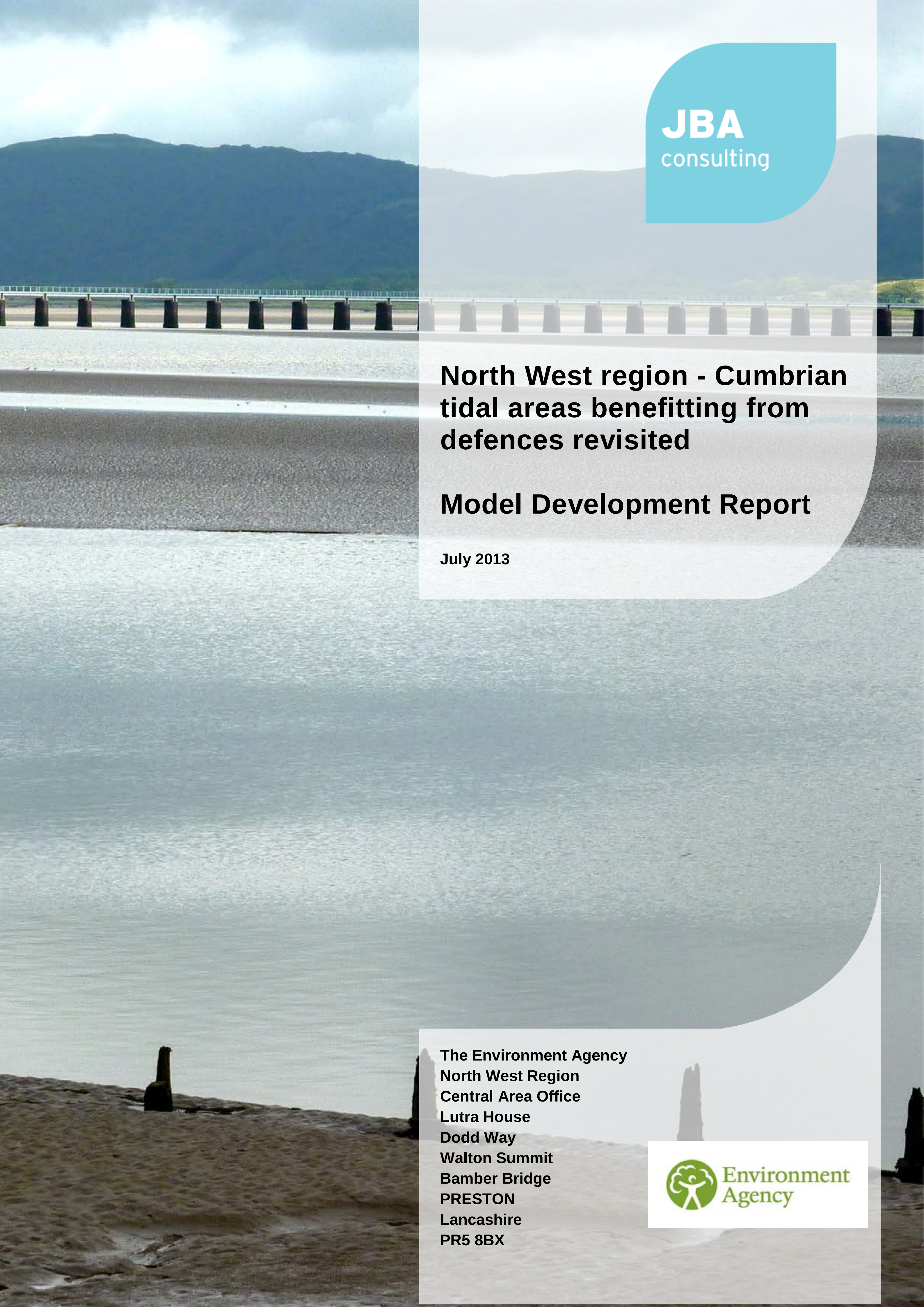

North West region - Cumbrian tidal areas benefitting from defences revisited

Model Development Report

July 2013

The Environment Agency
North West Region
Central Area Office
Lutra House
Dodd Way
Walton Summit
Bamber Bridge
PRESTON
Lancashire
PR5 8BX

Front cover photo showing the Leven estuary from the mouth of the Ulverston Canal.

JBA Project Manager

Matthew Hird
South Barn
Broughton Hall
SKIPTON
North Yorkshire
BD23 3AE

Revision History

Revision Ref / Date Issued	Amendments	Issued to
Draft / 03 July 2013		Dominic Nickson
Final Report		Laura Lamb

Contract

This report describes work commissioned by the Environment Agency North West region. The Environment Agency's representative for the contract was Dominic Nickson. The JBA Consulting Project Manager for the contract was Matthew Hird. Ian Gaskell carried out the work.

Prepared by ....Ian Gaskell BSc MSc

Analyst

Reviewed by ....Matthew Hird BSc, MCIWEM, C.WEM, CEnv, CSi

Chartered Senior Analyst

Purpose

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Acknowledgements

We would like to thank Dominic Nickson, Mark Franklin, David Snaith and Jeff Davidson of the Environment Agency for their input and the supply of project data. We would also like to thank Lee Whittle of Sefton Metropolitan Borough Council for the supply of additional defence data.

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Abbreviations

1D .... One dimensional
2D .... Two dimensional
3D .... Three dimensional
ABD................................ Areas Benefitting from Defences
CFB................................ Coastal Flood Boundary
CEH .... Centre for Ecology and Hydrology
CSV................................ Comma separated value
DEFRA .... Department for the Environment, Food and Rural Affairs
DEM .... Digital Elevation Model
DTM .... Digital terrain model
ESL .... Extreme sea level
GIS................................. Geographical information systems
HAT................................ Highest Astronomical Tide
HT .... Head versus Time
HX .... Head from an eXternal Source
JBA .... Jeremy Benn Associates
LIDAR .... Light Detection and Ranging
MoD .... Ministry of Defence
NFCDD .... National Flood and Coastal Defence Database
RAM .... Random Access Memory
RFRA .... Residual flood risk area
OS.................................. Ordnance Survey
SAR .... Synthetic aperture radar
SEPA .... Scottish Environment Protection Agency
SMP .... Shoreline Management Plan
SMS .... Surface-Water Modelling System
ST .... Flow versus Time
SWAN .... Simulating Waves Nearshore (a wave transformation model)
TIN .... Triangulated Irregular Network
TUFLOW .... A hydrodynamic flood inundation model
UK .... United Kingdom
UKCP09 .... UK Climate Change Impact Programme 09
UKHO .... United Kingdom Hydrographic Office
ZSHAPE......................... Model elevations modified by delineation of a polygon (within TUFLOW)
ZTIN .... Triangulated Irregular Network (within TUFLOW)

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1 Introduction

1.1 Project background

This project was commissioned by the Environment Agency's North West Region. The aim of the project was to improve understanding of the area's exposure to coastal flood risk by updating the Penrith Tidal Areas Benefiting from Defences Study. The previous modelling work was carried out by JBA Consulting and was completed in 2007. The project aims were to identify and map flood defences and areas that are likely to benefit from flood defences within the Cumbrian tidal zone.

In February 2011, the Environment Agency's Evidence Directorate published the Improved Coastal Flood Boundary Conditions for the UK mainland and islands (CFB). This was part of the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme, SC060064. The tidal Flood Zones that were produced for the Cumbrian coastline were therefore out-of-date. The new modelling covers the same area as the previous modelling but uses the latest Coastal Flood Boundary data and the latest modelling practices for wave transformation, wave overtopping and flood inundation. New coastal flood outlines and hazard maps for a range of event simulations will be produced. Additional runs were carried out for flood resilience work by removing infrastructure for undefended scenarios and lowering infrastructure by 30cm for defended scenarios.

The purpose of this Model Development Report was to outline the methods used to construct, calibrate and validate the numerical flood models built for the study. This report should be read in conjunction with the project's Summary Report, which provides a broader outline of the project objectives, methods and results.

1.2 Report structure

In addition to this Introductory Chapter, this report includes the following 14 chapters:

- **Chapter 2 (Model Overview)** summarises the scope of the modelling study, the modelling software used, and the general model schematisation adopted.
- **Chapter 3 (Model A)** outlines how model A was developed and constructed for the study. Model A covers Leighton Moss Nature Reserve in north Lancashire.
- **Chapter 4 (Model C)** outlines how model C was developed and constructed for the study. Model C covers the Lyth Valley up the Kent Channel from Arnside Moss to Holme Island.
- **Chapter 5 (Model E)** outlines how model E was developed and constructed for the study. Model E covers the Leven estuary from Bardsea to Humphrey Head and includes Ulverston.
- **Chapter 6 (Model H)** outlines how model H was developed and constructed for the study. Model H covers Barrow-In-Furness and the coastline from New Biggin in the east to Roanhead in the north-west.
- **Chapter 7 (Model K)** outlines how model K was developed and constructed for the study. Model K covers the Duddon Estuary and includes Haverigg and Millom.
- **Chapter 8 (Model M)** outlines how model M was developed and constructed for the study. Model M covers the River Annas from Annaside to Bootle.
- **Chapter 9 (Model O)** outlines how model O was developed and constructed for the study. Model O covers the River Esk estuary and includes Ravenglass.
- **Chapter 10 (Model Q)** outlines how model Q was developed and constructed for the study. Model Q covers Whitehaven.
- **Chapter 11 (Model S)** outlines how model S was developed and constructed for the study. Model S covers Workington area from the River Derwent mouth to Maryport in the north.
- **Chapter 12 (Model W)** outlines how model W was developed and constructed for the study. Model W covers the south west section of the Solway Firth estuary and includes Silloth and Skinburness.

- **Chapter 13 (Model Y)** outlines how model Y was developed and constructed for the study. Model Y covers the Solway Firth spanning from Rockcliffe Marsh in the west to Longtown in the east and includes Carlisle.
- **Chapter 14 (Fluvial Modelling)** summarises the previous fluvial modelling in the catchment and the updates carried out for the study area.
- **Chapter 15 (Projection Modelling)** summarises how projection modelling was carried out for the study area.

2 Model overview

2.1 Summary of model requirements

The overall aim of the project was to improve understanding of the area's exposure to coastal flood risk. To this end, the specific objectives of the study were:

- To produce two dimensional (2D) TUFLOW models to represent flood depths, velocities, and extents in the Cumbrian tidal estuaries.
- To carry out flood resilience simulations by removing infrastructure from undefended scenarios and by lowering infrastructure by 30cm for defended scenarios.
- To carry out projection modelling for the coastline in-between the 2D TUFLOW models.
- To estimate flood levels for the 1 in 30, 1 in 75, 1 in 100, 1 in 200 and 1 in 1,000-year flood events.
- To estimate climate change flood levels for the 1 in 200-year flood event (the impact of climate change will need to be accounted for tidal input/boundary condition over the 100-year time frame) for both with and without defences scenarios.
- To map extents of flooding for the modelled events and produce updated Flood Zones 2 and 3.
- To derive the areas benefiting from defences (ABD).

2.2 Modelling software

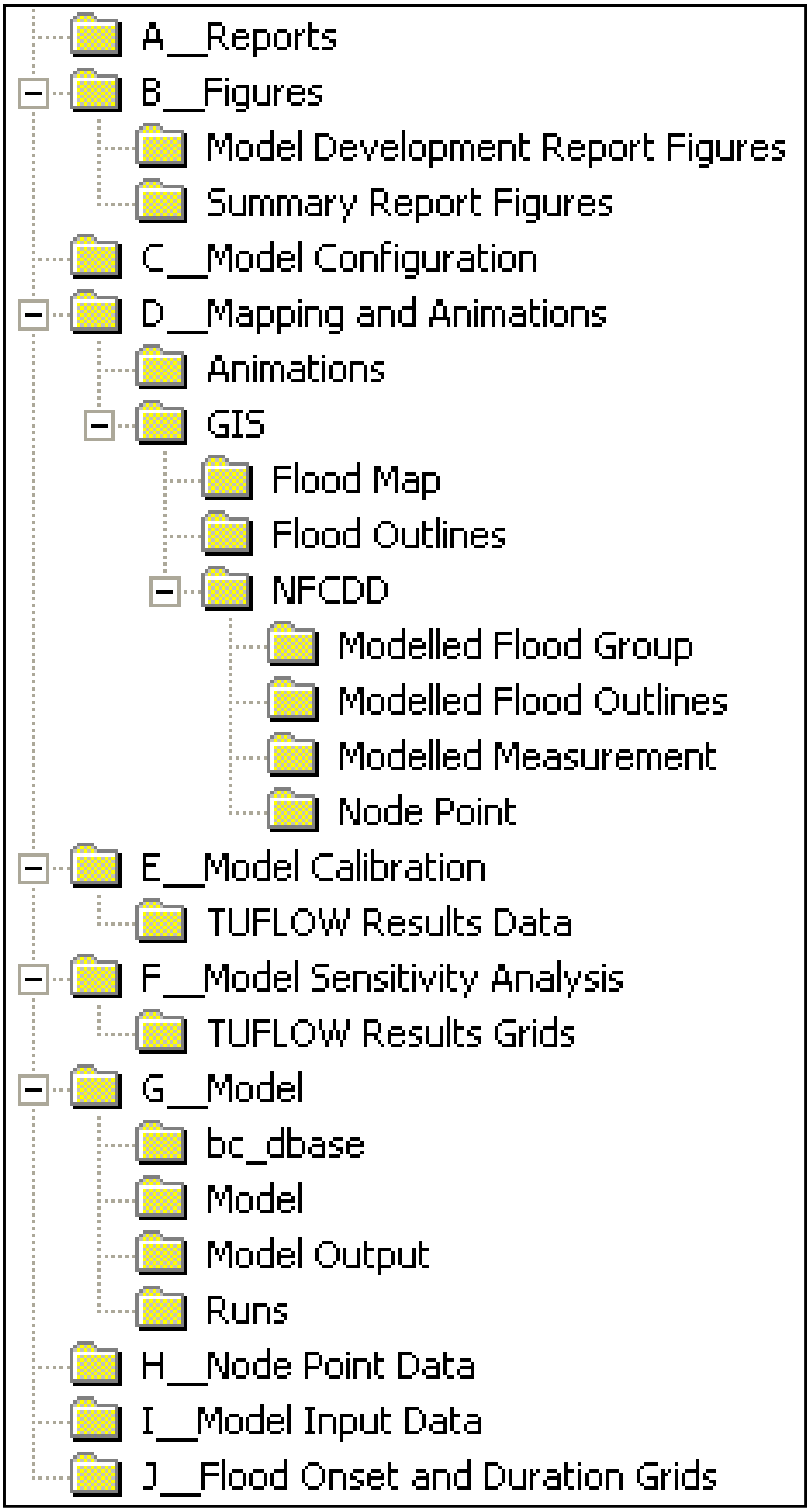
Modelling for this study was undertaken using a 2D hydrodynamic model constructed using TUFLOW. The latest 64bit version of TUFLOW (2012-05-AC-w64) was used to run the models.

2.3 Model folder structure

TUFLOW modelling requires the use of many different files.

Figure 2-1 shows the folder structure that was used to provide digital deliverables to the Environment Agency.

Figure 2-1: Digital deliverables folder structure



2.4 TUFLOW domain overview

The aim of the model schematisation was to maximise the spatial resolution of the models, whilst avoiding the limitations of TUFLOW. The number of grid cells that may be modelled in TUFLOW is limited by computer random access memory (RAM) and therefore any model has to be a compromise between coverage and resolution. The entire study area covers a large area; spanning from Gretna in the north to Leighton Moss in Silverdale to the south (Study location plan can be found in the associated Summary Report). In total the active TUFLOW model areas covers 733 km^2 and therefore the spatial resolution of modelling is limited by computer RAM and model run times.

The model domain grids were orientated to maximize the extent of the area that could be modelled and is approximately perpendicular to the flow direction at the estuary mouth. The grids are also approximately parallel to the coastline and tidal inflow boundaries to ensure model stability at the tidal boundary. The model architecture that was used is consistent for each river for each event and scenario.

The model resolution used varies between 5 and 10m depending on the size of the model domain (the largest requiring a larger 10m grid). At this resolution, many small features such as small embankments and channels are not fully represented. Indeed, the extensive networks of drainage ditches that characterise the study area are not fully represented within the model domains. The resolution chosen does however give an overall representation of the underlying land surface and produces models that can be easily rerun within reasonable time scales. Topographical features of particular importance were directly added to the TUFLOW digital elevation model (DEM).

2.5 Bed and floodplain resistance overview

Hydraulic roughness across the 2D model domains was set using material classifications derived from Ordnance Survey (OS) MasterMap data. An appropriate Manning's *n* value was applied for each of these classifications. The Manning's *n* that was applied was derived approximately from Hicks & Mason (1998)[1], and cross-checked with Chow (2009)[2]. These values are shown in Table 2-1. There is no definitive guidance on defining roughness values to 2D hydraulic models. Sensitivity testing was undertaken to assess the impact of varying Manning's *n*. The sensitivity testing undertaken and the results are described in detail for each TUFLOW model from chapter 3.

Table 2-1: Land use descriptions and applied manning's *n* Values

Land Use description	Manning's n
MASTERMAP - Buildings	0.300
MASTERMAP - Inland and coastal water	0.030
MASTERMAP - Natural surface and gardens	0.070
MASTERMAP - Manmade surface roads and paths	0.025
MASTERMAP - Trees, rough land and scrub	0.100
MASTERMAP - Marsh, reeds or saltmarsh	0.046
MASTERMAP - Structures	0.100

2.6 Modifications to the ground model

TUFLOW requires a topographic grid, or Digital Terrain Model (DTM), to represent the surface of the earth. The accuracy of the DTM is one of the most important controls on the quality of flood inundation modelling.

Ground level information was principally derived from Light detection and Ranging (LIDAR) data. Composite LIDAR grids at 2m resolution were used as the base topography for the modelling; this is a grid at a 2m resolution but made up of the latest 0.25, 1 and 2m LIDAR data.

[1] Hicks, D.M. & Mason, P.D., Roughness Characteristics of New Zealand Rivers, NIWA, Christchurch, (1998), 329pp.

[2] Chow, V.T. (1959). Open Channel Hydraulics. New York, NY: McGraw-Hill Book Co.

Grids of 2m LIDAR flown at low-tide were also provided by the Environment Agency. A combined 2m grid was created using the 2m composite LIDAR data for the land based topography and the low-tide LIDAR for the offshore areas where the bathymetry was non-existent or poor quality. This grid was created and then read into TUFLOW as a combined 2m grid which sits on top of the bathymetry.

Some areas of the study area are covered by high resolution 0.25m and 1m LIDAR data and where available these were used to extract detailed information to stamp into the grid, such as defences, as well as to extract defence profiles for wave overtopping calculations.

Any areas that were not covered by LIDAR data were filled with 5m resolution synthetic aperture radar (SAR) data.

LIDAR data were processed and modified for the purposes of the model. The following describes modifications that were made to the DTM for this study.

Interpolation of null data

Areas of null data (i.e. holes) in the LIDAR data were considered. Holes in the 2m LIDAR (base DTM) were filled using interpolation methods to ensure a smoother topography and prevent model instabilities. This interpolation involved point inspection of ground levels around holes in the LIDAR and the construction of a Triangulated Irregular Network (TIN) using the resultant point elevation dataset. The resulting TIN was then merged with the LIDAR to fill the holes.

Identification of blocked flow paths

The DTM for each model was also reviewed to identify blocked flow paths. The LIDAR data used to create the model grid were in “filtered” format and therefore excluded buildings and vegetation that could block potential flow paths. However, other features such as railway and road bridges also block flow paths in the TUFLOW model and must be removed. Culverts must also be ‘opened’ in the DTM so that flood water can realistically pass through them. These structures were identified using OS mapping and National Flood and Coastal Defence Database (NFCDD) structures (supplied by the Environment Agency), the LIDAR DTM, site visits and through an iterative process of inspecting draft model results. For each structure, a line with a point at each end was digitised. The points were assigned elevations based on the grid cell they intercept. In TUFLOW the line was used to interpolate between these points and lower the elevation at the location of the structure during the model run; these changes were not made to the DTM.

The initial identification of these features in the DTM was based on their size. In particular, only flow paths equal to or greater than the model domain grid size were reviewed since no flow path smaller than the model grid size can be accurately modelled. Further blocked flow paths were identified from model outputs during the modelling process.

Representation of small channels

The extensive networks of drains that characterise the study area are not fully represented in the model grids. These drains are in most cases only a few metres wide and therefore it is not possible to fully model them in a 5 or 10m grid. Ground elevations of these drains will, however, inevitably be present in the model where model grid points fall across them. This representation will not be continuous and therefore will not form a flow path but will contribute to flood storage.

Representation of railway and road embankment levels

It is important to emphasise that whilst the DTM used for modelling Flood Zones 2 and 3 did not include any formal flood defences, it did include structures such as railway and road embankments, which are considered to be part of the “permanent” terrain. This is in line with the ABD guidelines.

Model simulations for flood resilience works were also carried out; railway embankments were lowered by 30cm to account for the ballast in the defended scenario and railway and road embankments were removed entirely from the undefended scenario.

Removal and representation of flood defences

To ensure that the newly derived Flood Zones 2 and 3 produced for this study are a true reflection of the risk of flooding in the absence of flood defences (i.e. “No Defences”), the footprint of all formal flood defences in the study area were identified. Formal coastal flood defences are mainly located along the coastline and along the river banks.

The footprints of the defences were assigned a ground level interpolated from the defence toe levels on either side. The interpolation method was carried out in TUFLOW which creates a series of TIN grids that are then read on top of the base topography grid and act to remove the defences from the model grid.

For the "With Defences" flood modelling, where overtopping of flood defences is simulated, the formal defence datasets collated for the study were then read into the "With Defences" models as 3D breaklines. This dataset effectively raised the DTM levels in the vicinity of the defences to the appropriate crest levels.

Bathymetry

The tidal boundaries for all of the models are located offshore so bathymetry was required. It was necessary to process bathymetry data where offshore and deep water areas were not covered by LIDAR. A bathymetric survey of the coastline was provided by SeaZone Solutions Limited in raster grid format. In addition to this a point cloud of elevations were supplied for the Solway estuary from a previous MIKE-21 model which was converted into a raster grid. The Environment Agency provided an additional LIDAR dataset flown at low-tide. To make use of the most up-to-date and accurate bathymetry data, a composite grid comprising all of these datasets was developed to provide the best representation of the offshore area.

2.7 Representation of buildings

The representation of buildings within the 2D hydraulic model has important implications for determining the flood outline and local flood depths, velocities and flood hazard ratings. There are a number of modelling options available within TUFLOW for modelling buildings; these are discussed in detail in Syme (2008)[3]. The following method was used in this study:

- Application of a relatively high Manning's *n* value to represent individual buildings and a lower Manning's *n* to represent the surrounding roads/gardens. In this scenario, flow may pass across the building but floodwaters are slowed down by the increased surface resistance.

2.8 Initial water level

Initial water levels were set in the 2D TUFLOW model domains. The initial water levels set in the 2D domain apply to the land. They were set to make sure that low lying areas onshore are dry at the start of the model simulation.

Some of the models include 1D elements. This allows for an interpolating offshore water level boundary. In these cases initial water levels were set in the 1D domain and apply to the 1D nodes where the tidal still water levels are applied. 1D initial water levels were used to prevent an initial rushing of water into the models at the tidal boundary.

2.9 Hydraulic structures

In-channel structures such as bridges were not included in the modelling. It is beyond the scope of this study to accurately survey and model these structures. Therefore, the flow that occurs within the model is largely assumed to be open channel. This is a reasonable assumption in coastal modelling, in which most channels are relatively wide and deep.

