Annex 32.2

Hydraulic Model Set-up Report

(Black & Veatch)

Cherry Cobb Sands Compensation Site

Hydraulic Model Set Up Report

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Figures 4 and 5 have been produced using Ordnance Survey data.

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1 INTRODUCTION

1.1 GENERAL

1.1.1 Able UK propose to construct a Marine Energy Park (AMEP) on the south bank of the Humber. This is expected to require compensation for the loss of designated estuary habitat and bird feeding areas. A managed realignment on the north bank of the Humber at Cherry Cobb Sands is proposed to meet this compensation requirement.

1.1.2 This report is a summary of the model set up work carried out to investigate flow patterns inside the compensation site and across the surrounding intertidal to understand how the presence of the compensation site will affect flow velocities and directions and hence the anticipated changes in the morphology of the intertidal banks and major creeks.

1.2 MODELLING BACKGROUND

1.2.1 JBA Consulting (JBA) carried out an initial modelling study (JBA 2011) to examine how the presence of a new quay facility at South Killingholme in the Humber estuary might affect estuarine processes. The model extent was from Trent Falls to Spurn Point at the mouth of the Humber estuary as shown on Figure 1. The model has a rectilinear grid with the maximum model grid size in the domain of 100 m by 100 m. In order to more accurately resolve hydrodynamic flow around the proposed development site, the model grid resolution is increased in this location. The grid resolution here is 25 m by 25 m, which slowly increases with distance from the site.

1.2.2 Subsequently JBA developed and calibrated a more extensive model of the Humber estuary shown on Figure 2 that included a representation of the tidal portions of the rivers Ouse and Trent. This is reported in Annex 8.1. This second model uses a similar grid resolution to the initial model close to the new development but a coarser grid further away. Overall this model provided a better calibration to measured flows and water levels throughout the estuary.

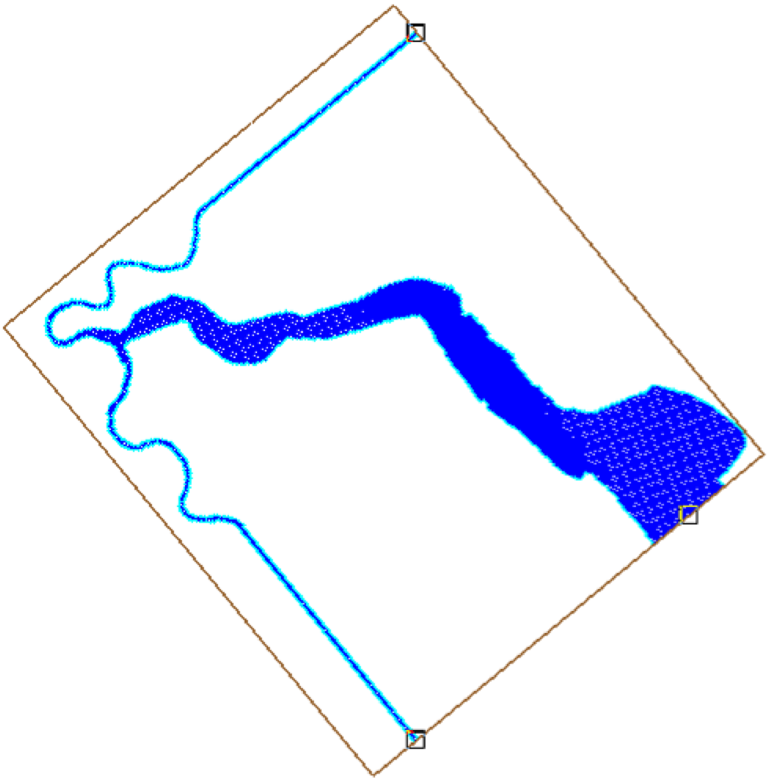
1.2.3 To aid design of the proposed Compensation Site on the north bank of the Humber at Cherry Cobb Sands, Black & Veatch (B&V) developed a detailed model of flows in this area including the southern part of Foul Holme Sand, the large intertidal bank offshore of this part of the Humber.

1.2.4 The B&V model boundary conditions were derived from flows and water levels calculated by the JBA models. The B&V model was initially set up using flows and water levels from the initial JBA model (JBA 2011). In this initial set up no specific calibration or comparison with the results from the original JBA model was carried out for the detailed model as it was known that this model would be updated. The initial B&V model was used for design of the breach for the Compensation Site.

1.2.5 Once the results of the second JBA model reported in Annex 8.1 were available, the water levels and flows around the boundary of the detailed model were obtained for both the low spring (May 2010) and high spring (September 2010) tidal sequences used in the JBA model. Output for the high spring tide sequence was obtained for seven sites within the detailed model domain to be used to compare the performance of the detailed model with the whole estuary model. This method of model verification was adopted as there are no measured data within the area of the detailed model for independent calibration of this model.

Source: JBA 2011

Figure 1 Initial JBA model extent



Source: Annex 8.1

Figure 2 Revised JBA model configuration

1.3 STRUCTURE OF THIS REPORT

1.3.1 Section 2 of this report describes the set up and extent of the detailed model and the boundary conditions that were chosen. This section applies equally to both the initial and final models.

1.3.2 Section 3 describes the verification of the performance of the final version of the detailed model in comparison with results from the final version of the JBA estuary model that provided the boundary conditions.

2 *MODEL BUILD*

2.1 MODEL EXTENT

2.1.1 The outflow from the Cherry Cobb Sands Compensation Site is expected to flow into a large creek named for this study as "Cherry Cobb Sands Creek" that runs parallel to and about 80 m seaward of the existing flood defences. The model extent and the topography of the creek and foreshore is shown on Figure 3. Cherry Cobb Sands Creek drains to the south and picks up drainage flowing through the four sluices at Stone Creek and continues parallel to the coast for a further 2 to 2.5 km before turning seaward and entering the low water channel of the Humber. The southernmost part of the creek is believed to be fairly dynamic. Foul Holme Sands separates Cherry Cobb Sands Creek from the main Humber low water channel.

