EstProc

Wave modelling in estuaries with regard to changes in wave activity occurring over the tide

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Summary

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This report describes research into the performance of a number of existing wind wave models for application in UK estuaries. Estuaries in the UK are commonly characterised by wave generation areas that vary significantly with the tide, relatively strong currents due to river flows and the tides, as well as being exposed to waves that penetrate from offshore.

This report describes the performance of two spectral wave models (SWAN and TOMAWAC) that are presently considered to be the state-of-the-art in coastal area wave models. A more simplistic single point model is also considered that is computationally more efficient, but typically requires more effort in configuring. Results from all three models are compared against measured data. However, the measured data is only partly publicly available and one of the recommendations is for public freely data repositories such as the Defra funded CEFAS/Wavenet resource to be expanded to include wave measurement sites within UK estuaries.

Comparison with the measured data indicates that the computational models generally provide reasonably good performance and a number of conclusions have been derived from these results. However, there remain some unexplained inconsistencies and a series of simplifications and assumptions have been identified in the models which may contribute towards these. Further work is recommended to assess the implications of these aspects on the model results. Ideally, further tests should include more extensive measured datasets covering the range of UK estuaries and a range of wave/tide/flow events.

An algorithm is provided within this report. This algorithm outlines the methodology of the simplistic, single point model. The purpose of this algorithm is to assist in the application of simple single point wave models for estuarial applications.

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1. Introduction

1.1 BACKGROUND

Waves in estuaries can comprise of locally generated waves and more distantly generated waves that propagate into the estuary from offshore. Both sets of waves are subject to a wide range of physical processes that makes their prediction difficult. Waves generated within the estuary will depend on the growth area, which may change shape during the tidal cycle, and the wind. These locally generated waves, and those that are generated more distantly that propagate into the estuary, will be subject to the processes of shoaling, refraction, reflection, diffraction, blocking, white-capping and depth induced wave breaking. All these processes will depend on the currents and water levels associated with the tides.

There are, presently, a large number of computational wave models that represent some of these processes, but none that represent all. Recent advances over the last 10 years has led to the development of a group of phase averaged spectral wave models that can be regarded as the present state of the art in coastal area wave models. These models are based on the research and development of models devised for wave modelling on a global scale, but with considerable research and development, that is ongoing, to incorporate representations of the shallow water processes characteristic of the coastal environment.

The work described in this report considers two such shallow water spectral wave models (SWAN (Booij et al., 1996) and TOMAWAC (Benoit et al., 1996)) in their application to the Outer Thames Estuary (see Figure 1). The results of these models are compared with limited available measured data at two sites within the Outer Thames. Model results from a more simplistic computational wave generation model (HINDWAVE-TELURAY) are also compared. However, the focus of the work carried out was using the third generation model SWAN. This model is one of the most widely applied spectral wave models at present in coastal engineering studies and is freely available for both research and consultancy studies.

The main purpose of this work, carried out within Defra Project FD1905 (EstProc) is to examine the performance of these models for a UK Estuary with the aims of:

- improving the modelling of waves in Estuaries with particular reference to changes in wave activity over the tide
- validating SWAN for British Estuaries.

In order to achieve these aims requires measured data for verification. Unfortunately, this data is not widely available, particularly for estuaries. This makes the second aim unattainable at present, but it is hoped that the work carried out, as part of this study, is a step in the right direction in validating SWAN for British estuaries.

Measuring waves accurately in open seas is relatively straightforward and well established. There are a number of suitable devices, with directional wave riders regarded as one of the most reliable. In the estuarial environment the tidal range can lead to problems of wetting and drying that limits the number of suitable devices. These devices tend to be less well established.

Despite the relative ease of measuring waves in the open sea, there is surprisingly little available measured wave data around the UK coast (Harford, 1998). The Met Office owns a series of buoys deployed around the UK coast that are used to calibrate their global and mesoscale wave models. However, these buoys are located in open seas. A recent government funded initiative has led to the deployment of a series of buoys managed by CEFAS. The data from these buoys and a number of additional buoys including a selection of those owned by the Met Office is available freely via a web site (www.cefas.co.uk/wavenet). The location of the CEFAS buoys tends to be in relatively open water and only one device was deployed in a genuinely estuarial location. This location is the Outer Thames Estuary (as shown in Figure 2).

Prior to this study HR Wallingford had acquired a limited period of measured wave data in the Stour and Orwell Estuaries. However, this data was understood to be unreliable for the shorter period, locally generated waves, due to the combined effect of pressure attenuation over the water column and inadequate sampling rates. This site would have been an ideal test site since waves in this estuarial system comprise of both locally generated and more distantly generated longer period waves that propagate from offshore. HR Wallingford was also provided with a limited period of wave measurements for a site along the North Coast of Kent, in the area known as Kentish Flats as part of a consultancy project.

Wave generation and propagation in the Outer Thames Estuary is complex. The seabed, as illustrated in Figure 1, is characterised by a series of sandbanks and channels, some natural, others modified by dredging. Within these channels the tides result in strong currents and at low water the sandbanks provide a significant sheltering effect to waves propagating from offshore. The area is also characterised by a number of large coastal flats that become exposed at low water, thus changing the potential generation area significantly. These features make the Outer Thames Estuary an appropriate test site for the computational wave models considered in this study.

Another important factor influencing our choice of the Outer Thames Estuary is the availability of accurate boundary conditions. Modelling of any estuary requires information on the bathymetry, the tidal currents and water levels, the wind and offshore wave conditions. HR Wallingford has recently carried out a number of independent consultancy studies in both the Inner and Outer Thames Estuary. Data generated as part of these studies, e.g. the tidal currents and the bathymetry, has been re-used to make the process more efficient.

Computational model runs were carried out for a selection of five periods when wave conditions were relatively severe when there were records of waves. As well as being relatively severe these periods were also selected to cover a wide range of possible forcing conditions. In order to examine the performance of the models, when possible, a series of tests were carried out to examine the sensitivity of the model results to a number of controllable parameters and methods for applying the models. For example, it was of interest to know if the results for SWAN run as a non-stationary model could be reproduced as a set of stationary model runs. Results have been presented with the measured data as time histories. The time histories give an immediate visual comparison of the wave model results and errors. Error estimates have also been tabulated to allow more quantitative comparison.

From the series of model tests presented, a number of conclusions regarding the performance of the model has been made.

1.2 LAYOUT OF REPORT

Chapter 2 gives an outline of the computational models considered in this study. A description of the available measured data for the Outer Thames Estuary is given in Chapter 3. This is followed, in Chapter 4, by a description of the boundary conditions and forcing used in the model tests. The application of the models is described in Chapter 5, with a discussion of the sensitivity tests described in Chapter 6. In Chapter 7 the model results are presented and compared with the measured wave conditions. Conclusions and recommendations from this work are given in Chapter 9.

Also provided is an algorithm that summarises the methodology for application of models such as HINDWAVE-TELURAY in estuaries. This algorithm is given in Appendix A. A summary of the assumptions and simplifications used in the modelling work is given in Appendix B.

2. Computational wave models for modelling in Estuaries

Spectral wave models such as SWAN and TOMAWAC have been developed to represent the physical processes that affect wave generation and transformation in shallow water, theoretically then including estuaries. How well these models perform in these circumstances is the subject of this study.

The focus of this study considers the performance of the SWAN model by its application to the Outer Thames Estuary and comparison with measured wave data. The performance of TOMAWAC and the more simplistic computational wave generation model HINDWAVE-TELURAY (Hawkes (1987) and Abernethy and Gilbert (1976)) is also considered by application of these models to the Outer Thames Estuary.

SWAN and TOMAWAC are applied without modification and are applied in the format as supplied. HINDWAVE-TELURAY has been adapted for the particular application to sites such as the Outer Thames, to account for the changing generation areas and sheltering effect of the sandbanks.

In the following sections general descriptions of the models are provided. Details on how HINDWAVE-TELURAY has been adapted for the Outer Thames is also provided.

2.1 SIMPLE WAVE GENERATION MODELS (HINDWAVE-TELURAY)

Simple (first generation) wave generation models such as the coupled HINDWAVE-TELURAY model have been developed to represent the generation and transformation of waves by the wind over restricted fetches. Typically these fetches are measured from the point or points of interest in a radial direction to the extents of the generation area. Wave breaking is often neglected in such models rendering them inaccurate for sites sheltered by areas of shallow water.

HINDWAVE-TELURAY combines the processes of wave generation and wave shoaling and refraction. HINDWAVE represents the process of wave generation and TELURAY represents the processes of wave shoaling and refraction. TELURAY can be used with HINDWAVE to represent the generation and associated shoaling and refraction of these waves, or it can used on its own to represent purely the shoaling and refraction of waves from deep to shallow water.

Other models in the class are given include Wilson's method (Wilson (1965) and in Goda(2003)), other models described in Hasselmann et al. (1973), Donelan (1980), Young et al. (1996) and the SMB method described in the Shore Protection Manual (1984).

2.1.1 Description of HINDWAVE

The locally generated waves were predicted from wind data using the HINDWAVE wave prediction model. HINDWAVE uses the JONSWAP wave generation formulation which hindcasts wave conditions at a given location from wind conditions and fetch lengths measured at constant angular increments from the wave prediction point. HINDWAVE produces a set of site specific wave forecasting tables, giving wave height, period and direction for a wide range of wind speeds, directions and durations.

HINDWAVE then uses these tables with the wind data to produce a time-series of wave at the wave prediction point.

The spectral density S(f), expressing the energy as a function of wave frequency, f, has the following form for a JONSWAP spectrum (Hasselmann et al., 1973). In this case γ=3.3 for all direction sectors.

$$S(f) = \alpha H_s^2 T_p^{-4} f^{-5} \exp\left[-1.25\left(T_p f\right)^{-4}\right]\gamma^a$$

where $a = \exp\left[-\left(T_p f - 1\right)^2 / 2\sigma^2\right]$

$$\alpha = \frac{0.0624}{0.230 + 0.0336\gamma - 0.185(1.9 + \gamma)^{-1}}$$

$$\sigma = \begin{cases} 0.07 \text{ for } f \le 1/T_p \\ 0.09 \text{ for } f > 1/T_p \end{cases}$$

Hs is the significant wave height in metres,
Tp is the peak wave period (seconds) and
γ is the peak enhancement factor, a dimensionless constant. In this case γ=3.3.

2.1.2 Description of TELURAY

TELURAY predicts wave activity at nearshore sites by representing the effects of refraction (due to both the bathymetry and by currents) and shoaling on all components of a given offshore spectrum. The model uses an efficient back tracking ray method (Abernethy and Gilbert, 1976). This method involves the tracking of wave rays from a nearshore point to the offshore boundary of a grid system covering the area being modelled. Since the ray paths are reversible, each ray gives information on how energy travels between the seawards edge of the mesh system and the nearshore points of interest. The results from TELURAY can then be used to transform offshore wave conditions to nearshore locations of interest. Being a back-tracking model means that TELURAY can model the transformation of a large number of offshore wave conditions to a selected inshore point within a single model run. TELURAY computes the refraction and shoaling of waves over an unstructured grid of triangles. The model requires the digital representation of the seabed and any currents to be provided on the same unstructured triangular mesh.

2.1.3 Description of combining HINDWAVE-TELURAY

HINDWAVE and TELURAY can be combined to represent the processes of wave generation and transformation. These models were originally devised to represent these processes independently. However, if shoaling and refraction effects are important then TELURAY can be used to modify the transformation of wave generated using HINDWAVE. TELURAY can also be used to represent the transformation of waves from offshore (derived from another source) to an inshore point. These waves can then be combined, on an energy basis, with the locally generated waves to provide a prediction of the total wave energy at a point.

2.1.4 Representation of changes in wave activity over the tide

To represent the change in wave growth over the tide fetches can be measured for a set of appropriate water levels to account for the change in shape of the generation area. Where shallow banks provide shelter to the point of interest, fetches can be limited so that the broken wave height at the bank cannot be exceeded, but continued generation occurs beyond the bank.

Where a point of interest lies in a shallow water area and the waves are affected by wave breaking locally, wave breaking formulations based on empirically derived equations, can be used to account for this process. If wave energy is dissipated by wave breaking occurring at a greater distance away the application of such a method will be inappropriate. The effect on waves, for example, of largely impenetrable defences such as shallow banks, can be achieved by representing these areas as islands in the model mesh. Only waves from offshore that propagate between these islands will contribute to the overall wave energy inshore of these banks. The extent of these shallow water "islands" may be different for different states of the tide, therefore different model meshes may be required.

2.2 SPECTRAL WAVE MODELS

Second and third generation spectral wave models such as the third generation model SWAN have been developed to represent the propagation and generation of waves in shallow water where the fetches may be restricted. Third generation models can largely be distinguished from second generation models by the integration of the spectral energy density equation which is computed without any priori restrictions on the spectrum (Ris, 1997). Second generation models make an assumption of the frequency distribution of energy e.g. a JONSWAP spectrum. This makes third generation models more accurate in representing bi-modal sea states comprising of locally generated short period waves as well as more distantly generated, longer period swell sea.

2.2.1 Descriptions of third generation models SWAN and TOMAWAC

SWAN (Booij, et al., 1996, Booij et al., 1999 and Ris et al., 1999) and TOMAWAC (Benoit et al., 1996) are both time-stepping (i.e. unsteady or non-stationary) phase-averaged spectral wave transformation models.

SWAN was developed by the Technical University of Delft in the Netherlands and is presently available freely to the public. TOMAWAC was developed by EDF-Laboratoire National d'Hydraulique and is part of the TELEMAC finite element modelling suite of hydrodynamic and short wave models.

These models represent the processes of spatial propagation of waves over relatively large distances, refraction due to spatial variations in seabed and current, shoaling due to spatial variations in seabed and current. The models also represent the processes of generation by unsteady wind fields, dissipation by whitecapping, dissipation by depth-induced wave breaking, dissipation by seabed friction and non-linear wave-wave interactions (quadruplets and triads).

The main differences between these models are that SWAN solves the wave action balance equation over a finite difference grid system whereas TOMAWAC solves it over an unstructured triangular finite element mesh. The latter allows flexibility in the mesh sizes providing a balance between accuracy and computational efficiency. Similarly, TOMAWAC uses a piece-wise ray method for wave propagation which allows rather large time steps, which in turn keeps the computational time at a moderate level. SWAN uses an efficient finite difference scheme for wave propagation and includes the processes of wave reflection from exposed structures and wave blocking due to currents.

Both models exclude the process of wave diffraction, although there is ongoing research and development to incorporate this process at least approximately.

2.2.2 Representation of changes in wave activity over the tide

Spectral wave models such as SWAN and TOMAWAC handle the variation in wave activity over the tide without modification. SWAN determines which points are wet or dry and computes the corresponding wave conditions. TOMAWAC requires a minimum depth to be specified, i.e. all nodes must be wet.

3. Available measured data sets for verification

There is little available measured wave data in UK Estuaries. Two sources of suitable and independently measured wave data within the Outer Thames estuary were available for this study, although unfortunately the periods of measurements do not overlap. The measured data comprises of non-directional wave measurements at a location on Kentish Flats and directional wave measurements at a location in The Warp (See Figure 2 for their locations). The measurements on Kentish Flats were carried out using a bed mounted pressure sensor and those in The Warp were carried out using a directional wave rider.

It has already been noted that the availability of measured data is limited, and the reliability of the data must also be considered. For example, the pressure sensor data is recognised as not always being accurate particularly for lower, shorter period, waves where wave attenuation over the water column limits the range of accuracy of this type of device despite corrections for attenuation usually being made.

This shortcoming may account for why some of the SWAN and TOMAWAC model results compared poorly against the measured data. Nevertheless this data was useful in demonstrating the HINDWAVE/TELURAY methodology and calibration process, and to some extent the accuracy of the SWAN and TOMAWAC model runs.

3.1 GREP PRESSURE SENSOR WAVE DATA (LOCATION: KENTISH FLATS)

This data was measured using a pressure sensing wave recorder deployed by GREP UK Marine Limited as part of preliminary studies for a proposed wind farm. The device was located on Kentish Flats in approximately 7m of water at MWL (see Figure 2). The available wave data record covers the period October 2002 to January 2003.

The location of the Kentish Flats pressure sensor (KF1) is:

51°28’34.6”N 1°6’39.3”E or 616005 179902 British Grid

3.2 CEFAS WAVERIDER (LOCATION: THE WARP)

Wave data records from the CEFAS WARPBUOY waverider covers the period 19/3/02 to 13/7/02. This waverider was located in a relatively deep channel to the east of The Warp in approximately 18m of water (see Figure 2). This wave data is available to the public via CEFAS on the following website: http:// www.cefas.co.uk/wavenet. Figures 3a, 3b and 3c, respectively, show the time series of significant wave height, mean and peak wave periods and wave direction from this buoy for the full period of measurements available.

The corresponding wave spectra were not obtained for this project, but are available from CEFAS. Similarly, although not used within this project, but worth noting, is that a CEFAS smartbuoy is located at The Warp and a multi year record from that site is now available in terms of temperature, salinity, nutrients, suspended sediment concentration and chlorophyll (all at surface). CEFAS have also deployed a MiniLander (seabed frame) for short periods with temperature, salinity, chlorophyll and suspended sediment sensors. A Nortek AWAC "ADCP" current meter was also deployed on the MiniLander.

The location of The Warp wave rider (TH1) is:

51°31.51’N 1°1.82’E or 610186 185101 British Grid.

4. Computational model boundary conditions

4.1 INTRODUCTION

The Outer Thames Estuary is characterised by a series of intertidal sandbanks and channels. Figure 1 shows an image of the UK Admiralty Chart for the area of interest.

Although moderate compared with some other estuaries in the UK, the tidal range is quite large. The tidal range at Shivering Sand is 4.7m. The sandbanks of the Outer Thames can become very shallow and may dry at the lowest states of the tide. This results in large changes to the generation area and causes depth induced breaking of waves propagating from the North Sea, thus providing shelter to those waves. The pattern of the seabed topography in the Outer Thames also leads to complex tidal current patterns which may have an important effect on the wave conditions, through the processes of wave-current refraction, shoaling and blocking. These complex hydrodynamic processes make the Outer Thames Estuary a challenging area for wave modelling techniques.

As well as having verification data for the Outer Thames, another important reason for selecting this estuary was the availability of the necessary boundary conditions for the model, namely wind data, offshore wave data, bathymetry data, water level data, tidal current data. This section describes the sources of data available for the Outer Thames Estuary tests. A summary of notable assumptions and simplifications in the application of these boundary conditions is given in Appendix B.

4.2 OFFSHORE WAVE

4.2.1 Met office European wave model

Rather than try to represent the generation and propagation of waves over the entire North Sea the application of the wave models in this study only included the Outer Thames Estuary. Thus waves, generated in the North Sea, were required as input to the models at the offshore boundaries. For this study integrated wave parameters were extracted from the archive of UK Meteorological Office (Met Office) European Wave Model data held by HR Wallingford for a single representative wave prediction point located at 51.5N 1.53E close to the offshore boundary of the models (see Figure 2). This archive covers the period October 1986 to March 2002 inclusive.

4.3 WIND

Wind data is required as input to the models. Since the area of interest is relatively small, winds over the models were assumed to be uniform. Two sources of wind data were available including in-situ measurements for the period of wave measurements at Kentish Flats and computational atmospheric model wind data for the period of measurements at The Warp.

4.3.1 In situ Met Station

For the period of wave measurements on Kentish Flats, in situ measurements of wind conditions were available. Ten minute-averaged mean wind speeds were available. This wind data was used for runs carried out when comparison with the Kentish Flats wave heights.

4.3.2 Met Office European wave model wind data

Wind data was also extracted from the Met Office European Model for a model point east of North Foreland at 51.5N 1.53E. The wind record covers the period of the two sets of wave measurements and is provided with 3 hourly intervals. Although it is model data it has been calibrated extensively against a wide range of measurements.

The Met Office model point is out of the estuary and has a slightly different aspect to the locations of the wave recorders. To verify that these winds were appropriate, the in-situ measurements of winds were also used to check the validity of the Met Office data for the area under consideration. Met Office wind data from October 2002 was compared to wind measurements from a meteorological mast located on Kentish Flats, close to the location of the pressure sensor. Figure 4 shows that the time series of wind data are in close agreement. Therefore, the Met Office wind data can be assumed to be representative of winds experienced over the Outer Thames Estuary. Met Office model winds were used in the test periods for comparison with the CEFAS waverider.

4.4 TIDAL CURRENTS

Part of this study was to investigate the importance of tidal currents on wave transformation in the Outer Thames. Therefore, accurate predictions over the complete area of interest were required. To provide this information a computational flow model was used to generate tidal current predictions. To verify these predictions three sources of data were used:

- Admiralty tidal diamonds
- Vessel mounted acoustic Doppler current profiler (VMADCP)
- Autonomous ADCP.

The locations of the various sources of current data for model calibration are shown in Figure 5a. Those locations marked by a letter represent Admiralty tidal diamonds from UK Admiralty Chart 1607. The numbered locations represent VMADCP (vessel mounted acoustic Doppler current profiler) survey points, where currents were measured during a spring tide in January 2003. The Fisherman's Gat, Mouse Channel and West Oaze points are taken from autonomous ADCPs.

A description of the computational flow model, its application to the Outer Thames Estuary and comparison with the available tidal and flow data is given in the following section.

4.4.1 Computational Flow modelling in the Outer Thames Estuary

An existing HR Wallingford TELEMAC-2d model of the Thames estuary, Southern North Sea and English Channel was used to provide predictions of current velocities for the study area. The model included a recent survey of bathymetry in parts of the estuary. The model was calibrated against Admiralty tidal diamonds and other measured data.

The model mesh and bathymetry over the whole domain is shown in Figures 5b and 5c. The locations of various sources of data for model calibration, described in Section 4.4 above, are shown in Figure 5a.

Figures 5d and 5e present the calibration plots for spring tides against the tidal diamonds and other data sources. The model set up achieved an appropriate representation of the tidal flows under the existing conditions.

Figures 5f and 5g present the peak flood and ebb flow vectors under a mean spring tide condition, respectively. Note, these vectors are plotted at a significantly coarser spacing than the model resolution.

4.5 WATER LEVELS

For the period of wave measurements on Kentish Flats, in situ measurements of water levels were made. These water levels were used directly for the wave predictions.

For the period of the CEFAS waverider wave measurements, water levels were not reported. Therefore, water levels based on standard tides were used in the wave prediction runs.

The TELURAY, TOMAWAC and SWAN wave models and the TELEMAC-2d flow model were set up with bathymetry referenced to Ordnance Datum (OD). The conversion between OD and Chart Datum (CD) varies over the area of the model. The nearest port listed in Admiralty tide tables to Kentish Flats is Herne Bay. At Herne Bay OD = +2.72 CD. Lowest Astronomical Tide (LAT) varies across the area, relative to both OD and CD. Admiralty tide tables do not state LAT at Herne Bay, however interpolation between the standard ports of Margate and Sheerness give LAT as 0m CD.

4.6 BATHYMETRY

There were a number of different sources of bathymetry data available for this study with the appropriate UK Admiralty Charts providing the depths over the majority of the study area. The UK Admiralty Chart data was supplemented with a variety of bathymetry surveys provided by the Port of London Authority as part of a series of unrelated studies. In addition, recent survey data covering Kentish Flats, were also made available from another unrelated study. These different sources of bathymetric information were incorporated into the various wave and flow models considered in this study to provide the most accurate and up to date models in the area of interest as possible.

5. *Application of models to the Outer Thames Estuary*

5.1 HINDWAVE-TELURAY

Wave conditions in the Outer Thames comprise of two main components: those generated offshore in the Southern North Sea that propagate into the Outer Thames and those that are generated more locally within the estuary. The locally generated waves were modelled by the HINDWAVE model which predicts wave conditions from given (measured) wind data and fetch information. TELURAY was used to transform waves generated in the North Sea to give wave conditions at the specified location, taking account of refraction and shoaling on all components of the offshore wave spectra. The two components were then combined to give the total wave conditions at the location of the measurement device. The methodology applied, as described below, follows the algorithm presented in Appendix A.

5.1.1 Representation of bathymetry and spatial discretisation.

Model depths in the TELURAY model were derived from bathymetry data digitised from Admiralty charts and a recent survey of depths in the area of interest. The resolution of the model bathymetry varies over the area of the model. In an area, approximately 10km square, around the area of interest the resolution is 50m. This increases to 1000m at the offshore boundary. The mesh and bathymetry of the TELURAY model is shown in Figures 6a and 6b.

5.1.2 Representation of the wave growth area

Fetch lengths were measured from the location of the measurement device. Since there are large drying banks in the area of interest the fetch lengths are very different for different states of the tide. Therefore fetch lengths were measured for five water levels corresponding to approximately MHWS, MHWN, MWL, MLWN and MLWS. Fetches were also limited to ensure the broken wave height would not be exceeded over the sandbanks.

5.1.3 Transformation of waves from offshore

To account for the sheltering effect of the large sandbanks in TELURAY these areas were incorporated as impenetrable islands in the model mesh. Only waves from offshore that propagate between these islands will contribute to the overall wave energy inshore of the banks, i.e. waves that would have been depth limited by these banks are neglected.

The offshore boundary of TELURAY was the North Sea boundary, stretching east from Clacton-on-sea for approximately 40km then due south, for approximately 48km, and west to North Foreland. The wave conditions from the Met Office model point are applied at the offshore boundary.

Tidal currents were provided by the TELEMAC flow model. TELEMAC was only run to model a spring tide cycle and a neap tide cycle. TELURAY was then run with the water level and flow fields output from TELEMAC at 8 times from the spring cycle and 4 times from the neap cycle. During the spring cycle, TELURAY was run with tidal levels at MHWS, MLWS, MWL and two intermediate levels above and below MWL. For each of the intermediate states and at MWL, TELURAY was run with flood and ebb tidal currents. To represent the neap cycle, TELURAY was run at MHWN, MLWN and MWL flood and ebb. A single time series of wave conditions was assembled for each of these 12 tide conditions for the appropriate tidal state.

5.1.4 Verification of HINDWAVE-TELURAY

Offshore waves

TELURAY does not account directly for any dissipative processes, such as white-capping, depth induced breaking, bottom friction and wave-wave interaction. However, for this area, offshore waves are expected to attenuate significantly when crossing the numerous broad shallow banks offshore towards the prediction point.

To account for energy dissipation, TELURAY was run with a mesh modified to block a proportion of the energy crossing the banks. This mesh was generated so that offshore waves were able to penetrate through the channels between the banks and reach the wave prediction point, but not penetrate through shallower areas.

Locally generated waves

Model results for the full period of measurements show that the model performs well when predicting large wave events. However, during calmer conditions, the wave recorder reports smaller, shorter period waves. In these conditions, the wave periods are short (typically T_p<2.5s) and the pressure sensor is not as accurate due to depth attenuation of pressure and possibly the sampling rate. Therefore, during these periods the model appeared to over predict the wave heights, but may actually be a good representation of wave conditions. For this study, we have focussed on relatively large wave events, so we can expect the pressure sensor data to provide more reliable measurements of wave conditions.

5.2 APPLICATION OF SWAN TO THE OUTER THAMES ESTUARY

A SWAN model was set up to cover the Outer Thames Estuary (see Figure 7). The model extends offshore beyond Margate, in Kent, and Clacton-on-Sea, in Essex, and up the Thames slightly beyond East Tilbury. It consists of a single rectangular grid aligned with North. Figure 7 shows the extent of the model area. Figure 2 shows the Met Office model point used and the location of the two analysis points KF1 (see section 3.1) and TW1 (see section 3.2) at the Kentish Flats measurement location and at The Warp measurement location, respectively. A grid spacing of 400m was used and the number of grid cells is 143 by 120 and the origin of the model is at (602400, 166900) British Grid.

