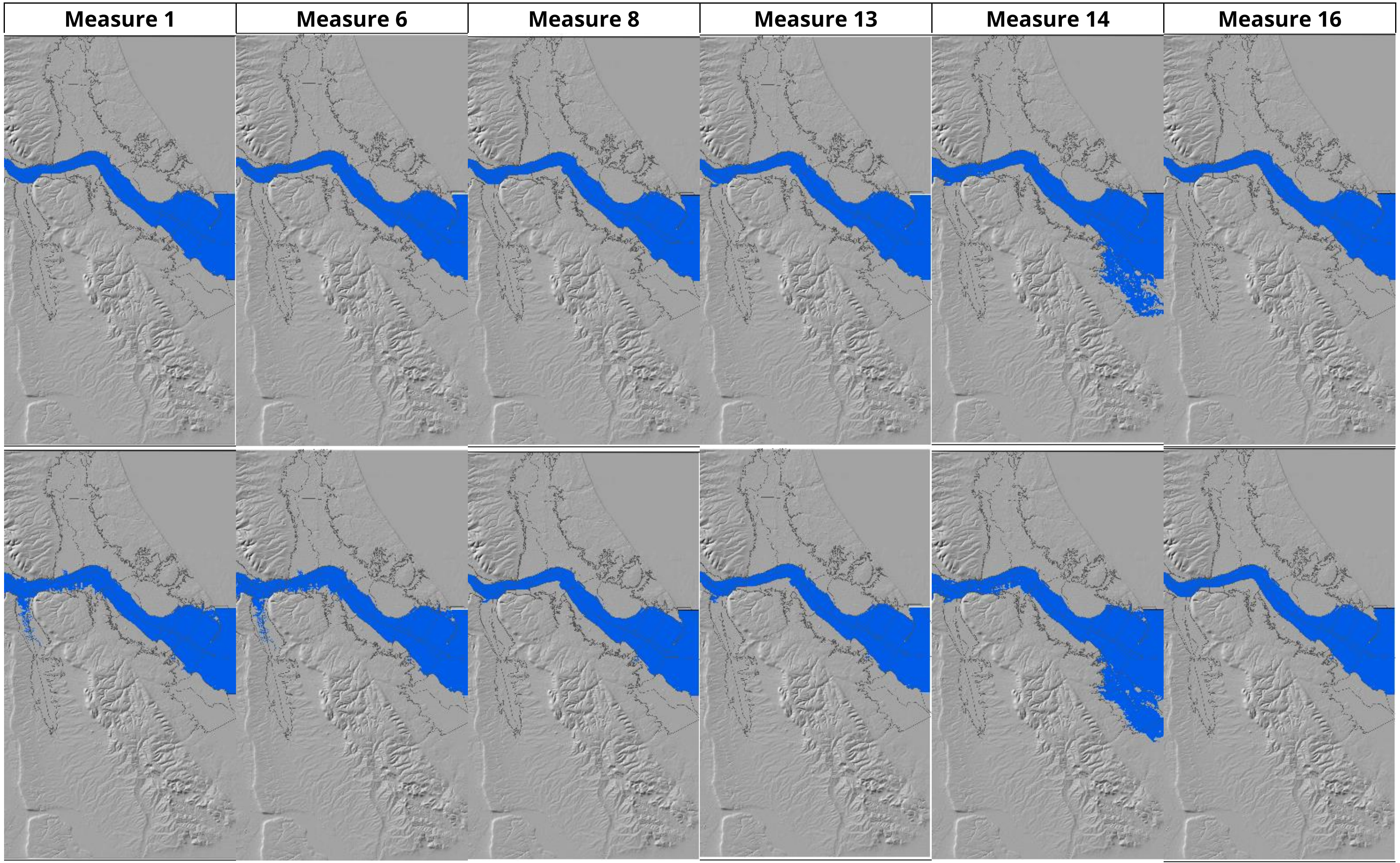

Figure 4.2 – Outer estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 0 m (i.e., present day).

