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EVALUATION OF COASTAL AREA MODELLING SYSTEMS AT AN ESTUARY MOUTH

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Key Words

Tidal estuary, numerical model, information strategy, performance statistics, model evaluation.

Abstract

The hydrodynamics around the mouth of the Teign estuary (UK) have been simulated using two coastal area numerical modelling systems. Model performance statistics were calculated to assess the accuracy of the predictions of the measured currents at a number of locations around the estuary mouth. The relative mean absolute error was used as it is applicable to vectors as well as scalars and measures all types of errors. An adjusted relative mean absolute error was also used to reduce the effect of measurement error. A classification table was adopted that categorises the results according to the size of the error. In additions, time series and scatter plots were used to judge the performance of the modelling systems.

Most numerical models are run and compared to data in a subjective manner. This paper demonstrates how model performance statistics can be used to calibrate and/or validate hydrodynamic models in a more objective way. Statistics were used to compare model runs that used different amounts of data. This case study will inform the debate about the optimum mix of modelling and measurement.

Calm conditions during a spring tide were simulated, as was a relatively large storm. The two modelling systems gave more or less equal performance when run in engineering mode (where default values were used for most of the system settings). In each case, one modelling system performed better than the other at some locations and worse than it at other locations. One model was also run using a scientific approach, where different amounts of information were used to alter the model settings and sensitivity tests were performed. The modelling showed that using more data does not necessarily lead to better model predictions. New methods for incorporating data into the operation of a model need to be evaluated thoroughly before they can be used without site-specific calibration.

1 Introduction

Much effort has been spent in recent years in the development of numerical coastal area modelling systems, in order to be able to simulate the physical processes at coastal sites. These systems consist of a number of modules that simulate processes such as wave and current propagation, sediment transport and morphodynamic bed updating. Much of the work has been done using systems featuring two-dimensional, depth-averaged (2DH) flow modules, as reviewed by de Vriend (1996) and described in the intercomparison papers by de Vriend et al. (1993) and Nicholson et al. (1997). Three-dimensional flow modules are available in some systems although they are much more computationally intensive, so are rarely used for the modelling of large coastal areas. In contrast, 2DH coastal area modelling systems of hydrodynamics and sediment transport are being used increasingly for coastal zone management and consultancy studies.

There are many alternative tools for dealing with coastal areas, however, and the coastal zone manager need to decide when it is necessary to instigate a study, what tools to use (if they do so) and how to use the chosen tools. Mulder et al. (2001) state that the question of what tools to use requires an information strategy that depends on:

1 The availability of data and tools and the possibilities for monitoring and measurements
2 Availability and validity of numerical models, considering the spatial and temporal scales of interest
3 The optimum combination of tools in terms of accuracy and cost

This paper describes a case study to look at the effect of varying the combination of field experiments (the data) and numerical modelling (the tools) on the final accuracy and the cost. The study used the performance of two 2DH coastal area numerical modelling systems, applied at an estuary mouth at Teignmouth (UK) over the spatial scale of a few kilometres squared and the temporal scale of days to weeks. Such applications are best suited to providing guidelines for coastal zone management problems associated with the same time and space scales. At Teignmouth the problems include the navigability of the main shipping channel and the width of the beach.

The coastal area modelling systems used were PISCES, developed by HR Wallingford, and DELFT3D, developed by Delft Hydraulics. The simulations were performed and their predictions evaluated against current meter readings made at Teignmouth, as parts of the COAST3D project (Soulsby 1998, 2001, HR Wallingford, 2001). The case study described herein takes three parts:

1 Two tidal flow modules, from the PISCES and DELFT3D modelling systems, were driven by boundary conditions from the same regional model and their tidal currents were compared.
2 Both models were run using an “engineering approach”, utilising only a few measurements. The differences between them were then evaluated.
3 DELFT3D was run using a “scientific approach”, utilising additional data sources. The differences between the results from the model runs were used to judge the improvement resulting from using additional data and the cost of doing so.

2 The optimal mix of modelling and measurements

The Teignmouth site was modelled using the coastal area modelling systems PISCES (Chesher et al., 1993) and DELFT3D (Roelvink and van Banning, 1994). The paper is not aimed at comparing the models, although a short comparison of the flow modules is included, but is rather a comparison between modelling approaches. Increasing the number of measurements could potentially lead to better modelling results (due to better tuning and improvements in boundary conditions) so the best model results should in principle be obtained using the greatest amount of data. However, in any modelling study (with finite resources) a balance must be drawn between the collection of data and the running of the model. More data collection can only be undertaken at the expense of modelling runs and evaluation and vice versa. The optimal mix of measurements and modelling should produce a sufficiently accurate answer at an affordable cost and within a reasonable time.

In order to decide on the optimal mix a number of questions have to be asked. These include (Mulder et al., 2001):

1 What type of model should be used and what area should it cover?
2 What information is necessary to set up and run the model?
3 What data is desirable to tune the models as best as possible?
4 How much value is added by the desirable data?
5 How does the value added compare to the additional cost of providing the desirable data and incorporating it into the modelling?

2.1 What type of model and what area should it cover?

The coastal zone manager has a range of tools to draw on and must decide which processes must be included. The manager must consider, for example, whether to simulate waves and/or currents, or whether wind or density-driven currents are important?

It was decided to simulate the estuary using coastal area modelling systems, using 2DH flow modules as the area is highly complex and non-uniform. Moreover, the area of interest (roughly defined as the area affected by the estuary outflow) covers an area of about 1.5km offshore and 1.5km alongshore and the model has to extend sufficiently far from the estuary outflow that it is not affected by the outflow. This includes ensuring that any model boundary effects do not reach into the area affected by the outflow. As the inflow and outflow from the estuary drive large currents and are believed to have a major influence on the morphodynamic development of the site, a reasonable representation of the estuary is also important. Therefore the local area simulated has to be a few kilometres in each direction. There is a low river discharge into the Teign estuary (Whitehouse and Sutherland, 2000) compared to the tidal flow through the estuary mouth so stratification was considered to be unimportant. Model runs using a 3D flow module (van Ormondt, 2000) demonstrated that 3D effects were insignificant except for a limited area at the mouth of the estuary, where there were no measurement stations.

2.2 What information is necessary?

The minimum information necessary to produce nearshore tidal flows in a local model is a reasonably detailed and accurate bathymetry and boundary conditions for the flow module. The local area (detailed) models were nested within regional models, driven by tidal harmonics derived in previous studies. The regional models used here had been previously calibrated so were usable without further calibration. Therefore the nearshore tidal flows could be simulated without direct measurements in the area of interest. However, the flows and sediment transport were also affected by the wave climate so waves had to be included in the local model. Wave conditions were taken from measurements in this case. However, it is possible to derive (past) wave conditions from wind records generated by a computer model (for example from the UK Meteorological Office) or from measurements, so that wave data could have been derived without any direct measurements in the model domain. An approximate bathymetry for the local model could have been derived from charts (and the bathymetries for the regional models were derived from charts). However, in a morphologically active area such as Teignmouth it would be unwise to simulate a particular scenario without a representative bathymetry so detailed surveys of the area of interest, made as part of the COAST3D project, were incorporated into the local models.

The bathymetry, flow boundary conditions (from the regional model) and wave conditions near the offshore boundary of the local model were sufficient information to run the model. However, this minimum requirement does not include any data for verifying the accuracy of the model (or improving it by tuning) for the particular application being tested. The authors consider it necessary (rather than desirable) to calibrate and validate a new model against field data to demonstrate that the main physical processes are being well represented. A minimum level of data would be a single tide gauge or a single current meter, or the harmonics for water level or current at a point.

2.3 What data is desirable?

The type and quantity of data that is desirable depends on the availability of data and the possibilities for monitoring and measurements (part 1 of the CZM information strategy). The modeller would like as much information as possible to set up and tune the model to give the best possible results (providing there is no constraint on the budget). Desirable data include:

- Temperature and conductivity of the water, so that salinity and density can be estimated
- Estimate of freshwater inflow so the need for stratified flow (3D) modelling can be estimated
- Surface elevations known with respect to a fixed datum, for calibration or validation of flow module
- Phase-averaged currents (averaged over a few minutes, either at a point or depth-averaged) for calibration or validation of flow module
- Nearshore and offshore synoptic wave height, period (and direction) for calibration or validation of wave module
- Bed composition and grain-size distributions across the model area for calibration or validation of sediment transport module
- Bedforms and/or bed roughness for tuning of current module
- Suspended sediment concentrations for calibration or validation of sediment transport module
- Bathymetry at end of modelling period so measured bed changes can be compared to predicted

Other data, such as remote-sensing data for currents over a large area (e.g. using OSCR or X-band radar) or wave-breaking data provided by an Argus system could also be used. However, before demanding any or all of the above measurements, their availability and suitability should first be considered. If an instrument cannot be deployed at a site or is not suitable (for some technical reason) the modeller must cope without it. Once the list of available and desirable instruments is determined, two further questions (numbers 4 and 5 above) should be asked to determine the optimum mix of modelling and measurement.

2.4 How much value is added by the desirable data and at what cost?

The last two questions to be answered are:

- How much value is added by the desirable data?
- How does the value added compare to the additional cost of providing the desirable data and incorporating it into the modelling?

Unfortunately, there is no general answer to these questions – the answers will always be site-specific and problem-specific. However, a case study is used here to illustrate the difference between two approaches that will shed light on them. The approaches are:

- *Engineering approach* – where default or standard parameters are used wherever possible and only the minimum, necessary data is used in the running of the model. The result from the engineering approach is a measure of how accurate the model is, given limited site-specific data.
- *Scientific approach* – where all the available data is evaluated and where much of that data is used in the calibration and running of the model. The result from the scientific approach is a measure of how well a model can perform, given a lot of data.