Depths in the SWAN model were based on UK Admiralty Charts, supplemented with recent survey data in the area of interest provided by a number of sources as described in Section 4.6. Figure 7 shows the model depths below OD(m), where OD is approximately 2.72m above CD.

Typically, waves approaching the coast will have components of wave energy with a range of frequencies and directions. In order to represent this as realistically as possible, wave energy spectra were fitted to each of the extreme offshore wave conditions. In the absence of further information the offshore wave conditions were modelled using a JONSWAP spectrum and a symmetric spreading function of $\cos^2$. These distributions are representative of wind generated waves in the North Sea. The number of spectral components used in SWAN were 36 directions by 25 frequencies.

For the non-stationary applications of SWAN the standard (Stelling and Leendertse) propagation scheme had to be changed to the BSBT (backward-space, backward-time) optional scheme to achieve stability.

5.3 APPLICATION OF TOMAWAC TO THE OUTER THAMES ESTUARY

TOMAWAC models (see Figure 8a and 8b) were set up to cover approximately the same area of the Outer Thames Estuary as the SWAN model. TOMAWAC runs on an unstructured triangular finite element mesh. Two different meshes were set up. The first mesh has a similar resolution to the SWAN model, described above, i.e. 400m and the course mesh has as resolution of approximately 1500m. Since TOMAWAC uses an unstructured triangular finite element mesh the boundaries of the model area closely follow the land-sea boundaries; this reduces the number of surplus computational model points.

Depths in the model were based on exactly the same input data as the SWAN model grid (described above). Figures 8a and 8b also show the representation of the seabed in the TOMAWAC models.

As in the SWAN model runs, a JONSWAP frequency and $\cos^2$ directional distribution were fitted to the offshore boundary wave conditions. The number of spectral components used in TOMAWAC was 24 directions by 20 frequencies.

6. Test programme and summary of sensitivity tests

6.1 SELECTION OF TEST PERIODS

Five test periods were selected on the basis that they represent relatively stormy periods when measured wave data was available. The test periods were also selected so that different wind and wave conditions in the Outer Thames were represented. The test periods include winds from a range of directional sectors, thus including a variety of typical conditions.

Two test periods were selected when waves were measured at Kentish Flats and three when measurements at The Warp were available. The test periods cover between 1 to 3 days during which time the peak of the storms occurred.

Table Summary of test periods

Date Label	Date/Time	Dominant wind direction(s)	Hs_{max} (m)	Measurements Location	Measurement Device
26/03/02	26/03/2002 00:00 to 28/03/2002 00:00	N-NE-E	0.85	The Warp	Directional wave rider
26/04/02	26/04/2002 00:00 to 29/04/2002 00:00	NE-E	1.21	The Warp	Directional wave rider
05/04/02	05/04/2002 00:00 to 08/04/2002 00:00	SW-W	1.66	The Warp	Directional wave rider
06/11/02	06/11/2002 12:00 to 07/11/2002 12:00	NW	0.65	Kentish Flats	Pressure Sensor
14/11/02	14/11/2002 02:00 to 15/11/2002 02:00	SE-S	1.16	Kentish Flats	Pressure Sensor

where Hs_{max} is the maximum significant wave height recorded during the period.

6.2 SENSITIVITY TESTS OF SWAN

Numerical experimentation using the spectral wave model SWAN was the main focus of research in this study. SWAN is frequently used by HR Wallingford and many other organisations in consultancy studies to provide design and operation wave conditions over an area and wave induced currents and bed orbital velocities for sedimentation studies. Several questions of interest arise from these consultancy studies in the application of SWAN to sites such as the Outer Thames Estuary:

- How critical is the model grid resolution?
- How significant a difference in prediction will be given for non-stationary runs of SWAN versus a series of stationary model runs covering the same period?
- How important is the influence of currents on waves?
- How important are the non-linear triad interactions?

The following sections describe the series of sensitivity tests carried out to try to help answer some of these questions.

6.2.1 Spatial model resolution

Preliminary model runs of SWAN were carried out using a system of nested grids with a series of successively higher resolution grids centred on the area of interest. Grids with spacing from 400m down to 50m were nested. The SWAN model runs over each nested grid were carried out taking boundary conditions from the adjacent courser grid to provide wave conditions at the same locations. Although there were differences in the predicted wave conditions in the area of interest they were small. Therefore, for efficiency reasons nested grids were not used in subsequent tests.

The selection of nested grids in SWAN for sites like the Outer Thames Estuary requires careful consideration if used to represent non-stationary conditions. This is because the order in which grids are run may have to be different depending on the prevailing environmental conditions. This is a clear limitation for estuary cases with complex boundaries where it will be more computationally efficient to use a series of nested grids to define the model area.

6.2.2 Stationary vs. Non stationary

Spectral wave models such as SWAN can be run to predict both stationary and non-stationary conditions. Stationary conditions can be assumed if the time it takes for waves to travel over the model area is short compared with the variation of the prevailing environmental conditions.

For the Outer Thames Estuary, waves from offshore will take between approximately 1 to 2 hours to travel from the offshore boundary to the sites of interest. During this period both the tidal conditions and generation area can vary significantly. Therefore, it is uncertain if conditions can be considered as stationary. Therefore, both stationary and non-stationary model runs were carried out for each test period.

Stationary model runs of SWAN solve the stationary version of the action balance equation with the partial derivative of the action with respect to time ignored. This provides a fetch limited solution. Non stationary model runs of SWAN solve the full time dependent action balance equation. With time-varying boundary conditions this provides duration or fetch limited waves. In practice non-stationary model runs of SWAN require a warm up time. The warm up time can be reduced by starting the model with a stationary model run to provide initial “hotstart” conditions.

6.2.3 With/without current action

Currents can affect wave conditions in a variety of ways. Firstly currents can lead to waves refracting which will result in a change in wave height and direction. Currents can also lead to the blocking of waves, whereby the incoming waves are held back by the strength of the currents. This process often results in wave attenuation due to wave breaking. These effects on the waves will depend on the strength and direction of the current and the height, period and direction of the incident waves.

Tidal currents can be expected to be strong in most estuaries and if so will noticeably influence wave conditions. For many estuaries the currents are also likely to be highly spatially variable. The accurate prediction of waves under the influence of currents requires accurate prediction of temporal and spatial variability of these currents. There are ways to monitor currents over an area (eg HF Radar), but to provide flows over the entire area of interest a practicable and accurate approach is to carry out computational flow modelling.

In this study, tidal current fields from previous studies of the area of interest were re-used to provide approximate current fields for the wave model test periods. Due to the time taken to assemble appropriate flow fields for each time step in the test periods, not all test periods include model runs with currents.

6.2.4 With/without triad interactions

As waves travel in shallow water non-linear interactions between groups of frequencies in threes (triad interactions) become important (Eldeberky, 1996). In particular, these interactions give rise to energy at higher frequencies. Taking into account this nonlinear interaction accurately requires an excessive amount of computational resources therefore, at present spectral wave models such as SWAN include a source term that takes into account this process approximately. Since this term has the effect of increasing energy at higher frequencies it could be construed that this term is the reason why SWAN and similar spectral wave models quite often under-predict the mean wave period. Thus SWAN model runs were carried out with and without the triad interaction term. It should be noted that since SWAN has been calibrated with all the source terms active the change in results due to disabling one source term may also be a function of effectively altering the calibration.

6.3 GUIDE TO MODEL RUNS.

The set of model runs presented in this report are summarised in Table 1. This gives the complete list of test codes used in the presentation of results. Additional, preliminary model runs were also carried out, but are not considered to be of importance and are not presented in this report.

Both SWAN and TOMAWAC are presently actively being developed. The versions used in these tests were the standard releases: SWAN 40.11 and TOMAWAC 5.2.

7. Presentation of results

The results from the model runs are presented as time series graphs. Each graph includes the corresponding parameters from the in-situ measurements and the tidal profile in the area of interest (plotted against the secondary y-axis). For each period considered wind conditions and offshore wave conditions from the Met Office European wave model are also presented on the same time scale. A selection of 2d contour plots of significant wave height and mean wave period are also presented for a selection of conditions. These figures enable a comparison of model results over the area of interest.

Tables of simple statistical measures of the error in the predictions with respect to the measured data are given in Tables 2 to 16. Each table summaries the root mean square error (rmse), the standard deviation of the error (sd(err)), the minimum (min(err)) and maximum error (max(err)) and the average deviation of the error (avedev(err)). These relatively simple parameters are quite severe measures of model performance, since small errors in the timing or phasing of events can lead to relatively large errors. However, they provide a quantitative measure of the skill of the predictions over the test period that can be compared for each model run.

7.1 TEST PERIOD 26/03/02 (SITE: THE WARP)

For this test period wind directions veered from west, through north, to east with speeds between 2 and $8ms^{-1}$ (see Figure 9a). Offshore waves (see Figure 9b) at the Met Office model point (see Figure 2) started approximately southerly, but were predominately north easterly to easterly. Corresponding offshore significant wave heights vary between 0.2m and 1m.

Figure 9c shows the predicted significant wave heights plotted with the measured significant wave heights. There is an apparent tidal dependence in the observations and predicted conditions. The period of the maximum measured significant wave heights (covering a period of approximately 5 hours) occurs during a flood tide. During this period the measured significant wave heights are above 0.6m

The stationary run of SWAN (H260302) is in reasonably good agreement for the full length of the test period. Although the non-stationary runs of SWAN are initialised with a stationary model run there is an apparent warm up period with an unaccountable initial period of 6 hours. During this period the model results are approximately constant and very low before rising up for a period of 9 hours to approximately the same predictions as the stationary run of SWAN. After about 24 hours the non-stationary model predictions appear to be in much better agreement with the measured and stationary model predictions. IN this situation it should be remembered that the model was started at a time when the wind was shifting direction so it is difficult to specify steady state conditions. Table 2 shows that rms errors in significant wave height are less than 0.2m for all the SWAN runs presented. This includes the start up period, where relevant, so is possibly conservative. Table 2 shows that the model consistently under-predicted the significant wave height.

The influence of the tidal currents is most evident in the graphs of mean wave period (see Figure 9d). SWAN appears to have a tendency to under-predict the wave period. Without current effects (H260302 and U260302-1) the wave periods show a degree of variability over the tide, but not as distinct as shown for the measured mean wave period. With currents (although only approximate) the effect is clear with the variation over the tidal cycle reproduced well, although consistently approximately 1 second low. Table 3 shows that the corresponding improvement in the rms error in mean wave period is quite small (only about 0.2s) compared with the run without flows.

Figure 9d also shows that for the run without triad interactions the under-prediction increases, with an rms error given in Table 3 of approximately 1.5 seconds.

Regarding the predicted wave directions, Figure 9e, shows that the models predict the trend in wave directions measured. However, it is only in the later period that the model accurately reproduces the wave direction. In the earlier part of the period some of the more obvious fluctuations evident in the measured wave directions are not well represented by the model and there is also a long section when the model predictions are between approximately 20° to 30° in error. This is possibly because the offshore waves and winds are producing waves from opposing directions, complicating the measurement and prediction of wave direction. It is also interesting to note the difference in the predicted mean direction for the run with and without triad interactions (F260302-2 and F260302-3, respectively). Table 4 gives rms errors of between 30° and 60°, with the lowest errors for those runs of SWAN with currents included.

Figures 9c, 9d and 9e also present the results of the (steady state) run of TOMAWAC which was run for a single time step (26/03/02 17:00) at the peak of the storm. The predicted significant wave height (Figure 9c) with TOMAWAC is similar to that predicted by SWAN, and similarly under-predicts the maximum significant wave height during the period, by approximately 0.35m. However, the mean wave period (Figure 9d) is noticeably closer to the mean wave period for the measured data. The mean wave direction (see Figure 9e) is only slightly closer to the mean wave direction of the measured data, compared with the SWAN results.

In summary the main observations were:

- Runs with flows gave more noticeable improvement to the wave period and wave direction prediction
- Shorter time steps than the boundary conditions did not give any noticeable improvement
- Without triad interactions resulted in noticeably worse errors
- Stationary runs gave the lowest errors on significant wave height; but note no stationary runs were carried out with flows.

7.2 TEST PERIOD 05/04/02 (SITE: THE WARP)

For this test period the wind speeds are significantly higher with speeds in excess of $13ms^{-1}$ (see Figure 10a). Wind directions are also consistently north easterly. Similarly offshore waves (see Figure 10b) at the Met Office model point are higher and increase to as much as approximately 2.5m with corresponding mean periods of approximately 6s.

Figure 10c shows again the apparent tidal dependence in the observations and predicted conditions. In general the model predictions compare well with the measured conditions, although the maximum wave heights during this period are slightly under-predicted. This is confirmed in the statistics given in Table 5. This table shows that rms errors in significant wave height are below 0.2m for all runs. Little difference in error is given between the cases with and without flows, but there is greater error without triad interactions.

As previously noted, mean wave periods (see Figure 10d) are generally under-predicted, by approximately 1s, but the variation is much better represented by the inclusion of tidal currents in the wave model. This is confirmed in Table 6 which gives rms errors below 1s for all three tests.

Values of Tp (see Figure 10e) for the measured data appear to be better predicted than the mean period, with rms errors (Table 7) for the run with currents (HF050402) down to approximately 0.7s. Again a worsening in predicted wave periods can be observed for the runs without triad interactions. Table 7 gives rms errors of predicted peak period below 0.7s for runs presented with the triad interactions, but only below 0.9s for those without triads.

Predictions of the mean wave directions are in reasonably good agreement and, as given in Table 8, are generally within 10° of the measured directions.

7.3 TEST PERIOD 26/04/02 (SITE: THE WARP)

For this period the winds are between 10 and 17ms^{-1} and are generally westerly (see Figure 11a). The generation area to the west is relatively short and also varies in shape with the tide. As shown in Figure 11b offshore the significant wave heights are between 0.5 and approximately 2m with mean periods of between 3.5s and 5.5s. Figure 11b also shows the direction of these waves is also westerly, so that the waves reaching the measurement point are predominately locally generated within the area of interest.

For this period measured significant wave heights are as high as 1.2m and occur at high water when winds are strongest and are from the south-west. Figure 11c shows that the model predictions are, in general, in good agreement with the measured significant wave heights, but appear to slightly over predict. Both model runs for this period were carried out without flows, but the runs show the difference between using predictions of the tide level and a constant tide level. Little difference is shown between these two runs, which suggests that it is the flows rather than the water level that have greater influence on the wave conditions. Rms errors in significant wave height, as shown in Table 9, are less than 0.2m, and maximum errors less than 0.4m

Figure 11d clearly shows that the measured mean wave periods vary with the tidal cycle. This is not reproduced in the predictions because the runs were carried out without flows. This figure shows a general under-prediction of wave periods with mean periods in error by as much as approximately 2 seconds. Table 10 gives rms errors of below 1s (see Table 10). Predictions of peak period have slightly lower rms errors, below 0.9s.

For the majority of the test period the mean wave direction is accurately predicted and consistently within 10° of the measured directions. Rms errors of the direction predictions, given in Table 12, are less than 11°.

7.4 TEST PERIOD 06/11/02 (SITE: KENTISH FLATS)

Within this period winds start from the south-west and quickly veer to the north, then slowly change to a more north-westerly direction (see Figure 12a). Similarly, the associated wind speeds reduce quickly from approximately 12ms^{-1} to 6ms^{-1} then gradually increase to a maximum of approximately 13ms^{-1}. The corresponding offshore total sea waves (see Figure 12b) vary between 1m and 2.5m, with directions that vary from southerly through westerly to north-westerly and mean periods between 5 and 7 seconds.

For the test period the measured wave heights at the site are comparatively low with maximum significant wave heights of just over 0.6m. Similarly, mean wave periods are comparatively low and are always below 4 seconds.

For this test period, Figure 12c shows that the SWAN model results appear to be in poorer agreement with the measured wave heights. Non-stationary model runs (U061102-3, F061102-1, F061102-3, F061102-4) all give similar results. Although these model runs all over-predict the wave heights at the start of the period they appear to recover. However, they also over-predict during the latter part of the test period. Forcing SWAN to start with the measured significant wave height (F061102-2) test does not appear to improve the situation, with this model run predicting very similar wave heights towards the latter part of the test period. Table 13 gives rms errors in significant wave height of below 0.3m.

Mean wave periods (see Figure 12d) predicted by SWAN also appear to be noticeably worse, although the rms errors, given in Table 14, are below 1.5s

The HINDWAVE predictions, shown in Figure 12c, are consistently higher than the measured wave heights, but appear to follow the trend in the measurements, better than the SWAN model model runs. HINDWAVE starts by predicting very similar wave heights to those predicted by SWAN, but then as the tide level increases, HINDWAVE appears to slightly over predict compared with the measured wave heights. Table 13 shows that the rms error (less than 0.4m) in significant wave height for HINDWAVE is slightly higher than given for the SWAN runs.

Figure 12d shows that HINDWAVE predicts mean wave periods that are in better agreement with the measured mean wave periods, but at times in excess of 1 second errors can be observed. Table 14 shows that the rms error in predicted mean wave period is below 0.6s; a significant improvement over the SWAN values.

Since the measurement device was a pressure sensor no directional information was recorded. As discussed earlier, pressure sensors have a tendency to underestimate wave heights and periods of waves with relatively short period, due to attenuation of wave pressure over the water column. It therefore cannot be ruled out that some of the discrepancies between the modelled and measured wave conditions may be due to this rather than inaccuracies in the modelling.

Figures 12c and 12d also show the steady-state TOMAWAC predictions of significant wave height and mean wave period for the peak at 07/11/02 04:00. In terms of both significant wave height and mean wave period, TOMAWAC provides a more accurate prediction than that of the equivalent SWAN run (H061101-1). TOMAWAC under-predicts the significant wave height and mean wave period by approximately 0.1m and 1.5s respectively.

Figures 12e and 12f provide colour contour plots of significant wave height with vectors indicating mean wave direction corresponding to the steady state SWAN and TOMAWAC model runs, respectively. The results show a noticeable difference between the SWAN and TOMAWAC predictions for this period dominated by wind generated waves.

7.5 TEST PERIOD 14/11/02 (SITE: KENTISH FLATS)

This test period covers just 1 day. During this period wind speeds vary between approximately 18ms^{-1} and 4ms^{-1} with directions varying from south east, through south to south west (see Figure 13a). The significant height of the waves offshore remain above 1m for the period, the mean wave periods are between approximately 5.5 and 8 seconds and the wave directions are between south-east and south-west (see Figure 13b).

Figure 13c shows that the models predict the peak of the measured significant wave heights, but appear to be less accurate in representing the reduction on wave energy as the wind speed drops. The stationary model runs of SWAN (H141102) appear to represent this process most accurately. Table 15 gives rms errors of less than 0.3m for this SWAN model run and less than 0.4m for all runs presented. HINDWAVE appears to be out of phase with the measured wave conditions, with the predicted peak in significant wave height occurring approximately 6 hours after the peak in the measured data. Table 15 gives a rms error of below 0.6m for HINDWAVE. Applying a shift in phase to the HINDWAVE results is expected to significantly improve this error statistic.

As in the previous test period, since the measured wave conditions are based on a pressure sensor device it is possible that due to wave attenuation effects the shorter wave periods may be under-measured. Therefore, the model predictions may have, in reality, been less different to the actual conditions.

Regarding wave periods, Figure 12d shows that HINDWAVE gives comparatively better agreement than SWAN with errors becoming larger as the measured wave energy reduces. The errors in SWAN (Table 16) are generally in excess of 1s below the periods derived from the measurements and during the latter period when wave energy is lower the wave periods predicted by SWAN are as much as approximately 2s lower.

The (steady state) TOMAWAC runs for this test period are also shown in Figures 13c and 13d. The predicted significant wave height (Figure 13c) is in good agreement with the measured data and Figure 13d shows some improvement over SWAN in predicting the mean wave period. However, TOMAWAC is in error by approximately 1 second.

Figures 13e and 13f give contour plots of significant wave height, with mean wave directions indicated as vectors for SWAN and TOMAWAC respectively. These figures show a significant reduction in the offshore wave height due to the depth limitations and sheltering effect of the North Kent coast. Generally, TOMAWAC appears to provide higher wave conditions in the Northern areas, whereas SWAN appears to predict higher waves in the southerly areas.

8. Conclusions and recommendations

Two types of wave model have been shown to provide reasonably accurate predictions of wave generation and transformation in an UK Estuary. This is despite a number of simplifications and assumptions (summarised in Appendix B). Firstly, a simple single point model was applied that required an adaptation from normal application to account for the change in wave activity over the tide. Secondly, more complex spectral area-wide wave models, with little additional effort to their normal application for open coasts, were also applied and demonstrated to provide reasonably accurate predictions of the change in wave activity over the tide.

The estuary considered was the Outer Thames Estuary. Wave modelling in the Outer Thames Estuary provides a demanding challenge of the wave models since it features a series of shallow offshore banks and intertidal areas which influence the wave generation area, provide shelter from offshore waves and lead to complex tidal current patterns. Independent measurements at two different locations within the Estuary were available for comparison when concurrent boundary conditions necessary for the model runs were also available.

For simple single point models such as HINDWAVE-TELURAY (as used in this study) the method for accounting for the sheltering effects of shallow banks is somewhat subjective and relies on experience of the user, with the accuracy of the achieved result being determined with validation data. These simplistic models are computationally very efficient making it possible to produce long term time series of wave conditions and associated wave climates often used in deriving extreme wave conditions.

It has also been shown that more complex area-wide third generation spectral wave models such as SWAN and TOMAWAC can provide reasonably accurate predictions of wave conditions. This is achieved without modification to their normal use. Note for non-stationary model runs of SWAN the non-default BSBT propagation scheme was required to avoid model instability. Third generation models such as SWAN and TOMAWAC are expected to provide more accurate predictions than their first and second generation counterparts since waves at the sites of interest are expected to be bi-modal, something that the first and second generation models cannot represent. This can only be verified by comparison with 2d-spectra from measured data.

For The Outer Thames Estuary, HINDWAVE-TELURAY resulted in predictions of significant wave height and mean periods with rms errors within 0.6m and 0.7s respectively. For SWAN and TOMAWAC rms errors in predicted significant wave height and mean periods were between 0.2 to 0.5m and 1 to 2s, respectively.

The main problem with the application of a simple model like HINDWAVE-TELURAY to the Outer Thames Estuary was the requirement of measured data to provide confidence in the modelling approach. However, when available, model results have been demonstrated to be reasonably accurate.

The application of SWAN and TOMAWAC to the Outer Thames Estuary was more straightforward; the main problem is that the wave periods are consistently underestimated. Sensitivity tests of SWAN showed that:

- non-stationary model runs gave no notable improvement in accuracy compared with a series of stationary model runs

- for non-stationary model runs no significant improvement in the results is obtained with time steps shorter than the time steps of the boundary conditions
- including triad interactions provides more accurate results than without triad interactions
- including refraction due to tidal flows made more notable difference to the wave periods and wave directions rather than the wave height
- tidal flows had a greater influence on the wave conditions compared with the water levels.

Spectral wave models such as SWAN and TOMAWAC are computationally intensive so their use to predict a long term time series and subsequent wave climates is not generally feasible at present. In open coasts it is possible to use these models to estimate inshore wave climates by considering discrete components of an offshore wave climate i.e. a lookup table. However, in an estuarial environment the number of variables increases, i.e. the number of components of a lookup table must be expanded to include tidal currents, water levels (which will affect the generation and transformation of waves) and wind conditions. Under such circumstances the use of lookup tables is expected to impractical, without substantial computing resources.

Finally, it must also be acknowledged, that despite the recognised modelling assumptions and simplifications (summarised in Appendix B), the work required generating all the required inputs and boundary conditions for all the wave models considered in this study remain time consuming and costly.

8.1 RECOMMENDATIONS

Partly due to the limited availability of measured wave data in UK estuaries only one estuary has been considered in this study. It is therefore recommended that other estuaries be considered to further validate the performance of the models in UK estuaries.

Summarised in Appendix B are a number of simplifications and assumptions made within this study. Further consideration of these of the simplifications and assumptions may lead to improved results.

Further work is also recommended to identify the cause of the under-prediction of wave period in the spectral wave models. This is expected to require consideration of the representation in the models of specific physical processes, i.e. the source terms rather tuning of existing source terms.

One of the emphases of this study has been the testing and validation of SWAN in a UK Estuary. Less emphasis and effort was placed on the testing and validation of TOMAWAC. The main advantage of TOMAWAC over SWAN is the use of unstructured finite element meshes. This allows the model to be coupled more directly with finite element tidal flow models such as TELEMAC-2d and may reduce computational effort. Further work, in particular the consideration of TOMAWAC for non-stationary conditions is recommended.

Also, both SWAN and TOMAWAC are actively being developed, by their respective proprietors, and continued validation of both models for UK Estuaries is recommended as new releases are made available.

These recommendations rely on the availability of suitably measured data preferably at a variety of locations and preferably including 2d-wave spectra. It is therefore strongly recommended that resources like the Defra funded Cefas/WAVENET wave monitoring programme are extended to include sites within major estuaries.

9. Acknowledgments

The work described in this report relies on available measured data for confirmation of the computational model results. Such data is scarce, particularly for UK estuaries. We therefore gratefully acknowledge GREP UK Marine Limited and Defra/CEFAS for making their data available for this study.

The methodology for modifying the standard application of the simple wind wave model, i.e. limiting fetch lengths to account for offshore banks is credited to Dr Peter Hawkes of HR Wallingford, who is the originator of the HINDWAVE model.