2.10 Model boundaries

2.10.1 Tidal boundary

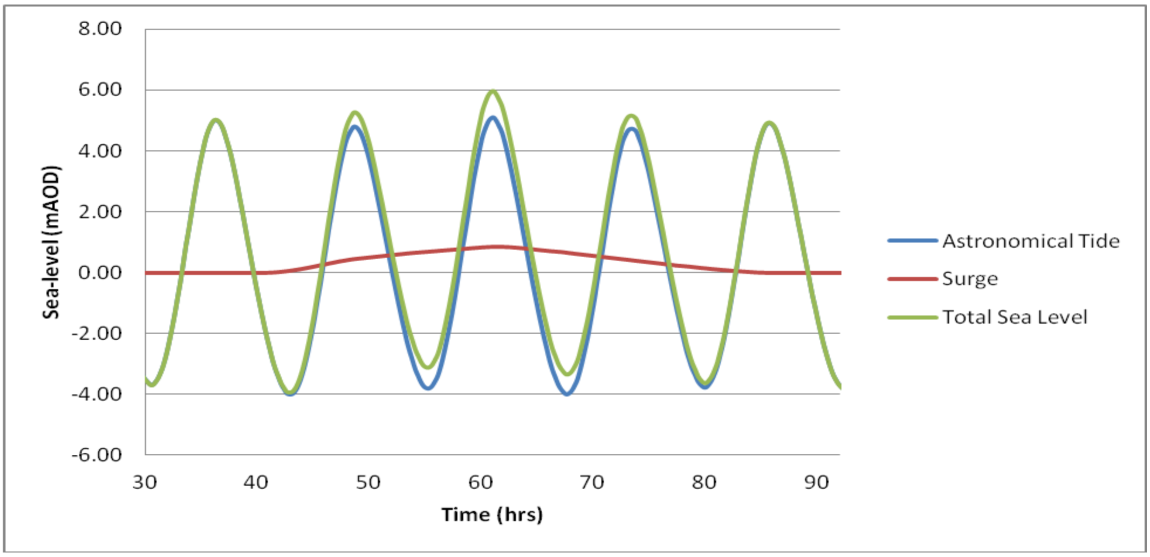
The tidal boundaries vary between the models in the study area. Most have a tidal boundary represented by sea-level time series data calculated at points along the coastline and linked using TUFLOW to form a continuous inflow boundary. The tidal Head versus Time (HT) data are applied at 1D network points and TUFLOW interpolates tidal levels along the Head from eXternal source (HX) line between points. A few of the smaller models have a simpler HT boundary where an interpolating boundary was not needed and this is represented purely in the 2D part of

[3] Syme W. J. (2008). Flooding in Urban Areas – 2D Modelling Approaches for Buildings and Fences. Engineers Australia, 9th National Conference on Hydraulics in Water Engineering.

the model. The extreme still water sea-levels were taken from the latest coastal flood boundary guidance for the UK[4].

An example of the sea-level time series data input based on a highest astronomical tide and surge at Workington and scaled to a 200 year total sea level is presented Figure 2-2.

Figure 2-2: Design tidal-graph for a 200-year event (Present Day) based on Workington tide data



2.10.2 Fluvial inflow boundary

Fluvial inflows were not included in the TUFLOW models. Fluvial modelling was carried out separately using an in-house 2D modelling package called JFLOW. This will be discussed further in Chapter 14 Fluvial Modelling.

2.10.3 Wave overtopping boundary

Wave overtopping discharges were input into the TUFLOW models using Flow versus Time (ST) lines. The discharge applied to each cell is based on the discharge per metre of defence, as given in the inflow comma separate value (csv) file, multiplied by the cell size of the cells crossed by the ST line. The ST lines were placed approximately one cell behind coastal defences such that the line of cells immediately behind the cells attributed with defence levels had a wave discharge (m^3/s/m) applied to them. Further information on how the overtopping discharges were derived is given in the Summary Report.

2.11 Stability improvements

Stability overview

The stability of a TUFLOW model is in part gauged by the number of “Negative Depth” warning messages that occur during the simulation. Large numbers of these messages in one location would suggest instability in the model.

The topography of the model domains is relatively “bumpy” since the cell size used (5-10m) is different to the cell size of the LIDAR from which the elevation data were derived. This means that low elevations were included from small channels or high elevations from small embankments, but neither of these features are fully represented. Instabilities are more likely to occur at these isolated low and high elevations.

[4] Defra. SEPA. The Scottish Goverment. Environment Agency (2011). Coastal flood boundary conditions for UK mainland and islands. Project: SC060064/TR2: Design sea levels.

Stability patches

To rectify stability issues where there were clusters of error messages, stability patches have been applied. Stability patches take the form of polygons, using a TIN of surrounding ground levels to smooth out the problem area. Alternatively, a higher roughness patch may be applied to the problem area to help remove the instability and allow flood water to propagate.

Model timestep

The model timestep provides another indication of whether a model has any major instability. The recommended range is between 0.25 to 0.50 times the model cell size. Anything lower than this would suggest there could be serious model instabilities. All the TUFLOW models constructed for this study have a timestep of either 0.25 or 0.50 the model cell size and are therefore within the recommended range.

Additional stability details will be discussed for each model in the following chapters.

3 Model A - Leighton Moss

3.1 Design run information

Table A 1 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 2, Appendix A.

3.2 TUFLOW domain

The model A study area covers Leighton Moss Nature Reserve in north Lancashire (Figure 3-1). The model domain spans the coast from Honeysuckle Hill in the north to Scout Cragg in the south and stretches as far inland as Yealand Hall allotment. The area is largely covered by marsh land, open pasture and woodland and there are no major urban populations.

The adopted model grid size was 5m and the active area of the model was 5km^2.

3.3 Model boundary

Tidal boundary

The tidal boundary runs parallel to the coastline and ties into high ground at Honeysuckle Hill to the north and Scout Scar to the south (Figure 3-1). The tidal boundary applies two HT tide curves at 1D network points at either end of the model boundary line and TUFLOW interpolates tidal levels along the HX line between the two points. The coastal flood boundary data used can be seen in Table 3-1.

Table 3-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Morecambe	Heysham	1266	BNDRY_1
Morecambe	Heysham	1268	BNDRY_2

Wave overtopping boundary

Three wave overtopping inflow lines were read into the model (Figure 3-1). Wave overtopping was calculated for the grassed embankment across Quicksand Pools up to the point at which it becomes sheltered as it turns back on itself to head northwards, as well as the railway line embankment to the south east of this.

3.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 3-1). The formal defences consist of a raised man-made grassed earth embankment (Figure 3-2) that runs across Quicksand Pools. The infrastructure is the railway line that runs from Carnforth to Arnside which sits behind the grassed earth embankment and acts to limit the spread of water. The defences and infrastructure combine to stretch across the valley from Ings Point in the east to Dyke House in the west. The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

There is a sluice gate underneath a small road bridge which crosses Quicksand Pools (Figure 3-2). In the defended scenario this is assumed to be closed and was stamped into the model as a solid structure matching the level of the grassed earth embankment with which it joins. In the undefended scenario the sluice gate was removed allowing water to pass freely through the bridge.

3.5 Stability improvements

The model timestep used was half the model grid size of 5m. In order to stabilise the climate change scenarios the model timestep was dropped to a quarter of the model grid size. This is still within the recommended range of between 0.25 to 0.50 times the model cell size.

No other stability improvements were made to the model topography.

3.6 Model stability summary

Messages

"Negative Depth" warning messages reported during the simulation range from 0 to 1 for all simulations apart from the 1,000-year undefended no infrastructure scenario which has 26 messages. The 26 messages occur in roughly the same area but they do not occur on the peak tide and there are no major water level spikes at this time in the model so it is not considered to affect the model results.

The few messages within this model are a sign that the model is stable.

Checks

There are two check messages during each simulation. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

There is some small oscillation in the change in volume during the model simulations but it generally fits the expected volume flux of the model. A noticeable jump in volume in the model occurs once water levels become higher than the marsh land as water can then pour into the model across the whole boundary rather than just the deepest part of the channel.

Cumulative mass balance error

The cumulative mass error for the first few hours of the model run is very high. This is as a result of the model grid (which is largely marsh land) being higher than the lowest water level during low tide. Once water starts to flow into the model at roughly 59 hours the cumulative mass balance drops swiftly to almost zero for the rest of the model simulation. This error is well within the recommended +/-1.00% acceptable error stated in the TUFLOW guidelines.

3.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the mean water levels are within +/-3cm of the base Manning's *n* run. When roughness is increased by 20% there is a difference in the maximum and minimum water level change of 30cm and 39cm respectively but these occur in isolated areas and the affect is not widespread.

Figure 3-3 shows the difference in flood extents between the different roughness scenarios. In general flood extents are very similar with the most noticeable difference occurring in the northern part of the nature reserve towards Brow Foot Farm. This is shown by the zoomed in section on Figure 3-3. It shows that the lowered Manning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 3-1: Model A study area and defences

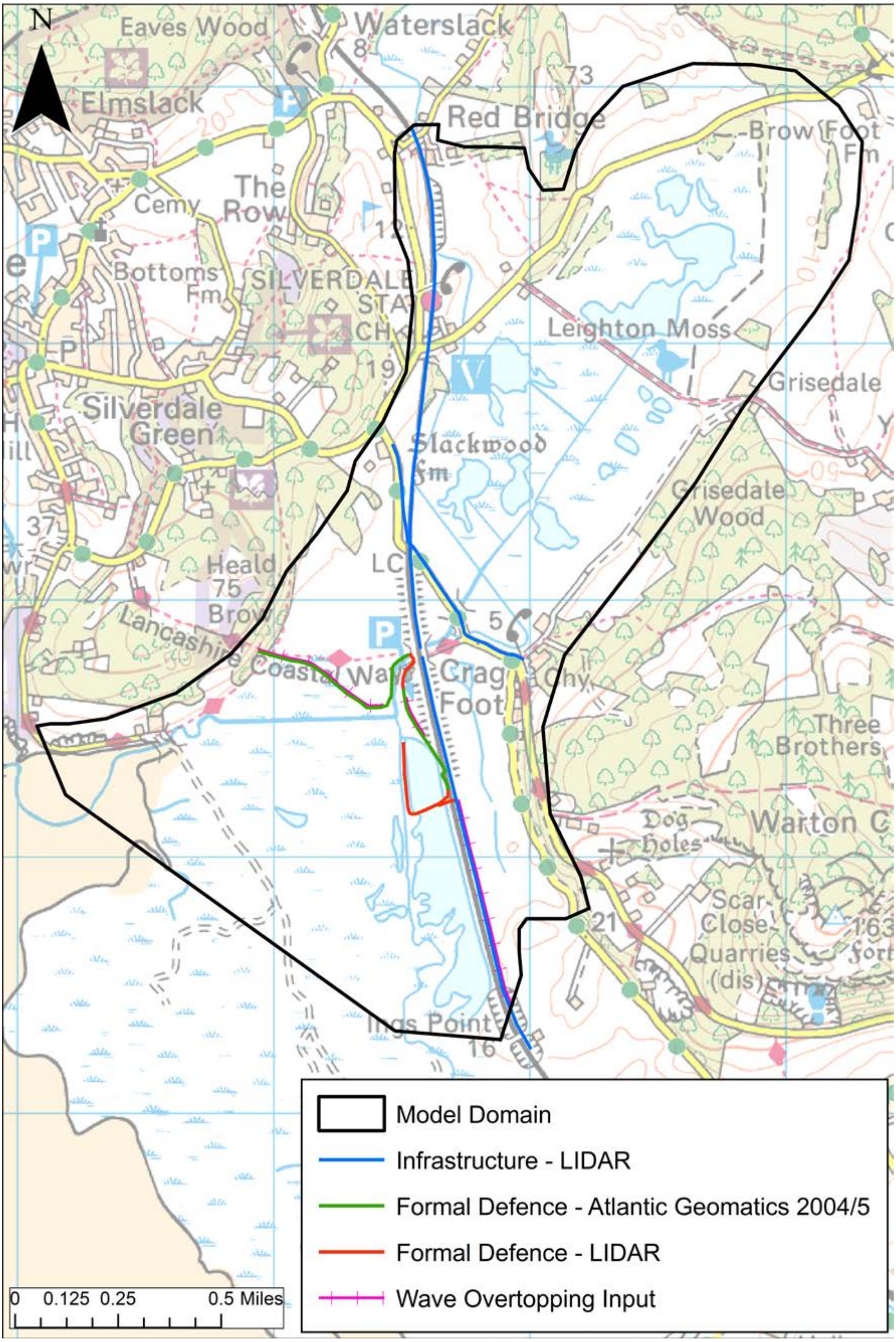
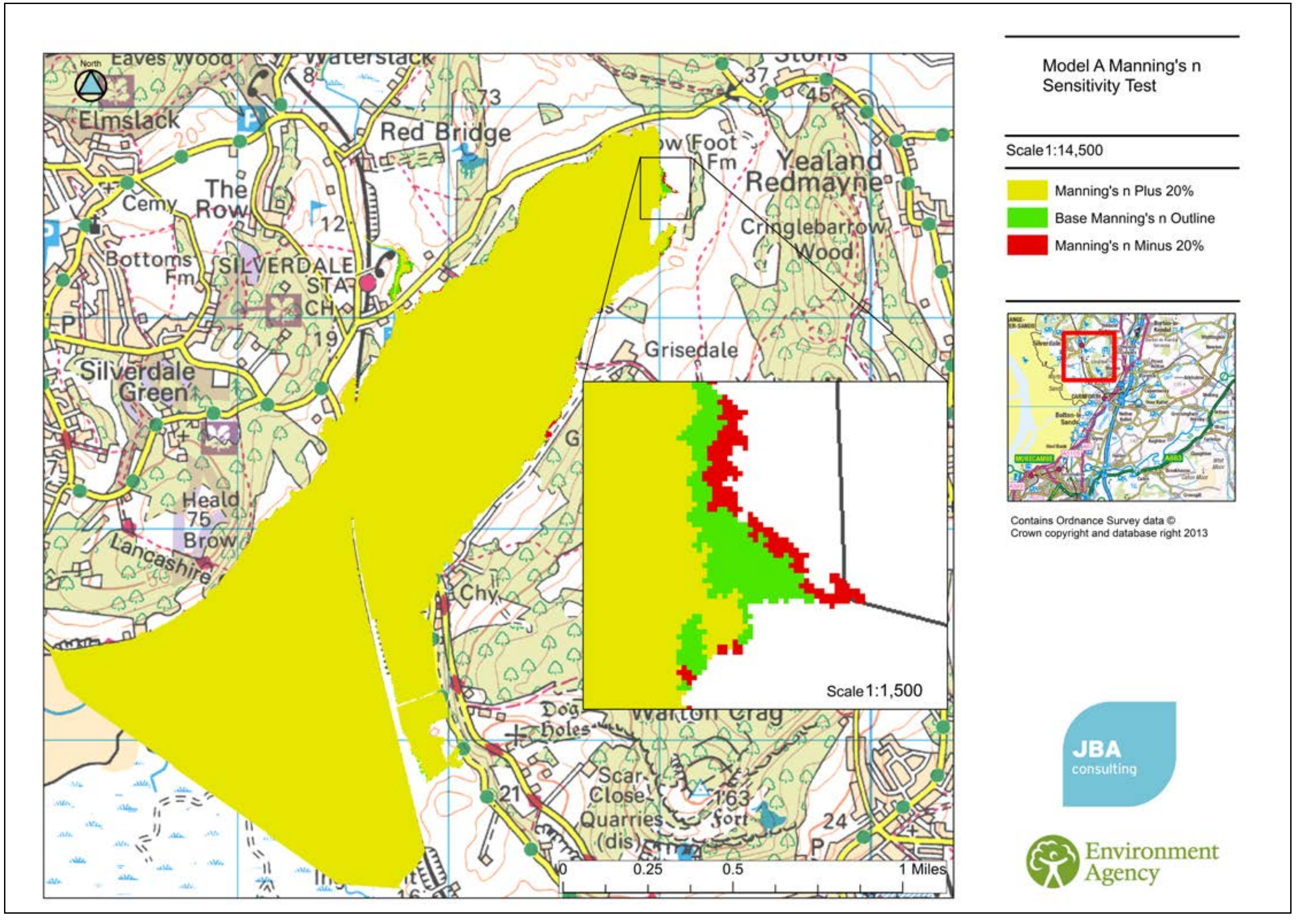


Figure 3-2: Earth embankment at Quicksands Pools (top). Tidal flap at Quicksands Pool Drain (bottom)

Figure 3-3: Model A Manning's *n* sensitivity test.



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4 Model C - Kent Estuary

4.1 Design run information

Table A 3 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 4, Appendix A.

4.2 TUFLOW domain

The model C study extent covers the Lyth Valley up the Kent Channel from Arnside Moss to Holme Island. The area is largely covered by marsh land, open pasture and woodland. It covers several communities including Arnside, Lindale, Levens, Milnthorpe, and Storth.

The adopted model grid size was 5m and the active area of the model was 94km^2.

4.3 Model boundary

Tidal boundary

The tidal boundary spans the Kent estuary tying into high ground at Grange-Over-Sands to the west and Cow Close Wood (south of Silverdale) to the east (Figure 4-1). The tidal boundary applies two HT tide curves at 1D network points at either end of the model boundary line and TUFLOW interpolates tidal levels along the HX line between the two points. The coastal flood boundary data used can be seen in Table 4-1.

Table 4-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Morecambe	Heysham	1270	BNDRY_1
Morecambe	Heysham	1272	BNDRY_2

Wave overtopping boundary

No wave overtopping was included in Model C. Analysis was undertaken using SWAN nearshore wave heights but no wave overtopping was calculated.

4.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 4-1). The formal defences consist of raised earth embankments that run alongside the Kent Channel and alongside the River Winster towards Lindale. At Arnside there is a flood wall with five pedestrian access tidal gates and one vehicle access tidal gate (Figure 4-2 - top) which runs from the railway line to the north of Arnside in a southerly direction along the B5282. The infrastructure in the model is the A590 road and the railway line that runs from Arnside to Grange-Over-Sands (Figure 4-2 - bottom) and acts to limit the spread of water along Meathop Road to the Kent Viaduct.

The infrastructure was kept in the model for both the defended and undefended simulations.

Sluice gates

There are several tidal gates that were included in the defended scenarios for Model C. These include:

- The Promenade at Arnside (345659, 478835)
- Station Road east of Arnside (346110, 478892)
- Railway line at Grange-Over-Sands (340864, 477871)

- Ulpha pump station at Meathorp Marsh (345587, 480720)
- Heversham main drain, north of Milnthorpe (348869, 481485)
- Sampool pump station (348761, 484938)
- A590 Bridge (347168, 485303)
- Gilpin Farm (346840, 485577).

In the undefended scenario the tidal gates were removed allowing water to pass freely through the bridge.

4.5 Stability improvements

The model timestep used was half the model grid size of 5m. This is well within the recommended range of between 0.25 and 0.50 times the model cell size.

Two stability patches were used within the model. A TIN created within TUFLOW (ZTIN) was used to smooth out unrealistic bathymetry elevations in order to ensure smooth propagation of water up the estuary. Nine TINs were used in this patch, the largest of which was used to remove the Kent Viaduct from the channel.

In addition a further stability patch was used to roughen the Manning's *n* values of an area of higher ground next to the Winster Channel. This was used to slow flood waters as it ran across the floodplain.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

4.6 Model stability summary

Messages

"Negative Depth" warning messages reported during the simulation range from zero to two for the majority of the model simulations. The 1,000-year undefended scenario has six messages and the 200-year climate change undefended scenario has 133 messages. This number of messages is large and occurs in roughly the same area as flow passes through a narrow culvert under the A590 road bridge. The messages do not occur at the peak and there is no obvious issue when inspecting the flow in this location in Surface-Water Modelling System (SMS) and so this is acceptable.

The few messages within the lower event model scenarios are a sign that the model is stable. There are large numbers of messages in the 200 and 1,000-year scenarios but they do not indicate a major instability.

Checks

There are two check messages during each simulation. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

There are some small oscillations in the change in volume output. These are reflected in the spikes shown in the volume entering and leaving the model but it generally fits the expected volume flux of the model.

Cumulative mass balance error

The cumulative mass error for the first few hours of the model run reaches 1.00%. Once the model stabilises the cumulative mass balance is generally around -0.20% which is well within the recommended +/-1% error stated as being acceptable in the TUFLOW guidelines.

4.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, The maximum water levels are within 2cm of the base Manning's *n* run while mean water levels are within 5cm.

Figure 4-3 shows the difference in flood extents between the different roughness runs. In general flood extents are similar but there are some considerable differences in particular in the upstream end of the catchment in the Lyth Valley where the flood extent is larger when topography roughness is reduced by 20%. There is also a larger flood extent during the lowered roughness at Lindale and Silverdale Moss.

In general the lowered Manning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 4-1: Model C study area and defences

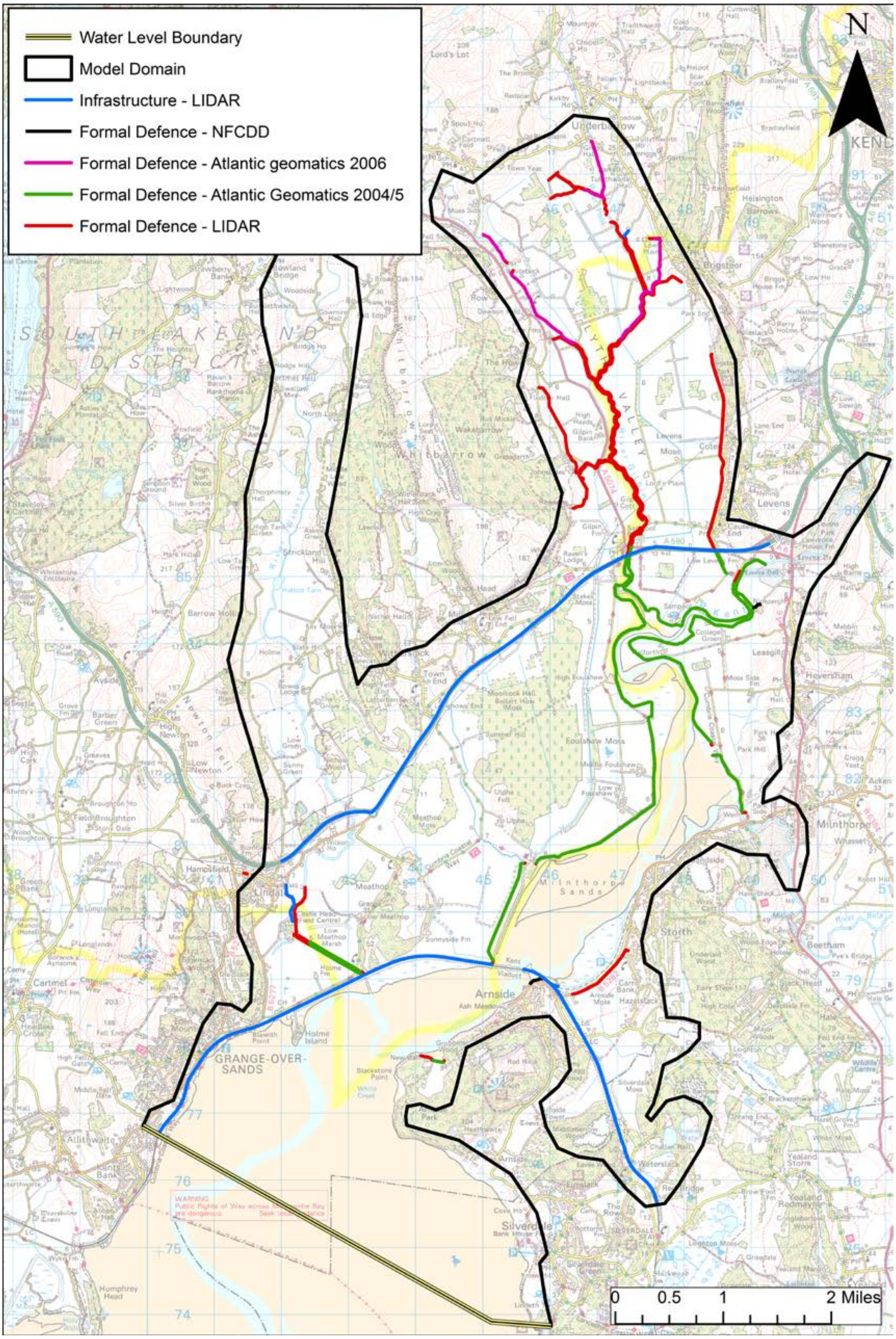

Figure 4-2: Flood wall and pedestrian access flood gate at Arnside (top). Railway embankment along Meathop Road (bottom)

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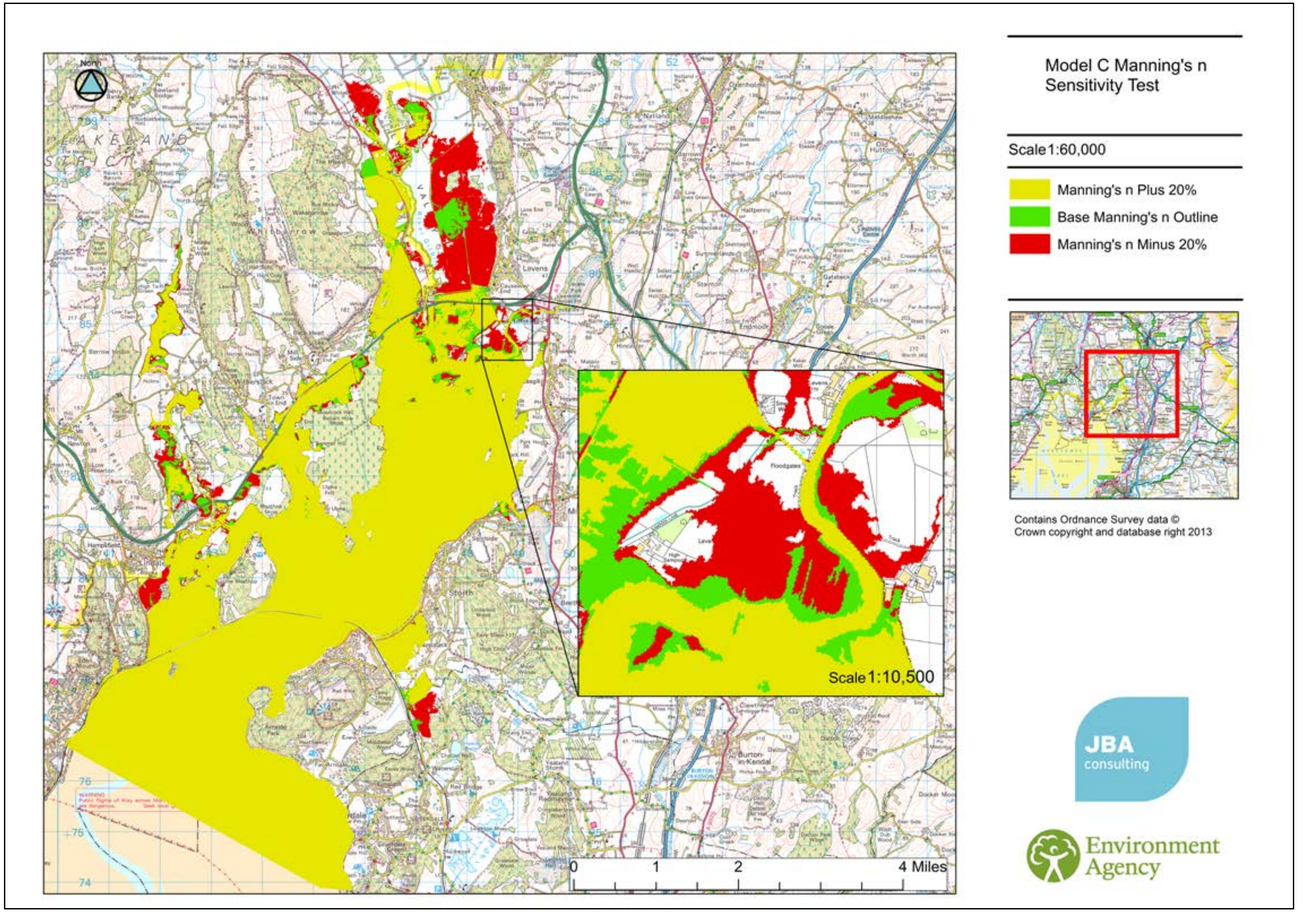
Figure 4-3: Model C Manning's *n* sensitivity test



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5 Model E - Leven Estuary

5.1 Design run information

Table A 5 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies. Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 6, Appendix A.

