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Modelling Water Surface Topography at a Complex Inlet System – Teignmouth, UK

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ABSTRACT

Accurate water surface topography data and its spatial and temporal variability provide information about the interaction of physical processes acting in coastal regions. At the inlet system in Teignmouth, UK, these data complement methods for the extraction of nearshore morphology using remotely sensed video techniques. The video methods normally assume that the water surface is horizontal over the region, an assumption that is often invalid in shallow water. The study area is a complex macro-tidal inlet system bounded by a rocky headland and a 2 km-long beach. In order to predict the water surface topography and its response to different tide, wave and river discharge conditions, a calibrated and validated numerical model (MIKE21 HD, NSW) was applied. The water surface topography at the inlet and adjacent coast exhibits high spatial and temporal variability, mainly related to the tidal phase. It is the interaction between the tidal phase and the sandbar morphology, defining the velocity field in the channels, which drives the water surface topography distribution across the region. Since a small, unaccounted, difference in water level may result in significant deviations of the horizontal shoreline position, this study highlights the importance of using numerical modelling in conjunction with the video image techniques for the extraction of nearshore morphology.

ADDITIONALINDEX WORDS: *Nearshore hydrodynamics, waves, MIKE21, water elevation.*

INTRODUCTION

Spatial and temporal changes in water surface topography in coastal regions are a response to the balance of pressure gradient forces due to combined effects of irregular bathymetry (e.g. sandbars, channels), varying bed resistance (dependent on depth, grain size, bedforms), wave effects (run-up and set-up) and freshwater discharge. Accurate water surface topography data and information on its spatial and temporal variability can provide important information about the interaction of these physical processes. At the inlet system in Teignmouth, UK, these data complement the application of remotely sensed video methods for the study of nearshore morphology. Teignmouth is one of the sites included in the international Argus programme (LIPPMANN and HOLMAN, 1989; HOLMAN, 1994), with five video cameras overlooking the inlet and the sandbar system. Recently, several different techniques of shoreline identification and subsequent extraction of intertidal topography from video images have been developed (e.g. PLANTand HOLMAN, 1997; DAVIDSON *et al*., 1997; HOLLAND and HOLMAN, 1997; JANSSEN, 1997; AARNINKHOF and ROELVINK, 1999; KINGSTON *et al*., submitted). The basis of all these video methods is the detection of the shoreline location at a number of instances during a tidal cycle, the shoreline being considered the contour line corresponding to the location of the local water level. Therefore, determination of the shoreline comprises its horizontal spatial location and the associated vertical elevation (KINGSTON *et al*., submitted). One source of inaccuracy in these methods comes from the assumption of a spatially horizontal water surface, an assumption that is often invalid in shallow water.

As it is difficult to measure these irregularities in coastal regions due to both the density and spatial extent of the measurements required, the use of numerical area models provides valuable insight into the important physical processes. The model applied in this study is the MIKE21 Hydrodynamic model (HD) and the Nearshore Spectral Wind-wave model (NSW).

Data used in this study originated from the European COAST3D project, in which Teignmouth was one of the studied areas. A detailed description of the COAST3D project and its achievements can be found in SOULSBY (2001).

The motivation of this work is the need for accurate spatial and temporal surface elevation data for the application of methods for the extraction of nearshore morphology using remotely sensed video techniques. The objective of this paper is to describe the varying water surface topography in the complex coastal region of Teignmouth, UK, and to evaluate the relative importance of the various physical processes acting in this area.

STUDYAREA

The dynamic estuarine inlet of river Teign is located in the southern portion of Teignmouth's beach (Figure1). This coastal region has a strongly 3-dimensional nature, with a rocky headland (The Ness), an estuary mouth and nearshore sandbars (Poles) all adjacent to a 2 km-long beach, backed by a seawall (WHITEHOUSE and WATERS, 2000). It has been suggested that complex interaction between waves and currents lead to a cyclic movement of sandbars systems in the mouth of the estuary (CRAIG-SMITH, 1970; ROBINSON, 1975).

Tides are semi-diurnal with tidal range varying between 1.7 to 4.2 m. Both nearshore tidal currents and waves are known to have large influence on sediment transport processes at this site. Offshore currents are generally low (0.2 to 0.4 m s^{-1}) but within the ebb shoal system influenced by the tidal outflow from the estuary the current speed is locally enhanced, with values exceeding 0.5 m s^{-1} and flowing in variable directions (WHITEHOUSE, 2001). Circulation around and over the sandbars is complex due to wave refraction and diffraction effects. River discharge varies between less than 20 m^3 s^{-1} in summer to 50-100 m^3 s^{-1} in autumn and winter. These river discharges can enhance the current speeds in the channel, which can reach up to 2 m s^{-1}. The channel width varies from up to 300 m at high tide to just 80 m at low tide, funnelling the flow. Storm wave heights greater than 0.5 m are present 10% of the year, and are due to easterly gales (MILES *et al*., 1997).