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Tables

Table 1a Guide to model runs and code numbers (site: The Warp)

Test Period	Model	Test Code	Description
26/3/02	SWAN	H260302	Individual stationary runs – no currents
26/3/02	SWAN	U260302-1	Nonstationary 48hr run. 1hr timesteps. 3hr winds & offshore waves. 1hr water levels from tidecalc (Shivering Sand)
26/3/02	SWAN	F260302-1	Nonstationary 48hr run. 1hr timesteps. 3hr winds & offshore waves. 1hr water levels from tidecalc and Telemac currents (spring)
26/3/02	SWAN	F260302-2	As F260302-1 but with 20 min timesteps
26/3/02	SWAN	F260302-3	As F260302-2 but with triads switched OFF
26/3/02	TOMAWAC	TOMAWAC	Stationary (26/3/02 04:00)
05/4/02	SWAN	H050402	Stationary. No flow
05/4/02	SWAN	HF050402	Stationary. Flow
05/4/02	SWAN	HFT050402	Stationary. Flow. No Triads
26/4/02	SWAN	H260402-1	Stationary. No flow
26/4/02	SWAN	H260402-1	Stationary. No flow Constant water level (=0.0mOD)

Codes:
H: Stationary – without currents
U: Non-stationary – without currents
F: Non-stationary – with currents

Table 1b Guide to model runs and code numbers (Site: Kentish Flats)

Test Period	Model	Test Code	Description
14/11/02	SWAN	H141102	Individual stationary runs – no currents
14/11/02	SWAN	U141102-8	Nonstationary run for 24hrs. 1hr timesteps, 3hr winds and offshore waves. 1hr water levels from wave recorder
14/11/02	SWAN	U141102-9	Nonstationary run for 24hrs. 20min timesteps, 1hr winds and water levels. 3hr offshore waves
14/11/02	SWAN	F141102-1	Nonstationary run for 24hrs. 1hr timesteps, winds, water levels and currents from TELEMAC2D neap tide. 3hr offshore waves
14/11/02	TOMAWAC	TOMAWAC	Stationary (7/11/02 04:00)
14/11/02	HINDWAVE	Hindwave	
6/11/02	SWAN	H061102-1	Stationary (7/11/02 04:00)
6/11/02	SWAN	U061102-3	Nonstationary – 24hrs. 1hr timesteps, winds, water levels. 3hr offshore waves
6/11/02	SWAN	F061102-1	Nonstationary - 24hrs. 1hr timesteps, winds, water levels. 3hr offshore waves. 1hr currents from Telemac spring tide
6/11/02	SWAN	F061102-2	As F061102-1 but forced start with Hs=0.29m
6/11/02	SWAN	F061102-3	As F061102-1 but with Janssen wave growth formulation
6/11/02	SWAN	F061102-4	As F061102-1 but with water levels from tidecalc
6/11/02	TOMAWAC	H061102	Stationary (7/11/02 04:00)
6/11/02	HINDWAVE	Hindwave	

Codes:
H: Stationary – without currents
U: Non-stationary – without currents
F: Non-stationary – with currents

Table 2 Significant wave height (Hs(m)) error statistics (26/03/02) (The Warp)

	SWAN non-stationary	SWAN with flow	SWAN stationary	SWAN with flow	SWAN with flow
	U260302-1	F260302-1	H260302	F260302-2	F260302-3
	Hs	Hs	Hs*	Hs	Hs
rmse	0.15	0.17	0.08	0.14	0.20
sd(err)	0.15	0.15	0.08	0.13	0.13
min(err)	-0.35	-0.39	-0.21	-0.36	-0.52
max(err)	0.17	0.11	0.13	0.13	0.05
mean(err)	-0.05	-0.08	-0.01	-0.06	-0.16
avedev(err)	0.12	0.13	0.06	0.11	0.10

* Indicates statistics based on comparison of 3 hourly data

Table 3 Mean wave period (Tm02(s)) error statistics (26/03/02) (The Warp)

	SWAN non-stationary	SWAN with flow	SWAN stationary	SWAN with flow	SWAN with flow
	U260302-1	F260302-1	H260302	F260302-2	F260302-3
	Tz	Tz	Tz*	Tz	Tz
rmse	1.21	1.02	1.09	1.05	1.46
sd(err)	0.39	0.35	0.46	0.35	0.45
min(err)	-1.95	-1.57	-1.79	-1.52	-2.12
max(err)	-0.59	0.24	-0.28	0.19	0.12
mean(err)	-1.14	-0.96	-0.99	-0.99	-1.39
avedev(err)	0.33	0.24	0.39	0.24	0.30

* Indicates statistics based on comparison of 3 hourly data

Table 4 Mean wave direction (Dir(°)) error statistics (26/03/02) (The Warp)

	SWAN non-stationary	SWAN with flow	SWAN stationary	SWAN with flow	SWAN with flow
	U260302-1	F260302-1	H260302	F260302-2	F260302-3
	Dir	Dir	Dir*	Dir	Dir
rmse	58	30	43	32	34
sd(err)	58	30	45	32	33
min(err)	-153.8	-84	-143	-83	-83
max(err)	146.2	35	38	40	48
mean(err)	7.8	-4	-4	-5	9
avedev(err)	36.1	23	27	24	25

* Indicates statistics based on comparison of 3 hourly data

Table 5 Significant wave height (Hs(m)) error statistics (05/04/02) (The Warp)

	SWAN stationary H050402	SWAN with flow HF050402	SWAN with flow/no triads HFT050402
	Hs	Hs	Hs
rmse	0.12	0.13	0.17
sd(err)	0.12	0.13	0.13
min(err)	-0.34	-0.37	-0.45
max(err)	0.18	0.20	0.12
mean(err)	-0.02	-0.04	-0.11
avedev(err)	0.10	0.10	0.11

Table 6 Mean wave period (Tm02(s)) error statistics (05/04/02) (The Warp)

	SWAN stationary H050402	SWAN with flow HF050402	SWAN with flow/no triads HFT050402
	Tm02	Tm02	Tm02
rmse	0.92	0.86	0.96
sd(err)	0.39	0.21	0.21
min(err)	-1.61	-1.29	-1.42
max(err)	-0.28	-0.45	-0.56
mean(err)	-0.84	-0.84	-0.94
avedev(err)	0.33	0.17	0.17

Table 7 Peak wave period (Tp(s)) error statistics (05/04/02) (The Warp)

	SWAN stationary H050402	SWAN with flow HF050402	SWAN with flow/no triads HFT050402
	Tp	Tp	Tp
rmse	0.66	0.66	0.84
sd(err)	0.67	0.63	0.65
min(err)	-1.18	-1.51	-1.65
max(err)	2.47	2.11	2.02
mean(err)	-0.08	-0.22	-0.54
avedev(err)	0.46	0.43	0.43

Table 8 Mean wave direction (Dir(°)) error statistics (05/04/02) (The Warp)

	SWAN stationary H050402 Dir	SWAN with flow HF050402 Dir	SWAN with flow/no triads HFT050402 Dir
rmse	8.84	8.71	9.31
sd(err)	8.54	8.30	8.86
min(err)	-25.75	-24.75	-26.25
max(err)	17.45	16.88	17.21
mean(err)	2.68	3.00	3.23
avedev(err)	6.45	6.27	6.86

Table 9 Significant wave height (Hs(m)) error statistics (26/04/02) (The Warp)

	SWAN stationary H260402-1 Hs	SWAN stationary H260402-2 Hs
rmse	0.17	0.18
sd(err)	0.11	0.13
min(err)	-0.03	-0.06
max(err)	0.36	0.39
mean(err)	0.11	0.11
avedev(err)	0.09	0.10

Table 10 Mean wave period (Tm02(s)) error statistics (26/04/02) (The Warp)

	SWAN stationary H260402-1 Tm02	SWAN stationary H260402-2 Tm02
rmse	0.94	0.95
sd(err)	0.53	0.55
min(err)	-1.84	-1.85
max(err)	-0.14	-0.08
mean(err)	-0.80	-0.80
avedev(err)	0.41	0.43

Table 11 Peak wave period (Tp(s)) error statistics (26/04/02) (The Warp)

	SWAN stationary H260402-1 Tp	SWAN stationary H260402-2 Tp
rmse	0.79	0.80
sd(err)	0.79	0.80
min(err)	-1.61	-1.67
max(err)	1.34	1.15
mean(err)	-0.21	-0.25
avedev(err)	0.64	0.66

Table 12 Mean wave direction (Dir(°)) error statistics (26/04/02) (The Warp)

	SWAN stationary H260402-1 Dir	SWAN stationary H260402-2 Dir
rmse	10.93	10.60
sd(err)	11.06	10.75
min(err)	-23.93	-19.98
max(err)	20.29	21.12
mean(err)	1.28	1.13
avedev(err)	9.11	9.19

Table 13 Significant wave height (Hs(m)) error statistics (06/11/02) (Kentish Flats)

	SWAN non-stationary U061102-3 Hs	SWAN with flow F061102-1 Hs	SWAN with flow F061102-2 Hs	SWAN with flow F061102-3 Hs	SWAN with flow F061102-4 Hs	HINDWAVE Hs
rmse	0.27	0.28	0.15	0.19	0.28	0.37
sd(err)	0.20	0.20	0.15	0.20	0.20	0.14
min(err)	-0.10	-0.09	-0.18	-0.31	-0.09	0.16
max(err)	0.54	0.54	0.32	0.32	0.55	0.64
mean(err)	0.19	0.20	0.03	-0.01	0.20	0.34
avedev(err)	0.17	0.17	0.13	0.17	0.17	0.11

Table 14 Mean wave period (Tm02(s)) error statistics (06/11/02) (Kentish Flats)

	SWAN non-stationary U061102-3	SWAN with flow F061102-1	SWAN with flow F061102-2	SWAN with flow F061102-3	SWAN with flow F061102-4	HINDWAVE
	Tz	Tz	Tz	Tz	Tz	Tm
rmse	1.46	1.42	1.47	1.28	1.42	0.55
sd(err)	0.42	0.36	0.33	0.39	0.35	0.34
min(err)	-2.23	-2.10	-2.09	-2.00	-2.09	-0.99
max(err)	-0.81	-0.85	-0.88	-0.76	-0.90	0.05
mean(err)	-1.40	-1.38	-1.44	-1.22	-1.38	-0.45
avedev(err)	0.34	0.29	0.27	0.32	0.28	0.28

Table 15 Significant wave height (Hs(m)) error statistics (14/11/02) (Kentish Flats)

	SWAN stationary H141102	SWAN non-stationary U141102-7	SWAN non-stationary U141102-8	SWAN non-stationary U141102-9	SWAN with flow F141102-1	SWAN with flow F141102-2	HINDWAVE
	Hs	Hs	Hs	Hs	Hs	Hs	Hs
rmse	0.27	0.36	0.36	0.31	0.36	0.36	0.54
sd(err)	0.12	0.16	0.17	0.12	0.17	0.17	0.30
min(err)	-0.01	-0.03	-0.05	0.05	-0.04	-0.05	-0.14
max(err)	0.44	0.50	0.50	0.46	0.50	0.51	0.74
mean(err)	0.24	0.33	0.32	0.29	0.32	0.32	0.45
avedev(err)	0.09	0.13	0.14	0.10	0.13	0.14	0.25

Table 16 Mean wave period (Tm02(s)) error statistics (14/11/02) (Kentish Flats)

	SWAN stationary H141102	SWAN non-stationary U141102-7	SWAN non-stationary U141102-8	SWAN non-stationary U141102-9	SWAN with flow F141102-1	SWAN with flow F141102-2	HINDWAVE
	Tz	Tz	Tz	Tz	Tz	Tz	Tz
rmse	1.29	1.52	1.52	1.64	1.52	1.51	0.69
sd(err)	0.13	0.52	0.50	0.55	0.54	0.53	0.52
min(err)	1.08	-2.28	-2.25	-2.48	-2.34	-2.32	-1.26
max(err)	1.54	-0.80	-0.83	-0.94	-0.81	-0.81	0.17
mean(err)	1.32	-1.43	-1.44	-1.55	-1.43	-1.42	-0.46
avedev(err)	0.11	0.45	0.43	0.48	0.45	0.46	0.46

Figures

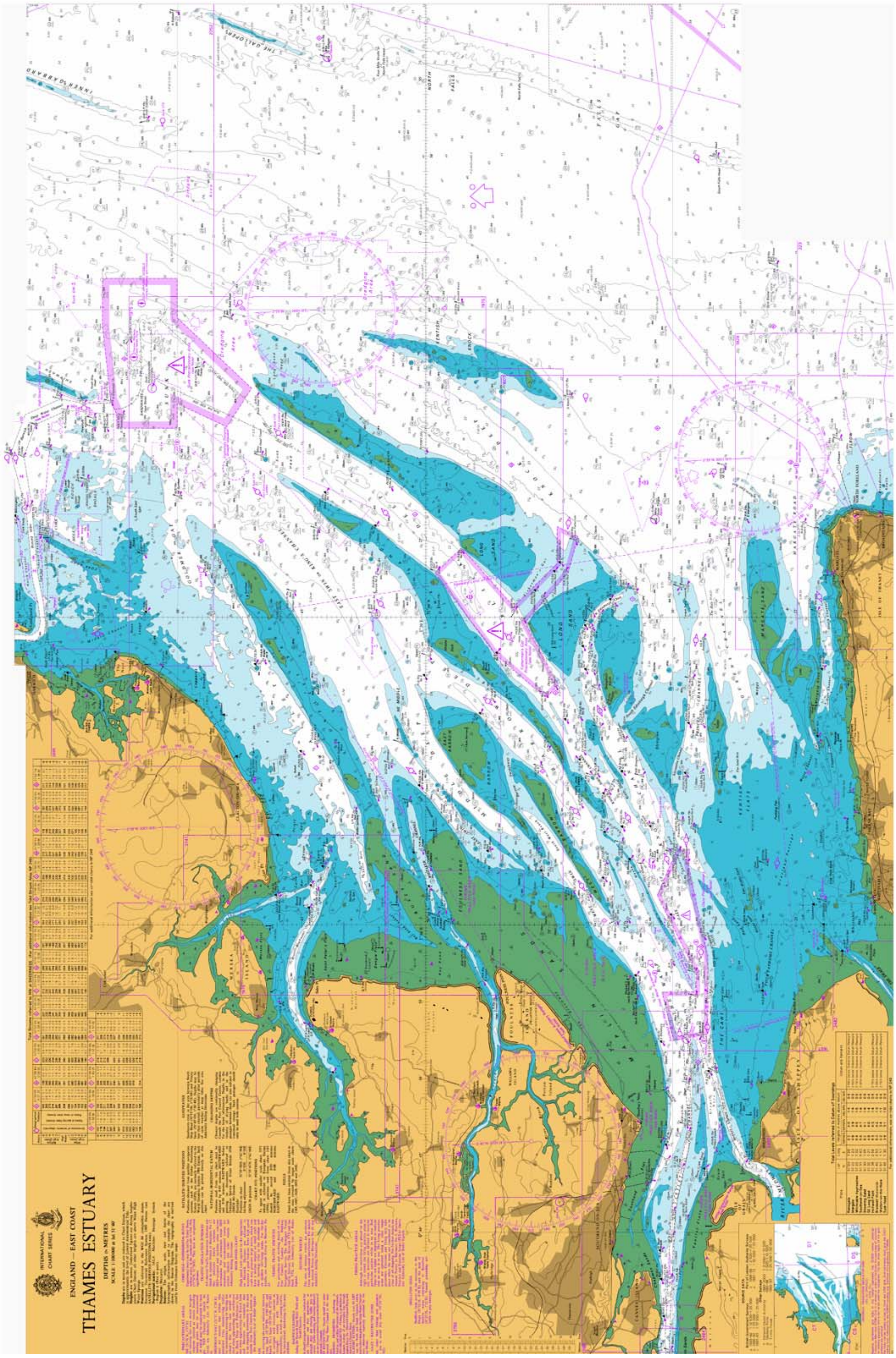

Figure 1 ***Site Location***
(Reproduced from Admiralty Chart 1183 by permission of the Controller of HMSO and the Hydrographic Office).

