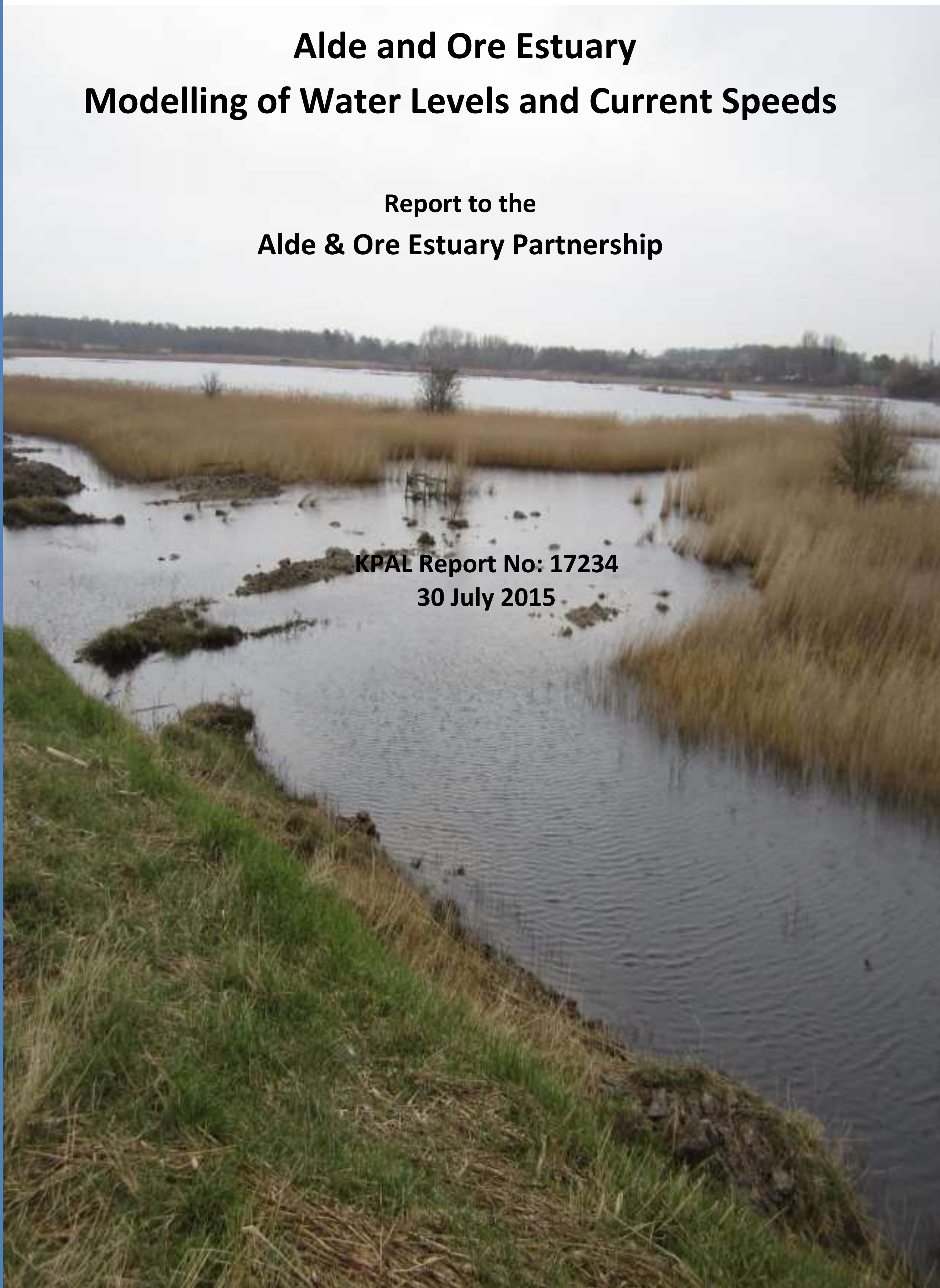
Alde and Ore Estuary
Modelling of Water Levels and Current Speeds

Report to the

Alde & Ore Estuary Partnership



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30 July 2015

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Scientific Research, Consultancy and Investigations

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Contents

Summary

S1. This report presents the results of a preliminary modelling study undertaken using Telemac-2D to assess the effect of changing estuary morphology on water levels and current speeds in the Alde-Ore estuary. The initial model runs considered normal spring and neap tides and three morphological scenarios: (A) Baseline pre-December 2013, (B) post-December 2013 following breaching of the walls at Hazlewood Marshes and Lantern Marshes South, and (C) a hypothetical large scale managed realignment (MR) breach at Boyton marshes in conjunction with the unrepaired Hazlewood Marshes breach. The results for scenario (B) show the effect on water levels and maximum current velocities is relatively small compared with the baseline scenario. The model simulations indicate a 5 to 7% increase in maximum flood and ebb velocities in the Slaughden area, a change which is of a similar magnitude to the increases estimated by KPAL (2014) on the basis of tidal prism analysis and expert geomorphological assessment. The predicted velocity increases are consistent with local reports of an observed (though un-quantified) increase in current speeds near Slaughden since December 2013.

S2. The model simulations for Scenario C predict significantly larger impacts in the lower estuary south of Boyton but suggest only a very small effect on water levels and current speeds upstream of Orford. This modelling result is counter to some local expectations that making space for floodwater at Boyton would significantly reduce flow and water levels further up the river. However, the potential effects of MR at Boyton require more detailed investigation to examine the potential effects of alternative design options, since the effect of water levels may be sensitive to details of breach design (e.g. wider or artificially deepened breaches, removal of long sections of wall, partial wall realignment, presence of absence of sills).

S3. Modelling of a 300 mm rise in sea level with unchanged estuary morphology, equivalent to a modern day spring tide with a surge of 300 mm, indicated an increase in current speeds throughout the estuary, under all three morphological scenarios. This reflects the additional tidal prism associated with a 300 mm increase in water depth throughout the estuary. The modelling indicated maximum increases in peak tidal current velocity of around 20% for the lower estuary under these conditions.

S4. Additional model runs were carried out to assess current speeds associated with estimated 1 in 20 and 1 in 200 year levels. For the Boyton Marshes inundation scenario (C), the modelling suggested a slight increase rather than decrease in water level in much of the upper estuary, whereas the Hazelwood and Lantern inundation scenario (B) showed a slight decrease of water levels in the upper estuary compared with the Baseline scenario (A). The implication is that managed realignment in the upper estuary would have the greatest beneficial effect on extreme water levels in the upper estuary between Aldeburgh and Snape. However, this result needs to be tested by further modelling involving different Boyton MR geometries and sensitivity tests involving varying channel friction.

S5. Compared with the Baseline geometry (A), the realignment geometries (B, C) result in increased extreme tide flood and ebb flows in much of the estuary, and especially

in the lower estuary. This is an expected response to the greatly increased tidal prism. Around Slaughden and Hazelwood Marshes, extreme water level velocities increase under both scenarios although the pattern is indicated by the modelling to be spatially variable. Flood tide velocities are predicted to increase throughout the estuary and by more than ebb velocities, as expected given the asymmetrical nature of the modelled surge tides (based on the December 2013 event). The pattern of change in ebb velocities is more variable than that for the flood velocities.

S6. The hydrodynamic model implementation presented to date could be refined by including spatially varied friction to fine tune model performance, especially within the intertidal areas, by adjustments to the turbulence parameterisation, minor adjustments to the computational mesh and the depiction of the flood defences and breaches, and a more critical evaluation of the calibration datasets. Further modelling work would benefit from the acquisition of tidal current data at different depths in the water column for a number of locations along the estuary length in order to provide data for further 2D, and potentially 3D, model validation. This would require another 30 day field campaign (probably commissioned by the Environment Agency).

S7. The AOEP Estuary Plan proposes to raise the flood embankments to a level which will withstand overtopping by 300 mm for up to two hours in the year 2050, taking into account 300mm of projected sea level rise by that date. This implies a *minimum* crest level of approximately 3.28 m OD in the Snape area, 3.5 m OD around Orford, and 3.60 m OD near the mouth of the estuary. An allowance of 300 mm for increases in high water levels by 2050 can be considered to be conservative based on current climate change projections and the fact that recent increase in annual mean high water level at Lowestoft have been smaller than the increase in annual mean sea level. Considered in terms of currently projected increases in mean sea level, the AOEP strategy can therefore be considered to be realistic. However, it should be noted that statistical estimates of extreme still water levels are subject to uncertainty, at least of the order of +/- 0.6 m, and future changes in the frequency and magnitude of meteorologically induced surges are difficult to forecast.

S8. As noted above, further modelling is required to assess the potential effects of alternative design options for possible managed realignment at Boyton or other changes to the estuary morphology (e.g. rollback of the shingle barrier south of Slaughden). There is also a requirement for further (ideally 3D) modelling to examine the effects of changes in current velocities on bed / bank shear stresses and the likely implications for saltmarsh and mudflat erosion. However, before further modelling is undertaken, a new 30 day field data campaign is required to obtain water level, depth-related tidal current and suspended sediment data at several locations along the estuary, since the December 2014 field campaign failed to deliver data of the required quality. Consultation will be required between the AOEP, EA, RSPB and Natural England to ensure that the further data acquisition and modelling work are adequate to meet all objectives.

1.0 Report scope and purpose

1.1 The Alde and Ore Estuary Partnership (AOEP) has developed a Draft Whole Estuary Plan (AOEP, 2014) which includes a Flood Cell Survivability Assessment based on information about the present condition of the flood walls surrounding the estuary and assumptions regarding the ability of the walls to survive without multiple breaches during storm surge events, both at the present time and in the year 2050. Sections of wall within each Flood Cell have been graded as BLACK, RED, BLUE or GREEN in terms of relative need for improvement. This assessment was based on:

(1) data from an EA crest level survey in 2009 and additional field inspections
(2) predicted storm surge levels along the length of the estuary obtained from modelling by JBA Ltd on behalf of the Environment Agency (JBA, 2012a,b)
(3) An assumption that a wall can survive a 300 mm overtopping event undamaged (supported by observations in the Alde and Ore estuary during the surge events of November 2007 and December 2013, and observations elsewhere)
(4) an assumption that mean sea level and storm surge water levels will increase by 300 mm by the year 2050 (relative to 2012)

1.2 The condition of each category of wall is defined as follows:

BLACK: a wall will overtop and may breach during a 1 in 20 year event in 2011 but cannot survive a 1 in 20 year event in the year 2050

RED: a wall will not overtop during a 1 in 75 year event in 2011, can survive a 1 in 20 year surge event in 2050 but cannot survive a 1 in 75 year event in 2050

BLUE: a wall will not overtop during a 1 in 200 year event in 2011, can survive a 1 in 75 event in 2050 but cannot survive a 1 in 200 surge event in 2050

GREEN: a wall can survive a 1 in 200 event in the year 2050.

1.3 The AOEP Plan proposes that all walls around the estuary should be improved to a design crest height equivalent to the 1 in 200 surge height predicted by JBA (2012) which will survive 300 mm of overtopping in the year 2050. Allowances for an increased overtopping depth of 500 mm may be made if walls are protected by mesh and anchored.

1.4 The increase of 300 mm by 2050 assumed in the AOEP Estuary Plan is broadly in line with mean sea level rise projections made by the United Kingdom Climate Programme (UKCP09) analysis, based on the Fourth Scientific Assessment of Intergovernmental Panel on Climate Change (IPCC). These projections included an increase in mean sea level of 324 mm by 2060 (relative to 2008) for the 95th percentile medium emissions scenario, and 395 mm for the 95% percentile high emissions scenario. It should be noted, however, that these values relate to mean sea level and there is great uncertainty regarding possible changes in storm surge frequency and magnitude which can affect high and low water levels in different ways.

1.5 In order to inform the Sustainability Assessment of the AOEP Plan, Kenneth Pye Associates Ltd (KPAL) was commissioned by the Alde and Ore Association (AOA), on behalf of the AOEP, to undertake an independent assessment of tidal levels and associated current speeds within the estuary. Changes in current speeds are of potential significance in terms bank erosion rates and potential effects on saltmarsh habitat extent, flood defence stability, the sediment budget of the estuary, and navigation. Increases in current speeds in the Aldburgh Marshes - Slaughden area have been noted (but not quantified by field measurements) since the walls surrounding Hazlewood Marshes were breached in December 2013.

1.6 The assessment of water levels and current speeds described in this report has included hydrodynamic modelling of the effects of changes in estuary morphology arising from the December 2013 storm surge event, and also the potential effects of a hypothetical large scale breach at Boyton Marshes. The potential effects of an increase in sea level of 300 mm, equivalent to a normal spring tide combined with 300 mm surge, has also been investigated, and additional model runs have been undertaken to assess current speeds associated with 1 in 20 and 1 in 200 year surge tide events.

2.0 Methods

2.1 The assessment presented in this report is based on the following:

(1) consideration of the AOEP proposals

(2) the results of the flood risk modelling undertaken by JBA Consulting Ltd (JBA, 2012a,b; 2015)

(3) assessment of other available data relating to tidal levels in the estuary, including recent tide gauge data for Orford and Snape

(4) the results of Telemac2D modelling of water levels and current speeds in the estuary, undertaking in association with University College London.

2.2 The hydrodynamic modelling work has been undertaken using a new bathymetric model of the estuary compiled by KPAL which incorporates the most recent lidar and bathymetric data available. A copy of the bathymetric model was also provided to JBA for use in their most recent (JBA, 2015) flood risk modelling.

2.3 When the assessment summarised in this report was first proposed in the summer of 2014, a request was made that the Environment Agency (EA) commission a field data campaign to obtain up-to-date water level, current speed and suspended sediment data which could be used to calibrate and validate 2D and 3D hydrodynamic and sediment transport models. A data acquisition campaign was subsequently undertaken by Gardline over a 30 day period in November and December 2014 using instruments deployed at pre-defined stations along the estuary. Unfortunately, no water level data were gathered and the current speed data were not referenced to water depth. Several of the instruments malfunctioned and some were lost, resulting in poor overall data recovery. It has not therefore been possible to use these data for hydrodynamic model calibration / validation purposes, as originally intended.

2.4 Attempts were made by KPAL to obtain hydrodynamic data collected by Gardline (2003) and reported by Black and Veatch (2006), but the original data could not be located. For these reasons, it was decided to use water level data collected at six stations in the Alde-Ore estuary by University College London (UCL) on behalf of the EA in 1995-96 to calibrate and validate a Telemac-2D hydrodynamic model operated by UCL. Owing to the unavailability of depth profiles of current velocity, validation was restricted to water levels only.

2.5 Salinity, turbidity and suspended solids data for high and low tide periods were successfully obtained by the EA Monitoring Team from three locations in the estuary (Shingle Street, Orford and Slaughden) during December 2015. These data have been synthesised and are presented in Appendix 1 to this report. The data show that salinity and suspended solids concentrations vary at all stations over the tidal cycle, but only relatively small variations with depth were recorded, indicating that the estuary is generally well mixed and that 2D (depth averaged) modelling can adequately capture the broad-scale spatial variations in current velocity within the estuary.

3.0 Extreme water levels predicted by previous modelling

3.1 Table 1 provides a summary of predicted and measured tidal levels in the Alde-Ore estuary and on the adjacent coast. The estimated levels based on short-term (30 days or less) measurements by Gardline (2003) are generally higher than the predicted Admiralty values, but both show a slight decrease in tidal levels between Orford Haven Bar and Orford, followed by a slight increase between Orford and Iken. The predicted level of HAT at Orford Haven Bar is 1.9 m above Ordnance Datum (OD). This value is considerably lower than the height of the 1 in 1 year resultant water level (combined astronomical tide plus surge) of 2.52 OD estimated for this location by McMillan *et al*. (2011) based on statistical analysis of tide gauge data for East Coast ports (excluding Lowestoft), demonstrating the influence of meteorological forcing on recorded high water levels in this area. The 1 in 20 year water level estimated by McMillan *et al*. for this location (Chainage 4218 off Shingle Street), is 3.15 m OD and the predicted 1 in 200 year water level is 3.75 m OD (Table 2). However, independent assessment of extreme water levels based tide gauge data for Lowestoft and other East coast ports (Pye & Blott, unpublished data) suggest that the values reported by McMillan *et al*. may well be underestimates.

3.2 Based partly on the outputs of the McMillan *et al.* (2011) study, combined with hydrodynamic modelling, JBA (2012a,b) reported estimates of the 1 in 20, 1 in 50, 1 in 75, 1 in 200 and 1 in 1000 year water levels at a number of points ('nodes') between the mouth of the Ore and the estuary head (Table 3). For ease of interpretation, the 1 in 20, 1 in 50 and 1 in 200 year estimated levels have been plotted in their spatial context in Figures 1, 2, & 3, respectively. The 1 in 20 year event levels estimated by JBA drop sharply just inside the estuary mouth, reaching a minimum of 3.08 to 3.09 m OD between Boyton Marshes and a point upstream of Orford, before increasing again up the estuary to maximum of 3.12 m OD between Hazlewood Marshes and Snape. The 1 in 50 year event levels decrease progressively between the estuary mouth and Slaughden, with no further change in level between Slaughden and Snape. The 1 in 200 year event levels decrease sharply from a maximum of 3.61 m OD near Hollesley to 3.34m OD near Orford and 3.28 m OD at Aldeburgh Marshes, with no further change in the Inner Estuary up to Snape. The JBA modelling results therefore suggest a slight change in the form of the surge tidal wave as a function of maximum surge height which may reflect the varying effect of channel friction and changing estuary cross-section with water depth.

3.3 A more recent report by JBA Consulting (2015) provided an updated flood risk assessment and economic options appraisal for selected locations in the estuary. The assessment utilized the updated bathymetry provided by KPAL (2015) and combined 1D-2D modelling of tidal and river flows. However, the report did not present updated flood levels for the node points previously reported in 2012. Consequently, the analysis reported below uses estimated extreme water level values in the original JBA study which are referenced to the year 2011.

3.4 All statistical estimates of extreme sea levels on the East Anglian coast, and particularly those for locations within confined estuaries such as the Alde-Ore, are subject to considerable uncertainty owing to the fact that they are based on relatively short and incomplete periods of instrumental record, the fact that widely varying estimates of extreme levels are produced when different statistical models are applied to the data, and hydrodynamic model predictions are subject to errors associated with the limitations of model bathymetry, model configuration, and the driving boundary conditions. Meaningful estimates of the true level of uncertainty associated with predicted water levels are difficult to obtain, but confidence limits of up to +/- 0.6 m can be associated with the process of mathematical curve fitting to observational data alone. The true magnitude of uncertainty, taking account of data and model deficiencies, is considerably larger. A conservative approach needs to be taken in factoring in these uncertainties in the determination of design sea levels for coastal structures including flood defences.

4.0 Embankment crest height distribution in 2009 and likelihood of overtopping / breaching

4.1 A survey of flood defence crest heights in each flood cell (Figure 4) was undertaken by the EA in 2009. The frequency distributions of crest levels for each flood cell have been calculated and are presented in Appendix 2. A summary of the mean and standard deviations of the crest height determinations in each flood cell is provided in Table 4. Table 5 shows the percentage of recorded crest heights in each flood cell where overtopping and breaching could be expected during 1 in 20 and 1 in 200 year events, both for present sea level conditions and with an assumed sea level rise of 300 mm. The greatest risk of breaching during a 1 in 20 year event lies in flood cells FC12, FC7, FC13, and FC9. The pattern is similar in the case of an estimated 1 in 200 year event. Although crest heights have been raised in a few locations, and some areas have experienced subsidence or breaching since 2009, the overall pattern in the estuary has not changed significantly since that time.

5.0 The storm surge of 5-6 December 2013

5.1 During the storm surge of 5 - 6 December 2013 the highest water level recorded at the Orford gauge was 3.06 m OD, including a skew surge of 1.66 m (KPAL, 2014). No tide gauges existed in the inner estuary at that time, but estimates from observed water line spot heights suggest that the tide reached approximately 3.00 m OD at Hazlewood Marshes and 2.96 at Snape Maltings (Table 6).According to the JBA analysis, this would indicate that the December 2013 event had a return period of just under 1 in 20 years.

5.2 The surge caused wall damage at a number of locations around the estuary, including breaches at Oxley Marshes, Lantern Marshes South and Hazlewood Marshes. At Hazlewood Marshes two breaches were formed at locations where the crest height was particularly low, and there were a number of other near-breaches (KPAL, 2014).

5.3 Less severe wall damage at Iken, Ham Creek and elsewhere was repaired quickly after the surge event. Repairs to the breach in the American Wall at Lantern Marshes South are scheduled for completion in the summer of 2015, but there are no plans to repair the breaches to the walls at Hazlewood Marshes.

6.0 Comparison of Orford and Snape tide gauge records

6.1 The EA tide gauge at Orford has been operational at least since the early 2000s, but reliable data extend back only to 2010 (Figure 6). Since 5th February 2015 an EA gauge has also been operational at Snape (Figure 7). A preliminary analysis of overlapping data for the two gauges has been undertaken and the results are shown in Figures 8, 9 and 10. On neap tides the maximum water level recorded at Snape is approximately 6 to 8 cm higher at Snape than at Orford, while on normal high spring tides the maximum water level is 2 to 4 cm higher at Snape.

6.2 Figure 10 shows a best fit trend line through data for 130 tides recorded simultaneously at Orford and Snape between February and April 2015. The trend line shows that the high tide height difference between Snape and Orford decreases with increasing tidal height, and extrapolation of the trend line suggests that the relationship reverses for positive surge tidal heights greater than approximately 2.0 m AOD.

6.3 Extrapolation of the trend line to the level recorded at Orford on 6 December 2013 (3.06 m OD) indicates a predicted maximum level of 2.996 m OD at Snape Maltings. This is slightly higher than the estimated maximum water level based on observed water lines in this area during the December 2013 event (2.96 m AOD), possibly due to localised lowering of the top of the tide as a consequence of breaching at Hazlewood Marshes and overtopping of the defences at Snape and elsewhere. Further extrapolation of the trend line to the JBA modelled 1 in 200 year level of 3.34 m OD at Orford indicates a value of 3.25 m OD at Snape, similar to the JBA modelled value of 3.27 m AOD.

6.4 The relationship between minimum low water levels recorded at Snape and Orford is shown in Figure 11. Minimum low water levels are typically 20 to 27 cm higher at Snape than at Orford, partly due to the effects of freshwater flow.

6.5 Fitting of a linear trend line to the times of high water indicates that normal high waters occur 55 +/- 8 (mean +/- 1 standard deviation) minutes later at Snape than at Orford (Figure 12), while low waters occur 88 +/- 17 minutes later at Snape (Figure 13).

6.6 The Orford tide gauge record in not sufficiently long or complete to allow estimates to be made of temporal trends in mean sea level or high and low water levels. However, analysis of data for Lowestoft for the period 1964- 2013 has indicated an average rate of in mean sea level of 3.73 mm/ yr and an average increase in high water levels of 2.20 mm /yr (KPAL, unpublished data, Figure 14). The total increase in annual mean high water levels during the period 1995 – 2014 relevant to this study is approximately 42 mm.

7.0 Telemac 2D modelling of water levels and current speeds

7.1 Modelling objectives

7.1.1 The main objectives of the hydrodynamic modelling undertaken as part of this assessment were:

(1) to implement a Telemac 2D hydrodynamic model covering the entire Alde-Ore estuary, including the Butley River, making use of a new composite bathymetric dataset produced by KPAL (2015)

(2) to undertake an initial validation of the modelled water levels using tide gauge data for 6 stations within the estuary acquired by UCL in 1995-1996

(3) to undertake a preliminary investigation of the effect on water levels and current speeds of changes in estuary planform and tidal volume arising under three different scenarios:

Scenario A: a pre- December 2013 Baseline scenario, with walls intact around Hazlewood Marshes and at Lantern Marshes South

Scenario B: restoration of tidal exchange to the Hazlewood and Lanterrn Marshes South following the storm surge of 5-6 December 2013

Scenario C: a possible future scenario where tidal exchange is maintained at Hazlewood Marshes, the existing breach in the wall at Lantern Marshes South has been repaired, and where large-scale management realignment has been implemented at and Boyton Marshes

(4) to extend the analysis described above to include analysis of the possible effect of (a)a 300 mm rise in sea level (equivalent to a 300 mm surge on an average spring tide), (b)a 1 in 20 year extreme water level event, and (c) a 1 in 200 year extreme water level event, assuming all wall heights are sufficiently high to prevent overtopping.

7.1.2 The Telemac modelling suite has previously been used widely in industry and academia. It contains a proven finite element code that resolves tidal wetting and drying very well and is computationally efficient for large simulations. Telemac -D solves the depth-averaged equations of fluid motion to provide estimates of water level (and therefore depth) and velocity in both x and y directions at each node of an unstructured triangular mesh. This makes it well-suited to representing complex estuary planform shapes that include narrow deep channels flanked by shallower tidal flat, saltmarsh and low lying terrain. The latest Telemac-2D release (v6p3r2) was used in this study, implemented using parallel processing on a Linux compute cluster.

7.2 Construction of the bathymetric mesh

7.2.1 Unstructured triangular meshes were constructed within GIS shape files generated by KPAL (2014) to define the planform configuration of the Alde-Ore estuary representing the three estuary morphology scenarios, as outlined above and illustrated in Figure 15. These domains were used to construct meshes with element dimensions varying from approximately 22 m to 5 m, and comprised approximately 105,000 to 116,000 triangular elements, depending on the configuration. Figure 16 shows the level of detail resolved by these meshes.

7.2.2 This composite bathymetric dataset was provided as a 1 m gridded data product. For modelling purposes, elevation values were interpolated onto the computational mesh nodes using an inverse distance weighting function of the closest four data values to each node. This interpolation approach introduced local smoothing to minimize the effect of localized 'spikes' in the elevation data whilst preserving topographic detail along channel edges. Figure 17 shows the final model bathymetry for Scenario B.

7.3 Model boundary conditions and parameter settings

7.3.1 The Telemac-2D simulations were driven by a time series of tidal water levels imposed at the estuary mouth and a constant river inflow at the estuary head (for locations, see Figure 18). It is commonplace in estuary modelling to extend the computational mesh seawards of the physical mouth in order that any spurious behaviour arising at the boundary occurs well away from the region of interest. In the case of the Suffolk estuaries, however, the inlet shoals are constantly evolving their morphology and tidal jets from the estuaries interact with strong tidal streams along the open coast. Given the limited scope of this pilot study to resolve such behaviour it was decided to locate the tidal level boundary within the well-defined lower estuary channel at Orford Haven. The channel was 'pinched in' slightly at the boundary to avoid instabilities due to boundary nodes drying out at low tidal stages.

7.3.2 Water levels at the seaward boundary were taken from the 1995-96 monitoring campaign undertaken by UCL for the EA, referred to above. During this campaign a 12 month dataset of hourly tidal water levels was obtained at 7 sites within the estuary (Figure 18). Data for Orford Haven (Site 1 in Figure 18) were interpolated onto the 1s time step required by Telemac and used to force (drive) the model runs.

7.3.3 The river inflows to the Alde-Ore estuary are negligible in comparison with the tidal prism (tidal exchange volume) and for the purposes of this study could probably be ignored. However, for compatibility with the recent JBA studies, the river inflow at Snape was represented in the Telemac-2D model by an assumed mean monthly flow of 0.6 $m^3 s^{-1}$.

7.3.4 Bed friction was treated simply using a Manning formulation, with the bed friction coefficient, *n*, being assumed to be constant over the domain. An initial calibration was undertaken by adjusting *n* over a realistic range (0.015 < 0.03) to obtain the best fit between model output and observation.

7.3.5 An Elder-type turbulence model was used, with values of 6 and 0.6 for the dimensionless dispersion coefficients along and across the direction of the mean current respectively, throughout the estuary.

7.3.6 Telemac-2D offers various options for the treatment of intertidal wetting and drying. The option selected detects dry elements and corrects the free surface gradient to avoid negative depths in the solution.

7.3.7 The model was run using a 1 s time step (required for numerical stability purposes), with outputs being generated at a 15 minute interval for analysis and comparison with observational data. All computational runs were undertaken in parallel mode using either 16 or 32 processors.

7.4 Modelling Results

7.4.1 Calibration against observed water levels

7.4.1.1 Hydrodynamic model codes such as Tuflow (used by JBA Consulting) and Telemac have been widely applied to shallow coastal and estuarine problems and are sufficiently tried and test that one can have reasonable confidence that they will perform well, provided that the bathymetry and boundary condition data are accurate. However, calibration is normally carried out by adjusting certain parameters, chiefly those relating to bottom friction and/or the turbulence sub-model, and by evaluating model output using quantitative performance statistics (e.g. Sutherland *et al.*, 2004; French, 2010). Where there is reason to doubt the accuracy of the bathymetry, this may also become a calibration parameter (Cea & French, 2012), although this is computationally expensive.

7.4.1.2 Normally, calibration is undertaken with respect to both the free surface (water level) and the velocity field. However, no tidal current velocity data were available for the Alde-Ore and so the initial evaluation of model performance has been restricted to comparison of modelled and observed 1995 water levels obtained for sites 2 to 7 shown in Figure 18.The extent of these tidal water level datasets is summarized in Figure 19, from which it can be seen that a number of data gaps exist. To ensure data availability at all stations, the month of June 1995 was selected for calibration and as a source of boundary condition data for later scenario evaluations. A nominal 15 day sequence was used, preceded by a 5 day 'spin up' sequence that was discarded for analysis.

7.4.1.3 Model performance was evaluated using the root mean square error (*rmse*; units in m):

$$RMSE = \left\{ \frac{\left[\sum_{i=1}^{N} \left(O_i - M_i\right) \right]^2}{N} \right\}^{0.5}$$

and the Nash-Sutcliffe efficiency (*nse*; dimensionless) (Nash-Sutcliffe, 1972; Henriksen *et al*., 2008):

$$nse = 1 - \left(\sum_{i}^{N} \left(O_i - M_i\right)^2 / \sum \left(O_i - O_{mean}\right)^2 \right)$$

where O and M are observed and modelled values (e.g. water level), O_{mean} is the mean of the observations and N the number of data points. The smaller the *rmse* the better, and the closer *nse* is to 1.0 the better. A value of n = 0.02 (Manning friction coefficient) gave the best fit of model output to observed data. This fit is visualized as model and observed time series in Figure 18 and is summarised numerically in Table 7.

7.4.1.4 Absolute *rms* errors are good (around 5 to 10 cm) for all stations except Orford. It is possible that the data for this station may be in error, or are affected by the artificial cross-section of the estuary channel between Orford quay and the National Trust quay on Orford Ness; this requires further investigation. It should be noted that both the Iken and Snape gauges dried at low tide. The calibrated model shows a general tendency to slightly over-predict the high water levels, especially in the upper estuary (Figure 20). Further investigation is required to explore the possibility that the model performance could be improved by adjusting the friction and/or turbulence parameterization within the model.

7.4.2 Along-estuary variation in water levels and tidal currents

7.4.2.1 Figures 21 and 22 show the variation in modelled water levels and tidal current velocity series at each of the six water level validation sites along the estuary.

7.4.2.1 Flood and ebb velocities are very similar in the outer estuary but the upper estuary becomes more ebb-dominated in terms of peak velocities, as expected given the extensive tidal flats above Slaughden. The strong ebb dominance at Snape is the result of the imposed river inflow in the narrow channel section.

7.4.3 Modelling of Hazlewood and Boyton Marshes breach scenarios for average tides

7.4.3.1 The different estuary planform scenarios were investigated using modelled tidal current velocities extracted from specified mesh nodes around the flood defence breach locations and at Slaughden. Output locations were chosen to correspond with a subset of those used by JBA (2012a, b) (see Table 3 and Figure 22). Nodes 34, 31 and 29 were used to illustrate changes in the vicinity of the breach in Hazlewood Marshes. Nodes 27, 28 and 26 were used to illustrate changes in the channel at Slaughden. Nodes 8, 4 and 6 were used to illustrate the zone close to a hypothetical partial sea defence removal at Boyton Marshes.

7.4.3.2 Table 8 summaries the changes in peak tidal current velocity at selected nodes in the vicinity of the Hazlewood Marshes breach. These were extracted from two representative neap tides and two representative spring tides in June 1995. Time series plots of the water level forcing at Orford Haven, tidal current velocities, and changes in tidal current velocity between scenarios are presented in Figures 23 to 25.

7.4.3.3 Overall, the Scenario B changes in velocity are small, which is not unexpected given that Hazlewood Marshes are not as low within the tidal frame as some other reclaimed flood compartments within the estuary. However, there is generally an increase in velocity magnitudes, both on flood and ebb. The delta velocity (change in velocity) magnitude plots show some negative ‘transients’, which appear to be due to slight shifts in the phase of the tidal wave. These are therefore not indicative of equivalent increases in peak current velocity and the tabulated peak flood and ebb magnitudes are more meaningful. These show that effect is consistently to increase velocities but by only a small amount (typically less than 6%).

7.4.3.4 A similar analysis for the Slaughden and Boyton areas is presented in Tables 9 and 10 and in Figures 27 to 32. The simulated velocity changes in the Slaughden Bend area under Scenario B are 5.3 to 5.4% on the flood and 4.8 to 7.2% on the ebb, which is towards the lower end of the range predicted by KPAL (2014) on the basis of tidal prism analysis. Adding a large realignment at Boyton Marshes (Scenario C) is indicated by the modelling to make very little difference to the current speeds and water levels near Slaughden and in the upper part of the estuary (<0.15%). However, significant additional increases in flood (8.5%) and ebb (6.3%) current speeds, above those predicted in Scenario B, are evident between Boyton and the estuary mouth with Scenario C.

7.4.4 The effects of a 300 mm sea-level rise or 300 mm surge

7.4.4.1 The above analysis was repeated but with the tidal boundary water levels raised by 300 mm to simulate a plausible near-future sea-level rise. It should be emphasised that the bathymetry was not modified and therefore the subsequent analysis simulates a rather extreme change to the estuary process regime that does not factor in sedimentary processes that might be expected to counter some of the impacts. It does, however, approximate the tidal flows that might be expected under a modest (300 mm) tidal surge event.

7.4.4.2 The effect of sea-level rise is essentially twofold. First, it increases the time-averaged depth of the estuary, which influences the propagation of the tidal wave. Second, it increases the volume of water (tidal prism) exchanged on each tide, since the intertidal area is quite large and this draws in more water as the height of high water is increases.

7.4.4.3 Tables 11 to 13 and Figures 33 to 41 repeat the previous analysis for this 300 mm step change in sea level. Changes are calculated relative to the present Scenario A baseline, in order to factor in both the change in bathymetry due to sea defence failure/removal and the increase in mean water level and tidal prism. As expected, the changes are rather larger in this case, with some locally quite significant increase in current velocity magnitudes in each study area. Near Hazlewood Marshes and at Slaughden, flood velocities in particular are higher, and the ebb runs for longer than under the baseline scenario. At Boyton and in the lower estuary channel (Node 4), peak flood velocities are higher by up to 20% under Scenario C.

7.4.5 Extreme surge scenarios

7.4.5.1 To better understand the pattern of tidal currents under more extreme surge conditions, a further set of simulations was undertaken using hypothetical surges based on the surge of 5-6 December 2013. The observed December 2013 water level record for Orford was taken as a starting point for this analysis. The first few days were used to 'spin-up' the Telemac runs and the surge tide of 5-6 December was scaled in amplitude to give high water levels of 3.106 m OD and 3.610 m OD, corresponding to estimates of the 1 in 20 and 1 in 200 year extreme levels for the estuary mouth (Orford Haven). The 1 in 20 year event is almost indistinguishable from the actual surge of 5-6 December 2013 (Figure 42), whereas the 1 in 200 year event is significantly larger.

7.4.5.2 The synthetic water-level series for the model boundary at Orford Haven was then used to drive the model for each of the geometries considered in the preceding analysis. The phase difference between Orford Haven and Orford is immaterial here, since the analysis is considered to represent hypothetical events with an arbitrary time origin. The analysis of tidal currents presented below also considers only the main surge tide, which is clearly flood-dominated, and omits the subsequent tide, which becomes ebb-dominated as the surge decays.

7.4.5.3 Results are presented for the same sets of model nodes used previously. Table 14 summarises the variation in maximum water level along the estuary. The Telemac modelled water levels show a similar pattern for all geometries under both the 1 in 20 year and 1 in 200 year surge scenarios. However, it is interesting to note an apparent slight tendency of the Boyton Marshes inundation (geometry C) to increase rather than decrease water levels, whereas the Hazelwood and Lantern configuration seemingly act to decrease them slightly. This tendency may be due to the effect on tidal propagation within the whole estuary of a significant increase in tidal prism near the mouth.