MODEL DESCRIPTION

MIKE21 Hydrodynamic Module (HD)

The hydrodynamic model component of MIKE21 is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas (WARREN and BACH, 1992). It simulates unsteady two-dimensional flows in one layer (vertically homogeneous) fluids in response to a variety of forcing functions. The water levels and flows are resolved on a square or rectangular grid covering the area of interest. The main inputs to the model are bathymetry, bed resistance coefficients, wind fields, and water level and/or flux boundary conditions. The model allows flooding and drying over the computational grid during the simulation.

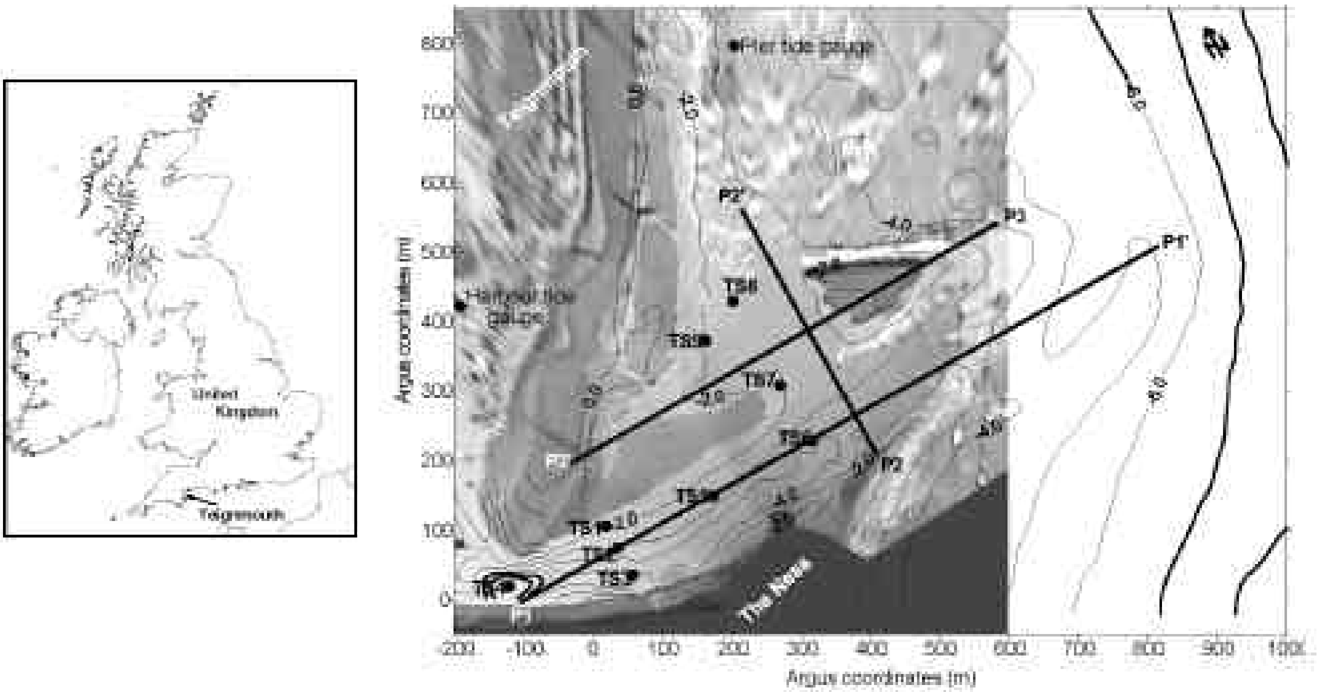

Figure 1. Study area. The nearshore bathymetry is plotted over a rectified Argus image highlighting the positions of Profile 1 (P1 – P1'), Profile 2 (P2 – P2'), Profile 3 (P3 – P3'), extracted time series (TS1 to TS9) and the Pier and Harbour tide gauges.

MIKE21 HD solves the vertically integrated equations of continuity and momentum in two horizontal dimensions. The equations are solved by implicit finite difference techniques with the variables defined on a spatially staggered grid. MIKE21 HD makes use of a Alternating Direction Implicit (ADI) technique to integrate the equations for mass and momentum conservation in the space-time domain. The equation matrices that result for each direction and each individual grid line are resolved by a Double Sweep (DS) algorithm.