5.2 TUFLOW domain

The model E study extent covers the Leven estuary from Bardsea to Humphrey Head. The area is largely covered by marsh land, open pasture and woodland. It covers several communities including Ulverston, Flookburgh, Greenodd, and Haverthwaite.

The adopted model grid size was 5m and the active area of the model was 110km^2.

5.3 Model boundary

Tidal boundary

The tidal boundary spans the Leven estuary tying into high ground at Aldingham to the west and Humphrey Head to the east (Figure 5-1). The tidal boundary applies six HT tide curves at 1D network points at either end of the model boundary line: TUFLOW interpolates tidal levels along the HX line between the points. The coastal flood boundary data used can be seen in Table 5-1. The sixth point is a copy of BNDRY_5.

Table 5-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Morecambe	Heysham	1274	BNDRY_1
Morecambe	Heysham	1276	BNDRY_2
Morecambe	Heysham	1278	BNDRY_3
Morecambe	Heysham	1284	BNDRY_4
Morecambe	Heysham	1288	BNDRY_5

Wave overtopping boundary

Five wave overtopping inflow lines were read into the model (Figure 5-1). Wave overtopping was calculated for the embankments around the holiday home south of Flookburgh and for the raised flood walls at Hammerside Hill.

5.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 5-1). The formal defences consist of:

- flood walls at Hammerside Hill
- a short recurve wall in front of the houses to the north of Hammerside Hill (Figure 5-2 - top and middle)
- earth embankments to the south of Greenodd and along the Leven channel
- small inland flood walls around Ulverston
- raised embankments running westwards from Humphrey Head Wood to Cowp Scar and then up to Sandgate Farm in the south east of the study area (Figure 5-2- bottom).

The infrastructure included in the model consists of railway lines and roads and includes the railway line running from Flookburgh to Ulverston, a stretch of dismantled railway line to the south of Hammerside Hill that is similar to a raised earth embankment with vegetation on the top, and the A590 road which runs across the catchment.

The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

There are several tidal gates that were included in the defended scenarios for Model E. These include:

- Strand Bridge (335271, 475387)
- Dragley Beck/Estuary Confluence (330686, 477226)
- Mearness Point Farm (332262, 481868)
- Footbridge north of Daffy Wood (331797, 483463).

In the undefended scenario the tidal gates were removed allowing water to pass freely through the bridge.

5.5 Stability improvements

The model timestep used was half the model grid size of 5m. This is well within the recommended range of between 0.25 to 0.50 times the model cell size.

Two stability patches were used within the model. The first was a ZTIN which was used to smooth out unrealistic bathymetry elevations within the Level estuary channel in order to ensure smooth propagation of water up the estuary. Four TINs were used in this patch.

A second stability patch was used to roughen the Manning's *n* of two areas within the model to slow the propagation of flood waters at these locations and improve the model stability. The first area was the sluice gate at Dragley Beck confluence (330680, 477226). This was used to remove instabilities as water passes was constricted through a narrow channel when the sluice gate has been removed for the undefended scenario, or as water flows over the top of the sluice level here for the defended scenario. The second area was at a DTM edit, representing an underpass, underneath the dismantled railway to the east of Flookburgh (337840, 475470). The patch was used to slow water that was being constricted through the underpass.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

5.6 Model stability summary

Messages

"Negative Depth" warning messages reported during the simulation range from zero to six for the majority of the model simulations. The 200-year climate change undefended and defended scenarios have 11 and 34 messages respectively. The bulk of these messages occur either at the start of the model as it stabilises and settles down or on the receding tide rather than the peak and so is acceptable.

The few messages within this model are a sign that the model is stable.

Checks

There are six check messages during each simulation. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

The change in volume throughout the model simulations is sensible and smooth and fits the expected volume flux of the model.

Cumulative mass balance error

The cumulative mass error for the first few hours of the model run reaches a peak error of -0.5% in the 200-year climate change scenarios. Once the model stabilises the cumulative mass balance is generally less than -0.1% which is well within the recommended +/-1% error stated as being acceptable in the TUFLOW guidelines.

5.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the maximum water levels are within 2cm of the base manning's run while mean water levels are within 5cm.

Figure 5-3 shows the difference in flood extents between the different roughness runs. In general flood extents are very similar with the most noticeable difference occurring near Lower Street Bridge to the north of Bromeswell where the lowered Manning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 5-1: Model E study area and defences

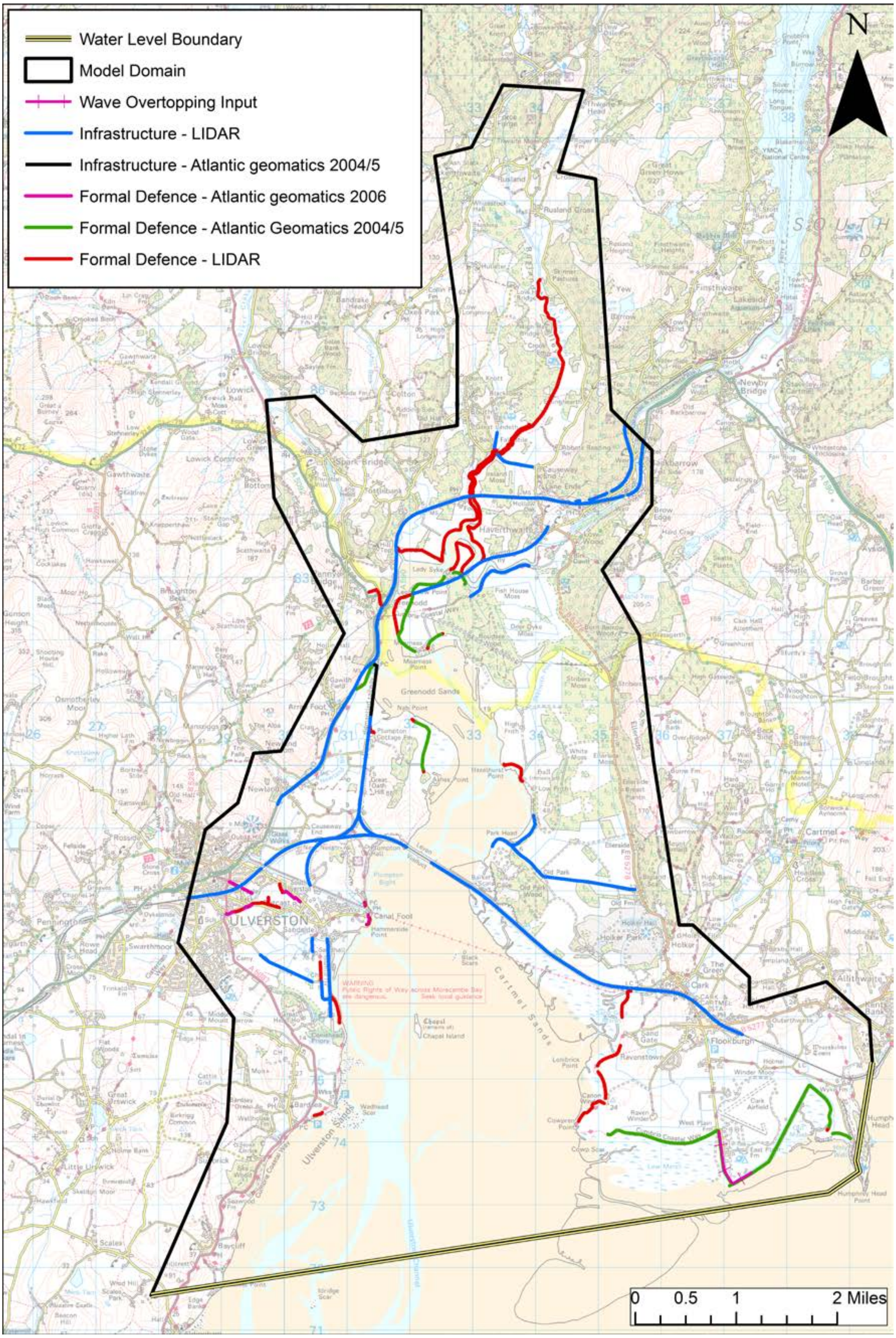

Figure 5-2: Masonry wall at Hammerside Hill (top). Short recurve wall to the north of Hammerside Hill (middle). Earth embankments south of Flookburgh (bottom).

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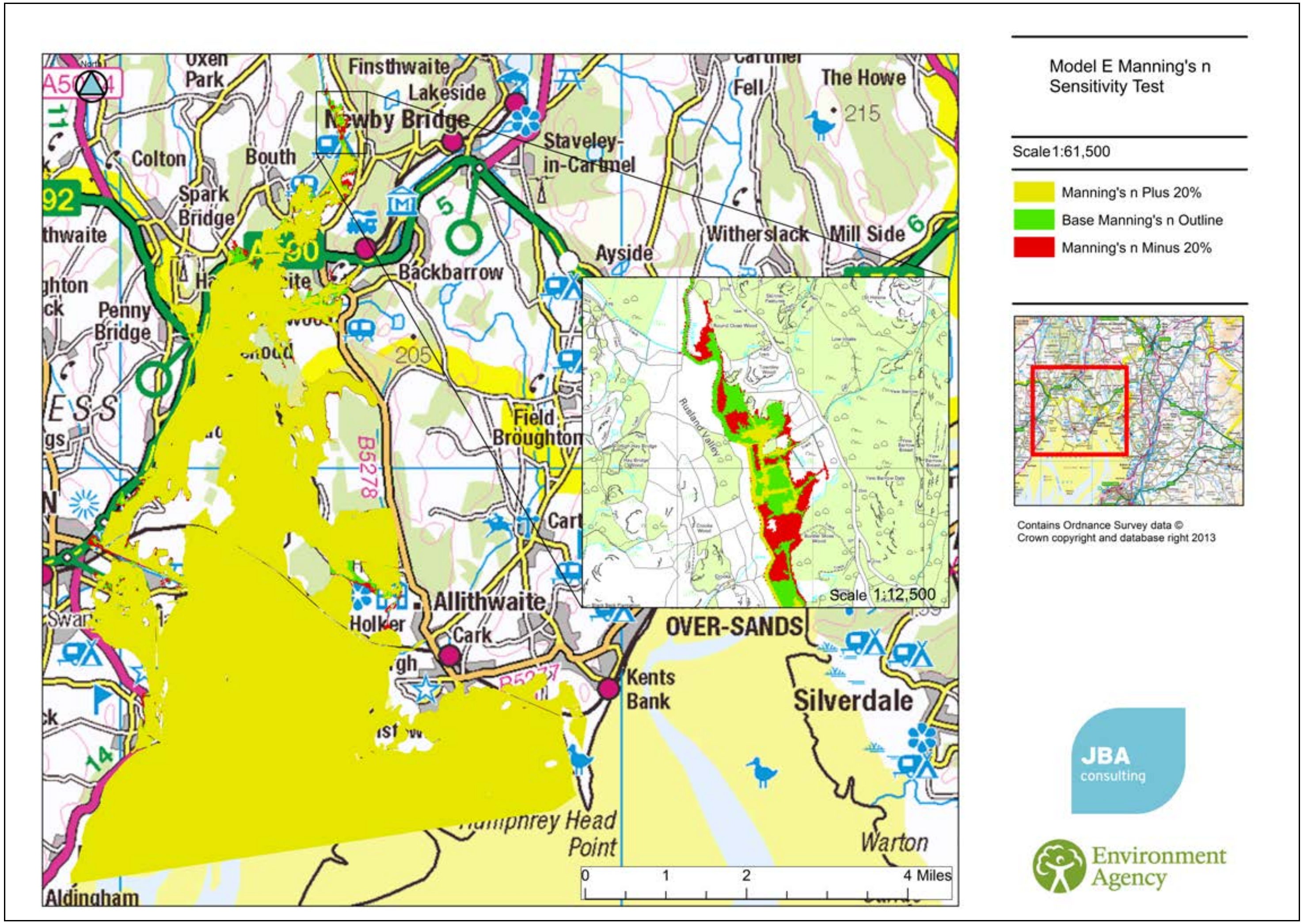
Figure 5-3: Model E sensitivity testing



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6 Model H - Barrow-in-Furness

6.1 Design run information

Table A 7 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 8, Appendix A.

6.2 TUFLOW domain

The model H study extent covers the coastline from New Biggin in the east to Roanhead in the north-west. The area is largely covered by open pasture. It covers the key urban areas of Barrow-In-Furness, Barrow Island, and Walney Island, as well as Rampside.

The adopted model grid size was 10m and the active area of the model was 102km^2.

6.3 Model boundary

Tidal boundary

The tidal boundary runs from high ground in the east at Moat Scar (east of New Biggin) to Roanhead Crag (south of Askam-in-Furness) in the west. The boundary runs largely parallel to the coastline encompassing Walney Island allowing for flow to pass from the north and south of Walney Channel (Figure 6-1). The tidal boundary applies six HT tide curves at 1D network points at either end of the model boundary line: TUFLOW interpolates tidal levels along the HX line between the points. The coastal flood boundary data used can be seen in Table 6-1.

Table 6-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Barrow	Heysham	1292	BNDRY_1
Barrow	Heysham	1298	BNDRY_2
Duddon Bar	Heysham	1306	BNDRY_3
Duddon Bar	Heysham	1312	BNDRY_4
Duddon Bar	Heysham	1318	BNDRY_5
Duddon Bar	Heysham	1324	BNDRY_5

Wave overtopping boundary

Eleven wave overtopping inflow lines were read into the model (Figure 6-1). Wave overtopping was calculated along the docks at Barrow Island, low lying sections of Walney Island, the floodwalls running from Rampside to New Biggin, and Roa Island.

6.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 6-1). The formal defences consist of a small raised masonry wall on top of Cavendish dock wall, sections of raised earth embankments in front of the Roosecote power station and gas terminals, and floodwalls running along the coastline from Rampside to New Biggin (Figure 6-2). There are some embankments on Walney Island that have also been stamped into the model.

The infrastructure wasincluded in the model is the railway line in Barrow-in-Furness, Cavendish dock wall, and Mawflat Lane Road on Walney Island.

The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

There are five tidal gates that were included in the defended scenarios for Model H. These include:

- Deep Meadows Beck (326736, 468931) - Figure 6-3
- Sarah Beck (325389, 467430) - Figure 6-3
- Rampside (323574, 466234)
- Salthouse Pool (322004, 468261)
- Seawood Caravan Park (327123, 469421).

In the undefended scenario these tidal gates were removed allowing water to pass freely through the bridge.

The dock gates at Barrow Island (320048, 467146) were assumed to be shut during the defended model simulations and open during undefended model simulations.

6.5 Stability improvements

The model timestep used was a quarter of the model grid size of 10m. This is within the recommended range of between 0.25 to 0.50 times the model cell size.

Two stability patches were used within the model and a third was used to blend the LIDAR topography into the bathymetric grid.

A ZTIN stability patch was used to smooth out unrealistic bathymetry elevations near Walney Island and offshore. The largest of which was used to smooth topography offshore at Piel Bar (323450, 461280) in order to ensure a smooth propagation of water into the model. It was also used to remove Jubilee Bridge from the bathymetry which was causing a blockage to flow.

In addition a further stability patch was used to increase the Manning's *n* roughness of two areas within the model to slow water as it enters the model; these locations were at Piel Bar (323440, 461270) and at Duddon Sands (319680, 476050).

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

6.6 Model stability summary

Messages

There are no "Negative Depth" warning messages reported during any of the model simulations. The lack of messages within this model is a sign that the model is stable.

Checks

There are six check messages during each simulation. These state ‘Connecting a 1D H boundary to 2D HX link’ and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

The change in volume throughout the model simulations is sensible and smooth and fits the expected volume flux of the model.

Cumulative mass balance error

The cumulative mass error for the first hour of the model run reaches a peak of -0.60% in the 200-year climate change scenarios. Once the model settles down the cumulative mass balance is less than -0.10% which is well within the recommended +/-1.00% error stated as acceptable in the TUFLOW guidelines.

6.7 Model sensitivity

Manning’s *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the mean water levels and maximum water levels do not change from that of the base Manning's *n* run. There is a difference in the minimum water level change of 32cm and 29cm when roughness is increased and decreased by 20% respectively.

Figure 6-3 shows the difference in flood extents between the different roughness runs. In general flood extents are very similar with only a few additional model cells being inundated at Ramsden and Buccleuch Locks where the lowered Manning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 6-1: Model H study area and defences

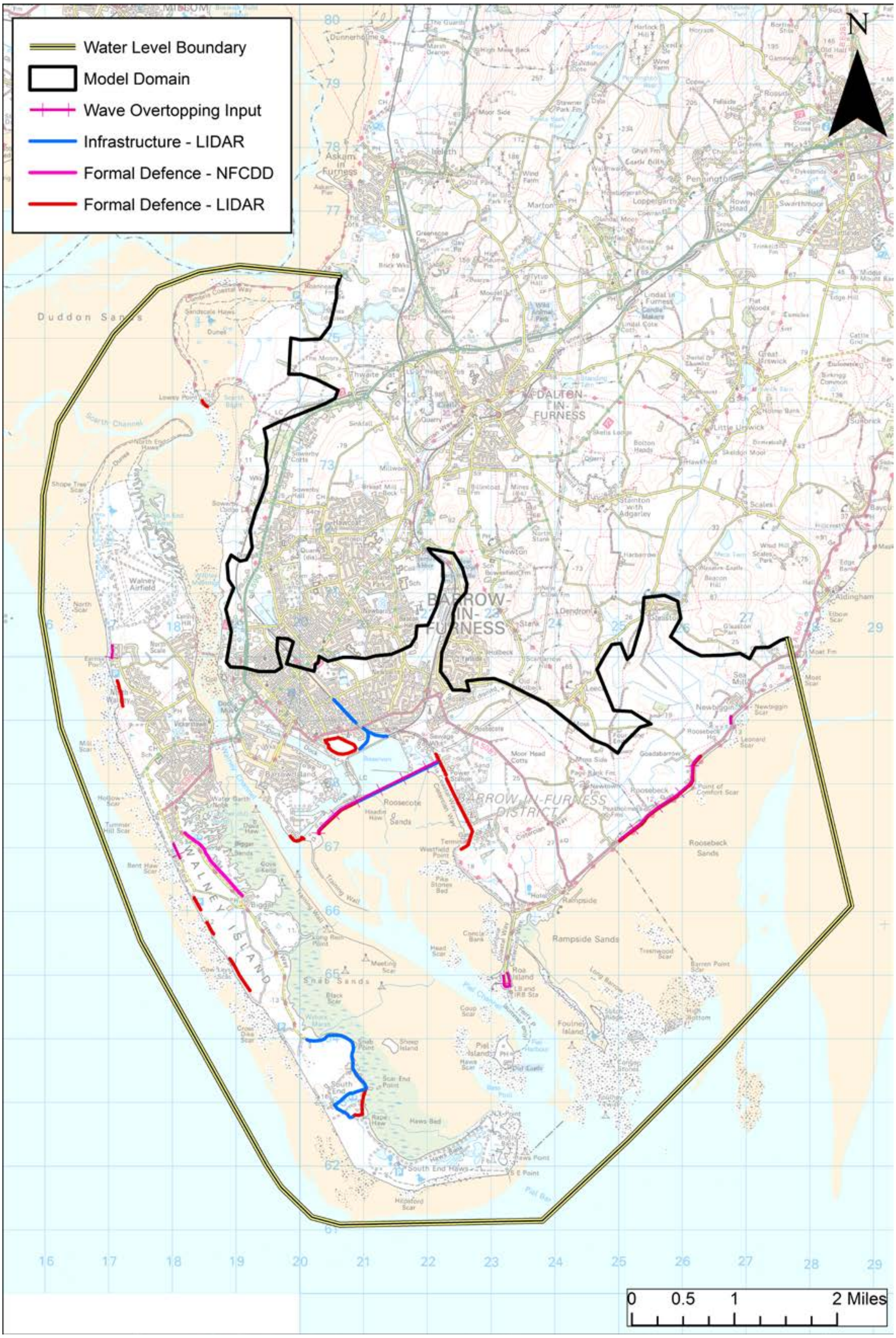
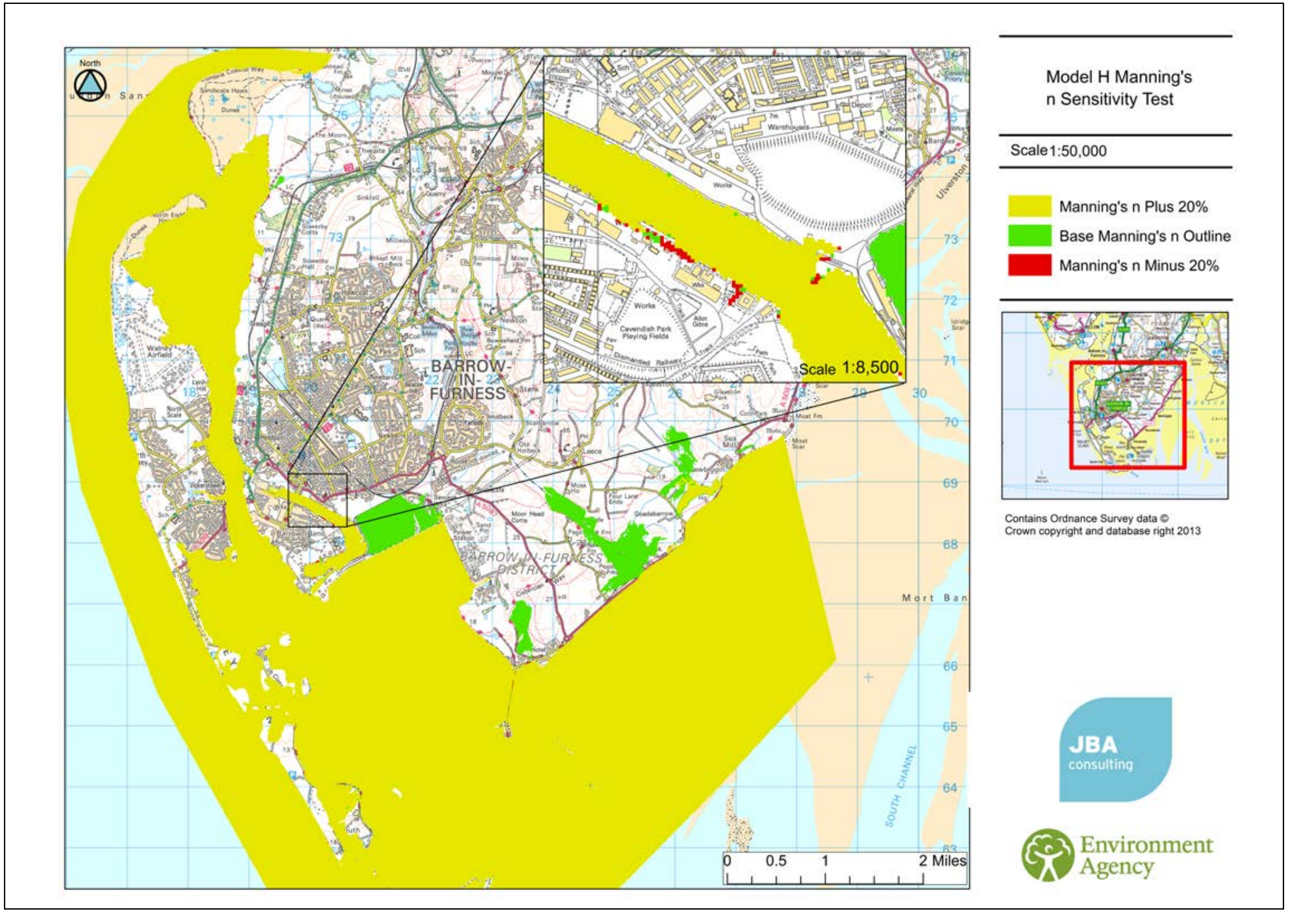


Figure 6-2: Masonry wall east of Roosebeck (top). Masonry wall at Roosebeck (bottom).