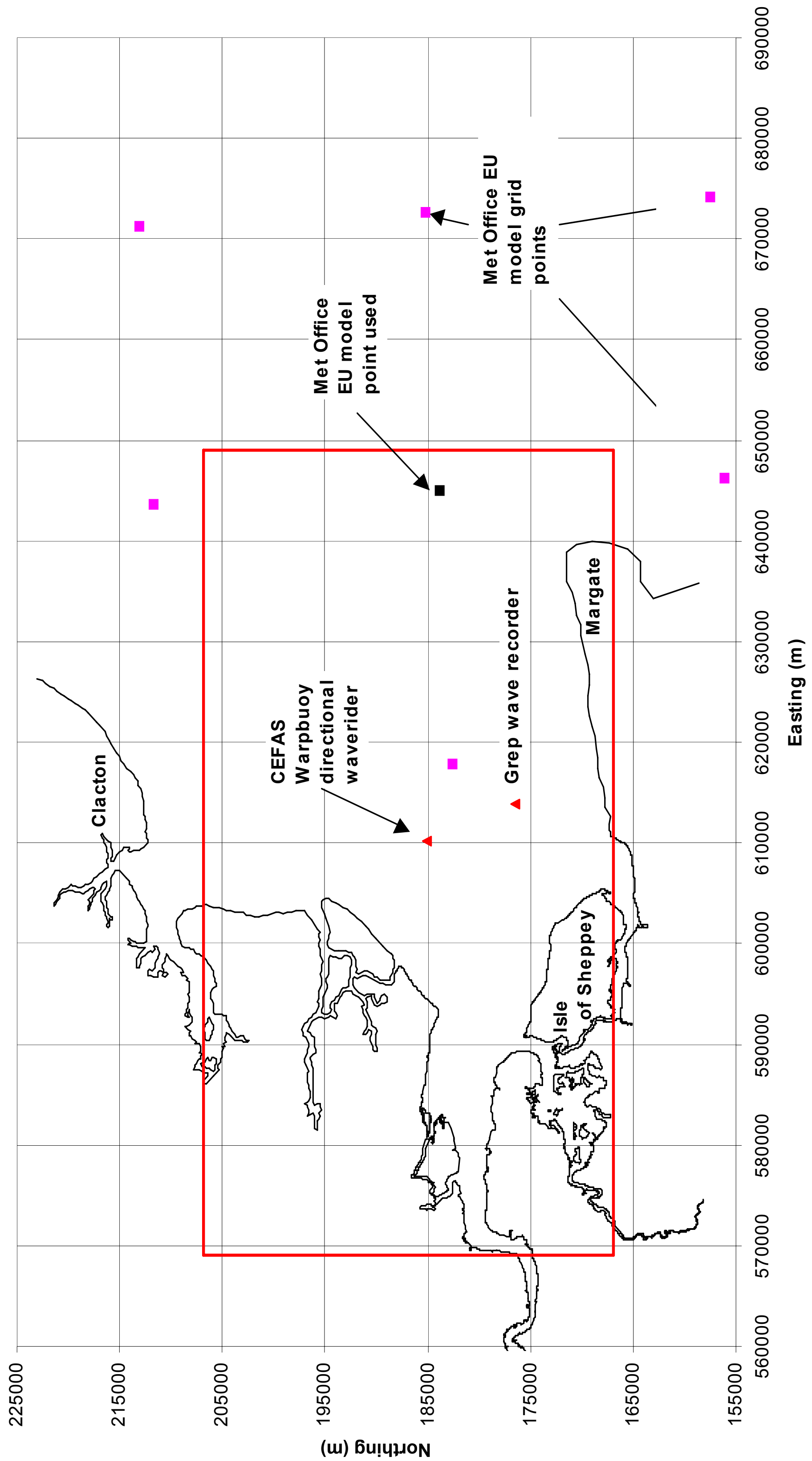

Figure 2 Wave measurement devices and model point locations

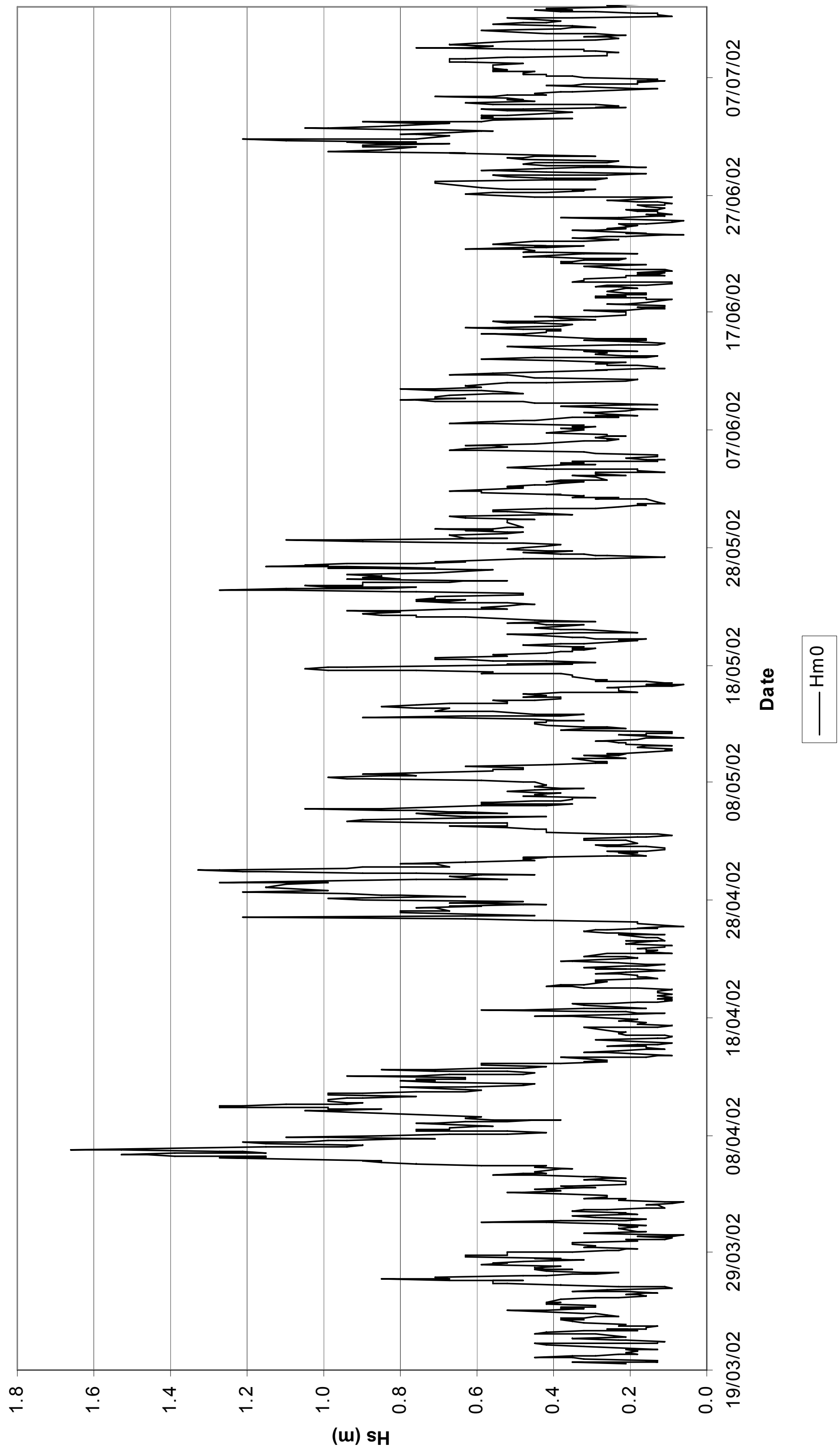

Figure 3a Significant wave height from the measured data at The Warp

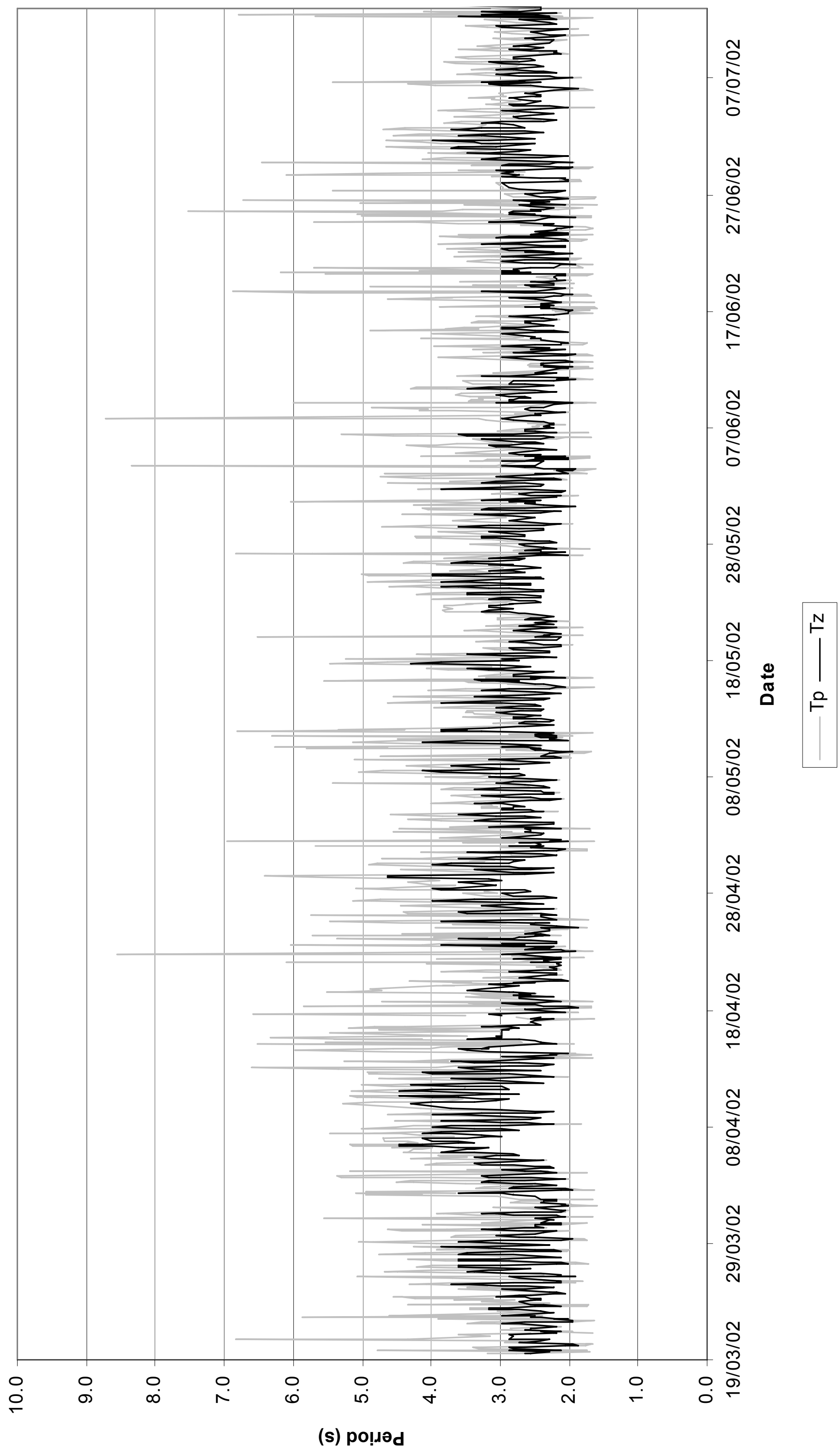

Figure 3b Wave periods from the measured data at The Warp

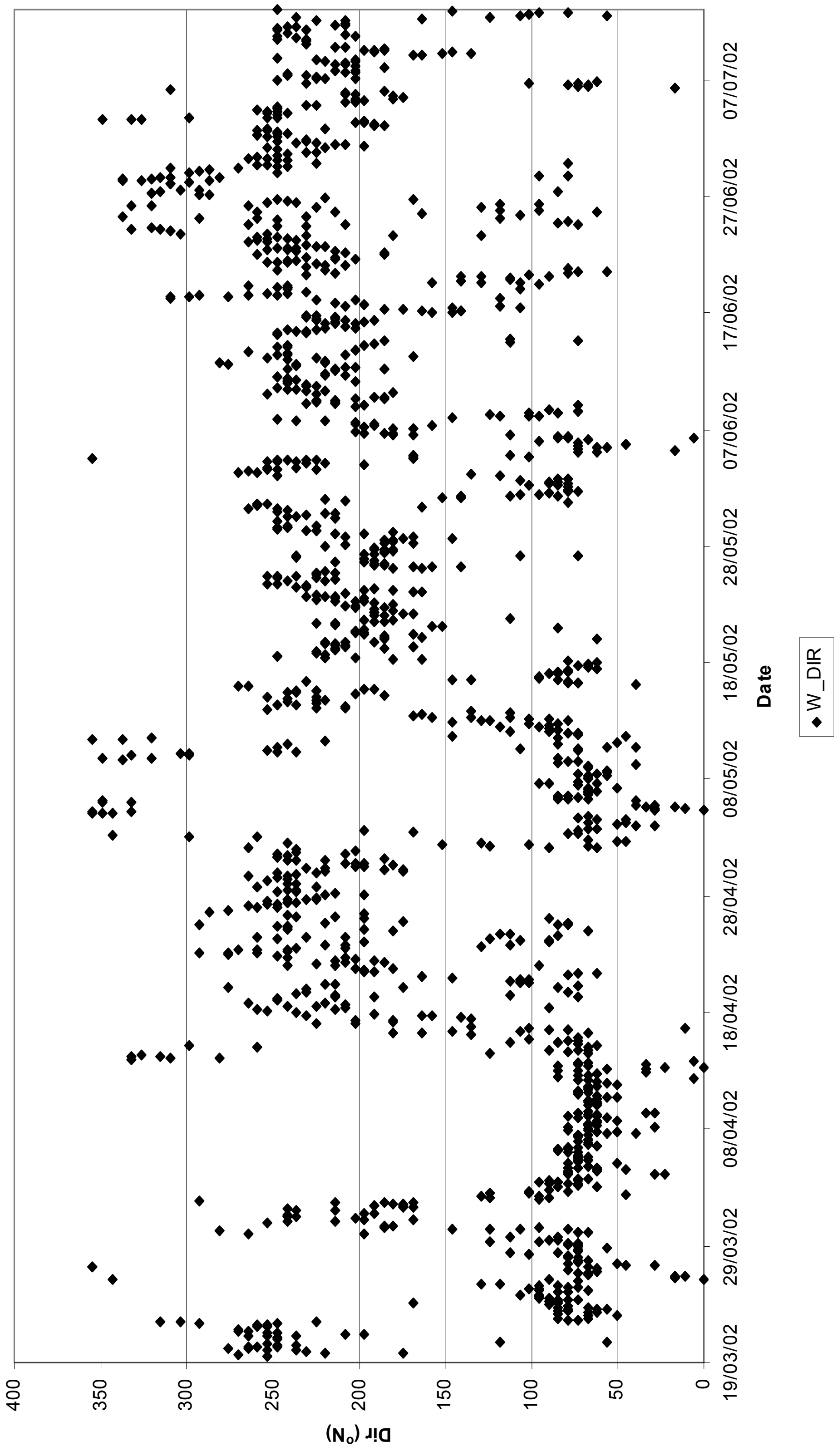

Figure 3c Mean wave direction from the measured data at The Warp

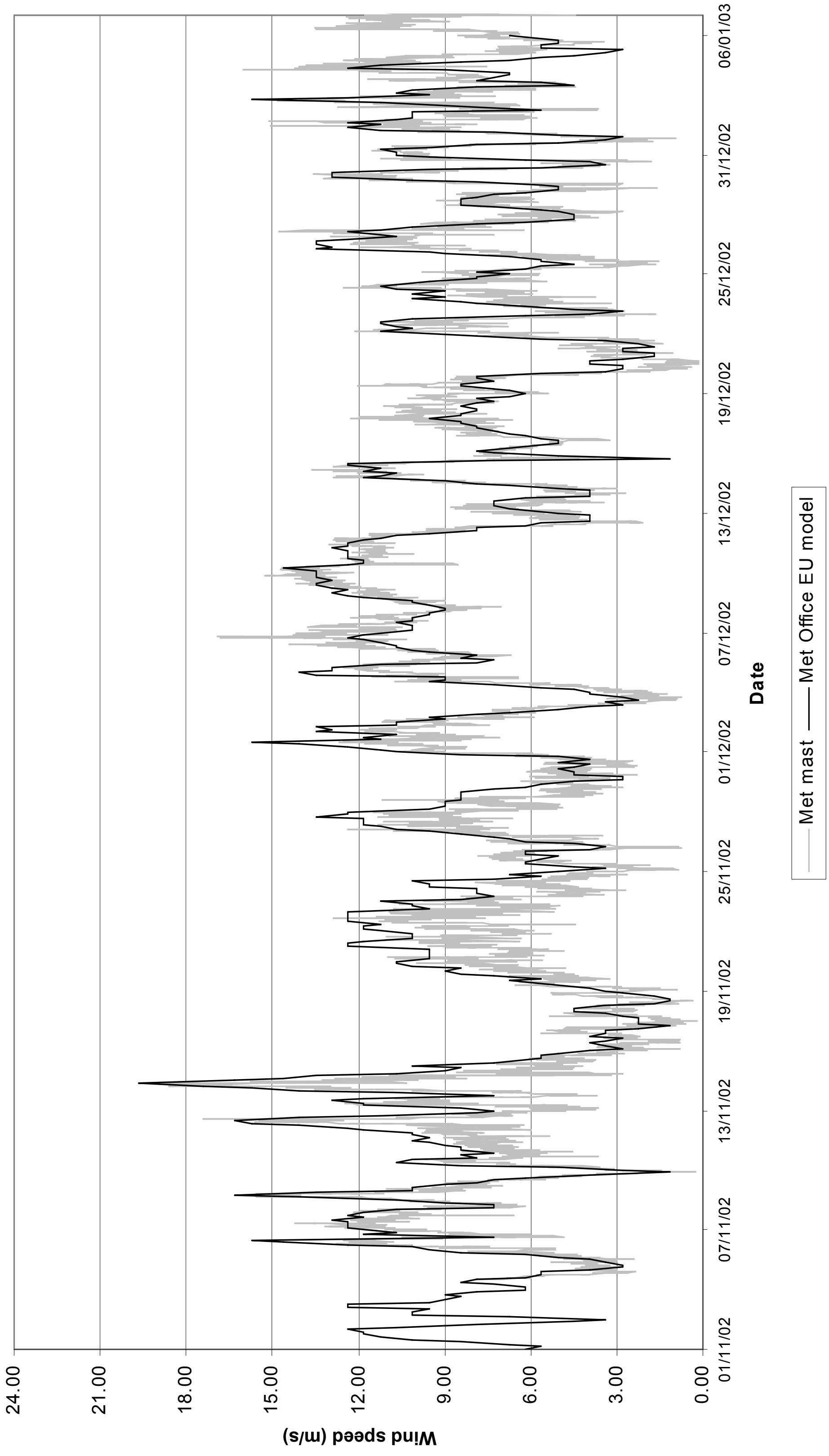

***Figure 4		Comparison of measured and model wind data***

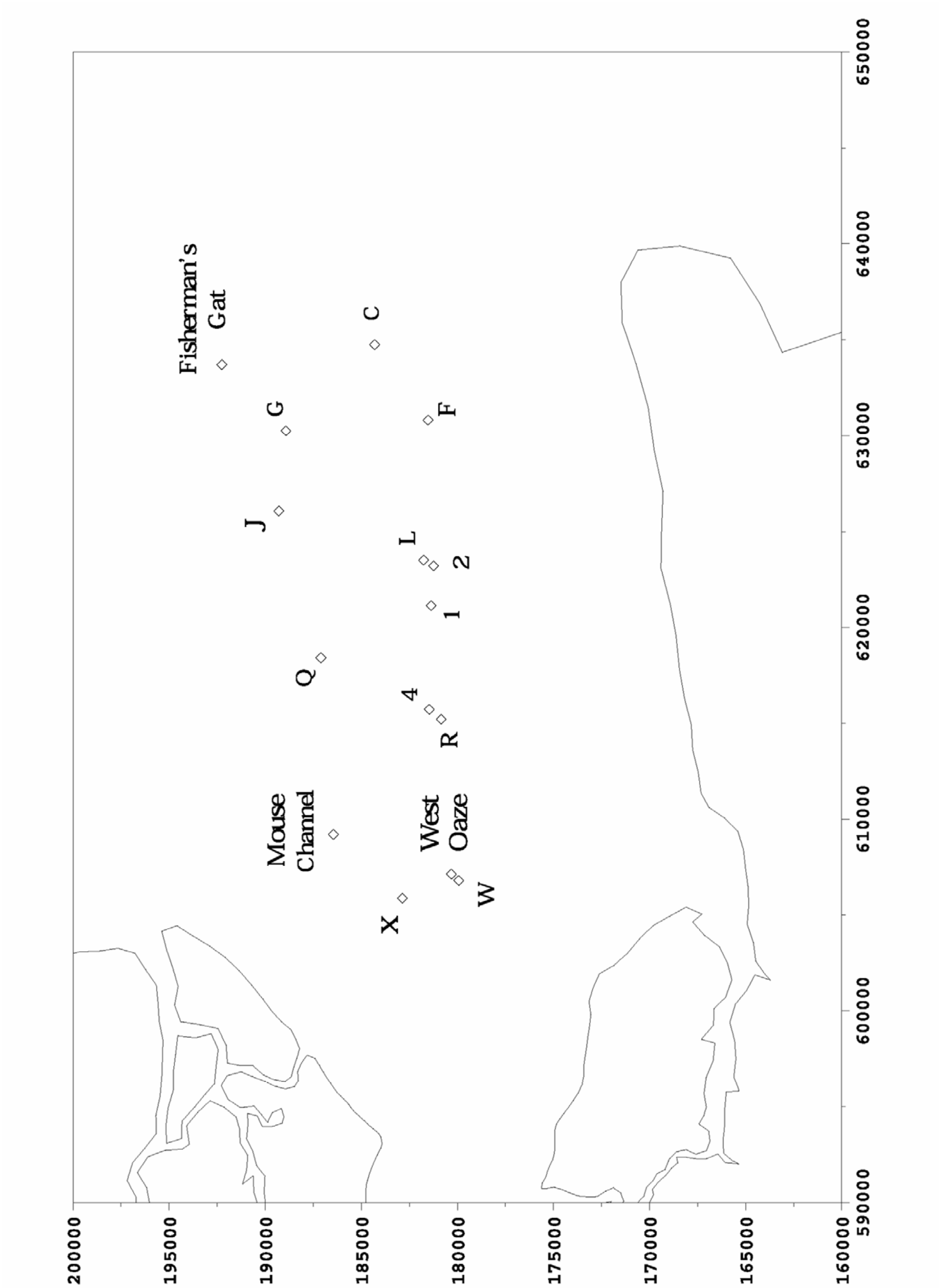

Figure 5a TELEMAC-2d flow model – calibration points

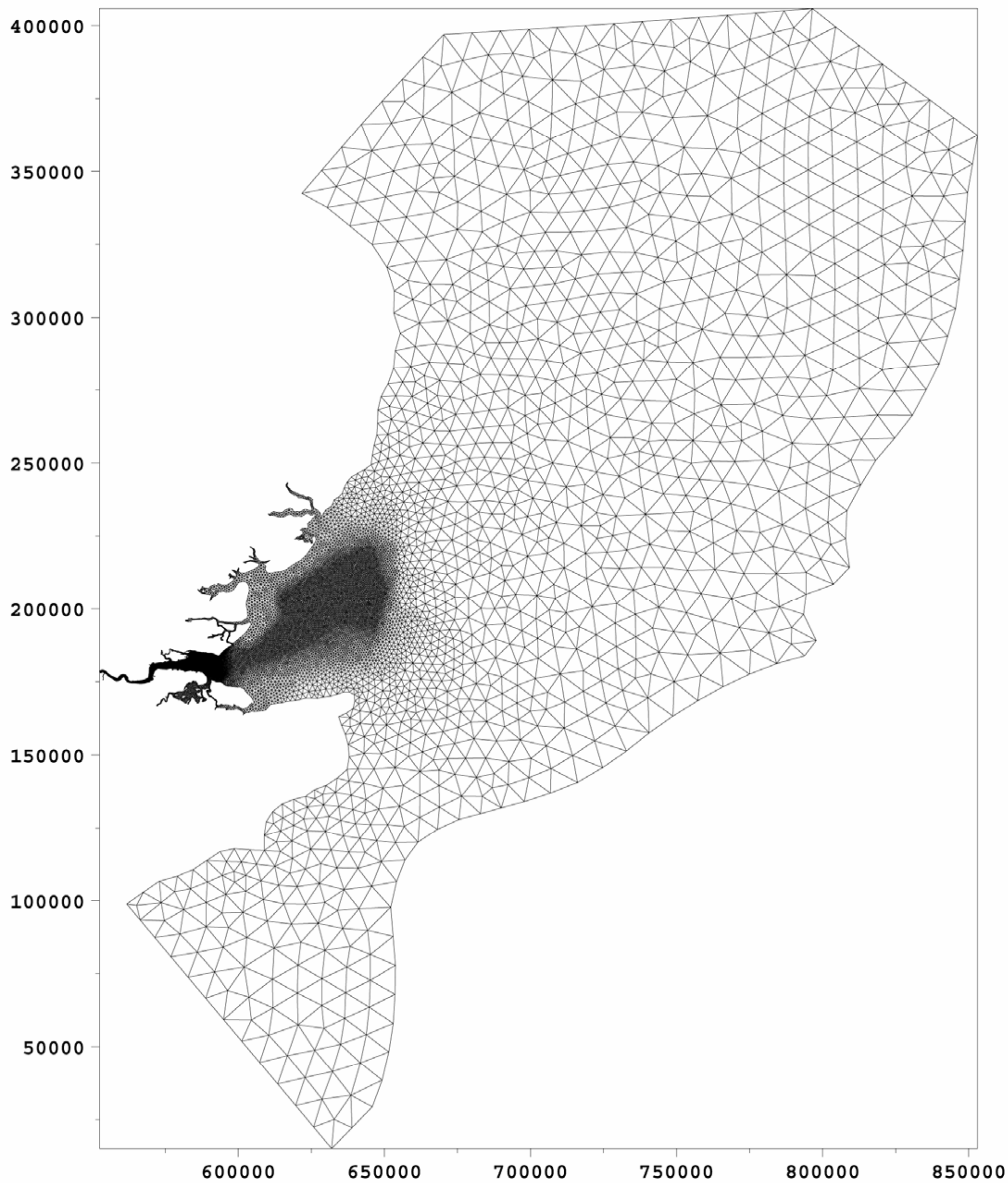

Figure 5b TELEMAC-2d flow model – model mesh

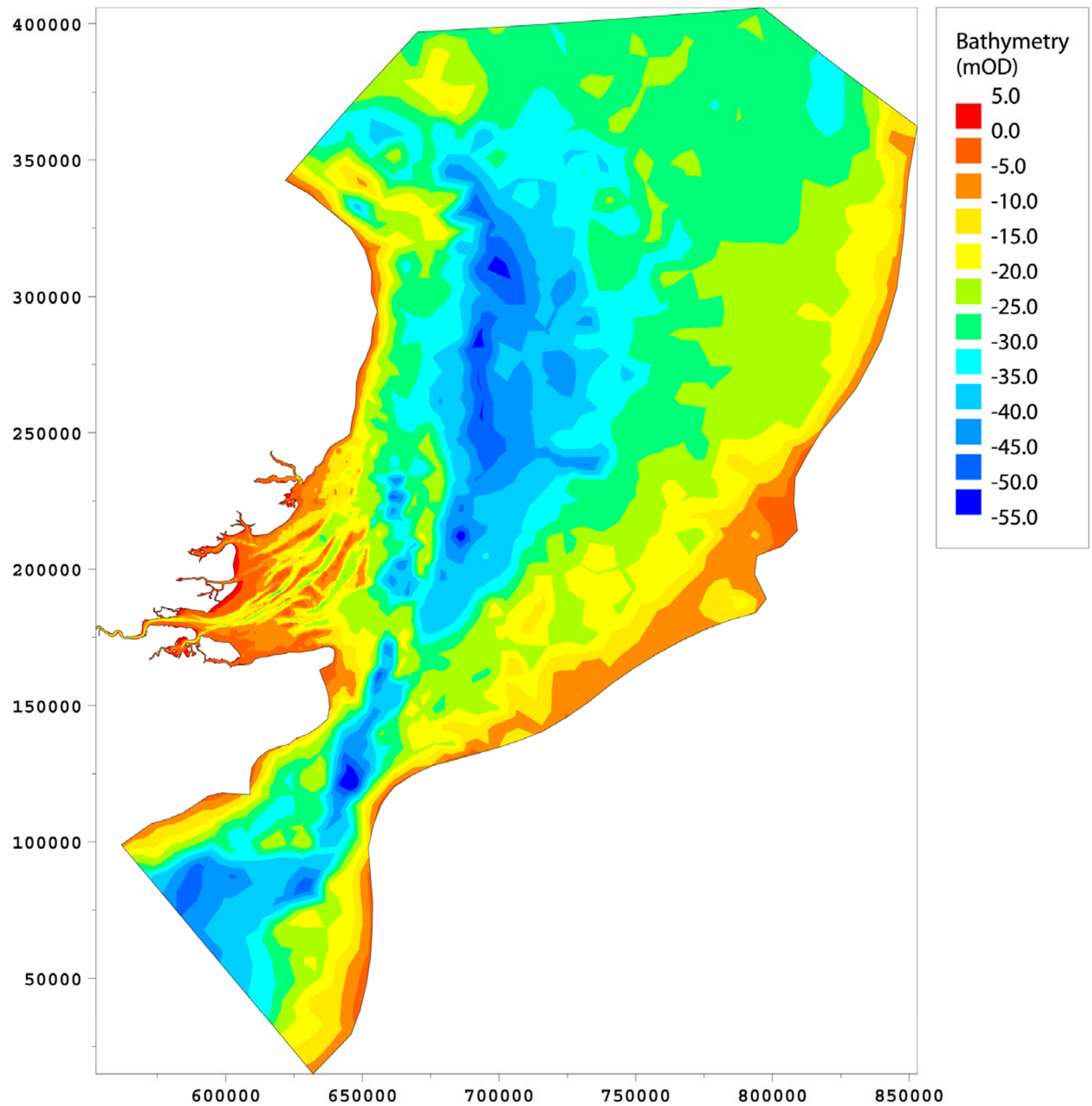

Figure 5c TELEMAC-2d flow model – model bathymetry

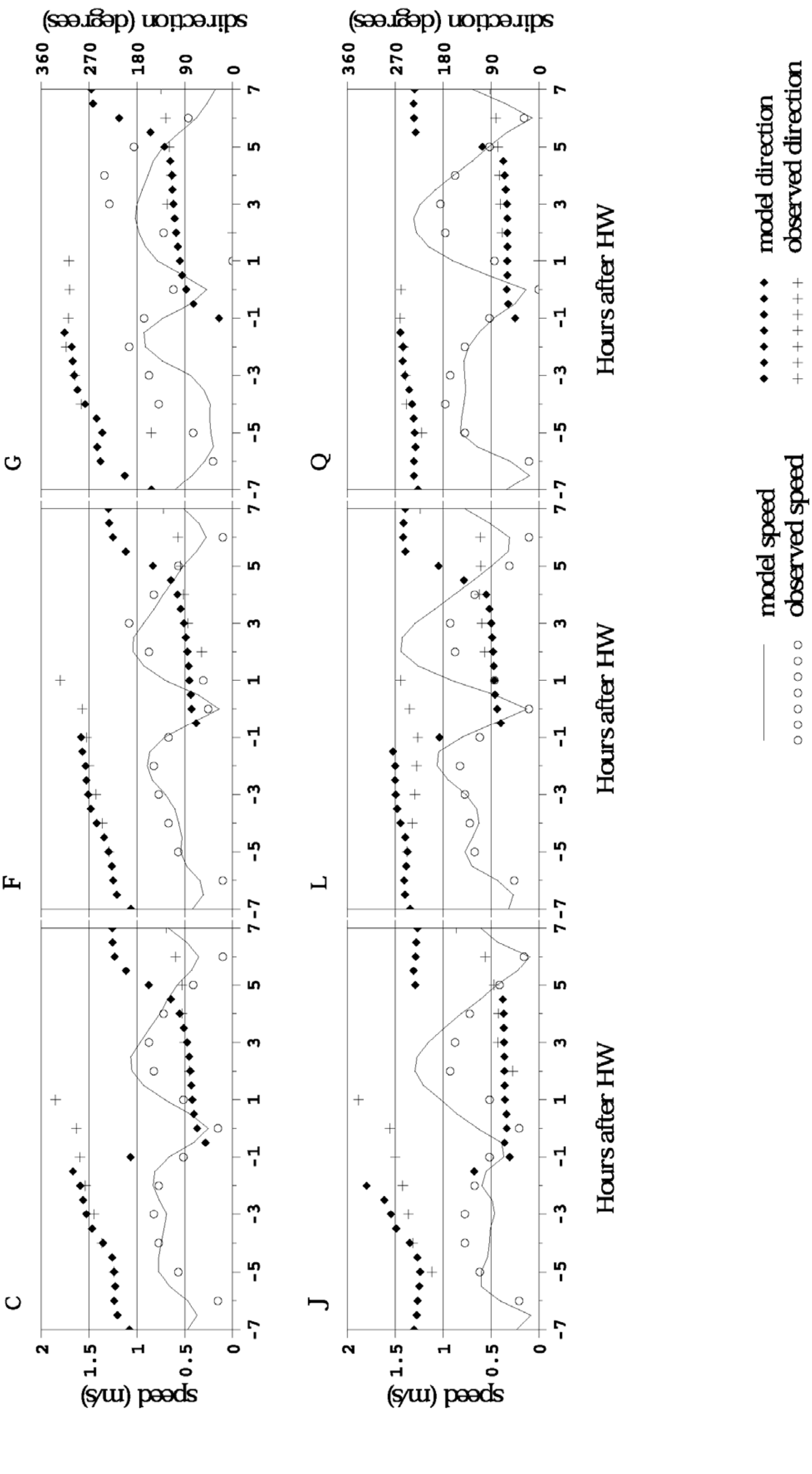

Figure 5d TELEMAC-2d flow model – comparison of modelled and measured flow

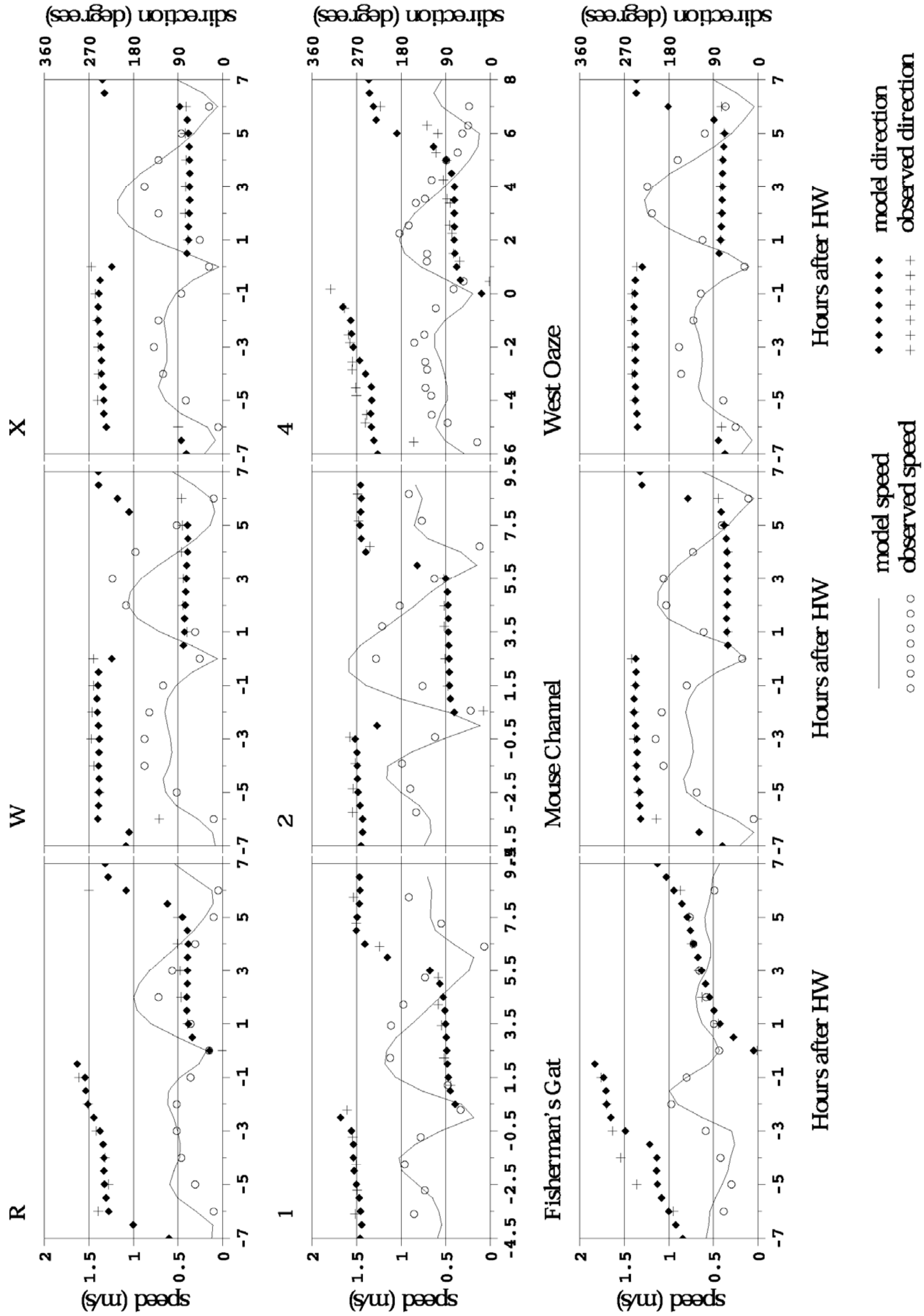

Figure 5e TELEMAC-2d flow model - comparison of modelled and measured flow

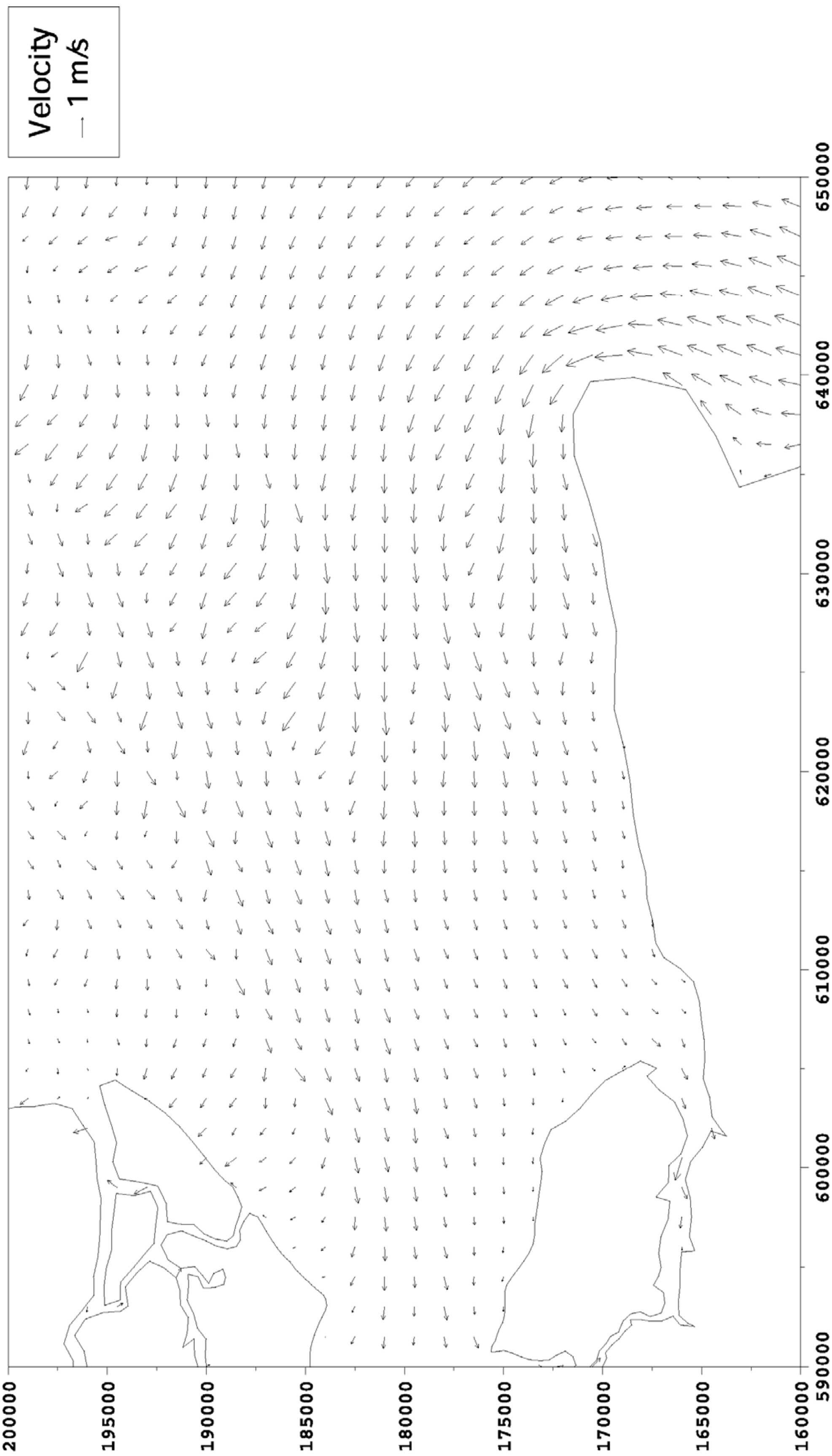

Figure 5f TELEMAC-2d flow model – peak flood vectors (mean spring tide)