In this paper, the engineering approach was used as the baseline run for model evaluation (performed mainly on current velocity using a number of model performance statistics). A number of sensitivity tests were then performed using increasing amounts of data and the improvement in the model performance was measured. This approach indicated what data/information was most essential, what was desirable and what did the most to increase model performance. An estimate of the cost (in man-days of effort, rather than the monetary cost) was balanced against changes in model performance.

3 COAST3D: a data-rich environment

This comparison between the two approaches can only be carried out in a data-rich environment. If there is not a lot of data available, there will only be a small difference between the two approaches. Here, the data from the EC MAST-III project Coastal Study of Three-Dimensional Sand Transport Processes and Morphodynamics, COAST3D (Soulsby 1998, 2001, HR Wallingford, 2001) measurement campaigns at Teignmouth, UK were used. The measurement campaigns were aimed at

1 improving the understanding of the physical processes at the sites
2 providing a detailed set of measurements for the evaluation of the present generation of coastal modelling systems.

A dense spatial coverage of instruments was used. This allowed an assessment of model performance over the entire study area. A pilot experiment and a main experiment were performed in March 1999 and October/November 1999 respectively. The Main Experiment had more instrumentation and lasted for longer than the Pilot Experiment. Measurements were made over two spring-neap tidal cycles, which allowed measurements to be made in spring and neap tides, during storms and calm periods. Moreover, there was a common set of rules for the analysis of the data, ensuring compatibility between the measurements from different institutions. The measured data from the study is available from the first author.

3.1 The Teignmouth site

Teignmouth is located on the south coast of the UK, on the western side of Lyme Bay. The site comprises a tidal inlet adjacent to a beach. The measured bathymetry at the start of the main experiment in October 1999 is shown in Figure 1. A rocky headland (the Ness) is to the south of the estuary mouth, while a spit of sand and shingle is located on the north side. The beach to the north is about 2km long, is groyned and backed by a seawall. Outside the estuary there are a number of morphologically active sandbanks. The three main sandbanks, Pole Sand, East Pole Sand and Spratt Sand are shown in Figure 1. The beach and nearshore bank system comprises mixed sediments and the sediment offshore is fine sand. The ebb tidal shoal (Pole Sand and East Pole Sand) is dredged using a small plough dredger to maintain navigability as the long-term circulation of sediment on the near-shore banks presents a real hazard to navigation. The sandbank system at Teignmouth has been studied since the mid-19th century when Spratt (1856) documented cyclic movements of the bars.

Figure 1 also shows the locations of the instrument packages (items) used in the evaluation of the models from the main experiment. Item 7 was a directional waverider buoy, used to provide input wave heights, periods and directions. Item 8 was a tide gauge on the pier. Items 3, 4, 5, 9, 14, 15, 23, 24, 25, 32 and 33 were current meters that provided point measurements of the current. Wave heights, periods and directions were available from most of the items that measured point currents, although the modelling systems were evaluated against the currents only. Item 5 was at slightly different locations before and after servicing, referred to as A and B respectively.

The site faces east and infrequent high winds from the northeast cause the highest waves. The spectral significant wave height at item 15 exceeded 0.83m for 10% of the year and 0.25m for 50% (Sutherland et al., 2001a). The mean tidal range is 1.7m on neaps and 4.2m on springs. Tidal currents rarely exceeded 0.3ms-1 about 1km offshore, but in the mouth of the estuary velocities greater than 2ms-1 can occur.

4 Numerical Modelling Systems

The Teignmouth site was simulated using the coastal area modelling systems PISCES developed at HR Wallingford (Chesher et al., 1993) and DELFT3D developed at WL | Delft Hydraulics (Roelvink and van Banning, 1994). Coastal area modelling systems are process-based and attempt to model the important phenomena deterministically (De Vriend, 1996, Nicholson et al., 1997). Both PISCES and DELFT3D comprise a number of modules for calculating flows, waves and sediment transport in complex coastal areas, with routines for linking the appropriate modules. Such modelling systems are typically applied to areas of a few square kilometres in detail over timescales of a few tides and were used at Teignmouth as the bathymetry and flow patterns are highly complex. Time variation in the wave field was simulated in a quasi-stationary manner in both models, with sequences of conditions (waves, water levels and flow fields) modelled in a single run. Preliminary results from Teignmouth were reported by Walstra et al. (2001).

4.1 PISCES (HR Wallingford)

The PISCES modules used in this study were the finite element flow module TELEMAC-2D (Hervouet et al., 1991) and the finite difference wave module FDWAVE (Southgate and Goldberg, 1989). The key processes of refraction, shoaling and breaking are represented in FDWAVE, which is based on a time-independent form of the mild-slope equation. TELEMAC-2D solves the shallow water equations including terms to represent the flow accelerations due to wave breaking. It uses an unstructured model grid of triangular elements that allows accurate boundary fitting and the ability to refine specified areas in fine detail whilst keeping the rest of the computational domain relatively coarse.

4.2 DELFT3D (Delft Hydraulics)

The DELFT3D system comprises finite-difference modules operated on a curvilinear grid system, which also allows an efficient representation of complex areas. DELFT3D used the wave module HISWA (Holthuijsen et al., 1989) and the flow module, FLOW. HISWA is a wave generation and propagation module that can be used to derive wave conditions offshore and inshore. The flow module is a hydrodynamic (and transport) simulation program that calculates non-steady flow resulting from wave, tidal and meteorological forcing on a curvilinear, boundary-fitted grid (e.g. Tanaka et al., 1988).

4.3 Model Schematisations

The flow modules of both systems were run in 2D, depth-averaged mode. Three-dimensional flow modules are available in both modelling systems, but are very computationally intensive and were not employed in this case.

Two applications of the PISCES system were used by HR Wallingford to simulate the flows at Teignmouth, a local model that included the estuary and a regional model (for currents only) that covered the whole of the English Channel and Southern North Sea, with limits approximately at Cromer in the North Sea and Dartmouth. The Tidal Flow Forum (Werner and Lynch, 1987) provided the boundary conditions and area for the PISCES regional model. The regional model had a refined grid near Teignmouth. The local model was nested directly within it and was driven by water level on the southern boundary and currents at 11 points on the offshore and northern boundaries, taken from the regional model. It included the whole of the estuary and extended approximately 7km north of the estuary mouth, 5km south of the estuary mouth and between 3.5km and 4.5km offshore. The local model mesh is shown in Figure 2 and had 16790 nodes. The smallest grid cell length was 20m and the largest about 250m. Further details of the modelling can be found in Hall et al. (2000), Sutherland et al. (2001), and Walstra et al. (2001).

Three applications of DELFT3D were used: a Continental Shelf model, a Lyme Bay regional model and a local model. The Continental Shelf model was driven by tidal harmonics. Its resolution was too low at the COAST3D site to allow the direct nesting of the local model so an intermediate model of Lyme Bay was used. The DELFT3D local model grid also includes the whole of the estuary and extends approximately 3.5km seawards and 5.5km alongshore. The smallest grid cell length was 15m and the largest was 300m. There were 11010 grid points. The local model mesh is shown in Figure 3. Further details of the modelling at Teignmouth can be found in van Ormondt (2000), Blogg (2001) and Walstra et al. (2001).

5 Model Performance Statistics

The statistics below have been used to evaluate the performance of the numerical modelling systems. Additional information on the statistics, alternative statistics and more examples of their use at Teignmouth can be found in Sutherland et al. (2001b). Let X be a set of N observed values (x1,…,xN) and let Y be a set of N predicted values (y1,…,yN) with the nth value (n = 1,…, N) of each being at the same position in space and time. These values may be scalars (wave height or water level) or vectors (currents). The mean absolute values of the observed values (set X) and the predicted values (set Y) are given by:

$$\langle |X| \rangle = \frac{1}{N}\sum_{n=1}^{N} |x_n| \tag{1}$$

$$\langle |Y| \rangle = \frac{1}{N}\sum_{n=1}^{N} |y_n| \tag{2}$$

where the angular brackets denotes an average and |x| is the modulus of x. The average could be replaced by a weighted average for points that are not evenly spread in space or time. Similarly the Mean Absolute Error is given by:

$$MAE = \langle |Y - X| \rangle \tag{3}$$

The use of the modulus makes the statistic non-analytic and thus more difficult to work with than using a root-mean-square error (RMSE). However the MAE is not as heavily influenced by outliers as RMSE (Hedges, 2001), is equally applicable to vector and scalar quantities, and includes errors of magnitude and direction in a single statistic. Note that RMSE ≥ MAE.

The quality of the modelling may be judged from the value of the Relative Mean Absolute Error:

$$RMAE = \frac{\langle |Y - X| \rangle}{\langle |X| \rangle} = \frac{MAE}{\langle |X| \rangle} \tag{4}$$

A RMAE value of zero implies a perfect match between predictions and observations. This will never, in practice, be achieved as the RMAE includes contributions from the measurement error. Van Rijn et al. (2000) discussed the errors in measurements made in COAST3D. The measurement errors were related to the physical size of the instrument, the measurement principle and the conversion principle including assumptions of applied theories. The measurement errors for velocity were estimated for different velocity ranges and combined to give an estimated average value of observed error, OE = 0.05m/s. The simplest approach to estimating the relative effect of observational errors was to compare the observational error to the mean absolute error. Another approach taken to reduce the influence of the observational errors was to subtract OE from each absolute error, thus defining an adjusted RMAE:

$$ARMAE = \frac{\langle |Y - X| - OE \rangle}{\langle |X| \rangle} \qquad (5)$$

with negative values of the numerator set to zero before averaging. As with any statistic the inherent variability of the statistic reduces as the number of samples increases. In common with other model performance statistics derived from the ratio of two quantities the RMAE and ARMAE are unbounded at the upper limit and are highly sensitive to small changes in the denominator when the denominator is small.