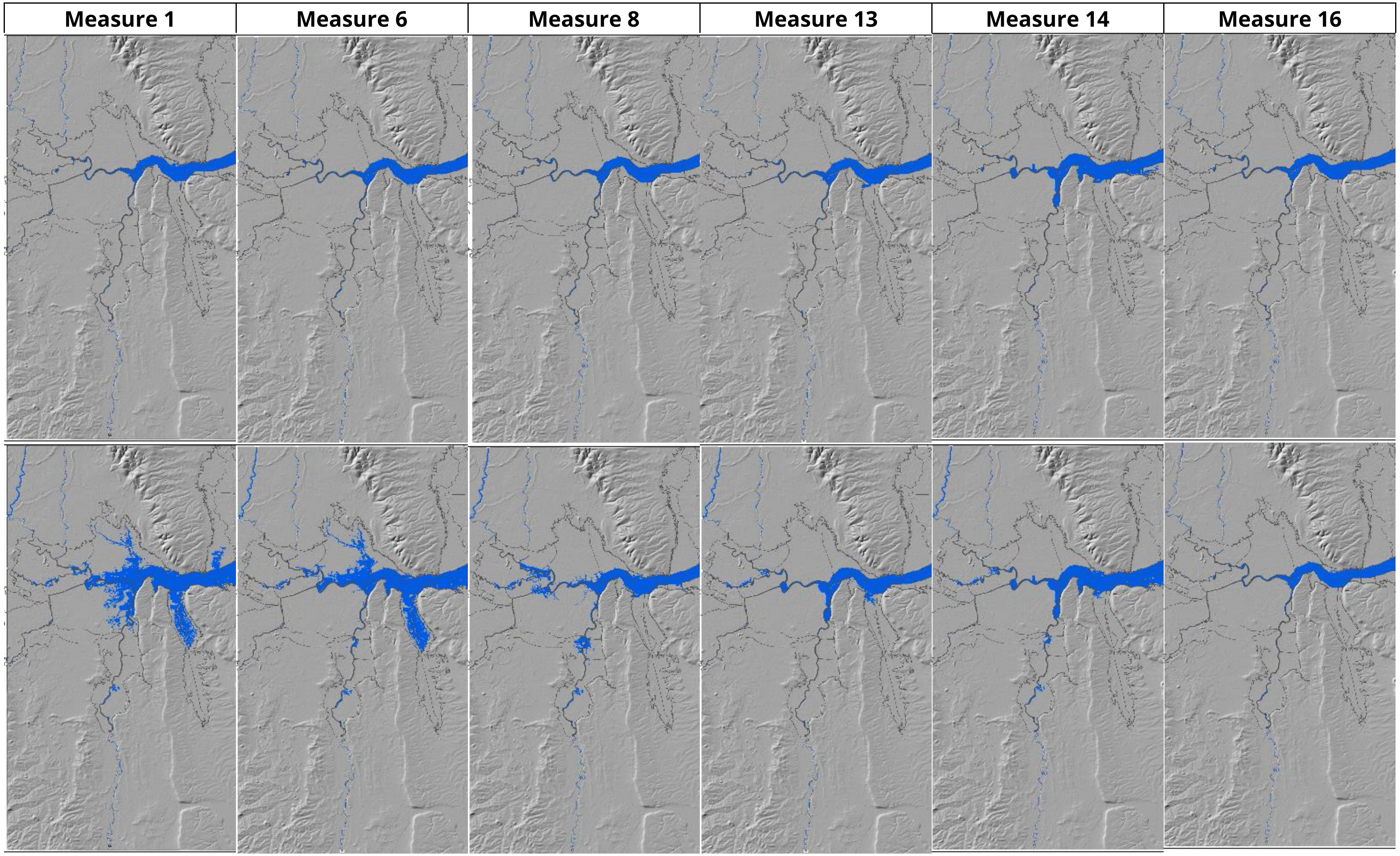

Figure 4.3 – Inner estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 0.5 m.

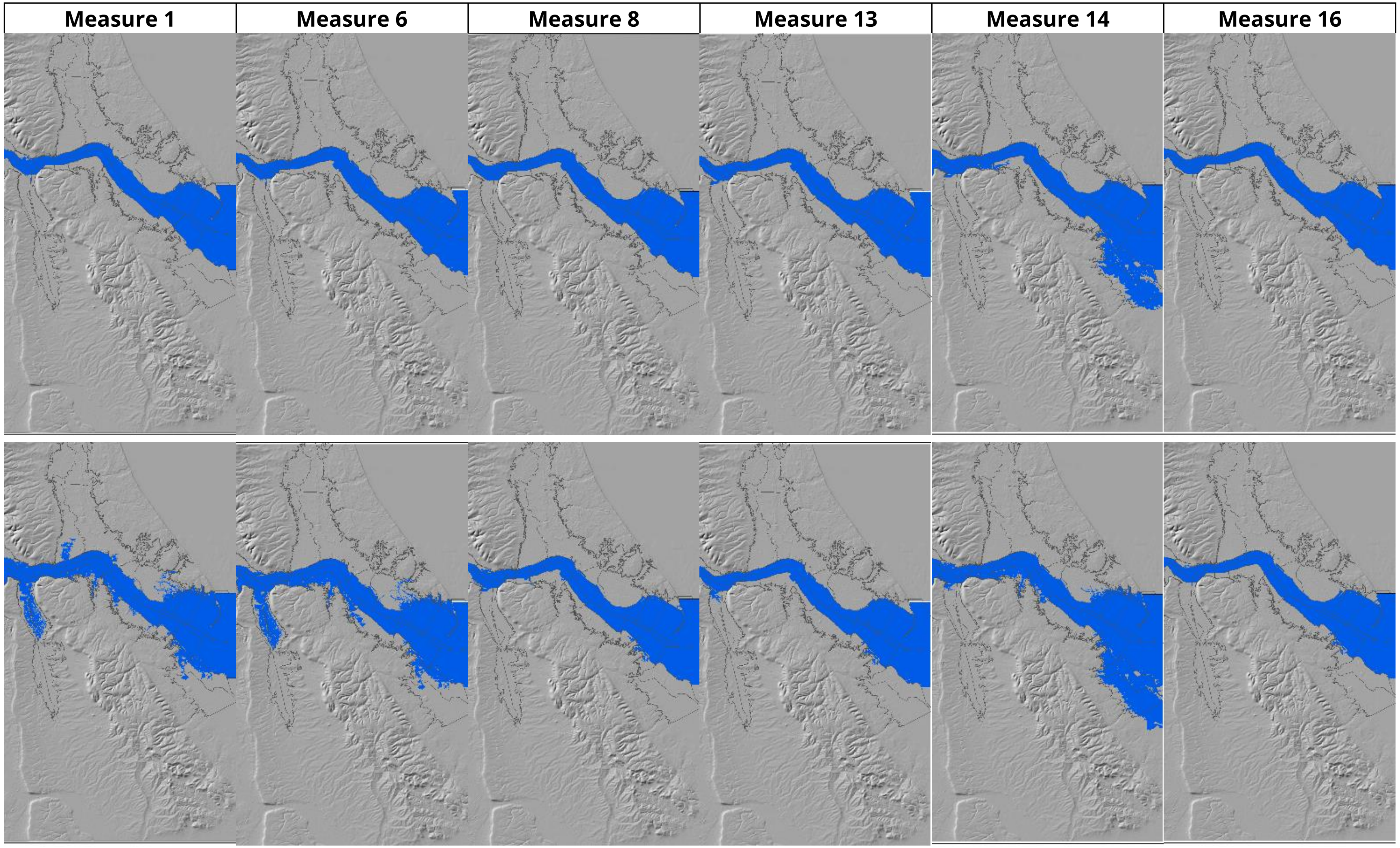

Figure 4.4 – Outer estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 0.5 m.