7.4.5.4 Changes in peak flood and ebb current velocity magnitude for different water levels under each of the Scenarios A, B and C are summarised in Tables 15, 16 and 17, respectively. Illustrative time series plots are presented for the outer estuary (Node 4), Slaughden (Node 28), and vicinity of Slaughden marshes (Node 29) in Figures 43 -

45. These show the 20 year and 200 year water level curves and the tidal current velocities for A, B and C geometries and both the 20 and 200 year events.

7.4.5.5 In the case of the Baseline (Scenario A) morphology, the 1 in 20 and 1 in 200 year events lead to large increases in flood velocities of 20 to 35% and 33 to 63 %, respectively, compared with the medium spring tide case (Table 15). However, the peak ebb velocities show a more varied pattern of increases and decreases in different parts of the estuary, and with an overall predominance of *reduced* velocities compared with the Baseline medium spring tide case. It should be noted that the surge tide has a steeply rising (flood) limb but a more gently falling ebb limb which reflects the fact that the estuary does not drain fully or quickly following a large surge high tide.

7.4.5.6 In the case of Scenario B, the 1 in 20 and 1 in 200 year events also cause increases in flood velocities of 20 to 44% and 36 to 63%, respectively. This is an expected response to the increase in tidal prism and this effect is greater for higher surge event magnitudes. Once again, ebb velocities show a more varies spatial pattern but with a predominance of reduced ebb velocities for both the 1 in 20 and 1 in 200 year events (Table 16).

7.4.5.7 For Scenario C, the 1 in 20 and 1 in 200 year events produce increases in peak flood velocities of 20 to 45% and 34 to 66%, respectively Table 17). The pattern of predicted change in peak ebb velocities is again spatially variable, and with differences in the pattern of change between the 1 in 20 and 1 in 200 year events. On average, the predicted reductions in peak ebb velocities are larger for the 1 in 20 year event (up to 20%) than for the 1 in 200 year event (up to 13%). For both events, increases in ebb velocities as well as flood velocities are predicted between Boyton and the estuary mouth, but the tidal regime remains flood-dominated in terms of the peak velocities experienced in this area (and indeed throughout most of the estuary). Again, this is interpreted to reflect the clear flood dominance of a large surge tide, and incomplete draining of the estuary on the following ebb.

8.0 Comparison with previous modelling results

8.1 The water level values predicted by Telemac 2D for the 1 in 20 and 1 in 200 year events differ from those predicted for the mid and upper estuary by JBA (2012) and summarised in Table 3. Both the JBA and present studies estimated a 1 in 20 year event high water level of approximately 3.1 m OD at Orford Haven and Orford. However, whereas the JBA study also estimated a 1 in 20 level of approximately 3.1 m OD for Node 28 at Slaughden, the present study indicates a 1 in 20 year level of 3.25 m OD at this location. Comparative values for Node 34 near Hazlewood Marshes are 3.11 m OD estimated by JBA (2012) and 3.30 m OD in the present study. The JBA model predictions show a slight decrease in surge water levels inside the estuary entrance, followed by a slight increase between Orford and Snape, whereas the Telemac results indicate both higher overall levels and a steeper rise upstream of Slaughden. The principal reason for these differences arises from the fact that the JBA study simulated overtopping of the defences under the more extreme water levels, whereas in the present study it was assumed that the defences are of sufficient height not to be overtopped. Raising of the defences to prevent overtopping itself would increase water levels within the confined channel to a higher level than if overtopping occurs. Additional model runs would be required to examine the effect of overtopping for different lengths of time (e.g. a maximum overtopping depth of 300mm for a 2 hour period), in a uniform pattern throughout the estuary.

9.0 Conclusions

9.1 The preliminary hydrodynamic modelling of spring and neap tides undertaken using a Telemac-2D finite element model showed that the effect of breaching at Hazlewood Marshes and Lantern Marshes South on water levels and maximum current velocities is relatively small compared with the baseline (pre-breach) scenario. The modelling simulations indicate a 5 to 7% increase in maximum flood and ebb velocities in the Slaughden area, which is of a similar magnitude to the increases estimate by KPAL (2014) on the basis of tidal prism analysis and expert geomorphological assessment. However, the predicted effects are sufficiently large to be detected and are consistent with observations of increased velocities in the river near Slaughden since December 2013.

9.2 The combined effect of a hypothetical large scale breach at Boyton Marshes and continuing breaches at Hazlewood Marshes is predicted by the modelling to be significantly larger than the effect of breaching at Hazlewood and Lantern Marshes South alone, although the effects are mainly seen in the lower estuary south of Boyton. The preliminary modelling results suggest there would be only a very small effect on water levels and current speeds upstream of Orford, contrary to some local expectations.

9.3 Modelling of neap and spring tides including a 300 mm rise in sea level, (equivalent to a spring tide with a modest surge component of 300 mm) has shown a significant increase in current speeds throughout the estuary as a whole, under all three morphological scenarios. This reflects the relatively large added tidal prism within the re-flooded areas as well as over the estuary intertidal area as a whole. Maximum increases in peak tidal current velocity of around 20% are predicted for the outer estuary channel for the Hazelwood and Boyton Marsh inundation under the 300 mm sea-level rise / surge tide scenario.

9.4 Additional model runs to assess current speeds throughout the estuary associated with 1 in 20 and 1 in 200 year surge tide water levels, assuming a scenario where the walls around the estuary are sufficiently high to prevent overtopping in the 1 in 200 year event, indicate major increases in peak flood velocities and mostly small reduction in peak ebb velocities (except near the estuary mouth), indicating that the estuary becomes more flood dominant during higher magnitude events.

9.5 The Telemac-2D hydrodynamic model implementation presented to date could be refined by including spatially varied friction to fine tune model performance further, especially within the intertidal areas (e.g. French, 2010), adjustments to the turbulence parameterisation, minor adjustments to the computational mesh and the depiction of the flood defences and breaches, and a more critical evaluation of the calibration datasets. Further modelling work would benefit from the acquisition of tidal current data at different depth in the water column for one of more locations in order to provide model validation.

9.6 Further modelling to assess a scenario where the walls are constructed to withstand a maximum of 300 m overtopping up to the year 2015 is beyond the scope of the present work but could potentially be undertaken.

9.7 Achievement of the AOEP objective would require raising of the flood embankments to a minimum level of 3.28 m OD in the Snape area, c. 3.5 m OD around Orford, and c. 3.60 near the mouth of the estuary. Additional increases of up to 20 cm might be necessary on sections of wall exposed to the longest wave fetches, since waves create a greater risk of overtopping and scour of the landward banks than still water levels alone. Sections of wall which face to the west, southwest and southwest have the greatest additional risk.

9.8 An allowance of 300 mm for increases in high water levels by the year 2050 can be considered as conservative in view of current climate change projections and observations that in recent decades the increase in mean high water level at Lowestoft has been less than the increase in mean sea level.

9.9 The modelling showed that, throughout the estuary, water levels are very similar for all geometries under both the 1 in 20 year and 1 in 200 year surge scenarios. A very slight tendency was indicated for the Boyton Marshes inundation (geometry C) to increase rather than decrease water levels in the mid and upper estuary, whereas the Hazelwood and Lantern Marshes configuration showed a slight decrease. The implication is that further managed realignment in the upper estuary would have the greatest beneficial effect on surge water levels.

9.10. Relative to the baseline pre-2013 geometry (A), the realignment geometries (B, C) result in increased extreme surge flood and ebb flows, especially in the outer estuary channel. This is an expected response to the greatly increased tidal prism. Around Slaughden and Hazelwood Marshes, extreme surge velocities increase under all scenarios although changes are generally no more than 10%. Flood tide velocities are predicted to increase by more than ebb velocities, as expected given the asymmetrical nature of the modelled surge tides (based on the December 2013 event).

9.11 The hydrodynamic model implementation presented to date could be refined by including spatially varied friction to fine tune model performance further, especially within the intertidal areas, adjustments to the turbulence parameterisation, minor adjustments to the computational mesh and the depiction of the flood defences and breaches, and a more critical evaluation of the calibration datasets. Further modelling work would benefit from the acquisition of tidal current data at different depths in the water column for a number of locations along the estuary length in order to provide data for further 2D, and potentially 3D, model validation. This would require another 30 day field campaign commissioned by the Environment Agency.

9.12 The proposals in the AOEP Estuary Plan imply raising of the flood embankments to a level which will withstand overtopping by 300 mm for up to two hours in the year 2050, taking into account 300mm of projected sea level rise by that date. This would equate to a minimum crest level of approximately 3.28 m OD in the Snape area, 3.5 m OD around Orford, and 3.60 m OD near the mouth of the estuary. Based on the results of the hydrodynamic modelling and previous expert geomorphological assessment, it can be concluded that the AOEP strategy to raise the wall crest heights throughout the estuary is likely to successfully reduce the frequency of wall breaching and wall abandonment, thereby avoiding progressive increases in tidal prism and current speeds throughout the estuary over and above those which can be expected due to rising sea level over the next century. An allowance of 300 mm for increases in high water levels by 2050 can be considered to be conservative based on current climate change projections and observations that recent increase in mean high water level at Lowestoft have been smaller than the increase in mean sea level. However, it should be noted that present estimates of storm surge return periods and levels are based on a relatively short period of record and future changes in frequency and magnitude which may accompany climate change are difficult to forecast.

9.13 Further modelling will be required to assess the likely effects of different potential design options for a possible large scale managed realignment or controlled tidal flooding scheme at Boyton Marshes, and/ or the possible effects of allowing barrier rollover south of Slaughden. Before further modelling is undertaken, a new 30 day field data campaign should be undertaken to measure water levels, tidal currents and suspended sediments at several locations within the estuary. Depth profile data should be obtained in order to provide calibration and validation of 3D as well as 2D models. Consultation will be required between the AOEP, EA, RSPB and Natural England in order to ensure that the further data acquisition and modelling work match all objectives.

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11.0 Acknowledgements

Tidal water level data for 1995-1996 and for the period 2007 to 2015 are used here with permission of the Environment Agency.

TABLES

Table 1. Tidal levels on the open coast and within the Alde-Ore estuary: (A) predictions in Admiralty Tide Tables (UKHO, 2013); (G) Gardline (2003) who deployed Aquadopp (acoustic Doppler) meters and Aanderaa (pressure transducer) tide recorders over a period 32 days between 21st August and 23rd September 2003; *The Gardline Alde-Ore Mouth values are considered to be unrepresentative as only nine days of data were obtained. Values in **bold** have been estimated or calculated by extrapolation using the trend at the relevant Standard Port.

	HAT	MHWS	MHWN	MSL	MLWN	MLWS	LAT	CD	MSTR	MNTR	Source
Open Coast, north to south											
Lowestoft	1.4	0.9	0.6	0.16	-0.5	-1.0	-1.4	-1.50	1.9	1.1	A
Southwold	1.6	1.1	0.8	0.25	-0.4	-0.8	**-1.2**	-1.30	1.9	1.2	A
Aldeburgh	1.8	1.1	0.7	0.06	-0.7	-1.3	**-1.8**	-1.60	2.4	1.4	A
Martello Towers	**1.86**	1.56	1.04	nd	-0.25	-0.76	nd	nd	2.31	1.29	G
Orford Ness	1.4	1.2	1.1	nd	-0.8	-1.2	**-1.5**	-1.65	2.3	1.8	A
Orford Haven Bar	1.9	1.5	0.9	0.13	-0.7	-1.3	**-1.7**	-1.66	2.8	1.6	A
Bawdsey	2.0	1.6	1.0	0.09	-0.8	-1.5	**-2.0**	-1.77	3.1	1.8	A
Felixstowe	2.3	1.9	1.2	0.13	-1.0	-1.6	-2.1	-1.95	3.4	2.1	A
Harwich	2.4	2.0	1.4	0.12	-0.9	-1.6	-2.1	-2.02	3.6	2.3	A
Walton-on-the-Naze	2.5	2.0	1.2	0.08	-1.1	-1.8	-2.3	-2.16	3.8	2.3	A
Alde-Ore Estuary, mouth to head											
Orford Haven Bar	1.9	1.5	0.9	0.13	-0.7	-1.3	**-1.7**	-1.66	2.8	1.6	A
Alde-Ore Mouth	**1.78**	1.51	1.04	nd	-0.27	-0.75	nd	nd	2.25	1.31	G
Butley River Entrance	**1.57**	1.36	0.99	nd	-0.22	-0.60	nd	nd	1.97	1.21	G
Gedgrave Marshes	**1.56**	1.35	0.98	nd	-0.25	-0.63	nd	nd	1.98	1.23	G
East Havergate	**1.60**	1.38	1.00	nd	-0.25	-0.63	nd	nd	2.01	1.25	G
Orford Moorings	**1.64**	1.42	1.03	nd	-0.22	-0.61	nd	nd	2.03	1.25	G
Orford Quay	1.5	1.2	0.7	0.20	-0.5	-1.0	**-1.4**	-1.60	2.2	1.2	A
Main Channel	**1.67**	1.44	1.04	nd	-0.26	-0.66	nd	nd	2.10	1.30	G
Aldeburgh Yacht Club	**1.71**	1.48	1.08	nd	-0.23	-0.64	nd	nd	2.12	1.31	G
Slaughden Quay	1.5	1.3	1.0	0.19	-0.6	-1.0	**-1.3**	-1.60	2.3	1.6	A
Aldeburgh Marshes	**1.74**	1.50	1.08	nd	-0.27	-0.69	nd	nd	2.19	1.35	G
Iken Cliffs	1.6	1.3	0.8	0.20	-0.5	-1.0	**-1.4**	-1.60	2.3	1.3	A
Iken Cliffs	**1.72**	1.47	1.03	nd	-0.35	-0.80	nd	nd	2.27	1.38	G

Table 2. Return periods of extreme high waters near the mouth of the Alde-Ore. Taken from McMillan *et al*., (2011) 'Coastal flood boundary conditions for UK mainland and islands. Levels are given in m above Ordnance Datum (OD)

	Return Period (years)							
	1	2	5	10	20	50	100	200
Chainage 4196 (Thorpe Ness)	1.99	2.13	2.31	2.45	2.60	2.79	2.95	3.12
Chainage 4202 (Slaughden)	2.08	2.22	2.40	2.54	2.70	2.90	3.07	3.25
Chainage 4208 (Orford Ness)	2.18	2.32	2.50	2.66	2.81	3.03	3.21	3.40
Chainage 4214 (Orford Beach)	2.39	2.53	2.71	2.87	3.02	3.25	3.43	3.63
Chainage 4218 (Shingle Street)	2.52	2.66	2.84	3.00	3.15	3.38	3.56	3.75
Chainage 4222 (Bawdsey)	2.62	2.76	2.94	3.09	3.25	3.47	3.65	3.84

Table 3. Predicted extreme water levels at different node points within the Alde-Ore estuary, for 1 in 20, 50 75, 200 and 1000 year events, calculated by JBA in 2012. Node 369 (UCL node 1) lies near the mouth of the estuary, Node 1196 (UCL node 16) lies close to Orford, Node 2381 (UCL Node 28) is at Slaughden Bend, Node 2813 (UCL Node 34) lies downstream of the breach at Hazlewood Marshes, and .Node 2813 (UCL Node 35) lies downstream of the tidal barrier at Snape.

Node ID (JBA)	Node ID (UCL)	Easting	Northing	Storm Surge Return Periods				
				20 year	50 year	75 year	200 year	1000 year
369	1	637781	244590	3.106	3.303	3.403	3.610	3.961
405	2	638231	245040	3.095	3.280	3.370	3.547	3.854
452	3	638831	245640	3.090	3.264	3.345	3.495	3.755
496	4	639581	246240	3.082	3.243	3.313	3.427	3.663
531	5	640331	246540	3.089	3.249	3.317	3.433	3.674
564	6	639881	246840	3.083	3.240	3.306	3.415	3.663
592	7	640481	246990	3.083	3.238	3.302	3.401	3.638
639	8	639431	247290	3.081	3.229	3.283	3.363	3.613
654	9	641681	247290	3.085	3.236	3.293	3.392	3.618
681	10	641081	247440	3.083	3.235	3.297	3.389	3.615
721	11	642131	247590	3.086	3.235	3.293	3.385	3.615
816	12	641381	248040	3.087	3.237	3.297	3.391	3.620
843	13	639281	248190	3.086	3.226	3.275	3.350	3.579
899	14	642581	248340	3.085	3.231	3.285	3.373	3.599
117	15	642431	249090	3.082	3.227	3.280	3.362	3.565
1196	16	642581	249390	3.076	3.218	3.268	3.342	3.513
1223	17	639581	249540	3.096	3.228	3.276	3.351	3.534
1239	18	643481	249540	3.081	3.222	3.272	3.348	3.516
1378	19	639431	250140	3.099	3.227	3.276	3.350	3.530
1457	20	638831	250440	3.100	3.228	3.276	3.350	3.531
1529	21	644381	250590	3.084	3.216	3.262	3.331	3.500
1797	none	638681	251640	3.096	3.224	3.274	3.351	3.531
1839	22	644381	251790	3.087	3.210	3.254	3.319	3.487
1989	23	645281	252690	3.091	3.206	3.247	3.310	3.471
2063	24	645581	253290	3.094	3.206	3.246	3.309	3.465
2184	25	645881	254190	3.098	3.205	3.243	3.306	3.447
2277	26	646031	254940	3.101	3.204	3.240	3.302	3.433
2343	27	644831	255390	3.104	3.196	3.225	3.285	3.390
2381	28	646031	255540	3.099	3.195	3.226	3.284	3.387
2440	29	644381	255840	3.107	3.194	3.222	3.284	3.399
2537	30	640781	256290	3.122	3.193	3.217	3.282	3.415
2608	31	644681	256440	3.108	3.193	3.220	3.283	3.402
2733	32	643331	256890	3.115	3.192	3.217	3.282	3.409
2763	33	641081	257040	3.120	3.194	3.217	3.282	3.414
2785	34	644381	257040	3.109	3.191	3.217	3.281	3.404
2813	35	642731	257190	3.116	3.193	3.217	3.283	3.411
2880	none	638831	257490	2.023	2.120	2.306	2.839	3.417
2885	36	639581	257490	3.121	3.190	3.212	3.275	3.418
3029	none	636731	257940	0.000	0.000	0.000	2.820	3.419
3037	none	638081	257940	1.699	2.045	2.306	2.840	3.419

Table 4. Statistics and frequencies of observations of embankment heights (EA survey in 2009) within the 13 flood compartments in the Alde-Ore estuary.

	Flood Compartment												
	FC1	FC2	FC3	FC4	FC5	FC6	FC7	FC8	FC9	FC10	FC11	FC12	FC13
n	595	43	136	938	361	38	79	43	148	214	692	323	92
Mean	3.27	3.22	3.10	3.13	3.10	3.16	2.62	2.97	2.85	3.17	2.97	2.52	2.75
St. Dev.	0.30	0.36	0.25	0.19	0.26	0.28	0.27	0.38	0.23	0.17	0.24	0.18	0.25
Minimum	1.90	2.46	2.77	2.55	2.60	2.68	2.27	2.44	2.40	2.76	1.99	1.95	2.23
1 %ile	2.66	2.48	2.82	2.71	2.67	2.74	2.28	2.44	2.43	2.80	2.21	2.11	2.30
5 %ile	2.81	2.59	2.84	2.85	2.75	2.86	2.32	2.48	2.48	2.88	2.52	2.23	2.35
10 %ile	2.90	2.78	2.86	2.91	2.80	2.92	2.37	2.56	2.53	2.94	2.64	2.29	2.42
25 %ile	3.06	2.98	2.94	3.01	2.90	2.99	2.45	2.67	2.69	3.06	2.86	2.42	2.59
50 %ile	3.26	3.24	3.03	3.11	3.08	3.05	2.53	2.93	2.84	3.18	3.01	2.51	2.74
75 %ile	3.47	3.42	3.18	3.21	3.25	3.27	2.76	3.19	2.96	3.29	3.12	2.63	2.89
90 %ile	3.64	3.66	3.50	3.38	3.41	3.50	2.92	3.58	3.13	3.39	3.22	2.75	3.09
95 %ile	3.80	3.69	3.71	3.45	3.54	3.86	3.20	3.66	3.31	3.42	3.28	2.81	3.13
99 %ile	3.95	3.99	3.86	3.71	3.88	3.87	3.50	3.88	3.45	3.62	3.43	2.93	3.27
Maximum	4.00	3.99	3.90	3.98	3.95	3.88	3.59	4.00	3.69	3.75	3.82	3.00	3.30

Table 5. The highest 1 in 20 year and 1 in 200 year extreme water levels predicted by JBA for the main river channel beside each flood compartment in the Alde-Ore. Walls are assumed to overtop if this level is exceeded, and are assumed to breach if this level is exceeded by 30 cm. In addition, the level of breaching following a sea level rise of 30 cm is assessed. For each level, the frequency percentage of observations of embankment heights within each flood compartment has been calculated.

	Flood Compartment												
Scenario	FC1	FC2	FC3	FC4	FC5	FC6	FC7	FC8	FC9	FC10	FC11	FC12	FC13
1:20 year overtopping													
Level:	3.09	3.10	3.10	3.10	3.12	3.12	3.12	3.12	3.12	3.11	3.09	3.09	3.09
%ile:	29.9	33.3	70.0	48.4	55.4	55.3	94.4	68.4	89.9	34.8	70.5	100.0	89.8
1:20 year breaching													
Level:	2.79	2.80	2.80	2.80	2.82	2.82	2.82	2.82	2.82	2.81	2.79	2.79	2.79
%ile:	3.5	10.6	0.6	2.5	13.8	2.5	77.2	38.1	46.6	1.1	18.4	94.3	53.8
1:20 year breaching with 30 cm sea level rise													
Level:	3.09	3.10	3.10	3.10	3.12	3.12	3.12	3.12	3.12	3.11	3.09	3.09	3.09
%ile:	29.9	33.3	70.0	48.4	55.4	55.3	94.4	68.4	89.9	34.8	70.5	100.0	89.8
1:200 year overtopping													
Level:	3.50	3.35	3.35	3.40	3.28	3.27	3.27	3.28	3.28	3.29	3.37	3.39	3.43
%ile:	77.5	61.6	86.8	91.4	77.6	75.6	96.2	86.1	93.2	73.9	97.8	100.0	100.0
1:200 year breaching													
Level:	3.20	3.05	3.05	3.10	2.98	2.97	2.97	2.98	2.98	2.99	3.07	3.09	3.13
%ile:	44.7	29.8	61.1	48.4	37.4	20.3	91.9	56.0	76.9	15.3	63.8	100.0	95.7
1:20 year breaching with 30 cm sea level rise													
Level:	3.50	3.35	3.35	3.40	3.28	3.27	3.27	3.28	3.28	3.29	3.37	3.39	3.43
%ile:	77.5	61.6	86.8	91.4	77.6	75.6	96.2	86.1	93.2	73.9	97.8	100.0	100.0

Table 6. Levels of the surge on 5th December 2013 estimated by JBA (2015) from observed flood levels around the estuary. *Hole in Snape Malting's defence led to greater inundation during event than modelled. **Flood depths rather than flood levels

Site	Easting	Northing	Recorded	Modelled
Alliance House, Snape Maltings	639206	257533	2.58	1.53*
Maltings Concert Hall, Snape Maltings	639354	257479	2.96	3.04
Riverside Cottage, Snape Maltings	639208	257657	2.91	3.00
Box Cottage, Snape Village	639406	258096	2.89	3.02
Crown Pub, Snape Village	639412	258047	2.91	3.02
Hazlewood Marshes	644516	257788	3.00	3.05
Upsons Boatyard, Slaughden	646332	255444	1.1**	1.04**

Table 7: Summary of root mean square error (*rmse*) and Nash-Sutcliffe model efficiency (nse) for modelled versus observed water levels using June 1995 datasets.

Station	Water level performance	
	rmse (m)	*nse*
Flybury Point	0.074	0.987
Butley River	0.053	0.994
Orford	0.174	0.938
Slaughden	0.105	0.978
Iken	0.070	0.946
Snape	0.118	0.884

Table 8: Summary of changes in peak tidal current velocity at selected nodes in the vicinity of Hazlewood Marshes. Scenario A is pre-2013 baseline planform; B includes inundation of Hazlewood and Lantern marshes; C includes inundation of Hazlewood and Boyton marshes

Node 34 (closest to breach)	
Scenario A max flood neap	0.55 m/s
Scenario A max flood spring	0.62 m/s
Scenario A max ebb neap	-0.49 m/s
Scenario A max ebb spring	-0.52 m/s
Scenario B max flood neap	0.57 m/s
Scenario B max flood sprin	0.63 m/s
Scenario B max ebb neap	-0.52 m/s
Scenario B max ebb spring	-0.55 m/s
Scenario C max flood neap	0.57 m/s
Scenario C max flood spring	0.62 m/s
Scenario C max ebb neap	-0.51 m/s
Scenario C max ebb spring	-0.54 m/s
Node 31	
Scenario A max flood neap	0.42 m/s
Scenario A max flood spring	0.48 m/s
Scenario A max ebb neap	-0.46 m/s
Scenario A max ebb spring	-0.49 m/s
Scenario B max flood neap	0.43 m/s
Scenario B max flood spring	0.49 m/s
Scenario B max ebb neap	-0.48 m/s
Scenario B max ebb spring	-0.51 m/s
Scenario C max flood neap	0.45 m/s
Scenario C max flood spring	0.50 m/s
Scenario C max ebb neap	-0.48 m/s
Scenario C max ebb spring	-0.51 m/s
Node 29	
Scenario A max flood neap	0.68 m/s
Scenario A max flood spring	0.75 m/s
Scenario A max ebb neap	-0.63 m/s
Scenario A max ebb spring	-0.76 m/s
Scenario B max flood neap	0.70 m/s
Scenario B max flood spring	0.80 m/s
Scenario B max ebb neap	-0.67 m/s
Scenario B max ebb spring	-0.78 m/s
Scenario C max flood neap	0.70 m/s
Scenario C max flood sprin	0.80 m/s
Scenario C max ebb neap	-0.66 m/s
Scenario C max ebb spring	-0.77 m/s

Table 9: Summary of changes in peak tidal current velocity at selected nodes in the vicinity of Slaughden, Scenario A is pre-2013 baseline planform; B includes inundation of Hazelwood and Lantern marshes; C includes inundation of Hazlewood and Boyton marshes

Node 27	
Scenario A max flood neap	0.64 m/s
Scenario A max flood spring	0.70 m/s
Scenario A max ebb neap	-0.61 m/s
Scenario A max ebb spring	-0.73 m/s
Scenario B max flood neap	0.66 m/s
Scenario B max flood spring	0.75 m/s
Scenario B max ebb neap	-0.65 m/s
Scenario B max ebb spring	-0.75 m/s
Scenario C max flood neap	0.66 m/s
Scenario C max flood spring	0.75 m/s
Scenario C max ebb neap	-0.64 m/s
Scenario C max ebb spring	-0.74 m/s
Node 28	
Scenario A max flood neap	0.66 m/s
Scenario A max flood spring	0.74 m/s
Scenario A max ebb neap	-0.55 m/s
Scenario A max ebb spring	-0.63 m/s
Scenario B max flood neap	0.67 m/s
Scenario B max flood spring	0.78 m/s
Scenario B max ebb neap	-0.59 m/s
Scenario B max ebb spring	-0.66 m/s
Scenario C max flood neap	0.67 m/s
Scenario C max flood spring	0.78 m/s
Scenario C max ebb neap	-0.57 m/s
Scenario C max ebb spring	-0.65 m/s
Node 26	
Scenario A max flood neap	0.58 m/s
Scenario A max flood spring	0.64 m/s
Scenario A max ebb neap	-0.62 m/s
Scenario A max ebb spring	-0.73 m/s
Scenario B max flood neap	0.58 m/s
Scenario B max flood spring	0.64 m/s
Scenario B max ebb neap	-0.64 m/s
Scenario B max ebb spring	-0.75 m/s
Scenario C max flood neap	0.59 m/s
Scenario C max flood spring	0.65 m/s
Scenario C max ebb neap	-0.64 m/s
Scenario C max ebb spring	-0.74 m/s

Table 10: Summary of changes in peak tidal current velocity at selected nodes in the vicinity of Boyton Marshes: Scenario A is pre-2013 baseline planform; B includes inundation of Hazlewood and Lantern marshes; C includes inundation of Hazlewood and Boyton marshes

Node 8	
Scenario A max flood neap	0.60 m/s
Scenario A max flood spring	0.72 m/s
Scenario A max ebb neap	-0.68 m/s
Scenario A max ebb spring	-1.05 m/s
Scenario B max flood neap	0.59 m/s
Scenario B max flood spring	0.71 m/s
Scenario B max ebb neap	-0.69 m/s
Scenario B max ebb spring	-1.08 m/s
Scenario C max flood neap	0.60 m/s
Scenario C max flood spring	0.71 m/s
Scenario C max ebb neap	0.70 m/s
Scenario C max ebb spring	-1.09 m/s
Node 6 - closest to breach	
Scenario A max flood neap	0.76 m/s
Scenario A max flood spring	0.87 m/s
Scenario A max ebb neap	-0.77 m/s
Scenario A max ebb spring	-0.87 m/s
Scenario B max flood neap	0.75 m/s
Scenario B max flood spring	0.87 m/s
Scenario B max ebb neap	-0.78 m/s
Scenario B max ebb spring	-0.87 m/s
Scenario C max flood neap	0.80 m/s
Scenario C max flood spring	0.91 m/s
Scenario C max ebb neap	-0.75 m/s
Scenario C max ebb spring	-0.83 m/s
Node 4 - down-estuary of breach	
Scenario A max flood neap	1.09 m/s
Scenario A max flood spring	1.27 m/s
Scenario A max ebb neap	-1.00 m/s
Scenario A max ebb spring	-1.14 m/s
Scenario B max flood neap	1.11 m/s
Scenario B max flood spring	1.29 m/s
Scenario B max ebb neap	-0.99 m/s
Scenario B max ebb spring	-1.11 m/s
Scenario C max flood neap	1.29 m/s
Scenario C max flood spring	1.40 m/s
Scenario C max ebb neap	-1.07 m/s
Scenario C max ebb spring	-1.18 m/s

Table 11: Summary of changes in peak tidal current velocity at selected nodes in the vicinity of the Hazlewood Marshes breach. Scenario A is pre-2013 baseline planform; B includes inundation of Hazlewood and Lantern marshes + 300 mm SLR; C includes inundation of Hazlewood and Boyton marshes + 300mm SLR.

Node 34 (closest to breach)	
Scenario A max flood neap	0.55 m/s
Scenario A max flood spring	0.62 m/s
Scenario A max ebb neap	-0.49 m/s
Scenario A max ebb spring	-0.52 m/s
Scenario B max flood neap	0.59 m/s
Scenario B max flood spring	0.67 m/s
Scenario B max ebb neap	-0.51 m/s
Scenario B max ebb spring	-0.54 m/s
Scenario C max flood neap	0.60 m/s
Scenario C max flood spring	0.68 m/s
Scenario C max ebb neap	-0.50 m/s
Scenario C max ebb spring	-0.53 m/s
Node 31	
Scenario A max flood neap	0.42 m/s
Scenario A max flood spring	0.48 m/s
Scenario A max ebb neap	-0.46 m/s
Scenario A max ebb spring	-0.49 m/s
Scenario B max flood neap	0.47 m/s
Scenario B max flood spring	0.53 m/s
Scenario B max ebb neap	-0.47 m/s
Scenario B max ebb spring	-0.50 m/s
Scenario C max flood neap	0.49 m/s
Scenario C max flood spring	0.54 m/s
Scenario C max ebb neap	-0.47 m/s
Scenario C max ebb spring	-0.49 m/s
Node 29	
Scenario A max flood neap	0.68 m/s
Scenario A max flood spring	0.75 m/s
Scenario A max ebb neap	-0.63 m/s
Scenario A max ebb spring	-0.76 m/s
Scenario B max flood neap	0.75 m/s
Scenario B max flood spring	0.83 m/s
Scenario B max ebb neap	-0.69 m/s
Scenario B max ebb spring	-0.81 m/s
Scenario C max flood neap	0.76 m/s
Scenario C max flood spring	0.85 m/s
Scenario C max ebb neap	-0.69 m/s
Scenario C max ebb spring	-0.80 m/s

Table 12: Summary of changes in peak tidal current velocity at selected nodes in the vicinity of Slaughden, . Scenario A is pre-2013 baseline planform; B include inundation of Hazlewood and Lantern marshes + 300 mm SLR; C includes inundation of Hazlewood and Boyton marshes + 300mm SLR.

Node 27	
Scenario A max flood neap	0.64 m/s
Scenario A max flood spring	0.70 m/s
Scenario A max ebb neap	-0.61 m/s
Scenario A max ebb spring	-0.73 m/s
Scenario B max flood neap	0.70 m/s
Scenario B max flood spring	0.78 m/s
Scenario B max ebb neap	-0.67 m/s
Scenario B max ebb spring	-0.78 m/s
Scenario C max flood neap	0.72 m/s
Scenario C max flood spring	0.80 m/s
Scenario C max ebb neap	-0.67 m/s
Scenario C max ebb spring	-0.77 m/s
Node28	
Scenario A max flood neap	0.66 m/s
Scenario A max flood spring	0.74 m/s
Scenario A max ebb neap	-0.55 m/s
Scenario A max ebb spring	-0.63 m/s
Scenario B max flood neap	0.73 m/s
Scenario B max flood spring	0.82 m/s
Scenario B max ebb neap	-0.60 m/s
Scenario B max ebb spring	-0.67 m/s
Scenario C max flood neap	0.74 m/s
Scenario C max flood spring	0.83 m/s
Scenario C max ebb neap	-0.59 m/s
Scenario C max ebb spring	-0.66 m/s
Node 26	
Scenario A max flood neap	0.58 m/s
Scenario A max flood spring	0.64 m/s
Scenario A max ebb neap	-0.62 m/s
Scenario A max ebb spring	-0.73 m/s
Scenario B max flood neap	0.62 m/s
Scenario B max flood spring	0.69 m/s
Scenario B max ebb neap	-0.68 m/s
Scenario B max ebb spring	-0.78 m/s
Scenario C max flood neap	0.63 m/s
Scenario C max flood spring	0.70 m/s
Scenario C max ebb neap	-0.67 m/s
Scenario C max ebb spring	-0.77 m/s

Table 13: Summary of changes in peak tidal current velocity at selected nodes in the vicinity of Boyton Marshes. Scenario A is pre-2013 baseline planform; B includes inundation of Hazlewood and Lantern marshes + 300 mm SLR; C includes inundation of Hazlewood and Boyton marshes + 300mm SLR.

Node 8	
Scenario A max flood neap	0.60 m/s
Scenario A max flood spring	0.72 m/s
Scenario A max ebb neap	-0.68 m/s
Scenario A max ebb spring	-1.05 m/s
Scenario B max flood neap	0.67 m/s
Scenario B max flood spring	0.76 m/s
Scenario B max ebb neap	-0.90 m/s
Scenario B max ebb spring	-1.17 m/s
Scenario C max flood neap	0.69 m/s
Scenario C max flood spring	0.77 m/s
Scenario C max ebb neap	-0.87m/s
Scenario C max ebb spring	-1.16 m/s
Node 6 - closest to breach	
Scenario A max flood neap	0.76 m/s
Scenario A max flood spring	0.87 m/s
Scenario A max ebb neap	-0.77 m/s
Scenario A max ebb spring	-0.87 m/s
Scenario B max flood neap	0.83 m/s
Scenario B max flood spring	0.90 m/s
Scenario B max ebb neap	-0.81 m/s
Scenario B max ebb spring	-0.89 m/s
Scenario C max flood neap	0.89 m/s
Scenario C max flood spring	0.98 m/s
Scenario C max ebb neap	-0.77 m/s
Scenario C max ebb spring	-0.85 m/s
Node 4 - down-estuary of breach	
Scenario A max flood neap	1.09 m/s
Scenario A max flood spring	1.27 m/s
Scenario A max ebb neap	-1.00 m/s
Scenario A max ebb spring	-1.14 m/s
Scenario B max flood neap	1.23 m/s
Scenario B max flood spring	1.36 m/s
Scenario B max ebb neap	-1.04 m/s
Scenario B max ebb spring	-1.16 m/s
Scenario C max flood neap	1.36 m/s
Scenario C max flood spring	1.53 m/s
Scenario C max ebb neap	-1.12 m/s
Scenario C max ebb spring	-1.23 m/s

Table 14: Summary of maximum water levels (m OD) for hypothetical 1 in 20 year and 1 in 200 year surges. Scenario A is pre-2013 baseline planform geometry; B includes inundation of Hazelwood and Lantern marshes; C includes inundation of Hazelwood and Boyton marshes.