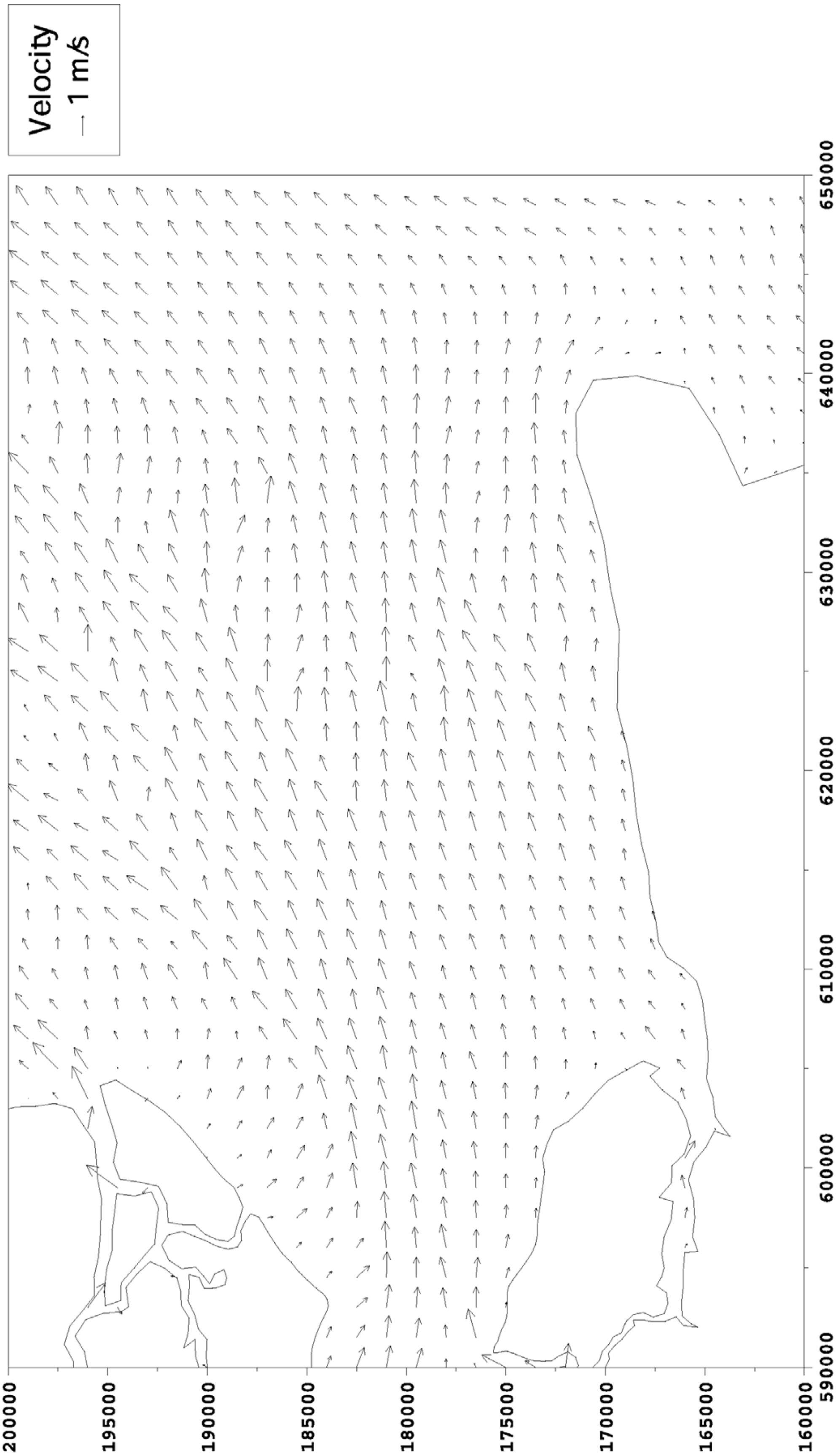

Figure 5g TELEMAC-2d flow model – peak ebb vectors (mean spring tide)

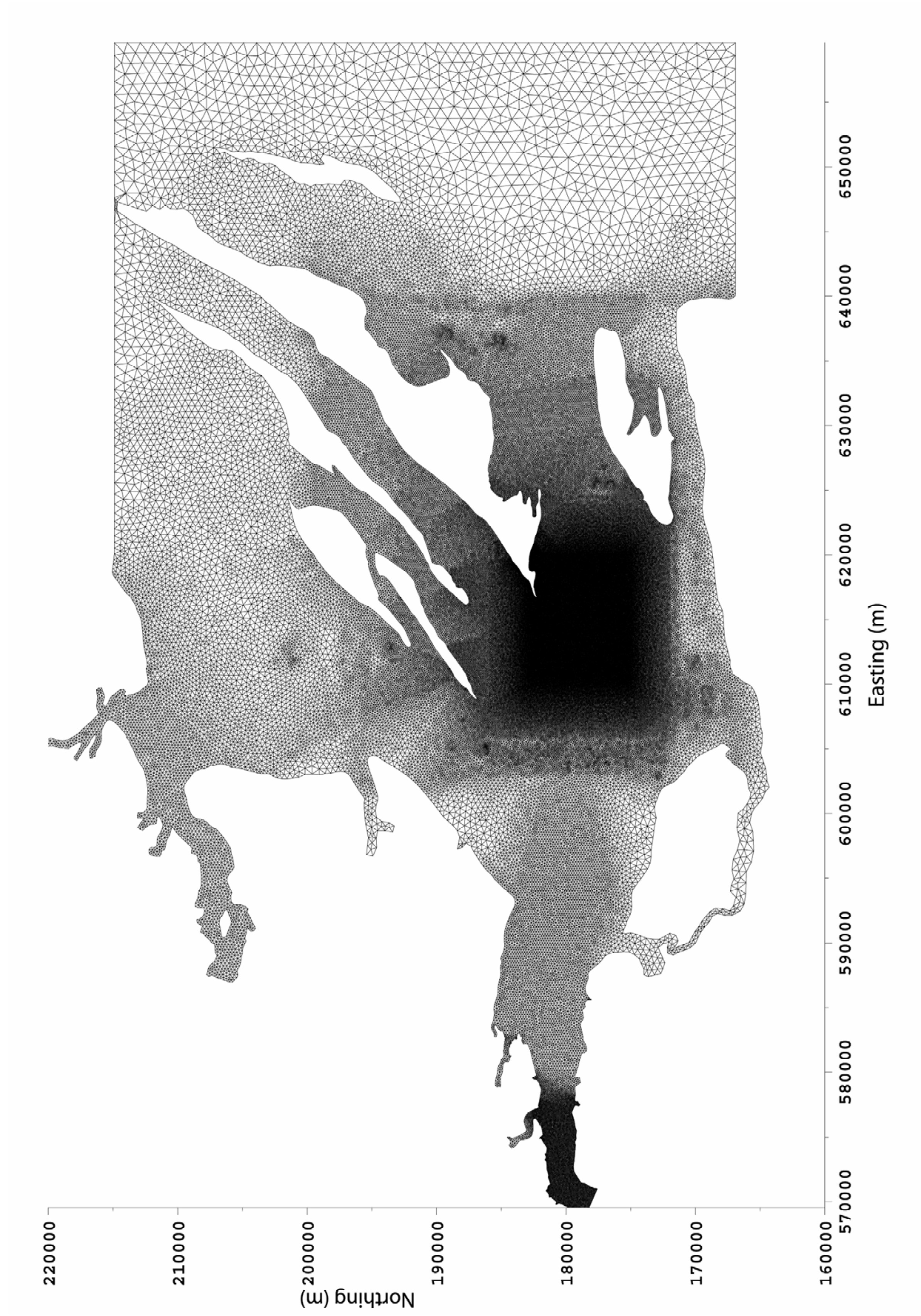

Figure 6a TELURAY model mesh

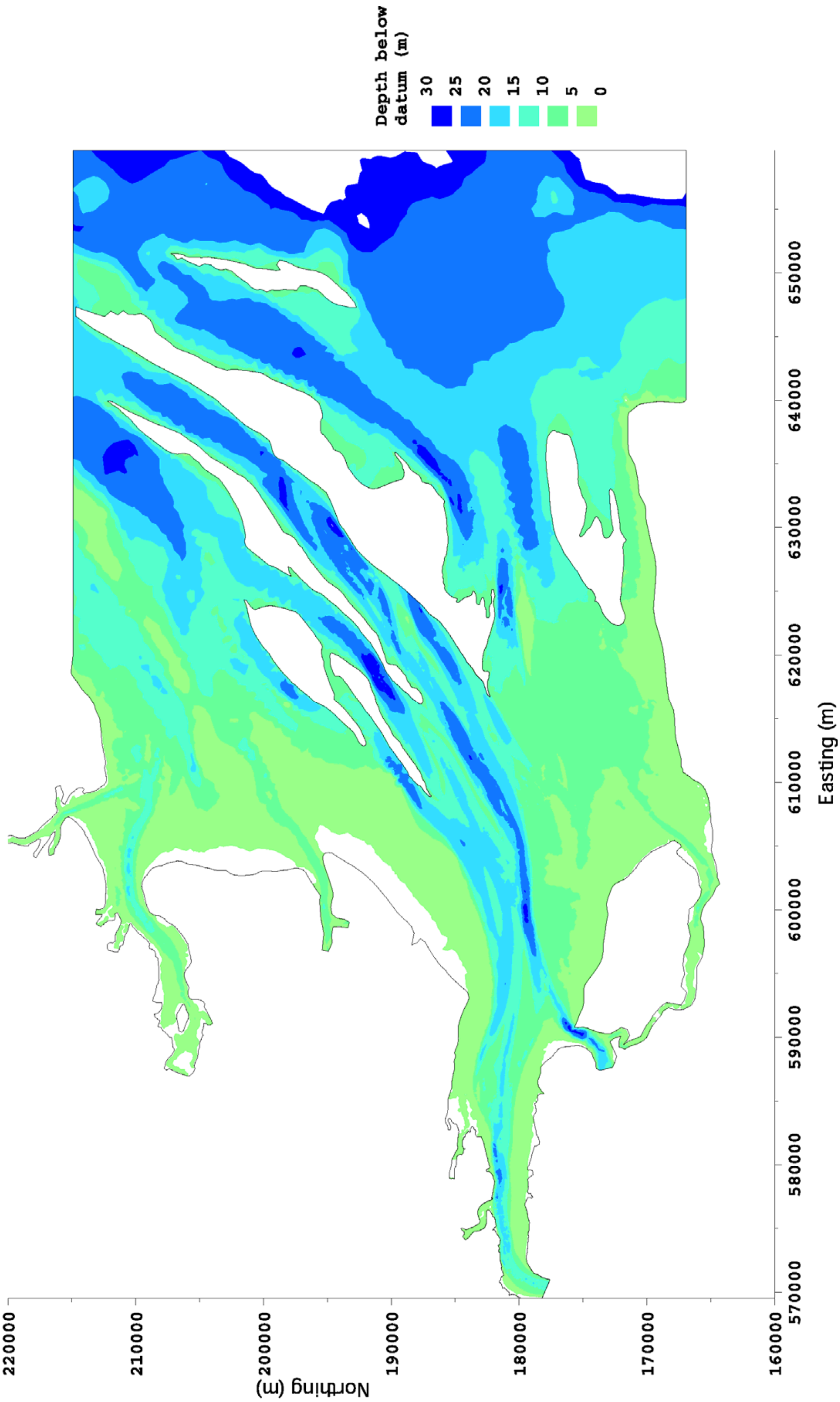

Figure 6b TELURAY model bathymetry

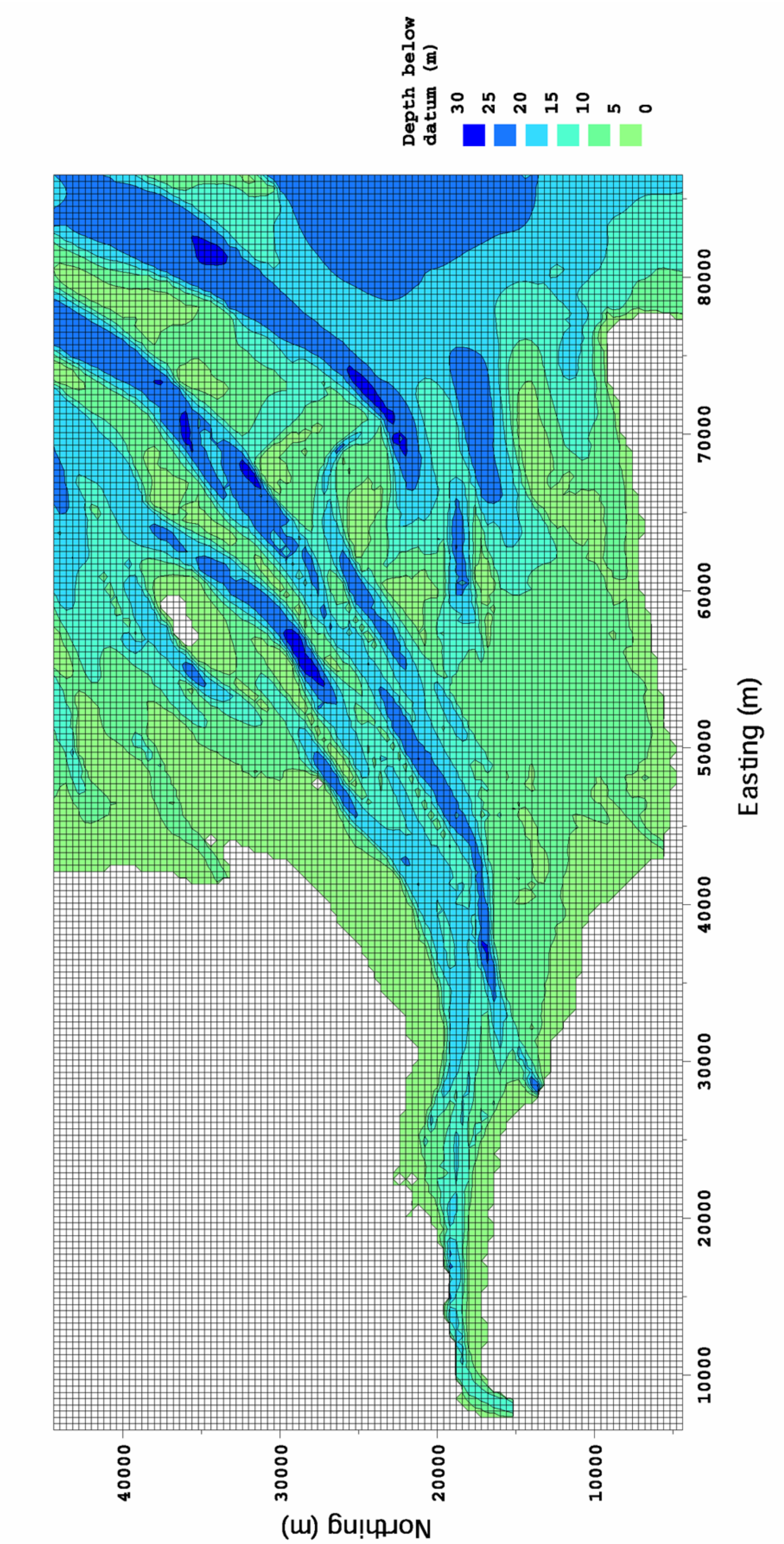

Figure 7 ***SWAN model grid and bathymetry***

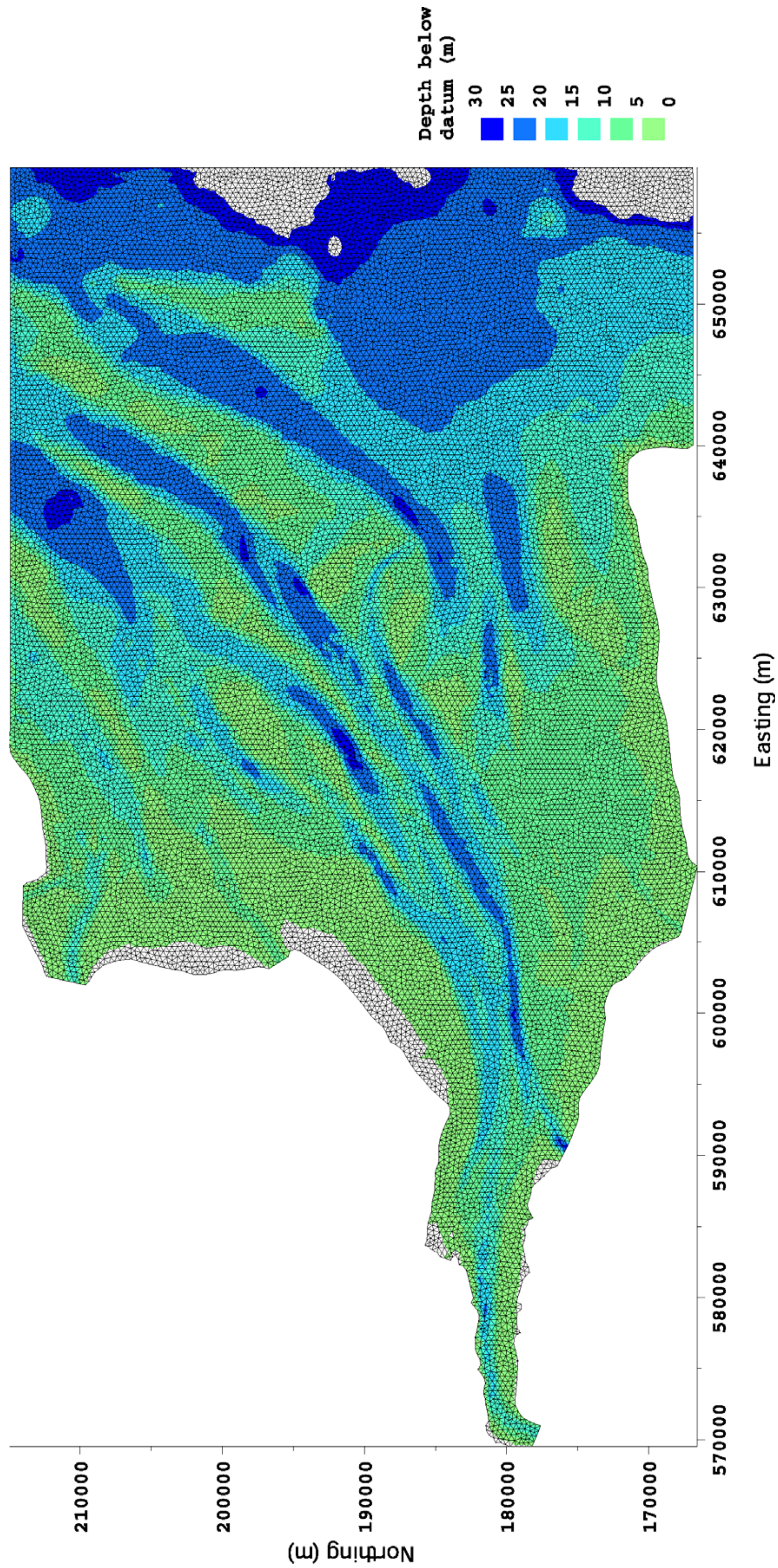

Figure 8a TOMAWAC model mesh and bathymetry

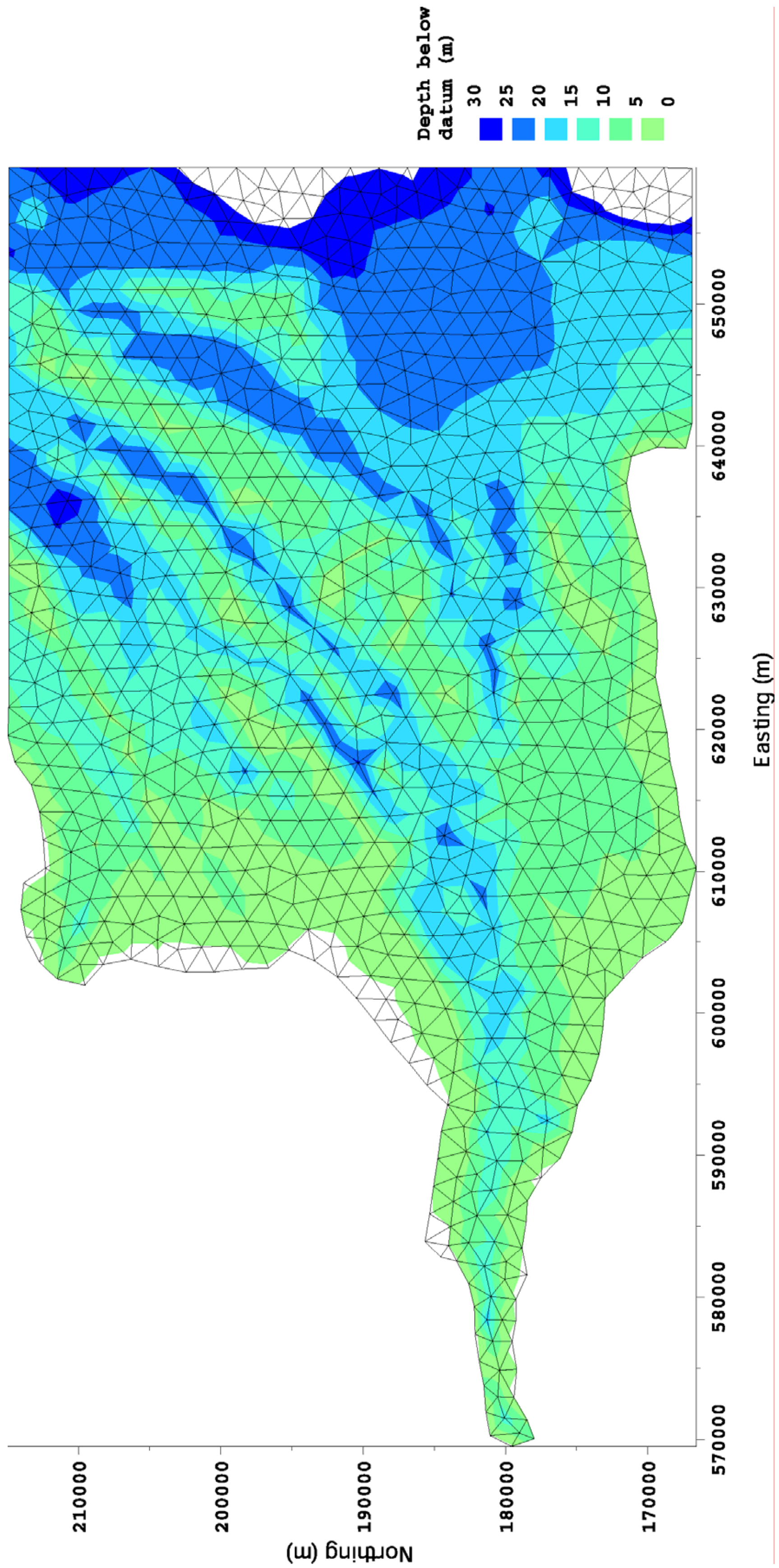

Figure 8b TOMAWAC model mesh (course grid)

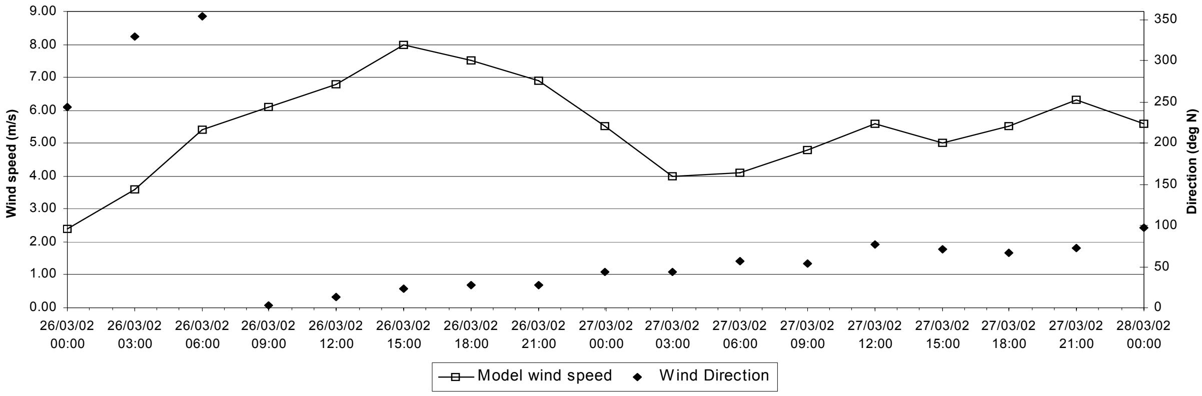

Figure 9a Met Office Model wind data (26/03/02 – 28/03/02)

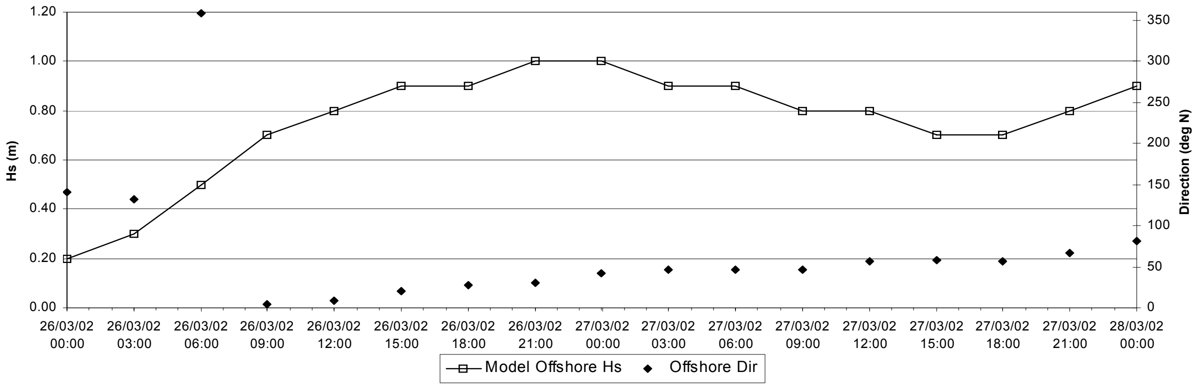

Figure 9b Met Office offshore wave data (26/03/02 – 28/03/02)

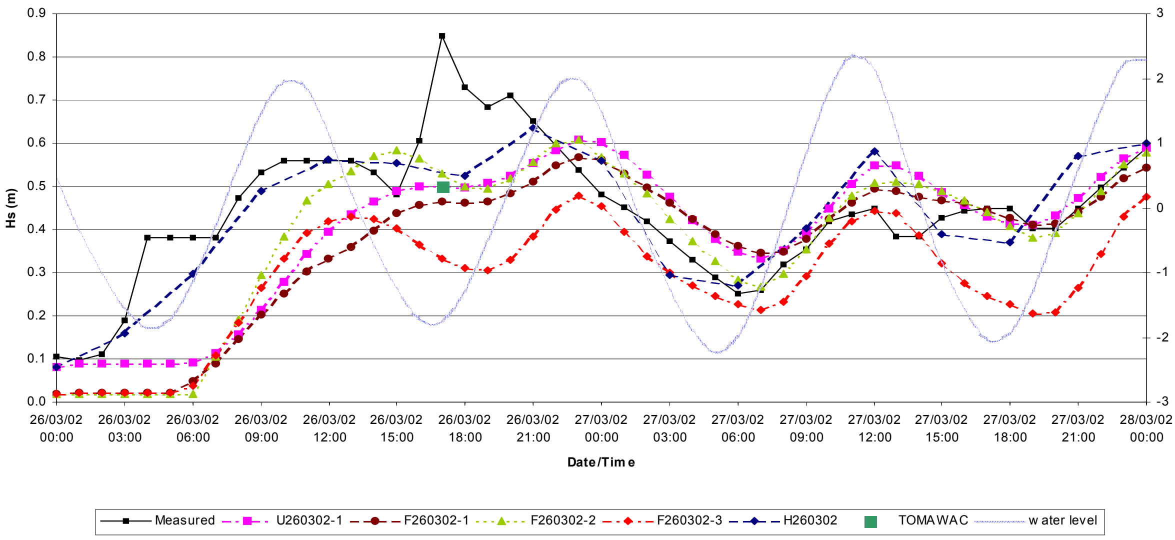

Figure 9c Measured and modelled significant wave height (26/03/02 – 28/03/02)