2.1.2 A digital terrain ground model (DTM) has been set up by combining bathymetry from the 2010 ABP navigation chart, the LiDAR flown in 2007 by the Environment Agency and a 2010 topographic survey of the Compensation Site and adjacent features carried out for Able. The match line between the bathymetry and LiDAR surveys was set at -2 mAOD, where a good match between both surveys was found. There was also no evidence of inconsistency between the levels obtained from the LiDAR survey and those measured in the topographic survey.

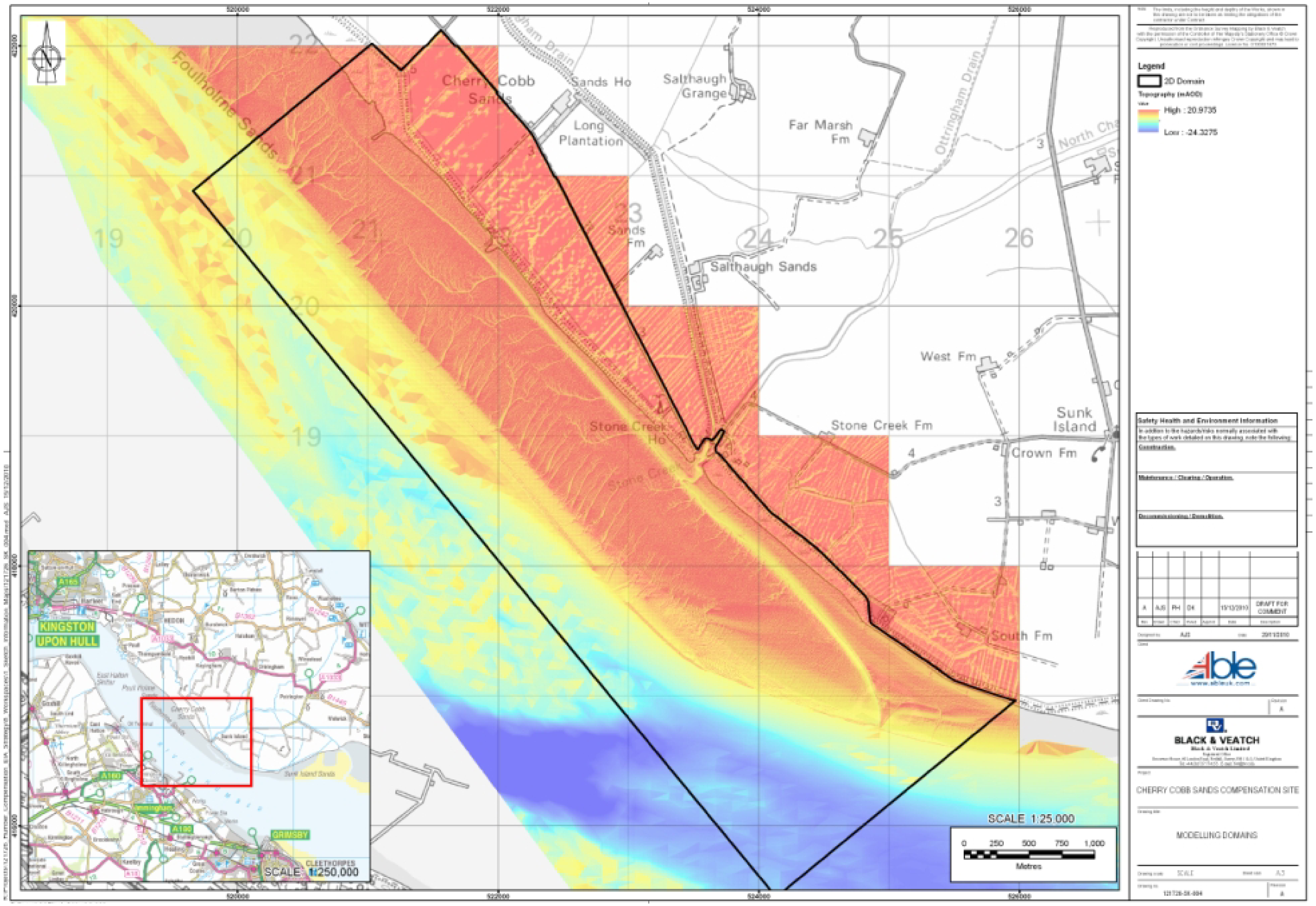


Figure 3 Model extent and foreshore topography near Cherry Cobb Sands

2.2 *Model boundaries*

2.2.1 The locations of the detailed model boundary are chosen to lie along grid cells within the JBA Humber model to provide easy transfer of boundary conditions between models. The south eastern boundary of the model is around 500m beyond the outfall of Cherry Cobb Sands Creek and extends into the middle of the Humber. The north western boundary of the model is around 700m beyond the change in flood defence alignment which marks the northern limit of where a breach might be located. The offshore model boundary runs roughly parallel to the flood defence alignment around 500m seaward of the low water mark. The whole of the proposed Compensation Site is included within the model.

2.2.2 The south east and north-west boundaries utilise tide levels outputted from the JBA model along these alignments. Along the offshore boundary, flows normal to the coastline are used as boundary conditions. A small freshwater inflow is introduced through the sluices at Stone Creek.

2.3 *Model development*

2.3.1 The modelling is carried out using TUFLOW software. TUFLOW is a 2D hydrodynamic modelling system, which incorporates a computational engine that solves the full 2D free surface shallow water flow equations. It was developed jointly by WBM Pty Ltd and the University of Queensland, and was made commercially available in 2001. It was subjected to extensive testing and evaluation both in the UK and worldwide and is specially configured for modelling flooded land.

2.3.2 The model was built based on the DTM using the TUFLOW Build 2009-07-DB hydrodynamic modelling software. A 10x10 m spatial grid resolution was used, that balances the need for a detailed representation of the Cherry Cobb Sands Creek and the proposed breaches into the Compensation Site with efficiency in running the model.