	1 in 20 year surge level			1 in 200 year surge level		
Node	A	B	C	A	B	C
Outer estuary / Boyton Marshes						
4	3.15	3.14	3.15	3.68	3.67	3.69
6	3.16	3.14	3.16	3.69	3.68	3.70
8	3.17	3.16	3.17	3.70	3.69	3.72
Slaughden						
26	3.25	3.20	3.24	3.79	3.74	3.79
28	3.25	3.21	3.25	3.80	3.75	3.80
27	3.27	3.25	3.28	3.83	3.78	3.83
Hazelwood Marshes						
29	3.29	3.26	3.29	3.84	3.81	3.85
31	3.30	3.27	3.30	3.85	3.82	3.86
34	3.30	3.28	3.31	3.86	3.83	3.87

Table 15. Percentage increase (relative to Scenario A) in peak flood and ebb tide velocities for a baseline spring tide under Scenario B and Scenario C:

Node ID		Max Flood						Max Ebb				
		Scenario A	Scenario B		Scenario C			Scenario A	Scenario B		Scenario C	
		(ms^{-1})	(ms^{-1})	(% inc.)	(ms^{-1})	(% inc.)		(ms^{-1})	(ms^{-1})	(% inc.)	(ms^{-1})	(% inc.)
Near Boyton Marshes	4	1.27	1.29	1.6	1.40	10.2		-1.14	-1.11	-2.6	-1.18	3.5
	6	0.87	0.87	0.0	0.91	4.6		-0.87	-0.87	0.0	-0.83	-4.6
	8	0.72	0.71	-1.4	0.71	-1.4		-1.05	-1.08	2.9	-1.09	3.8
Near Slaughden	26	0.64	0.64	0.0	0.65	1.6		-0.73	-0.75	2.7	-0.74	1.4
	28	0.74	0.78	5.4	0.78	5.4		-0.63	-0.66	4.8	-0.65	3.2
	27	0.70	0.75	7.1	0.75	7.1		-0.73	-0.75	2.7	-0.74	1.4
Near Hazelwood Marshes	29	0.75	0.80	6.7	0.80	6.7		-0.76	-0.78	2.6	-0.77	1.3
	31	0.48	0.49	2.1	0.50	4.2		-0.49	-0.51	4.1	-0.51	4.1
	34	0.62	0.63	1.6	0.62	0.0		-0.52	-0.55	5.8	-0.54	3.8

Table 16. Percentage increase (relative to Scenario A) in Peak flood and ebb tide velocity for a 1 in 20 year surge

Node ID		Max Flood						Max Ebb				
		Scenario A	Scenario B		Scenario C			Scenario A	Scenario B		Scenario C	
		(ms^{-1})	(ms^{-1})	(% inc.)	(ms^{-1})	(% inc.)		(ms^{-1})	(ms^{-1})	(% inc.)	(ms^{-1})	(% inc.)
Near Boyton Marshes	4	1.71	1.74	1.8	1.89	10.5		-1.15	-1.15	0.0	-1.26	9.6
	6	1.08	1.07	-0.9	1.17	8.3		-0.84	-0.86	2.4	-0.83	-1.2
	8	1.02	1.02	0.0	1.03	1.0		-0.90	-0.88	-2.2	-0.87	-3.3
Near Slaughden	26	0.77	0.81	5.2	0.82	6.5		-0.66	-0.74	12.1	-0.71	7.6
	28	0.89	0.95	6.7	0.97	9.0		-0.56	-0.58	3.6	-0.59	5.4
	27	0.89	0.96	7.9	0.98	10.1		-0.63	-0.71	12.7	-0.68	7.9
Near Hazelwood Marshes	29	0.93	1.00	7.5	1.02	9.7		-0.70	-0.78	11.4	-0.75	7.1
	31	0.58	0.59	1.7	0.60	3.4		-0.40	-0.42	5.0	-0.43	7.5
	34	0.76	0.81	6.6	0.83	9.2		-0.42	-0.46	9.5	-0.47	11.9

Table 17. Percentage increase (relative to Scenario A) in peak flood and ebb tide velocities for a 1 in 200 year surge

Node ID		Max Flood						Max Ebb				
		Scenario A	Scenario B		Scenario C			Scenario A	Scenario B		Scenario C	
		(ms^{-1})	(ms^{-1})	(% inc.)	(ms^{-1})	(% inc.)		(ms^{-1})	(ms^{-1})	(% inc.)	(ms^{-1})	(% inc.)
Near Boyton Marshes	4	1.99	2.04	2.5	2.22	11.6		-1.26	-1.27	0.8	-1.38	9.5
	6	1.20	1.19	-0.8	1.30	8.3		-0.93	-0.95	2.2	-0.91	-2.2
	8	1.17	1.16	-0.9	1.18	0.9		-1.00	-0.96	-4.0	-0.95	-5.0
Near Slaughden	26	0.87	0.92	5.7	0.93	6.9		-0.74	-0.84	13.5	-0.80	8.1
	28	1.04	1.12	7.7	1.14	9.6		-0.61	-0.63	3.3	-0.65	6.6
	27	1.04	1.11	6.7	1.13	8.7		-0.69	-0.77	11.6	-0.74	7.2
Near Hazelwood Marshes	29	1.09	1.16	6.4	1.19	9.2		-0.77	-0.88	14.3	-0.84	9.1
	31	0.64	0.67	4.7	0.67	4.7		-0.43	-0.45	4.7	-0.46	7.0
	34	0.85	0.94	10.6	0.96	12.9		-0.46	-0.49	6.5	-0.50	8.7

FIGURES

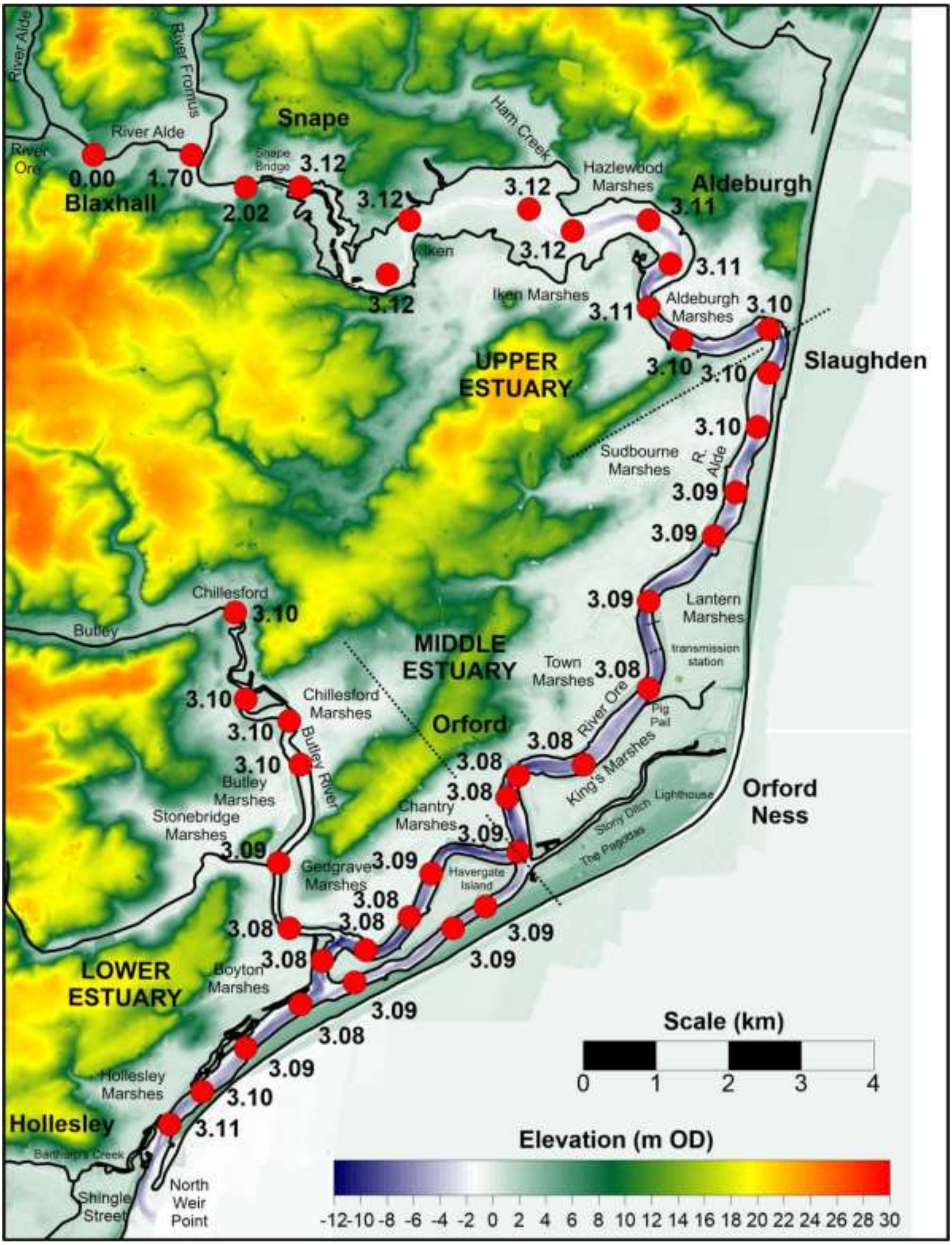


Figure 1. Modelled 1 in 20 year still water levels (JBA, 2012)

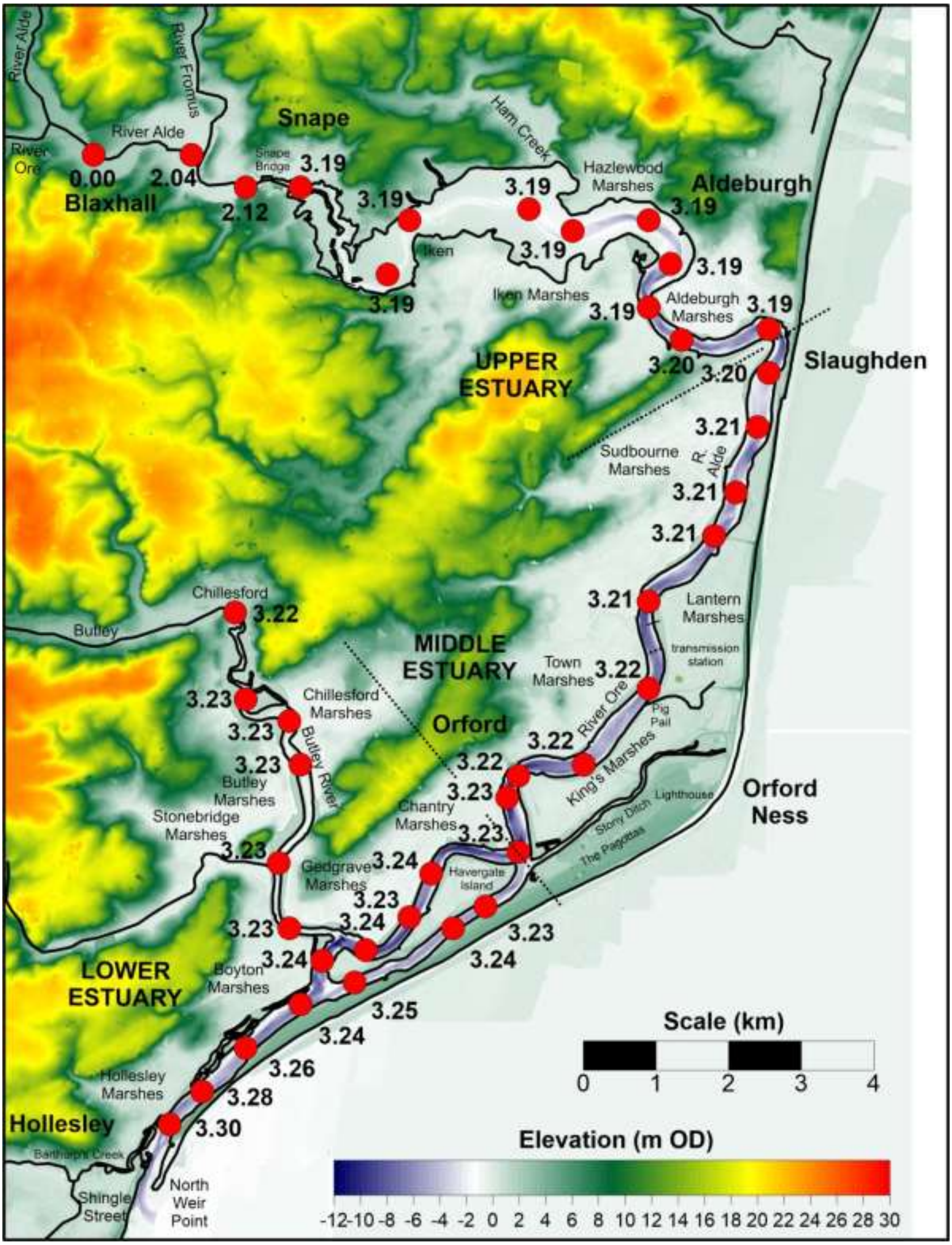


Figure 2. Modelled 1 in 50 year still water levels (JBA, 2012)

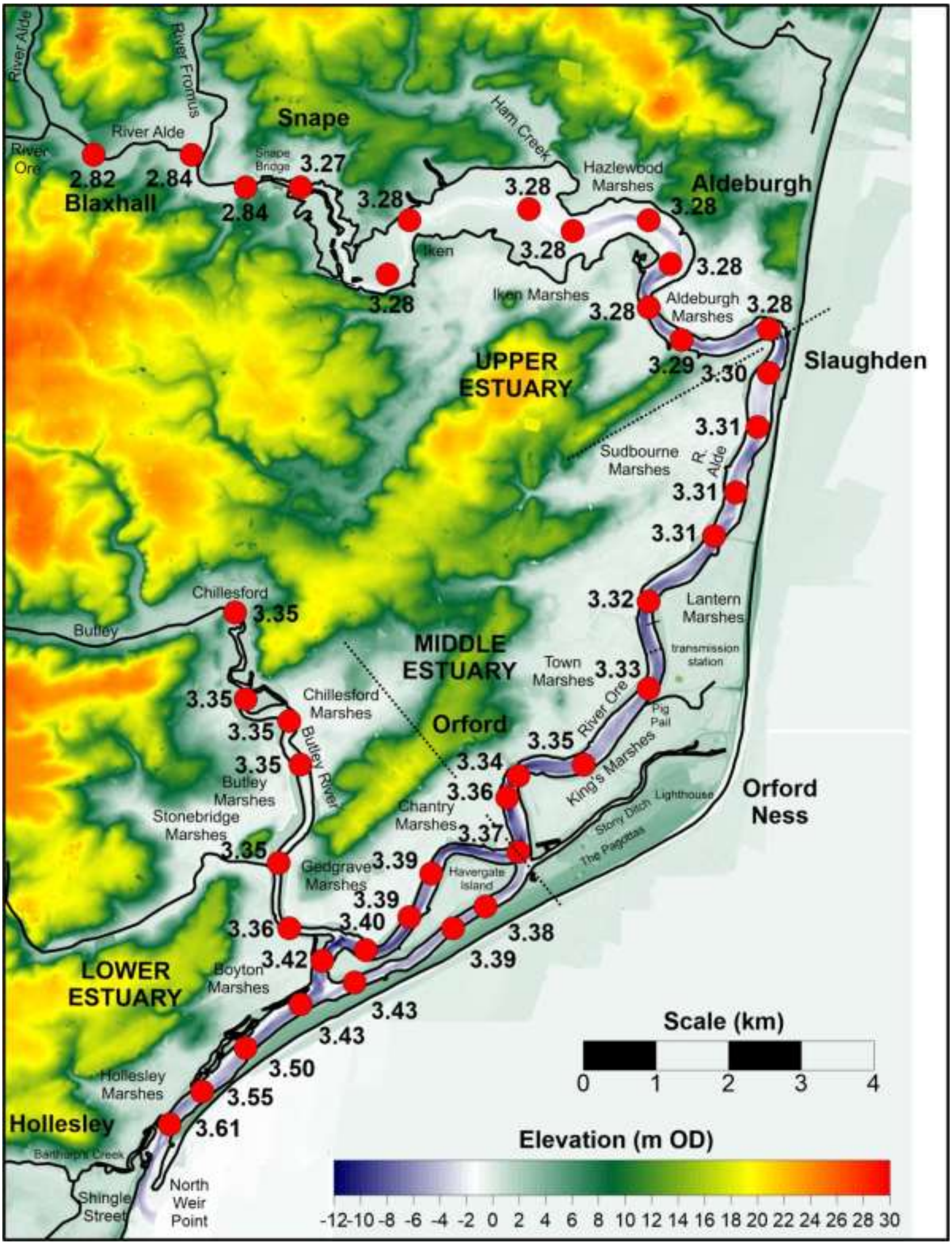


Figure 3. Modelled 1 in 200 year still water levels (JBA, 2012)

Figure 4. Flood Compartment (FC) embankments surveyed in 2009, and corresponding FC numbers.

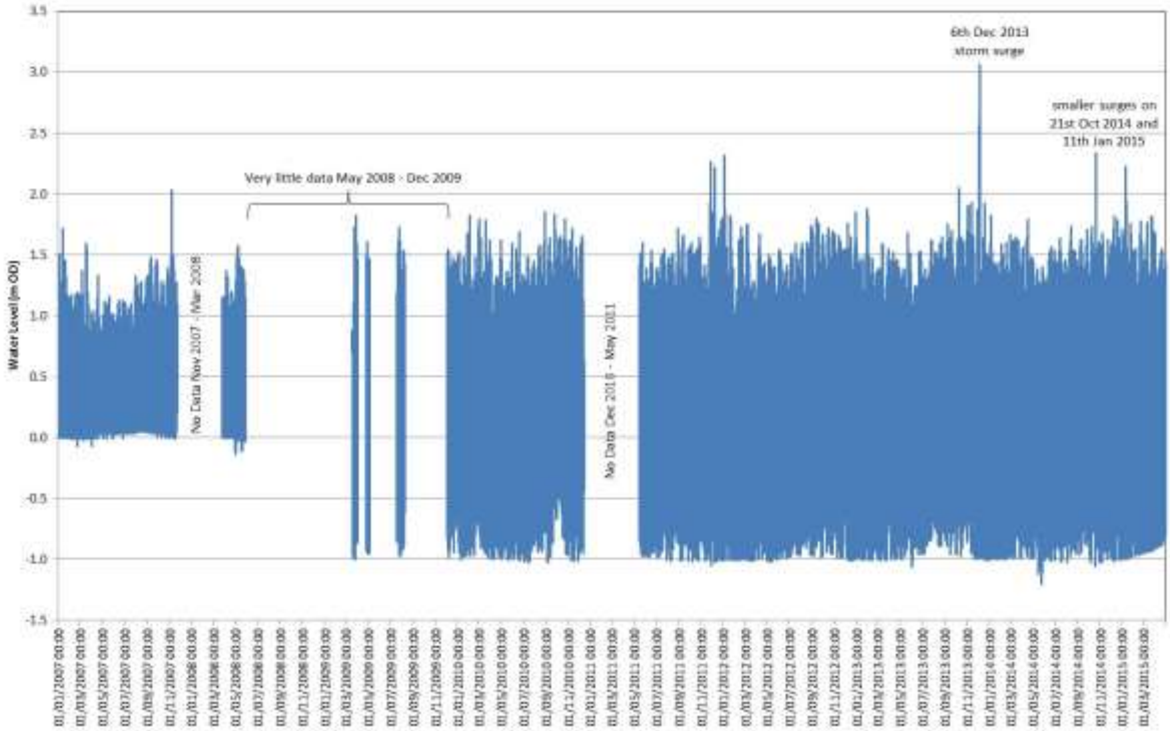


Figure 5. Orford tide gauge data record 1st January 2007 to 30th April 2015

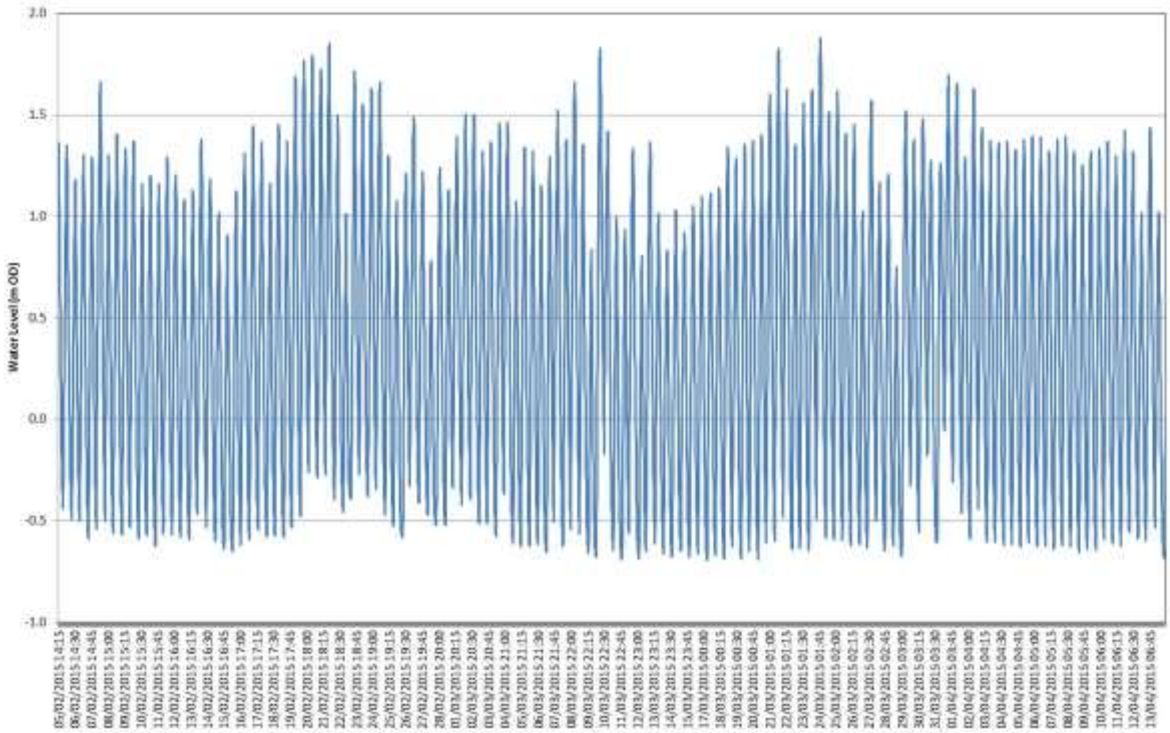


Figure 6. Snape Maltings tide gauge record 5th February 2015 to 14th April 2015

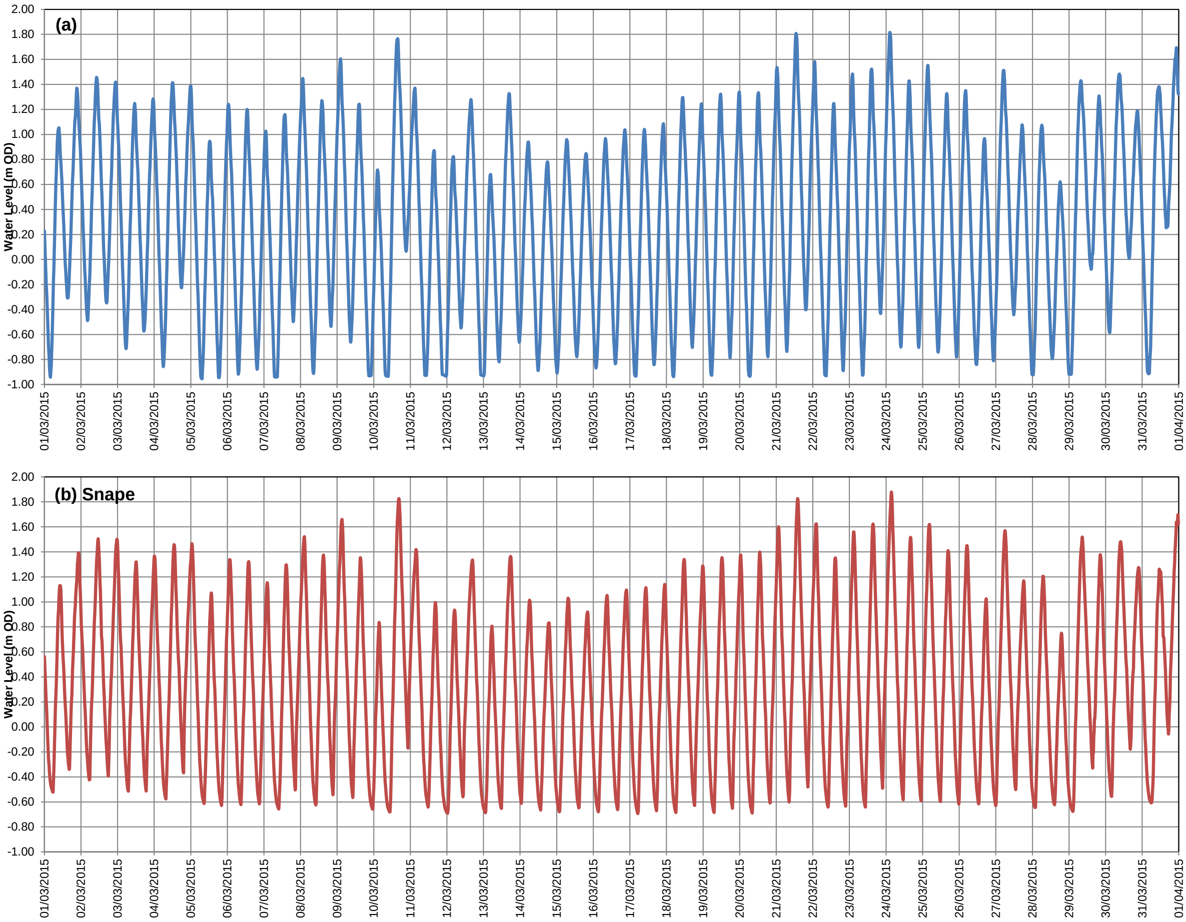


Figure 7. Comparison of tidal levels recorded at Orford and Snape Maltings for March 2015

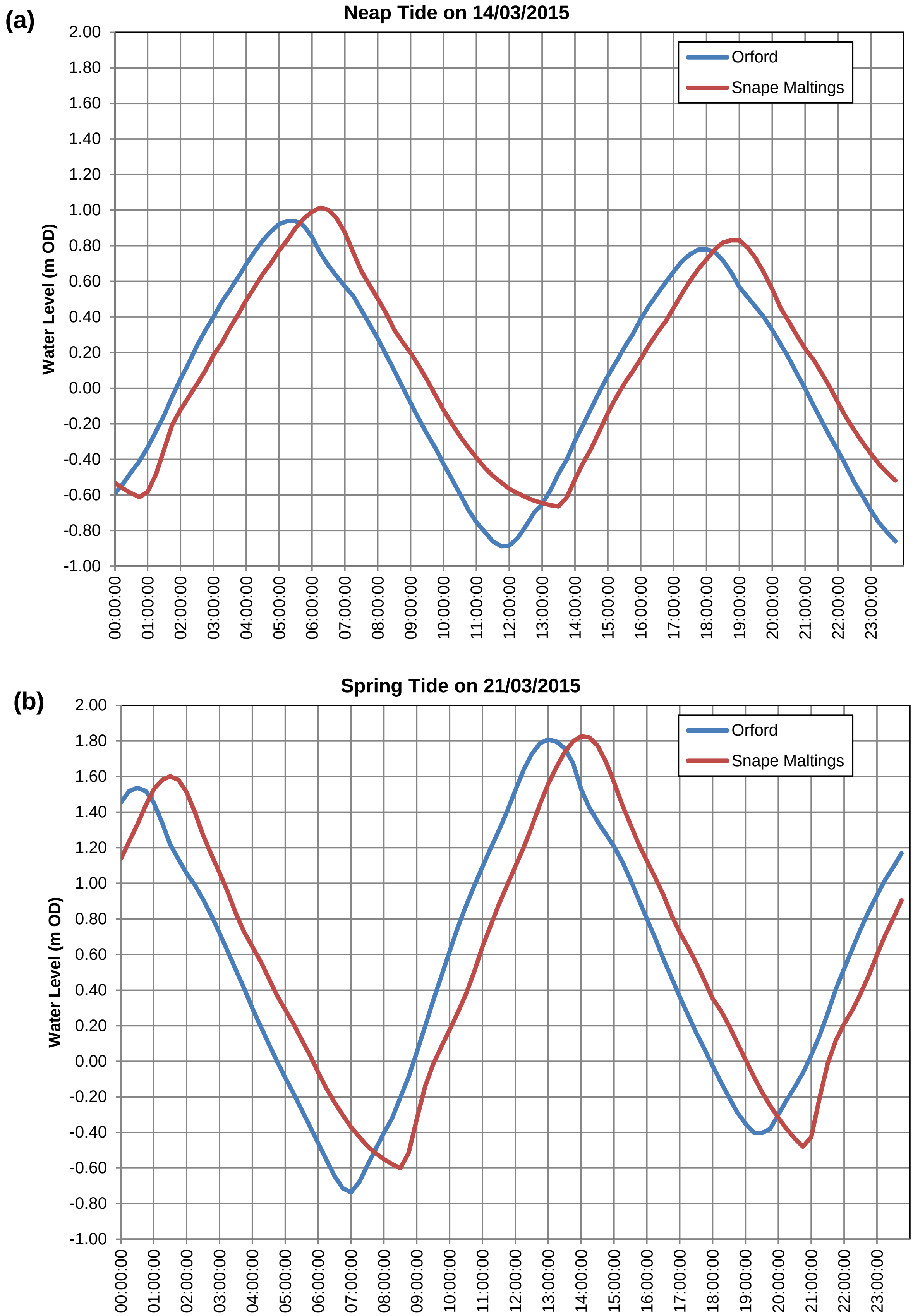


Figure 8. Comparison of water levels at Orford and Snape Maltings for a neap tide (14th March 2015) and a spring tide (21st March 2015).

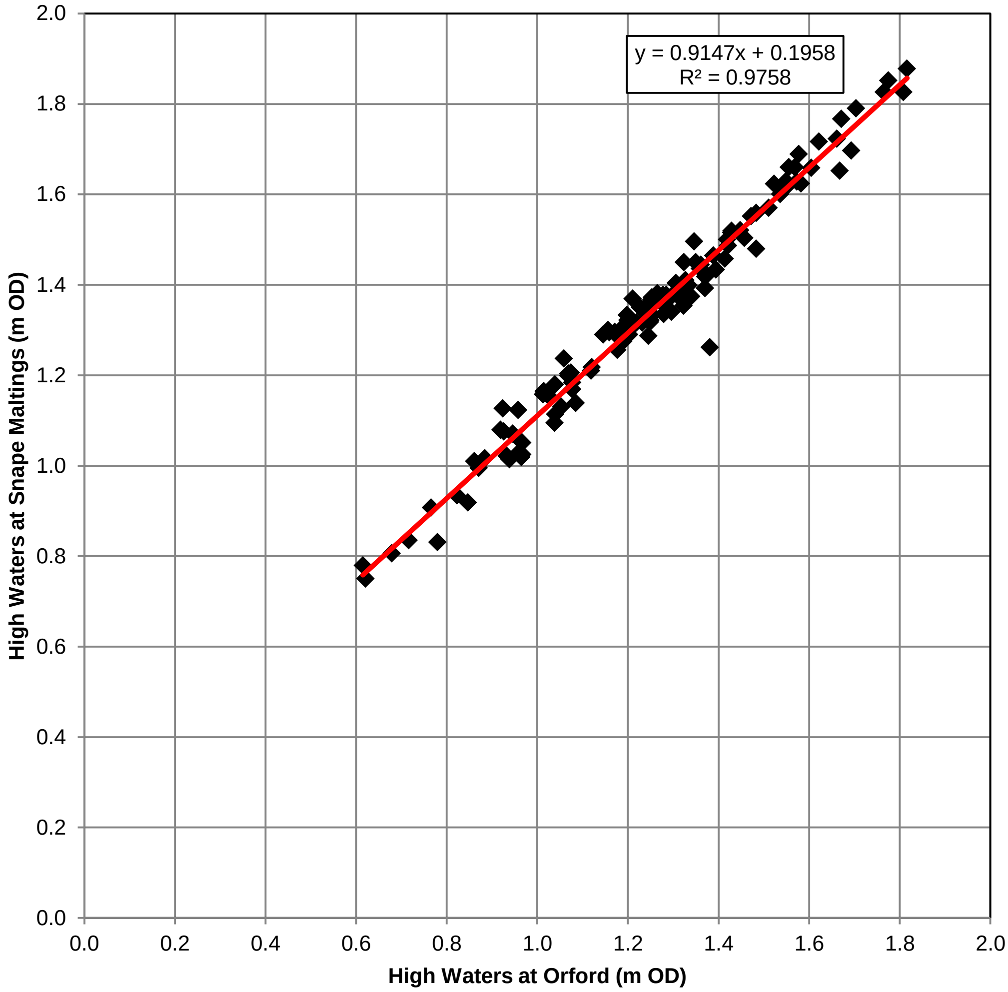


Figure 9. Relationship between 130 high water levels recorded at Orford and Snape Maltings between 6th February and 13th April 2015

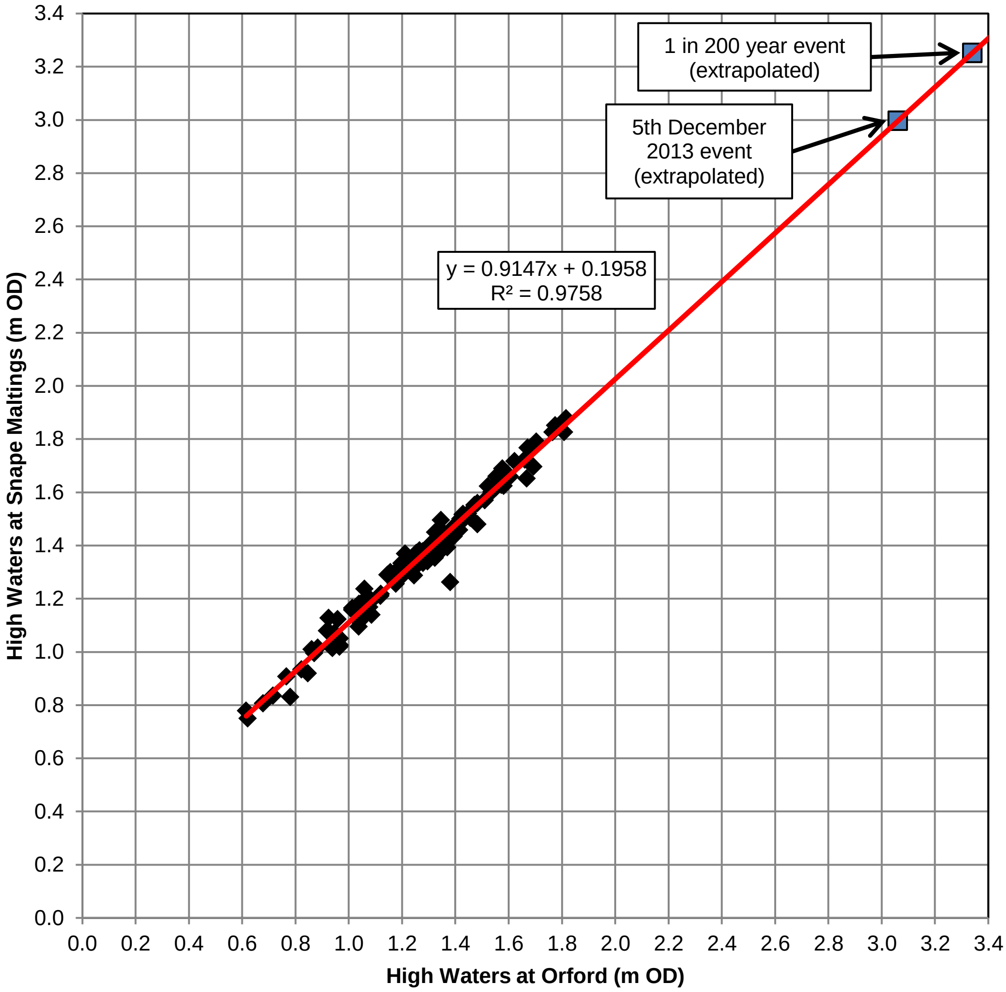


Figure 10. Extrapolation of high water levels at Orford and Snape Maltings based on the linear relationship for 130 recorded tides between 6th February and 13th April 2015. The trend line has been extrapolated to the level reached at Orford during the 5th December 2013 surge event (3.061 m OD, for which the predicted equivalent at Snape Maltings would be 2.996 m OD), and for a 1 in 200 year extreme water level calculated by JBA at Orford (3.340 m OD, for which the equivalent at Snape Maltings would be 3.251 m OD).