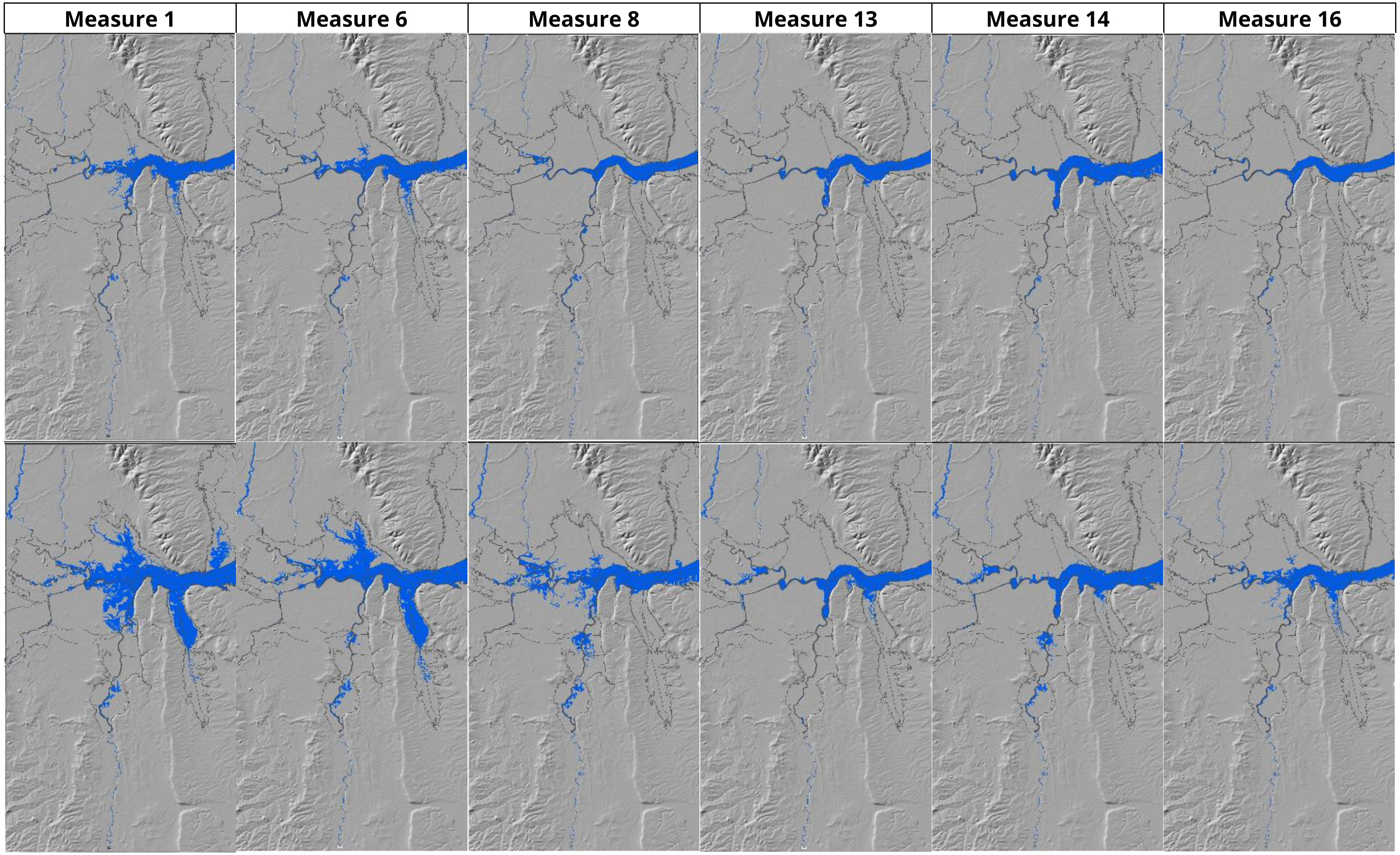

Figure 4.5 – Inner estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 1.0 m.