2.3.3 This model normally defines the flow field using the two horizontal dimensions (2D), but has the ability to embed an area where flows must travel along a predefined one dimensional (1D) channel. For this application, two versions of the model were initially developed and a decision as to which to use was made on consideration of the results obtained.

2.3.4 In one version the whole area is defined by a 2D 10x10 m grid. This allows the main channel of Cherry Cobb Sands Creek to be well defined over most of the length of the Compensation Site and also provides sufficient definition to identify some of the smaller creeks draining Foul Holme Sand both to the east and to the west as shown in Figure 4 where the topography is taken from the 10x10 m grid used in the model schematisation.

2.3.5 The second version uses the same basic 10x10 m 2D grid, but to better define flows within Cherry Cobb Sands Creek, the creek area was modelled in 1D with a cell length of 100 m located within the main 2D model grid. This forces flows to be aligned with the creek in this part of the model. There is full connectivity between the 2D and 1D grids so inflows and outflows across the boundary of the 1D section are well represented.

2.3.6 Preliminary model results revealed that the full 2D model gave a better spatial representation of the extent of changes in flow magnitude and direction across Foul Holme Sand. As the selected grid size also provided sufficient definition to identify the flow pattern within Cherry Cobb Sand Creek, the full 2D model version was chosen and is the one described throughout this report.

2.4 *BREACH MODEL*

2.4.1 Breaches at the Compensation Site were replicated in the model by lowering the existing ground level to the design invert level of each breach. For all breaches, a swath of foreshore was cut out for the full width of the breach down to its invert level between the foreshore and Cherry Cobb Sands Creek. This was done to allow good hydraulic access through the saltmarsh between the estuary and the Compensation Site. Figure 4 shows a typical schematisation of the breach model.

2.4.2 Breach lengths of 150 m to 300 m for the main breach were tested, sometimes with a 100 m subsidiary breach. The invert level of these breaches varied between 3.0 and 2.0 mAOD. Details of breach design are given in the Breach Design Report in Annex 32.3. The modelling of the finally chosen arrangement with the verified model described in this report is reported in Annexes 32.4 and 32.6.

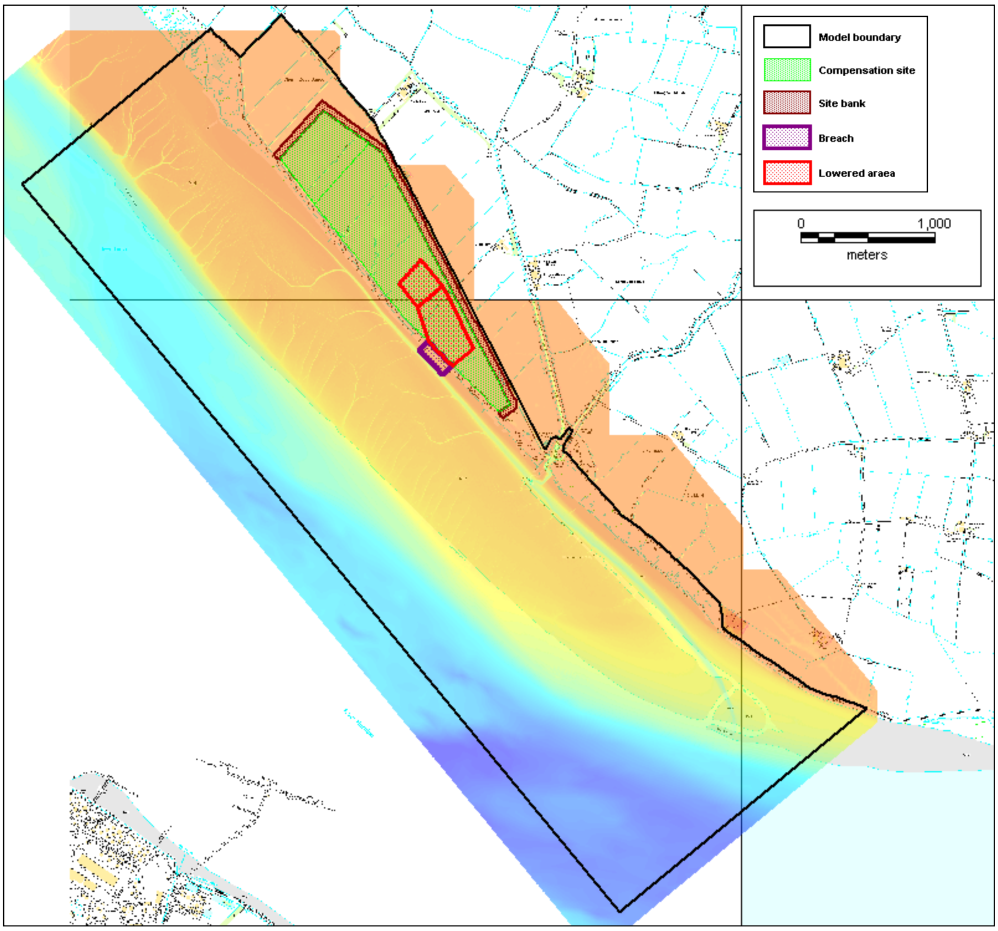


Figure 4 Typical breach model set up

2.5 *TUFLOW MODEL STRUCTURE*

2.5.1 The model build involved generating a series of MapInfo GIS layers, which were inputted to the TUFLOW computational engine through a series of ASCII control files. The GIS layers used in the study are detailed in Table 1.