Figure 6-3: Tide gates at Deep Meadows Beck (top) and Sarah Beck (bottom).

Figure 6-4: Model H Manning's *n* sensitivity



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7 Model K - Duddon Estuary

7.1 Design run information

Table A 9 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 10, Appendix A.

7.2 TUFLOW domain

The model K study extent covers the Duddon Estuary. The area is largely covered by marsh land, open pasture, and woodland. It covers several communities including Haverigg, Millom, Broughton-In-Furness, Grizebeck, and Sandside.

The adopted model grid size was 10m and the active area of the model was 92km^2.

7.3 Model boundary

Tidal boundary

The tidal boundary runs from high ground in the north at Silecroft to Lowsy Point (north of Barrow-in-Furness) in the south. The boundary runs across Duddon Sands spanning the width of the Duddon estuary (Figure 7-1). The tidal boundary applies a single HT tide curve at the model boundary line which spans the Duddon estuary. The coastal flood boundary data used can be seen in Table 7-1.

Table 7-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Barrow	Heysham	1324	BNDRY_1

Wave overtopping boundary

Eight wave overtopping inflow lines were read into the model (Figure 7-1). Wave overtopping was calculated along the coastal frontage at Haverigg, the grassed earth embankment from Millom to the Duddon Viaduct, and the railway line at Sand Side and Kirkby-in-Furness.

7.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure which run alongside the coastline and then up the Duddon Channel as far inland as Duddon Bridge (Figure 7-1).

The formal defences consist of a large man-made sea wall around Port Haverigg Holiday Village (Figure 7-2 - top), raised walls alongside Haverigg Pool channel, and several earth embankments to the north of Millom Road. These run from Millom to the Duddon Viaduct, to the north east of Duddon viaduct, at the caravan site to the north of Askam-in-Furness, and running alongside the channel of Kirkby Pool.

The infrastructure wasincluded in the model is the railway line that runs from Askam-In-Furness to Millom and parts of the A595 road that runs across the catchment. The infrastructure waswas kept in the model for both defended and undefended simulations.

Sluice gates

There are several tidal gates that were included in the defended scenarios for Model E. These include:

- Railway Line at Millom (317549, 480484)
- Embankment opposite end of Green Road Lane (319527, 483686)
- Embankment opposite end of Causey Lane (319760, 485856)

- Confluence of Ladyhall Delph Cut (320269, 487278)
- Embankment north of Foxfield Farm (320655, 486048)
- Galloper Pool Railway Crossing (321236, 484943)
- Railway Line at Soutergate (322028, 481378)
- Stoup Dub Cut (315603, 478128)
- Crab Marsh (319029, 479625).

In the undefended scenario the tidal gates were removed allowing water to pass freely through the structures.

7.5 Stability improvements

The model timestep used was a quarter of the model grid size of 10m. This is well within the recommended range of between 0.25 to 0.50 times the model cell size.

Two stability patches were used within the model. The first was a ZTIN which was used to smooth out unrealistic bathymetry elevations within the Duddon estuary channel in order to ensure smooth propagation of water up the estuary. Three TINs were used in this patch.

In addition a further ZTIN was used to smooth the topography in the Duddon channel near the offshore model boundary. The reason for this is that the SeaZone bathymetry were not suitable to use here. The low tide flown LIDAR that was used instead was not very good quality within the channel and had remnants of the Duddon Viaduct near Foxfield Point (319990, 485610); the ZTIN was used to remove this.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

7.6 Model stability summary

Messages

There are no "Negative Depth" warning messages reported during any of the model simulations. The lack of messages within this model is a sign that the model is stable.

Checks

There are zero check messages for the model simulations.

Change in volume

The change in volume throughout the model simulations is sensible and smooth and fits the expected volume flux of the model.

Cumulative mass balance error

The cumulative mass error for the first hour of the model run reaches a peak of -0.60% in the 200-year climate change scenarios. Once the model settles down the cumulative mass balance is less than -0.10% which is well within the recommended +/-1.00% acceptable error stated in the TUFLOW guidelines.

7.7 Model sensitivity

Manning’s *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the mean water levels are within 6cm of the base Manning's *n* run. There is a more considerable difference in the maximum and minimum water level change of +/-9cm and +/-13cm respectively when roughness is increased and decreased by 20%.

Figure 7-3 shows the difference in flood extents between the different roughness runs. In general flood extents are similar. When Manning's *n* is increased by 20% the flood extent is reduced; a significant example of where this can be seen occurring is at Millom. There are a few small areas of increase when Manning's *n* is reduced but these are very small by comparison.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 7-1: Model K study area and defences

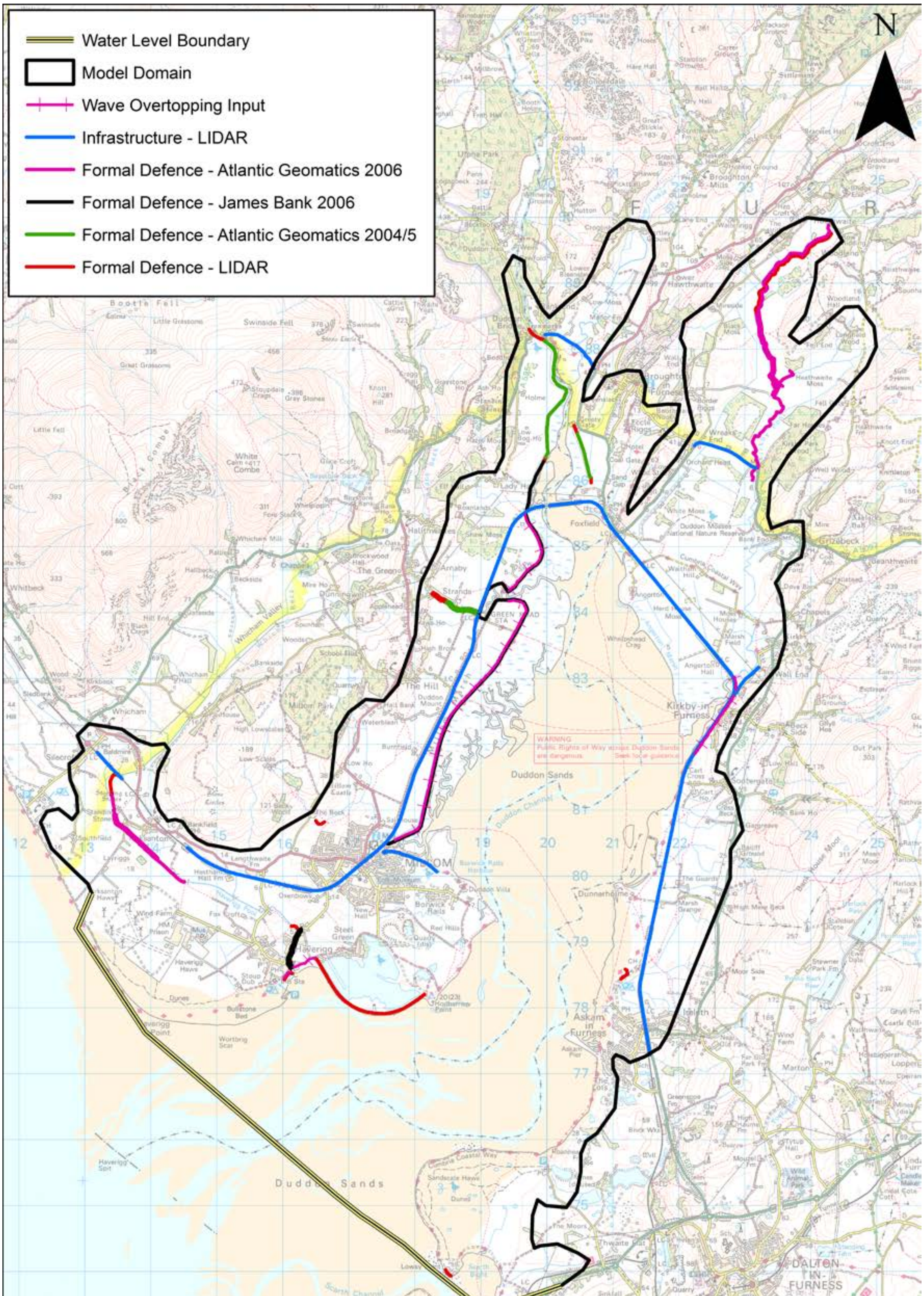

Figure 7-2: Large sea wall around pool at Haverigg Holiday Village (top). River mouth at Haverigg showing rock armour to the east (middle). Dunes to the west of Haverigg (bottom).

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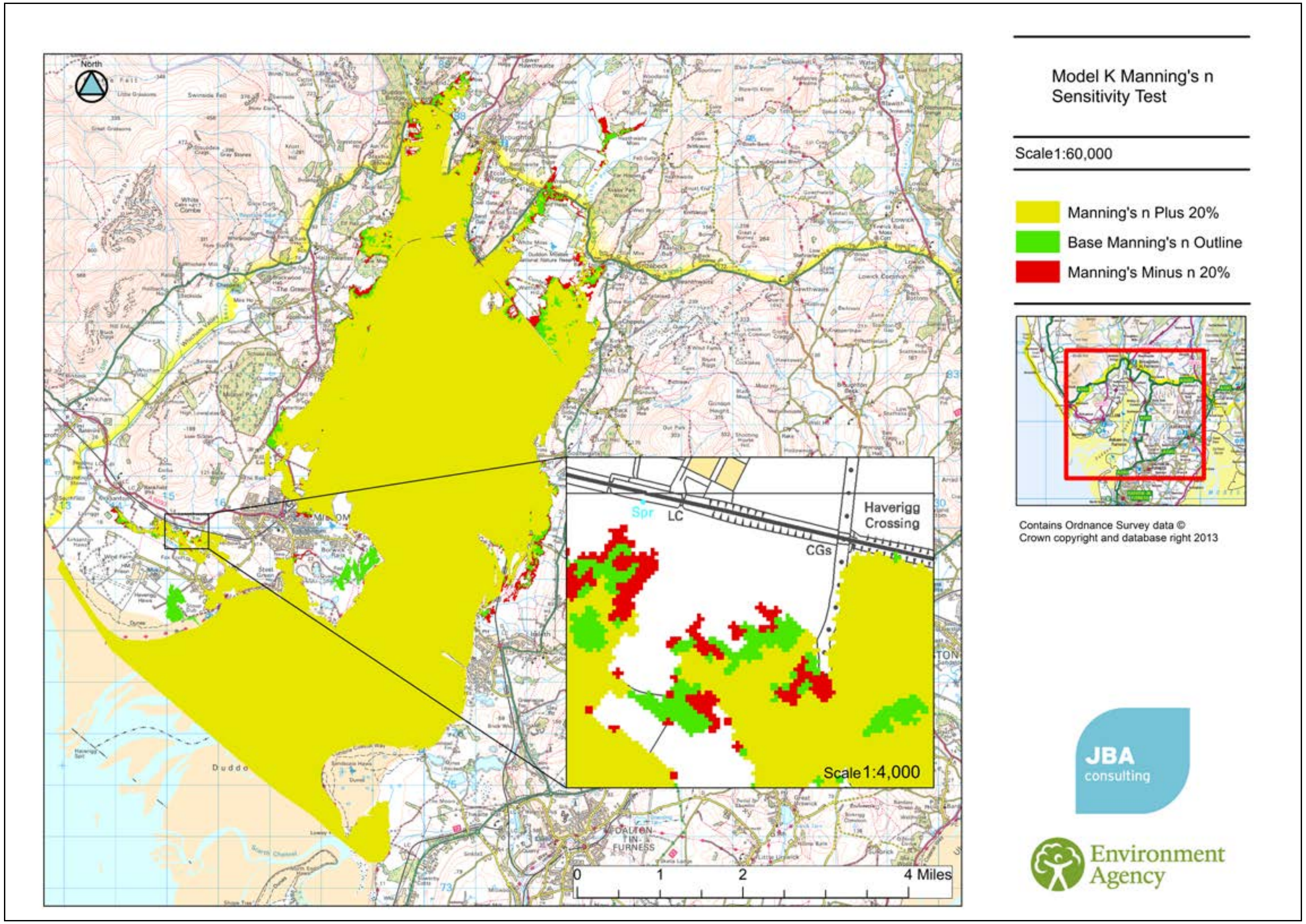
Figure 7-3: Model K sensitivity test



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8 Model M - Annaside

8.1 Design run information

Table A 11 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 12, Appendix A.

8.2 TUFLOW domain

The model M study extent covers the River Annas from Annaside to Bootle. The area is largely covered by open pasture. The area covers several small hamlets such as Annaside and High Kisken.

The adopted model grid size was 5m and the active area of the model was 5km^2.

8.3 Model boundary

Tidal boundary

The tidal boundary runs parallel to the coastline from high ground at Hill Farm in the north to Annaside Banks (south of Little Annaside) in the south (Figure 8-1). The tidal boundary applies three HT tide curves at 1D network points along the model boundary line: TUFLOW interpolates tidal levels along the HX line between the points. The coastal flood boundary data used can be seen in Table 8-1.

Table 8-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Barrow	Workington	1338	BNDRY_1
Barrow	Workington	1340	BNDRY_2
Barrow	Workington	1342	BNDRY_3

Wave overtopping boundary

No wave overtopping was included in Model M. Analysis was undertaken using SWAN nearshore wave heights but no wave overtopping was calculated.

8.4 Defences and sluice gates

Defences

The defences included in the model are formal defences, natural high ground, and infrastructure (Figure 8-1).

The formal defences consist of embankments running alongside the River Annas as far north as Bootle. There are also sections of part man-made and part natural high ground along the coastline from the River Annas mouth southwards to high ground to the west of Annaside (Figure 8-2).

The infrastructure wasincluded in the model is the railway line that runs from Silecroft to Hycemoor. The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

There are no tidal gates that were included in Model M.

8.5 Stability improvements

The model timestep used was a quarter of the model grid size of 5 metres. This is within the recommended range of between 0.25 to 0.50 times the model cell size.

One ZTIN stability patch was used within the model. It was used to smooth out topography in the Derwent channel, including the removing the railway line and bridge crossing, to ensure flow can propagate effectively up the channel. It was also used to smooth areas of the LIDAR at the Derwent mouth into the bathymetry.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

8.6 Model stability summary

Messages

There are no "Negative Depth" warning messages reported during any of the model simulations. The lack of messages within this model is a sign that the model is stable.

Checks

There are three check messages for the model simulations. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

There is some small oscillation in the change in volume throughout all model simulations undertaken. These oscillations are superimposed onto the expected volume flux of the model. Such oscillations are common within tidal models. The cause of these oscillations may be due to eddy effects in the offshore bathymetry which are generated by the action of flood water being squeezed into and out of the channel mouth. The oscillations are unlikely to have any significant affect on the flood outlines as the oscillations are small in comparison to the overall change in volume associated with the tidal cycles. Time series head levels were checked throughout the model simulation at various points along the coast and within the estuary channel. These show that the small oscillations in volume do not have an impact on head levels in the model.

Cumulative mass balance error

The cumulative mass error for the first hour of the model run reaches a peak error of -0.20% in the 30-year scenario. Once the model settles down the cumulative mass balance is less than -0.02% which is well within the recommended +/-1.00% error stated as acceptable in the TUFLOW guidelines.

8.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids (Table 8-2) show a relatively small change between the differing Manning's *n* runs, in particular the mean and maximum water levels do not show any change from that of the base Manning's *n* run. There is a more considerable difference in the minimum water level change of 47cm and 49cm when roughness is increased and decreased by 20% respectively but these occur in isolated locations and the affect is not widespread.

Figure 8-3 shows the difference in flood extents between the different roughness runs. In general flood extents are very similar with the most noticeable difference occurring to the west of Annaside where the lowered Manning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's given the flat nature of the topography and scale of the floodplain.

Figure 8-1: Model M study area and defences

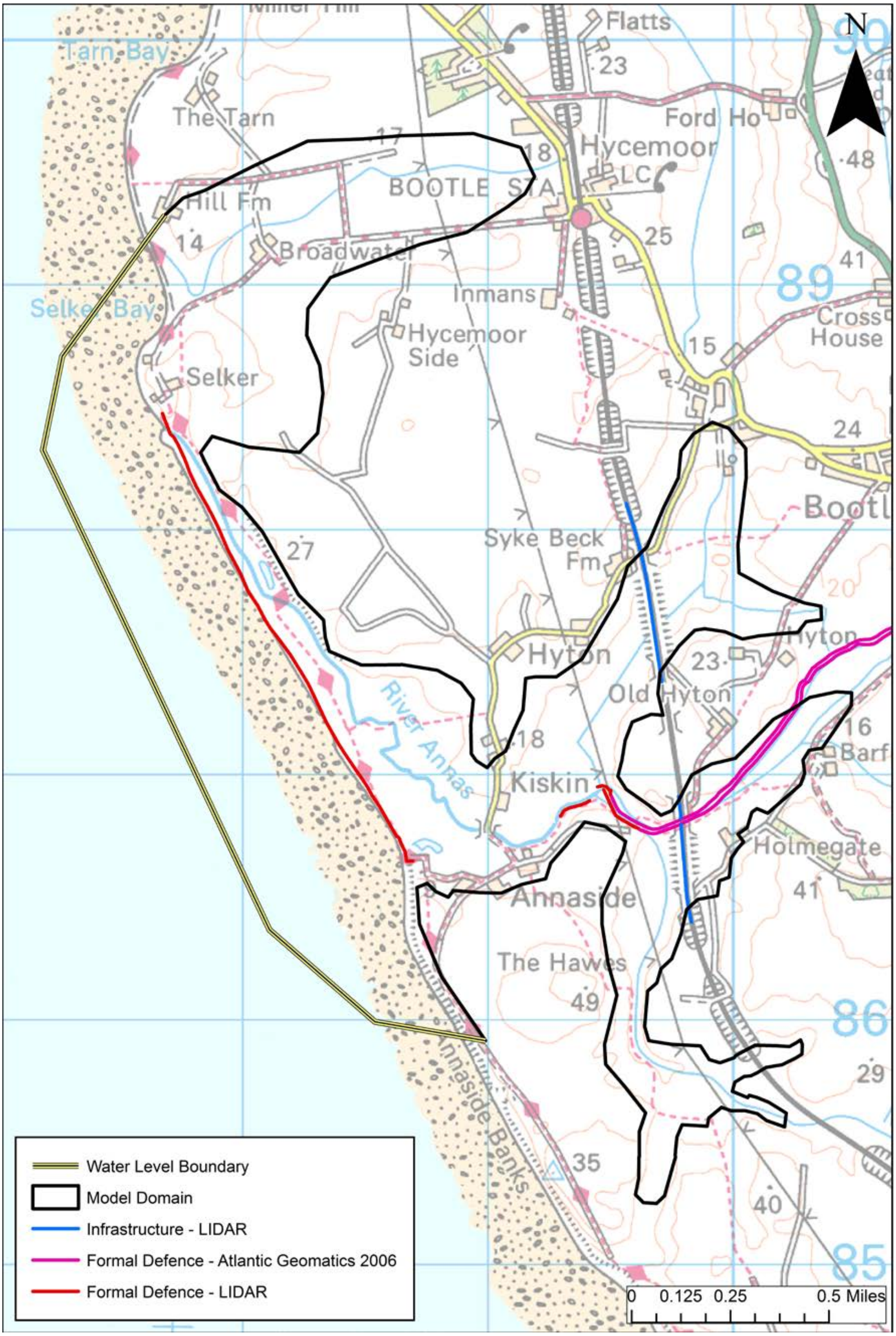

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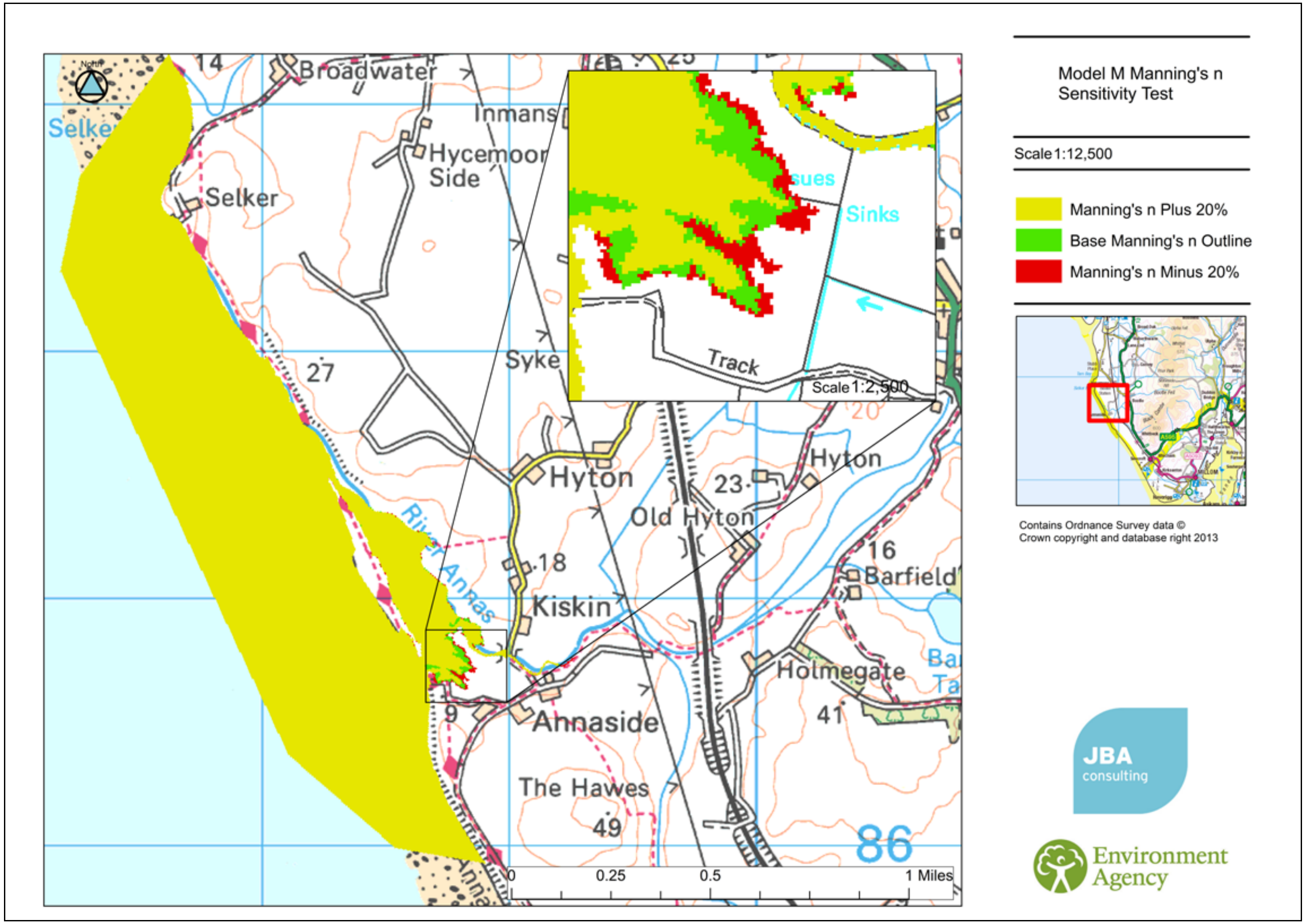
Figure 8-2: Earth embankment to the west of Annaside (top). High ground stretching to the north of Annaside (bottom).

Figure 8-3: Model M sensitivity test



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9 Model O - Ravenglass

9.1 Design run information

Table A 13 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 14, Appendix A.

9.2 TUFLOW domain

The model O study extent covers the River Esk estuary and the adjacent coastline. It covers several communities including Ravenglass, Holmrook, Saltcoats, and Newbiggin. The area is largely covered by dunes, open pasture and woodland.

The adopted model grid size was 5m and the active area of the model was 36km^2.