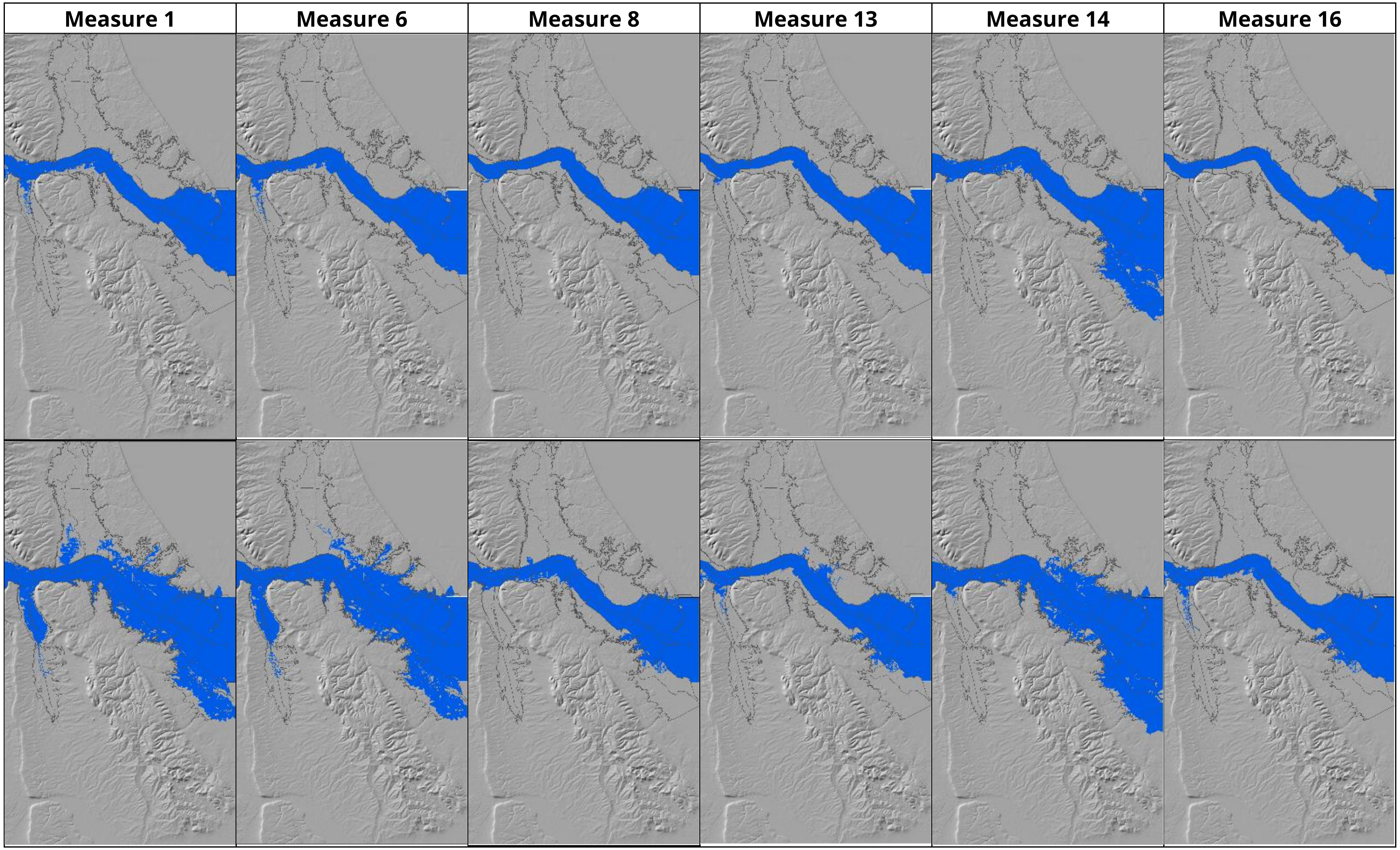

Figure 4.6 – Outer estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 1.0 m.

Table 4.2 – Summary table showing the percentage change (%) in flood volume relative to the Baseline (Measure 1) for six economically important regions of the Humber for each scenario. Light blue column headers identify scenarios with a 1-year return period event and dark blue column headers identify scenarios with a 1000-year return period event. Each storm surge event was run with 0.5 and 1.0 m sea level rise. Table cells coloured from ±100%. Values outside this range are coloured with the value at ±100%.

Sea Level Rise 0.0 m

Measure	1-year return period						1000-year return period					
	Grimsby	Immingham	Hull	CEMEX	Goole	Drax, Selby	Grimsby	Immingham	Hull	CEMEX	Goole	Drax, Selby
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	9.413	16.22	2.228	1.900	24.85
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-100.0	-100.0	-100.0	267.1	168.7
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-100.0	-100.0	-95.76	-100.0	273.2
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-100.0	-100.0	-20.48	-100.0	-6.445
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-100.0	-100.0	-100.0	-100.0	-100.0

Sea Level Rise 0.5 m

Measure	Grimsby	Immingham	Hull	CEMEX	Goole	Drax, Selby	Grimsby	Immingham	Hull	CEMEX	Goole	Drax, Selby
6	0.000	0.000	0.000	18.39	111.1	0.000	-70.58	204.0	-98.86	16.58	11.79	1.520
8	0.000	0.000	0.000	-100.0	182.6	0.000	-60.18	-100.0	-98.78	-96.23	289.0	113.3
13	0.000	0.000	0.000	-84.25	-100.0	0.000	-81.90	-100.0	-100.0	-91.79	-98.71	175.5
14	0.000	0.000	0.000	5677	-100.0	0.000	-75.15	-95.07	-100.0	-55.25	-98.66	231.8
16	0.000	0.000	0.000	-100.0	-100.0	0.000	-87.53	-100.0	-100.0	-99.97	-100.0	-100.0

Sea Level Rise 1.0 m

Measure	Grimsby	Immingham	Hull	CEMEX	Goole	Drax, Selby	Grimsby	Immingham	Hull	CEMEX	Goole	Drax, Selby
6	0.000	0.000	-100.0	17.89	31.64	10.51	-59.64	-18.96	-26.42	15.55	18.41	10.69
8	0.000	0.000	-100.0	-100.0	209.1	214.8	-78.91	-100.0	-97.51	-88.86	232.9	113.3
13	0.000	0.000	-100.0	-96.65	-100.0	460.2	-81.67	-100.0	-94.46	-90.47	-92.03	368.5
14	0.000	0.000	-100.0	11.04	-100.0	-99.90	-82.26	-34.71	-77.56	-76.26	-93.26	420.8
16	0.000	0.000	-100.0	-99.88	-100.0	-100.0	-83.41	-100.0	-99.90	-85.84	-88.72	-100.0

For the 1000-year return period storm surge and sea level rise of 0.5 m, the measures displayed very different behaviours (Figures 4.3 and 4.4). Measure 6 increased flood volumes in the inner estuary locations (the CEMEX site, the town of Goole and the Drax Power Station) and at the Port of Immingham in the outer estuary (Table 4.2). Of the other measures, Measure 16 reduced flood volumes at all locations by 87.53-100%, but Measures 13 and 14 increased flood volumes around the Drax Power Station by 175.5% and 231.8%, respectively, while Measure 8 increased flood volumes around the town of Goole and the Drax Power Station by 289% and 113.3%, respectively (Table 4.2). All measures reduced flood volumes at the town of Grimsby by 60.18 to 87.53% and at the City of Hull by 98.78% to 100% (Table 4.2). A similar trend was observed for the 1000-year return period storm surge and sea level rise of 1.0 m (Figures 4.5 and 4.6; Table 4.2).

Measure 16 resulted in the largest reduction in water levels upstream of the Sunk Island (outer estuary) barrier for all scenarios (Table 4.3, Figure 4.7) but this is not reflected in the largest reductions in flood volumes for SLRs of +0.5 m and +1.0 m because water levels still rise above defence levels between river kms 54 and 64 and river kms 48 and 70, respectively (Figures 4.7B and 4.7C). If Measure 16 was to be 100% effective at preventing flooding, there would still be a need for defences to be raised, at least in high priority areas (e.g. as per Measure 6; Figure 3.1). Nevertheless, it is apparent that Measure 16 is the only measure that would protect all the large and costly infrastructural assets within the estuary from flooding up to and including a 1000-year return period storm surge at the +1.0 m SLR scenario (Figures 4.5, 4.6, and 4.7). This has implications for the prevented economic damages.