6 Engineering Approach: tidal flow

In order to simulate conditions dominated by tidal action, a large spring tide (range 4.7m) with low significant wave heights (Hs < 0.25m) was modelled from 08:10 GMT to 20:40 GMT on 20/3/1999. Only the flow modules were used, as the wave conditions were so low. The PISCES and DELFT3D local models used a common set of boundary conditions for this study, supplied by Delft Hydraulics from their Lyme Bay model (van Ormondt, 2000). The PISCES local model used water levels at the southern boundary and flow boundaries at the northern and offshore sides of the local model. The DELFT3D local model used water levels along the offshore boundary and velocities along the north and south boundaries. Standard settings were used in both models. The bathymetry and instrument locations are shown in Figure 4. The time series of measured and modelled water levels (at item 8) and currents (at items 06, 14, 18, 24, 25, 32 and 33) were used in the comparison. Observations and predictions from items 8, 06, 14, 24 and 33 are shown in Figure 5.

6.1 Model-data comparisons

The velocities are generally low (less than 0.25m/s in magnitude). Neither model simulates the 'blip' in the measured velocity at item 6 around 4 hours after the start of the model run, although DELFT3D simulated a smaller 'blip' shortly before then. This feature is probably due to the estuary outflow passing over the current meter. Both models have reproduced the rapid variation in velocity at item 14 just before it dried out. The largest velocities occur at item 24, between Spratt Sand and East Pole Sand and both models reproduce the main features of the currents. Neither model reproduces the small westerly offset in velocity at item 32, indeed both models predict a small mean velocity to the east. This form of offset could be an instrument problem or an error incurred through the modelling approach.

Table 1 shows model performance statistics from the pilot experiment. PISCES over-predicts the mean absolute velocities (by an average of 9%) while DELFT3D under-predicts them (by an average of ¬31%). PISCES provides the lower error in 4 cases, while DELFT3D gives the lower error in 3 cases. The difference between the average of the ARMAE values is insignificant. The statistics indicate that the flow modules are broadly comparable in quality, when run using boundary conditions from the same regional model.

Item 18 held three electro-magnetic current meters, at elevations of 0.17m, 0.57m and 0.97m above the bed. The values in Table 1 were calculated using the current meter at 0.97m above the bed. Model performance statistics were calculated using depth-averaged velocities from PISCES and the three sets of measured velocities. The ARMAE values were 0.45, 0.40 and 0.16 at 0.17m, 0.57m and 0.97m above the bed. The bed was at about -1.1m ACD so the water depth varied between 1m and 6m. This shows that there was an improvement in results when comparing to measurements made further up the water column. For a point measurement to be broadly representative of the depth-averaged current it should be made at an elevation above about 1/3 of the total water depth (Soulsby, 1997). Many of the point measurements were made at depths below this level so may be lower than the depth-averaged velocity. If so, the underestimation by DELFT3D could be greater than shown.

A classification table has been adopted, that categorises the results according to the range of value of ARMAE. The classification is shown in Table 2, along with the number of items from each model that fall into each category. Table 2 shows that PISCES has a wider spread of performance than DELFT3D, with results in the excellent and reasonable categories as well as in the good category. All the DELFT3D results are in the good category. The ranges of ARMAE for each category have been set by the authors and may be regarded as somewhat arbitrary. The ranges may be revised in the light of experience.

7 Engineering Approach: storm conditions

PISCES and DELFT3D were both run using an engineering approach during the COAST3D Teignmouth main experiment. The engineering approach utilised a minimal amount of data to set up and run the regional and local models. Default values were used for many of the parameters that can be used to tune them.

The period modelled was between 07:00GMT on 11/11/1999 and 21:00GMT on 13/11/1999, during the main experiment. The data used to set up the local models was:

1. Boat survey of bathymetry in the experimental region made between 6-8/11/1999, at the start of the period modelled, as shown in Figure 1 and described in Whitehouse and Sutherland (2001)
2. DGPS beach survey of the inter-tidal zone performed on 8-10/11/1999 (Whitehouse and Sutherland, 2001)
3. Digitised contours of 1970 survey of estuary
4. Admiralty Chart 3315 for offshore bathymetry and for shoreline
5. Tidal boundary conditions from regional model
6. Wave height, period and direction. Here measured wave data from item 7 was used rather than a statistical representation of the wave climate, or a hindcast climate for the modelled period
7. Measured wind data.

The tidal range reduced from around 3.5m to around 2.5m during the modelled period. The wave height remained relatively constant, between 1.0m and 1.6m throughout. The wave period and direction also remain steady at around 6s and 110 degrees throughout the modelled period. Freshwater input from the main river was low (compared to volume fluxes through the estuary mouth) throughout the period modelled.

7.1 PISCES modelling

7.1.1 PISCES regional modelling

In order to provide boundary conditions for the local model, the flow module of the PISCES regional model was run twice, once with wind and once without. The wind speed measured at Portland (approximately 75km to the east) was applied throughout the model domain. No waves were simulated, nor was the discharge from the Teign estuary. Currents from the regional model were compared to measured currents at items 4, 6, 32 and 33 and water levels were compared at item 8. The run with wind provided a slightly better fit to the currents and was used to provide boundary conditions for the local model. Standard values were used for bed roughness, eddy viscosity and other tuneable parameters.

7.1.2 PISCES local model

The local model was driven by the regional model, with wind from Portland and waves measured at item 7. A running filter smoothed the input wind. Default values of bed roughness, friction coefficients and wave breaking coefficients were used. Surveys made at the start of the modelling period were used to provide an up-to-data initial bathymetry in the morphologically active area at the estuary mouth. Model output was available from 18:30 GMT on 8/11/1999 until 07:00 on 22/11/1999.

7.2 DELFT3D modelling

The Lyme Bay Model was run with boundary conditions from the Continental Shelf Model, but no discharge from the Teign estuary. The resulting boundary conditions were then imposed on the local model, which was run to provide a time series of flow through the estuary mouth. A new nesting run of the Lyme Bay Model was then executed, using the discharge from the estuary, and this run provided the boundary conditions for the local model. The local model was run with different combinations of surface elevation and flow boundary conditions. The currents from the Lyme-Bay model and the local model were time-averaged over one tidal cycle and compared. The combination of velocity boundaries in the south and north and a water level boundary on the offshore side of the model gave the best similarity with the Lyme Bay Model. This arrangement of boundary types was then used for the local model runs.

7.3 Model-data comparisons

7.3.1 Time series

The model results were evaluated against the observed currents at 11 items: numbers 3, 4, 5, 9, 14, 15, 23, 24, 25, 32 and 33, shown in Figure 1. The largest storm during the measurement period was modelled. Data from the five tides between 07:00GMT on 11/11/1999 and 21:00GMT on 13/11/1999, a total length of 62 hours, were used in the model evaluation. A traditional approach to model evaluation would be to qualitatively compare the main features of the time series. In this case, however, the number (11) and duration (62 hours) of the time series (each with two components) demonstrate the difficulty in determining the quality of a model by visual comparison of the time series and by qualitative descriptions of their features.

Nevertheless, time series of currents at items 3, 4 and 24 are shown in Figure 6 for illustrative purposes, with the time series of water level at item 8 and wave height at item 7. Here the measurements are the solid line, the DELFT3D results are the dotted line and the PISCES results are the dashed line. All times are plotted from 07:00GMT on 11/11/1999.

During the storm, PISCES predicted that the estuary outflow was deflected south-east over item 03, whereas this does not show up in the measurements. PISCES did not predict this during the calm conditions either in the main experiment or the Pilot (item 3 is in approximately the same position as item 25 in the pilot experiment) so it must be caused by the contribution to the currents by the wave effects. Neither model predicted the small blips in the measured currents at item 4, which occurred almost an hour before high tide.

7.3.2 Scatter Plots

Scatterplots of the northerly (UN) against the easterly (UE) components of current reveal the distribution of current magnitudes and directions. Illustrative examples are shown for items 03, 04 and 24 in Figure 7. The observed currents, the DELFT3D currents and the PISCES currents are in the left, centre and right columns respectively.

The scatter plots show that DELFT3D tends to predict smaller variations about the shore-parallel velocities than PISCES. The scatter plots show that the measured current distributions are complex in many areas and there were considerable variations across short distances – highlighting that this case was a challenging test for the models.

7.3.3 Model Performance Statistics

The mean absolute values of the observations, $\langle|X|\rangle$, the predictions, $\langle|Y|\rangle$ and the errors, MAE, are given with the relative mean absolute errors, RMAE, and the adjusted relative mean absolute errors, ARMAE in Table 3 for the engineering approach. The observed mean currents are between two and seven times the estimated observational error of 0.05m/s. An arithmetical mean of the statistics from each column is given in the bottom line. This did not take into account the number of results at each location.

The average of the mean absolute velocities predicted by PISCES was 30% higher than the observed value. This is partly explained by the fact that depth-averaged predicted currents are being compared to point measurements of current at elevations between 0.5m and 1.2m above the bed, where the currents were likely to be lower than the depth-averaged values. The average of the mean absolute velocities predicted by DELFT3D was 20% lower than the observed value.

PISCES mean absolute errors vary between 0.053ms-1 and 0.303ms-1 and the relative mean absolute errors were between 0.53 and 3.28. The average of the calculated RMAE values was 1.17, but the average of the adjusted RMAE values was 0.80. The relatively large difference between the average RMAE and ARMAE occurred because the estimated observational error is a significant fraction of the MAE (the mean absolute difference between observations and predictions). For DELFT3D the mean absolute errors vary between 0.086ms-1 and 0.203ms-1 and the relative mean absolute errors were between 0.27 and 1.48. The average of the calculated RMAE values was 0.99, but the average of the ARMAE values was 0.61. The variability in ARMAE values was greater for PISCES than DELFT3D.