9.3 Model boundary

Tidal boundary

The tidal boundary runs parallel to the coastline from high ground at Ravenglass Gullery and Nature Reserve in the north to Skelda Hill in the south (Figure 9-1). The tidal boundary applies four HT tide curves at 1D network points at either end of the model boundary line and TUFLOW interpolates tidal levels along the HX line between the two points. The coastal flood boundary data used can be seen in Table 9-1.

Table 9-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Whitehaven	Workington	1350	BNDRY_1
Whitehaven	Workington	1348	BNDRY_2
Whitehaven	Workington	1346	BNDRY_3
Whitehaven	Workington	1344	BNDRY_4

Wave overtopping boundary

Four wave overtopping inflow lines were read into the model (Figure 9-1). Wave overtopping was calculated for Ravenglass spanning from the railway line in the north to the higher ground to the east of the Main Street at its southern end.

9.4 Defences and sluice gates

Defences

The defences included in the model are formal defences, natural high ground, and infrastructure (Figure 9-1).

The formal defences consist of:

- masonry stone flood walls on the western side of the properties at Ravenglass (Figure 9-2 - top)
- an earth embankment that runs north alongside Main Street from Ravenglass to the railway line
- a raised embankment that runs along the coastline around the MOD land southwards from the estuary mouth (Figure 9-2 - middle)
- raised embankments running alongside the Esk, Mite and Irt river channels.

Natural high ground has also been picked up by the LIDAR along the coastline north of the estuary mouth, but this has not been formally stamped into the model grid.

The infrastructure that has been included in the model is the railway line that runs from Seascale to Hycemoor, the Ravenglass and Eskdale railway and sections of the A595 road that runs across the catchment.

The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

One tide gate was included in Model O for the defended scenario. The gate is at the southern end of Main Street in Ravenglass (Figure 9-2 - 308403, 496229).

In the undefended scenario the tidal gate was removed allowing water to pass freely up the Main Street in Ravenglass.

9.5 Stability improvements

The model timestep used was a quarter of the model grid size of 5m. This is within the recommended range of between 0.25 to 0.50 times the model cell size.

Two ZTIN stability patches were used in the model. The first patch was used to smooth the LIDAR into the SeaZone bathymetry to ensure there are no steps in elevations between the two.

The second patch was used to remove remnants of the railway line bridges that cross the Esk and Mite channels. It was also used to carve a channel in the upper Esk catchment (312111, 497369): this is to ensure flow can propagate up the channel effectively.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

9.6 Model stability summary

Messages

There are no "Negative Depth" warning messages reported during any of the model simulations. The lack of messages within this model is a sign that the model is stable.

Checks

There are four check messages for the model simulations. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

There are some small oscillations in the change in volume throughout all model simulations undertaken by this study. These oscillations are superimposed onto the expected volume flux of the model. Such oscillations are common within tidal models and the cause of these oscillations may be due to eddy effects in the offshore bathymetry. These are generated by the action of flood water being squeezed into and out of the channel mouth. The oscillations are unlikely to have any significant affect on the flood outlines as the oscillations are small in comparison to the overall change in volume associated with the tidal cycles. Time series head levels were checked throughout the model simulation at various points along the coast and within the estuary channel. They show that the small oscillations in volume are not having an impact on head levels in the model.

In the undefended scenario there are some initial spikes in 'volume in' at the start of the model. This relates to the restart file that was read in. The restart file was extracted from the 30-year scenario, therefore, for the higher return periods, such as the 200yr climate change undefended scenario the initial water levels are higher and there is an initial pouring of water into the model. This spike is short lived and the model settles down very quickly so it acceptable.

Cumulative mass balance error

The cumulative mass error for the first hour of the model run reaches a peak error of -1.20% in the 200-year climate change undefended scenario, the other simulations are less than this peak. Once the model settles down the cumulative mass balance is less than -0.01% which is well within the recommended +/-1.00% error stated as acceptable in the TUFLOW guidelines.

9.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200 year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the mean water levels show up to an 11cm increase from the base Manning's *n* run. There is a more considerable difference in the minimum water level change of 47cm and 49cm when roughness is increased and decreased by 20% respectively.

Figure 9-3 shows the difference in flood extents between the different roughness runs. In general flood extents are very similar with the most noticeable difference occurring at the tidal limit, for example at the upstream end of the River Esk tidal extent. The lowered Manning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 9-1: Model O study area and defences

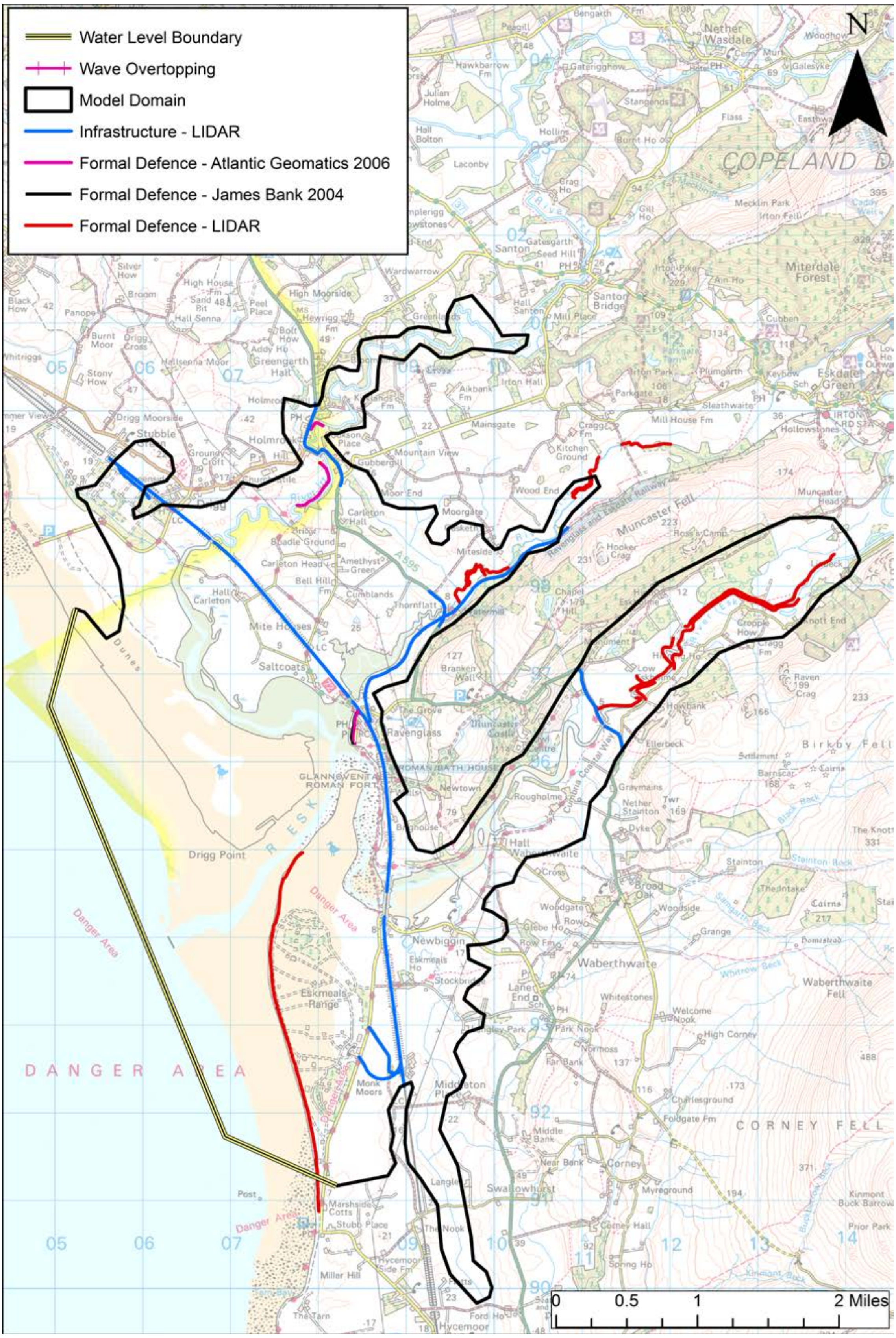

Figure 9-2: Masonry wall protecting Ravenglass properties (top). Man-made coastline defence near Monk Moors to the south of the Esk River Mouth (middle). Ravenglass flood gate (bottom).

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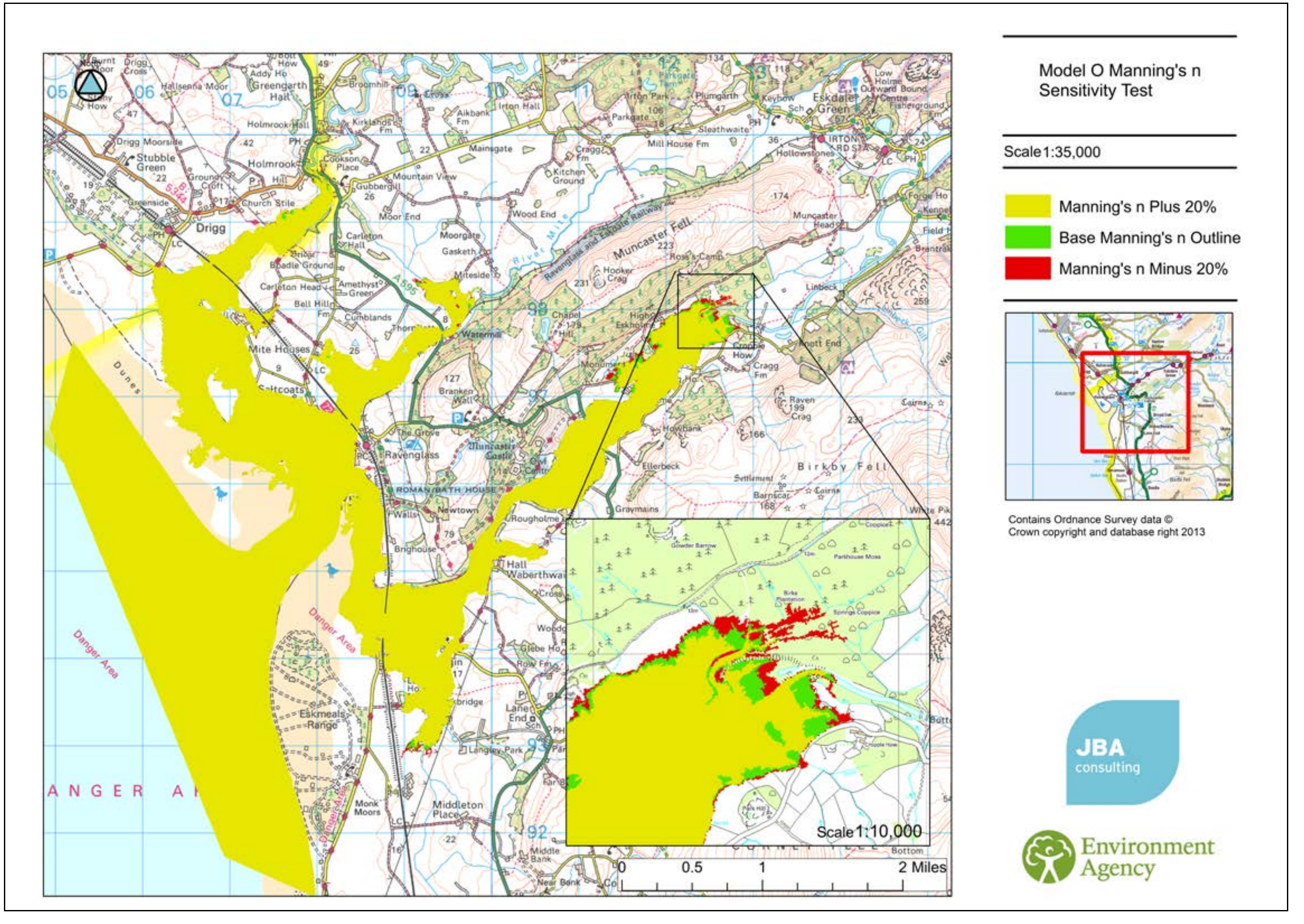
Figure 9-3: Model O sensitivity test



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10 Model Q - Whitehaven

10.1 Design run information

Table A 15 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 16, Appendix A.

10.2 TUFLOW domain

The model Q study extent covers Whitehaven from the South Beach to the Redness Point (north of North Beach) either side of Whitehaven harbour.

The adopted model grid size was 5m and the active area of the model was 1km^2.

10.3 Model boundary

Tidal boundary

The tidal boundary runs parallel to the coastline from high ground in the north at Redness Point to the west pier in the south (Figure 10-1). The tidal boundary applies a single HT tide curve along the model boundary line. The coastal flood boundary data used can be seen in Table 10-1.

Table 10-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Whitehaven	Workington	1380	BNDRY_1

Wave overtopping boundary

Nine wave overtopping inflow lines were read into the model (Figure 10-1). Wave overtopping was calculated for the Old Quay harbour walls, including both North and South harbour. Wave overtopping was also calculated for North Beach in front of North Shore Road.

10.4 Defences and sluice gates

Defences

The defences included in the model are entirely infrastructure (Figure 10-1).

The infrastructure that was included in the model is the railway line that runs through Whitehaven to Parton, and the harbour infrastructure including the Old Quay, the West pier and the North Pier (Figure 10-2).

The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

One tide gate was included in Model Q at the Old Quay in Whitehaven harbour in the defended scenario. The gate is next to the disused lighthouse (Figure 10-2 - 297060, 518498). The water level in the inner harbour was set to a maintained level (2.5 mAOD) during the defended scenario.

In the undefended scenario the tidal gate was removed allowing water to pass freely into the inner harbour. During this scenario the harbour bed level was stamped down to a similar level to the bed on the seaward side of the inner harbour wall (-2.2 mAOD).

10.5 Stability improvements

The model timestep used was a quarter of the model grid size of 5m. This is within the recommended range of between 0.25 to 0.50 times the model cell size.

One ZTIN stability patch was used in the model. The patch was used to smooth the LIDAR into the SeaZone bathymetry to ensure they blend into each smoothly and avoid any discontinuity. It was used to smooth out a small area of the topography on the coastal side of the tidal doors.

The use of these stability patches is standard practice when stabilising a model.

10.6 Model stability summary

Messages

There are no "Negative Depth" warning messages reported during any of the model simulations. The lack of messages within this model is a sign that the model is stable.

Checks

There are zero check messages for any of the model simulations.

Change in volume

There are some small oscillations in the change in volume throughout all model simulations undertaken by this study. These oscillations are superimposed onto the expected volume flux of the model. Such oscillations are common within tidal models. The cause of these oscillations may be due to eddy effects in the offshore bathymetry which are generated by the action of flood water being constricted as it passes into and out of the channel mouth. The oscillations are unlikely to have any significant affect on the flood outlines as the oscillations are small in comparison to the overall change in volume associated with the tidal cycles. Time series head levels were checked for each model simulation at various points along the coast and within the estuary channel. They show that the small oscillations in volume do not have an impact on head levels in the model.

Cumulative mass balance error

The cumulative mass error for the first hour of the model run reaches a peak error of -0.03% in the 200-year climate change defended scenario. Once the model settles down the cumulative mass balance is generally less than -0.01% which is well within the recommended +/-1.00% error stated as acceptable in the TUFLOW guidelines. This is typical of the mass balance error in all scenarios.

10.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum, and minimum water levels extracted from the maximum grids show very little change between from the base Manning's *n* run in terms of levels,, only +/-1cm. There were some small instabilities generated in the inner harbour when the roughness was reduced by 20% but these did not affect the flood extents for this comparison.

Figure 10-3 shows the difference in flood extents between the different roughness runs. In general flood extents are almost identical with the only a few model cells here and there affected by the change in topography roughness.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not sensitive to changes in Manning's *n*.

Figure 10-1: Model Q study area and defences

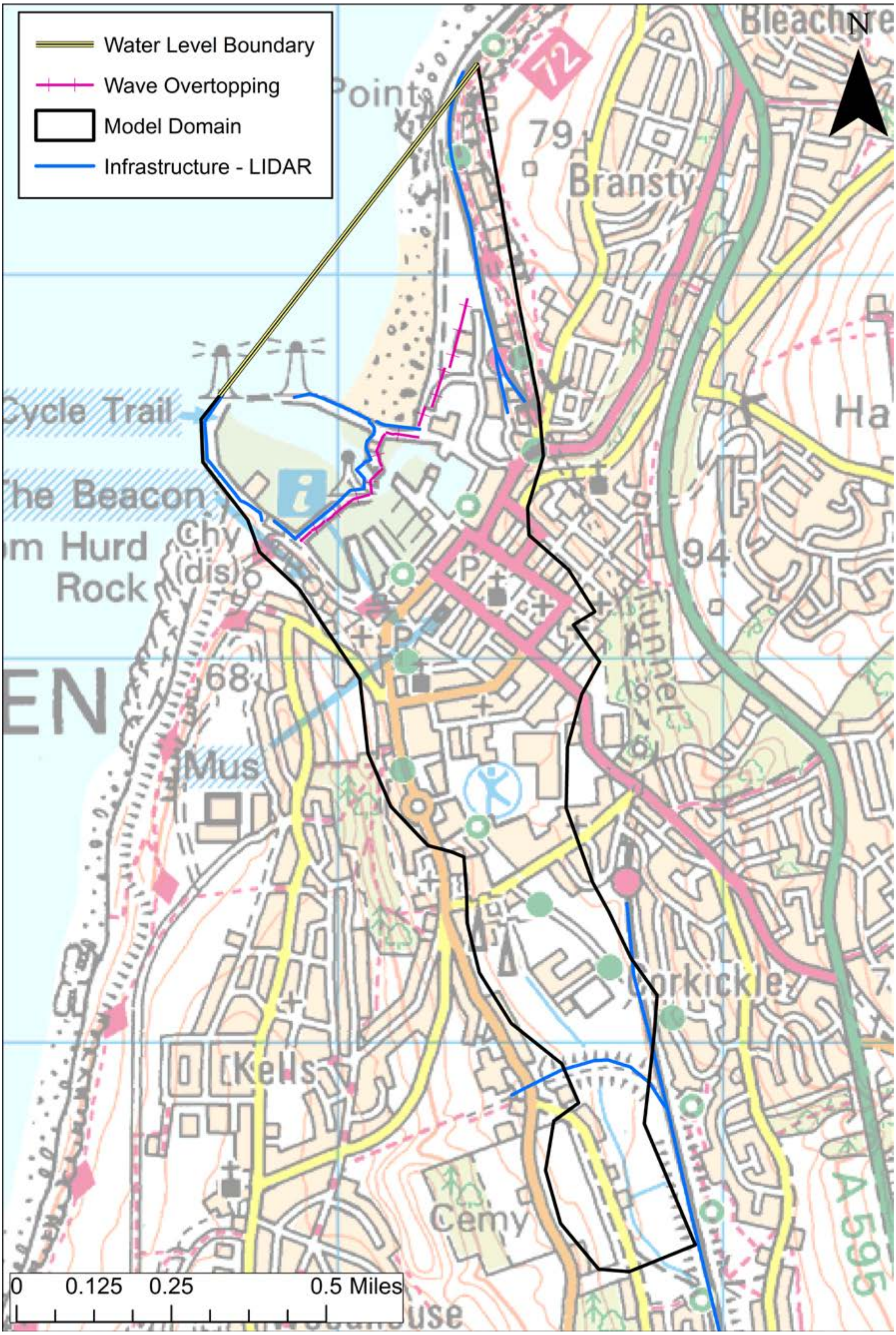

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Figure 10-2: Whitehaven North Pier (top). Old Quay with flood wall and flood gates (middle).

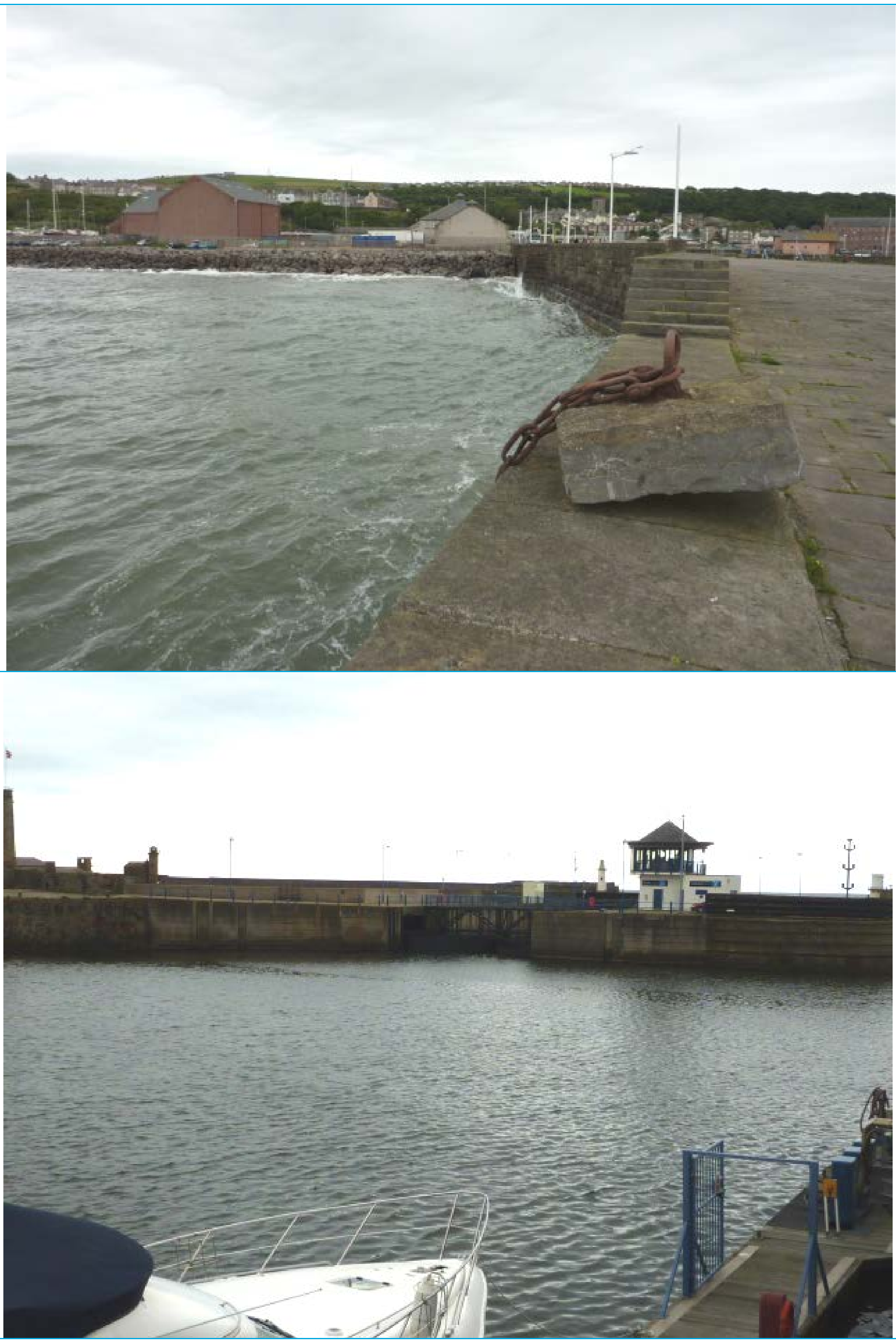
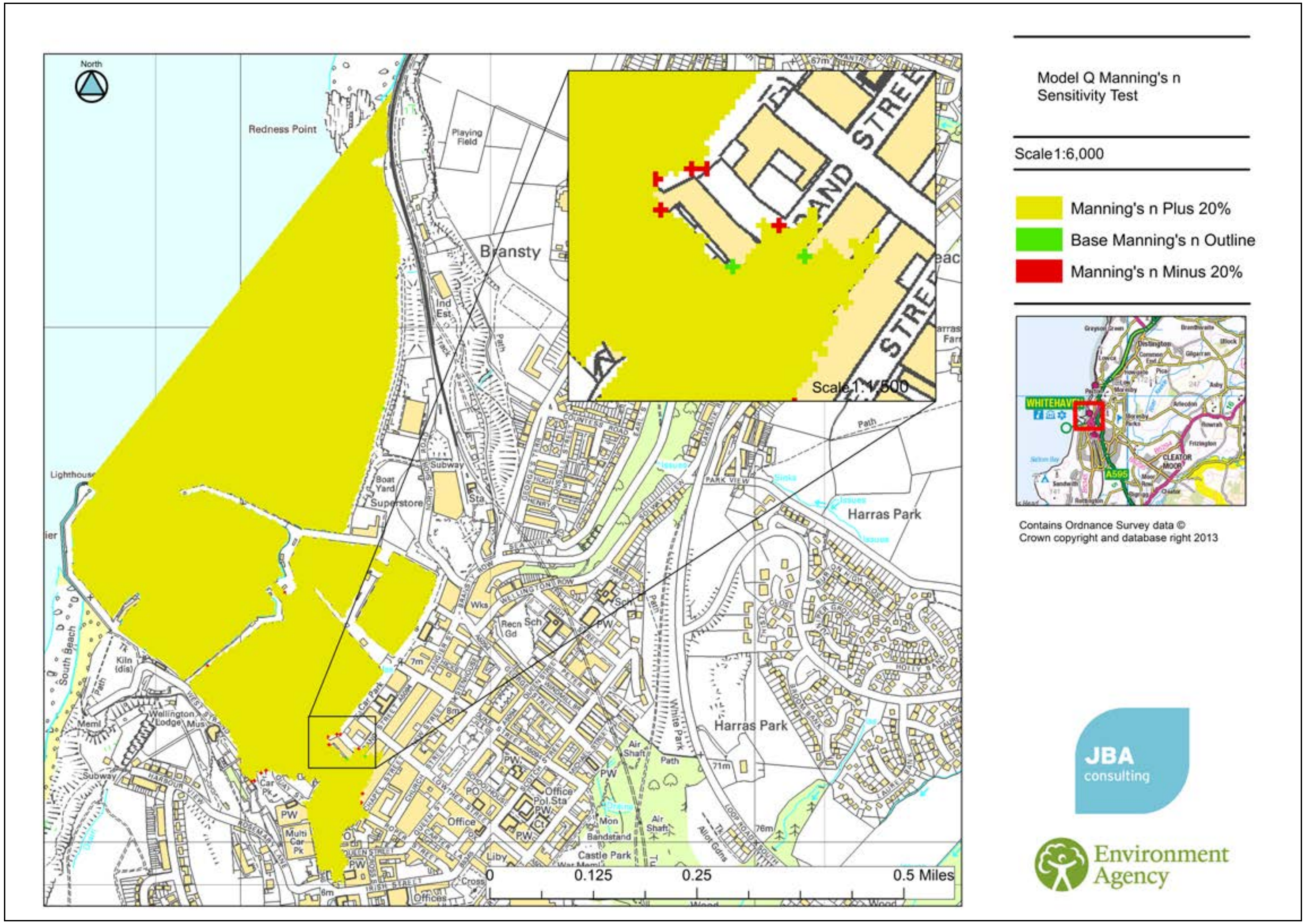


Figure 10-3: Model Q sensitivity test



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11 Model S - Workington and Maryport

11.1 Design run information

Table A 17 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 18, Appendix A.