4.2 Economic damages

Analysis of the economic indicators selected for study, 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), the number of directly affected businesses (i.e., business premises 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) indicates a consistent pattern (Table 4.4). Measure 16 resulted in the least damages and Measure 14 resulted in the most damages. Relative to Measure 1, Measure 16 resulted in more than a 70% reduction in impacts for all indicators and scenarios (between 51 and 160818 fewer people directly affected, between £4.6 million and £8,931 million less residential property value directly affected, between 4 and 5,872 fewer businesses directly affected, and between £2.3 and £3,691 million less GVA affected) (Table 4.4). Measure 13 resulted in more than a 65% reduction (between 3,751 and 158,808 fewer people directly affected, between £300 million and £8,815 million less residential property value directly affected, between 256 and 5,869 fewer

Table 4.3 – Summary table showing change in mean stage relative to the Baseline (Measure 1) for each scenario in metres. Light blue column headers identify scenarios with a 1-year return period event and dark blue column headers identify scenarios with a 1000-year return period event. Each storm surge event was run with 0.0, 0.5 and 1.0 m sea level rise. Table cells coloured from ±0.9 m.

Measure	1-year return period			1000-year return period		
	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR
6	-0.001	0.014	0.042	0.003	0.051	0.076
8	0.000	0.019	0.147	0.211	0.387	0.512
13	-0.018	0.009	0.096	0.131	0.267	0.518
14	-0.207	-0.215	-0.103	-0.056	0.121	0.322
16	-0.532	-0.525	-0.385	-0.898	-0.612	-0.381

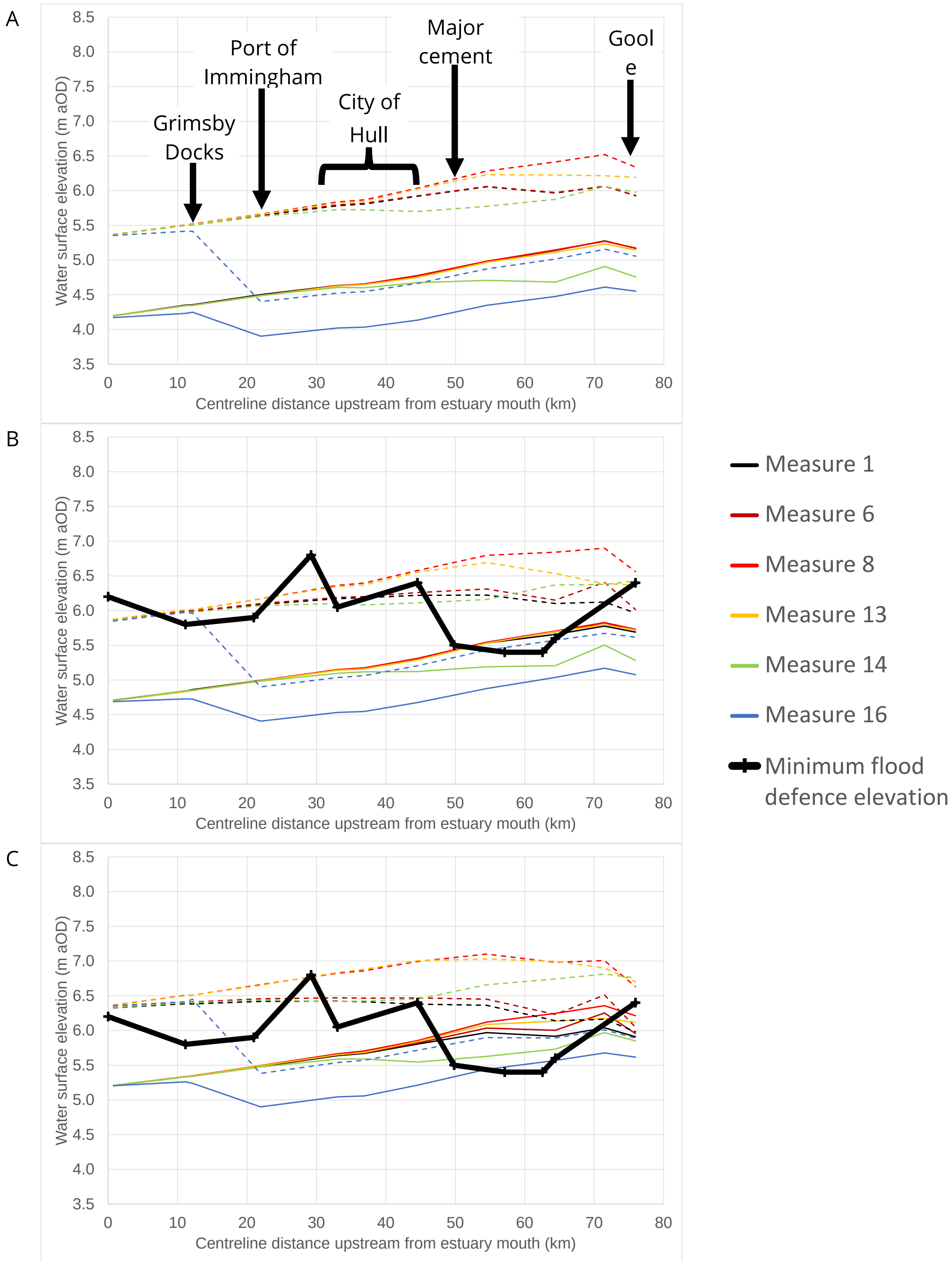

Figure 4.7 – Water surface profiles for Measures 1, 6, 8, 13, 14 and 16 at SLR values of A. 0 m (i.e., present day), B. 0.5 m and C. 1.0 m. Solid lines denote water surface for a storm surge with a 1-year return period while dashed lines denote water surface for a storm surge with a 1000-year return period.

Table 4.4 – Summary tables showing the percentage change (%) in the population directly affected, residential property value affected, number of businesses affected and potential Gross Value Added to the economy affected relative to the Baseline (Measure 1) for each scenario. The Table has been split to reflect residential-related variables (top half) and business-related variables (bottom half). Light blue column headers identify scenarios with a 1-year return period event and dark blue column headers identify scenarios with a 1000-year return period event. Each storm surge event was run with 0.0 (i.e., present day), 0.5 and 1.0 m sea level rise. Table cells coloured from ±100%. Values outside this range are coloured with the value at ±100%.