The difference between PISCES' mean ARMAE (0.80) and DELFT3D's (0.61) is entirely down to one current meter, item number 23. Excluding that would give PISCES essentially the same mean ARMAE as DELFT3D. PISCES predicted a strong westerly current at item 23 about 3 hours before high tide when no such current was measured. Item 23 is only 68m from item 24 (both are between Spratt Sand and East Pole Sand) and there were strong (>0.5m/s) westerly currents measured at item 24 at about 3 hours before high tide (Figure 7). PISCES predicted that these flows were south-westerly, however.

The classification table that had been used for the Pilot Experiment was also used to categorise the Main Experiment results according to the range of value of ARMAE. This classification is shown in Table 4, along with the number of items from each model that fell into each category.

7.4 Methods of model evaluation

The authors recommend the use of model performance statistics as a step towards a more systematic way of tuning and evaluating coastal numerical models. The strengths and limitations of such statistics should be acknowledged, however. The mean absolute error includes all forms of error in the measurements and the model simulations, including errors in amplitude, timing and mean value. In situations of complex flow patterns with rapid variations in flow speed and direction, small variations in predicting the timing of an event, for example, can lead to relatively large apparent errors. Often, the ability to predict the correct distribution of velocities will be sufficient and the timing of each event will not be important. In this case a scatterplot or cumulative probability distribution (Sutherland et al., 2001) can be used to compare the predicted and observed distribution of velocities and the limitations of statistics should be recognised.

7.5 Summary of engineering approach

Two coastal area modelling systems were run using an engineering approach, with little tuning. Time series, scatterplots and model performance statistics have been used to assess the accuracy of the modelling. The average adjusted relative mean absolute error (ARMAE) from the DELFT3D model was 0.61, whereas from PISCES it was 0.80. This difference was due to a single current meter situated between two sandbanks (Spratt Sand and East Pole Sand). There was again a greater spread in the classification of PISCES' results than in DELFT3D's. According to the classification table PISCES had more good and reasonable items than DELFT3D, which had more poor items than PISCES. PISCES however had two bad results while DELFT3D had none. Both models had one excellent result. The predicted velocities from DELFT3D were, on average, lower in magnitude than those from PISCES. The scatter plots indicated that the pattern of velocities from DELFT3D were closer to rectilinear (in an approximately shore-parallel direction) than those from PISCES.

The results were different because they used different methods of solving the equations, different boundary conditions, have different roughnesses, friction coefficients, grids and methods of interpolating bathymetric measurements onto the grid. The results illustrate the sorts of differences that can occur between different state-of-the-art numerical modelling systems run using an engineering approach.

8 Scientific Approach

8.1 Model runs and results

Delft Hydraulics also ran a series of scientific model runs to test the sensitivity of the model and to investigate the effect of using additional data in the model setup. The parameters varied with the use of additional measurements were: the water level boundary condition, the use of a spatially-varying bed roughness, and the wave update period (interval between updating the offshore wave conditions). The parameters varied (without the aid of measurements) to test the sensitivity of the model were eddy viscosity, constant bed roughness and including mass flux in the wave modelling.

The water level boundary condition was either taken from the Lyme Bay regional model (as for the Pilot experiment) or was adjusted using measured water levels at the pier (item 8). The adjustment procedure is described in van Ormondt (2000) and Blogg (2001) and gave the adjusted water level boundary condition used in model runs A to I (in Table 5).

The seabed roughness heights used were constant values of 0.18m and 0.05m and a spatially-varying roughness, derived from side-scan sonar survey of the area. The side-scan sonar was interpreted to determine the sediment type, then typical values of roughness were determined for that sediment type (Soulsby, 1997). The resulting roughnesses varied from about 0.01m to 0.20m and are shown in Blogg (2001). The smoothest areas were offshore more than 1km from the mouth of the estuary and well inside the estuary. The roughest areas were across the mouth of the estuary and on the Salty (Figure 1).

The wave conditions for the wave-current modelling were changed every 6 hours in the engineering run. They were determined from measured wave conditions at item 7. In some of the scientific runs the wave conditions were updated every hour, an approach which required additional data.

The eddy viscosity is a property of the flow, not of the fluid. It varies in space and time but a constant value was used in this modelling. Increasing the eddy viscosity generally leads to a reduction in the number of large horizontal eddies. Values of 0.3m2s-1, 0.5m2s-1 and 1.0m2s-1 were used for the eddy viscosity.

The parameters used in each model run are shown in Table 5. The engineering run is denoted by Eng, the scientific runs by the letters A – I. The resulting average ARMAE (calculated for the velocities at the 11 items used previously) and the number of items showing an improvement over the engineering run are also included. The number of model runs performed allows some conclusions to be drawn about the sensitivity of the model to different parameter settings and the effect of having additional data. These are discussed in the following two sections.

8.2 Model Sensitivity

The effect of decreasing the bed roughness from 0.18m to 0.05m was to increase the mean ARMAE by 0.07 (12% increase in the error). This can be seen by comparing run B (mean ARMAE = 0.57) with run C (mean ARMAE = 0.64).

The effect of including mass flux in the wave modelling was to decrease the mean ARMAE by 0.02 (an insignificant improvement). This can be seen by comparing run D (mean ARMAE = 1.06) with run F (mean ARMAE = 1.04).

The mean ARMAE was relatively insensitive to the eddy viscosity used. Varying the eddy viscosity from 0.3 (run D) to 0.5 (run H) and 1.0 (run I) changed the mean ARMAE from 1.06 to 1.07 and 1.04 respectively. The changes in the mean ARMAE were less than 2%.

Thus the DELFT3D local model was most sensitive to the bed roughness height used in the local model. Including mass flux in the wave modelling and varying the eddy viscosity between 0.3 and 1.0 had insignificant effects (typically less than 2%) on the mean ARMAE value calculated at 11 locations.

8.3 Effect of additional data on model performance

The effect of using the measured water levels to adjust the model water levels can be determined by comparing the engineering run and scientific run A. Adjusting the model boundary condition using the measured water level increased the mean ARMAE by 0.02 (an insignificant change). The adjustment to the model surface elevation boundary condition produced an improvement in the prediction of water levels at the tide gauge on the pier (item 8) but a small worsening in the prediction of velocities. It had been expected than improving the modelling of water level at the pier would have improved the modelling of the discharge of the Teign Estuary. This in turn was expected to improve the modelling of currents near the estuary mouth as the discharge from the estuary produced large velocities compared to the inshore tidal velocities. The fact that this improvement in surface elevation did not lead to an improvement in the predictions of velocities implies that caution should be taken in calibrating models (where velocities will be important) using surface elevations only. Surface elevations at or near the coast are relatively easy to obtain and have often been used in model calibration.

The effect of changing from a constant roughness of 0.18, to a spatially varying roughness determined from measurements was to increase the mean ARMAE by around 0.5 (80% increase in the error). This can be seen by comparing run B (0.57) with run D (1.06) or A (0.63) with run E (1.13). The use of a spatially constant roughness height has been seen by many researchers as a weakness in coastal area modelling as the actual bed roughness around an estuary entrance, such as Teignmouth, is clearly not uniform. Side-scan sonar images were interpreted in terms of bed roughness height for the model. This procedure was intended to produce a spatially varying bed roughness that reflected the actual bed roughness in a more realistic way than assuming the bed consisted of rippled sand throughout. Although it may have done so, this method of determining a spatially varying bed roughness led to a significant worsening in the model's prediction of the velocities around Teignmouth. The role of bed roughness in the operation of coastal area models needs to be investigated more thoroughly. Moreover, methods of using information on the sediment type and bedforms to generate model bed roughness need to be developed and validated before being used for consultancy studies. Work may also need to be done on methods of implementing variable bed roughness schemes as they may need to be run using different model settings.

The effect of decreasing the wave update period from 6 hours to 1 hour was to decrease the mean ARMAE by about 0.06

(roughly 10% reduction in the error). This can be seen by comparing run A (0.63) with run B (0.57) and run E (1.13) with run D (1.06).

The effect of not modelling waves during the storm, but only tides, was to increase the mean ARMAE from 1.06 (run D with wave updating every 1 hour) to 1.11 (run G, tides only). However, the mean ARMAE without wave modelling (run G) was 0.02 lower than the mean ARMAE from run E with wave updating every 6 hours. Comparing the results from run D and run G in more detail shows that run D (with waves) gave better predictions at seven locations (items 3, 4, 5, 9, 14,15 and 33) while run G (without waves) gave better results at four locations (items 23, 24, 25 and 32). Therefore the inclusion of waves in the modelling produced worse predictions in the region between the sandbanks at the mouth of the estuary. This is a region where the effect of wave breaking may be expected to have a large influence on the currents generated as the tops of the sandbanks dry out at low tide. The results indicate that the wave/current modelling in this inner region gave a poor representation of the currents. This may have been partly because the waves were not refracted by the currents in the DELFT3D model in a region where the currents are relatively strong. The modelling of waves and currents was simplified by passing water levels but not current from the flow model to the wave model. This approach saves computational time but does not model the wave-current interaction fully.

8.4 The benefits and cost of additional data

The previous section has shown how additional data, over and above the minimum necessary to run the model, were used to try and improve the accuracy of the modelling of the currents measured at Teignmouth. This additional data was:

- A side-scan sonar survey of the measurement area around the mouth of the Teign estuary.
- Water level measurements from a tide gauge attached to the pier (item 8)
- Wave data every hour from a wave buoy
- The eleven current meters used to determine the adjusted relative mean absolute errors. These were used to evaluate the model performance during the engineering approach, whereas they were used in the scientific approach to decide which settings to use.