11.2 TUFLOW domain

The model S study extent covers Workington area from the River Derwent mouth to just north of Maryport in the north. The area is largely covered by urban area and open pasture. The area covers the populations of Workington, Stainburn, Siddick, Flimby, and Maryport.

The adopted model grid size was 5m and the active area of the model was 14km^2.

11.3 Model boundary

Tidal boundary

The tidal boundary runs from high ground in the north at Bankend Quarry (north of Maryport) to the pier at the southern end of the Derwent mouth in the south. The boundary runs parallel to the coastline (Figure 11-1). The tidal boundary applies six HT tide curves at 1D network points at either end of the model boundary line and TUFLOW interpolates tidal levels along the HX line between the two points. The coastal flood boundary data used can be seen in Table 11-1. The sixth point (BNDRY_6) is a copy of BNDRY_1.

Table 11-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Workington	Workington	1392	BNDRY_1
Workington	Workington	1394	BNDRY_2
Maryport	Workington	1396	BNDRY_3
Maryport	Workington	1398	BNDRY_4
Maryport	Workington	1400	BNDRY_5
Workington	Workington	1392	BNDRY_6

Wave overtopping boundary

Sixteen wave overtopping inflow lines were read into the model (Figure 11-1). Wave overtopping was calculated to the north of the Derwent mouth in front of the Prince of Wales Dock, along the coast from Siddick to Flimby, and Maryport from North Quay to the north end of Nelson Street.

11.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 11-1). The former consist of:

- raised embankments between the dock gates and the car park to the north of the Derwent mouth (Figure 11-2 - top)
- grassed earth embankments providing protection around the wind turbines and the sewage works behind the railway line to the north of Siddick
- and raised embankments further inland up the Derwent channel to the north of Stainburn.

At Maryport there is a large earth embankment in front of Maryport Marina and flood walls and a flood gate run up the inside of the River Ellen estuary and protect North and South Quay (Figure 11-3 - top). The defences run northwards along the coast from the North Quay in the inner harbour (Figure 11-3 - middle and bottom). The defence north of Wallace Lane split into two defences, one in front of the other and are isolated by a series of flood gates.

The infrastructure that was included in the model is the railway line that runs from Workington through to Maryport and parts of low lying sections of road such as the A594 and Curzon Street in Maryport. The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

Two tide gates were included in the defended scenario for Model S. One is just to the north of Flimby (Figure 11-2 - bottom - 302197, 534059) and the other is adjacent to Brook Street (Figure 11-2 - middle - 302054, 533776). Both tide gates serve to seal off a flow paths under the railway line. There are also three tide gates from Workington Bridge heading north along Mill Stream but the model grid was not picking this channel up accurately so the tide gates were not required to be stamped into the model.

In the undefended scenario the tidal gates were removed allowing water to pass freely through the railway.

11.5 Stability improvements

The model timestep used was a quarter of the model grid size of 5m. This is within the recommended range of between 0.25 to 0.50 times the model cell size.

A ZTIN stability patch was used in the model to smooth out sections of the Derwent channel to ensure flow can propagate up the channel effectively. This included removing the railway line bridge and New Bride Road Bridge where they cross the Derwent channel as well as smoothing the mouth of the channel with the harbour levels. In addition to this, some smoothing was required on both the south and north piers at Workington to remove bumpy topography. A bridge in Maryport just inside the Old Harbour was also removed from the Ellen Channel to ensure the propagation of water up the channel.

Some additional modifications were required to be made for the climate change scenarios for stability reasons. Three small roughness patches were used:

- one at South Pier in Maryport
- two along the coast at Workington.

These were used to increase the friction of the topography to slow the floodwaters as they enter the model.

In the climate change defended scenario the boundary on the south pier at Workington was moved very slightly as the higher water levels of this scenario were breaching the pier and causing model instabilities. The boundary was moved so that it tied better into the pier and this solved the instability. This modification means the defended climate change scenario outline is slightly smaller in this specific location but the moved boundary does not affect the rest of the model and it can be directly compared to the climate change undefended scenario.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

11.6 Model stability summary

Messages

The "Negative Depth" warning messages reported during the model simulations range between zero and two. The lack of messages within this model is a sign that the model is stable.

Checks

There are six check messages during each simulation. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

There are some small oscillations in the change in volume throughout all model simulations undertaken by this study. These oscillations are superimposed onto the expected volume flux of the model. Such oscillations are common within tidal models and the cause of these oscillations may be due to eddy effects in the offshore bathymetry which are generated by the action of flood water being constricted into and out of the channel mouth. The oscillations are small in comparison to the overall change in volume associated with the tidal cycles. Time series head levels were checked throughout the model simulation at various points along the coast and within the estuary channel, and show that the small oscillations in volume do not have an impact on head levels in the model.

Cumulative mass balance error

The cumulative mass error spikes up to a peak error of up to -3.00% in most of the scenarios. Once the model settles down, and certainly within the first hour, the cumulative mass balance drops to generally less than -0.01% which is well within the recommended +/-1.00% error stated as acceptable in the TUFLOW guidelines.

11.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum, and minimum water levels extracted from the maximum grids show little change between from the base Manning's *n* run in terms of levels. There were some small instability generated in the model when the roughness was reduced by 20% but these did not affect the flood extents for this comparison.

Figure 11-4 shows the difference in flood extents between the different roughness runs. In general flood extents are similar but there are two noticable differences. The first is when topography roughness is increased the low ground at Siddick sewage works does not flood while it does with the base roughness and reduced roughness. The noticeable difference is next to Workington dock gates where an area floods when the topography roughness is reduced when it did not in the base roughness.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 11-1: Model S study area and defences

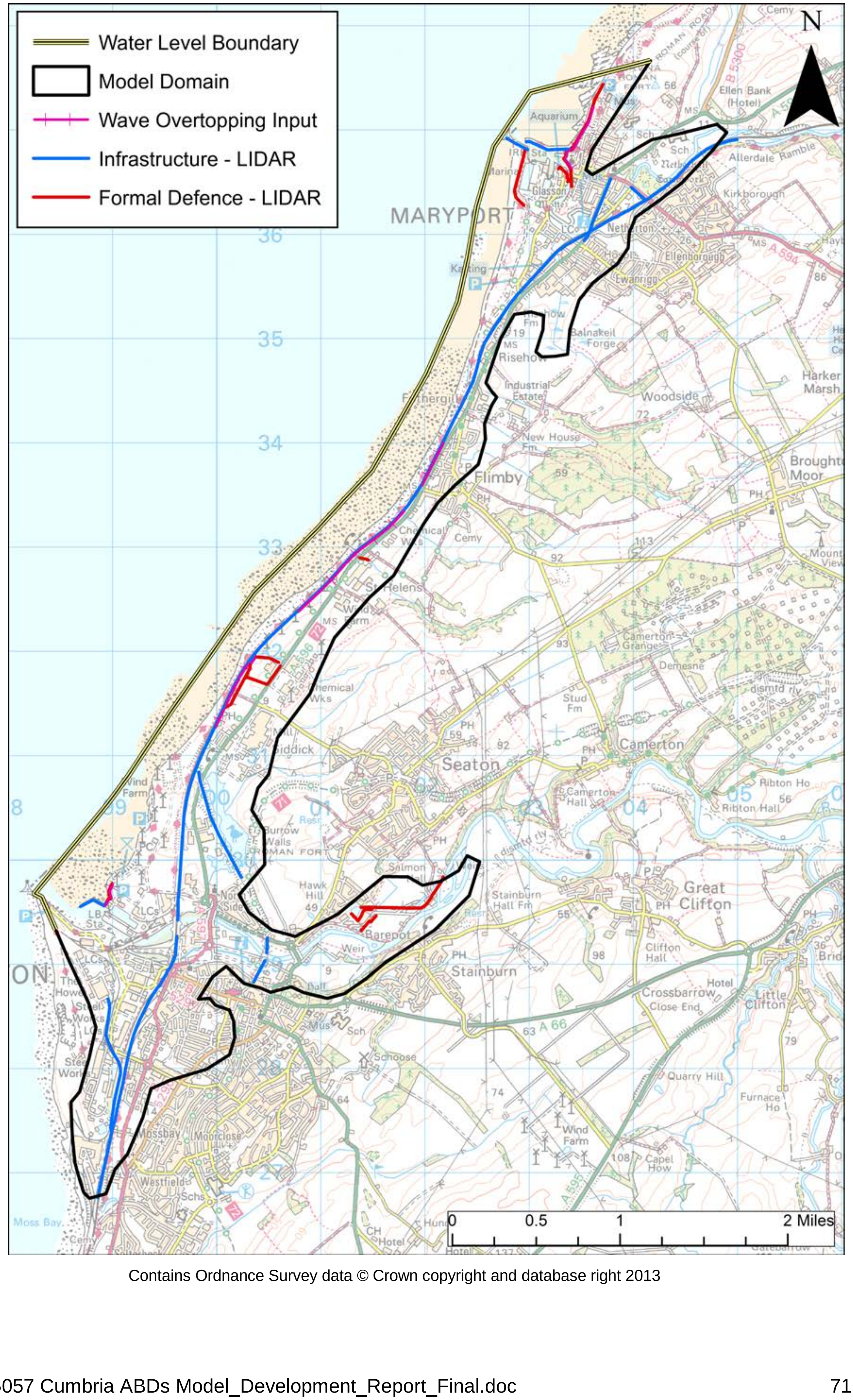
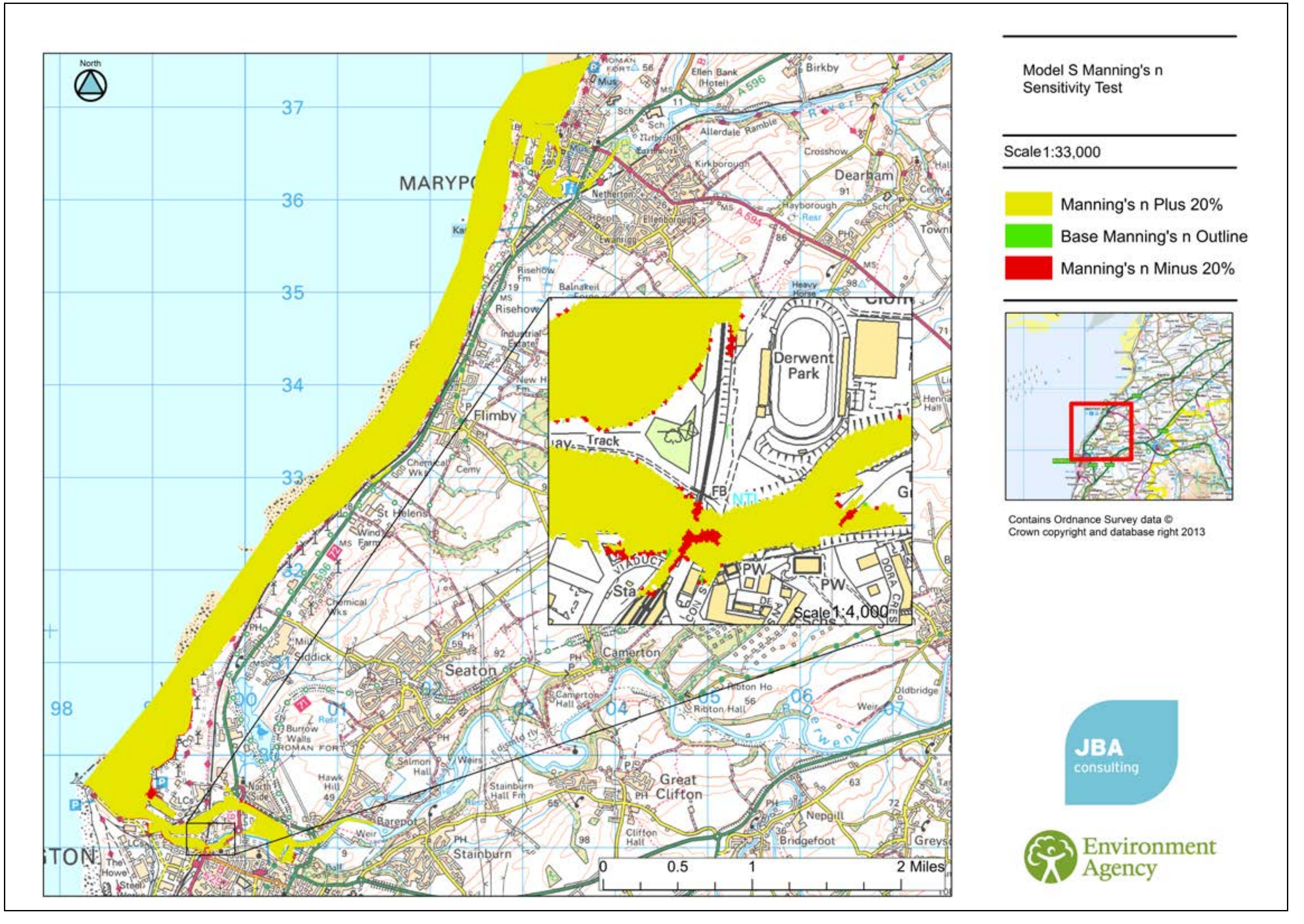


Figure 11-2: Embankment to the north of Derwent mouth (top). Railway embankment south of Flimby showing tide gated flow path underneath (middle). Flood gate near Flimby (bottom) - Picture from EA flood gate operations manual.

Figure 11-3: Flood walls and flood gate on North Quay (top). Flood wall backing the inner harbour (middle). Flood wall north of Wallace Lane, North Maryport (bottom).

Figure 11-4: Model S sensitivity test



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12 Model W - Silloth

12.1 Design run information

Table A 19 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 20, Appendix A.

12.2 TUFLOW domain

The model W study extent covers the south west section of the Solway Firth estuary. It covers part of the Waver and Eden channels and their surrounding marsh land and includes several communities including Skinburness, Abbeytown, Newton Arlosh, Kirkbridge, Easton, and Longburgh. The area is largely covered by open pasture and marsh land.

The adopted model grid size was 10m and the active area of the model was 202km^2.

12.3 Model boundary

Tidal boundary

Two tidal boundaries are included in Model W. The first runs from high ground to the south of Silloth to high ground to the north of Cardurnock. This was modelled by using an interpolating water level boundary by applying two HT tide curves at 1D network points at either end of the model boundary line and TUFLOW interpolates tidal levels along the HX line between the two points.

The second boundary runs from high ground at Port Carlisle to high ground north of Burgh by Sands. This boundary was represented by a single HT tide curve applied across the entire model boundary based on Scottish Environment Protection Agency (SEPA) extreme sea levels for the Solway Firth estuary[5].

Two boundaries were used to represent inflow from the Solway Firth estuary as it was not possible to model the area in its entirety due to its vast size.

The coastal flood boundary data used can be seen in Table 12-1.

Table 12-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Silloth	Workington	1418	BNDRY_1
Silloth	Workington	1426	BNDRY_2
Silloth	Workington	SEPA 1434-6	BNDRY_3

Wave overtopping boundary

Nine wave overtopping inflow lines were read into the model (Figure 12-1). Wave overtopping was calculated along the coastline from northern Silloth to northern Skinburness.

12.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 12-1). The formal defences consist of:

- flood walls with recurves, some raised from ground level and some not, spanning along the coastline between Silloth and Skinburness (Figure 12-2 - 1)

[5] SEPA (2013). F3004: Derivation of a National Coastal Flood Hazard Dataset. Royal Haskoning / JBA

- rock armouring along Dick Trod Lane to the north of Skinburness (Figure 12-2 - 2)
- a large grassed embankment (Sea Dyke) that runs from Skinburness in a southerly direction to Wath (Figure 12-2 - 3)
- an embankment that runs from Salt Cotes towards Kirkbride
- embankments running alongside the Waver and Wampool rivers
- and an embankment on Easton Marsh to the east of Drumburgh.

The infrastructure that was included in the model is the dismantled railway line that runs from Glasson eastwards to Burgh by Sands, and various sections of roads and dismantled railway across the catchment.

The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

Three flood gates were included in the model. The flood gates are interspersed along the large grassed embankment (Sea Dyke) that runs from Skinburness in a southerly direction to Wath (Figure 12-2 - 4).

In the undefended scenario the tidal gates were removed along with the embankment allowing water to pass past this area if the water level is high enough.

12.5 Stability improvements

The model timestep used was a quarter of the model grid size of 10 metres. This is within the recommended range of between 0.25 to 0.50 times the model cell size.

Two ZTIN stability patches were used in the model. One was used to blend the Solway bathymetry into the low-tide flow LIDAR DTM. The other was used to improve poor quality areas of the LIDAR DTM by smoothing out unrealistic elevations in channel and marsh areas or removing deep holes. The modifications included removing a deep hole south of Skinburness, improving the Wampool channel at Whitrigg and removing Whitrigg road bridge from LIDAR as well as smoothing a small section of the River Eden channel edge.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which is an issue with the quality of data supplied rather than the model itself.

12.6 Model stability summary

Messages

There are no "Negative Depth" warning messages reported during the design model simulations. There are two "Negative Depth" warning messages reported during the sensitivity model simulations. The low number of messages within this model is a sign that the model is stable.

There is a considerable number of warning messages prior to the model simulation. These relate to an error in the reading of the XF files which are used to speed up the reading in of model input files as the model initialises. This was not rectified as in this event where it cannot read the XF files the model simply reverts back to reading in the original source, which takes longer to load up, but does not affect the model in any way.

Checks

There are two check messages during each simulation. These state 'Connecting a 1D H boundary to 2D HX link' and occur where tidal inflow boundary nodes were applied around the coastline.

Change in volume

There are some small oscillations in the change in volume throughout all model simulations undertaken by this study. These oscillations are superimposed onto the expected volume flux of the model. Such oscillations are common within tidal models. The cause of these oscillations may be due to eddy effects in the offshore bathymetry which are generated by the action of flood water being constricted into and out of the channel mouth. The oscillations are unlikely to have any significant affect on the flood outlines as they are small in comparison to the overall change in volume associated with the tidal cycles. Time series head levels were checked throughout the model simulation at various points along the coast and within the estuary channel. They show that the small oscillations in volume do not having an impact on head levels in the model.

Cumulative mass balance error

The cumulative mass error spikes up to a peak of up to -1.00% in most of the 200-year climate change scenarios. Once the model settles down, and certainly within the first hour, the cumulative mass balance drops to generally less than +/-0.01% which is well within the recommended +/-1.00% acceptable error stated in the TUFLOW guidelines.

12.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the maximum water levels are within 1cm of the base Manning's *n* run while mean water levels are within 3cm.

Figure 12-3 shows the difference in flood extents between the different roughness runs. In general flood extents are similar. The lowered Nanning's *n* values lead to a more extensive outline and the raised Manning's *n* values leading to a smaller outline. Of particular importance the lowered roughness leads to some more properties being inundated at the north east of Silloth.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

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Figure 12-1: Model W study area and defences

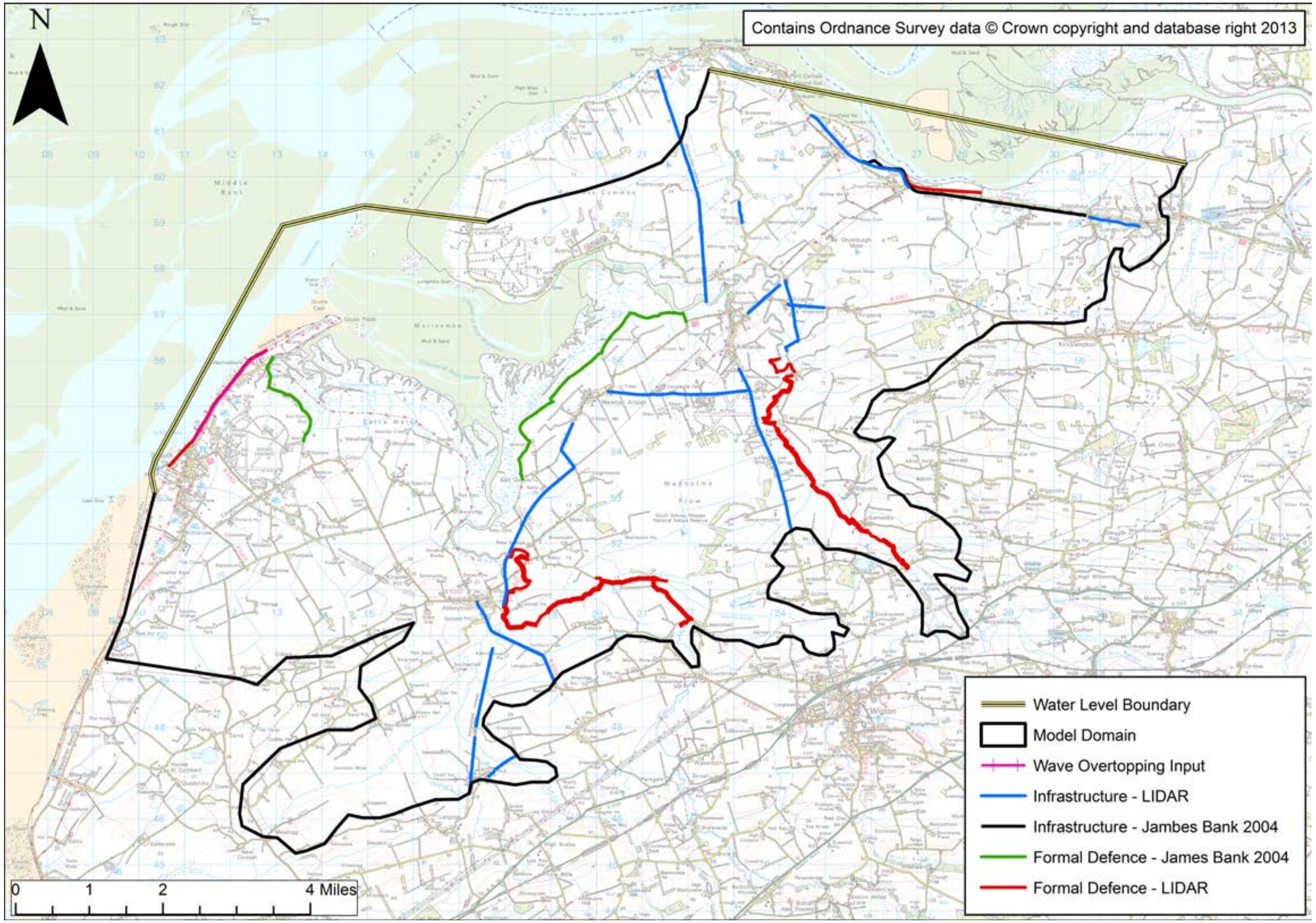

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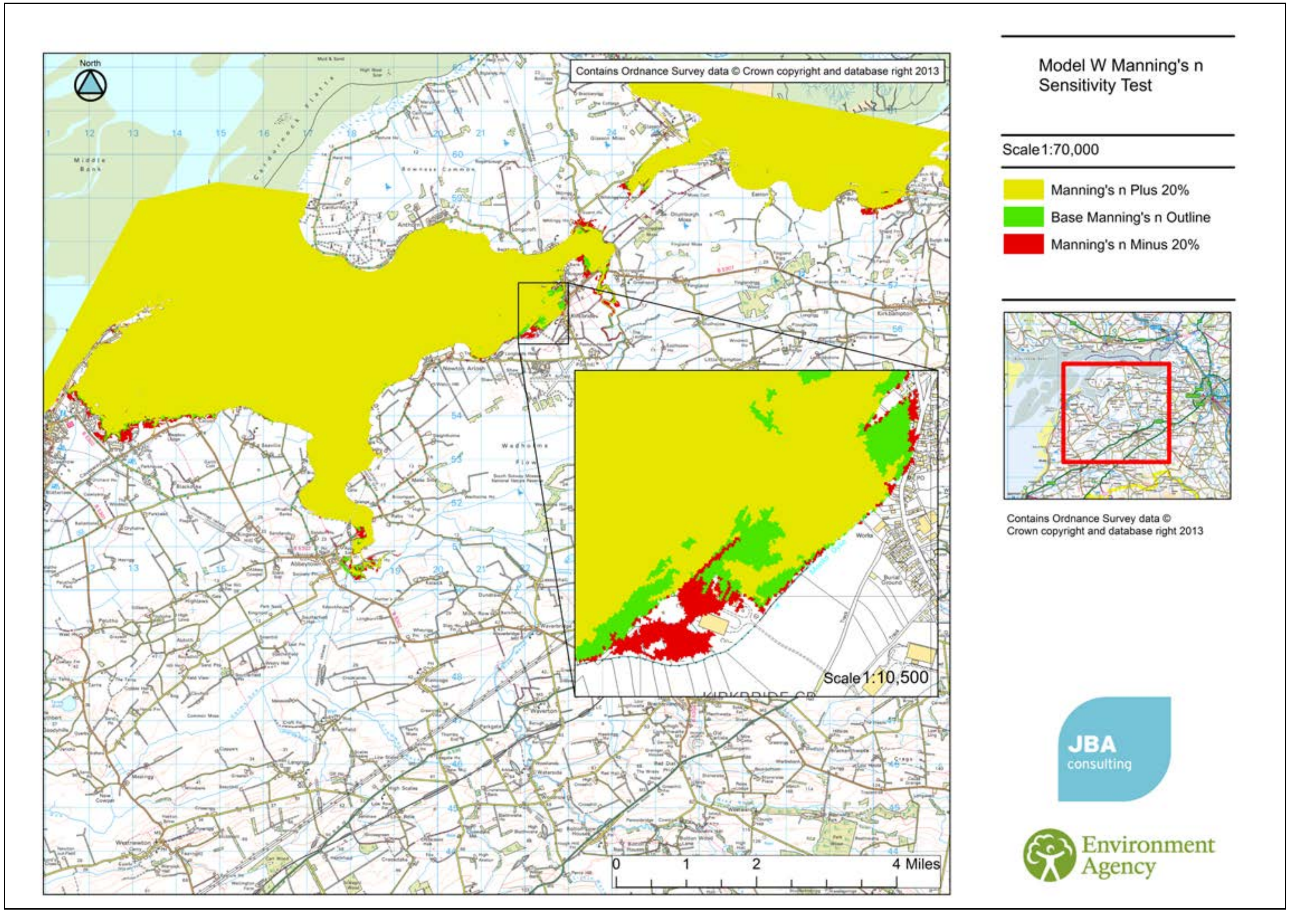
Figure 12-2: Wave return wall and stepped revetment along Skinburness Road (1). Rock armour at Dick Trod Lane (2). Skinburness embankment (3). One of three flood gates at Skinburness (4).