	Population directly affected						Residential property value					
	1-year return period			1000-year return period			1-year return period			1000-year return period		
Measure	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR
6	353.5	-21.07	-4.69	4.40	-53.69	-43.41	239.0	-39.37	-10.35	3.55	-48.68	-42.22
8	341.6	-33.21	-33.65	-45.55	-68.72	-70.01	225.5	-50.94	-44.96	-52.93	-67.34	-68.54
13	481.1	-18.02	-71.00	-78.20	-86.06	-80.55	380.8	-36.32	-69.99	-75.58	-82.56	-81.44
14	21877	2552	215.6	62.95	-57.51	-59.50	21512	2373	235.4	77.38	-48.56	-57.20
16	-100.0	-72.28	-85.97	-91.23	-90.35	-81.57	-100.0	-79.21	-83.84	-89.11	-87.76	-82.51

	Number of businesses directly affected						Gross Value Added to the economy					
	1-year return period			1000-year return period			1-year return period			1000-year return period		
Measure	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR	0.0 m SLR	0.5 m SLR	1.0 m SLR
6	252.9	-58.31	-21.54	2.53	-39.09	-37.08	135.7	-62.52	-27.31	2.45	-35.07	-36.87
8	250.8	-63.21	-56.26	-59.48	-68.00	-72.75	132.8	-67.93	-60.90	-64.27	-75.76	-80.39
13	233.6	-65.26	-76.51	-80.74	-86.33	-84.87	105.5	-70.92	-75.01	-81.82	-90.54	-88.65
14	10131	685.2	121.3	33.83	-49.67	-55.31	5335	570.0	90.86	6.50	-57.33	-54.88
16	-100.0	-80.25	-78.34	-91.01	-88.99	-84.91	-100.0	-83.92	-82.53	-94.62	-93.87	-90.77

businesses directly affected, and between £98 and £3,605 million less GVA affected) for all indicators and scenarios other than the 1-year return period storm surge at 0.0 m (i.e. present day), which resulted in 245 more people directly affected, £17.4 million more residential property value directly affected, 9 more businesses directly affected, and £2.4 million more GVA affected, and +0.5 m sea levels, which resulted in 96 fewer people directly affected, £18 million less residential property value directly affected, 45 fewer businesses directly affected, and £18.8 million less GVA affected (Table 4.4). Measure 8 resulted in more than a 33% reduction for all indicators and scenarios other than the 1-year return period storm surge for present day sea levels, which resulted in 174 more people directly affected, £10.3 million more residential property value directly affected, 10 more businesses directly affected, and £3.1 million more GVA affected (Table 4.4). Measure 6 resulted in inconsistent results, with reduced damages for all +0.5 and +1.0 m sea level rise scenarios, increased damages for present day sea levels, and improved efficacy for the 1000-year return period event at 0.5 m and 1.0 m sea level rise values. Measure 14 resulted in increased damages (between 6,484 and 13,613 more people directly affected, between £633 million and £1,173 million more residential property value directly affected, between 188 and 476 more businesses directly affected, and between £15.4 and £151 million more GVA affected) for all scenarios except the 1000-year return period event at the +0.5 and +1.0 m sea level rise scenarios (between 33,827 and 117,303 fewer people directly affected, between £1,874 million and £6,191 million less residential property value directly affected, between 1,081 and 3,825 fewer businesses directly affected, and between £630 and £2,232 million less GVA affected).

4.3 Construction cost comparison

The result of the construction cost estimates for all the measures is shown in Table 4.5. It can be seen that the least expensive measure is Measure 6, with an estimated construction cost of £80.3 million (range £53.4 - £110.8 million) for the 0.5 m SLR scenario and £126.0 million (range £79.8 - £179.9 million) for the 1.0 m SLR scenario, followed by Measure 14 (£347.2 million; range £209.2 – £497.7 million), Measure 8 (£429.5 million; range £254.2 – £639.1 million) and Measure 13 (£940.5 million; range £542.4 - £1,410 million) (Table 4.5). Measure 16 is the most expensive measure, with an estimated construction cost of £4,250 million (range £1,118 - £8,191 million), an order of magnitude more expensive than measures 6, 8 and 14 and more than four times the cost of Measure 13 (Table 4.5).

Table 4.5 – Summary of required construction activities and estimated construction cost of measures 6, 8, 13, 14 and 16.

Measure	Length of raised walls (km)	Length of raised embankments (km)	Length of removed embankments (km)	Area of added managed realignment (Ha)	Estimated cost (£ 2015 prices)
6 (0.5 m SLR)	19.63	100.5		304.3	£80,278,000
6 (1.0 m SLR)					£125,972,000
8	19.63	444.2		435.4	£429,491,000
13	19.63	293.8		1990.2	£940,491,000
14	19.63	161.0	55.32	2259.7	£347,210,000
16	4.22	53.55			£4,250,243,000

5 Discussion and Conclusions

This report has presented results of numerical modelling simulations of selected flood alleviation measures for the Humber estuary with 1- and 1000-year return period storm surge events combined with three different sea level rise scenarios: present day levels, +0.5 m and +1 m. These values were selected to approximate the most recent UK Climate Change Projections (Palmer et al., 2018), which suggest 50th percentile ± 95th percentile confidence interval sea level rise values of 0.492 ± 0.314 m to 2115 under RCP 2.6 and 50th percentile ± 95th percentile confidence interval sea level rise values of 0.925 ± 0.367 m to 2115 under RCP 8.5. The efficacy of measures was 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. In addition to the physical (i.e., maximum stages and flood volumes), economic (people and businesses affected, expected damages and GVA losses) and financial (construction costs) impacts outlined herein, the report by Cutts et al. (2023) outlines the anticipated ecological changes that could be expected as a result of the selected measures under the different sea level rise scenarios. This discussion performs a multi-criteria analysis in order to identify which of the selected measures ranks highest.

Multi-criteria analysis is a methodology by which non-monetised variables can be coupled with monetised variables in order to produce a quantitative comparison of measures (Dodgson et al., 2009). Herein, flood volume, stage change, and the number of directly affected people and businesses were treated in the same manner: median values for each variable were estimated using Tables 4.2, 4.3 and 4.4 and then scaled between 0 and 1, where 0 is the best performing measure (or a reduction of 100%) and 1 is the worst performing measure (Table 5.1). Ecological impacts on the inner and outer estuary were rated using information for +2.0 m SLR (as the most extreme case) in Cutts et al. (2023) on a sliding scale between 0 and 1, again with 0 as the least impactful/most beneficial and 1 as the most impactful/least beneficial (Table 5.1). The four scores were summed and then normalised by the maximum score to obtain a normalised total score for the non-monetised variables (Table 5.1). The total value of residential property damages and lost gross value added to the economy relative to the baseline, together with the construction costs were treated as continuous, monetised variables. The benefit (i.e., reduced losses to property values and GVA) to cost (i.e. the projected construction cost) ratio was thus computed for both the +0.5 m and +1.0 m SLR scenarios and then divided by the normalised total score to obtain a weighted benefit:cost ratio that attempts to account for the considered non-monetised variables (Table 5.1).