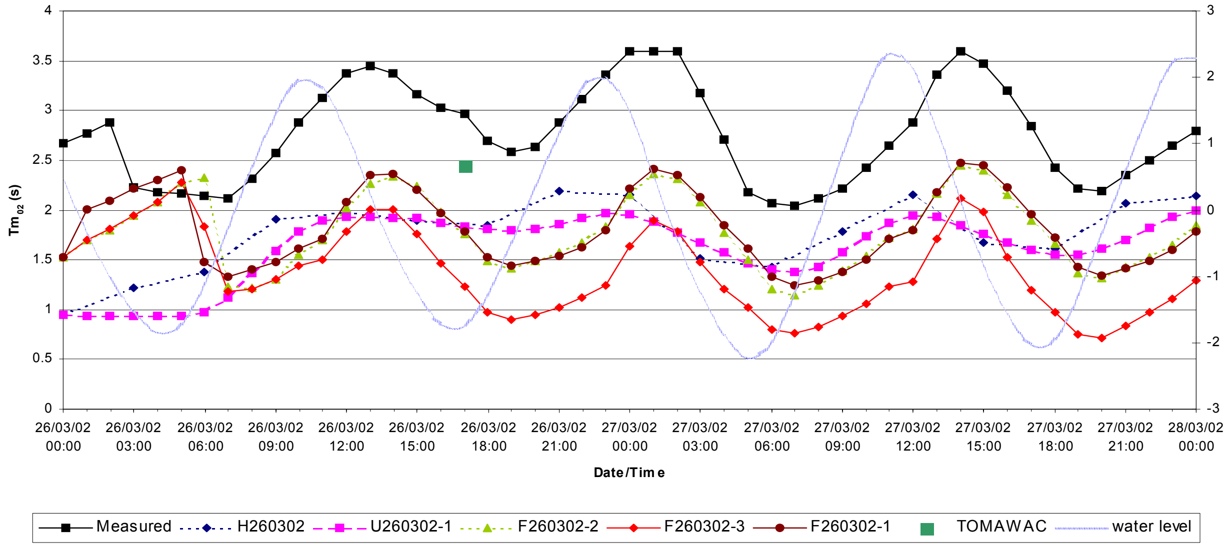

Figure 9d Measured and modelled mean wave period (26/03/02 – 28/03/02)

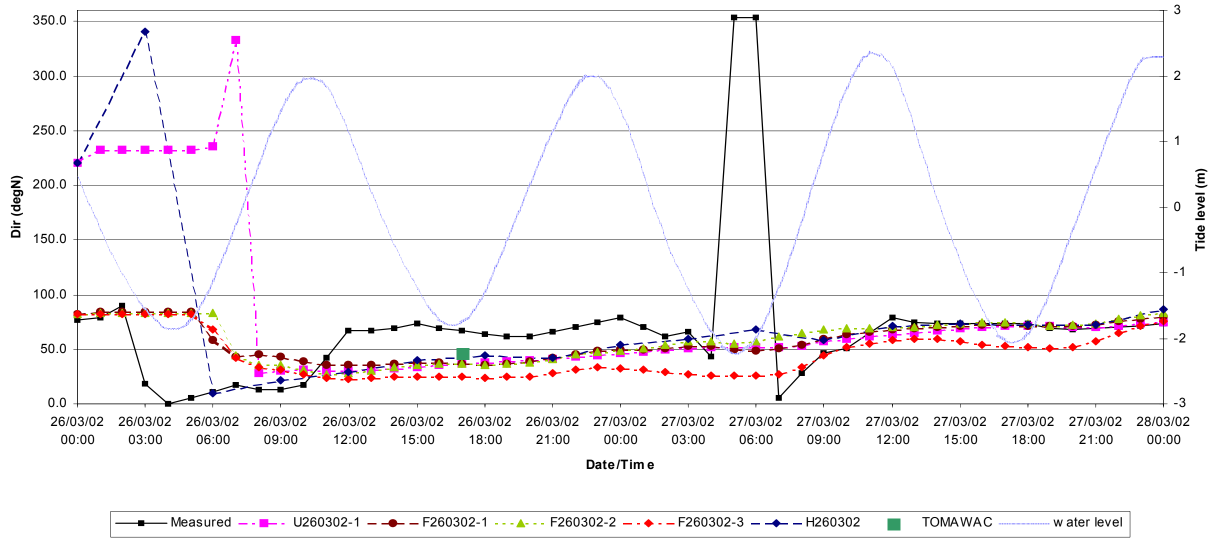

Figure 9e Measured and modelled mean wave direction (26/03/02 – 28/03/02)

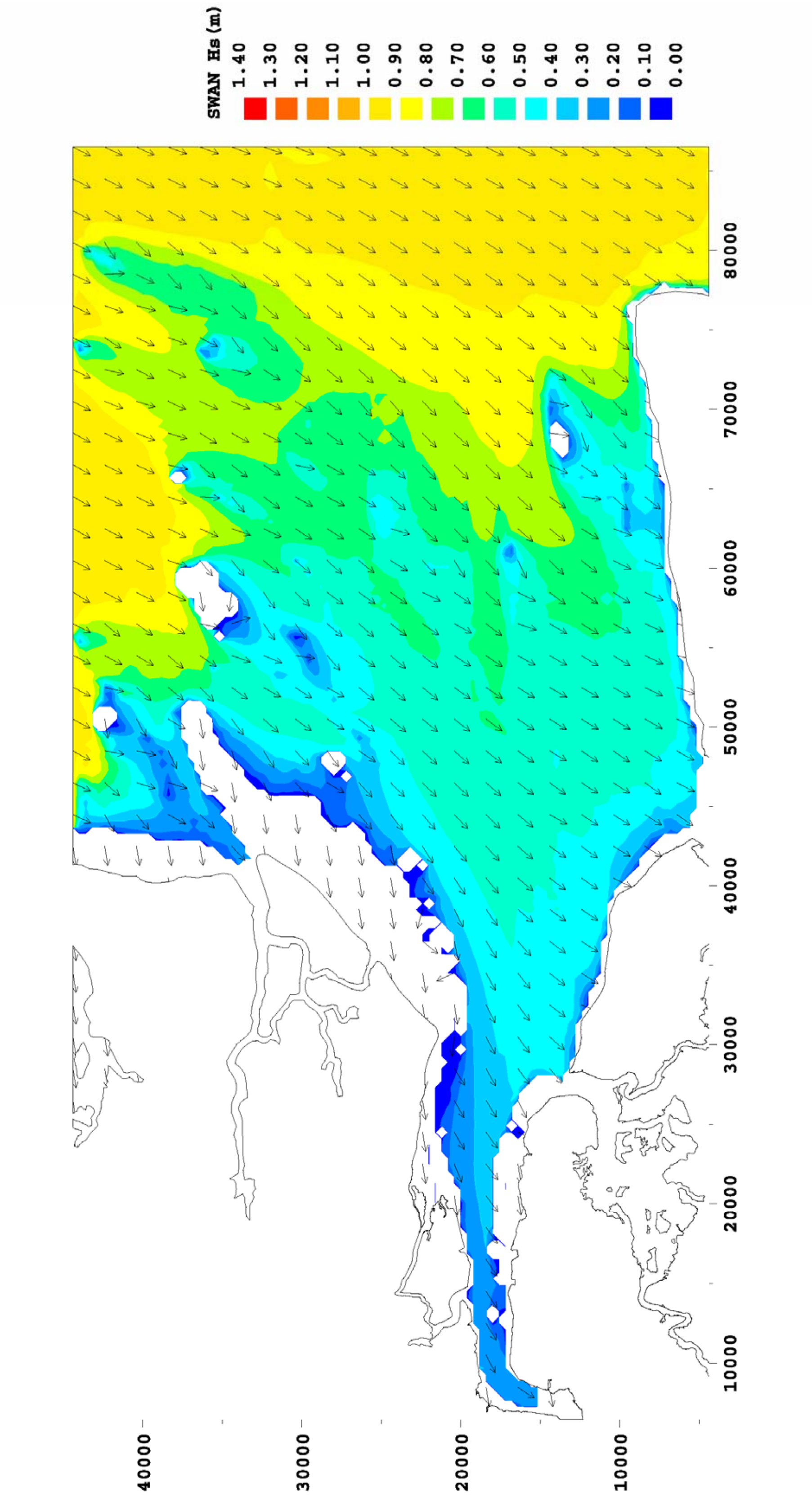

Figure 9f   Predicted significant wave heights over SWAN model (Test code: H260302)

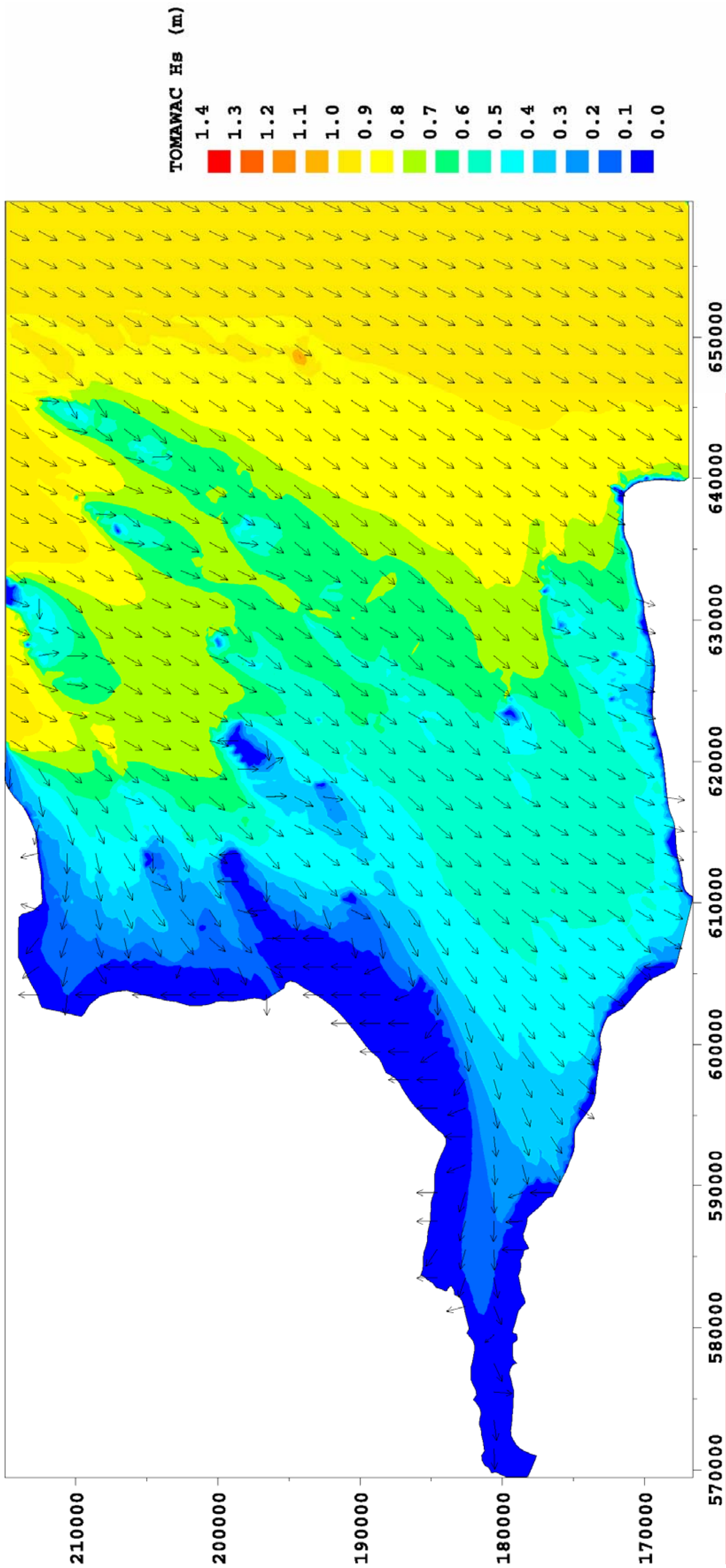

Figure 9g Predicted significant wave heights over TOMAWAC model (26/03/02)

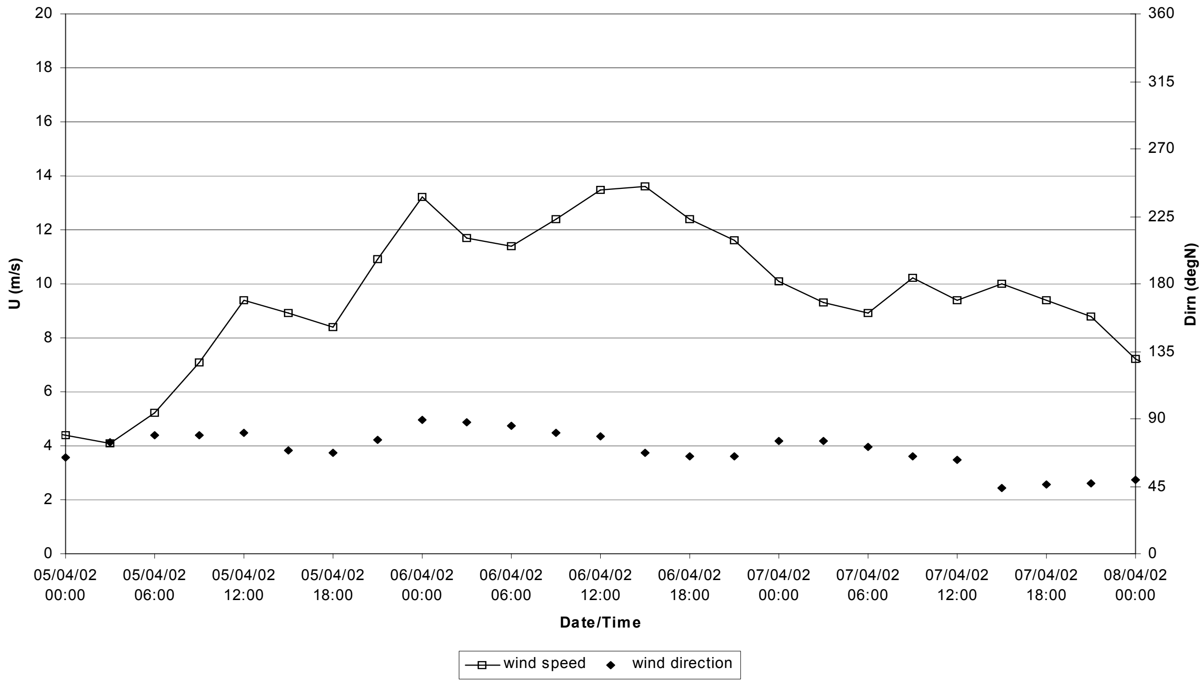

Figure 10a Met Office Model wind data (05/04/02 – 08/04/02)

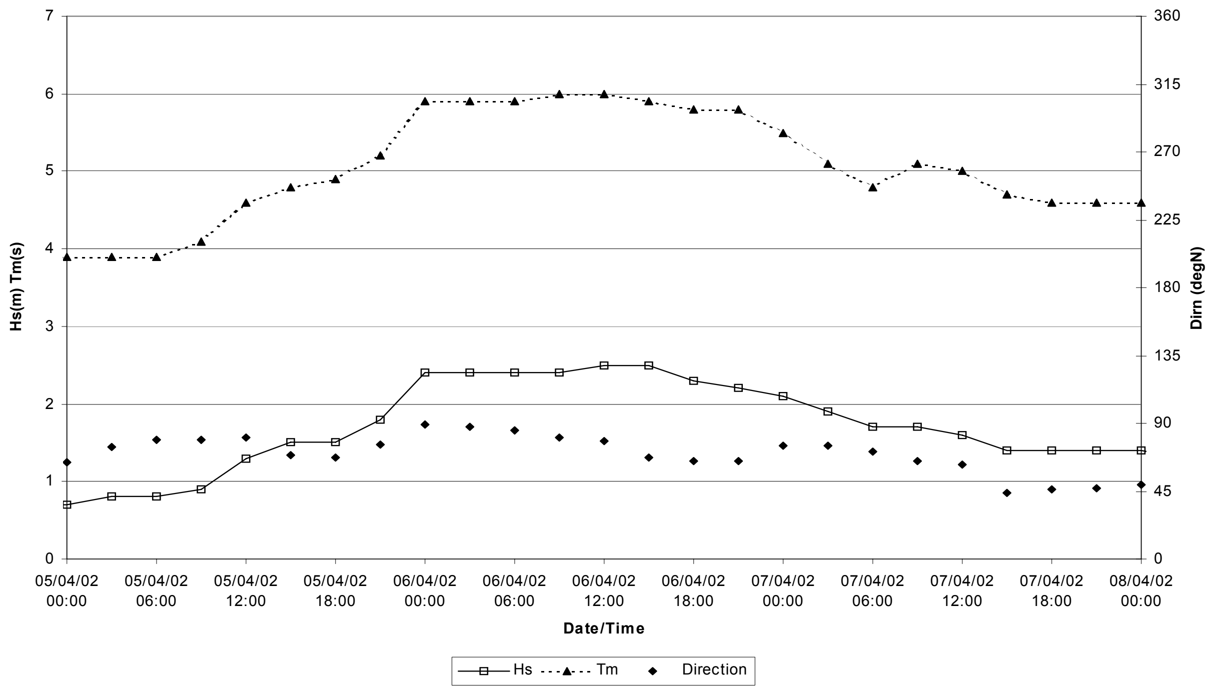

Figure 10b Met Office offshore wave data (05/04/02 – 08/04/02)

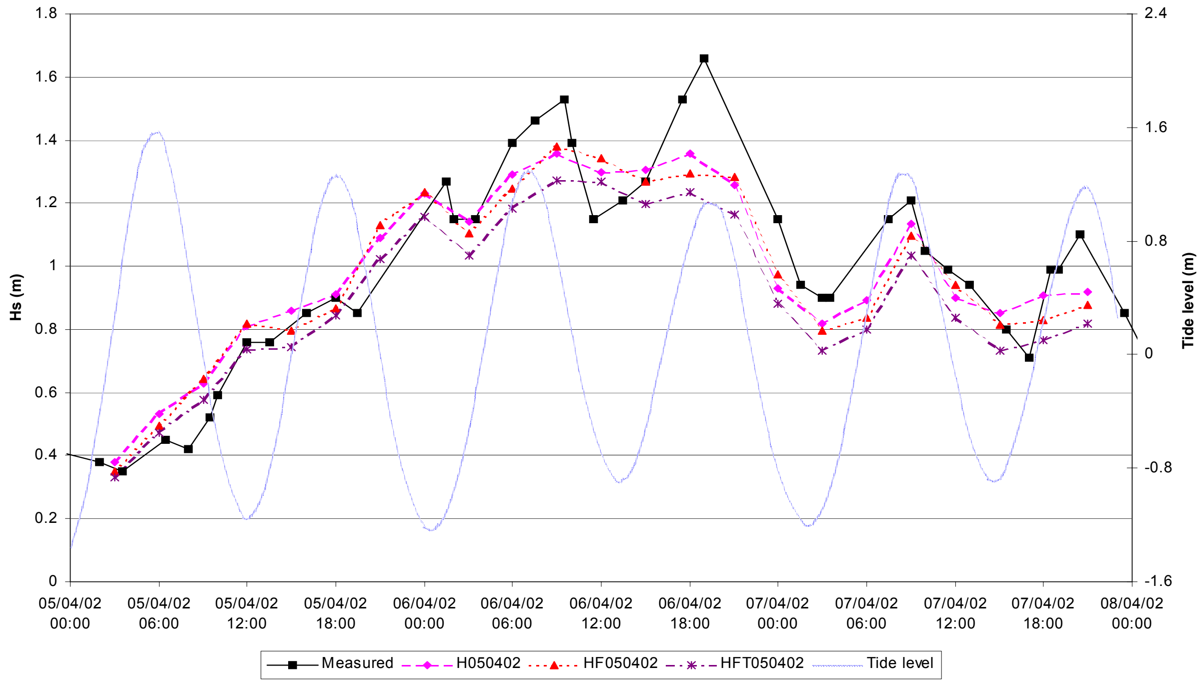

Figure 10c Measured and modelled significant wave height (05/04/02 – 08/04/02)

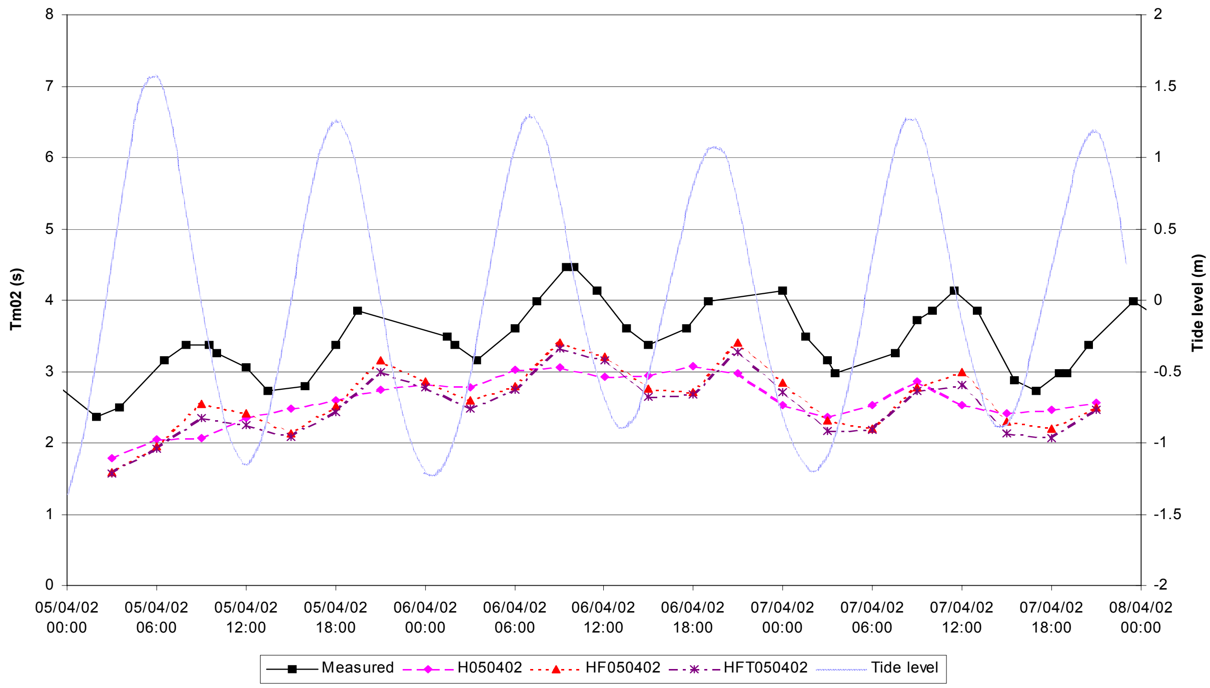

Figure 10d Measured and modelled mean wave period (05/04/02 – 08/04/02)

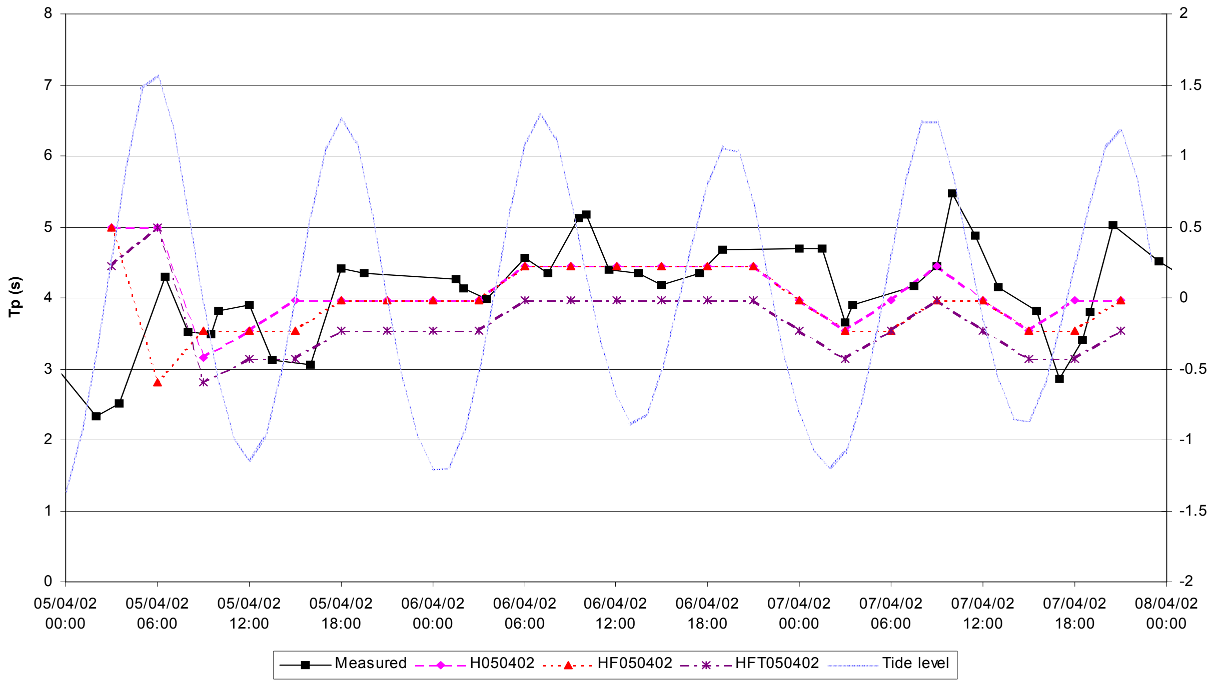

Figure 10e Measured and modelled peak wave period (05/04/02 – 08/04/02)