Table 1 TUFLOW input GIS layers

GIS data Type	GIS Layer Name	Description
1D Network 1D Boundaries	1d_nwk_Node_ccs_02 1d_bc_HT_ccs_02	1D nodes for tidal/water level boundaries 1D tidal boundary which links to 2D domain.
2D Boundaries	2d_bc_ccs_15E	Along the offshore flow boundary.
2D Cell Codes	2d_code_ccs_04	Polygons for active2D domain
2D Elevations as points	2d_zpt_ccs_10m_03	10m grid points, containing topographic information
2D Elevations over an area	2d_zplg_ccs_patch_01 2d_zplg_ccs_site_bank_110ha 2d_zplg_ccs_tracks_01 2d_zplg_ccs_250_2p0_Sbreach 2d_zplg_ccs_low_area_02 2d_zsh_ccs_low_area_02	Layer containing polygons to raise ground elevations from -9999 (values outside the limits of LiDAR coverage) to slightly more realistic levels to prevent instability. Layers containing polygons to lower ground elevations for the breach model: • On-site bank (110ha) • Lowered tracks (200m width) • Southern breach: 250m width; 2.0mAOD • Low area at south breach • Ramp for low area at south breach
Elevation Lines (Breaklines)	2d_zln_ccs_bank_01 2d_zln_ccs_patch_01	Existing bank elevation line from topo survey Smoothing DTM at the Creek outlet
2D Land-Use (Materials)	2d_mat_ccs_mud_01 2d_mat_ccs_land_01 2d_mat_ccs_bdy_01	Polygons defining Foul Holme Sand Polygons defining compensation site Polygons defining areas of boundary conditions

2.6 *TIME STEPS*

2.6.1 Time step for the model is based on the Courant stability criterion:

$$C_r = \frac{\Delta t\sqrt{2gH}}{\Delta x} < 10$$

where

Δt	=	time step (s)
g	=	acceleration due to gravity (m/s^2)
H	=	water depth (m)
Δx	=	element size (m)

2.6.2 As a rule of thumb to meet this criterion the time step should be roughly half the element size, although this may need to be reduced for steep models with high Froude numbers. These considerations and the evidence from test runs led to the choice of a 2 second time step.

2.6.3 Cumulative mass errors were monitored throughout the simulations and were generally significantly less than 1%. This indicates that the chosen time steps are sufficiently short. Higher mass errors occurred at the start up but reduced to close to zero shortly after the simulations were underway. This is normal and indicates an acceptable performance.

2.7 ROUGHNESS COEFFICIENTS

2.7.1 Bed friction is represented by Manning's 'n' roughness coefficients. Polygons which define the locations of different material types were digitised.

2.7.2 The roughness values used in this study are 0.015 for the Compensation Site and 0.020 for the rest of the model. This is similar to the Manning's 'n' value of 0.0175 (=1/57.1) used in the JBA Humber model (Annex 8.1 paragraph C8). For stability reasons, a roughness value of 0.04 has been adopted around the water level and flow boundaries of the model.

3 MODEL VERIFICATION

3.1 GENERAL

3.1.1 There are no specific data that can be used to calibrate this detailed model. The model is set up and adjusted to calculate velocities that are similar to those calculated within the final JBA model at the south east and north-west model boundaries where levels are specified.

3.1.2 The reliability of the detailed model depends on the reliability and accuracy of the JBA model from which its boundary conditions are derived. In Annex 8.1 paragraphs C8 to C14, the calibration and validation of the JBA model is reported. Paragraph C9 reports that for water levels '*the model is very well calibrated from Spurn Head to Albert Dock*' and '*shows very small errors in the timing of tidal flow*'. Some issues with the representation of velocities in mid channel during the calibration are discussed in paragraph C11.

3.1.3 For the validation tests from September 2010 that were actually used for the verification of the detailed model, Annex 8.1 paragraph C14 reports that '*the model performs very well against the validation data, simulating observed water levels well within the criteria specified above.... Comparisons of model currents against TotalTide predictions show the model simulates the predicted currents within the middle estuary well.*'

3.1.4 In order to demonstrate that the baseline detailed model is performing correctly and is consistent with the JBA model, the JBA model results for the period 2300 on 7th September 2010 to 1900 on 10th September 2010 were used for verification of the final detailed model. The verification points are on top of Foul Holme Sand (points 1-3) and points near the low water mark (points 4-7) as shown on Figure 5.

3.2 ISSUES FOR BOUNDARY CONDITIONS

3.2.1 As described in Section 2.1 , the locations of the boundary are chosen to lie along grid cells within the JBA Humber model. The main problem was that the JBA model grids are much larger than the detailed model grid so interpolation of the tide levels and velocities provided by the JBA model was required before they could be used as detailed model boundary conditions.

3.2.2 The tide levels for the south-east and north-west boundaries have been replicated in the model using a 1D tidal boundary which links to the 2D domain. The water levels along the boundaries are based on a linear interpolation of the 1D level hydrographs. This set up was adopted because the tide varies in height and phase along the boundary. The tide levels used in the detailed model are defined using 16 points along the south-east boundary and 7 points along the north-west boundary in the JBA model.

3.2.3 Flows normal to the coastline were used as boundary conditions along the offshore boundary. There are 117 JBA flow points along the boundary, with their width varying from 10 m to 210 m (i.e. 1- 21 detailed model grid cells). These flows have been converted from velocities outputted from the JBA model on the assumption that the velocities and water depths are constant across each JBA grid cell.

3.3 *MODEL RESULTS*

3.3.1 Figure 6 shows water level plots from both the JBA model and the detailed model results. The velocity magnitude plots and flow direction plots are shown on Figure 7 and Figure 8 respectively. The maximum level and velocity predicted at each point in the detail model each tide is compared with the values predicted in the JBA model in Tables A-1 and A-2.

3.3.2 The water level plots show that there is a good agreement between the JBA model results and the detailed model results at the seven comparison sites shown on Figure 5. The differences in tide peaks and low tide levels are summarised in Table 2 and Table 3 respectively. The difference in tide peaks for the 3rd tide (which is the biggest tide in the simulation period) ranges from 0.052 m to 0.134 m and on average the detailed model predicts levels that are 0.092 m higher than the JBA model at these seven points. The differences in low tide levels between the two models arise from the different grid resolution of the two models. This leads to the many detailed model cells within each larger Humber model cell having different bed levels because the detailed model picks up greater detail from the bathymetry that is common to both models.