The result of this analysis is shown in Table 5.1. For brevity, only the results for the +1.0 m SLR scenario are shown, since the outcome was identical for both SLR scenarios. It can be seen that although Measure 6 was amongst the least effective measure in terms of its flood defence efficacy, its relatively small cost for the net benefits results in the greatest benefit: cost ratio and weighted benefit: cost ratio. Measure 8, which was very much a middle-of-the-road performer in terms of both its flood defence efficacy and ecological impacts, had the second highest benefit: cost ratio, only slightly better than Measure 14, which had the worst performance in terms of flood defence efficacy but was the second cheapest option. However, when considering the weighted benefit: cost ratio, which incorporates consideration of the ecological impacts, Measure 14 ranks higher than Measure 8. The enormous expense of Measure 16 means that, although it was the most effective flood defence option, its benefit: cost ratio was the lowest of the five short-listed measures.

It should be noted that this analysis was undertaken without accounting for the priorities of decision makers and stakeholders. Each of the non-monetised variables could be weighted according to those priorities. However, preliminary sensitivity tests indicate that even for the most extreme weighting scenarios, the ranking shown in Table 5.1 is robust.

Table 5.1 – Multi-criteria analysis of measure options for the Humber estuary. Monetised variables are for the +1.0 m SLR scenario; the outcome for the +0.5 m SLR scenario was identical. Cells shaded light red = better and cells shaded dark red = worse in all cases.

	Non-monetised variables						Monetised variables			Outcome	
Measure	**Flood volume**	**Stage change**	**Socio-economic impacts (population and businesses directly affected)**	**Ecological impacts – Inner estuary**	**Ecological impacts – Outer estuary**	**Total normalised score (sum of scores/ max score)**	**Residential property value and economic damages avoided (£ millions)**	**Construction cost (£ millions)**	**BCR**	**Weighted BCR**	**Rank**
6	1.00	0.69	0.42	0.70	0.20	0.90	6,068	126.0	48.17	53.39	1
8	0.58	1.00	0.26	0.70	0.80	1.00	10,687	429.5	24.88	24.88	3
13	0.08	0.88	0.14	0.80	0.80	0.81	12,420	940.5	13.21	16.31	4
14	0.22	0.64	1.00	0.70	0.20	0.83	8,423	347.2	24.26	29.32	2
16	0.00	0.00	0.11	0.60	0.70	0.42	12,621	4,250	2.97	7.03	5

5.1 Limitations and Future work

It is important to remember when interpreting results 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 its efficiency, 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). Nevertheless, this work has assumed a constant, global, roughness value throughout the domain. Therefore, the unusually low Manning's n roughness value of 0.015 s $m^{-1/3}$ (Skinner et al., 2015), although justified through validation, has also been applied to overbank areas. 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 overestimated overbank velocities and floodplain inundation extents.

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 and areas distal to the estuary
- Precise predictions of water levels
- Precise predictions of flood volumes
- Precise predictions of flow velocities

There is capability in the CAESAR-Lisflood 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, accounting for salinity, bed material grain size, suspended sediment concentration (and hence benthic light intensity) be undertaken on the ecological impacts of the shortlisted measures before construction works begin.

The economic analyses that have been undertaken are simplified in nature and have employed a range of assumptions. It is therefore suggested that the efficacy of these assumptions is explored further and addressed if necessary. In addition, the cost benefit analysis would benefit from more formal estimates of the likely construction and maintenance costs associated with the different measures and more detailed, complex economic modelling to understand the impact on port operations within the Humber. Finally, at present, the perspective of the different stakeholders as to the relative importance of the different factors included within the multi-criteria analysis has not been incorporated; a workshop or series of workshops could be organised to ascertain how the different factors should be weighted within the analysis.