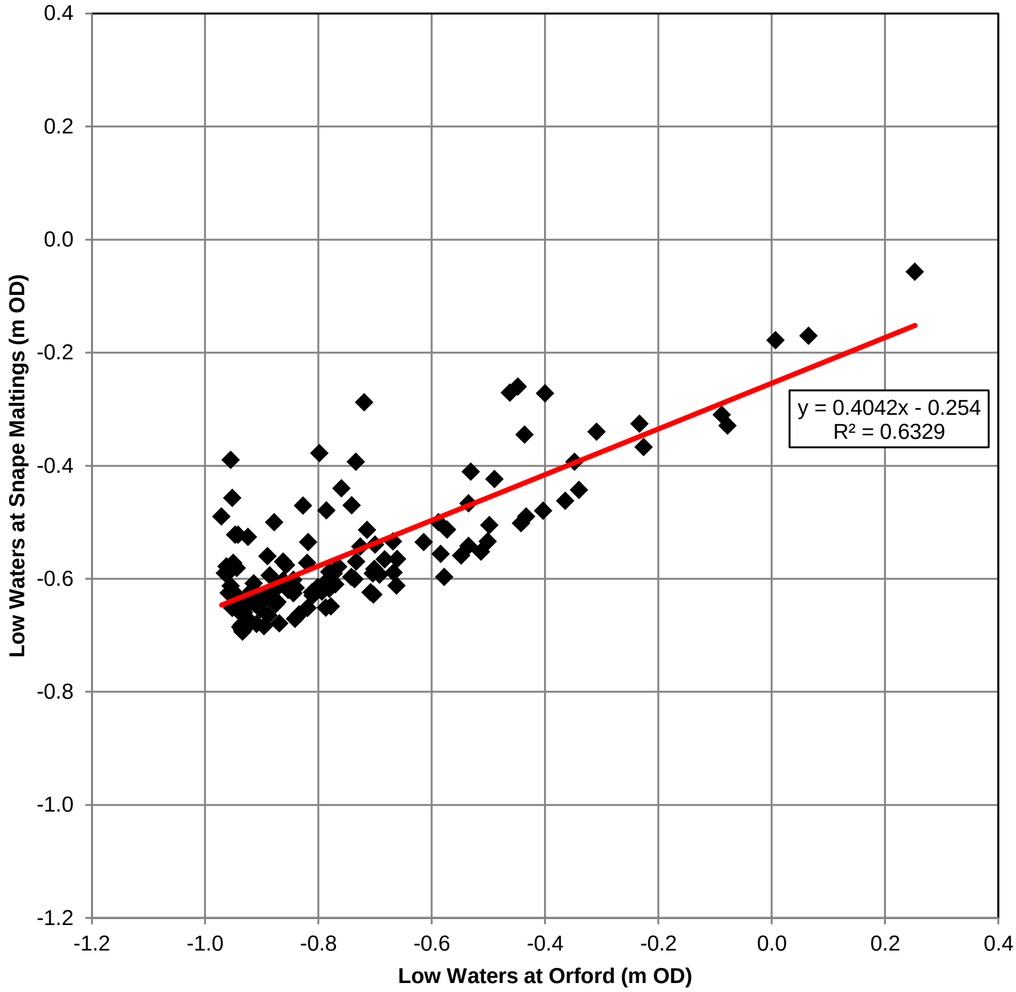


Figure 11. Relationship between low water levels at Orford and Snape Maltings for 131 recorded tides between 6th February and 14th April 2015.

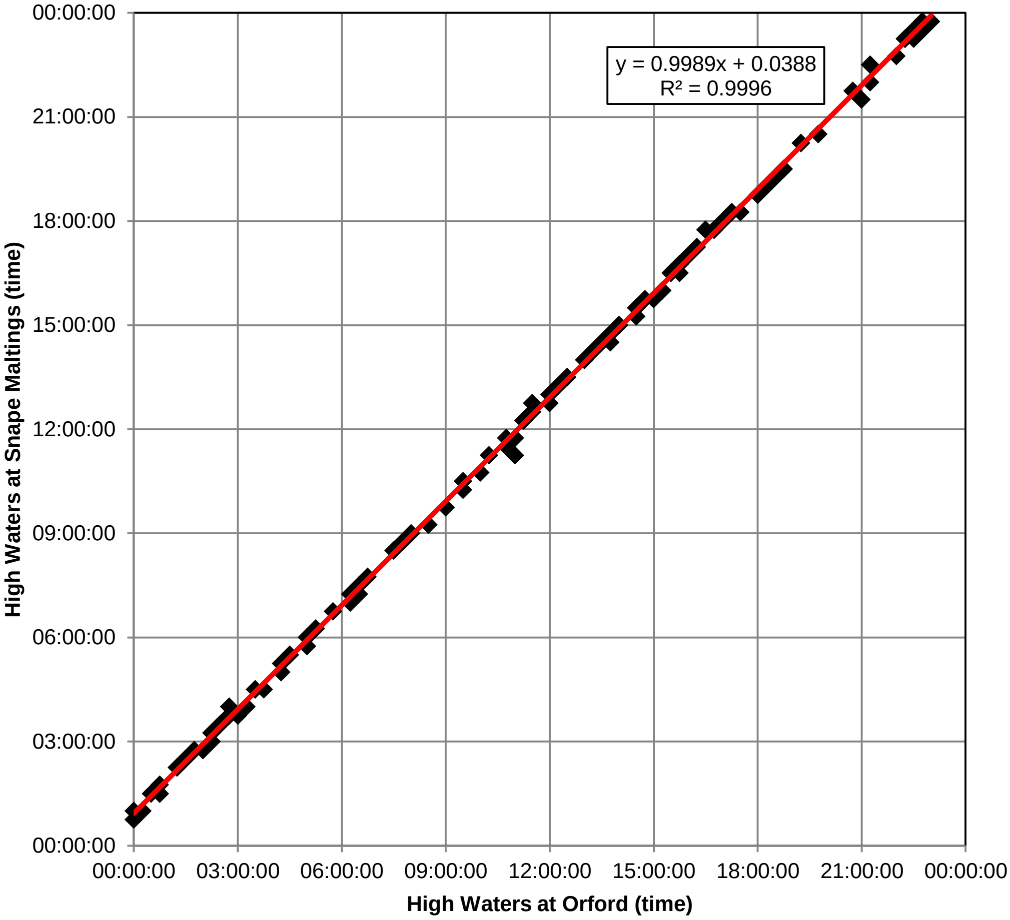


Figure 12. Relationship between the times of high water levels recorded at Orford and Snape Maltings for 130 tides between 6th February and 13th April 2015. The mean time difference and standard deviation between the two is 55 ± 8 minutes.

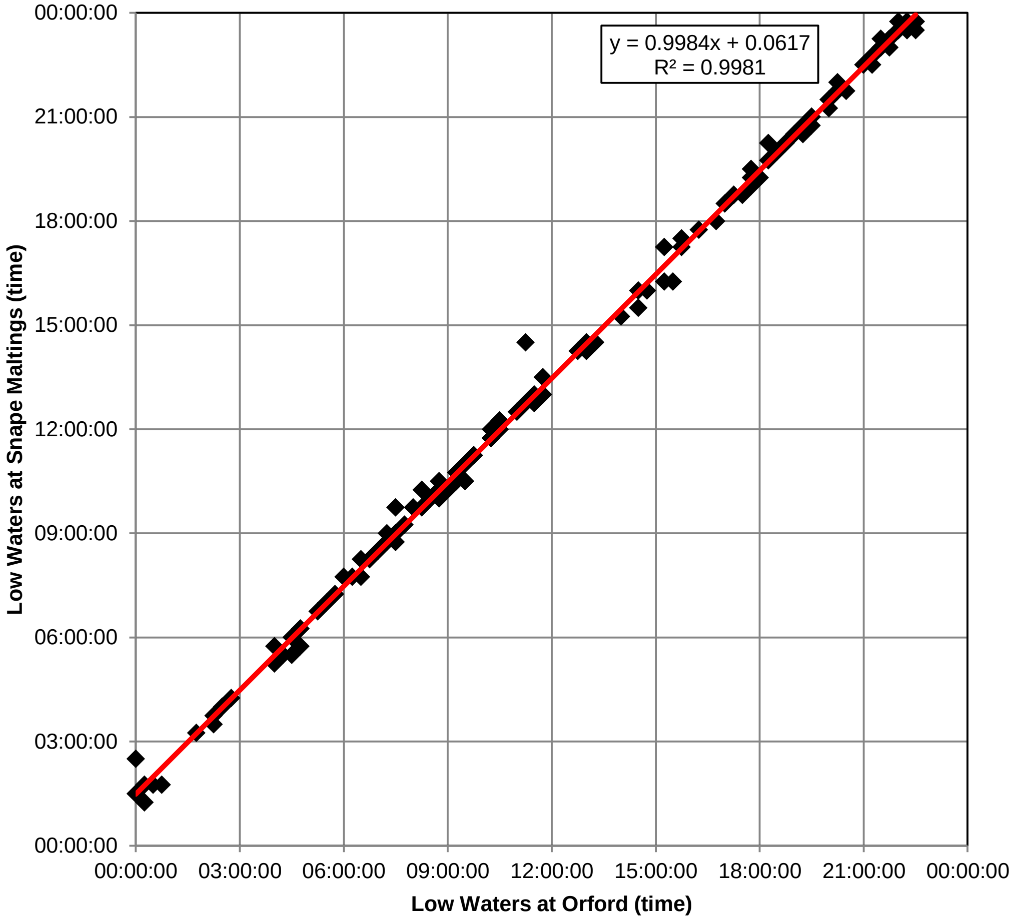
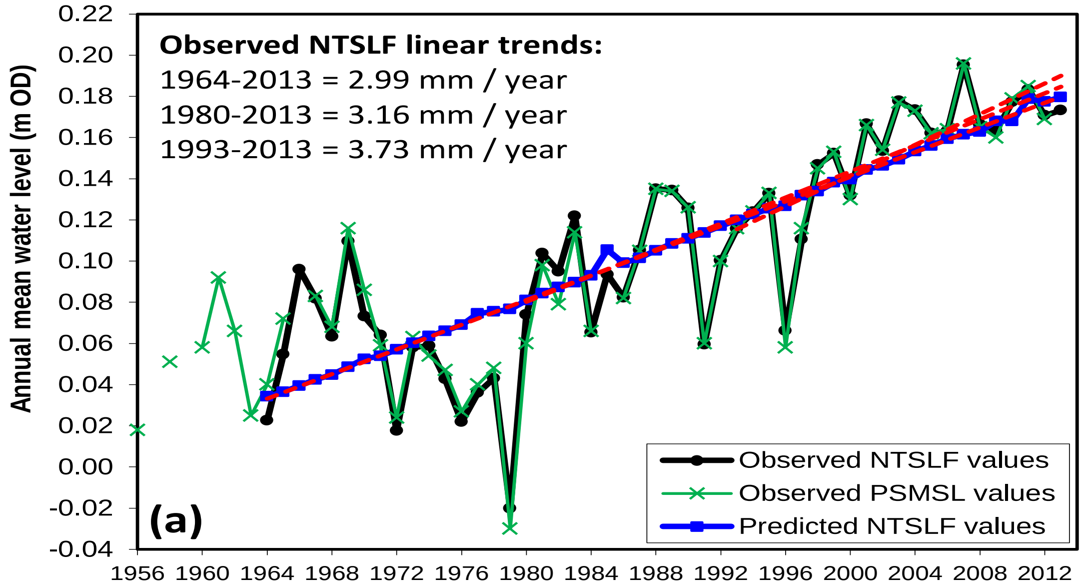


Figure 13. Relationship between the times of low water levels recorded at Orford and Snape Maltings for 131 tides between 6th February and 14th April 2015. The mean time difference and standard deviation between the two is 1 hour 28 minutes ± 17 minutes.



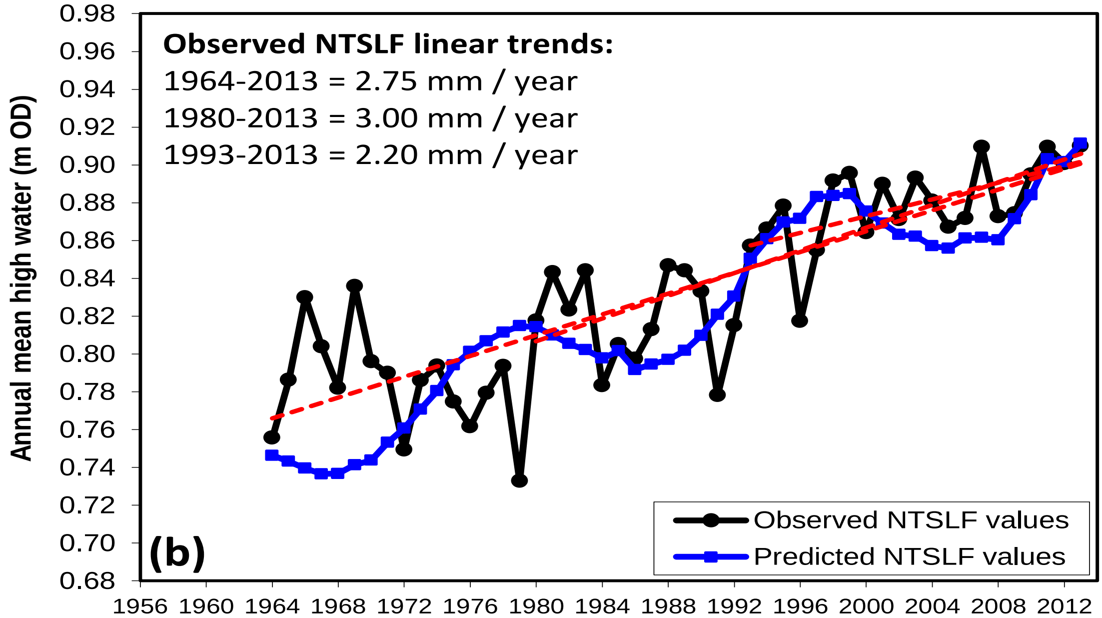


Figure 14. Long-term sea level records for Lowestoft: (a) trends in annual mean sea level; (b) trends in annual mean high water levels. The estimated total change in annual mean sea level in the period 1995 to 2013 is 75 mm; the total change in annual mean high water level in the same period is 44 mm.

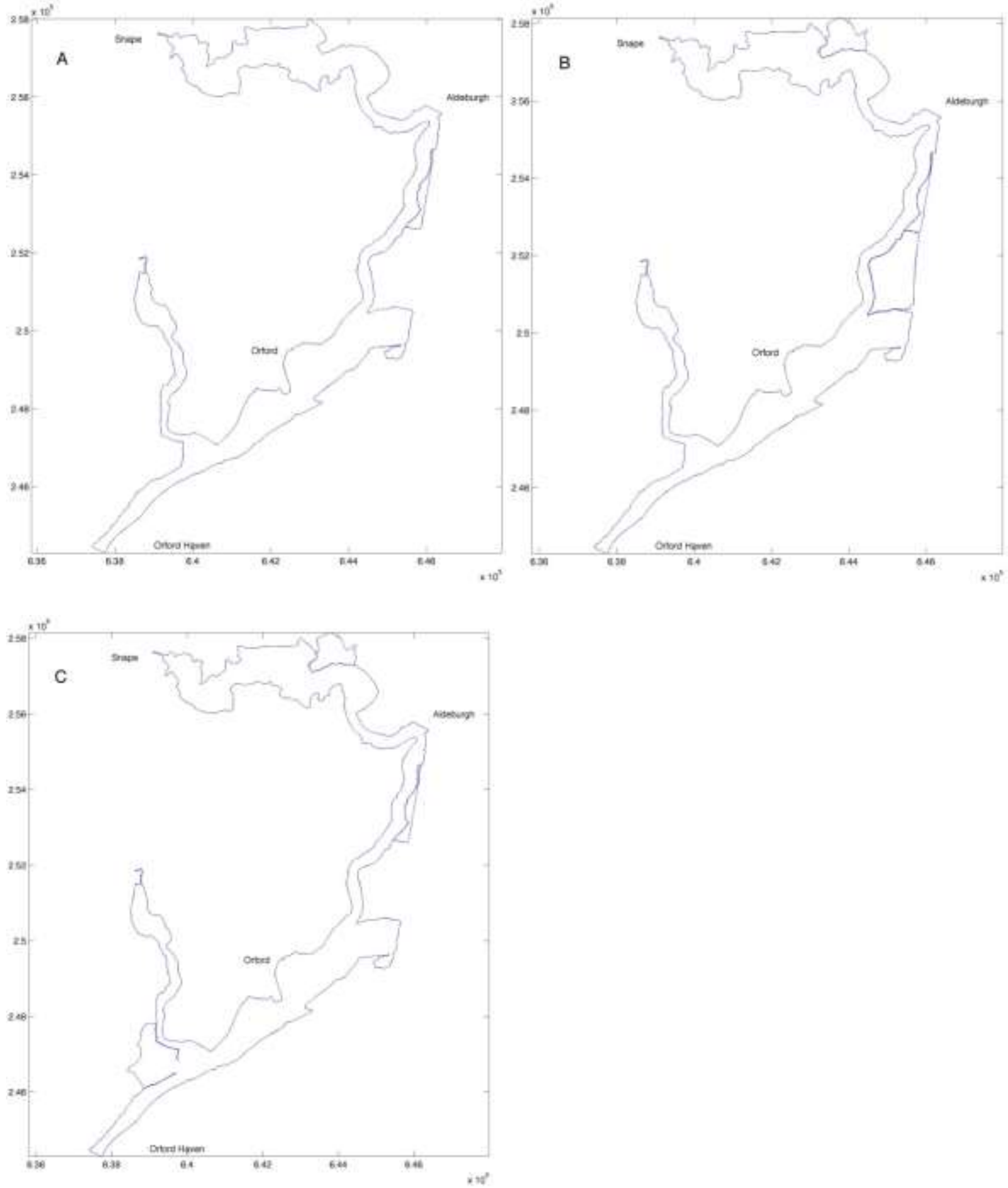


Figure 15: Summary of Alde-Ore planform configurations modelled: (A) pre-2013, with Hazlewood and Lantern Marshes South unflooded; (B) post-2013, with Hazelwood and Lantern Marshes South breached; (C) hypothetical breaching of Boyton marshes , Hazlewood Marshes breach not repaired and Lantern Marshes South breach repaired

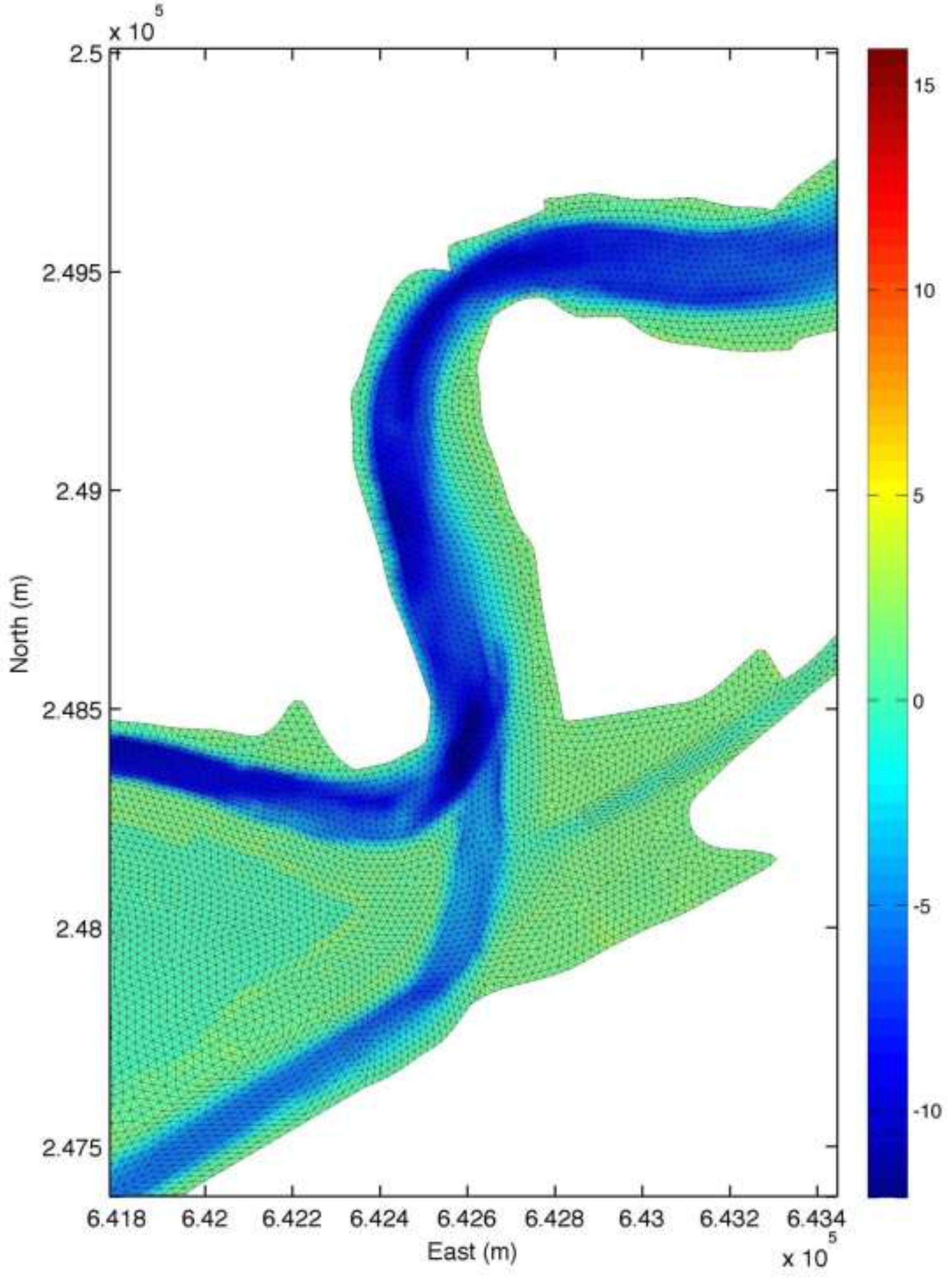


Figure 16: Illustrative model mesh detail, confluence of the Butley River and the Ore. Bathymetry scale in m (OD). For location see Figure 17

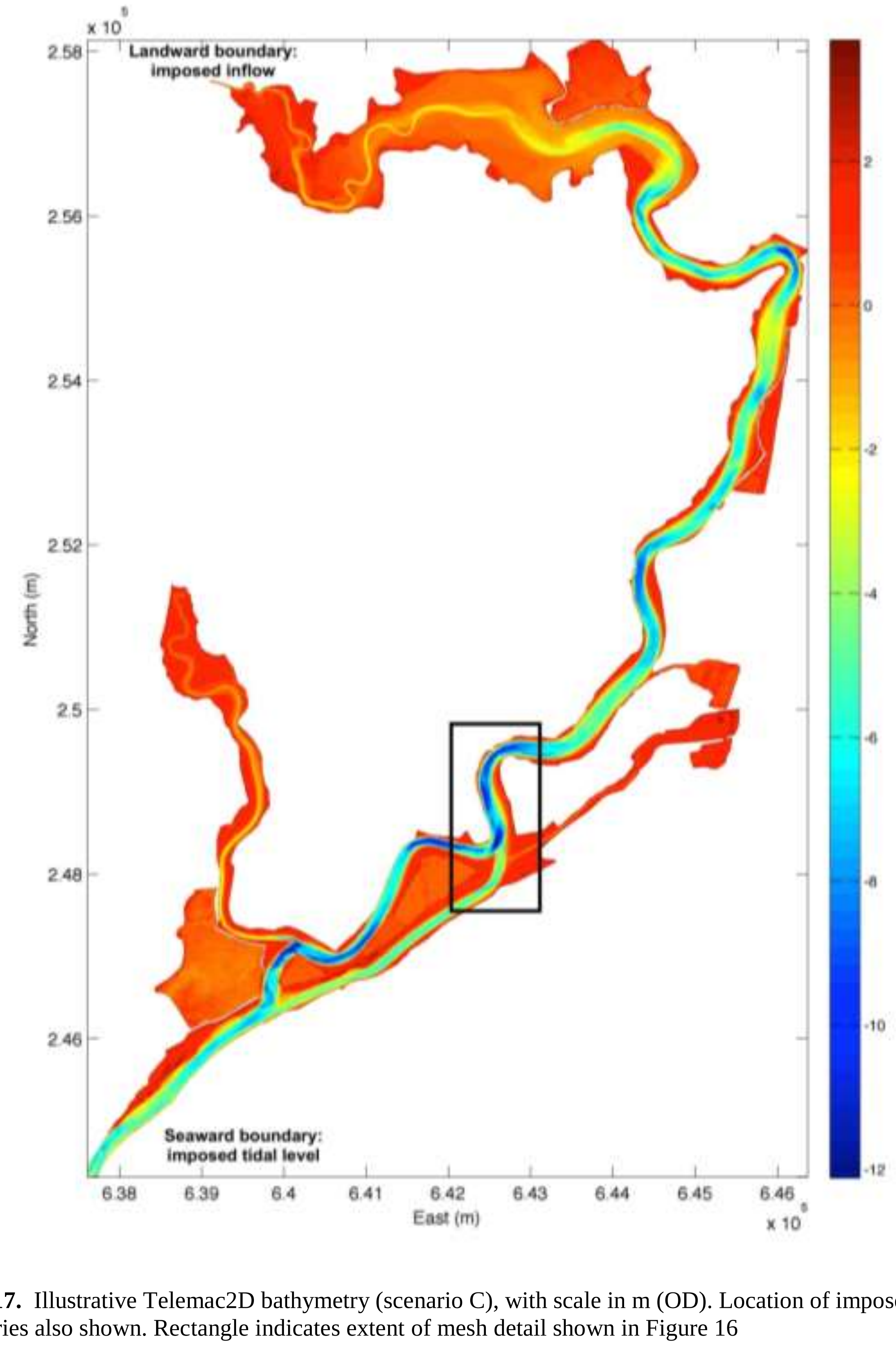


Figure17. Illustrative Telemac2D bathymetry (scenario C), with scale in m (OD). Location of imposed model boundaries also shown. Rectangle indicates extent of mesh detail shown in Figure 16

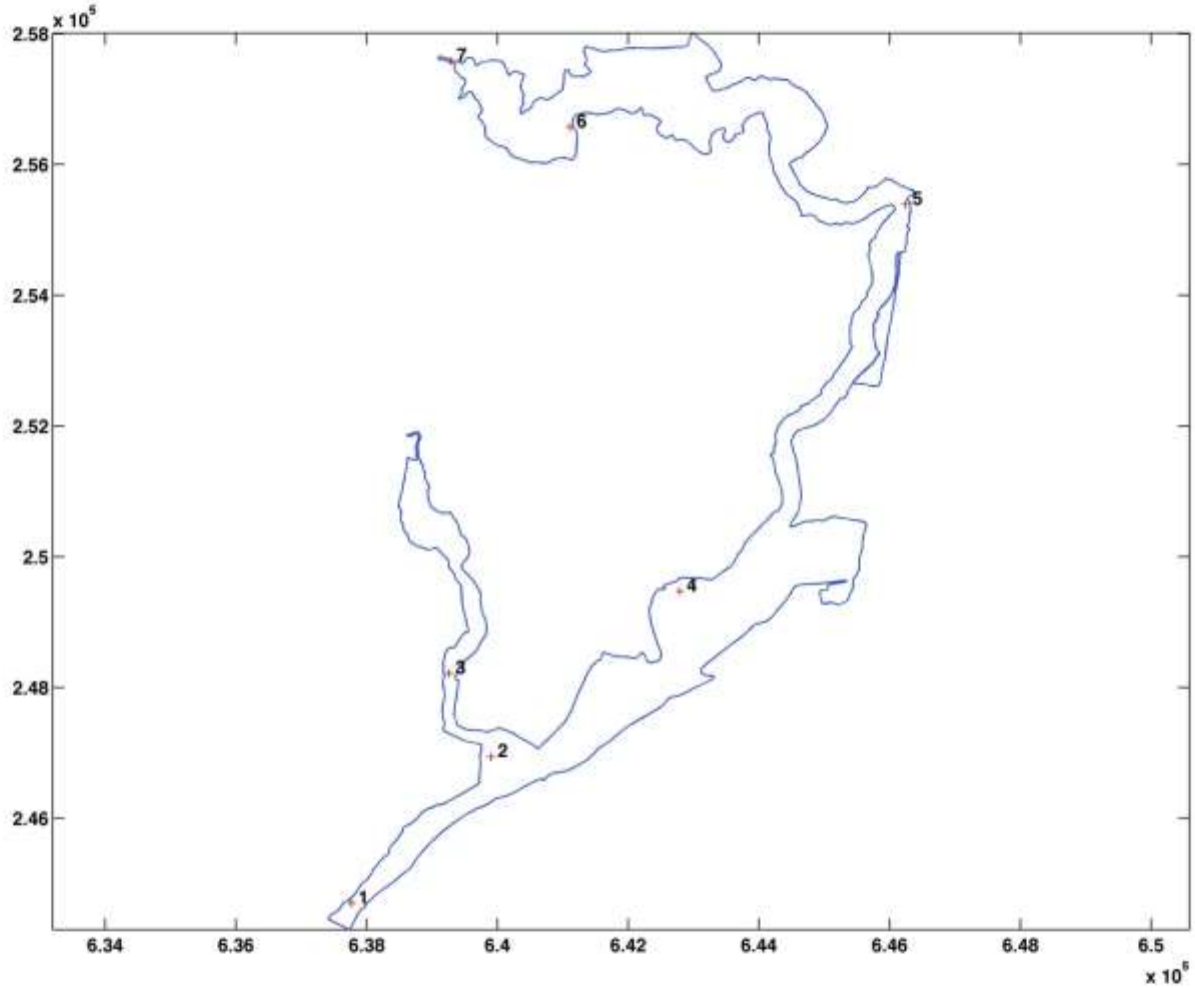


Figure 18: Location of EA tide gauges that were operated in 1995-96 and used as a seaward boundary (1: Orford Haven) and for model validation against observed water levels (2: Flybury Point; 3: Butley River; 4: Orford; 5: Slaughden; 6: Iken; 7: Snape).

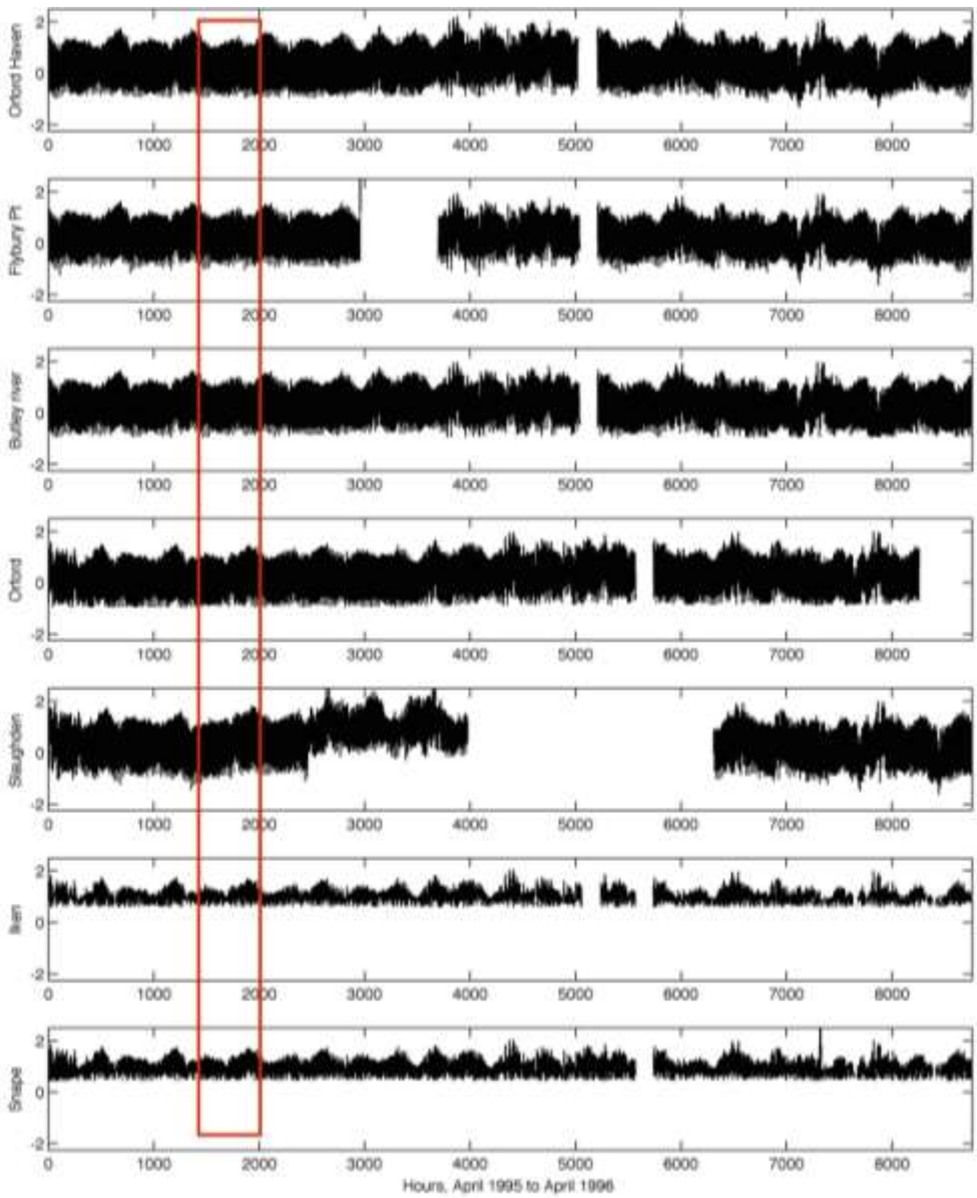


Figure 19: Extent of the 1995-1996 tidal water level records (EA data). Rectangle indicates sequence used for ‘spin up’ and calibration.

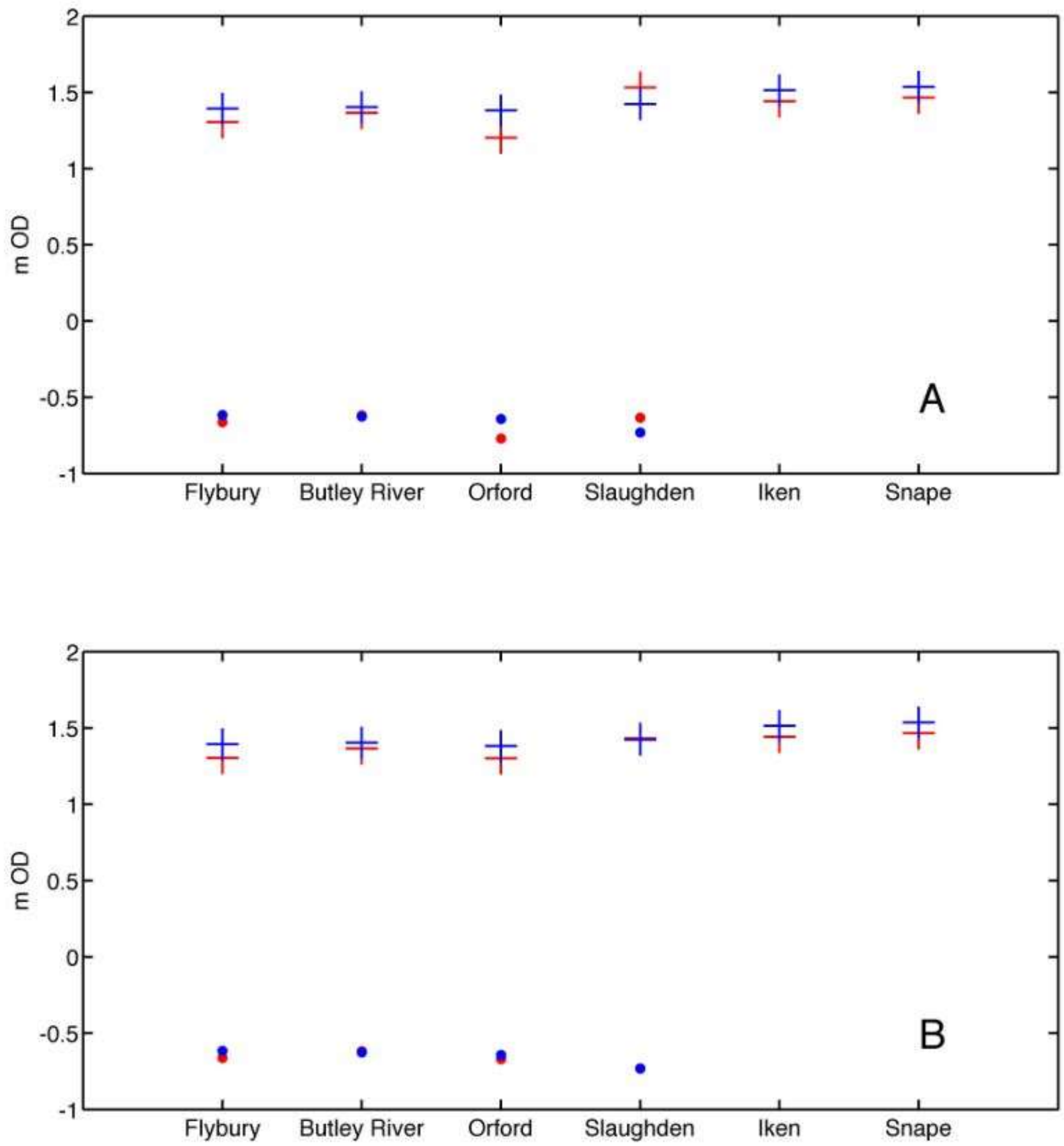


Figure 20. (a) Comparison of observed (red) and modelled (blue) mean High water (crosses) and low water (dots) levels at the EA 1995 gauge locations in the estuary; (b) as above, but with Orford and Slaughden observations adjusted to remove apparent datum errors of (-0.1 m) and + 0.1 m, respectively. Note that after datum adjustment the mean low water levels show very good agreement and the mean high water differences are reduced to better than 9 cm.