Table 2 Differences in tide peaks

Tide	Difference (m)		
	Minimum	Maximum	Average
1st	0.036	0.107	0.073
2nd	0.049	0.114	0.082
3rd	0.052	0.134	0.092

Table 3 Differences in low tide levels

Tide	Difference (m)		
	Minimum	Maximum	Average
1st	-0.332	0.572	-0.016
2nd	-0.128	0.002	-0.051
3rd	-0.429	0.595	-0.025

3.3.3

Table 4 summarises the differences in peak velocities between the two models at the same seven comparison points, with the details for each verification point shown in Table A-2. The figures in brackets in

Table 4 and in Table A-2 show differences in peak velocities excluding any short lived periods of high velocity predicted by the detailed model (see Sections 3.3.7 and 3.3.8).

3.3.4 Again, for the biggest tide in the simulation period (3rd tide), the difference in peak velocities ranges from -0.058 m/s to 0.560 m/s and on average the detailed model predicts velocities that are 0.156 m/s higher at the seven comparison points.

3.3.5 The differences in maximum velocity for the 3rd tide at the seven points range from -0.174m/s to 0.311m/s, if short periods of high velocity are excluded. On average the detailed model predicts maximum velocities that are 0.041 m/s higher. If these short periods are excluded, the maximum velocities in the detail model at five sites (Points 1, 3, 4, 5 and 6) are within 0.1m/s of the value calculated by JBA (Table A-2). At Point 2 the detail model predicts maximum velocities that are 0.1-0.2 m/s lower than the JBA model, while at Point 7 the detail model predicts velocities that are 0.2-0.3 m/s higher than the JBA model. The differences at Point 2 may reflect differences in model resolution, while those at Point 7 are likely to be due to proximity to the detail model water level boundary.

3.3.6 The shape of the velocity plots, however, shows that there are discrepancies between the JBA model results and the detailed model results. These differences are mainly due to the different grid sizes that were used in the models. The detailed model uses a smaller grid size which would make the ground levels more 'uneven' and lead to local variations in velocity that are not identified in the coarser gridded model.

3.3.7 There is an indication at Points 1 and 2 on Figure 7 that when the cell is initially wetted, the detailed model predicts a short lived period of high velocity. This is almost certainly a difference in the way the two models represent the wetting of previously dry cells.

3.3.8 There is also some evidence of model instability resulting in short lived velocity peaks just after high tide at Points 3 and 7 near the south end of the model. These peak velocities contribute significantly to the difference in average peak velocity highlighted in

Table 4 as indicated on Table A-2.

3.3.9 The flow direction plots show that there is a good agreement between the JBA model results and the detailed model results at Points 2, 3, 4, 5, and 6 shown on Figure 8. At Point 1, the detail model where suggests the tide turns at high water in an anticlockwise direction while the JBA model predicts a clockwise turn. With maximum velocities at this site of around 0.3 m/s the direction of flow will be very sensitive to local topography. At Point 7, the proximity to the detail model boundary is probably the major factor causing the difference in direction at this site during part of the ebb tide.

3.3.10 In general, the reasonably good agreement between the results provides confidence in the reliability of the detailed model for predicting the effects of the development of a Compensation Site at Cherry Cobb Sands on velocities within the site, over the adjacent Foul Holme Sand and in Cherry Cobb Sands Creek.

Table 4 Differences in peak velocities

Tide	Differences (m/s)		
	Minimum	Maximum	Average
1st	-0.016 (-0.104)	0.626 (0.250)	0.165 (0.037)
2nd	-0.122 (-0.134)	0.527 (0.238)	0.142 (0.029)
3rd	-0.058 (-0.174)	0.560 (0.311)	0.156 (0.041)