The side-scan sonar measurements required an operator to bring the equipment to Teignmouth and deploy it on the survey vessel, m.v. Sir Claude Inglis. This was already in Teignmouth to conduct the bathymetric survey considered necessary for getting an accurate local model bathymetry in the region of interest. Two days were spent conducting the survey, then the equipment was dismounted from the survey vessel and transported back to its base. Time was spent on creating a mosaic picture from the scanned tracks and interpreting the bedforms. Approximately 50 seabed samples had to be analysed as well. This required approximately eleven man-days of additional time to produce the bedform map. The bedform map then had to be interpreted in terms of the bed roughness and the new roughness map included in the numerical model. An additional model run had to be performed and results extracted, from which statistics could be derived. The total additional time to include bed roughness in one model run was therefore about 15 man-days.

Deploying the tide gauge and tide board took two men a day. The results were then checked against readings from the tide board at least once per day. The equipment took less time to remove than it did to deploy. Analysis was not time-consuming but comparisons between the tide board and tide gauge were made. About 6 to 7 days of additional work were spent obtaining the water level data.

In order to decide which of the sensitivity tests should be used, the results had to be compared to measured currents from 11 current meters. These took about three days for a crew of three to deploy and a similar length of time to remove. Batteries had to be replaced and data downloaded from most of the instruments during the experiment. Each dataset than had to be analysed (to a common standard) and checked for inconsistencies (at least two days per dataset). The total additional cost of obtaining the 11 current time series was about 45 to 50 person days of effort.

The assessments above indicate that there was a considerable cost in obtaining the additional data used in the various model runs. Using the additional water level data produced no improvement in the accuracy of the current modelling. The method devised for using the side-scan sonar data in the modelling led to a considerable worsening in the accuracy of the current modelling. This does not mean that additional data is worthless – all the additional data collected in the COAST3D experiments were useful for what they revealed about the physical processes at the Teignmouth site. Van Lancker et al. (2002) used the side-scan sonar in a sedimentological and morphological analysis of the Teignmouth site, based on a variety of measurements. The sidescan and sediment analyses were also used in the morphological modelling of the site (HR Wallingford, 2001, Sutherland et al., 2001b, Blogg, 2001). They were used to determine the size of sediment in the model, areas of no transport and areas where the sediment was larger than the sediment modelled (and therefore where the sediment transport modules may not perform well).

Additional data (over and above that necessary to run the model) can be used to alter the settings of a coastal area numerical model to improve its performance, provided that well-established and validated methods are used. New methods (such as tried here with the sidescan sonar) need to be established and validated using extensive datasets before they can be applied in consultancy studies. Additional data is useful if it can provide additional understanding of the physical processes at a site. This understanding can then be used with the interpreted results from the numerical models in addressing coastal zone management problems. The best understanding of the physical processes at a site may still come from the joint interpretation of essentially separate measurement and modelling studies. The optimum mix will depend on time and budget restraints as well as on the availability of existing information on the study site and the problem to be addressed. In many circumstances this will comprise a detailed modelling study backed by a judicious set of measurements aimed at improving the model setup or understanding particular physical processes.

9 Summary and Conclusions

The hydrodynamics around the mouth of the Teign estuary have been simulated using two coastal area numerical modelling systems, PISCES and DELFT3D, within the COAST3D project. The estuary mouth has a complex bathymetry and a large tidal range. The flow modules were compared for tidal flow only during the Pilot experiment. Then the models' predictions were compared for storm conditions during the Main experiment. An engineering approach was followed for both cases. PISCES' local model was nested within an English Channel model, while DELFT3D's local model was nested within a Lyme Bay model, which was nested within a Continental Shelf Model. The flow modules used in the English Channel model and the Continental Shelf Model were both driven using well-established tidal harmonics. The two local models were driven by the same regional model during the calm conditions and the predictions from the models were compared. The storm was modelled using an engineering approach and a scientific approach. In the engineering approach PISCES and DELFT3D simulated conditions using standard settings, wherever possible, aided by the measured wave conditions at the edge of the measurement area. DELFT3D was also run using a scientific approach, where different amounts of information were used to alter the model's settings and sensitivity tests were performed.

Model performance statistics were calculated to assess the models' ability to reproduce the measured currents at a number of locations around the estuary mouth. The relative mean absolute error was used as it is easily applicable to vectors and measures all types of errors. These include measurement error as well as mean, amplitude and timing errors in the modelling. An adjusted relative mean absolute error (ARMAE) which takes account of measurement error, was also used to try and reduce the effect of measurement error. A classification table was adopted that categorises the results (as excellent, good, reasonable, poor or bad) according to the range of ARMAE.

Both PISCES and DELFT3D ran in a stable manner, despite the large wetting and drying areas modelled. The two flow models produced very similar average errors when driven by the same boundary conditions for a calm spring tide during the pilot experiment. PISCES, however, produced a wider range of ARMAE (classified as excellent, good and reasonable) while all the DELFT3D predictions were classified as good.

The models' predictions differed rather more for the storm simulation. Both local models reproduced many of the observed features in the velocity time series. The measured time series were, in many places, highly irregular, especially around the inter-tidal sandbanks. PISCES produced higher mean absolute velocities than were measured, while DELFT3D produced lower. DELFT3D had the lower average ARMAE (0.61 compared to 0.80) but the difference was due to the results from a single location. DELFT3D produced the more accurate modelling at 6 locations, while PISCES was more accurate at 5 locations. PISCES had a greater variability in ARMAE than DELFT3D. PISCES produced more good and reasonable results than DELFT3D, but it also produced two bad results (while DELFT3D had none). DELFT3D produced more poor results than PISCES.

The results from the simulations using the engineering approach indicated the sort of similarities and differences that can be obtained from applying two state-of-the-art coastal area numerical models to the same problem, using a similar approach. The models were run using standard settings wherever possible, yet still reproduced many of the complex flow features measured.

A sensitivity analysis was performed using DELFT3D. The DELFT3D model was most sensitive to the bed roughness height used in the local model, with the mean ARMAE increasing by 12% as the bed roughness decreased from 0.18m to 0.05m. Including mass flux in the wave modelling and varying the eddy viscosity between 0.3 and 1.0 had insignificant effects (typically less than 2%) on the mean ARMAE value calculated at 11 locations.

The scientific approach used additional data collected during the experiment to alter the Lyme Bay model boundary conditions and to produce a spatially varying bed roughness map. Altering the regional model boundary conditions using measured surface elevations at the pier improved the modelled surface elevations at the pier, but did not improve the ability of the model to predict the observed currents. Model tuning should therefore be directed towards a particular aim and data collected accordingly.

Side-scan sonar was used to produce a spatially varying bed roughness in the local model. This significantly worsened the prediction of velocities. The role of bed roughness in the operation of coastal area models needs to be investigated more thoroughly. Moreover, methods of using information on the sediment type and bedforms needs to be developed and validated before being used for consultancy studies.

The paper has used a case study to look at how the accuracy of a model varies with the way it is used and the amount of data used to set the model up and run it. This should inform the debate over the optimal mix of measurement and modelling to be carried out when addressing coastal zone management problems. The case study has shown that using more data does not necessarily lead to better model predictions. New methods for incorporating data into the operation of a model need to be evaluated thoroughly before they can be used without site-specific calibration. This does not mean that additional data is worthless – all the additional data collected in the COAST3D experiments were useful for what they revealed about the physical processes at the site.

The evaluation of new techniques can only be carried out using extensive datasets, such as the COAST3D dataset collected at Teignmouth (UK) as used in this study.

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12 Tables

Table 1. Error statistics from PISCES and DELFT3D flow modules, using common boundary conditions.

		PISCES				DELFT3D			
Item	<|X|>	<|Y|>	MAE	RMAE	ARMAE	<|Y|>	MAE	RMAE	ARMAE
6	0.123	0.137	0.084	0.69	0.31	0.071	0.094	0.76	0.37
14	0.090	0.094	0.060	0.67	0.27	0.102	0.077	0.86	0.39
18	0.104	0.108	0.055	0.52	0.16	0.087	0.074	0.71	0.30
24	0.192	0.185	0.073	0.38	0.15	0.155	0.097	0.50	0.26
25	0.108	0.161	0.106	0.98	0.53	0.056	0.069	0.64	0.24
32	0.094	0.081	0.102	1.09	0.56	0.034	0.083	0.88	0.36
33	0.081	0.097	0.058	0.72	0.22	0.039	0.064	0.79	0.30
Mean	0.113	0.123	0.077	0.72	0.31	0.078	0.080	0.73	0.32

Table 2. Error classification and categorisation of results from tidal flow modules.

Classification	Range of ARMAE	No. items in class, PISCES	No. items in class, DELFT3D
Excellent	<0.2	2	0
Good	0.2 – 0.4	3	7
Reasonable	0.4 – 0.7	2	0
Poor	0.7 – 1.0	0	0
Bad	> 1.0	0	0

Table 3. Model performance statistics from the engineering approach

		PISCES				DELFT3D			
Item	<|X|>	<|Y|>	MAE	RMAE	ARMAE	<|Y|>	MAE	RMAE	ARMAE
3	0.097	0.226	0.170	1.76	1.30	0.095	0.086	0.89	0.46
4	0.114	0.136	0.084	0.73	0.33	0.068	0.141	1.23	0.80
5	0.098	0.125	0.053	0.53	0.16	0.056	0.087	0.88	0.43
9	0.123	0.128	0.114	0.92	0.54	0.101	0.135	1.10	0.71
14	0.259	0.206	0.303	1.17	0.98	0.176	0.203	0.78	0.60
15	0.094	0.165	0.110	1.17	0.69	0.101	0.116	1.23	0.73
23	0.085	0.285	0.278	3.28	2.69	0.126	0.118	1.39	0.86
24	0.282	0.211	0.234	0.83	0.66	0.189	0.230	0.82	0.64
25	0.388	0.528	0.175	0.45	0.33	0.333	0.105	0.27	0.15
32	0.100	0.121	0.100	1.01	0.56	0.083	0.147	1.48	0.99
33	0.098	0.120	0.097	0.99	0.52	0.051	0.077	0.79	0.34
mean	0.158	0.205	0.156	1.17	0.80	0.125	0.131	0.99	0.61

Table 4. Error classification plus number of items from each model that fall in each class.