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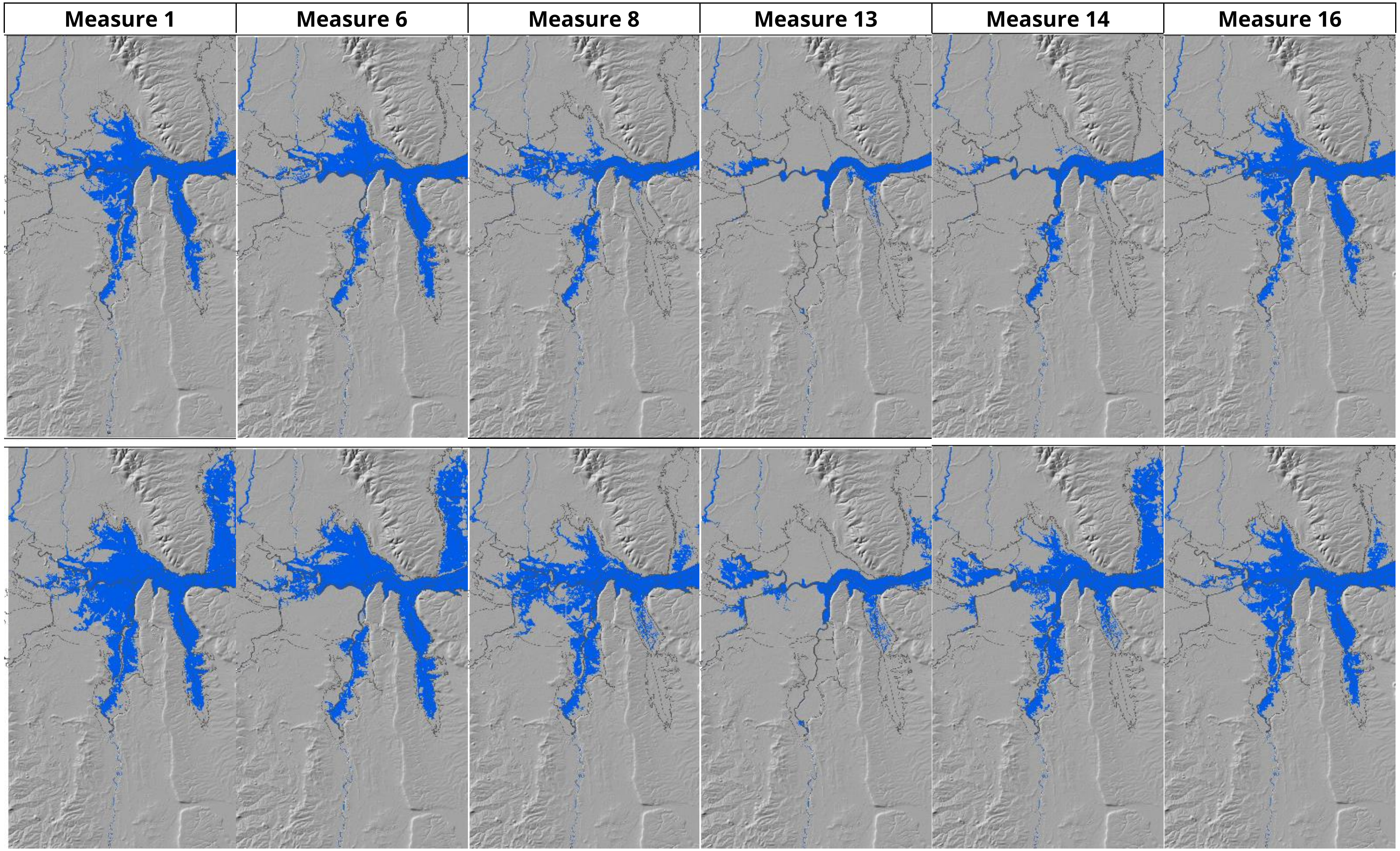
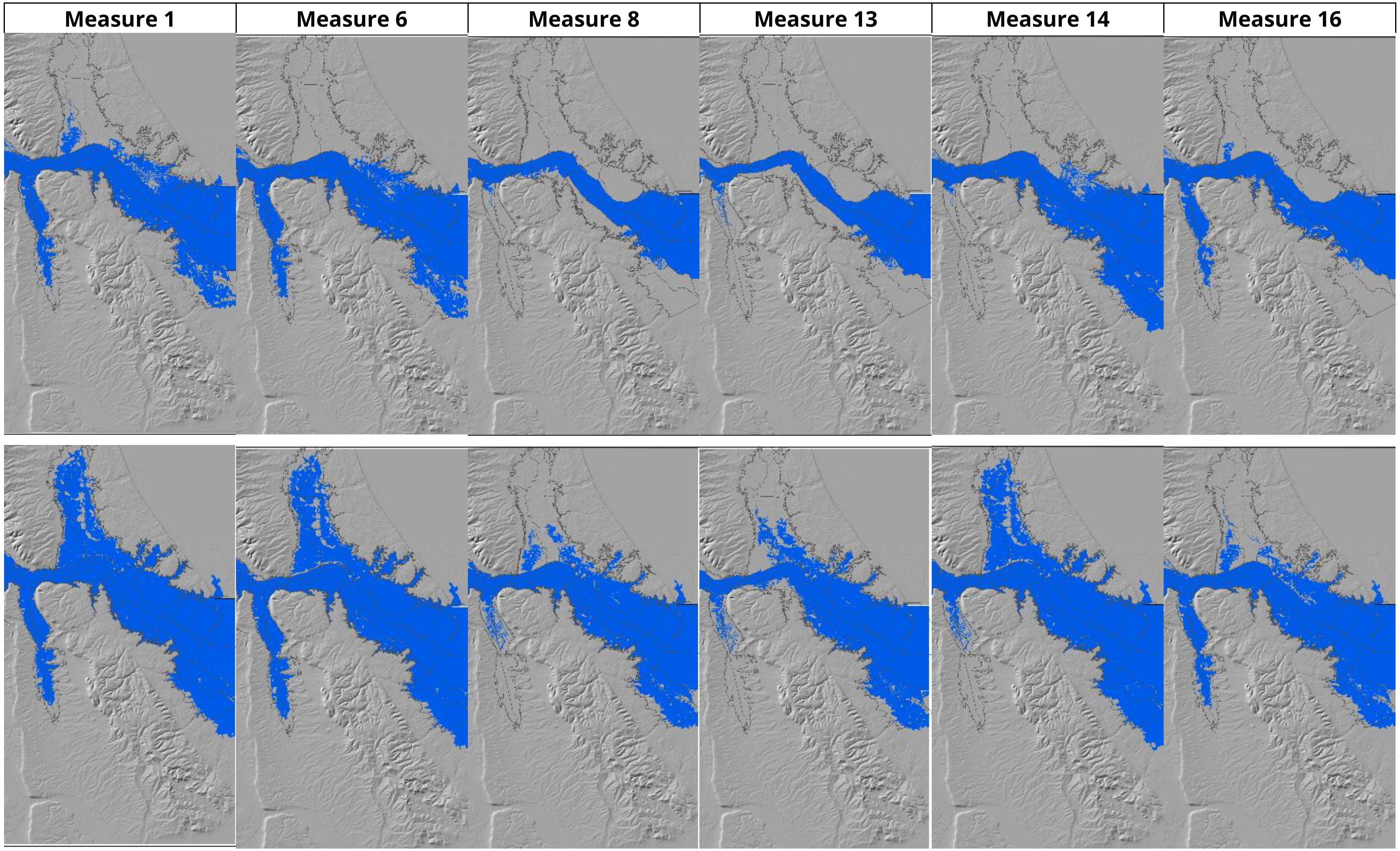
Appendix A. Flood outlines for a Sea Level Rise value of +2.0 m



Appendix A1 – Inner estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 2.0 m.



Appendix A2 – Outer estuary flood extents for Measures 1, 6, 8, 13, 14 and 16 for a storm surge with a 1-year return period (top row) and a storm surge with a 1000-year return period (bottom row) assuming a sea level rise (SLR) value of 2.0 m.