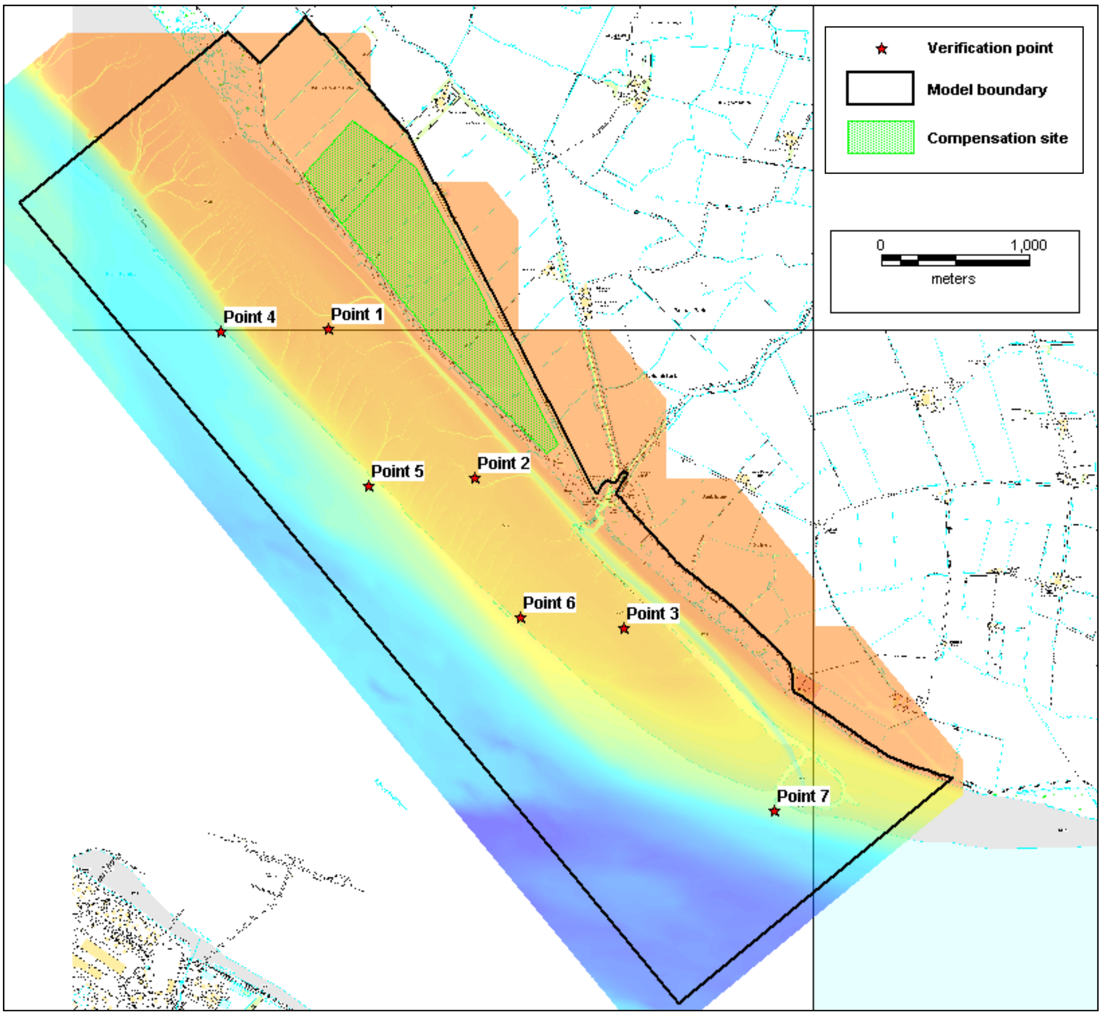


Figure 5 Verification points

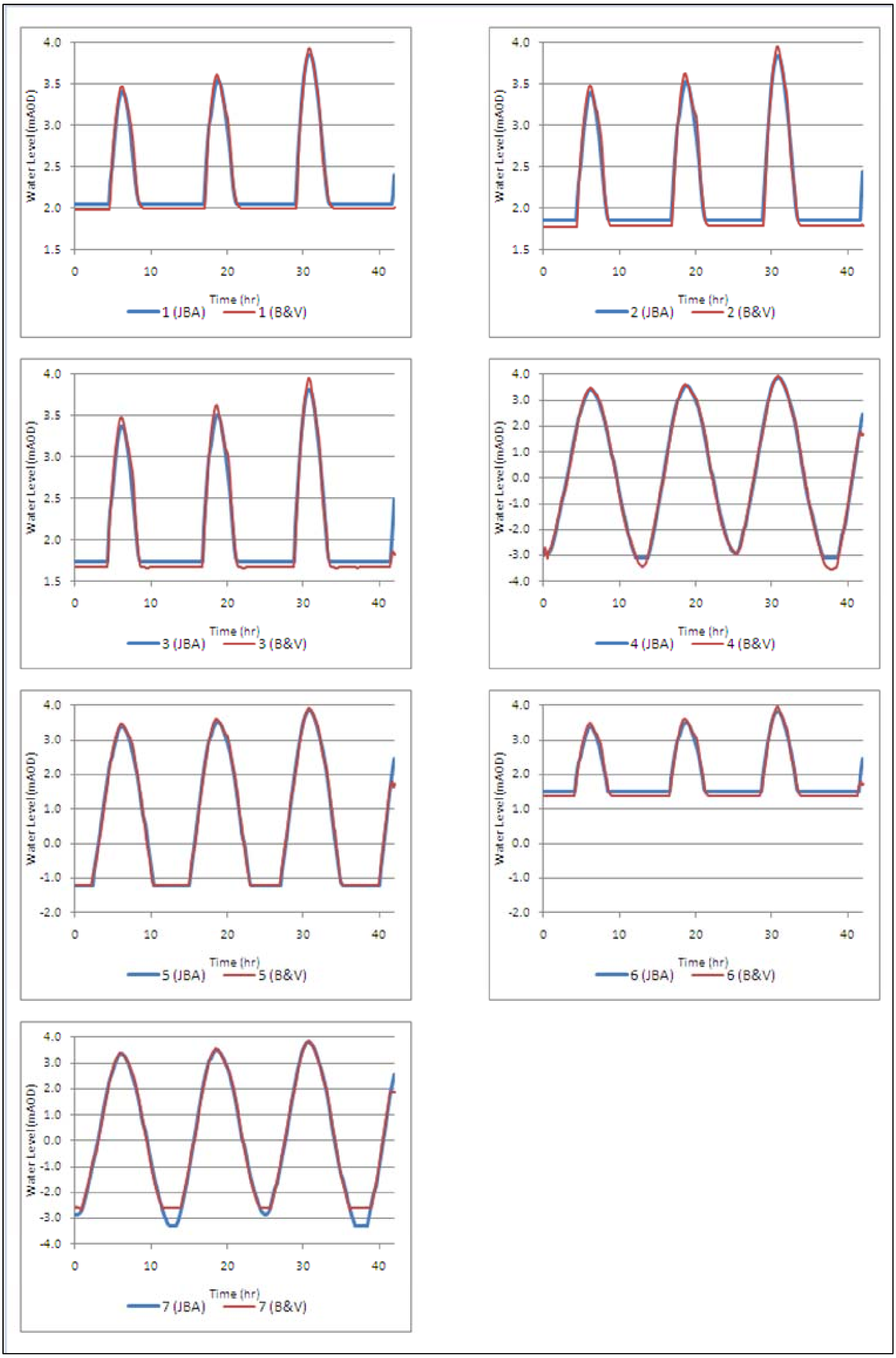


Figure 6 Tide levels at verification points

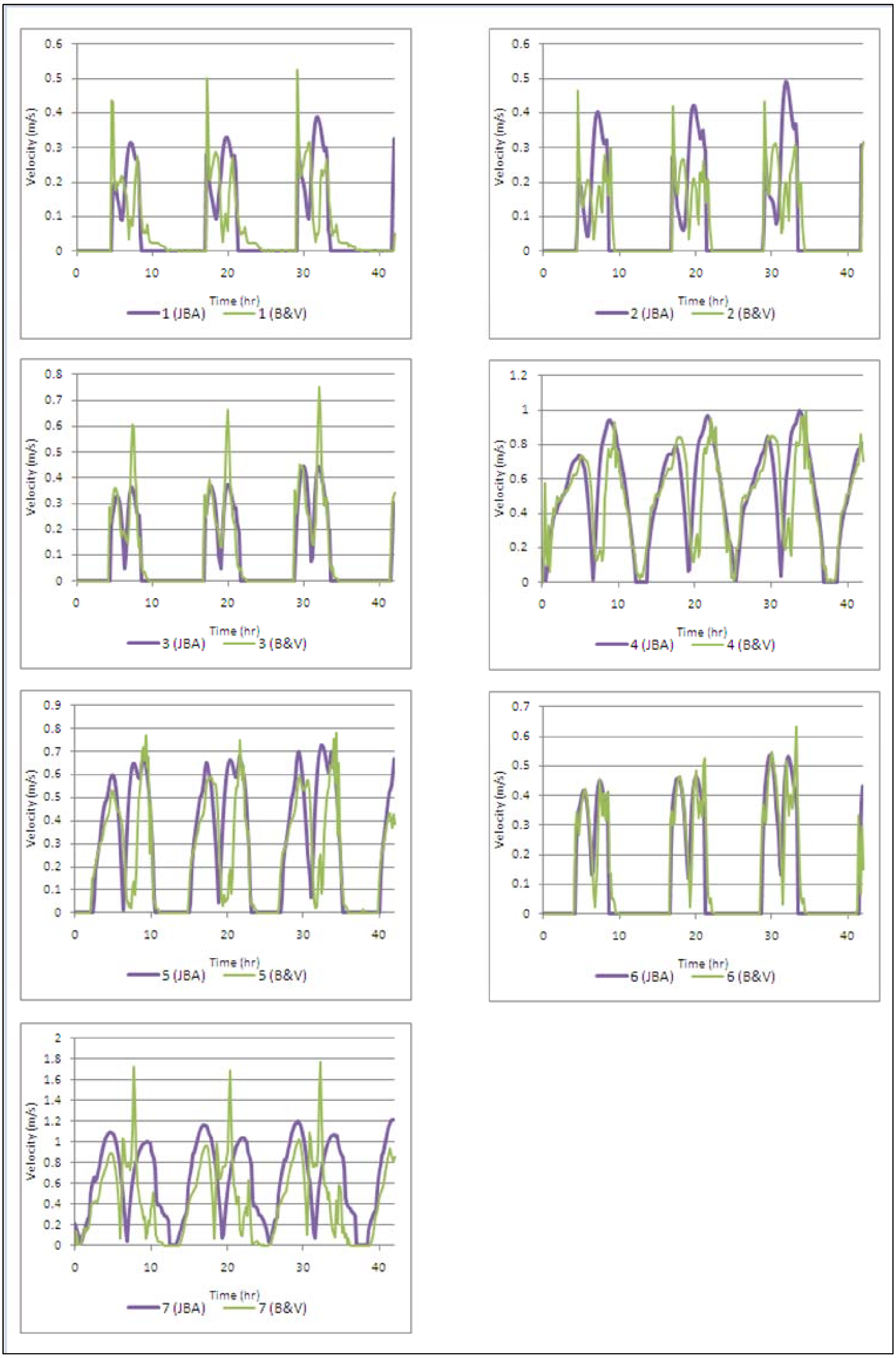


Figure 7 Velocity magnitudes at verification points

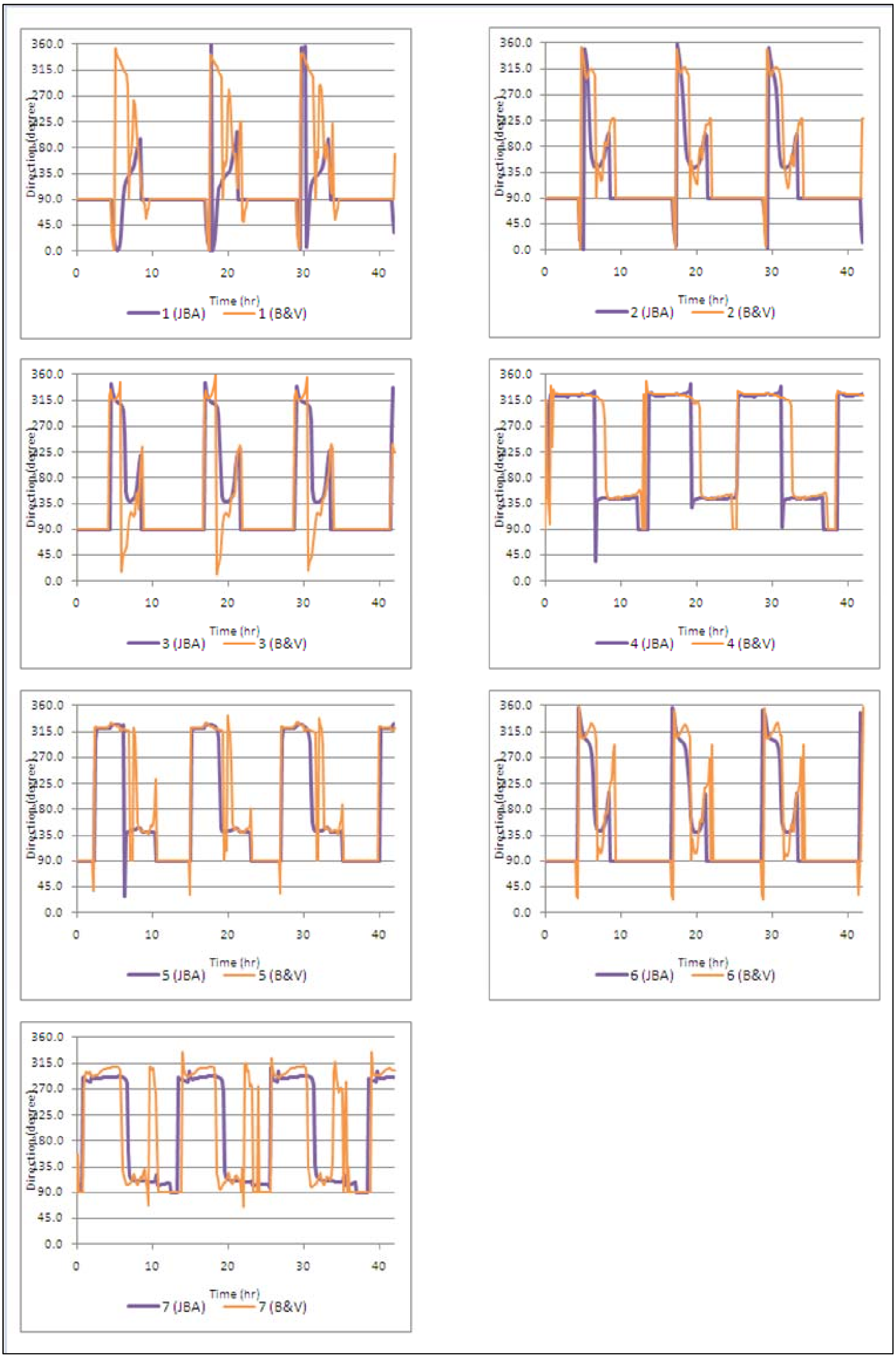


Figure 8 Flow directions at verification points

3.4 *MASS BALANCE REPORT*

3.4.1 Monitoring mass balance report is important so as to establish the "healthiness" of the TUFLOW model. The usual parameter to measure the healthiness of the model is cumulative mass balance error, which is outputted by TUFLOW.

3.4.2 The cumulative mass balance error (Cum ME (%)) in the detailed model run for the period 2300 on 7th September 2010 to 1900 on 10th September 2010 is less than ±1%, which is satisfactory. The plot of this parameter is shown in Figure 9.