Classification	Range of ARMAE	No. items in class, PISCES	No. items in class, DELFT3D
Excellent	<0.2	1	1
Good	0.2 – 0.4	2	1
Reasonable	0.4 – 0.7	5	4
Poor	0.7 – 1.0	1	5
Bad	> 1.0	2	0

Table 5. Model set-up for engineering and scientific simulations, plus mean ARMAE and number of items with ARMAE lower than in engineering run.

Run	Water Level	Wave update period	Mass flux	Roughness height	Viscosity m^2s^{-1}	Mean ARMAE	Improved items
Eng	LB Model	6 hours	No	0.18m	0.3	0.61	–
A	Adjusted	6 hours	No	0.18m	0.3	0.63	2
B	Adjusted	1 hour	No	0.18m	0.3	0.57	6
C	Adjusted	1 hour	No	0.05m	0.3	0.64	4
D	Adjusted	1 hour	No	varying	0.3	1.06	1
E	Adjusted	6 hours	No	varying	0.3	1.13	2
F	Adjusted	1 hour	Yes	varying	0.3	1.04	1
G	Adjusted	No waves	–	varying	0.3	1.11	2
H	Adjusted	1 hour	No	varying	0.5	1.07	1
I	Adjusted	1 hour	No	varying	1.0	1.04	1

13 List of Figure Captions

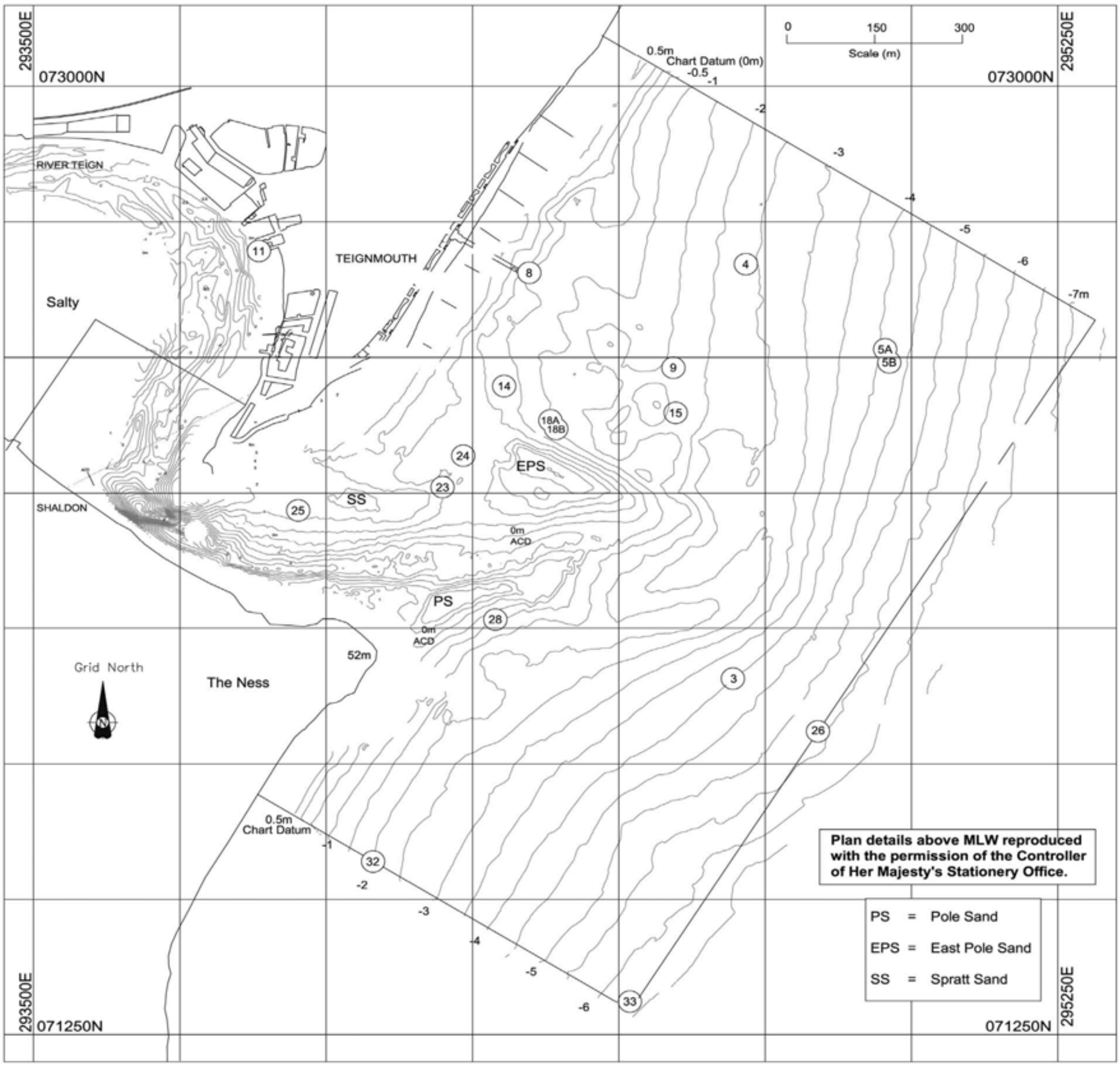

Figure 1. The Teignmouth site at the start of the main experiment, showing measurement locations used in model validation.