Figure 12-3: Model W sensitivity test



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13 Model Y - Carlisle

13.1 Design run information

Table A 21 in Appendix A provides a complete list of scenarios that were run for this model. There are five main model setups in total.

Due to the varying model architecture, the input file to each model also varies.

Details of general TUFLOW settings that were applied to all model scenarios are given in Table A 22, Appendix A.

13.2 TUFLOW domain

The model Y study area covers the area of the Solway Firth spanning from Rockcliffe Marsh in the west to Longtown in the east. It covers the Eden channel up to the M6 crossing at Linstock and the Esk channel to the north of Longtown. It covers the urban populations of Gretna, Carlisle, and Longtown. The area is largely covered by open pasture, marsh land and urban area.

The adopted model grid size was 5m and the active area of the model was 72km^2.

13.3 Model boundary

Tidal boundary

The tidal boundary spans the River Esk channel from high ground at Gretna in the north to high ground to the north of Burgh by Sands in the south. The tidal boundary applies a single HT tide curve along the model boundary line based on SEPA extreme sea levels for the Solway Firth estuary. The coastal flood boundary data used can be seen in Table 13-1.

Table 13-1: Tidal boundary data used

HAT Location	Surge Location	Coastal Flood Boundary Point Chainage	Model Reference
Silloth	Workington	SEPA 1434-12	BNDRY_1

Wave overtopping boundary

No wave overtopping was included in Model Y. Analysis was undertaken using SWAN nearshore wave heights around Rockcliffe Marsh but no wave overtopping was calculated.

13.4 Defences and sluice gates

Defences

The defences included in the model are formal defences and infrastructure (Figure 12-1). These consist of earth embankments that begin at high ground near Gretna and run south across Rockcliffe Marsh (Figure 13-2 - top and middle). Inland from the M6 Bridge the embankments follow the Esk channel banks quite closely; the Esk River defences run to Westlinton in the east and Longtown to the north. The Eden channel is largely protected by natural high ground but there are some earth embankments that run from Grinsdale to Willow Holme.There is a section of flood wall at Edentown.

The infrastructure included in the model includes railway lines, dismantled railway lines, and road. Of specific mention due to their size and importance is the M6 motorway and the railway line that runs past Gretna southwards to Carlisle running north to south across the catchment (Figure 13-2 - bottom).

The infrastructure was kept in the model for both defended and undefended simulations.

Sluice gates

Three flood gates were included in the model. The flood gates are interspersed along the earth embankment that runs from south of Gretna to the M6 Road Bridge across Mossband Hall Marsh. These include:

- Guards Cottage (332938, 566477)
- Mossband Hall Marsh (333445, 565503)
- Mossband Hall Marsh (334066, 564726).

In the undefended scenario the tidal gates were removed along with the embankment allowing water to pass past this area if the water level is high enough. There are several other sluice gates up the Eden channel around Carlisle but the tidal influence did not reach that far upstream so were not removed from the model for the undefended scenario.

13.5 Stability improvements

The model timestep used was half of the model grid size of 5 metres. This is well within the recommended range of between 0.25 to 0.50 times the model cell size.

Three stability patches (one ZTIN, one ZSHAPE (an area of model elevations modified by delineation of a polygon), and one roughness patch) were used in the model.

The ZSHAPE was used to raise some of the very small marsh channels at the boundary in order to stop flow coming into the main channel and going straight back out via these channels which was causing model instabilities.

The ZTIN was used to smooth the Solway bathymetry into the low-tide flown LIDAR.

The roughness patch was used to slightly increase the friction of a very small section of a channel that enters Mossband Hall Marsh.

The use of these stability patches is standard practice and most were required to remove unrealistic levels in the LIDAR which are an issue with the quality of data supplied rather than the model itself.

13.6 Model stability summary

Messages

There are between zero and one "Negative Depth" warning messages that occur during most of the design model simulations, apart from the 1,000-year and 200-year climate change scenarios where there were 15 and 12 messages respectively. These messages occur when the tide level is low and not at the peak and cause no obvious water level issues in the model so are acceptable.

The few messages within this model are a sign that the model is stable.

Checks

There are zero check messages during the simulations.

Change in volume

There are some small oscillations in the change in volume throughout all model simulations undertaken by this study. These oscillations are superimposed onto the expected volume flux of the model. Such oscillations are common within tidal models and the cause of these oscillations may be due to eddy effects in the offshore bathymetry which are generated by the action of flood water being constricted into and out of the channel mouth. The oscillations are unlikely to have any significant affect on the flood outlines as the oscillations are small in comparison to the overall change in volume associated with the tidal cycles. Time series head levels were checked throughout the model simulation at various points along the coast and within the estuary channel, and show that the small oscillations in volume are not having an impact on head levels in the model.

Cumulative mass balance error

The cumulative mass error spikes up to a peak of up to +/-1.00% in most of the model simulations after 2 hours which is when flow starts entering the model and wetting up model cells. Once the model settles down the cumulative mass balance drops quickly to generally less than +/-0.10% which is well within the recommended +/-1.00% error stated as acceptable in the TUFLOW guidelines.

13.7 Model sensitivity

Manning's *n* values were both increased and decreased by 20% in the 2D model to assess the sensitivity of the system to changing floodplain roughness. A large flood was used in the sensitivity testing as this allows for a suitable comparison between the results and their outlines. The flood return period used for the sensitivity testing was 200-year undefended.

Sensitivity results showed that the model was not overly sensitive to changes in hydraulic roughness. The mean, maximum and minimum water levels extracted from the maximum grids show a relatively small change between the differing Manning's *n* runs, in particular the maximum water levels are within +/- 12cm of the base Manning's *n* run while mean water levels are within +/- 2cm.

Figure 13-3 shows the difference in flood extents between the different roughness runs. In general flood extents are very similar with the most noticeable difference occurring along the Esk Channel to the east of the M6 Road Bridge crossing. The lowered Manning's *n* values lead to a more extensive outline and the raised manning's values leading to a smaller outline.

The difference in water levels and extents caused by a 20% change in hydraulic roughness show that this model is not overly sensitive to changes in Manning's *n* given the flat nature of the topography and scale of the floodplain.

Figure 13-1: Model Y study area and defences

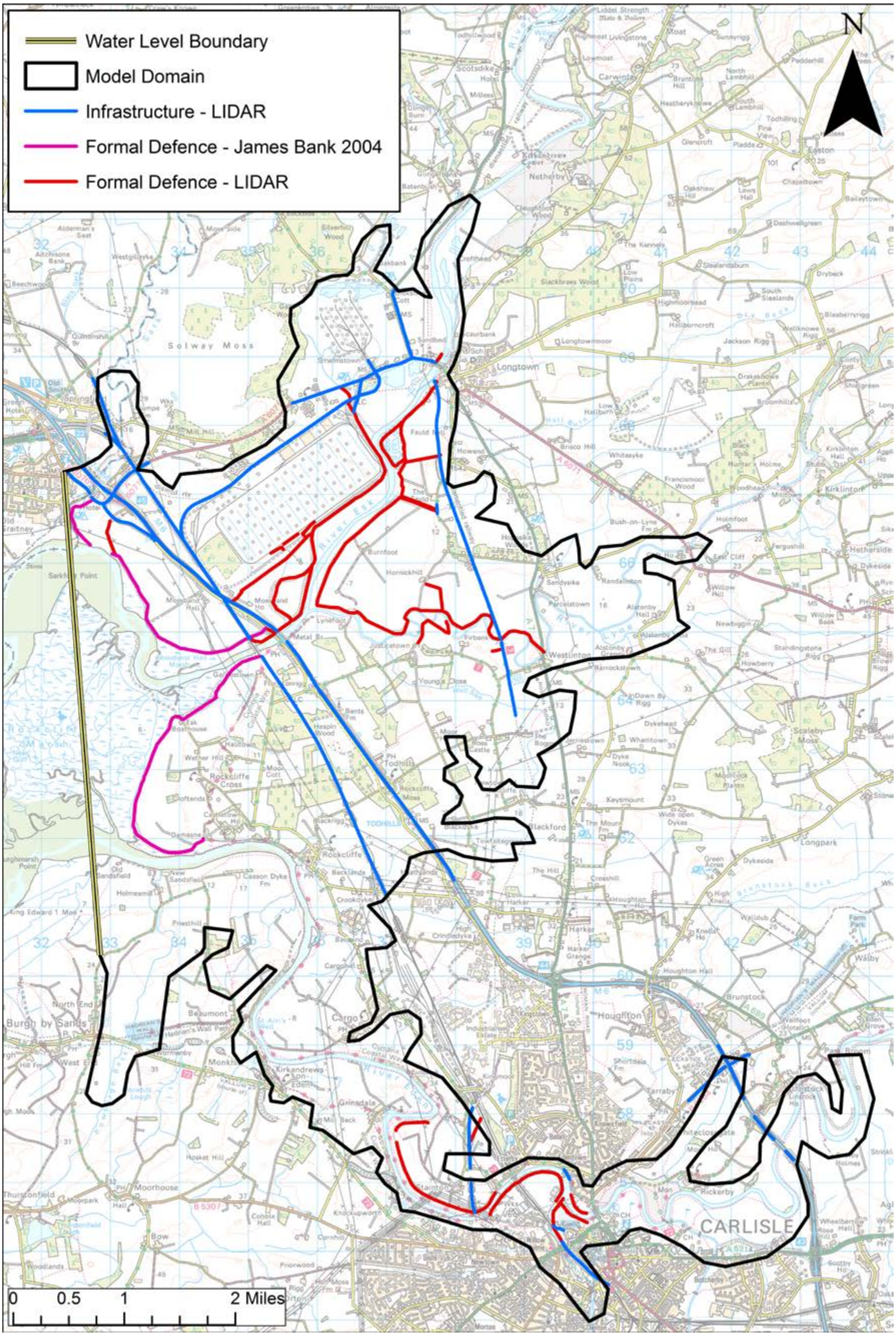

Figure 13-2: Earth embankments at Metalbridge on the Esk (top). Embankment running across Rockcliffe Marsh (middle). Railway line and M6 motorway infrastructure (bottom).

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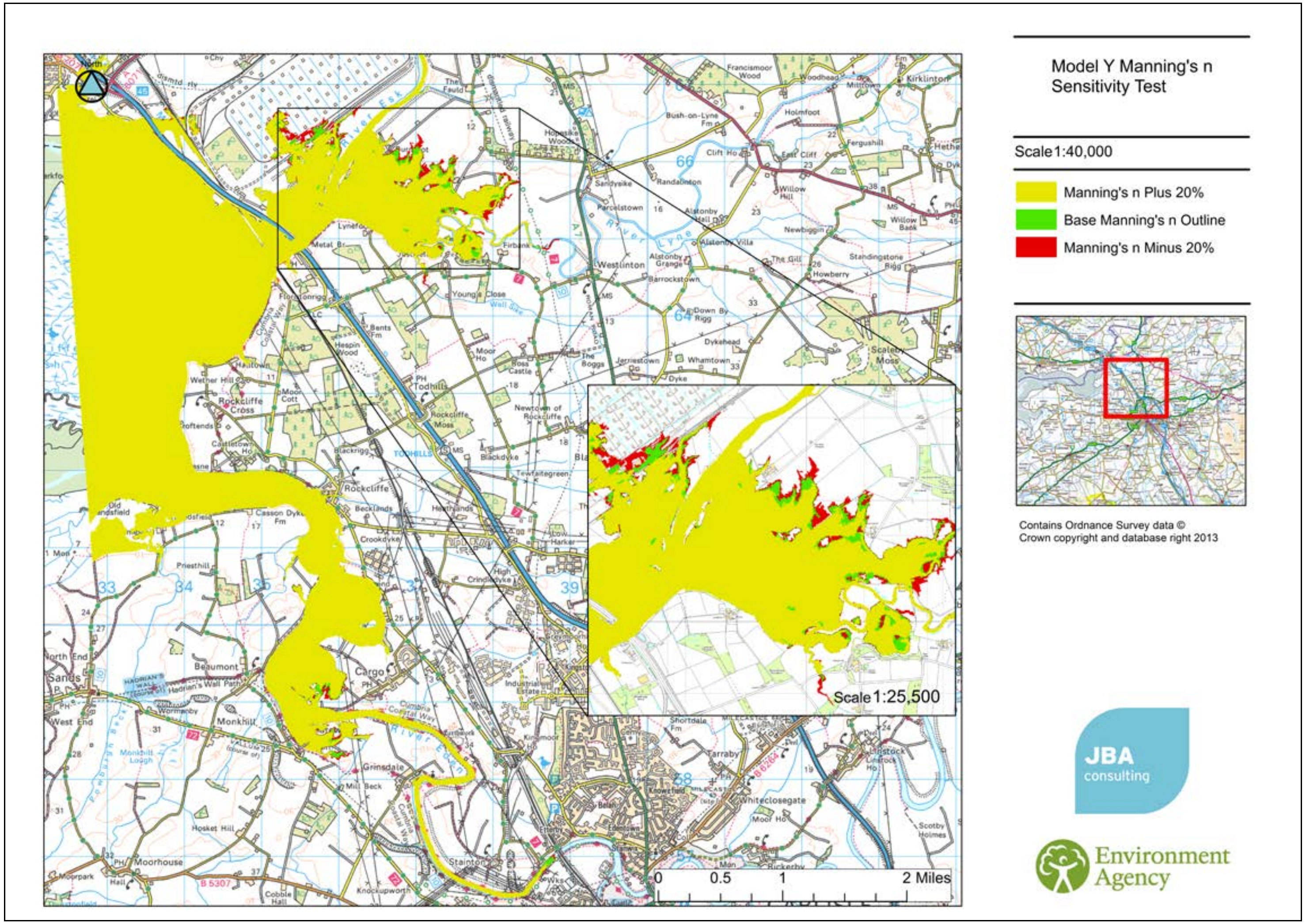
Figure 13-3: Model Y sensitivity test



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14 Fluvial modelling

14.1 Overview

In the 2006 study, the fluvial Flood Zone within the study area was modelled using JFLOW as part of the National Generalised Fluvial Flood Mapping Project. JFLOW is a JBA Consulting in-house 2D model developed for large scale over land inundation modelling.

The fluvial part of the National Flood zone will be updated by using the latest DTM. In order to inform the updates it was necessary to carry out some investigations into fluvial modelling that took place within the Cumbrian study area since 2006.

14.2 Existing fluvial modelling

The first step was to identify any fluvial models that were built within the catchment since the previous study in 2006. Of these models, assuming the 200 and 1,000-year event simulations were run, the outlines can be merged with the tidal flood zones in order to create an attributed Flood Zone for tidal, fluvial, and tidal/fluvial risk zones. The fluvial models that were developed since 2006 can be seen in Table 14-1.

Table 14-1: Fluvial model review

Model	River	Fluvial Model
C	River Kent	Halcrow 2009. 1D ESTRY model linked to 2D TUFLOW foodplain model of Lyth Valley.
C	River Gilpin	EA In-house J-Flow CPU v7.1 2011.
C	River Pool	Halcrow 2009. 1D ESTRY model linked to 2D TUFLOW foodplain model of Lyth Valley.
E	Dragley Beck	Kent and Leven ABD and modelled flood zones, JBA 2009.
E	Lund Beck	Kent and Leven ABD and modelled flood zones, JBA 2009.
E	River Crake	River Crake, Yewdale and Church Becks Flood Risk Mapping Study 2005.
K	Black Beck	South lakes Flood Risk Mapping Study, 2006.
K	Soutergate Beck	Cumbrian Villages Flood Map Improvements, JBA 2009.
Q	Midgey Gill	Flood Risk mapping Study of Whitehaven, coming 2012/2013.
Q	Pow Beck	Flood Risk mapping Study of Whitehaven, coming 2012/2013.
S	Eel Sike	River Ellen and Eel Sike Flood Mapping Project, 2009.
S	Ling Beck	North Area Ex-COWS Flood Mapping Ling Beck, Jacobs 2009. Only flood outlines, no levels.
S	River Derwent	Rivers Derwent and Cocker Flood mapping Study, 2009.
S	River Ellen	River Ellen and Eel Sike Flood Mapping Project, 2009.
S	Scale Beck	North Area Ex-COWS Flood Mapping Scale Beck, Jacobs 2009. Only flood outlines, no levels.

Model	River	Fluvial Model
W	River Wampool	River Wampool Flood Risk Study, 2009.
W	River Waver	Jflow model on River Waver section including Pow Gill, 2009.

14.3 New fluvial modelling

For all areas where no new modelling has taken place since 2006 new JFLOW runs were undertaken. The hydrology used was based on the Centre for Ecology and Hydrology (CEH) peak flow estimates from 2006. The topography was based on the new TUFLOW model mesh grids, which were extracted directly from the TUFLOW models, with a few additional terrain edits made through structures to ensure fluvial channels and flow paths are open. The rivers that were run using JFLOW can be seen in Table 14-2.

Table 14-2: New JFLOW simulation rivers and upstream point locations

Model	River	Eastings	Northings
Y	Alstonby Beck	341196	565054
	Beck burn	335774	569663
	Brunstock beck	341933	558689
	Cargo Beck	337115	559063
	DLO Longtown Drain	335419	566096
	Edentown Drain	339630	557060
	Gaitle Burn Tributary	336584	569810
	Greathill Beck	333674	558976
	Hall Burn	338434	567280
	Hether Burn	341646	566251
	Longtown Drain	337893	568245
	Old Eden	342300	556100
	Pow Maughan	343963	557916
	Powburgh Beck	332897	558159
	River Caldew	339968	555039
	River Eden	343595	558815
	River Esk	338260	571241
	River Lyne	341508	566410
	River Petterill	341731	555901
	Rockcliffe Beck	338212	562029
	Warren Burn	338050	570050
	Well Sike	337672	564132
W	Bampton Beck	326406	554242
	Colmire Sough	324437	550273
	Crummock Beck	317937	547258
	Grass Dyke	328332	557959
	Great Gutter	312838	554869
	Helledike Beck	312260	550526
	Holme Dub	314097	546670
	Langrigg Beck	317027	546582
	Longburgh Drain	331169	558881
	Pow Beck	328077	551345
	Ridding Sough	330139	557039
	Scotre Hill Drain	313286	551094
	Thornby Drain	327895	551935
	Wisa Beck	327217	550071
O	Black Beck	307710	500048

Model	River	Eastings	Northings
	Broadoak Beck	310997	495216
	Eskmeals Pool	309275	491405
	Plum Dub	314084	498348
	River Irt	310285	500803
	River Mite	311098	499157
	Whitrow Beck	310007	494095
M	Broomhill Beck	310470	487306
	Holegill Beck	310337	487129
	Millergill Beck	310187	485597
K	Blea Beck	321117	478295
	Galloper Pool	321417	485360
	Green Moor Beck	324390	488052
	Grize Beck	323776	485014
	Kirkby Pool	324281	489817
	Press Beck	323648	485153
	River Duddon	319567	489297
	River Lickie	321412	489885
	Salthouse Pool	317210	481111
	Silecroft Beck	313097	482096
	Whicham Beck	314190	481929
H	Green Meadows Beck	325823	470748
	Mill Beck	322177	471632
	Sarah Beck	323717	468981
	Whampsters Beck	324985	469520
E	Ashes Beck	334531	490059
	Bell Beck	333331	489066
	Colton Beck	331584	485147
	Deanholme Wood Drain	334280	480513
	Force Beck	333742	490785
	Levy Beck	328395	477414
	Main Drain (Winder Moor)	338328	475117
	Newland Beck	329625	480138
	River Eea	336821	477120
	Town Beck	328902	478199
C	Arndale Back	342711	489784
	Leighton Beck	348210	478213
	Mill Stream	344711	484293
	River Bela	349629	480354
	River Winster	341887	489306
	Silverdale Moss Drain	346821	477505
	Spannel Beck	341848	486868
A	The Pool (Leighton Moss Drain)	348364	474896

14.4 Fluvial Flood Zone attribution

The updates to the new Flood Zones will be a combination of the tidal extents from the TUFLOW modelling, and the fluvial extents.

The fluvial flood risk areas will be a combination of the new JFLOW outlines and outlines that were produced from the existing models that were built since 2006. Any flood risk outside of the tidal flood extents will be classified as fluvial and any areas that are at risk from both tidal and fluvial will be classed as tidal/fluvial.

15 Projection modelling

15.1 Overview

In the previous 2006 study projection modelling was undertaken for lengths of relatively steep coastline, where there is no benefit in applying hydrodynamic modelling. For the study update the projection modelling approach was adopted but it was updated based on the latest data inputs.

Digital terrain model construction

A DTM of the whole Cumbrian coastline was constructed using four different DTM layers. Each was stamped on top of each other to give the best possible resulting DTM for use in projection modelling. The order of the DTM construction from the topmost layer is:

- The TUFLOW model grids from the undefended with infrastructure model runs (this was done to ensure that the infrastructure was stamped into the grid)
- A combined 2m LIDAR DTM based on 2m LIDAR for the land based topography and 2m low-tide flown LIDAR for the foreshore areas
- A 5m SAR DTM, and finally SeaZone TruDepth grid of offshore bathymetry.

A mosaic of these data was constructed to provide a single layer in ArcGIS.

Water level grid construction

Extreme sea level (ESL) points from the latest coastal extremes guidance[6] were used for the basis of the water level grid used for the projection modelling. The 30-year ESL was not available and so was produced by a linear interpolation method between the 20 and 50-year ESL. Different extreme water levels were used for the Solway Firth Estuary which were provided by SEPA.