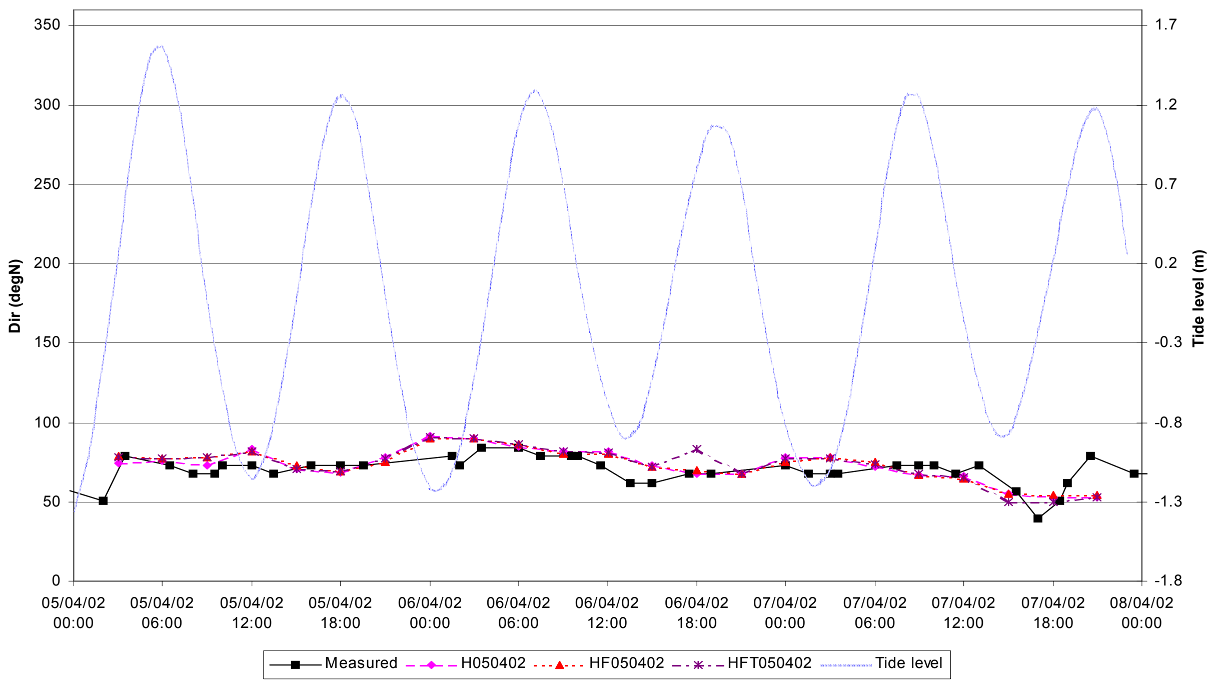

Figure 10f Measured and modelled mean wave direction (05/04/02 – 08/04/02)

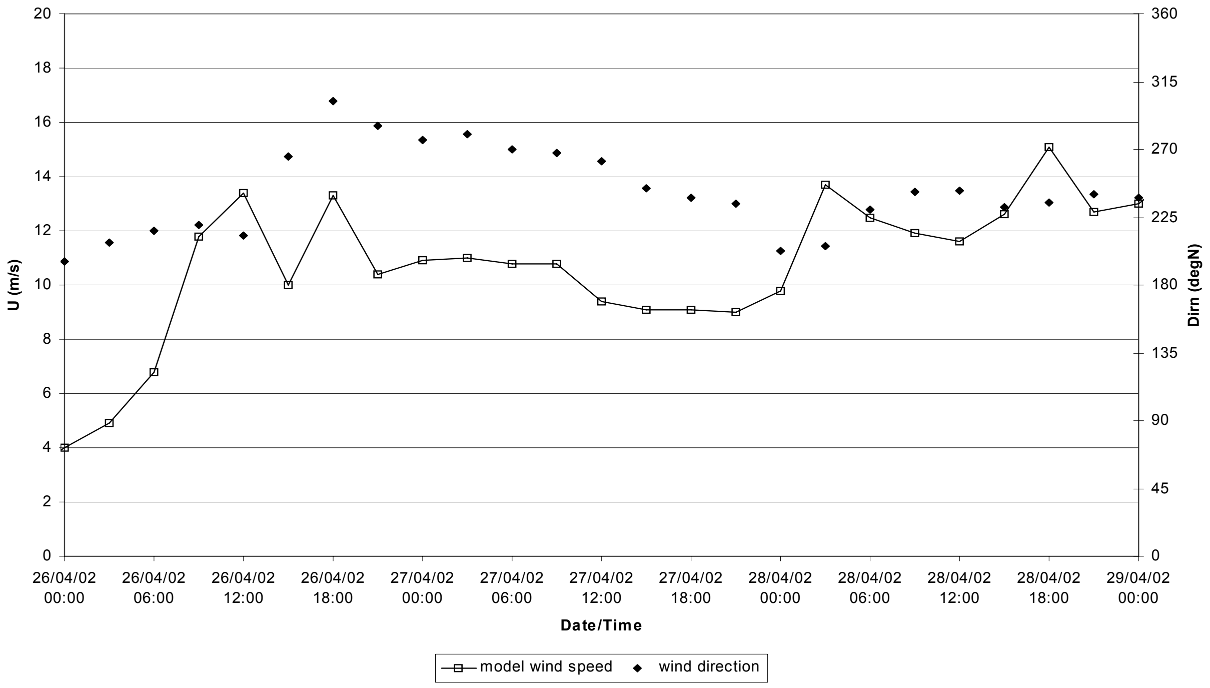

Figure 11a Met Office Model wind data (26/04/02 – 29/04/02)

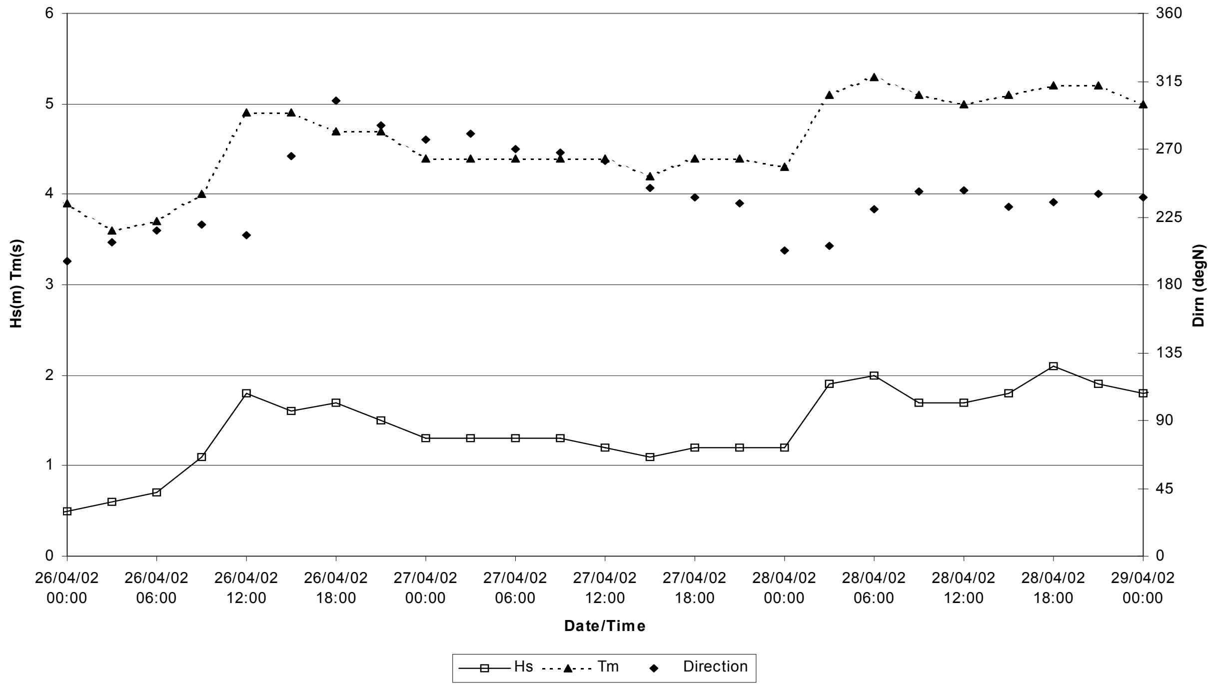

Figure 11b Met Office offshore wave data (26/04/02 – 29/04/02)

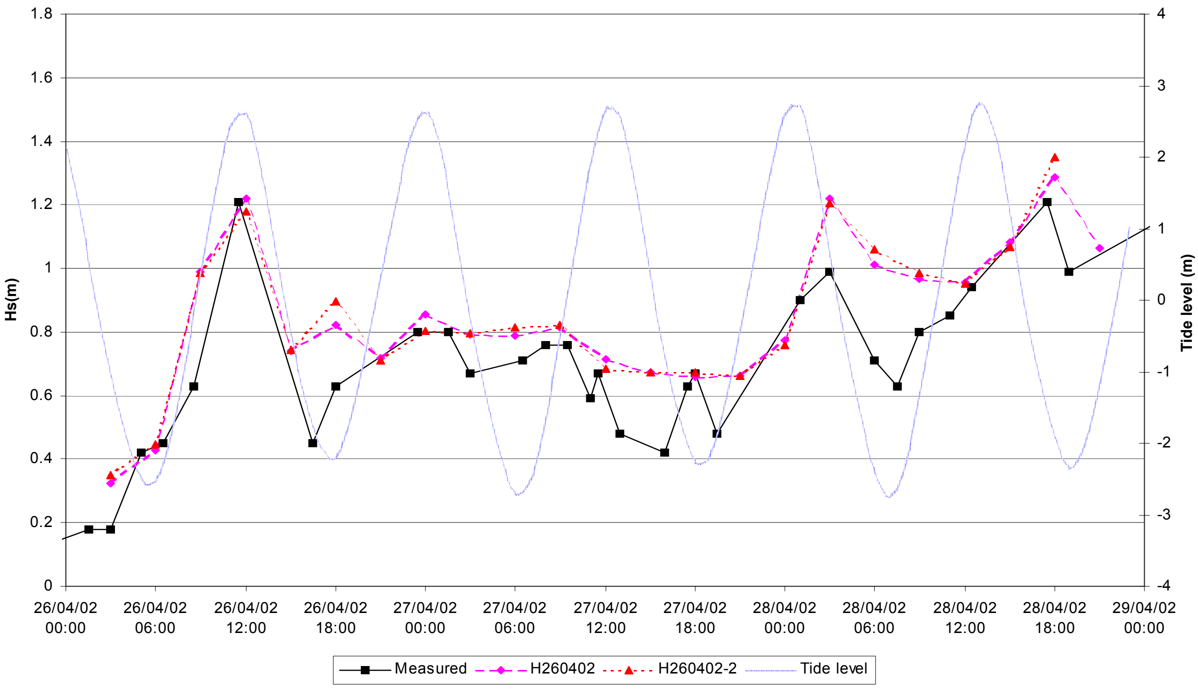

Figure 11c   Measured and modelled significant wave height (26/04/02 – 29/04/02)

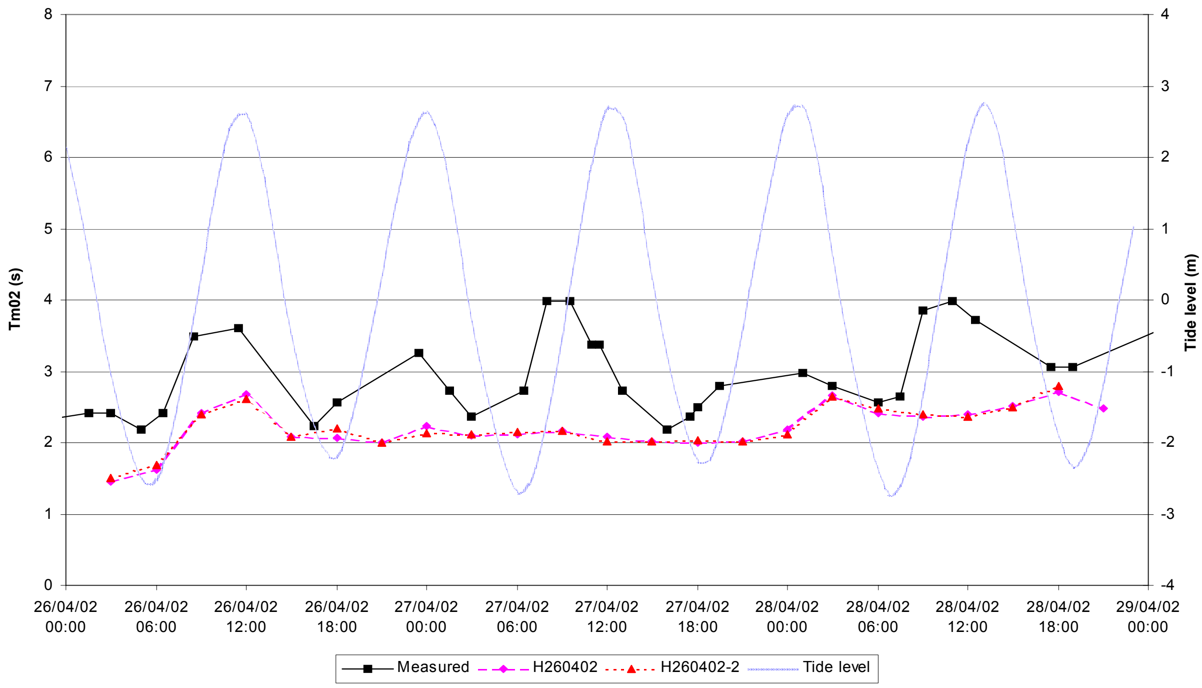

Figure 11d   Measured and modelled mean wave period (26/04/02 – 29/04/02)

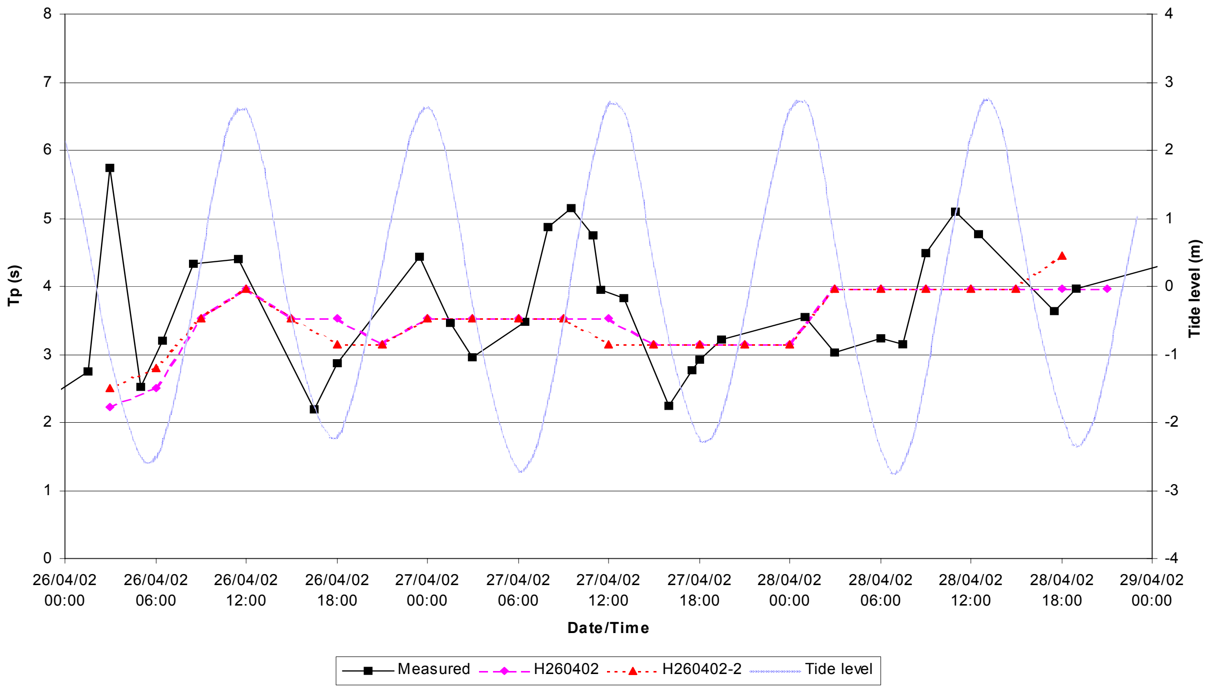

Figure 11e Measured and modelled peak wave period (26/04/02 – 29/04/02)

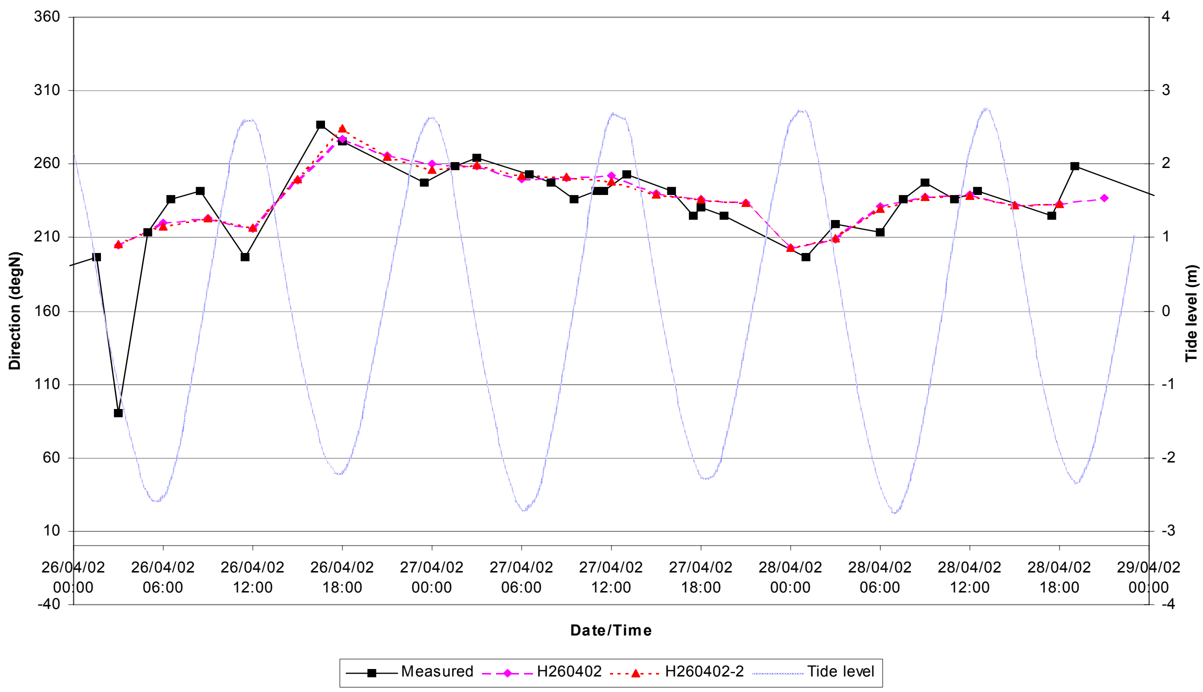

Figure 11f Measured and modelled mean wave direction (26/04/02 – 29/04/02)

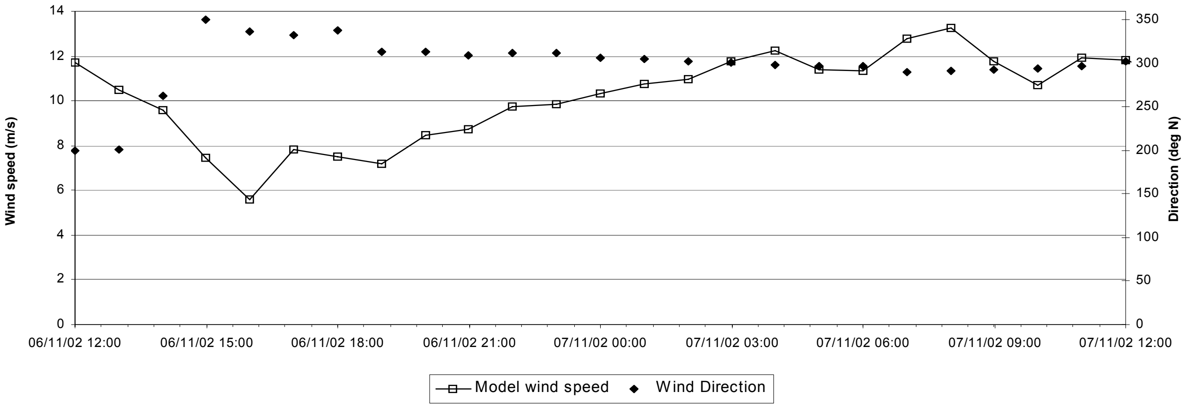

Figure 12a Met Office Model wind data (06/11/02 – 07/11/02)

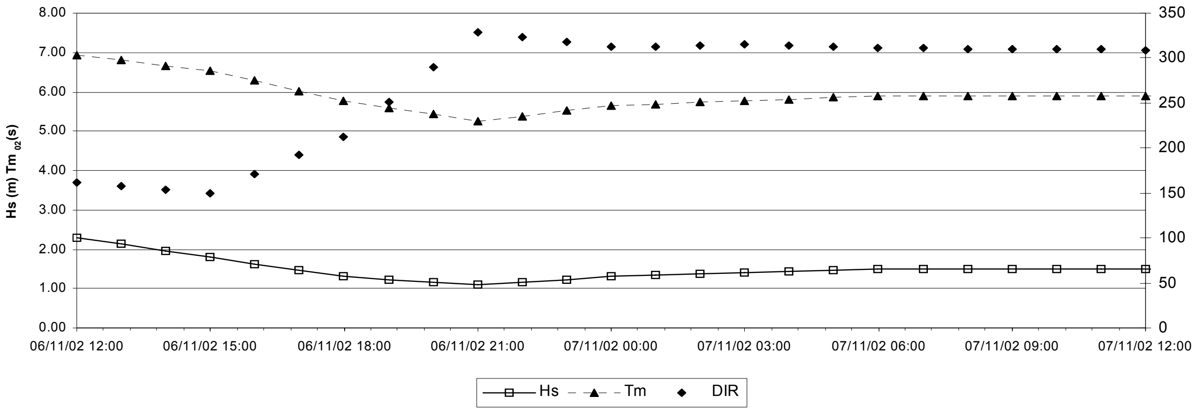

Figure 12b Met Office offshore wave data (06/11/02 – 07/11/02)

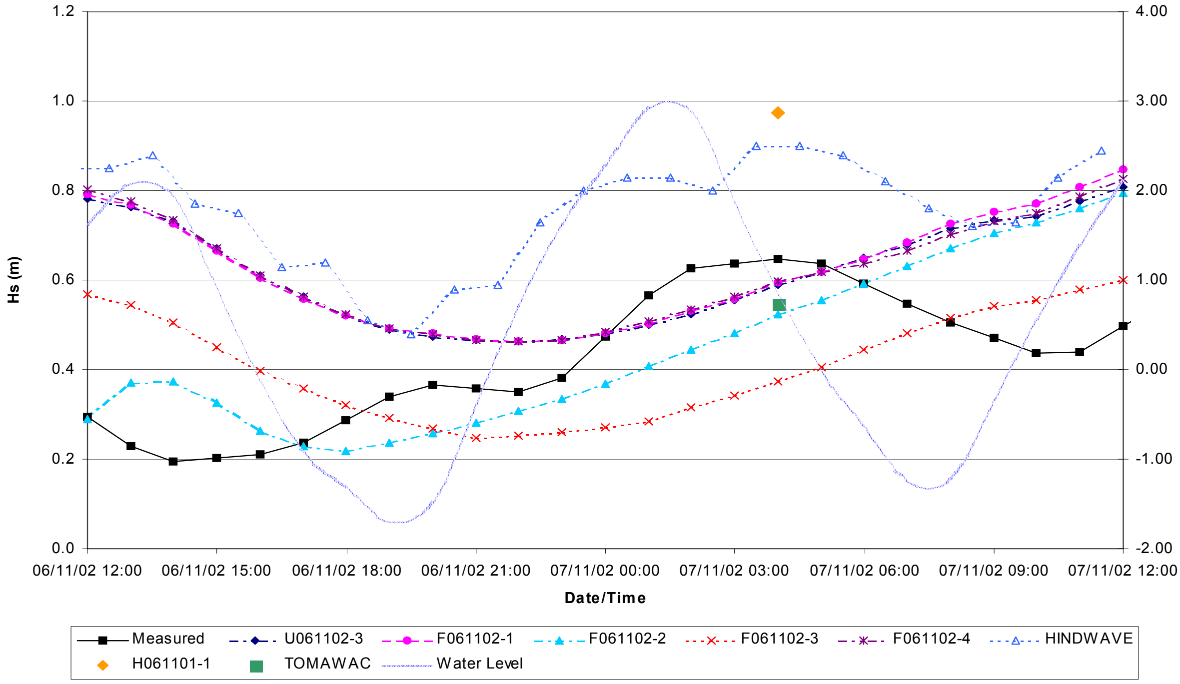

Figure 12c Measured and modelled significant wave height (06/11/02 – 07/11/02)

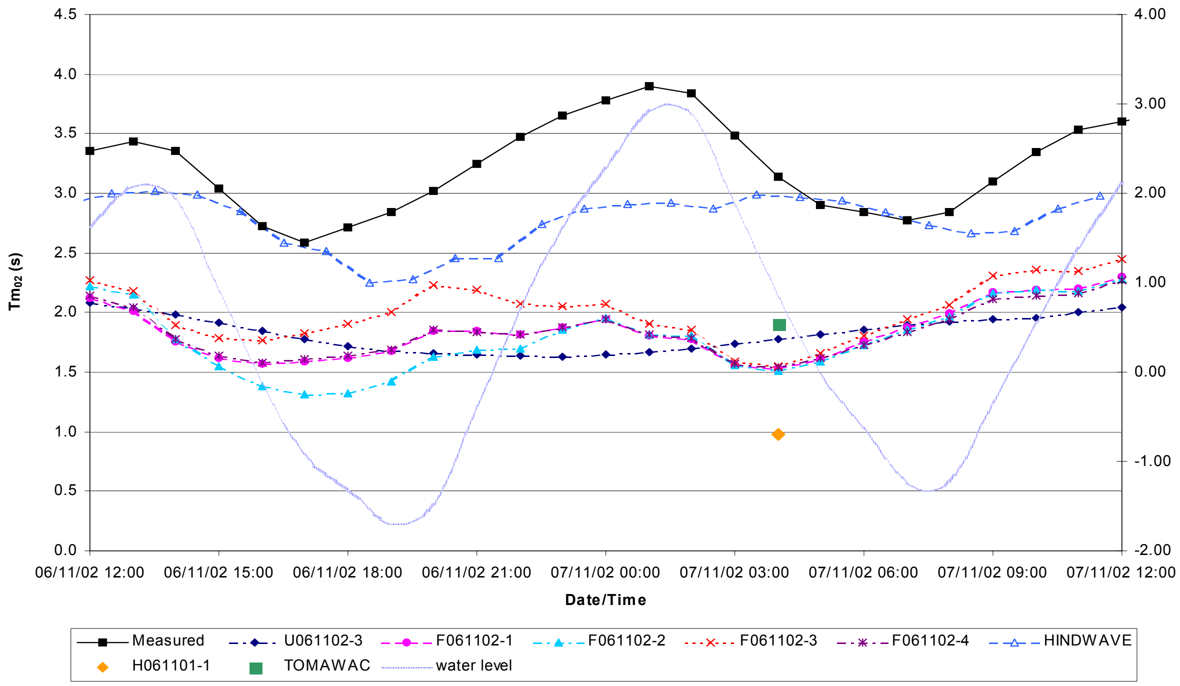

Figure 12d Measured and modelled mean wave period (06/11/02 – 07/11/02)