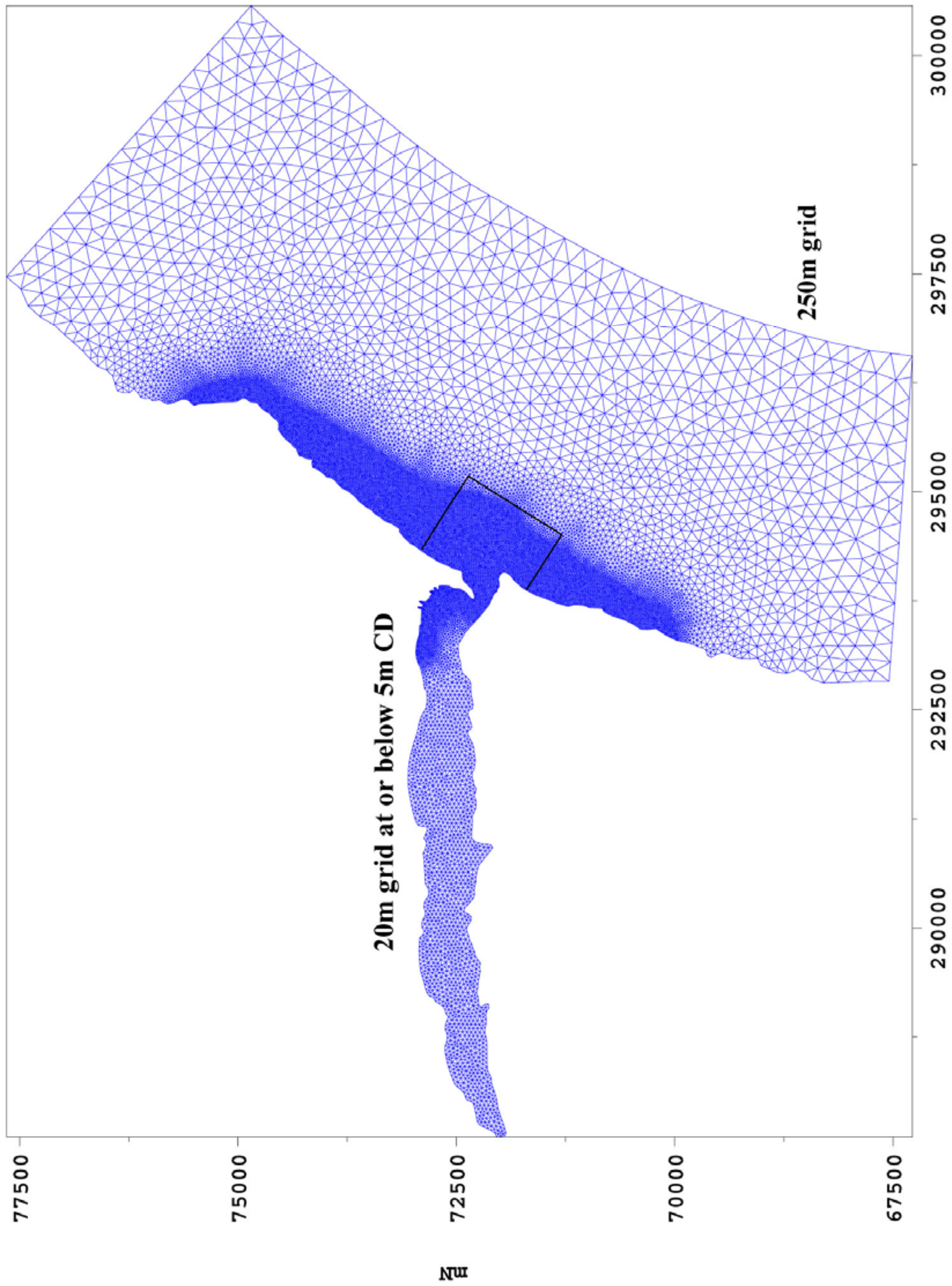

Figure 2. Local flow model grid for PISCES

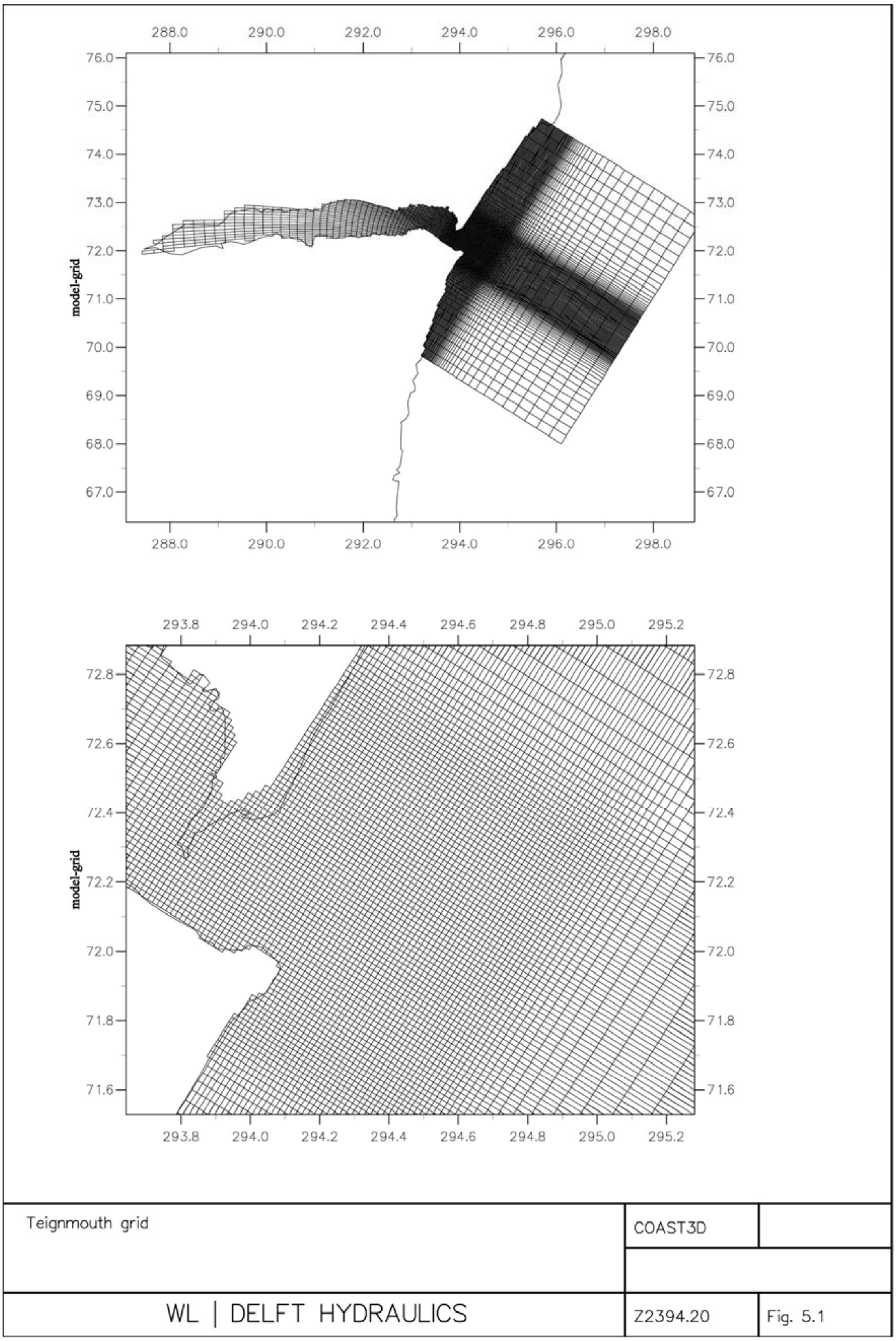

Figure 3. Local flow model grid for DELFT3D

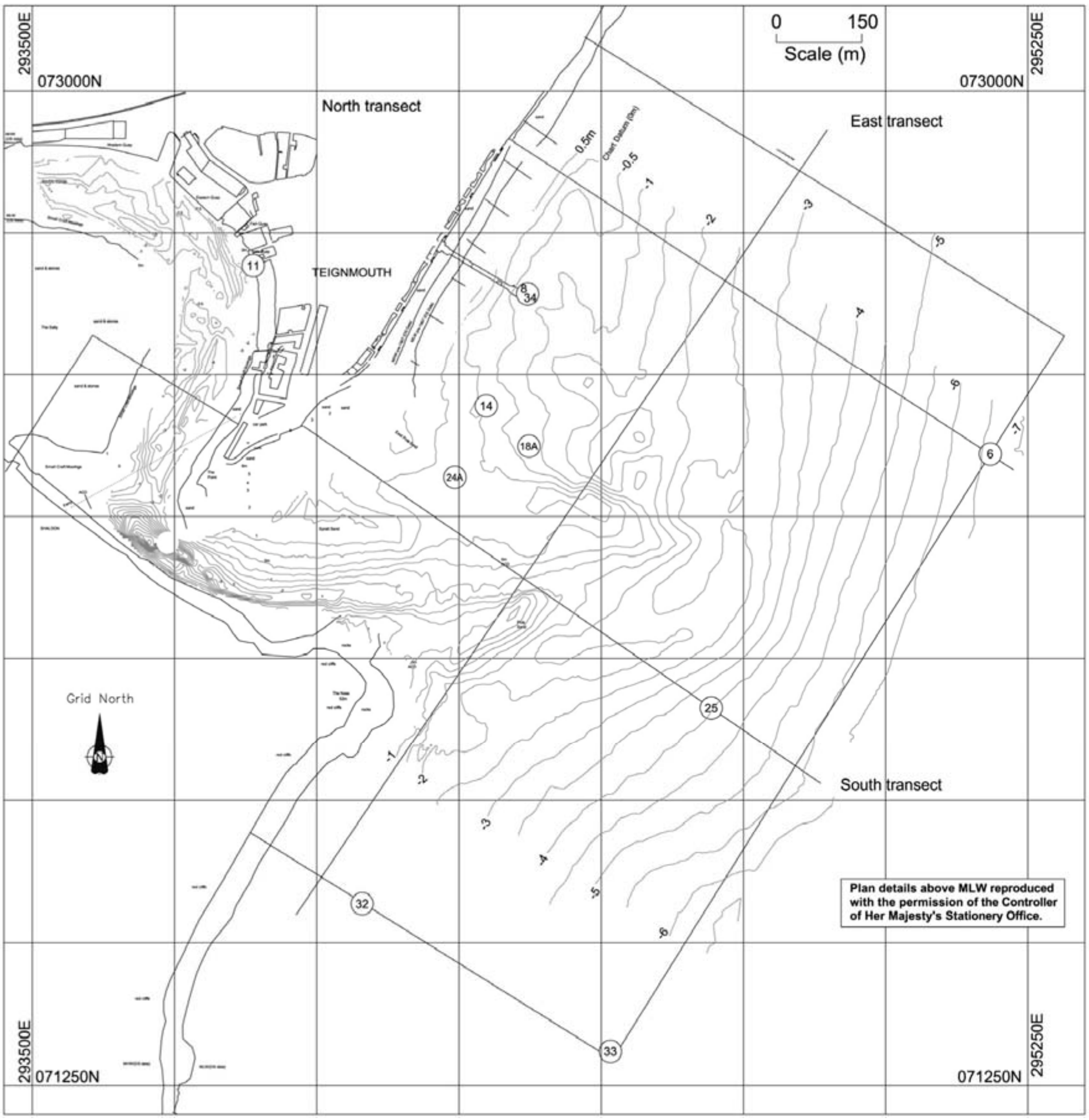

Figure 4. Bathymetry and location of instruments during pilot experiment.