The ESL values were applied to cross-sections that intersect the ESL point (Figure 15-1). These cross-sections were used to construct water level grid TINs for each of the required return periods. The TINs were converted to rasters with a 2m cell size within ArcGIS.

Depth grid construction

Depth grids for each return period were constructed by subtracting the DTM from the Water Level raster within ArcToolbox Spatial Analyst tool suite. To produce the final depth grid all values below 0m was converted to null values to leave only the resulting depth values. This was done using the “Setnull” function within Spatial Analysis ArcToolbox suite.

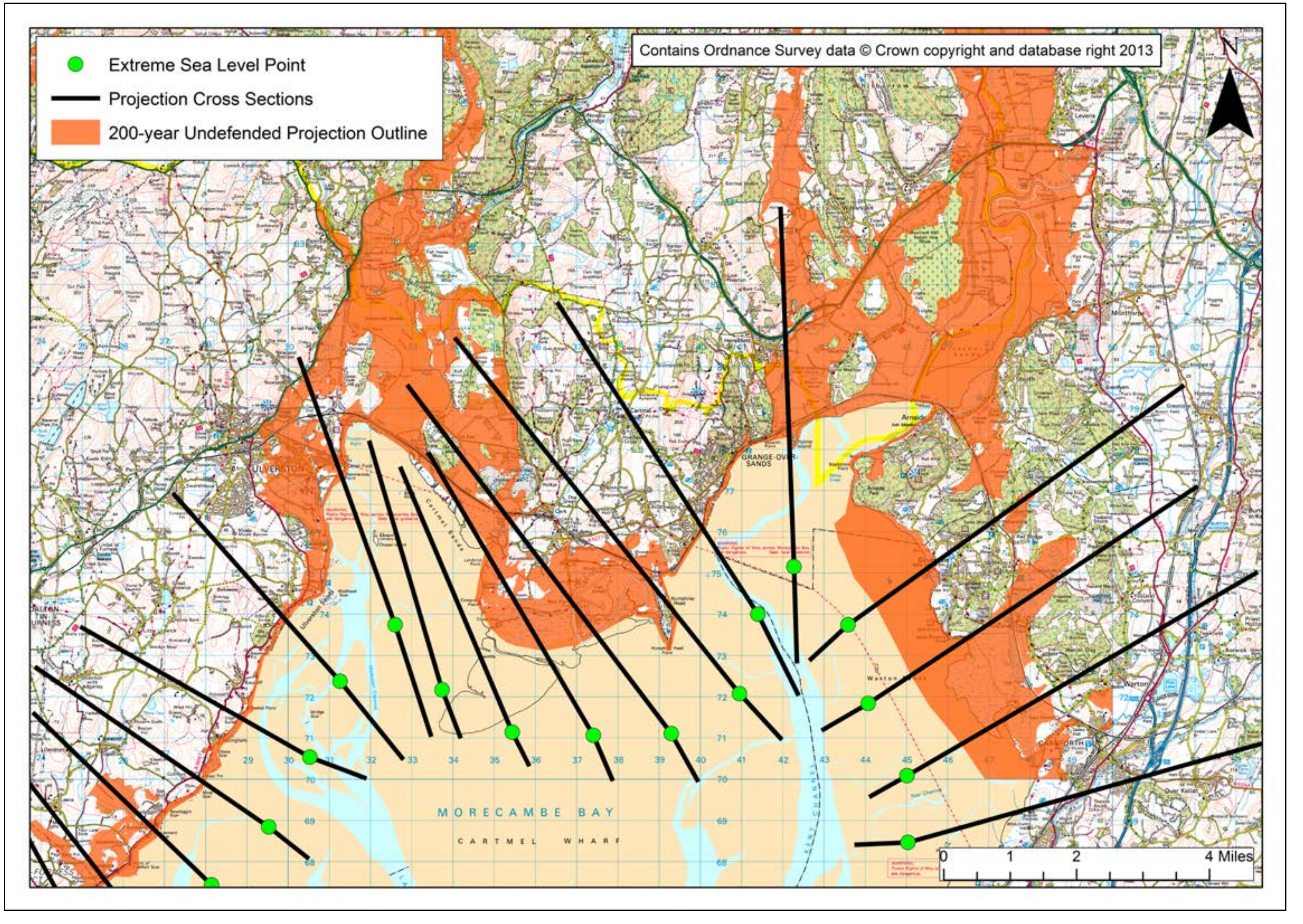
Outline construction

The final depth grids were converted into outline polygon shape files. During the process all isolated polygons smaller than 200m^2 were removed and dry islands smaller than 750m^2 were filled. All the flood outlines were manually edited by removing isolated polygons that were not related to the main body of flooding and where there was no known flow path or connection. The outlines were post processed in the same manner as the TUFLOW outlines.

The flood outlines created from the raw model output were defined in the British National Grid projection and smoothed using a GIS smoothing algorithm. After the outlines had been smoothed any nodes with a separation distance of less than 1m were then removed to create the final outlines.

[6] Defra. SEPA. The Scottish Goverment. Environment Agency (2011). Coastal flood boundary conditions for UK mainland and islands. Project: SC060064/TR2: Design sea levels.

Figure 15-1: Extreme sea level points and projection cross-sections for water level grid construction



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Appendix

A Model control files and general model settings

Table A 1: Model A control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_A_~e1~_~s1~.tcf	PR_bc_dbase_Model_A.csv	Cumbria_Model_A_Undefended_001.tgc	Cumbria_Model_A_Undefended_001.tbc	Cumbria_Model_A_001.tmf	2.5	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_A_~e1~_~s1~.tcf	PR_bc_dbase_Model_A_WO.csv	Cumbria_Model_A_Defended_001.tgc	Cumbria_Model_A_Defended_001.tbc	Cumbria_Model_A_001.tmf	2.5	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_A_~e1~_~s1~.tcf	PR_bc_dbase_Model_A.csv	Cumbria_Model_A_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_A_Undefended_001.tbc	Cumbria_Model_A_001.tmf	2.5	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_A_~e1~_~s1~.tcf	PR_bc_dbase_Model_A_WO.csv	Cumbria_Model_A_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_A_Defended_001.tbc	Cumbria_Model_A_001.tmf	2.5	64bit
Sensitivity	200-year	Cumbria_Model_A_~e1~_~s1~.tcf	PR_bc_dbase_Model_A.csv	Cumbria_Model_A_Undefended_001.tgc	Cumbria_Model_A_Undefended_001.tbc	Cumbria_Model_A_Minus/Plus20_001	2.5	64bit

Table A 2: Model A general model settings

General Settings	
Start Time (hrs)	55.5
End Time (hrs)	93.0
Grid Cell Size (m)	5.0
Timestep (s)	2.5
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	56.0
Map Output Interval (s)	1,800.0
Time Series Output Interval (s)	60.0
Restart File	
Undefended Scenario	Restart_Cumbria_Model_A_T1000_UDef.trf
Undefended CC Scenario	Restart_Cumbria_Model_A_T200CC_UDef.trf
Undefended No Infrastructure Scenario	Restart_Cumbria_Model_A_T1000_UDef_No_Infrastructure.trf
Defended Scenario	Restart_Cumbria_Model_A_T1000_TEST.trf
Defended CC Scenario	Restart_Cumbria_Model_A_T200CC_TEST.trf
Defended Lowered Infrastructure Scenario	Restart_Cumbria_Model_A_T75_Def_Lowered_Infrastructure.trf
Sensitivity Testing Scenario	Restart_Cumbria_Model_A_T1000_UDef.trf

Table A 3: Model C control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_C_~e1~_~s1~.tcf	PR_bc_dbase_Model_C.csv	Cumbria_Model_C_Undefended_001.tgc	Cumbria_Model_C_Undefended_001.tbc	Cumbria_Model_C_001.tmf	66	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_C_~e1~_~s1~.tcf	PR_bc_dbase_Model_C_WO.csv	Cumbria_Model_C_Defended_001.tgc	Cumbria_Model_C_Undefended_001.tbc	Cumbria_Model_C_001.tmf	45	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_C_~e1~_~s1~.tcf	PR_bc_dbase_Model_C.csv	Cumbria_Model_C_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_C_Undefended_001.tbc	Cumbria_Model_C_001.tmf	66	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_C_~e1~_~s1~.tcf	PR_bc_dbase_Model_C_WO.csv	Cumbria_Model_C_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_C_Undefended_001.tbc	Cumbria_Model_C_001.tmf	45	64bit
Sensitivity	200-year	Cumbria_Model_C_~e1~_~s1~.tcf	PR_bc_dbase_Model_C.csv	Cumbria_Model_C_Undefended_001.tgc	Cumbria_Model_C_Undefended_001.tbc	Cumbria_Model_C_Minus/Plus20_001	66	64bit

Table A 4: Model C general model settings

General Settings	
Start Time (hrs)	56.0
End Time (hrs)	93.0
Grid Cell Size (m)	5.0
Timestep (s)	2.5
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	56.0
Map Output Interval (s)	1,800.0
Time Series Output Interval (s)	60.0
Restart File	
Undefended Scenario	Restart_Cumbria_Model_C_T1000_UDef.trf
Undefended CC Scenario	Restart_Cumbria_Model_C_T200CC_UDef.trf
Undefended No Infrastructure Scenario	Restart_Cumbria_Model_C_T1000_UDef_No_Infrastructure.trf
Defended Scenario	Restart_Cumbria_Model_C_T1000_TEST.trf
Defended CC Scenario	Restart_Cumbria_Model_C_T200CC_TEST.trf
Defended Lowered Infrastructure Scenario	Restart_Cumbria_Model_C_T1000_Def_Lowered_Infrastructure.trf
Sensitivity Testing Scenario	Restart_Cumbria_Model_C_T1000_UDef.trf

Table A 5: Model E control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_E_~e1~_~s1~.tcf	PR_bc_dbase_Model_E.csv	Cumbria_Model_E_Undefended_001.tgc	Cumbria_Model_E_Undefended_001.tbc	Cumbria_Model_E_001.tmf	161	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_E_~e1~_~s1~.tcf	PR_bc_dbase_Model_E_WO.csv	Cumbria_Model_E_Defended_001.tgc	Cumbria_Model_E_Defended_001.tbc	Cumbria_Model_E_001.tmf	72	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_E_~e1~_~s1~.tcf	PR_bc_dbase_Model_E.csv	Cumbria_Model_E_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_E_Undefended_001.tbc	Cumbria_Model_E_001.tmf	161	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_E_~e1~_~s1~.tcf	PR_bc_dbase_Model_E_WO.csv	Cumbria_Model_E_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_E_Defended_001.tbc	Cumbria_Model_E_001.tmf	72	64bit
Sensitivity	200-year	Cumbria_Model_E_~e1~_~s1~.tcf	PR_bc_dbase_Model_E.csv	Cumbria_Model_E_Undefended_001.tgc	Cumbria_Model_E_Undefended_001.tbc	Cumbria_Model_E_Minus/Plus20_001	161	64bit

Table A 6: Model E general model settings

General Settings	
Start Time (hrs)	56.0
End Time (hrs)	93.0
Grid Cell Size (m)	5.0
Timestep (s)	2.5
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	56.0
Map Output Interval (s)	1,800.0
Time Series Output Interval (s)	60.0
Restart File	
Undefended Scenario	Restart_Cumbria_Model_E_T1000_UDef.trf
Undefended CC Scenario	Restart_Cumbria_Model_E_T200CC_UDef.trf
Undefended No Infrastructure Scenario	Restart_Cumbria_Model_E_T1000_UDef_No_Infrastructure.trf
Defended Scenario	Restart_Cumbria_Model_E_T1000_TEST.trf
Defended CC Scenario	Restart_Cumbria_Model_E_T200CC_TEST.trf
Defended Lowered Infrastructure Scenario	Restart_Cumbria_Model_E_T1000_Def_Lowered_Infrastructure.trf
Sensitivity Testing Scenario	Restart_Cumbria_Model_E_T1000_UDef.trf

Table A 7: Model H control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_H_~e1~_~s1~.tcf	PR_bc_dbase_Model_H.csv	Cumbria_Model_H_Undefended_001.tgc	Cumbria_Model_H_Undefended_001.tbc	Cumbria_Model_H_001.tmf	66	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_H_~e1~_~s1~.tcf	PR_bc_dbase_Model_H_WO.csv	Cumbria_Model_H_Defended_001.tgc	Cumbria_Model_H_Defended_001.tbc	Cumbria_Model_H_001.tmf	45	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_H_~e1~_~s1~.tcf	PR_bc_dbase_Model_H.csv	Cumbria_Model_H_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_H_Undefended_001.tbc	Cumbria_Model_H_001.tmf	66	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_H_~e1~_~s1~.tcf	PR_bc_dbase_Model_H_WO.csv	Cumbria_Model_H_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_H_Defended_001.tbc	Cumbria_Model_H_001.tmf	45	64bit
Sensitivity	200-year	Cumbria_Model_H_~e1~_~s1~.tcf	PR_bc_dbase_Model_H.csv	Cumbria_Model_H_Undefended_001.tgc	Cumbria_Model_H_Undefended_001.tbc	Cumbria_Model_H_Minus/Plus20_001	66	64bit

Table A 8: Model H general model settings

General Settings	
Start Time (hrs)	40.5
End Time (hrs)	90.0
Grid Cell Size (m)	10.0
Timestep (s)	2.5
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	40.5
Map Output Interval (s)	1,800.0
Time Series Output Interval (s)	60.0
Restart File	
No Restart Files Used	

Table A 9: Model K control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_K_~e1~_~s1~.tcf	PR_bc_dbase_Model_K.csv	Cumbria_Model_K_Undefended_001.tgc	Cumbria_Model_K_Undefended_001.tbc	Cumbria_Model_K_001.tmf	35	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_K_~e1~_~s1~.tcf	PR_bc_dbase_Model_K_WO.csv	Cumbria_Model_K_Defended_001.tgc	Cumbria_Model_K_Defended_001.tbc	Cumbria_Model_K_001.tmf	35	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_K_~e1~_~s1~.tcf	PR_bc_dbase_Model_K.csv	Cumbria_Model_K_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_K_Undefended_001.tbc	Cumbria_Model_K_001.tmf	35	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_K_~e1~_~s1~.tcf	PR_bc_dbase_Model_K_WO.csv	Cumbria_Model_K_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_K_Defended_001.tbc	Cumbria_Model_K_001.tmf	35	64bit
Sensitivity	200-year	Cumbria_Model_K_~e1~_~s1~.tcf	PR_bc_dbase_Model_K.csv	Cumbria_Model_K_Undefended_Sens_001.tgc	Cumbria_Model_K_Undefended_001.tbc	Cumbria_Model_K_Minus/Plus20_001	35	64bit

Table A 10: Model K general model settings

General Settings	
Start Time (hrs)	40.75
End Time (hrs)	90.00
Grid Cell Size (m)	10.00
Timestep (s)	2.50
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	40.75
Map Output Interval (s)	1,800.00
Time Series Output Interval (s)	60.00
Restart File	
No Restart Files Used	

Table A 11: Model M control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_M_~e1~_~s1~.tcf	PR_bc_dbase_Model_M.csv	Cumbria_Model_M_Undefended_001.tgc	Cumbria_Model_M_Undefended_001.tbc	Cumbria_Model_M_001.tmf	8	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_M_~e1~_~s1~.tcf	PR_bc_dbase_Model_M_WO.csv	Cumbria_Model_M_Defended_001.tgc	Cumbria_Model_M_Defended_001.tbc	Cumbria_Model_M_001.tmf	7	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_M_~e1~_~s1~.tcf	PR_bc_dbase_Model_M.csv	Cumbria_Model_M_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_M_Undefended_001.tbc	Cumbria_Model_M_001.tmf	8	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_M_~e1~_~s1~.tcf	PR_bc_dbase_Model_M_WO.csv	Cumbria_Model_M_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_M_Defended_001.tbc	Cumbria_Model_M_001.tmf	7	64bit
Sensitivity	200-year	Cumbria_Model_M_~e1~_~s1~.tcf	PR_bc_dbase_Model_M.csv	Cumbria_Model_M_Undefended_Sens_001.tgc	Cumbria_Model_M_Undefended_001.tbc	Cumbria_Model_M_Minus/Plus20_001	8	64bit

Table A 12: Model M general model settings

General Settings	
Start Time (hrs)	40.75
End Time (hrs)	90.00
Grid Cell Size (m)	5.00
Timestep (s)	1.25
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	53.00
Map Output Interval (s)	1,800.00
Time Series Output Interval (s)	60.00
Restart File	
No Restart Files Used	

Table A 13: Model O control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_O_~e1~_~s1~.tcf	PR_bc_dbase_Model_O.csv	Cumbria_Model_O_Undefended_001.tgc	Cumbria_Model_O_Undefended_001.tbc	Cumbria_Model_O_001.tmf	76	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_O_~e1~_~s1~.tcf	PR_bc_dbase_Model_O_WO.csv	Cumbria_Model_O_Defended_001.tgc	Cumbria_Model_O_Defended_001.tbc	Cumbria_Model_O_001.tmf	54	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_O_~e1~_~s1~.tcf	PR_bc_dbase_Model_O.csv	Cumbria_Model_O_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_O_Undefended_001.tbc	Cumbria_Model_O_001.tmf	76	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_O_~e1~_~s1~.tcf	PR_bc_dbase_Model_O_WO.csv	Cumbria_Model_O_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_O_Defended_001.tbc	Cumbria_Model_O_001.tmf	54	64bit
Sensitivity	200-year	Cumbria_Model_O_~e1~_~s1~.tcf	PR_bc_dbase_Model_O.csv	Cumbria_Model_O_Undefended_001.tgc	Cumbria_Model_O_Undefended_001.tbc	Cumbria_Model_O_Minus/Plus20_001	76	64bit

Table A 14: Model O general model settings

General Settings	
Start Time (hrs)	43.25
End Time (hrs)	92.75
Grid Cell Size (m)	5.00
Timestep (s)	1.25
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	43.25
Map Output Interval (s)	1,800.00
Time Series Output Interval (s)	60.00
Restart File	
No Restart Files Used	

Table A 15: Model Q control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_Q_~e1~_~s1~.tcf	PR_bc_dbase_Model_Q.csv	Cumbria_Model_Q_Undefended_001.tgc	Cumbria_Model_Q_Undefended_001.tbc	Cumbria_Model_Q_001.tmf	3	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_Q_~e1~_~s1~.tcf	PR_bc_dbase_Model_Q_WO.csv	Cumbria_Model_Q_Defended_001.tgc	Cumbria_Model_Q_Defended_001.tbc	Cumbria_Model_Q_001.tmf	3	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_Q_~e1~_~s1~.tcf	PR_bc_dbase_Model_Q.csv	Cumbria_Model_Q_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_Q_Undefended_001.tbc	Cumbria_Model_Q_001.tmf	3	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_Q_~e1~_~s1~.tcf	PR_bc_dbase_Model_Q_WO.csv	Cumbria_Model_Q_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_Q_Defended_001.tbc	Cumbria_Model_Q_001.tmf	3	64bit
Sensitivity	200-year	Cumbria_Model_Q_~e1~_~s1~.tcf	PR_bc_dbase_Model_Q.csv	Cumbria_Model_Q_Undefended_001.tgc	Cumbria_Model_Q_Undefended_001.tbc	Cumbria_Model_Q_Minus/Plus20_001	3	64bit

Table A 16: Model Q general model settings

General Settings	
Start Time (hrs)	43.50
End Time (hrs)	92.75
Grid Cell Size (m)	5.00
Timestep (s)	1.25
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	43.50
Map Output Interval (s)	1,800.00
Time Series Output Interval (s)	60.00
Restart File	
No Restart Files Used	

Table A 17: Model S control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_S_~e1~_~s1~.tcf	PR_bc_dbase_Model_S.csv	Cumbria_Model_S_Undefended/CC_001.tgc	Cumbria_Model_S_Undefended_001.tbc	Cumbria_Model_S_001.tmf	30	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_S_~e1~_~s1~.tcf	PR_bc_dbase_Model_S_WO.csv	Cumbria_Model_S_Defended/CC_001.tgc	Cumbria_Model_S_Defended_001.tbc	Cumbria_Model_S_001.tmf	30	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_S_~e1~_~s1~.tcf	PR_bc_dbase_Model_S.csv	Cumbria_Model_S_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_S_Undefended_001.tbc	Cumbria_Model_S_001.tmf	30	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_S_~e1~_~s1~.tcf	PR_bc_dbase_Model_S_WO.csv	Cumbria_Model_S_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_S_Defended_001.tbc	Cumbria_Model_S_001.tmf	30	64bit
Sensitivity	200-year	Cumbria_Model_S_~e1~_~s1~.tcf	PR_bc_dbase_Model_S.csv	Cumbria_Model_S_Undefended_001.tgc	Cumbria_Model_S_Undefended_001.tbc	Cumbria_Model_S_Minus/Plus20_001	30	64bit

Table A 18: Model S general model settings

General Settings	
Start Time (hrs)	30.50
End Time (hrs)	80.00
Grid Cell Size (m)	5.00
Timestep (s)	1.25
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	30.50
Map Output Interval (s)	1,800.00
Time Series Output Interval (s)	60.00
Restart File	
No Restart Files Used	

Table A 19: Model W control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_W_~e1~_~s1~.tcf	PR_bc_dbase_Model_W.csv	Cumbria_Model_W_Undefended_001.tgc	Cumbria_Model_W_Undefended_001.tbc	Cumbria_Model_W_001.tmf	28	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_W_~e1~_~s1~.tcf	PR_bc_dbase_Model_W_WO.csv	Cumbria_Model_W_Defended_001.tgc	Cumbria_Model_W_Defended_001.tbc	Cumbria_Model_W_001.tmf	28	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_W_~e1~_~s1~.tcf	PR_bc_dbase_Model_W.csv	Cumbria_Model_W_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_W_Undefended_001.tbc	Cumbria_Model_W_001.tmf	28	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_W_~e1~_~s1~.tcf	PR_bc_dbase_Model_W_WO.csv	Cumbria_Model_W_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_W_Defended_001.tbc	Cumbria_Model_W_001.tmf	28	64bit
Sensitivity	200-year	Cumbria_Model_W_~e1~_~s1~.tcf	PR_bc_dbase_Model_W.csv	Cumbria_Model_W_Undefended_001.tgc	Cumbria_Model_W_Undefended_001.tbc	Cumbria_Model_W_Minus/Plus20_001	28	64bit

Table A 20: Model W general Model settings

General Settings	
Start Time (hrs)	44.0
End Time (hrs)	93.5
Grid Cell Size (m)	10.0
Timestep (s)	2.5
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	44.0
Map Output Interval (s)	1,800.0
Time Series Output Interval (s)	60.0
Restart File	
No Restart Files Used	

Table A 21: Model Y control files

Scenario	Events	Control Files	BC Database File	Geometry Control File	Boundary Control File	Materials Control File	Approx. Run Time (hrs)	Computer OS Req.
Undefended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_Y_~e1~_~s1~.tcf	PR_bc_dbase_Model_Y.csv	Cumbria_Model_Y_Undefended_001.tgc	Cumbria_Model_Y_Undefended_001.tbc	Cumbria_Model_Y_001.tmf	64	64bit
Defended	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_Y_~e1~_~s1~.tcf	PR_bc_dbase_Model_Y_YO.csv	Cumbria_Model_Y_Defended_001.tgc	Cumbria_Model_Y_Defended_001.tbc	Cumbria_Model_Y_001.tmf	35	64bit
Undefended with Infrastructure Removed	1,000, 200, 100, 75, 30, and 200-year (2115)	Cumbria_Model_Y_~e1~_~s1~.tcf	PR_bc_dbase_Model_Y.csv	Cumbria_Model_Y_Undefended_No_Infrastructure_001.tgc	Cumbria_Model_Y_Undefended_001.tbc	Cumbria_Model_Y_001.tmf	64	64bit
Defended with Infrastructure Lowered by 30cm	200, 100, and 75-year	Cumbria_Model_Y_~e1~_~s1~.tcf	PR_bc_dbase_Model_Y_YO.csv	Cumbria_Model_Y_Defended_Lowered_Infrastructure_001.tgc	Cumbria_Model_Y_Defended_001.tbc	Cumbria_Model_Y_001.tmf	35	64bit
Sensitivity	200-year	Cumbria_Model_Y_~e1~_~s1~.tcf	PR_bc_dbase_Model_Y.csv	Cumbria_Model_Y_Undefended_001.tgc	Cumbria_Model_Y_Undefended_001.tbc	Cumbria_Model_Y_Minus/Plus20_001	64	64bit

Table A 22: Model Y general model settings

General Settings	
Start Time (hrs)	44.0
End Time (hrs)	93.5
Grid Cell Size (m)	5.0
Timestep (s)	2.5
Map Output Settings	
Map Output Format	XMDF
Map Output Data Types	d h v ZUK0
Start Map Output Time (hrs)	44.0
Map Output Interval (s)	1,800.0
Time Series Output Interval (s)	60.0
Restart File	
No Restart Files Used	

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t:+44(0)1756 799919
e:info@jbaconsulting.com

Jeremy Benn Associates Ltd
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