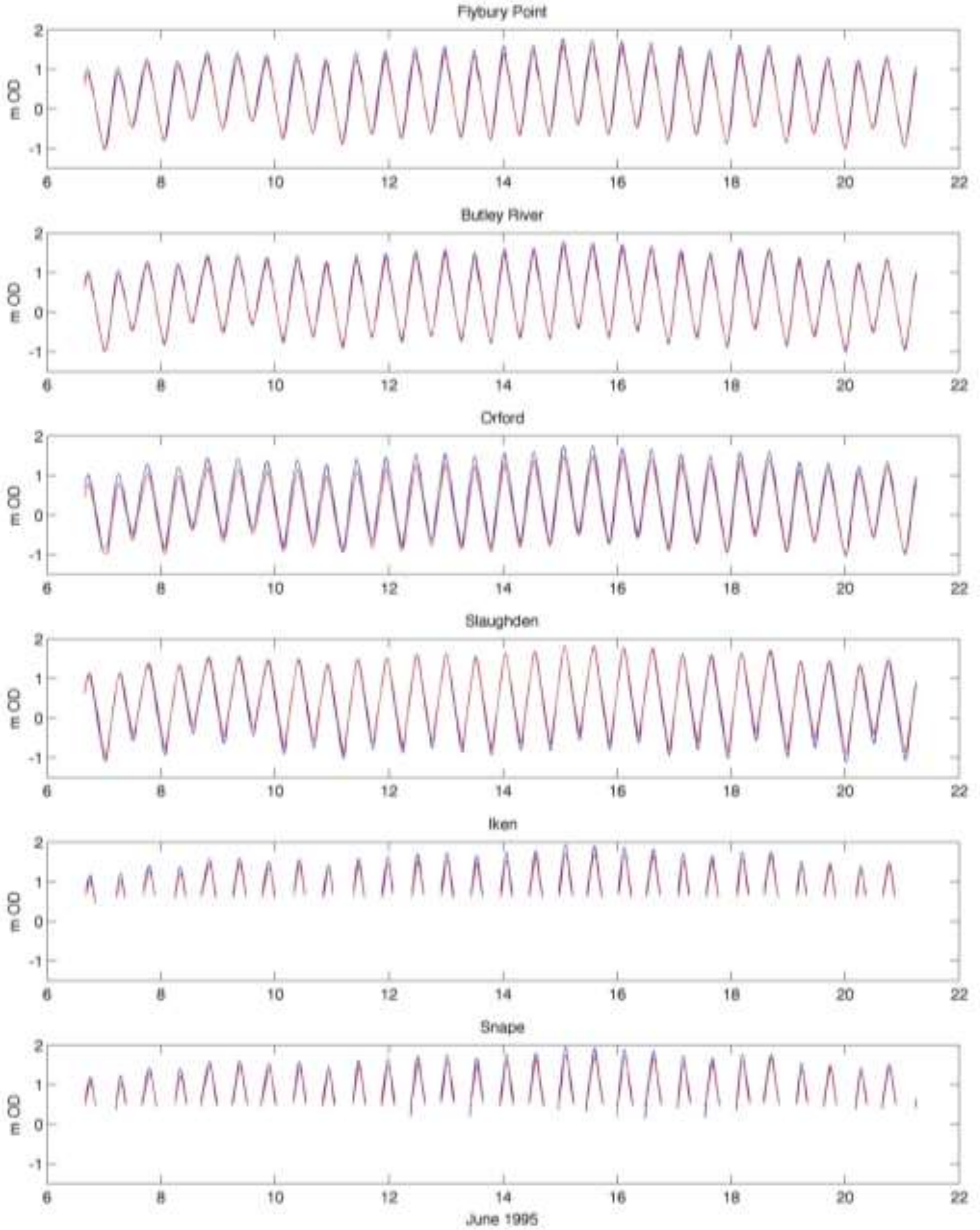


Figure 21: Comparison of observed versus modelled water levels, June 1995, for six locations shown in Figure 4. Performance is generally good, although there are some discrepancies at Orford that should be investigated further. Model output is blue, observations are red. There is some over-estimation of peak levels at Snape and Iken, which could possibly be reduced model tuning (e.g. the use of spatially-varied bottom friction).

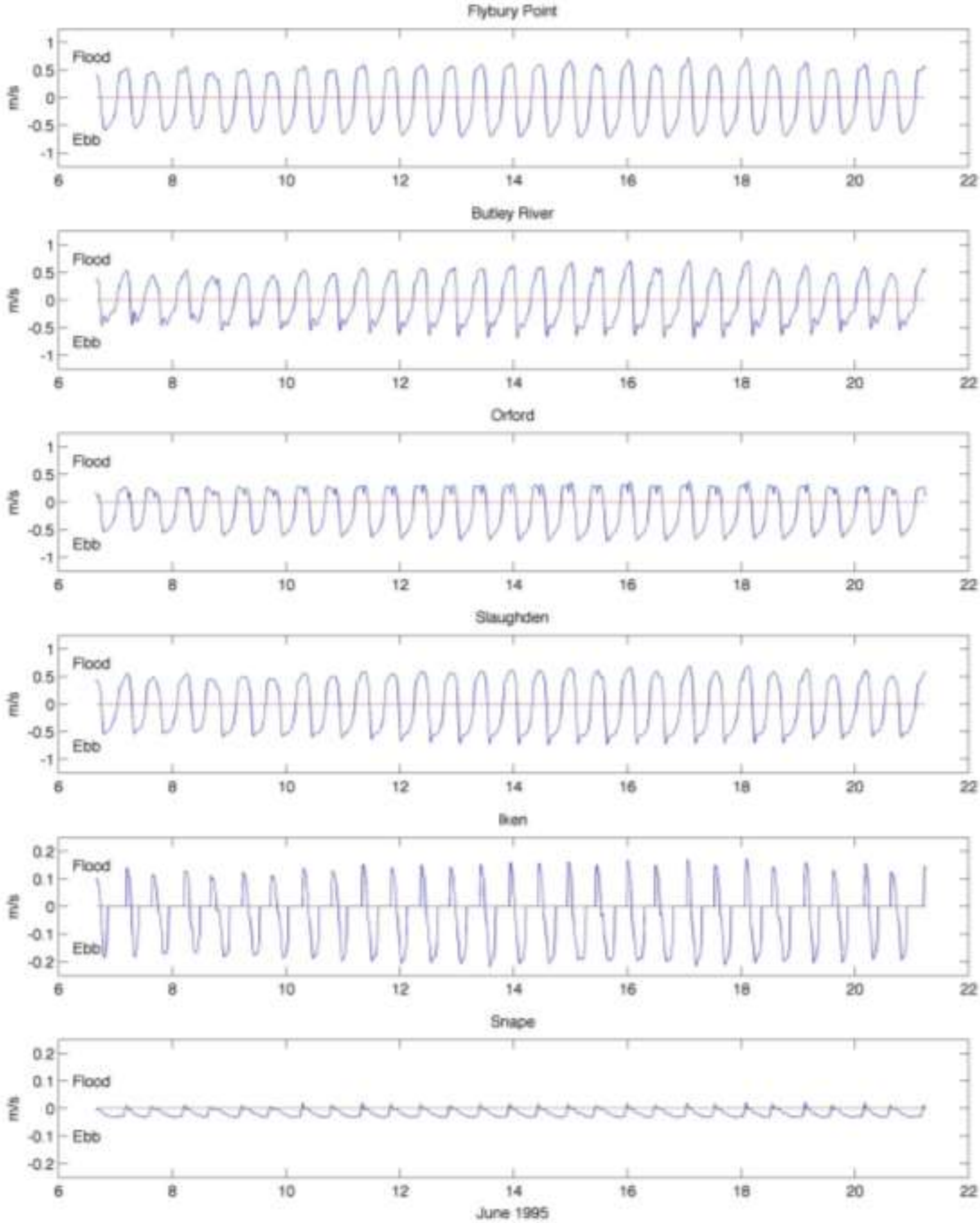


Figure 22: Modelled scalar velocity (current speed), June 1995, for locations in Figure 18. Note that these are model output only as no velocity measurements exist at these locations. Velocities have been signed positive for flood and negative for ebb. The strong ebb dominance at Snape is the result of the imposed river inflow in the narrow channel section.

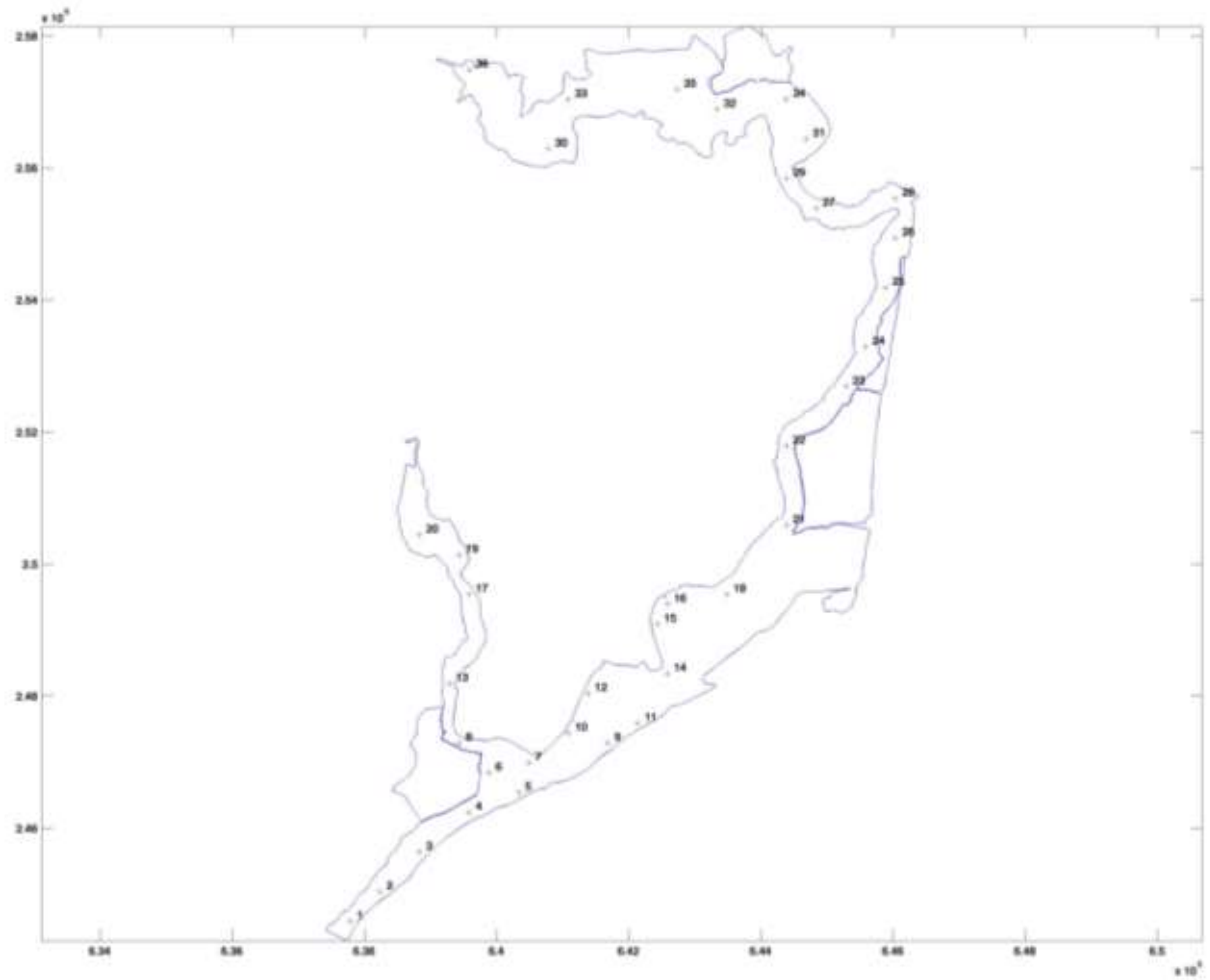


Figure 23: Location of JBA Consulting Tuflow output nodes that lie within Telemac2D domain. Output from selected nodes is used to investigate Scenarios A, B, C and sea-level rise sensitivity.

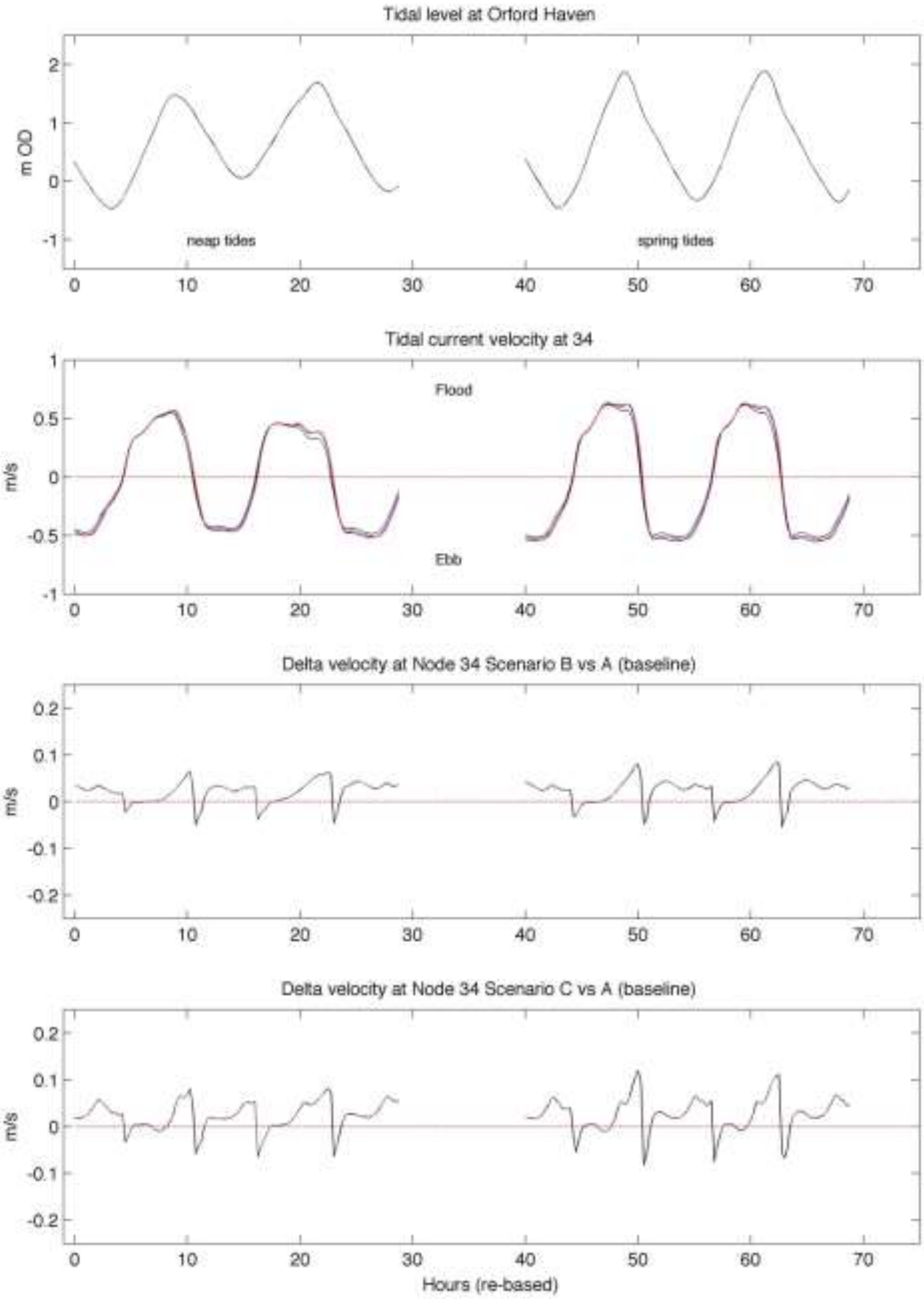


Figure 24. Node 34 analysis. Upper two plots: Water level and tidal current velocities for representative neap and spring tides (arbitrary time in hours, offset for presentation). Scenario A, B and C estuary bathymetries represented by black, blue and red curves respectively. Lower two plots: changes in velocity magnitude (i.e. ignoring flood-ebb sign of velocity) between Baseline (A) and Scenarios B and C, respectively

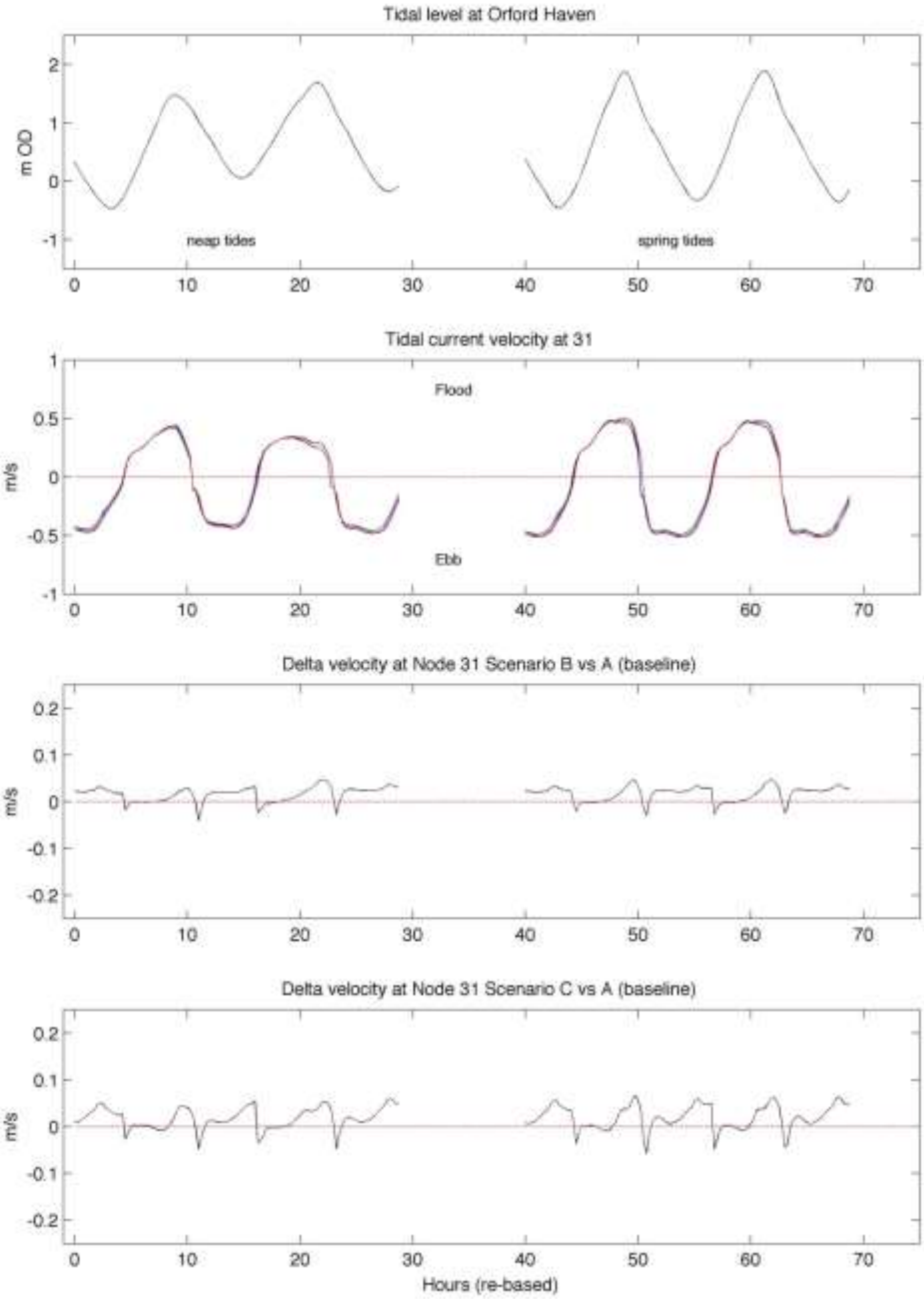


Figure 25: Node 31 analysis – see Figure 24 caption for explanation.

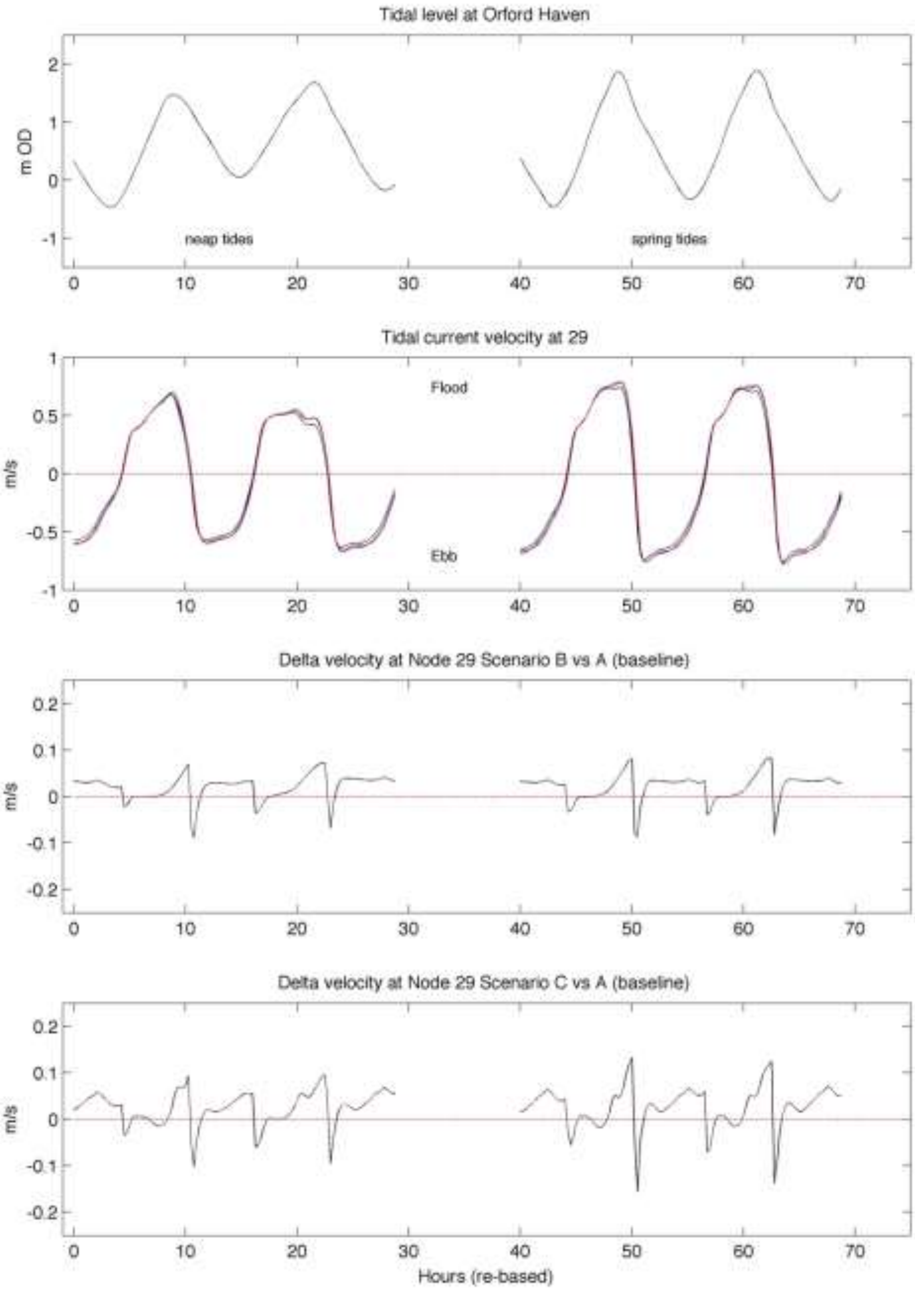


Figure 26: Node 29 analysis – see Figure 24 caption for explanation.

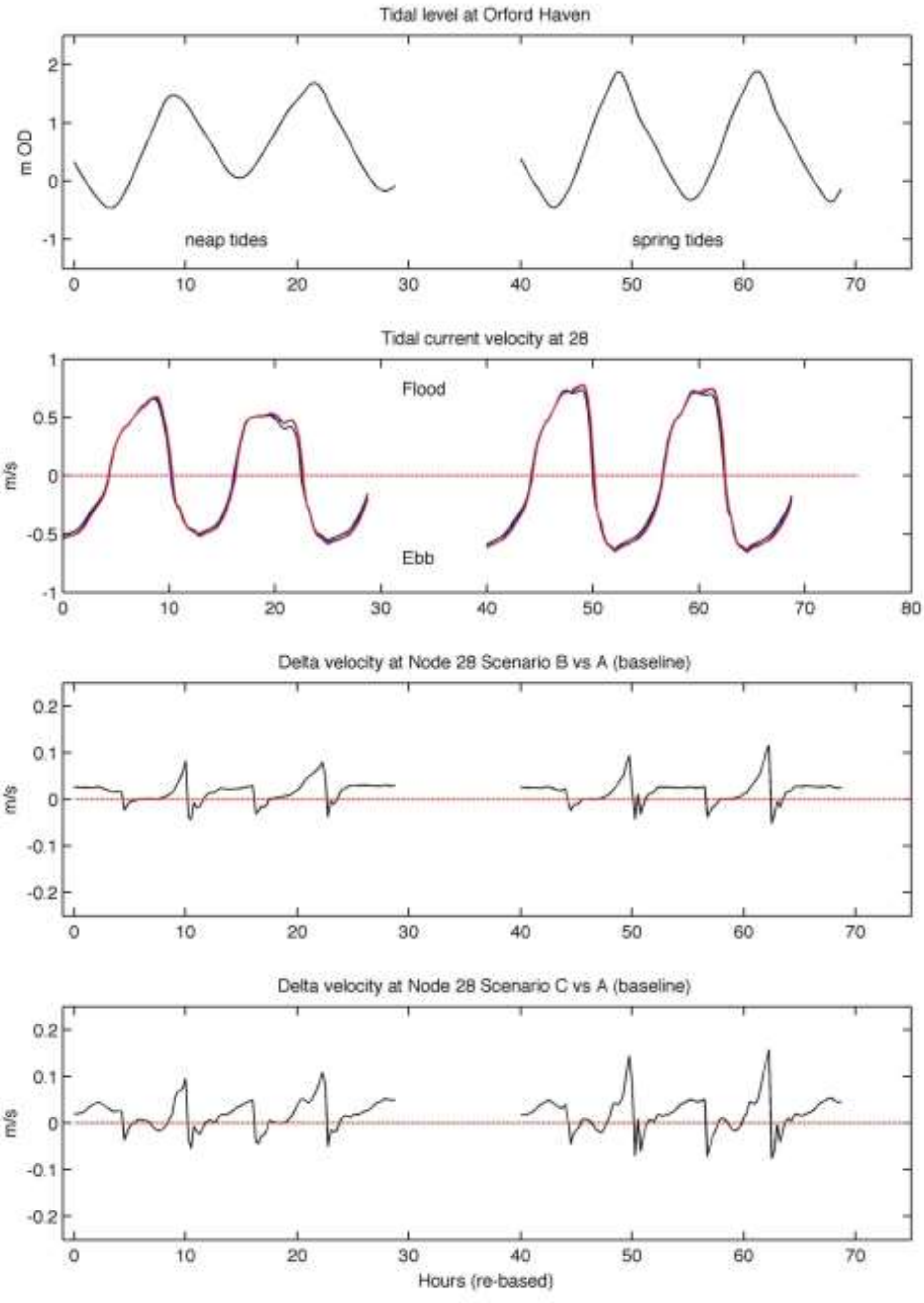


Figure 27: Slaughden - Node 28 analysis – see Figure 24 caption for explanation.

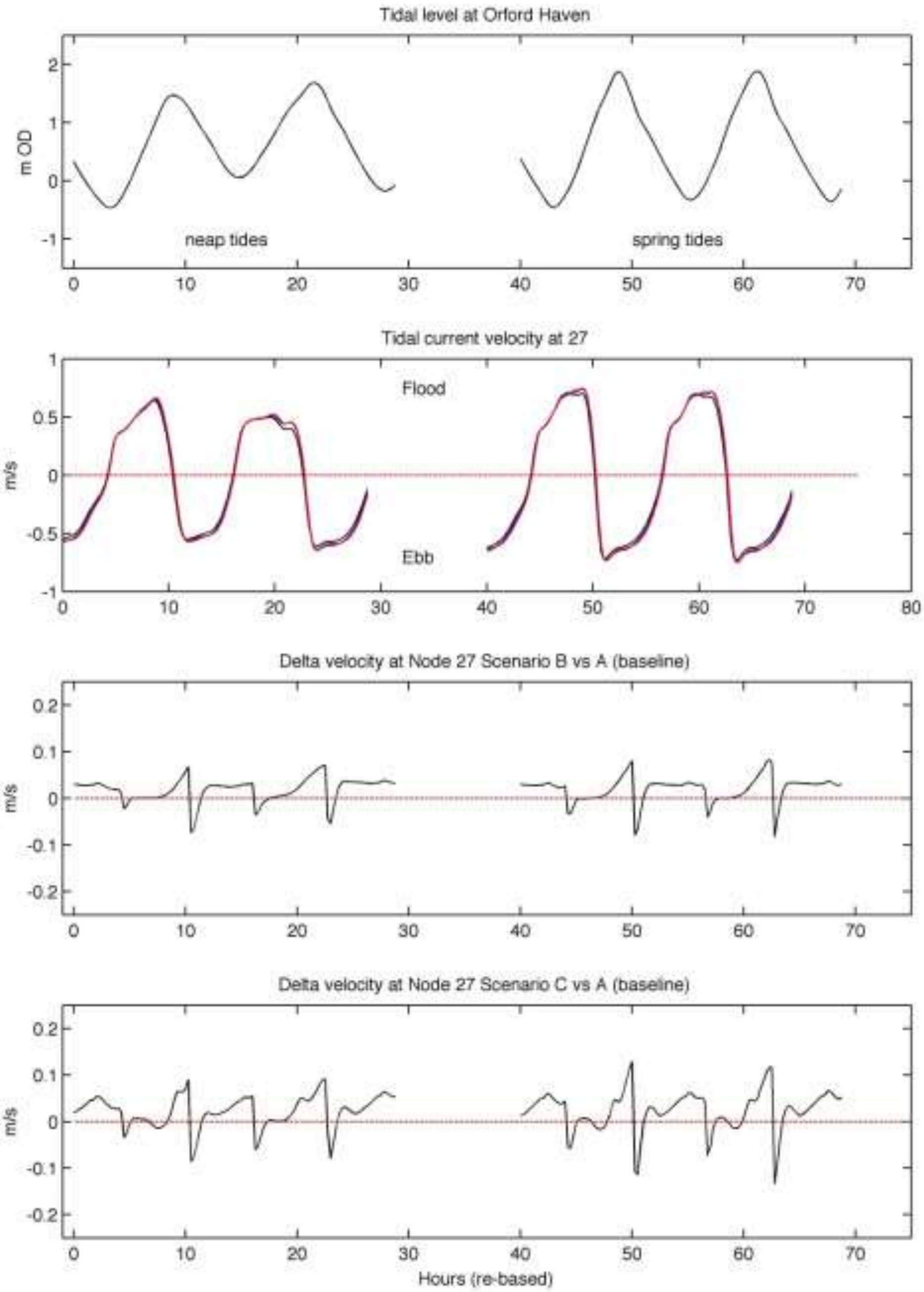


Figure 28: Slaughden - Node 27 analysis – see Figure 24 caption for explanation.

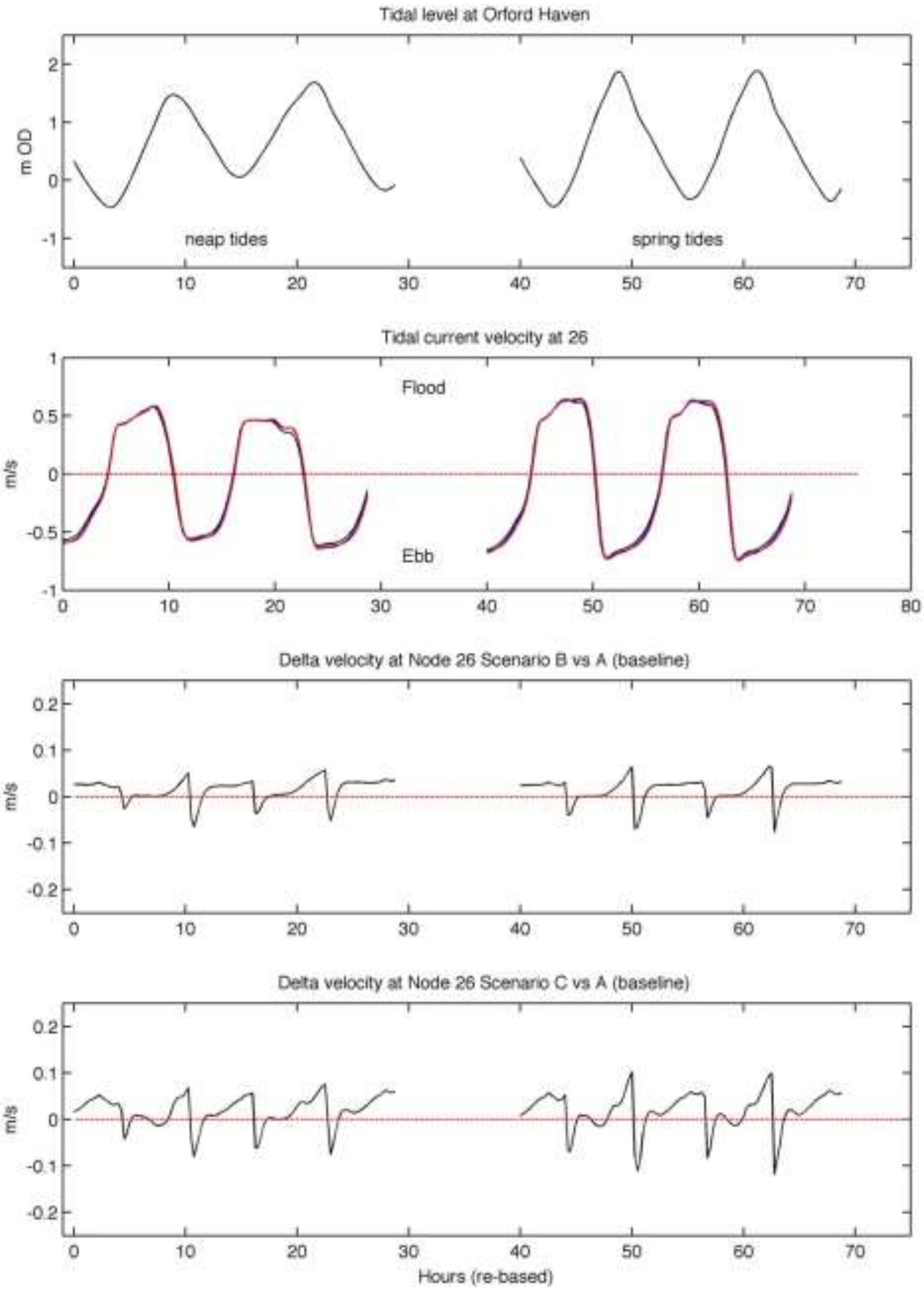


Figure 29: Slaughden - Node 27 analysis – see Figure 24 caption for explanation.