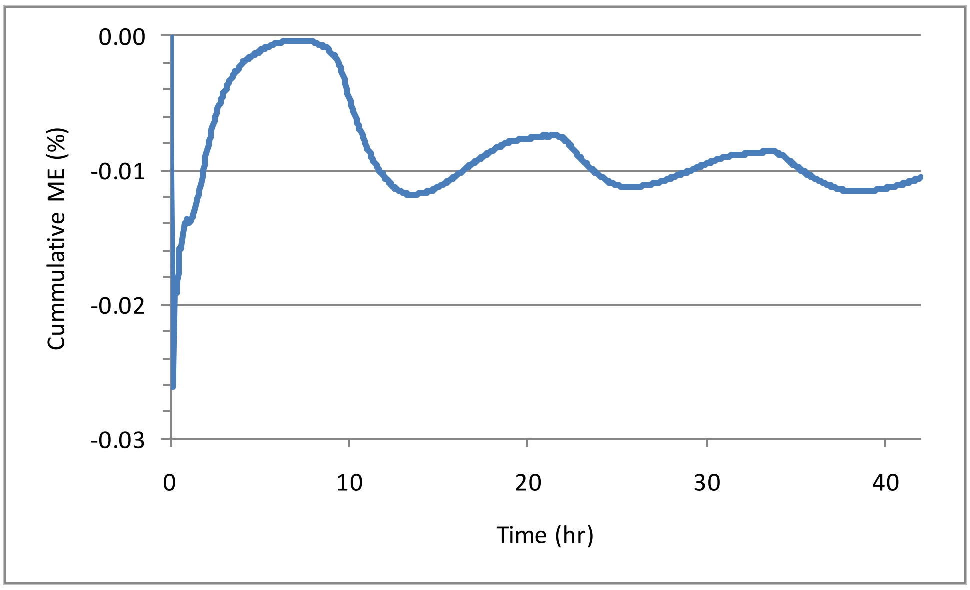


Figure 9 Cumulative mass balance error plot

Appendix A

Table A- 1 Tide peaks at seven locations (Figure 5)

Model	Tide	Peak tide (mAOD)						
		Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7
JBA	1st	3.419	3.396	3.377	3.427	3.400	3.383	3.361
	2nd	3.551	3.530	3.513	3.558	3.532	3.518	3.498
	3rd	3.866	3.843	3.820	3.877	3.846	3.827	3.803
B&V	1st	3.475	3.486	3.484	3.467	3.482	3.486	3.397
	2nd	3.617	3.628	3.627	3.607	3.621	3.624	3.550
	3rd	3.940	3.950	3.954	3.929	3.945	3.952	3.855
Difference	1st	0.056	0.090	0.107	0.040	0.081	0.103	0.036
	2nd	0.067	0.098	0.114	0.049	0.089	0.107	0.051
	3rd	0.074	0.108	0.134	0.052	0.099	0.125	0.052

Table A- 2 Velocity peaks at seven locations (Figure 5)

Model	Tide	Peak velocity (m/s)						
		Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7
JBA	1st	0.315	0.403	0.363	0.945	0.662	0.452	1.097
	2nd	0.331	0.423	0.375	0.968	0.678	0.464	1.164
	3rd	0.391	0.493	0.446	0.995	0.727	0.538	1.218
B&V	1st	0.437 (0.274)	0.466 (0.299)	0.607 (0.423)	0.928 (0.928)	0.770 (0.770)	0.457 (0.457)	1.723 (1.346)
	2nd	0.500 (0.373)	0.419 (0.289)	0.664 (0.421)	0.846 (0.846)	0.752 (0.752)	0.526 (0.526)	1.691 (1.401)
	3rd	0.526 (0.379)	0.435 (0.319)	0.751 (0.455)	0.997 (0.997)	0.781 (0.781)	0.634 (0.634)	1.779 (1.530)
Difference	1st	0.122 (-0.042)	0.063 (-0.104)	0.245 (0.061)	-0.016 (-0.016)	0.109 (0.109)	0.005 (0.005)	0.626 (0.250)
	2nd	0.169 (0.043)	-0.004 (-0.134)	0.289 (0.045)	-0.122 (-0.122)	0.073 (0.073)	0.062 (0.062)	0.527 (0.238)
	3rd	0.135 (-0.012)	-0.058 (-0.174)	0.305 (0.009)	0.001 (0.001)	0.055 (0.055)	0.095 (0.095)	0.560 (0.311)