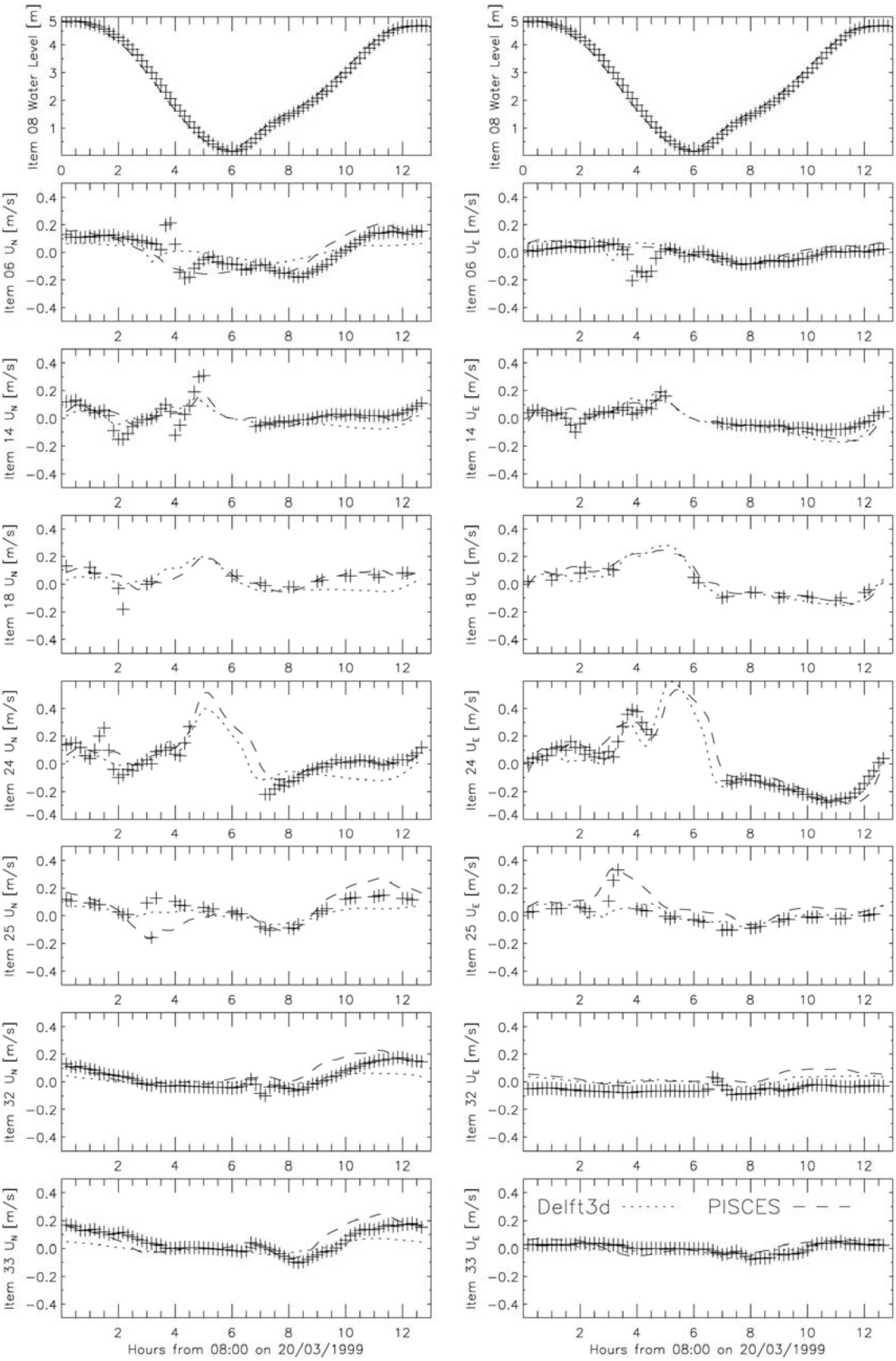

Figure 5. Observed (+) and predicted water levels and currents through a spring tide (no waves). Dotted line is from DELFT3D and dashed line is from PISCES.

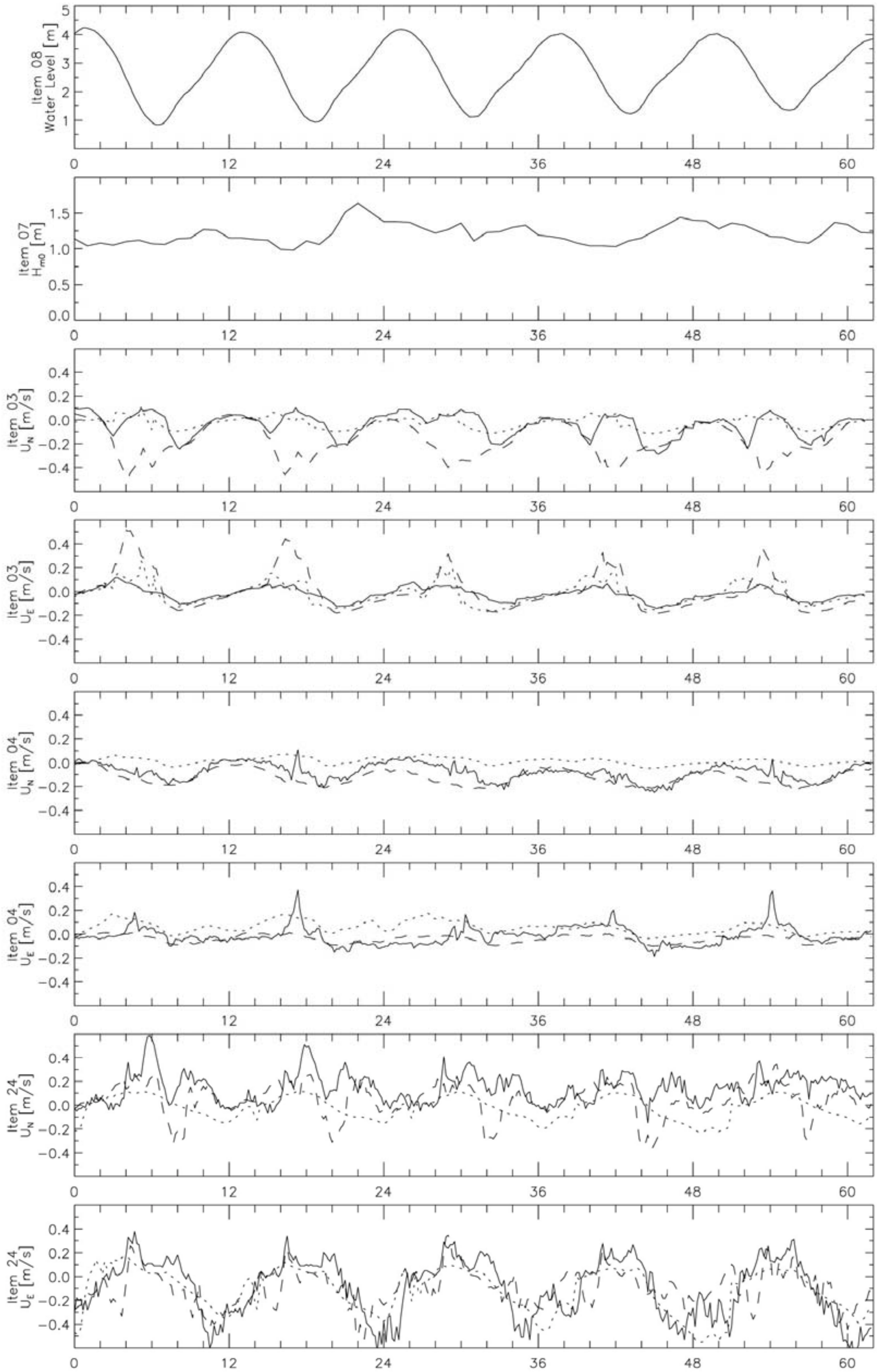

Figure 6. Measured water level at item 8, wave height at item 7, northerly (U_N) and easterly (U_E) components of the current at items 03, 04 and 24. Solid line is measurement, dotted line is from DELFT3D and dashed line is from PISCES.

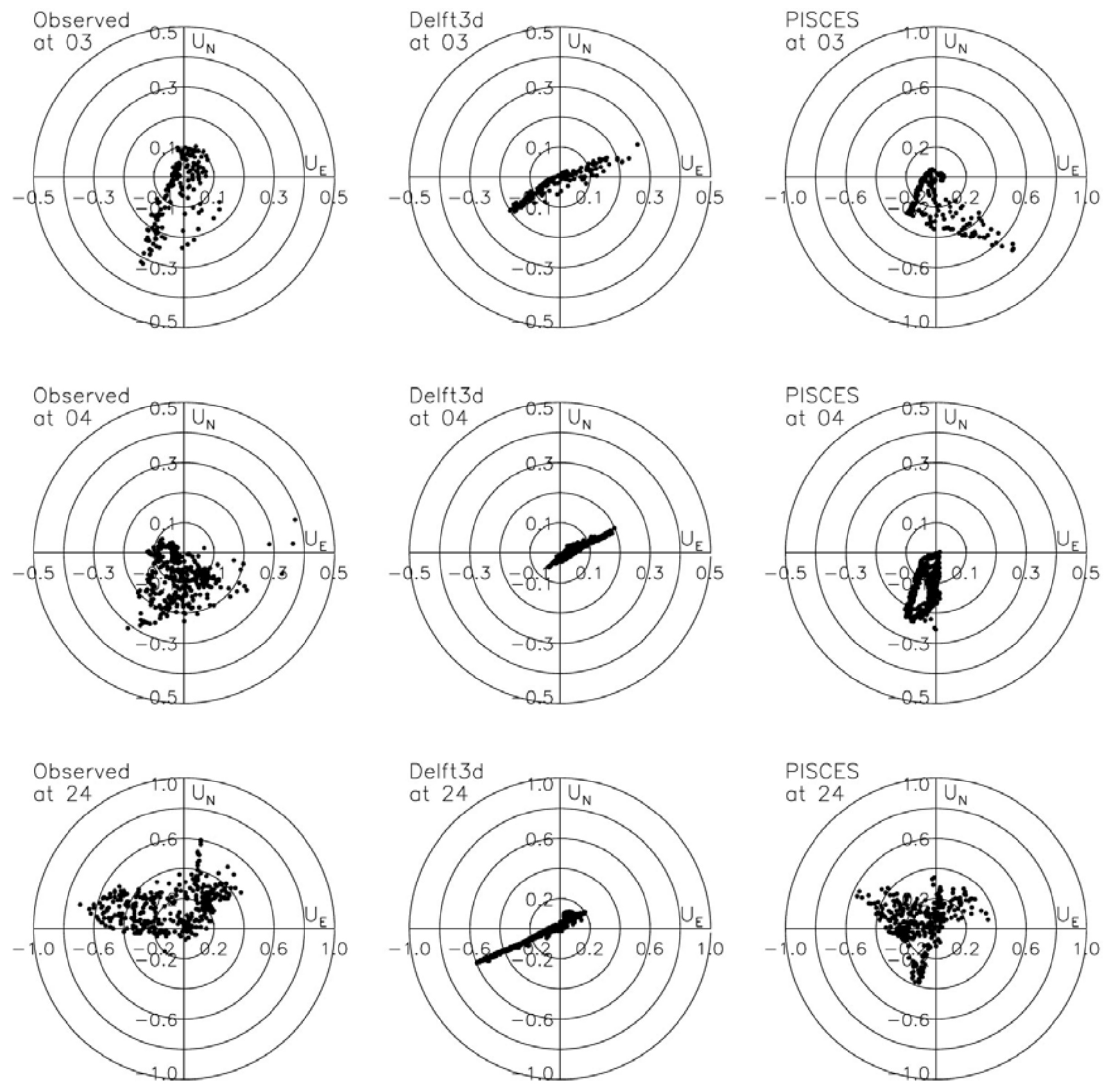

Figure 7. Scatterplots of observed and modelled currents at locations 03, 04 and 24 during the main experiment.

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