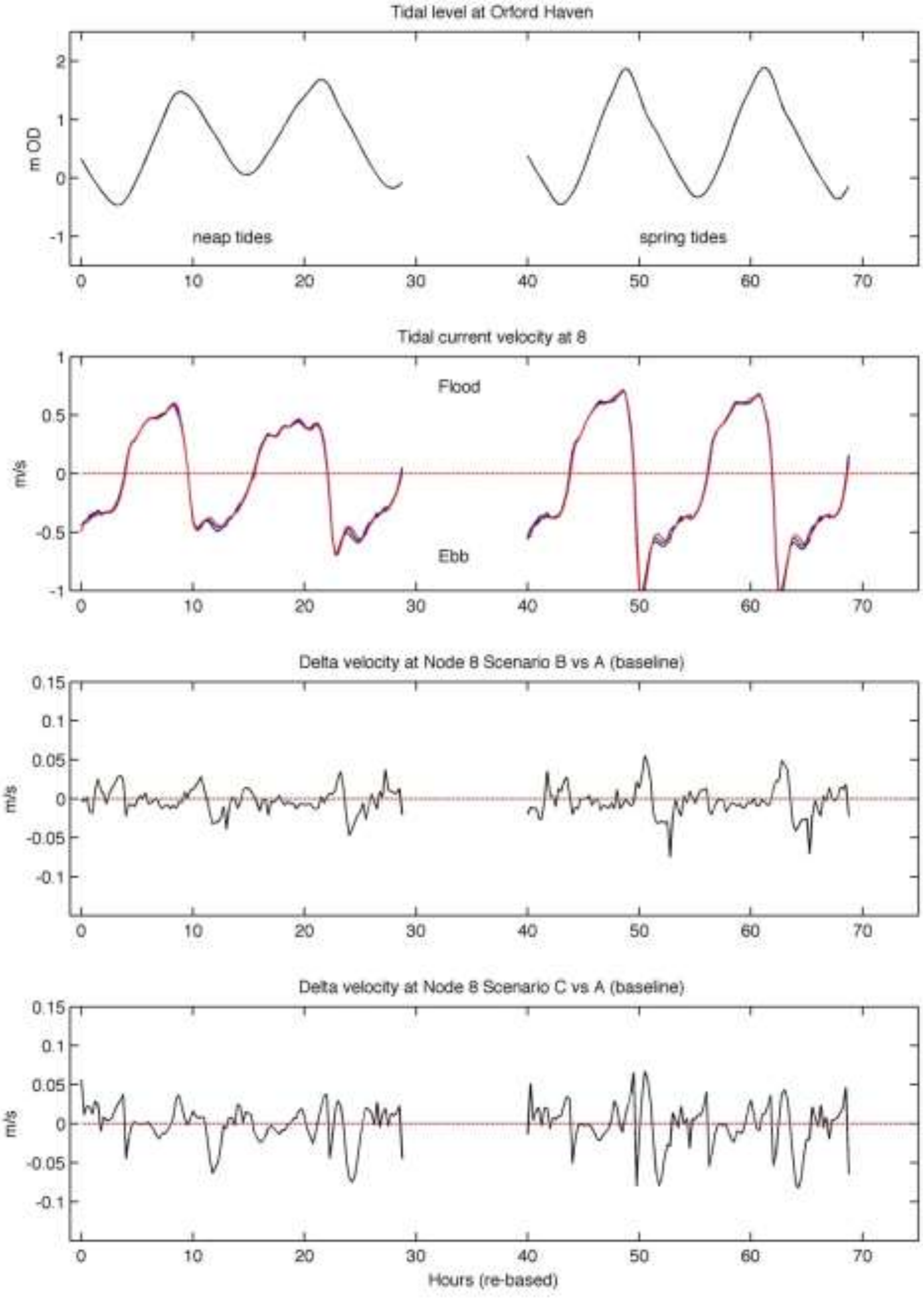


Figure 30: Boyton - Node 8 analysis – see Figure 24 caption for explanation.

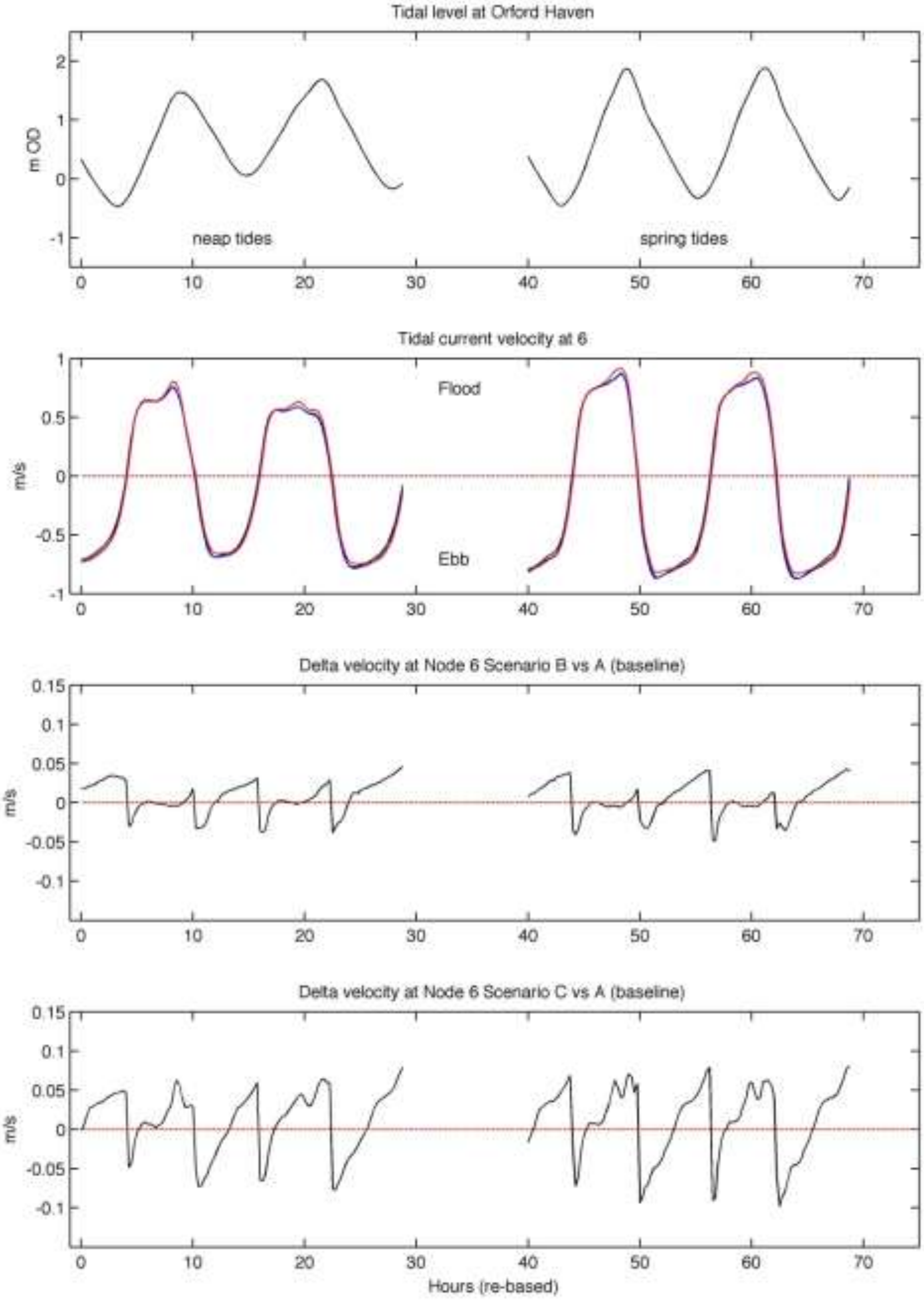


Figure 31: Boyton - Node 6 analysis – see Figure 24 caption for explanation.

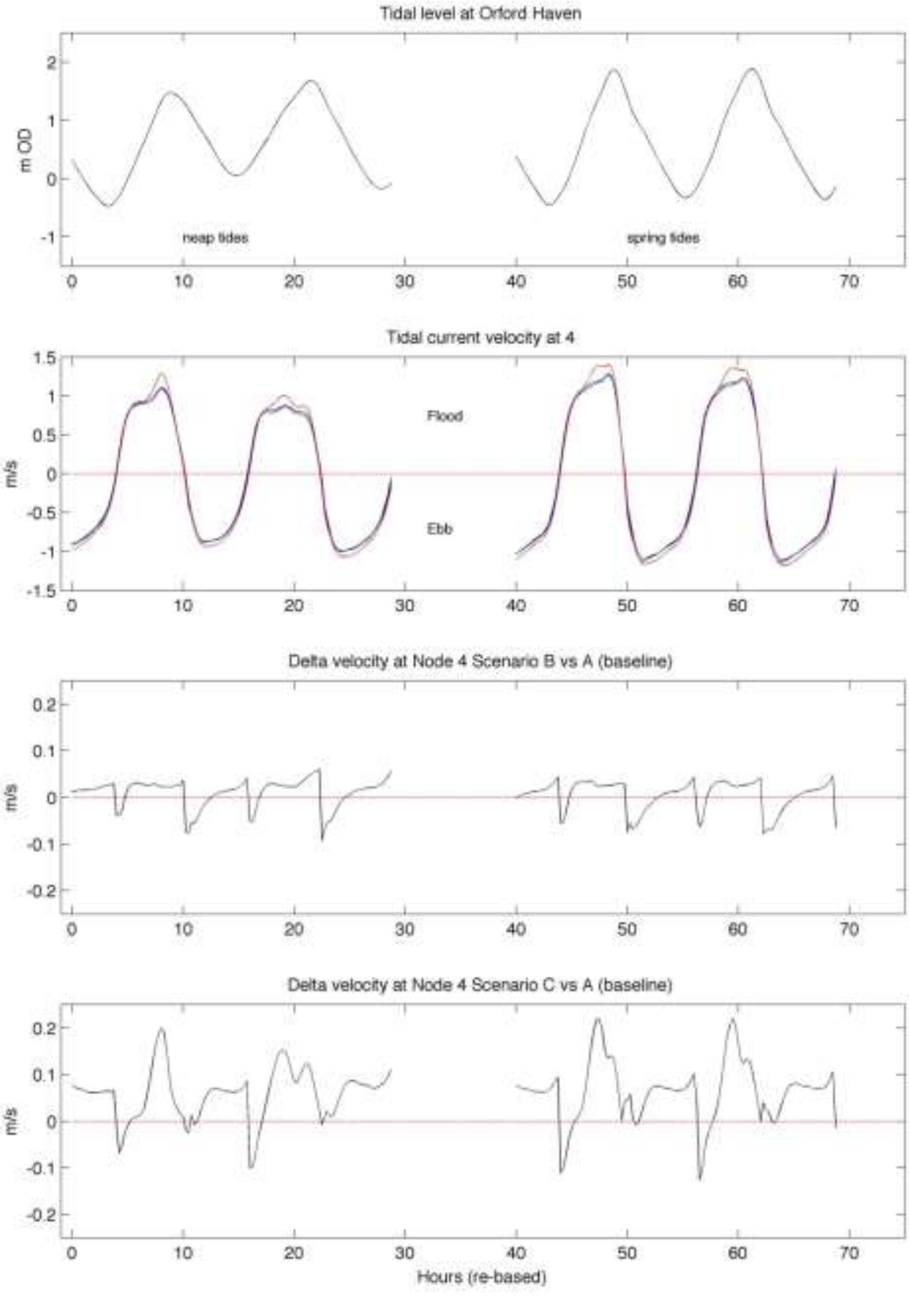


Figure 32: Boyton - Node 4 analysis – see Figure 24 caption for explanation.

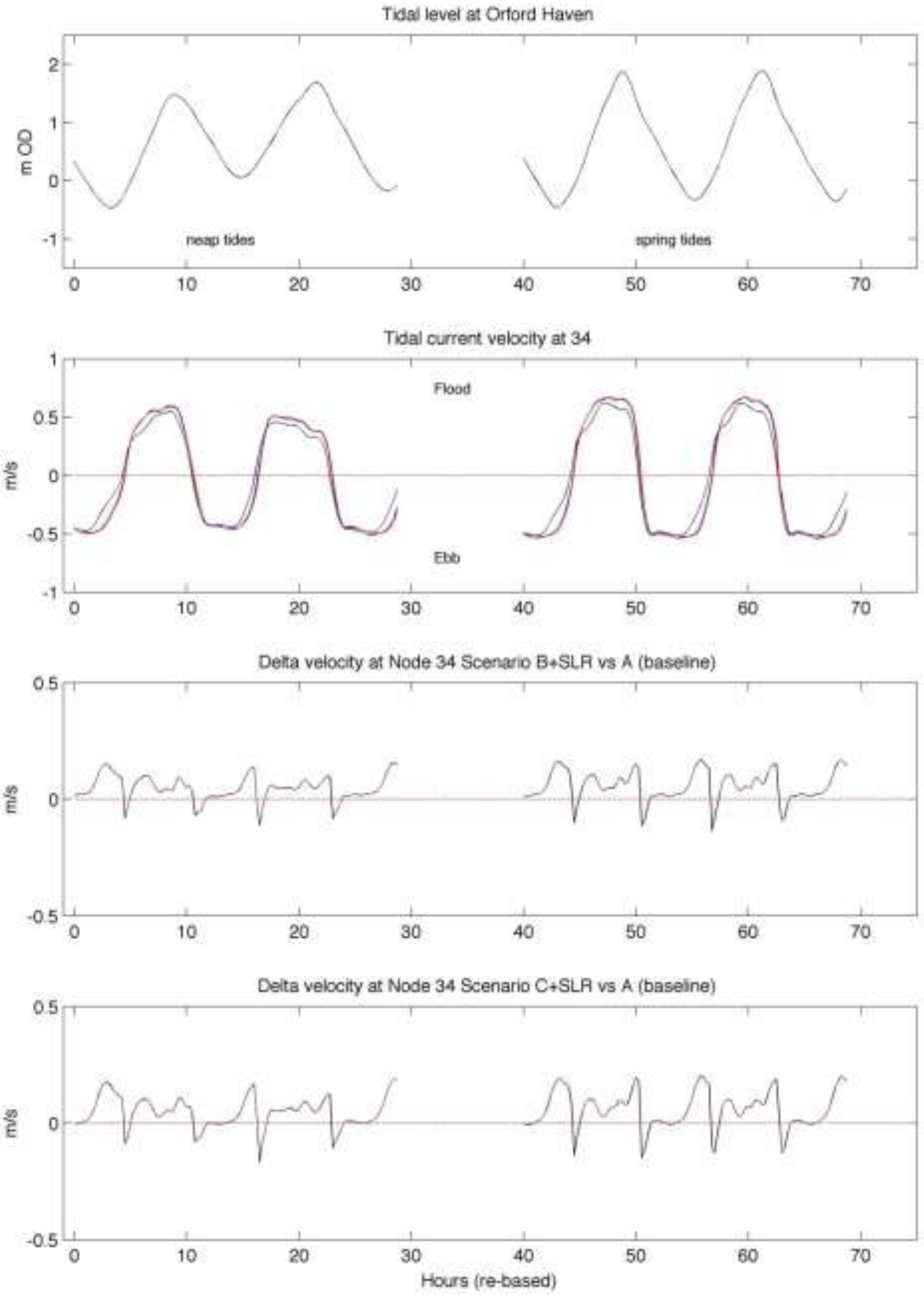


Figure 33: Hazelwood, Node 34 analysis, with sea-level rise of 300 mm included. Upper two plots: Water level and tidal current velocities for representative neap and spring tides (arbitrary time in hours, offset for presentation). Scenario A, B and C estuary bathymetries represented by black, blue and red curves respectively. Lower two plots: changes in velocity magnitude (i.e. ignoring flood-ebb sign of velocity) between baseline (A present sea-level) and B and C (raised sea level) cases.

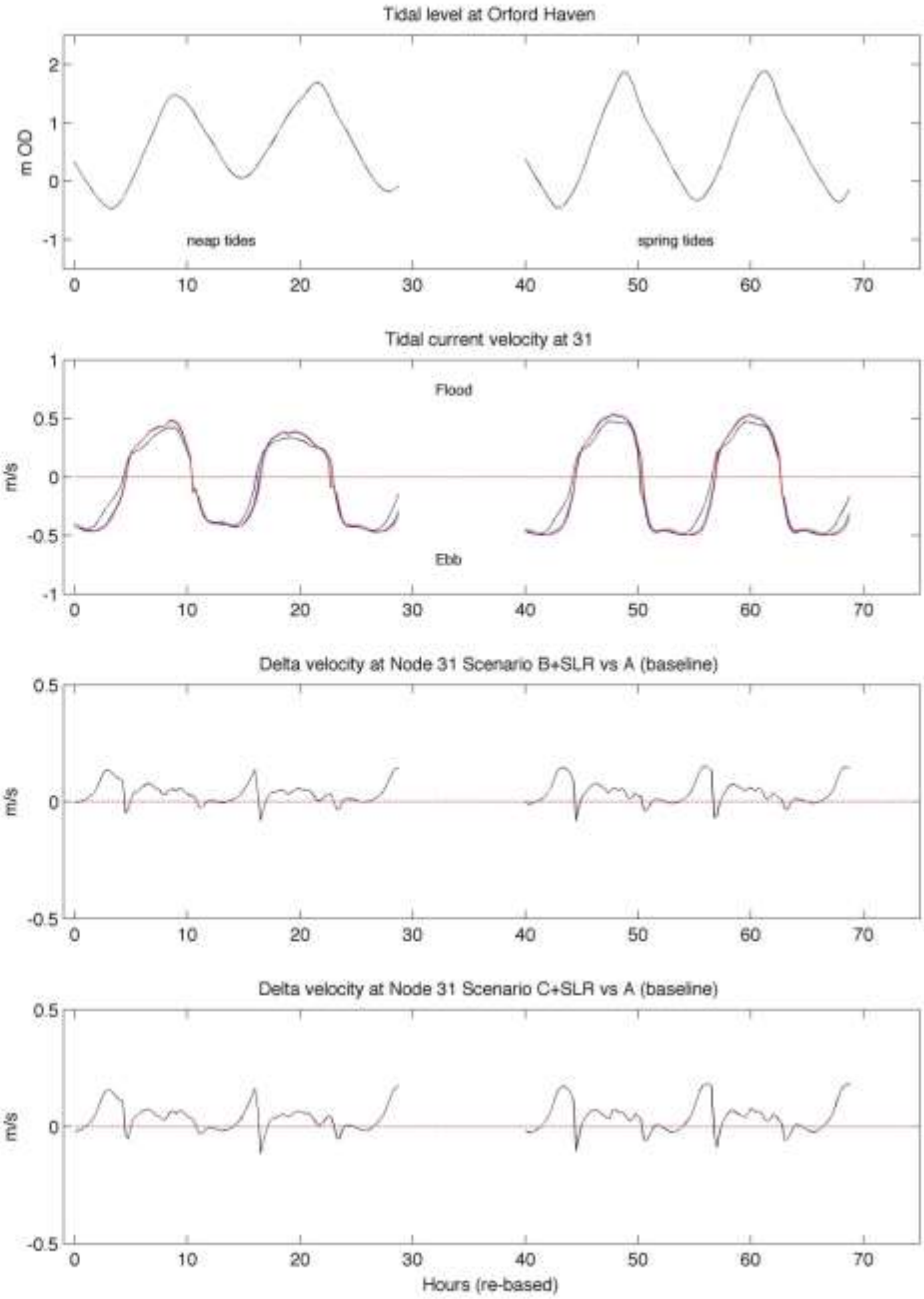


Figure 34: Hazelwood - Node 31 analysis – see Figure 33 caption for explanation.

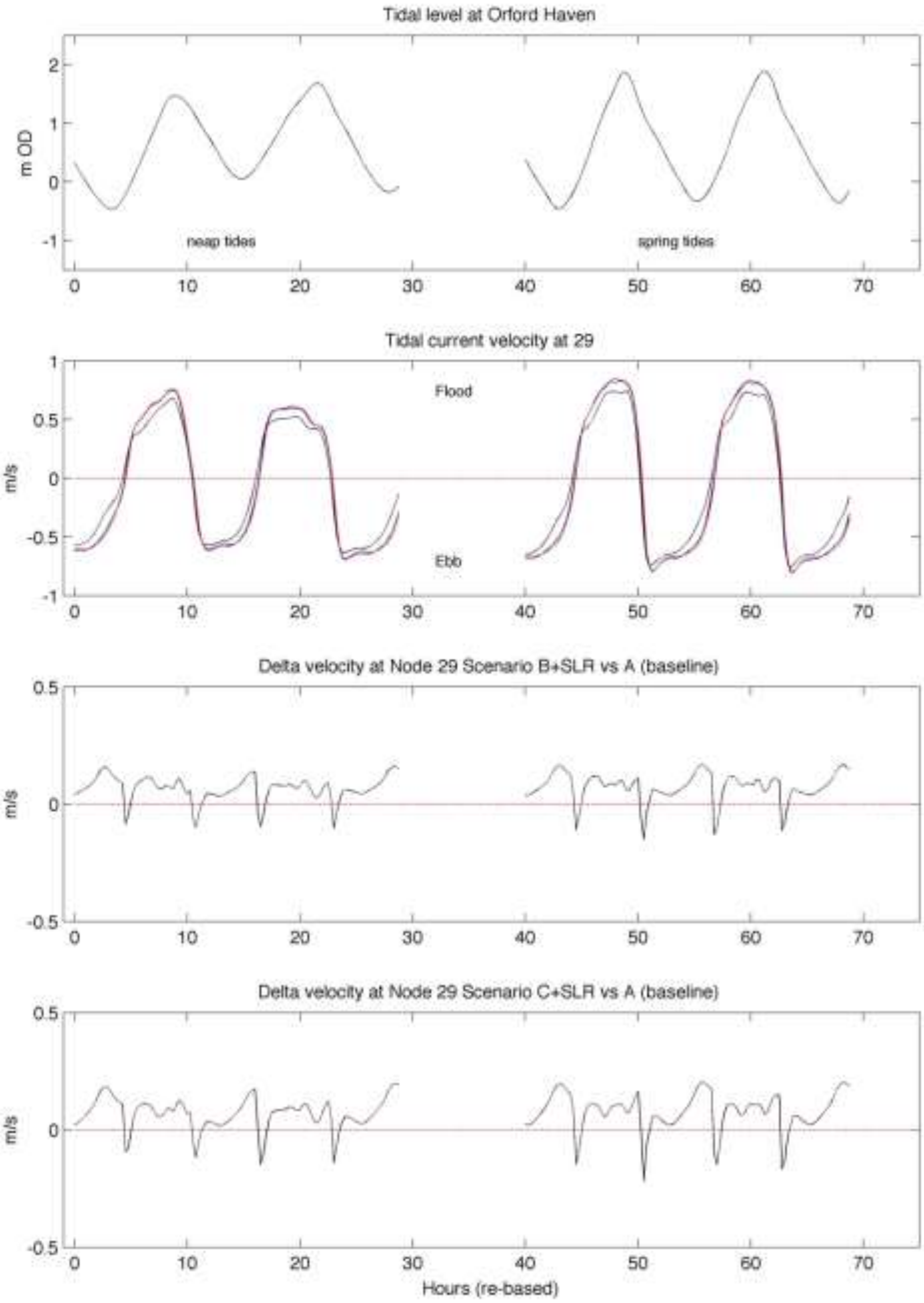


Figure 35: Hazelwood - Node 29 analysis – see Figure 33 caption for explanation.

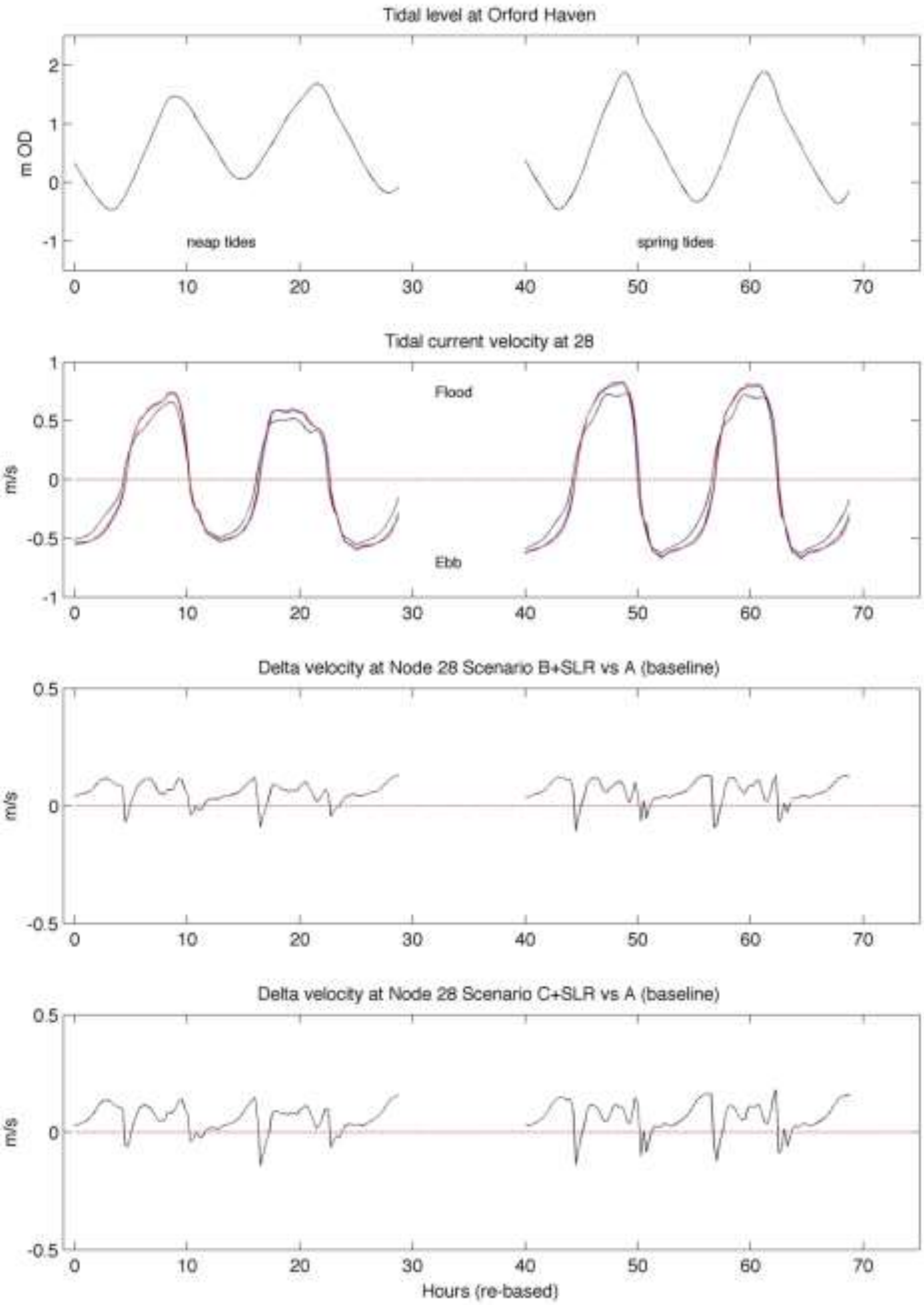


Figure 36: Slaughden - Node 28 analysis – see Figure 33 caption for explanation.

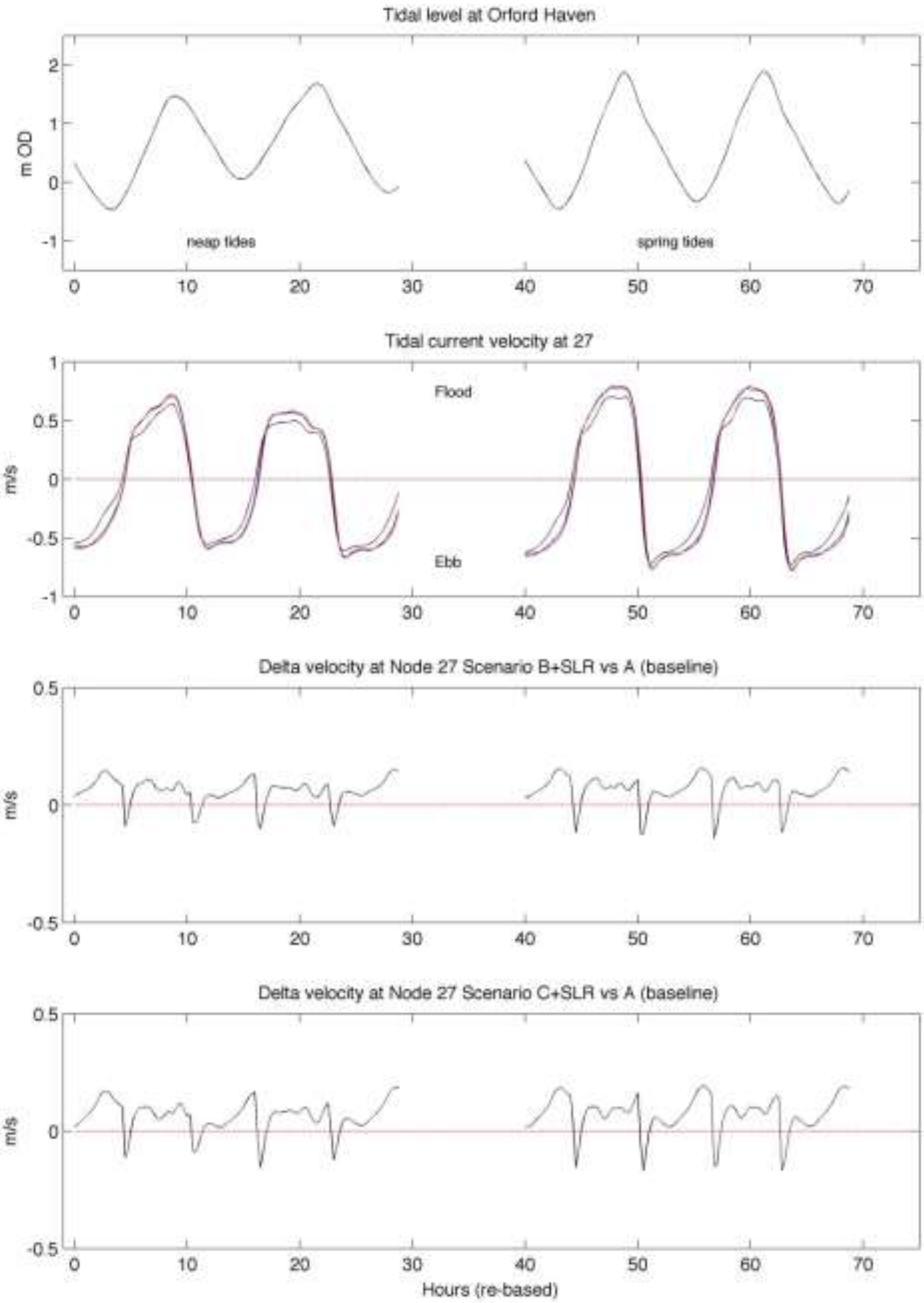


Figure 37: Slaughden - Node 27 analysis – see Figure 33 caption for explanation.

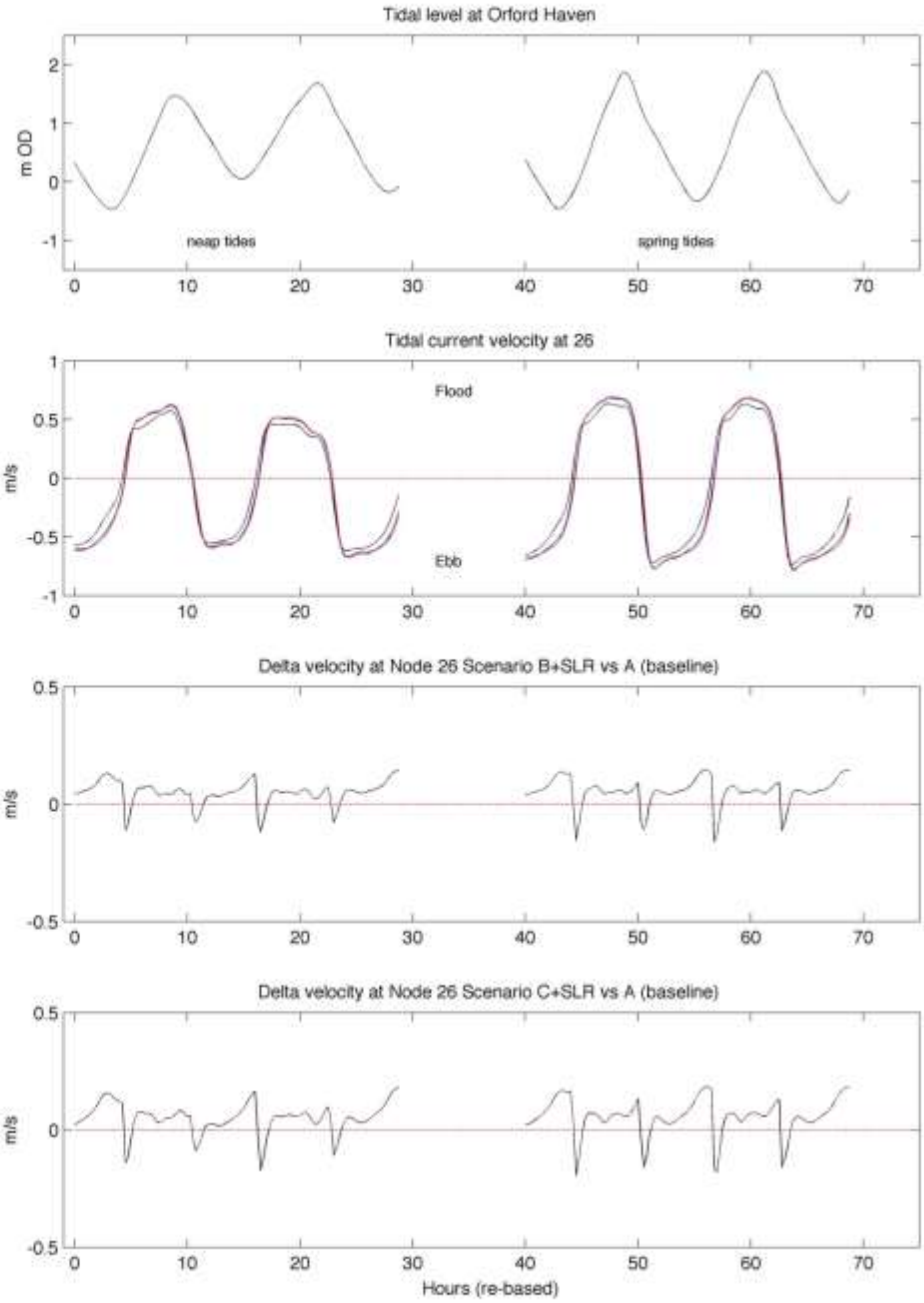


Figure 38: Slaughden - Node 26 analysis – see Figure 33 caption for explanation.