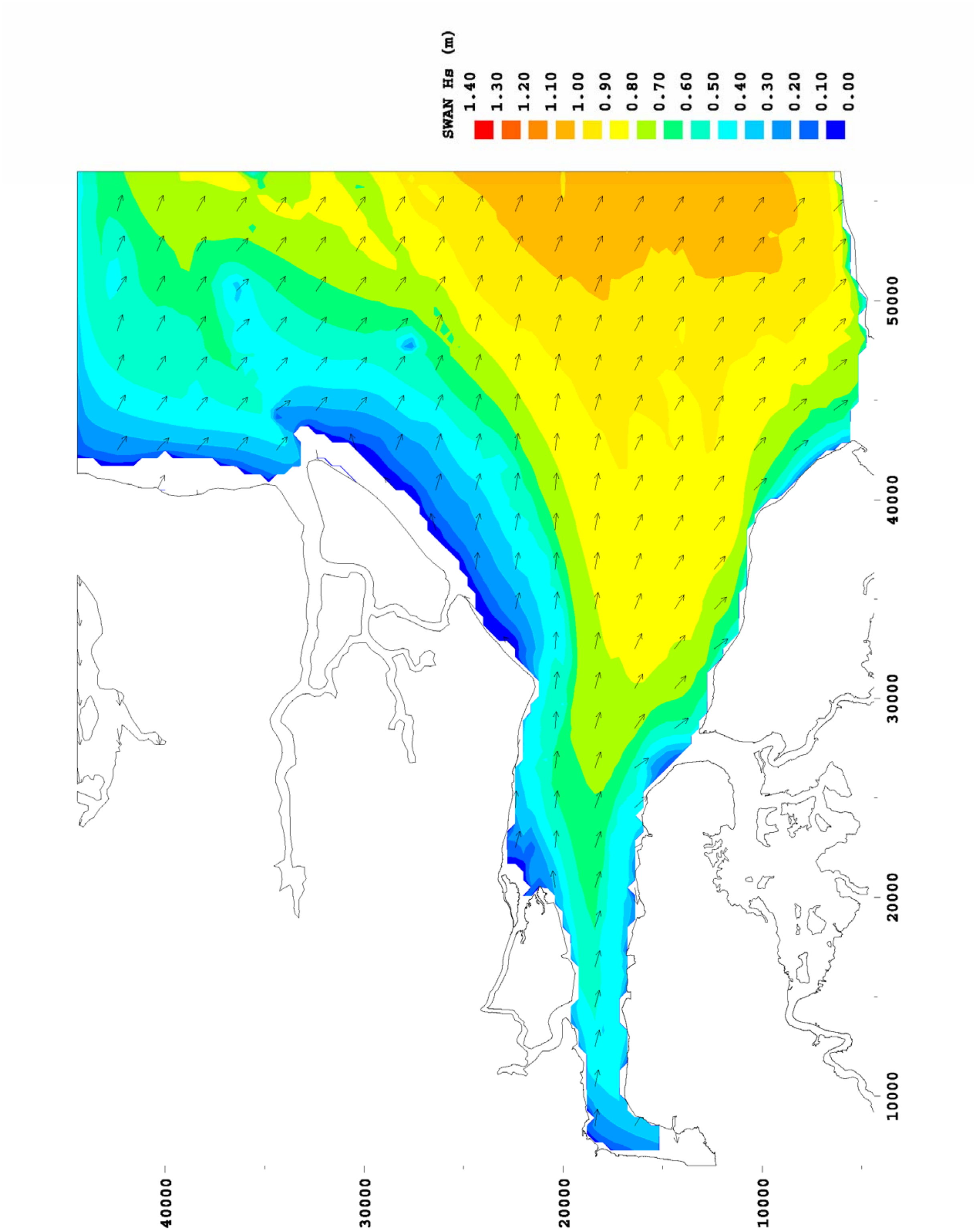

Figure 12e Predicted significant wave heights over SWAN model (Test code: H061102)

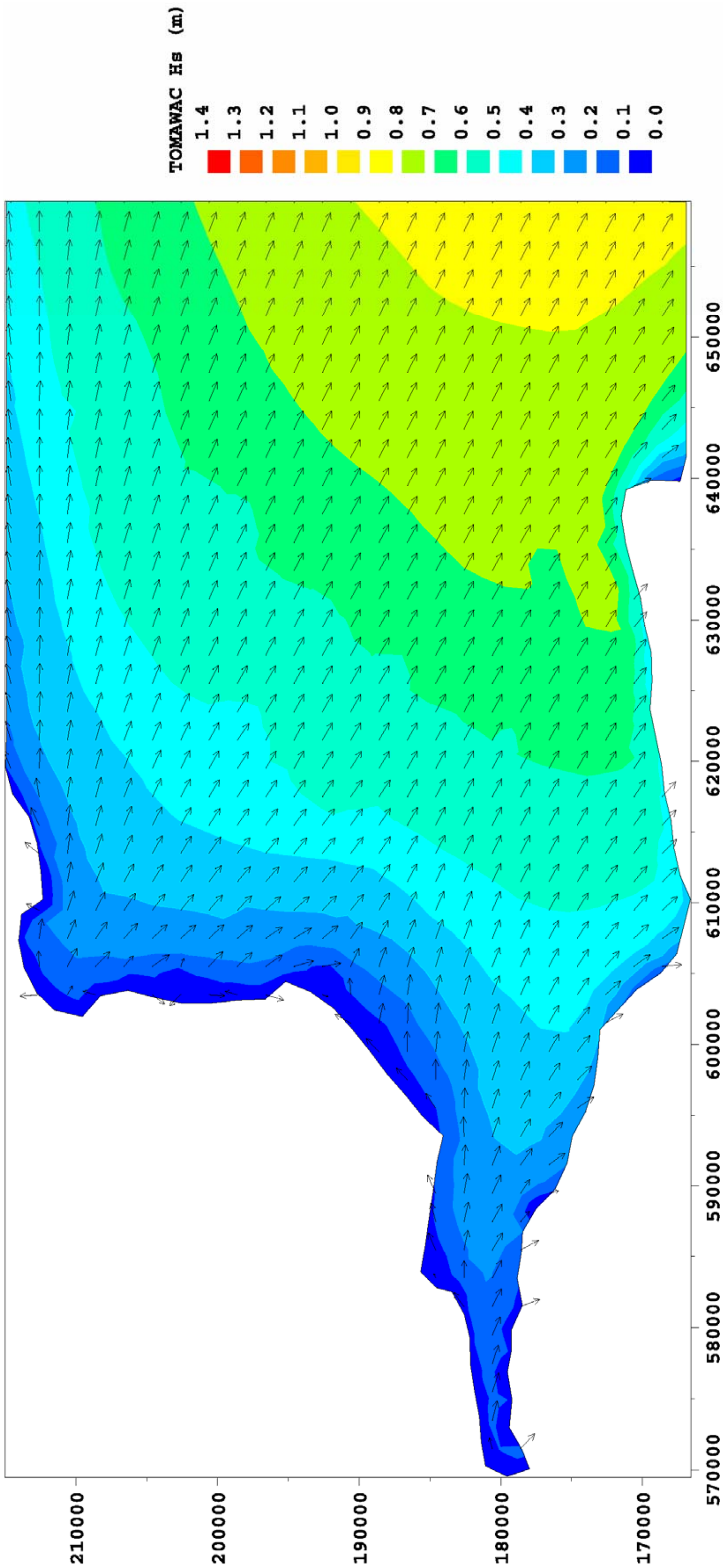

Figure 12f ***Predicted significant wave heights over TOMAWAC model (06/11/02)***

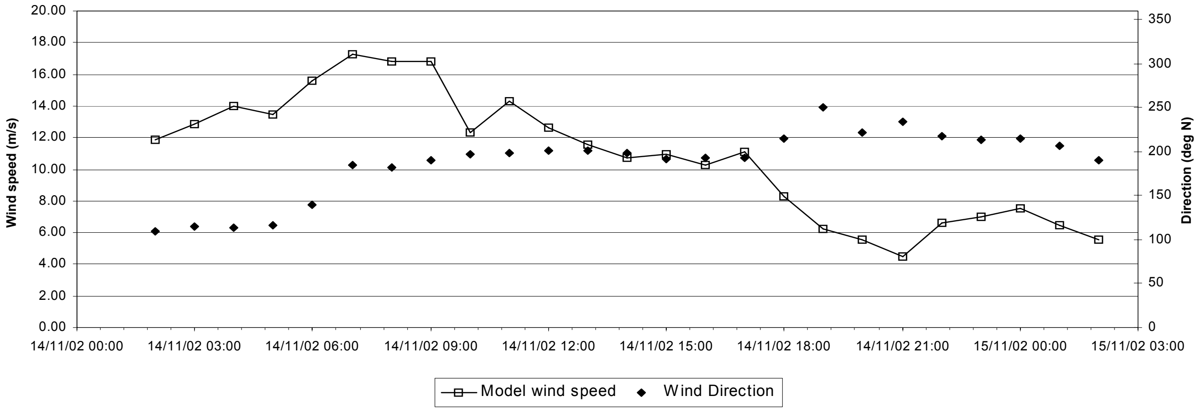

Figure 13a Met Office Model wind data (14/11/02 – 15/11/02)

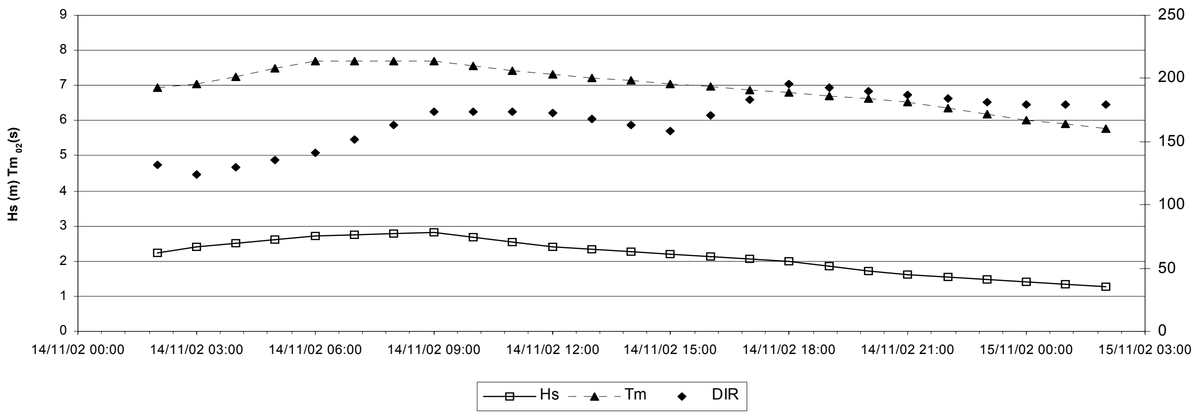

Figure 13b Met Office offshore wave data (14/11/02 – 15/11/02)

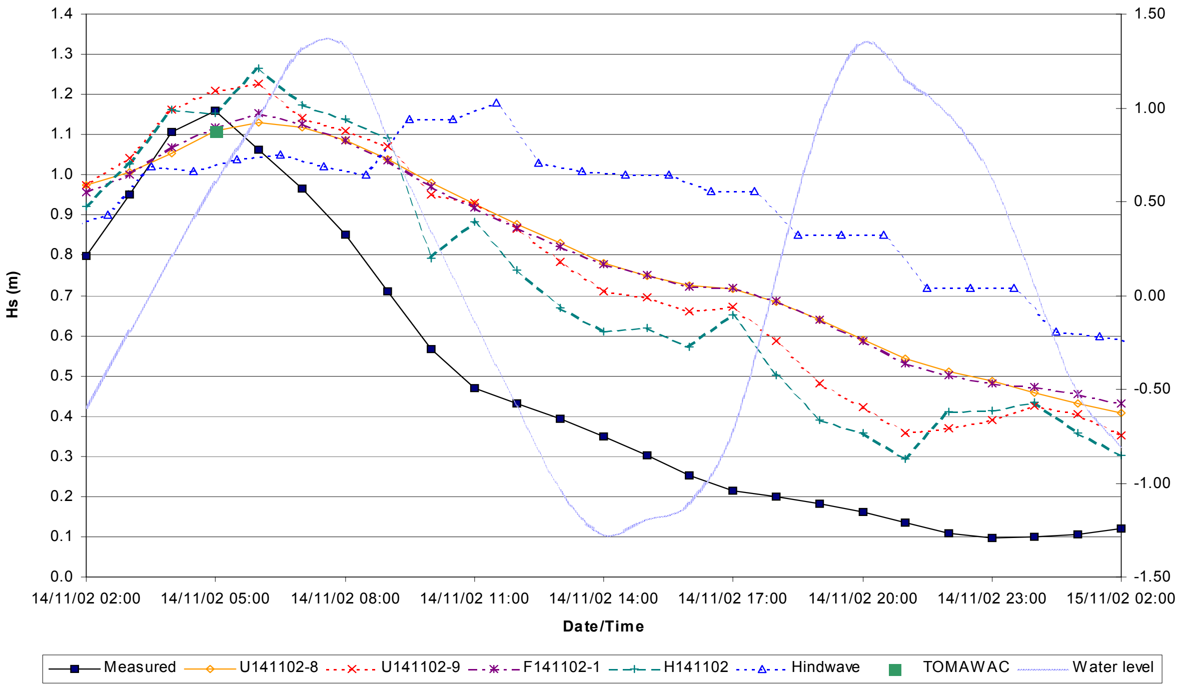

Figure 13c Measured and modelled significant wave height (14/11/02 – 15/11/02)

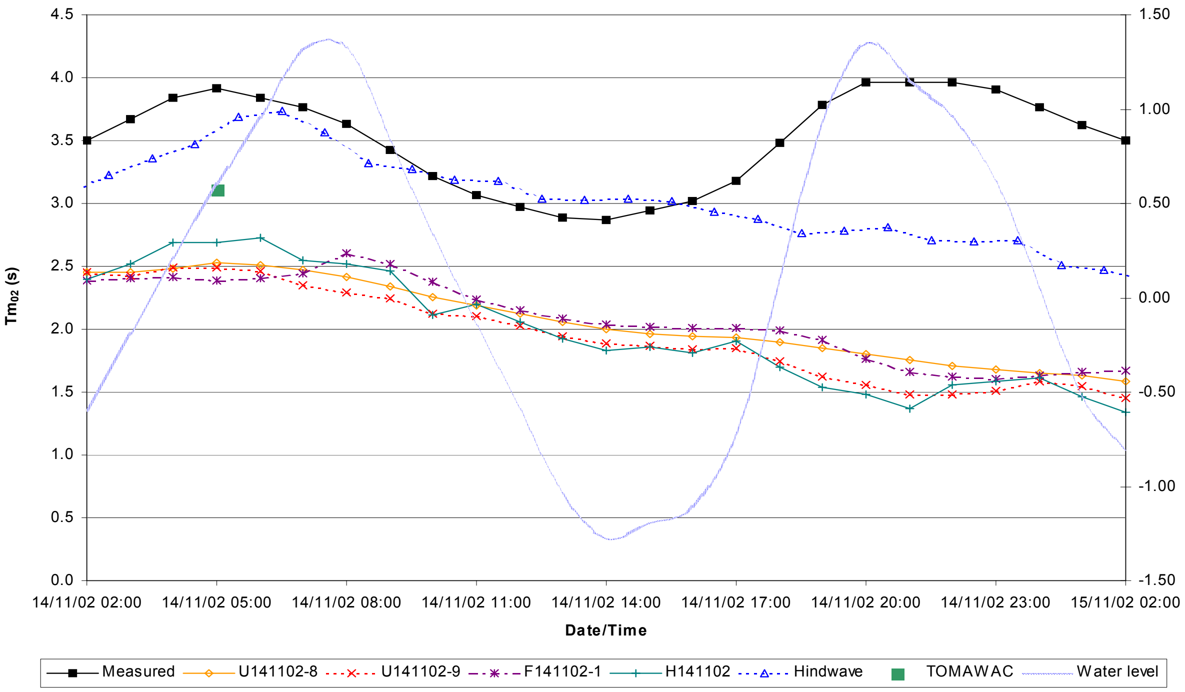

Figure 13d Measured and modelled mean wave period (14/11/02 – 15/11/02)

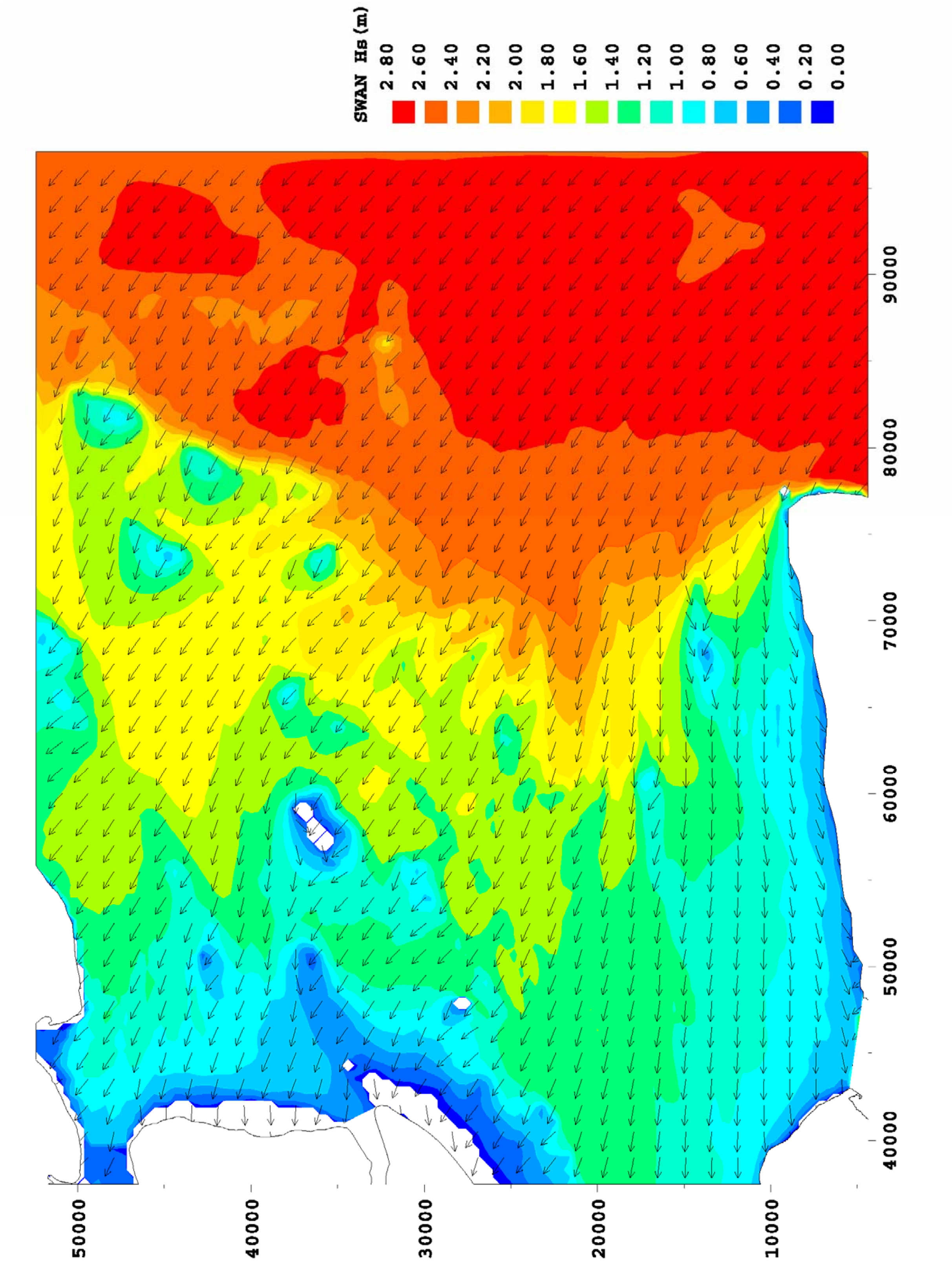

Figure 13e Predicted significant wave heights over SWAN model (Test code: H141102)

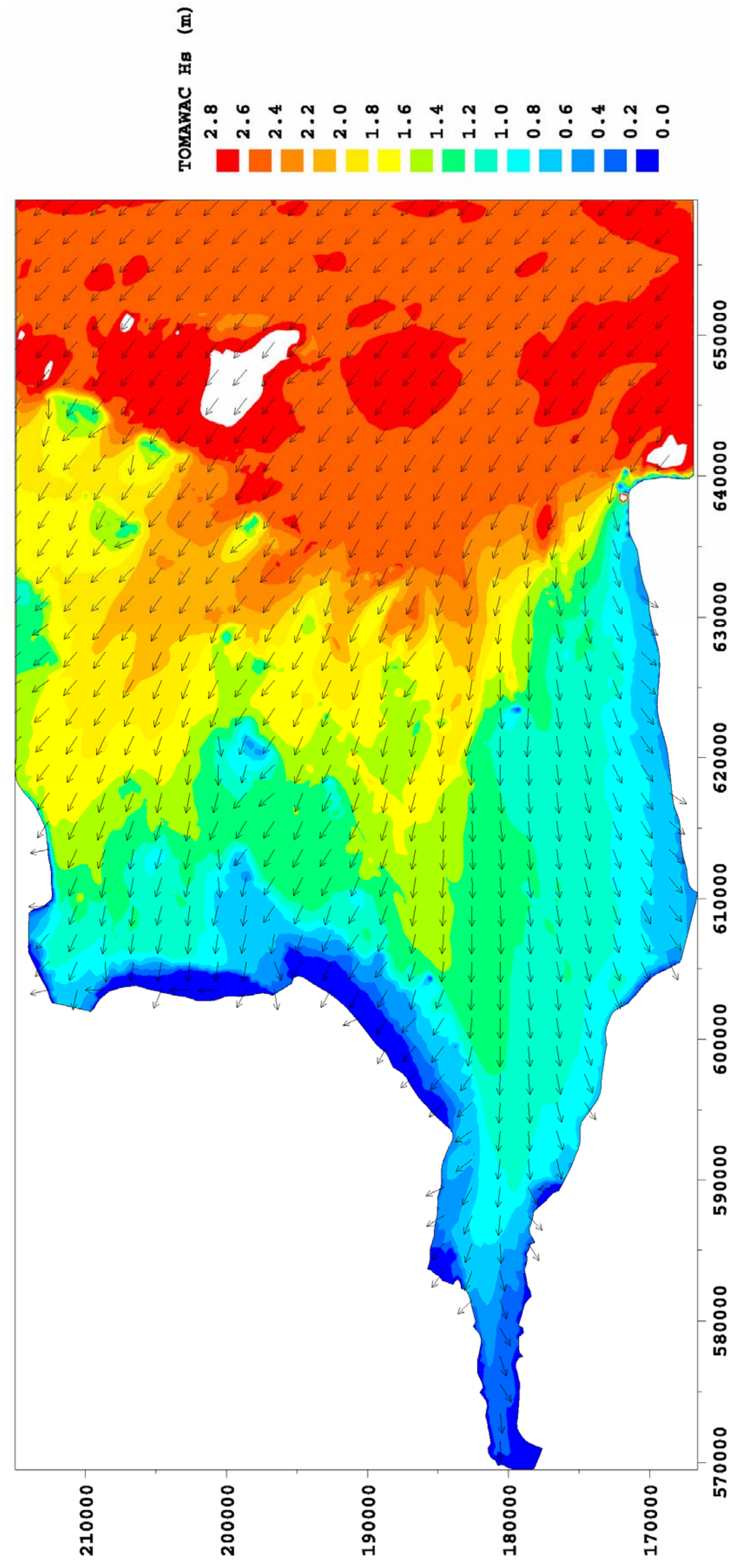

Figure 13f   Predicted significant wave heights over TOMAWAC model (14/11/02)

Appendices

Appendix A Method Algorithm (Single point wave generation and transformation models)

Aim To improve the representation of waves in estuaries with regard to changes in wave activity occurring over the tide

Scientific background

Waves in estuaries can comprise of locally generated waves and more distantly generated waves that propagate into the estuary from offshore. Both sets of waves are subject to a wide range of physical processes that makes their prediction difficult. Waves generated within the estuary will depend on the growth area, which may change shape during the tidal cycle, and the wind. These locally generated waves, and those that are generated more distantly that propagate into the estuary, will be subject to the processes of shoaling, refraction, reflection, diffraction, blocking, white-capping, and depth induced breaking. All these processes will depend on the currents and water levels associated with the tides.

There are, presently, a wide number of computational wave models that represent some of these processes, but none that represent all. Recent advances over the last 10 years has led to the development of a group of phase averaged spectral wave models that can be regarded as the present state of the art in coastal area wave models. These models are based on the research and development of models devised for wave modelling on a global scale, but with considerable research and development, that is ongoing, to incorporate representations of the shallow water processes characteristic of the coastal environment. These types of models are computationally intensive and in prediction of a long term time series of wave conditions remains impracticable. Simpler models exist, that are sufficiently computationally efficient, but at the expense of not representing as much of the physical processes.

The algorithm below describes a method for improving the representation of changes due to the tidal cycle in simple point wave models.

Improvement in understanding

The new method improves on existing methods because:

- It can improve the accuracy of the wave predictions, by accounting for the change in generation area occurring over the tide
- There is an associated increase in setup and run time which will be a function of the number of water levels in the tidal cycle considered.

Implementation

The algorithm is based on point models such as HINDWAVE that require only fetch lengths, wind speeds and directions as input.

Algorithm

INPUTS

Time series of water levels at times corresponding to model input wind data
Bathymetric detail over generation area.

OUTPUTS

Time series of wave predictions for different states of the tide that, dependent on water level, can be combined to provide a more representative prediction of wave conditions at a point.

To account for locally generated waves.

1. Measure fetch lengths radially from the point of interest to the intersection with land.
2. For fetches that extend over shallow banks their length should be restricted beyond the shallow banks so that the broken wave height can not be exceeded. Estimates of the broken wave height of 0.55 times the water depth and fetch lengths can be approximated from the standard JONSWAP curves published in a variety of sources.
3. Run the wave generation model for a time series of wind conditions to produce a set of time series of predicted waves.
4. Repeat steps 1 to 3 for a range of tidal levels to produce a time series of predicted wave conditions.
5. Combine the set of time series of predicted wave conditions dependent on the appropriate water level to produce a final time series of predicted locally generated wave conditions.

To account for the transformation of more distantly generated waves into the area of interest

1. Modify the wave model grid by introducing islands in areas where significant energy dissipation due to wave breaking is expected to occur, i.e. where the significant wave height of the offshore waves are reduced to a negligible amount or small compared with the locally generated significant wave height.
2. Run the wave transformation model using the time series of offshore wave conditions
3. Repeat steps 1 and 2 for different water levels
4. Combine the sets of time series of predicted transformed waves from offshore dependent on water level to produce a final times series of predicted transformed wave conditions.
5. Combine the time series of locally generated and transformed offshore wave conditions on an energy basis.

Limits of applicability

The algorithm only applies to models that do not already include energy dissipation due to wave breaking.

Validation

The effectiveness of the algorithm was investigated using a HINDWAVE-TELURAY model of the Outer Thames Estuary (Tozer et al, 2004, this report). Model results were compared against a reference data set based on measured wave conditions at a single point.

References

Tozer, N.P., Grey, S.M. and Ellam, T.J., (2004) Wave modelling in estuaries with regard to changes in wave activity occurring over the tide, HR Wallingford Report TR141, May 2004.

Appendix B Assumptions and simplifications in the modelling work

A number of assumptions and simplifications have been made in the application of the wave models in this study. The following list summarises a few of the more notable of them.

1. Offshore wave conditions were assumed to be uniform along the offshore boundary of the models. This simplification could be improved by interpolating from a number of offshore model points. Further improvement may be achieved by using offshore wave conditions derived from the Met Office UK Waters model which has a higher spatial resolution than the European wave model used in this study.

2. The spectral shape of the offshore wave conditions was assumed from the integrated parameters in the absence of offshore spectra. This simplification could be improved by calibration of the assumed spectra with measured spectra, or direct use of the spectra from the offshore wave model.

3. Winds were assumed to be (spatially) uniform over the model area. This assumption may be reasonable for applications over relatively small areas, but less so for large areas. Comparison of the model wind data with measured data showed good agreement at Kentish Flats. However, ideally, wind data should be interpolated from a high resolution atmospheric model and measured winds.

4. The model wind data was obtained from the Met Office European Wave Model archives held at HR Wallingford and had a relatively coarse temporal resolution (3-hourly). This could be improved by using higher temporal resolution (1-hourly).

5. The wind data ignored gusts. Gusts may have a noticeable effect on wave generation and therefore consideration of these winds may lead to improved predictions.

6. Tidal currents were selected from the nearest tidal state from either spring or neap tides. Improved agreement of wave conditions may be achieved by improving the representation of the flow patterns. This could be achieved by running the tidal state concurrent with the period of the measurements.

7. Water levels were predicted for periods when measured water levels were not available. These predictions do not include surges due to low atmospheric pressure or wind setup. Improved predictions of water levels over the area of interest, e.g. as provided by a tidal flow model may lead to an improvement in the predicted wave conditions.