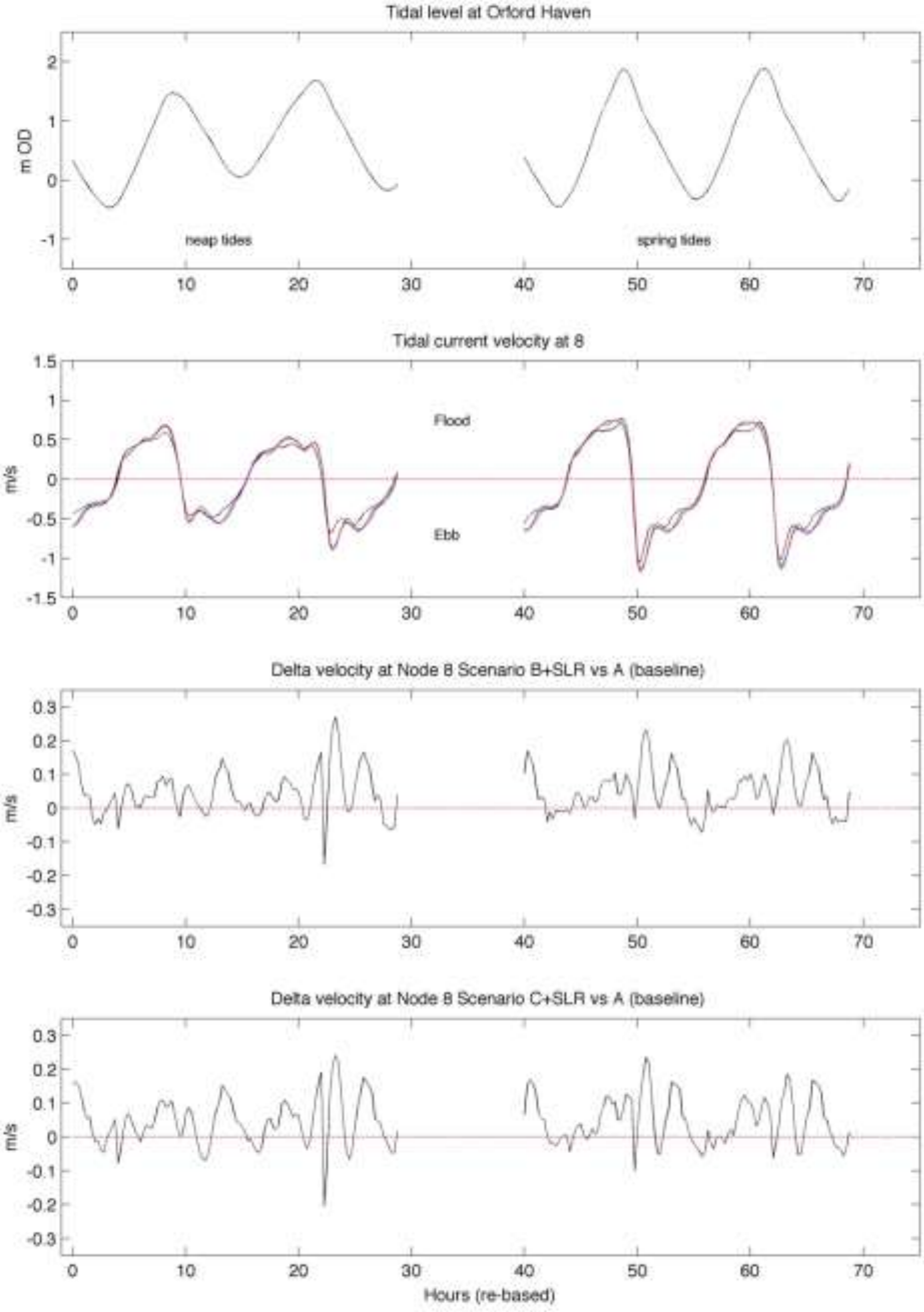


Figure 39: Boyton - Node 8 analysis – see Figure 33 caption for explanation.

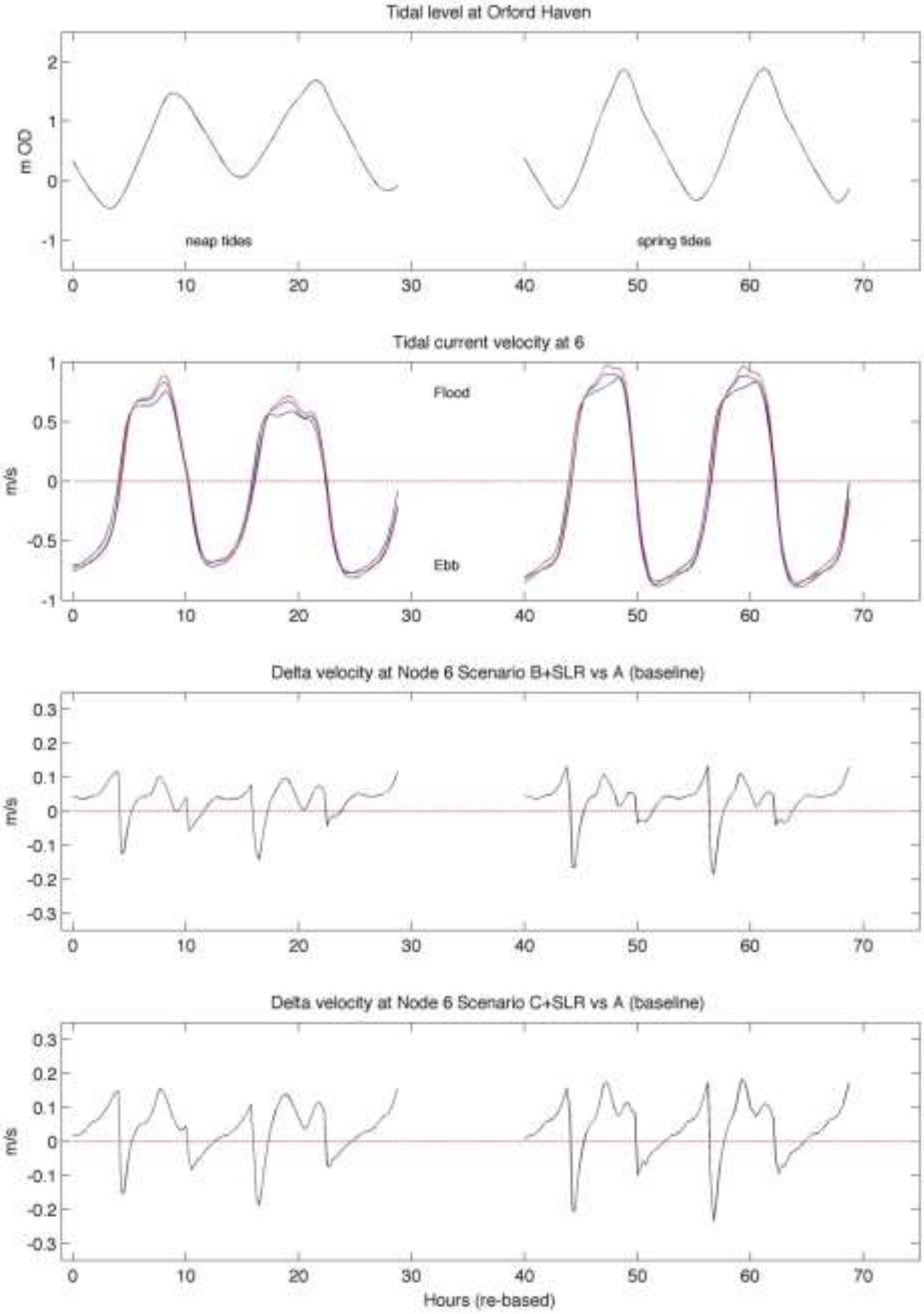


Figure 40: Boyton - Node 6 analysis – see Figure 33 caption for explanation.

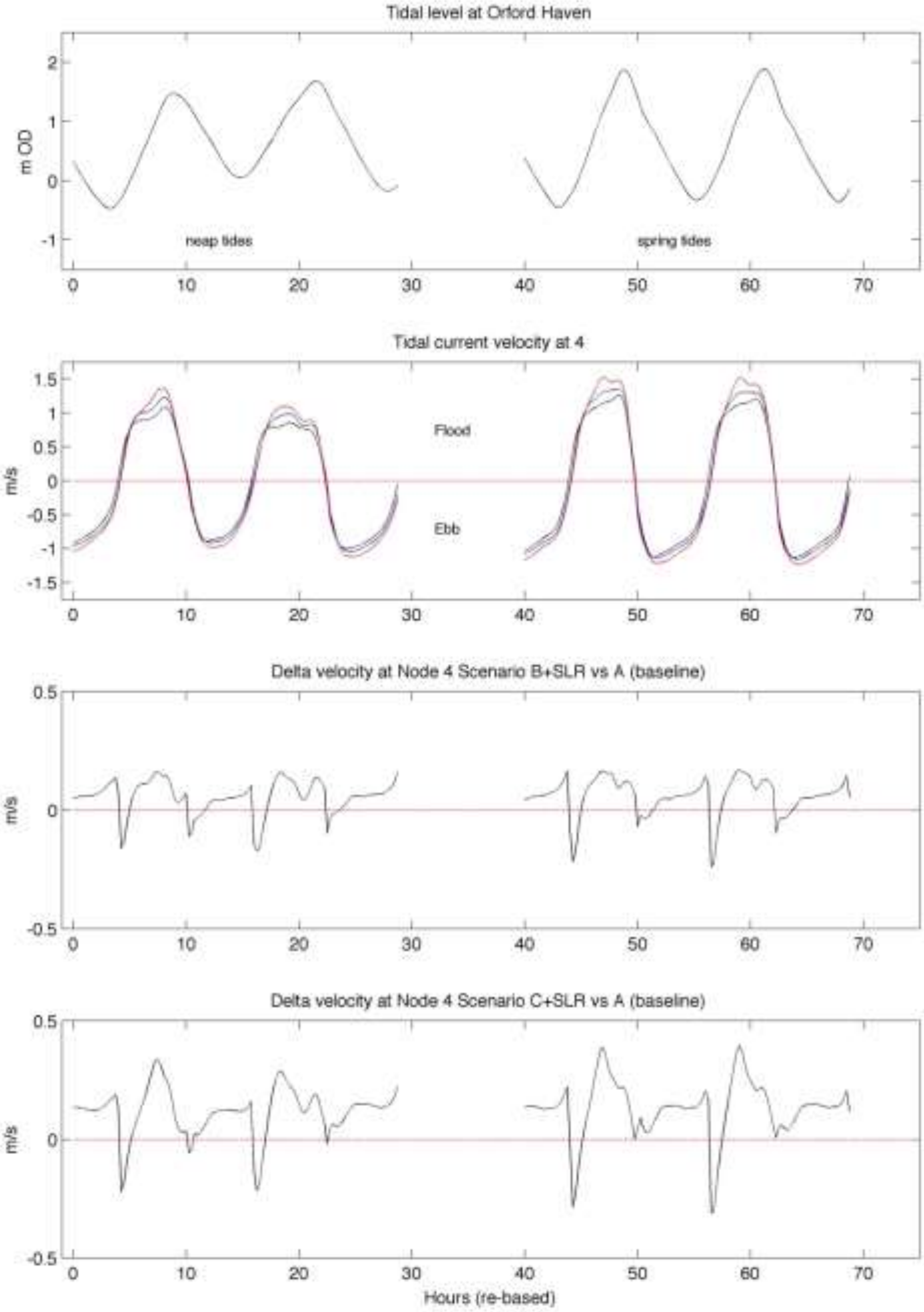


Figure 41: Boyton - Node 4 analysis – see Figure 33 caption for explanation.

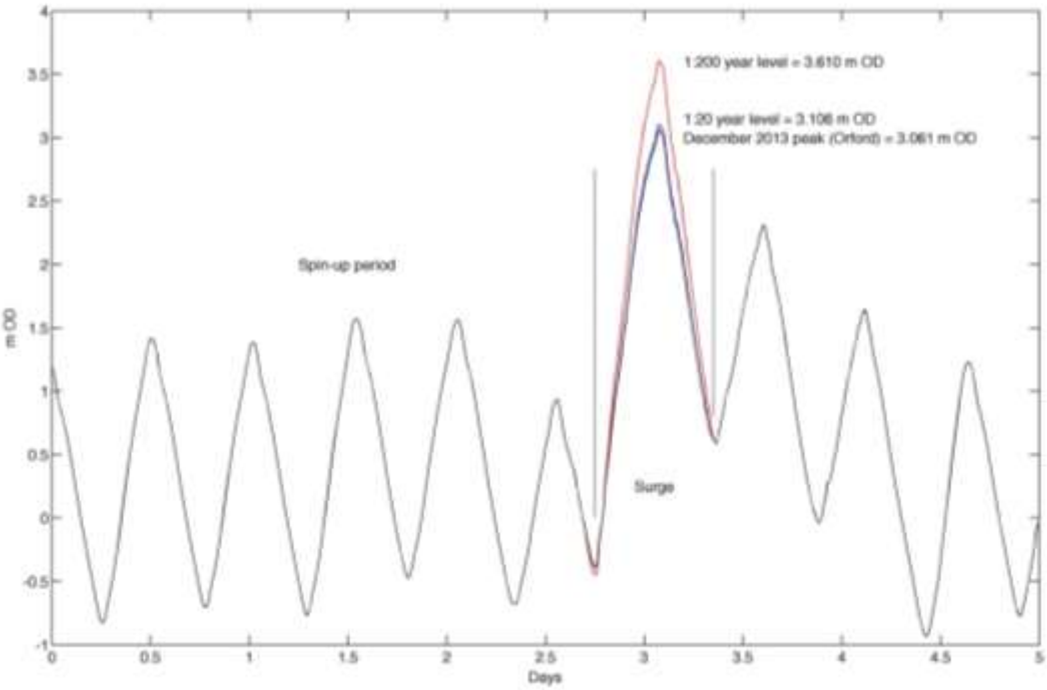


Figure 42: Basis for extreme surge simulations, showing the actual December 2013 water level curve for Orford, shifted to an arbitrary time origin, and scaled to give surges representative of 1 in 20 and 1 in 200 year events at the estuary mouth (Orford Haven). These series were then used as the model boundary condition

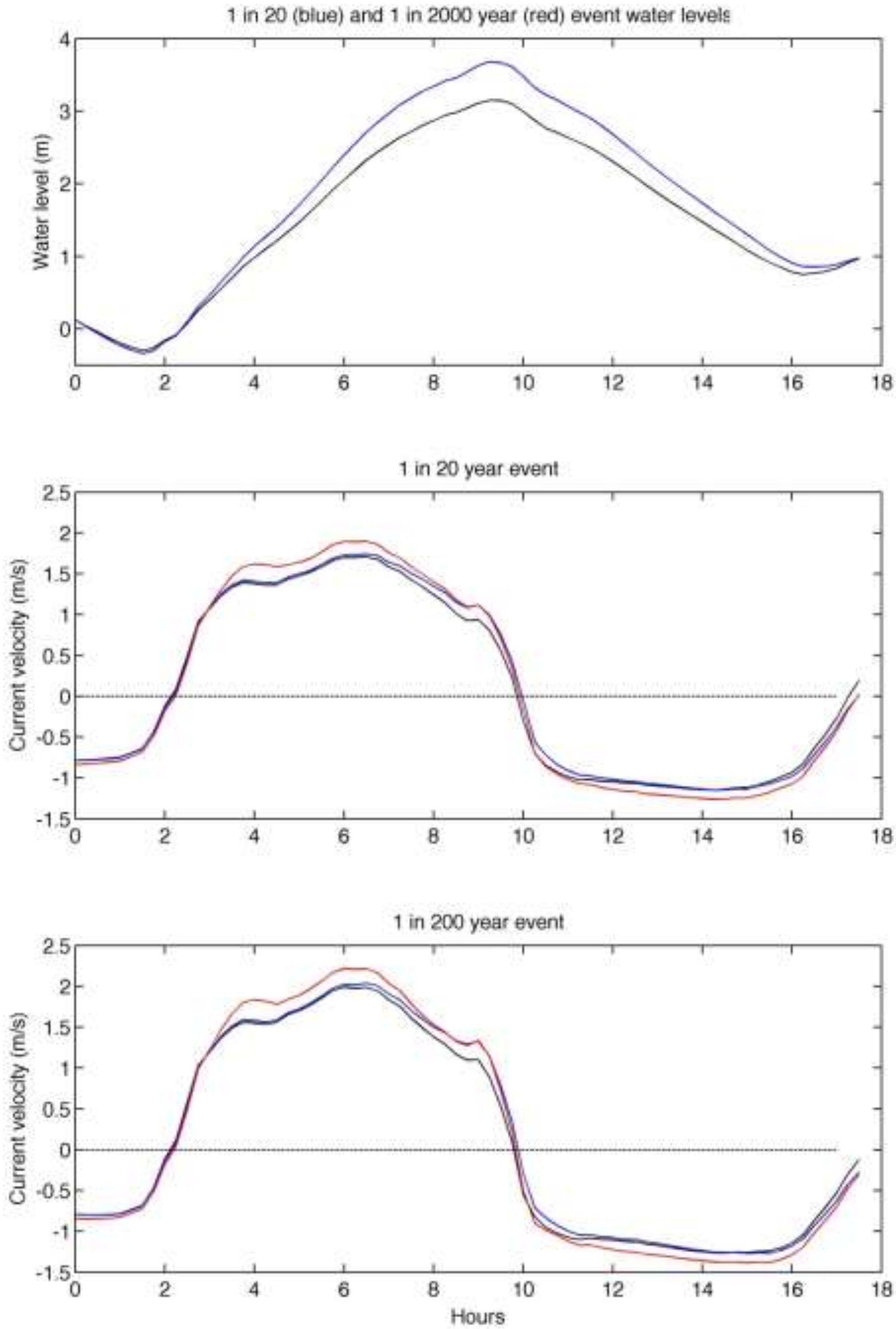


Figure 43: Water level curves for 1 in 20 and 1 in 200 year simulated surge event in the outer estuary, at node 4 (top panel). Lower panels show overlaid current velocity time series for scenario A (baseline, black), B (Hazelwood Marshes flooded, blues), and C (Hazelwood and Boyton marshes flooded, red) geometries during 1 in 20 and 1 in 200 year events. Ebb velocities are negative.

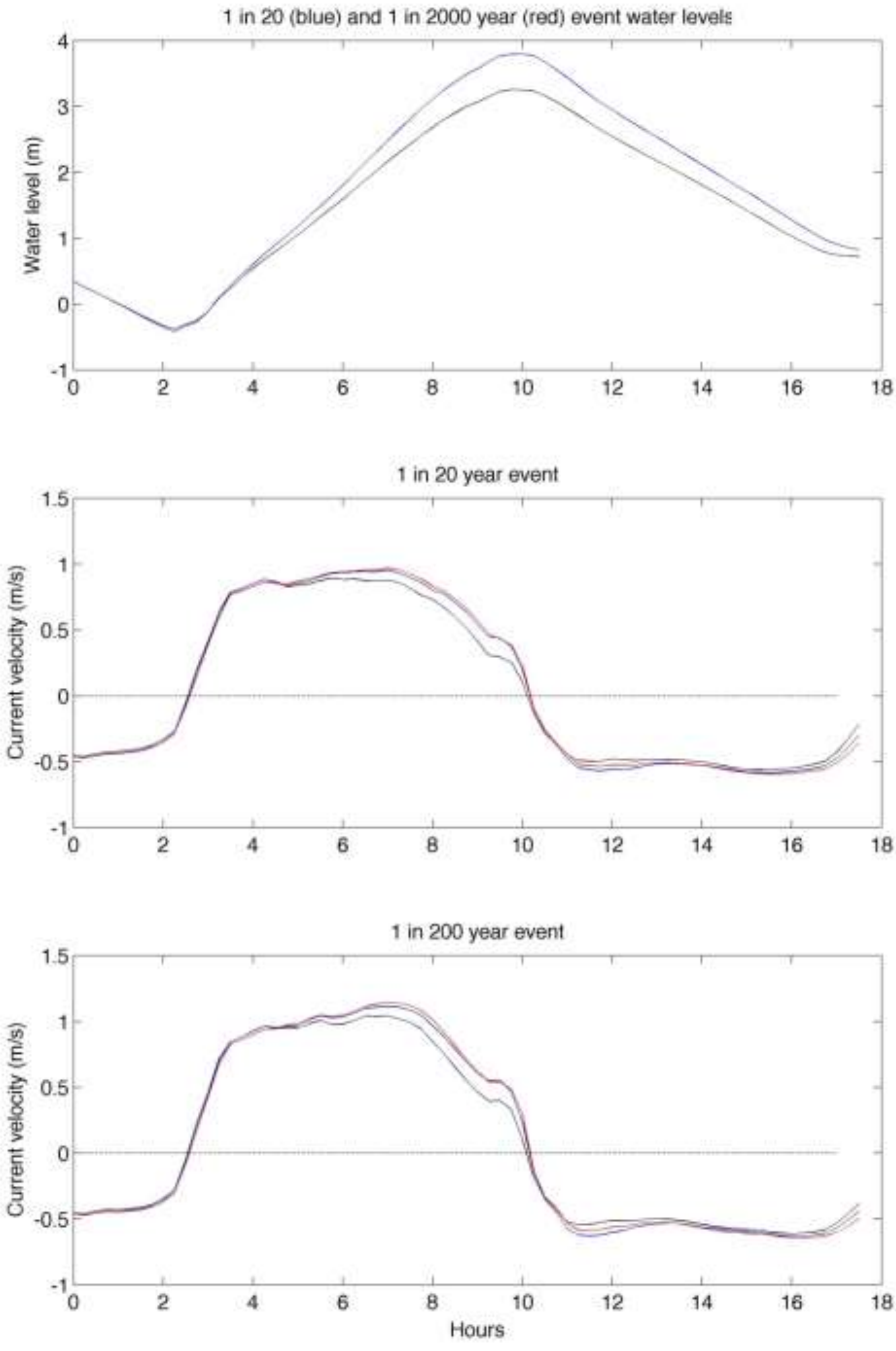


Figure 43: Water level curves for 1 in 20 and 1 in 200 year simulated surge events at Slaughden, node 28 (top panel). Lower panels show overlaid current velocity series for scenario A (baseline, black), B (Hazelwood Marshes flooded, blues), and C (Hazelwood and Boyton marshes flooded, red) geometries during 1 in 20 and 1 in 200 year events. Ebb velocities are negative.

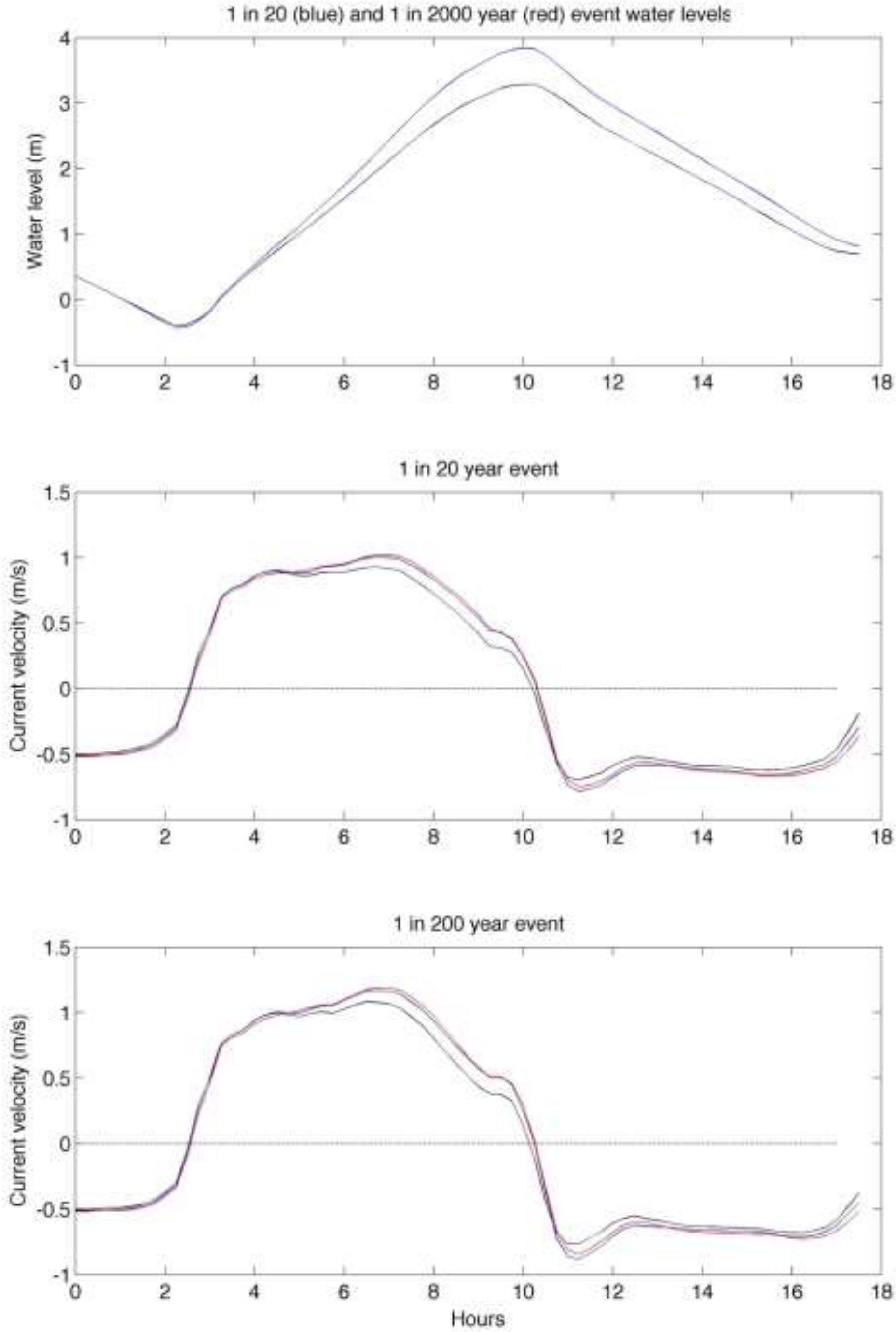


Figure 44: Water level curves for 1 in 20 and 1 in 200 year simulated surge events in the vicinity of Hazelwood marshes, at node 29 (top panel). Lower panels show overlaid current velocity series for scenario A (baseline, black), B (Hazelwood Marshes flooded, blues), and C (Hazelwood and Boyton marshes flooded, red) geometries during 1 in 20 and 1 in 200 year events. Ebb velocities are negative.

APPENDIX 1

Variation in salinity, turbidity and suspended solids concentration over neap and spring tidal cycles measured at three locations in the estuary by the EA in December 2014

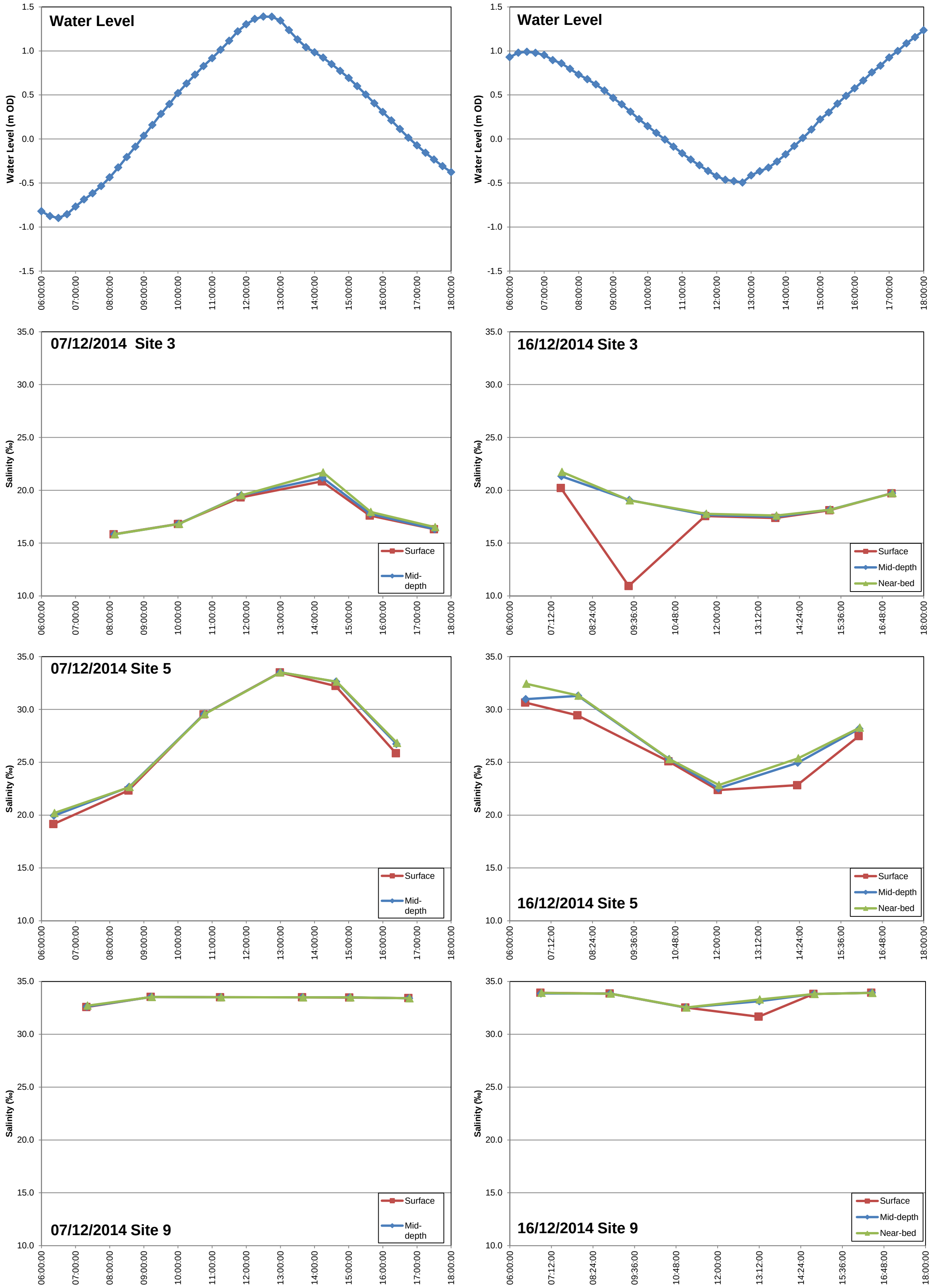


Figure A1.1. Measurements of salinity at Site 3 (Slaughden), Site 5 (Orford) and Site 9 (Shingle Street) on 7th and 16th December 2014 using Idronaut Ocean Seven 305/89 equipment. Data supplied by the Environment Agency.

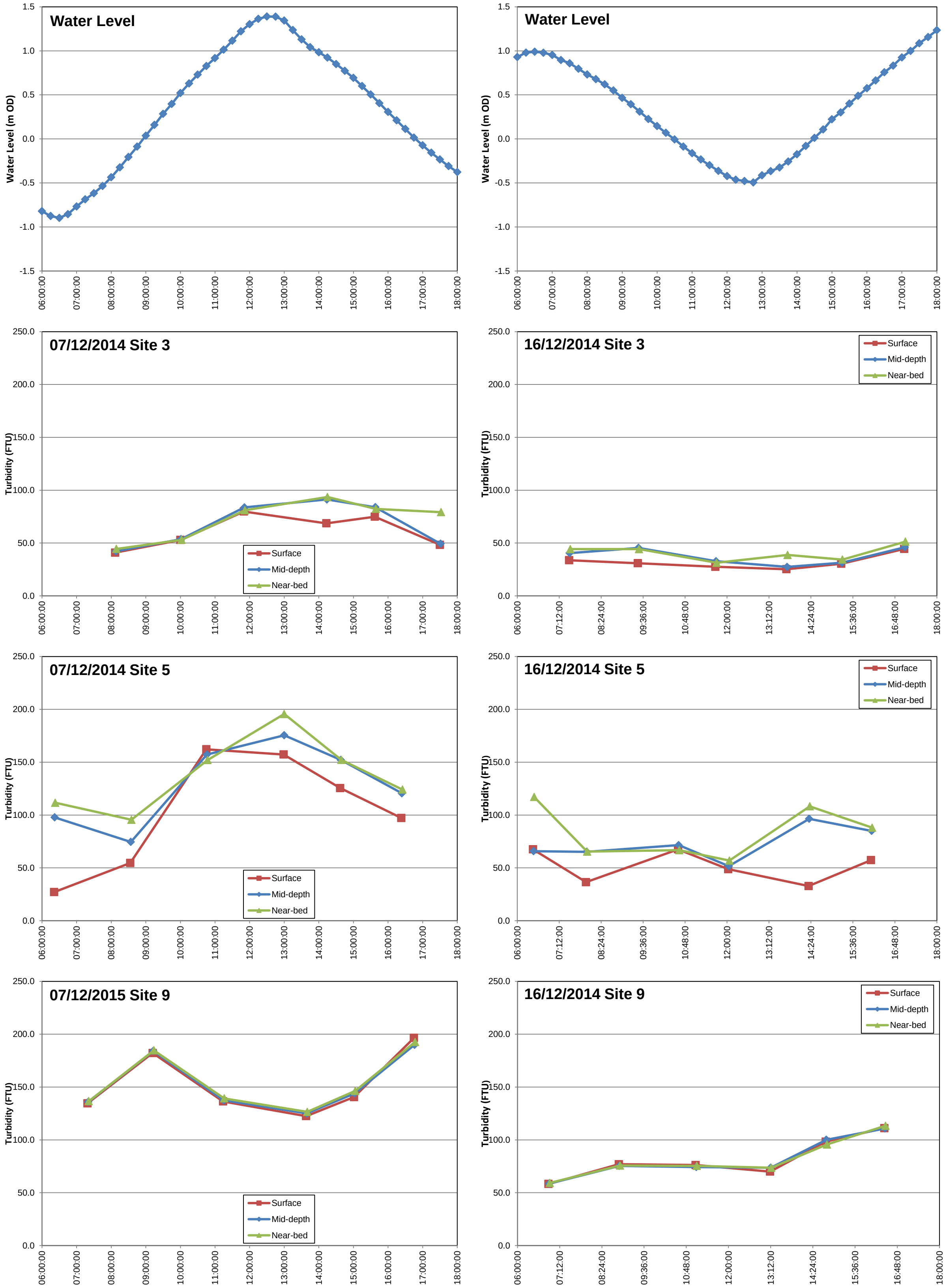


Figure A1.2. Measurements of turbidity at Site 3 (Slaughden), Site 5 (Orford) and Site 9 (Shingle Street) on 7th and 16th December 2014 using Idronaut Ocean Seven 305/89 equipment. Data supplied by the Environment Agency.

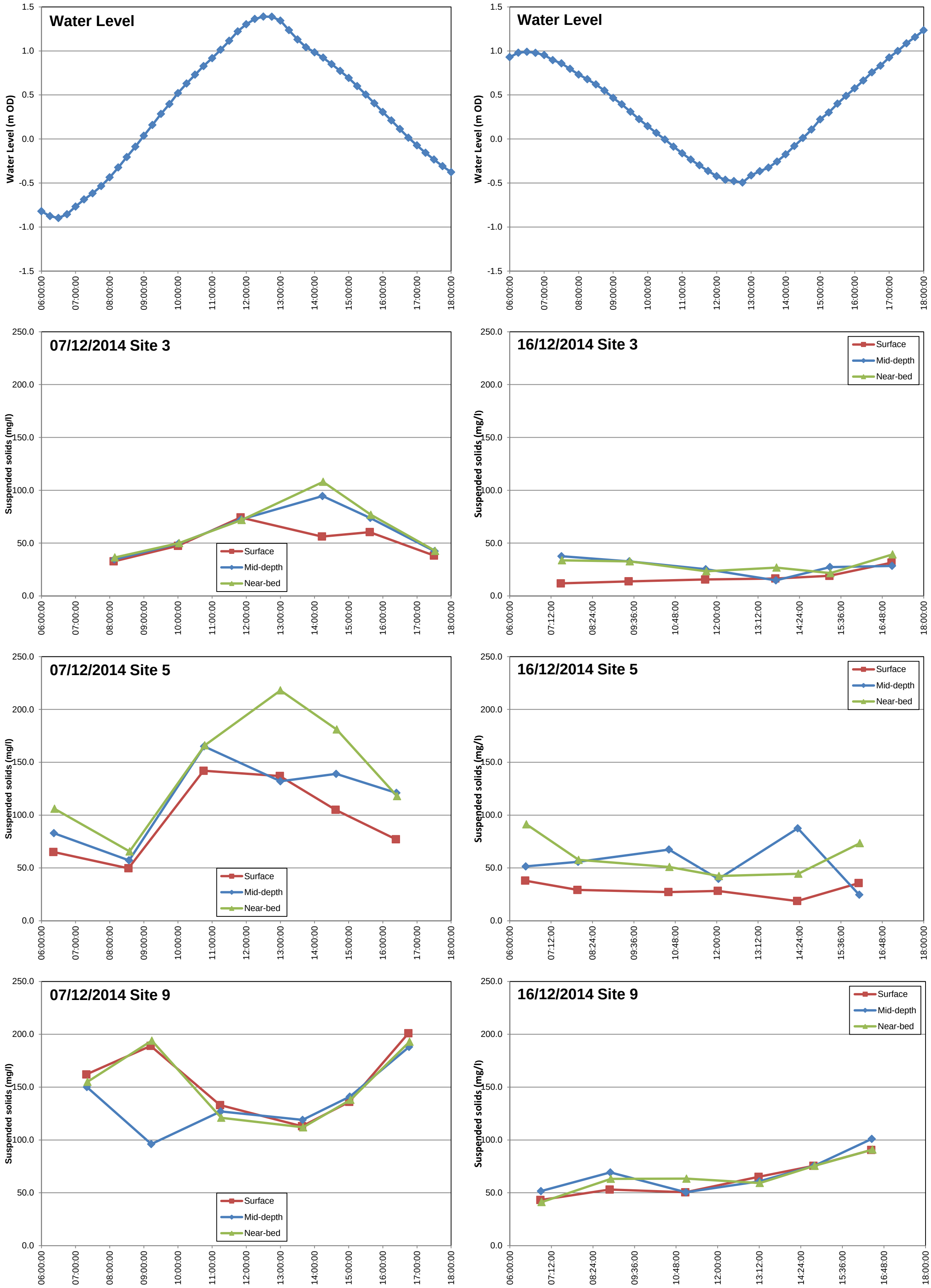


Figure A1.3. Measurements of suspended solids concentration at Site 3 (Slaughden), Site 5 (Orford) and Site 9 (Shingle Street) on 7th and 16th December 2014 using Idronaut Ocean Seven 305/89 equipment. Data supplied by the Environment Agency.

APPENDIX 2

Frequency distributions of wall heights in each Flood Cell determined by the EA 2009 survey

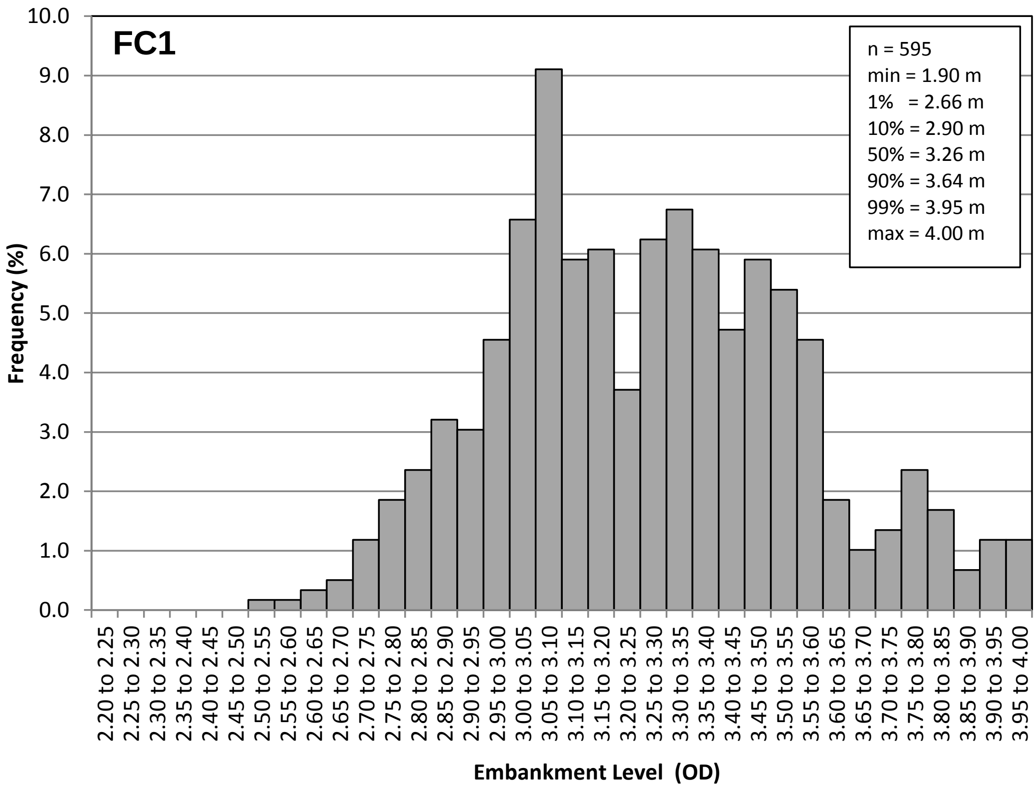


Figure A1.1. Frequency histogram of observations of embankment heights within Flood Compartment 1, excluding levels above 4.0 m OD.

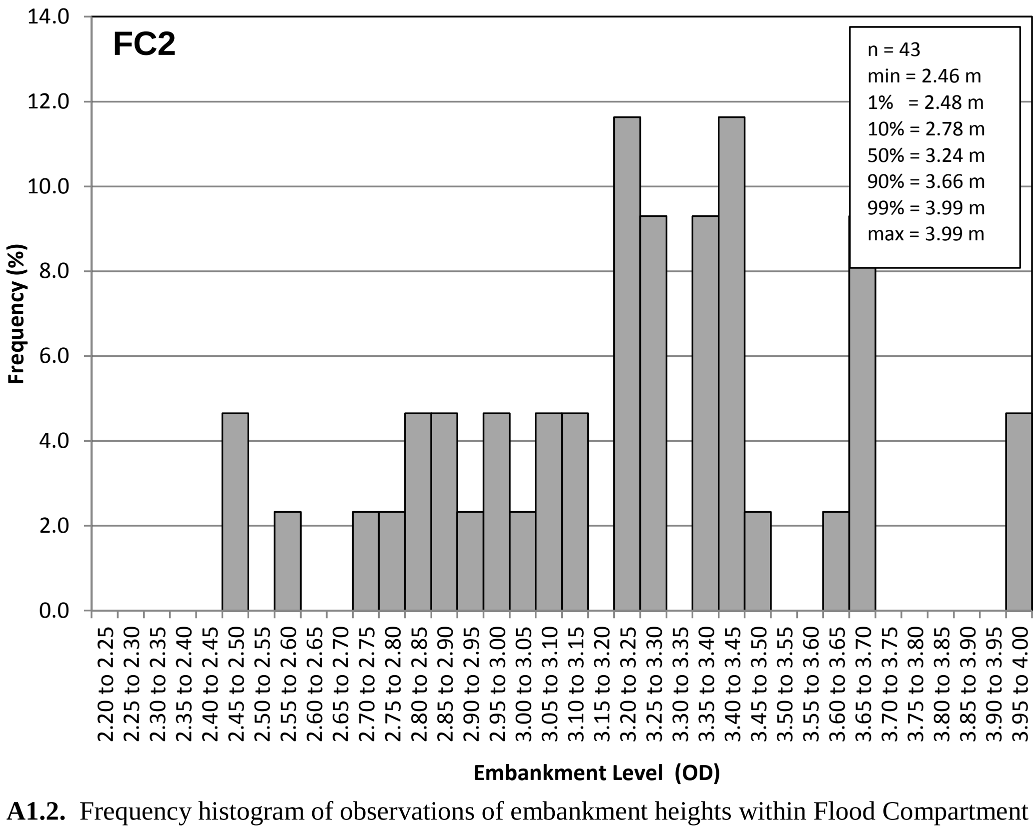


Figure A1.2. Frequency histogram of observations of embankment heights within Flood Compartment 2, excluding levels above 4.0 m OD.

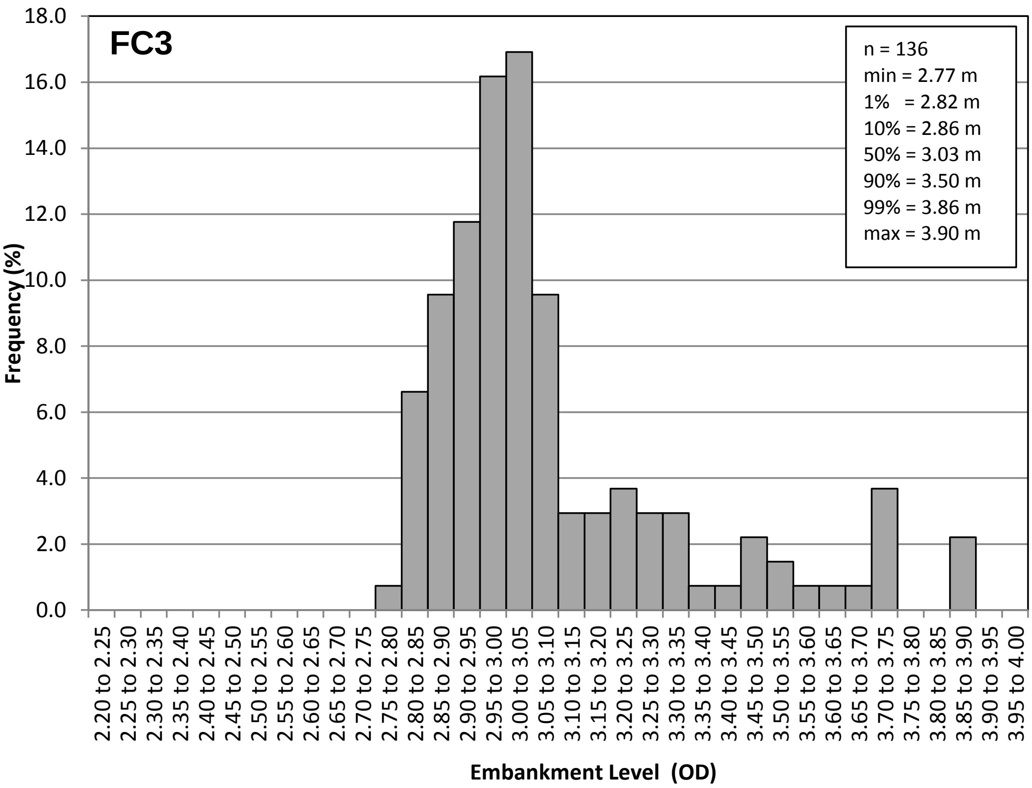


Figure A1.3. Frequency histogram of observations of embankment heights within Flood Compartment 3, excluding levels above 4.0 m OD.

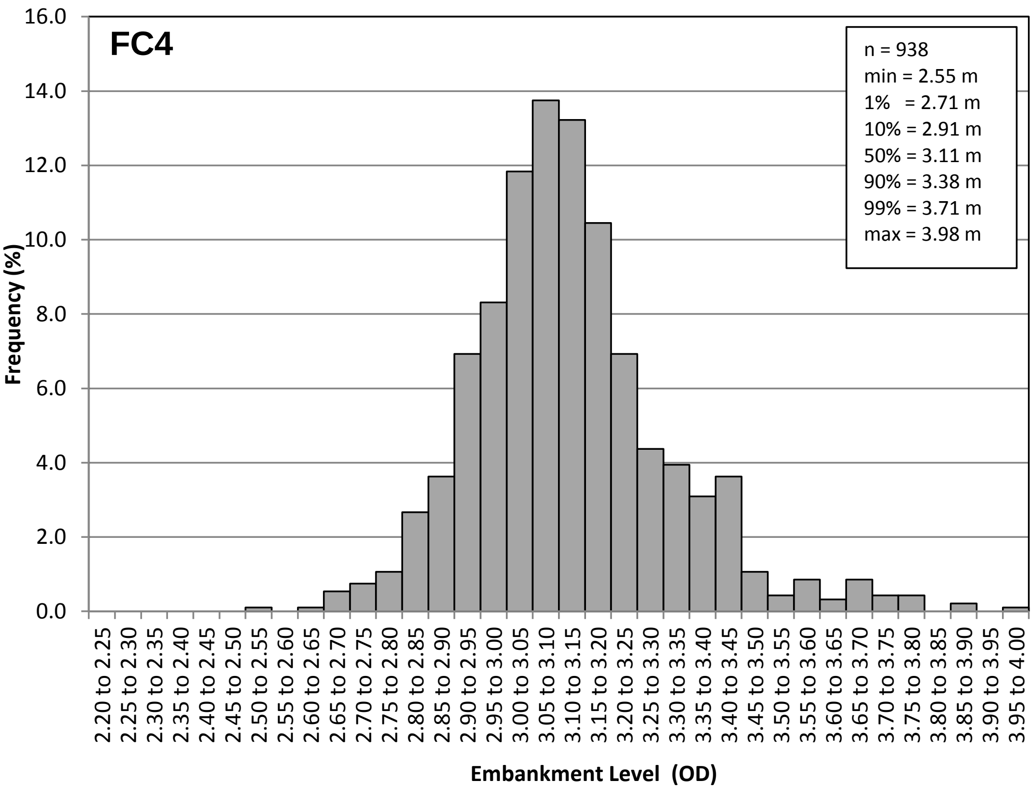


Figure A1.4. Frequency histogram of observations of embankment heights within Flood Compartment 4, excluding levels above 4.0 m OD.

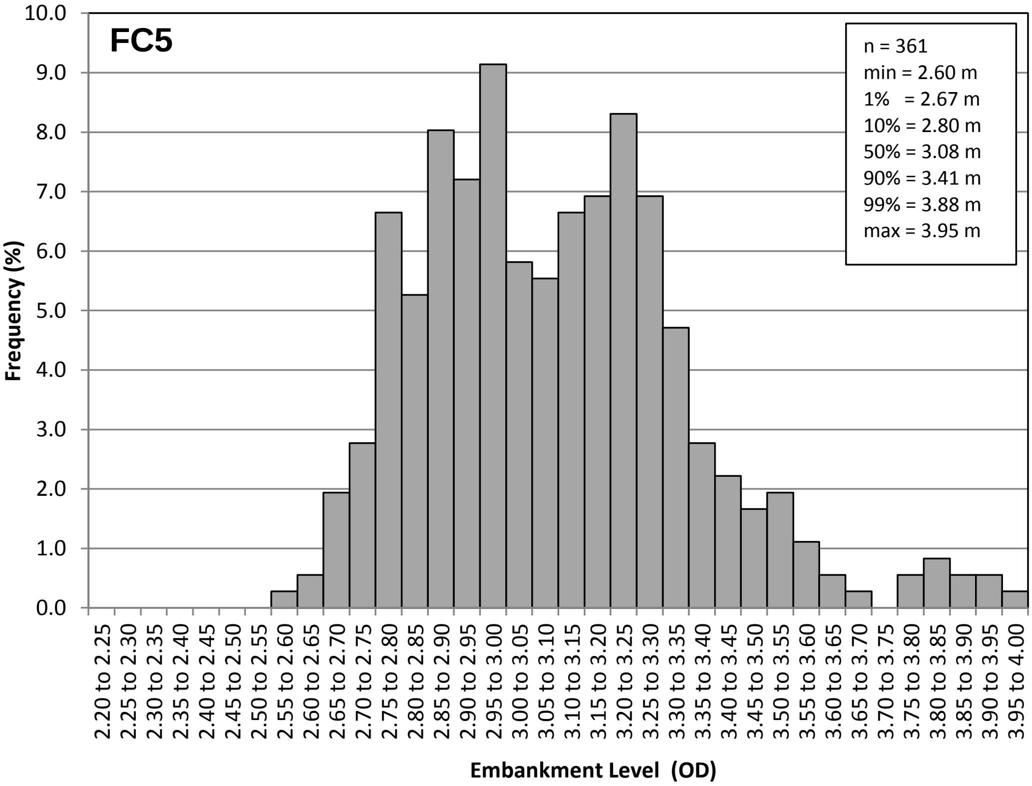


Figure A1.5. Frequency histogram of observations of embankment heights within Flood Compartment 5, excluding levels above 4.0 m OD.

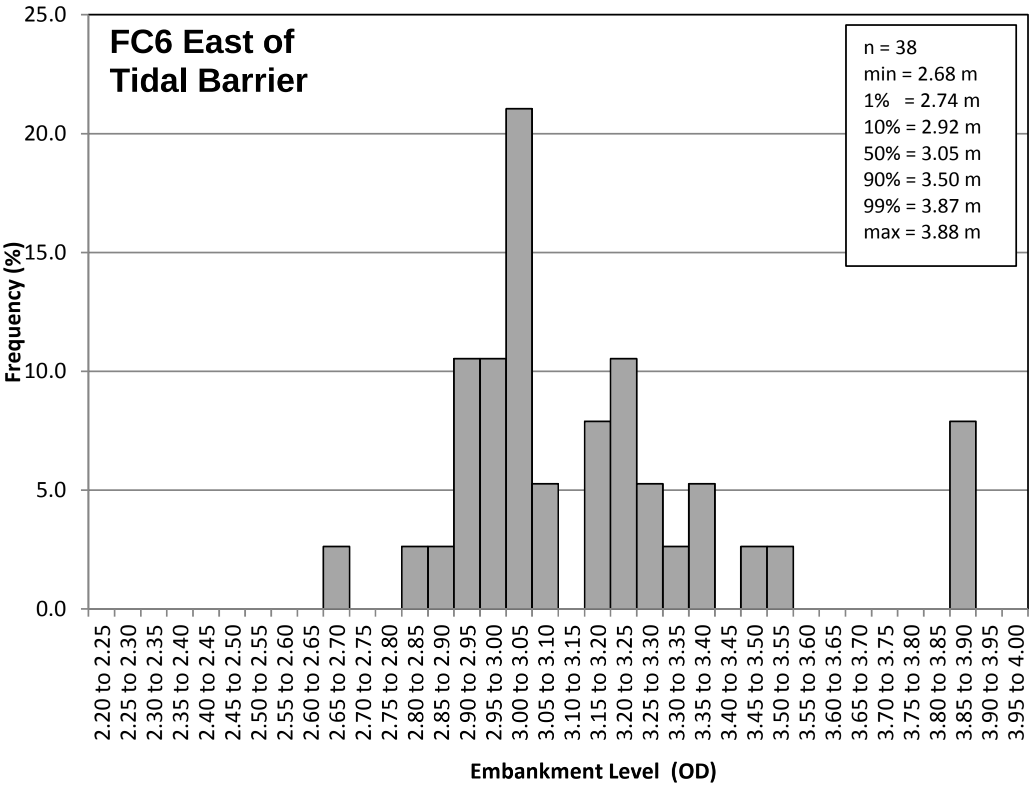


Figure A1.6. Frequency histogram of observations of embankment heights within Flood Compartment 6 east of the tidal barrier, excluding levels above 4.0 m OD.

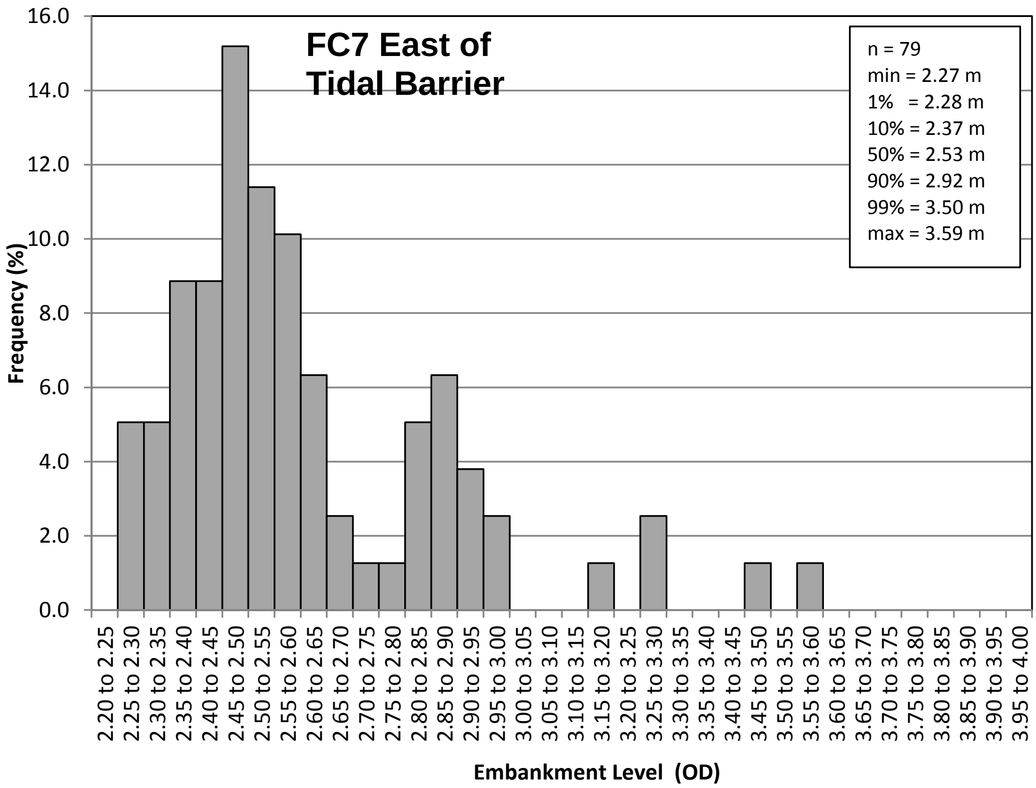


Figure A1.7. Frequency histogram of observations of embankment heights within Flood Compartment 7 east of the tidal barrier, excluding levels above 4.0 m OD.

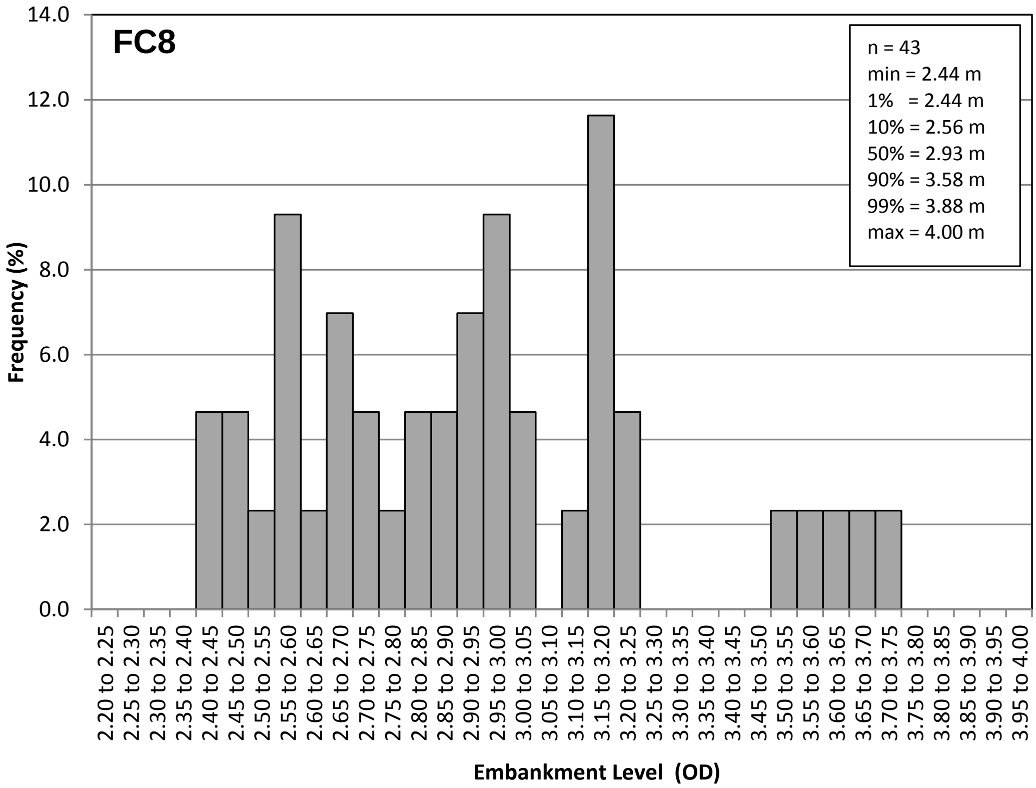


Figure A1.8. Frequency histogram of observations of embankment heights within Flood Compartment 8 east of the tidal barrier, excluding levels above 4.0 m OD.

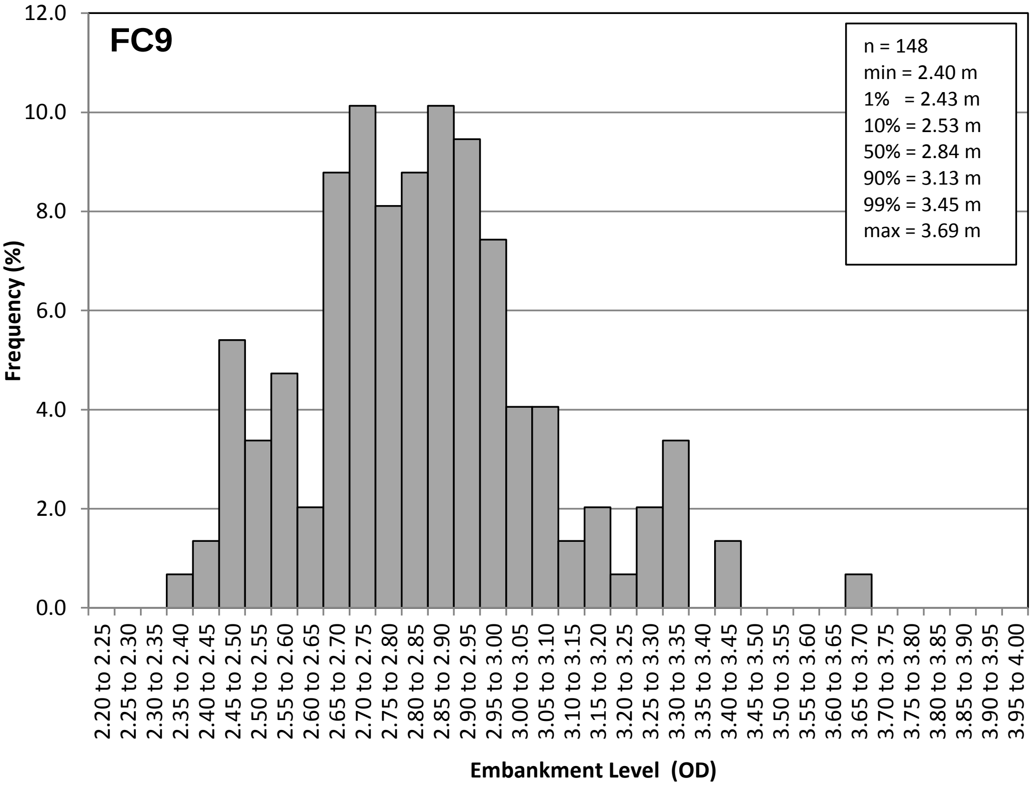


Figure A1.9. Frequency histogram of observations of embankment heights within Flood Compartment 9, excluding levels above 4.0 m OD.

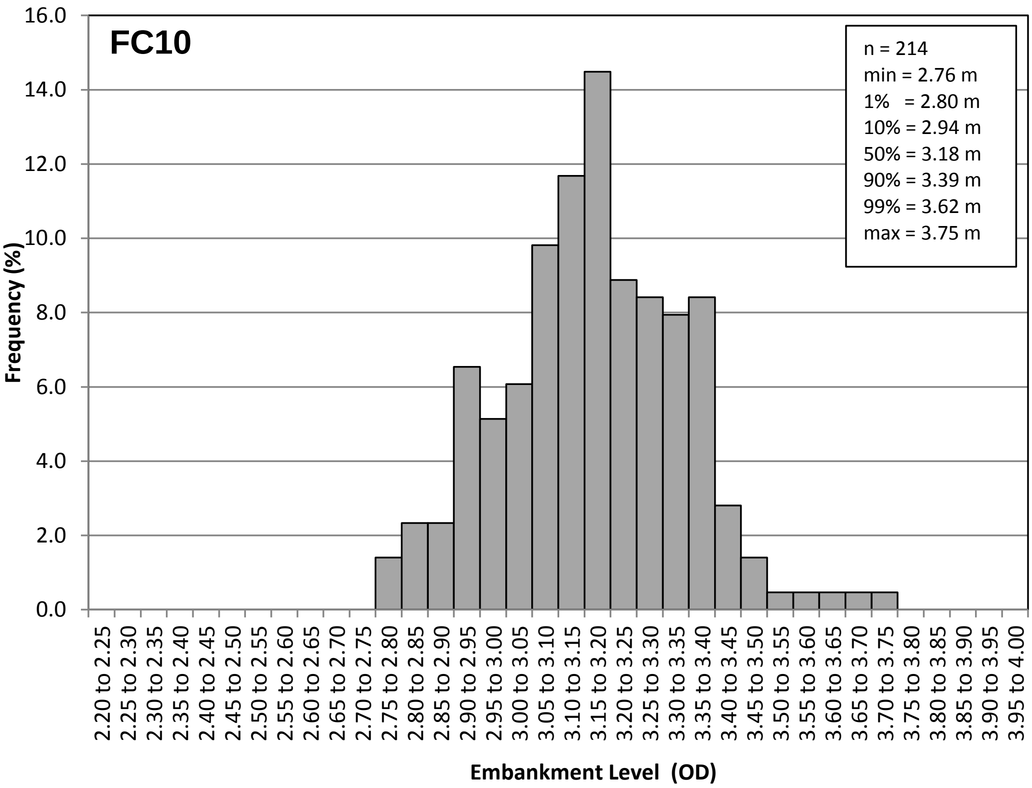


Figure A1.10. Frequency histogram of observations of embankment heights within Flood Compartment 10, excluding levels above 4.0 m OD.

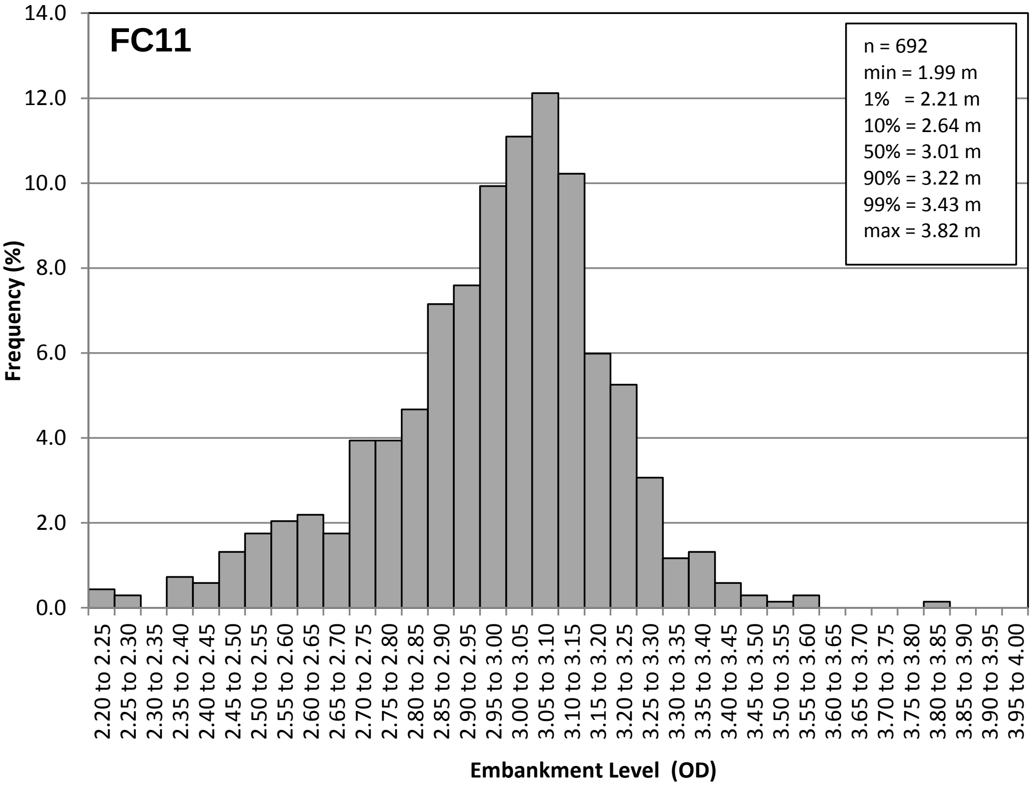


Figure A1.11. Frequency histogram of observations of embankment heights within Flood Compartment 11, excluding levels above 4.0 m OD, and gravel extraction areas beside Stony Ditch

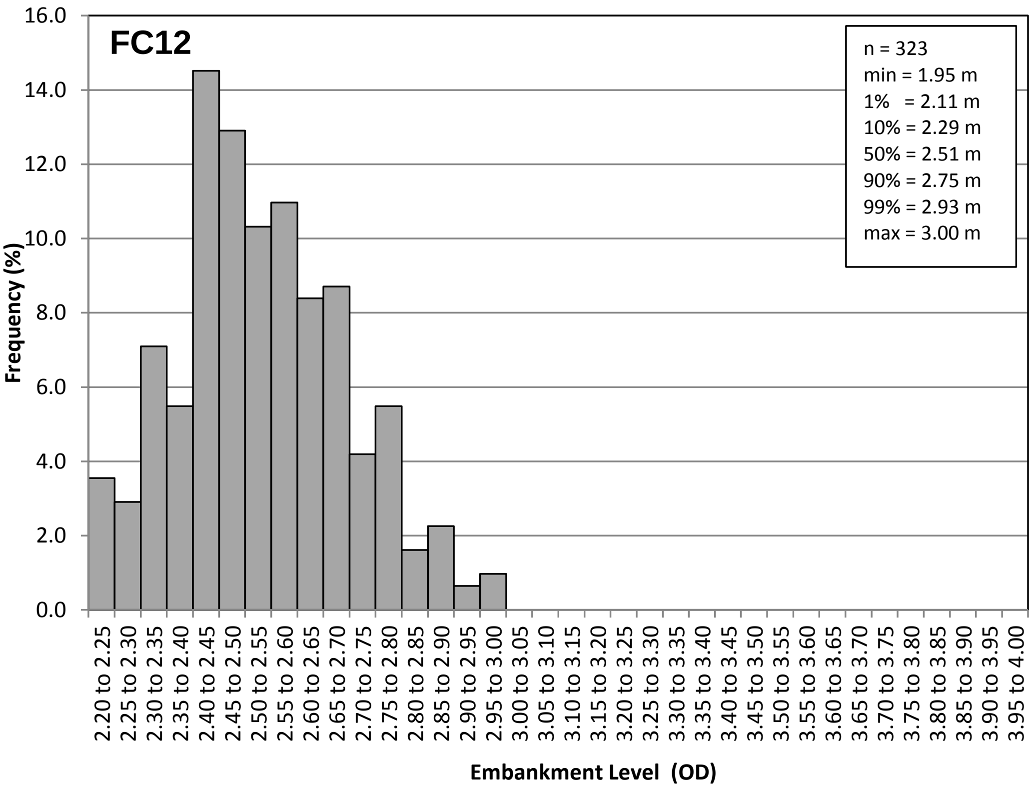


Figure A1.12. Frequency histogram of observations of embankment heights within Flood Compartment 12, including internal flood defence walls.

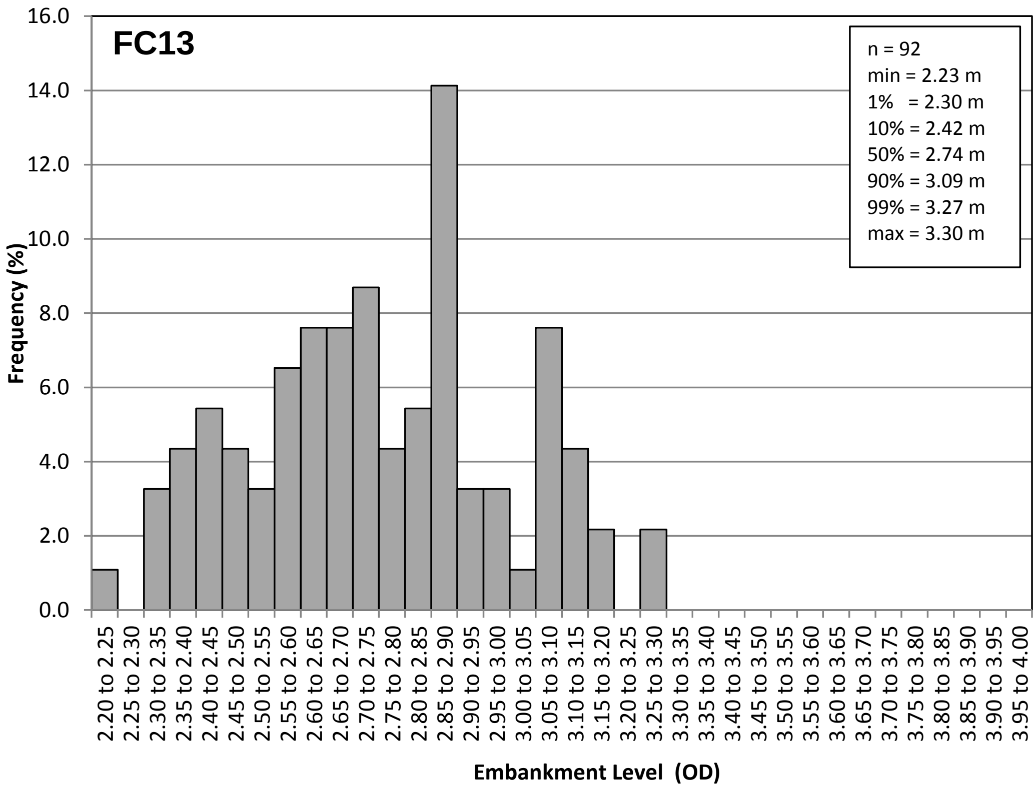


Figure A1.13. Frequency histogram of observations of embankment heights within Flood Compartment 13.