MIKE21 Nearshore Spectral Wind-Wave Module (NSW)

MIKE21 NSW is a spectral wind-wave model, which describes the propagation, growth and decay of short period waves in nearshore areas. The model includes the effects of refraction and shoaling due to varying depth, wave generation due to wind and energy dissipation due to bottom friction and wave breaking. The effects of current on these phenomena are included.

MIKE21 NSW is a stationary, directionally decoupled, parametric model. To include the effects of current, the basic equations in the model are derived from the conservation equation for the spectral wave action density. A parameterisation of the conservation equation in the frequency domain is performed introducing the zeroth and the first moment of the wave-action spectrum as dependent variables. The basic equations in MIKE21 NSW are derived from the conservation equation for the spectral wave action density based on the approach proposed by HOLTHUIJSEN *et al.* (1989). The various wind formulations in MIKE21 NSW are discussed and compared in JOHNSON (1998).

MODEL SETUP

The model covers the whole estuary and an area of approximately 3.5 km seaward and 4 km alongshore, resulting in a total grid area of 10 x 4 km (Figure 2). The grid resolution is 10 m in x and y directions, resulting in approximately 180,000 water points. As the MIKE 21 flow model is a finite difference model, the grid area has to be rectangular with the computational points displayed in a square or rectangular grid. The bathymetry used for the coastal region is the result of a survey carried out by HR Wallingford in October 1999. Bathymetry for the estuary was obtained from a 1979 digitised chart.

Boundary conditions applied to the hydrodynamic model include river discharge, water level (offshore boundary) and flux (north and south boundaries). Water level and flux boundaries were obtained from a larger well-validated model (Delft3D – Continental Shelf Model – WALSTRA *et al.*, 2001a). The wave model (NSW) used as offshore data the measured wave data and water level.

Since both modules (HD and NSW) work separately, it is necessary to run the NSWmodel using measured wave data (offshore boundary) and water level for the specified period. The radiation stresses calculated through the NSW are then used as input in the HD model.

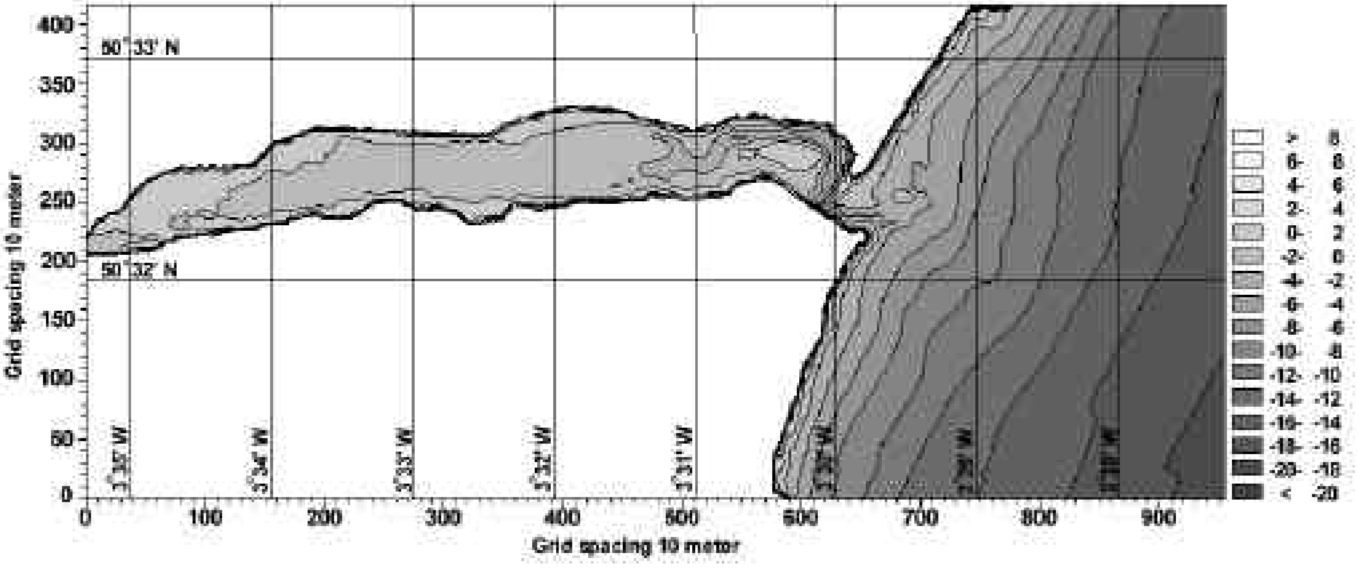

Figure 2. Model grid and bathymetry.

CALIBRATION AND VALIDATION

The MIKE21 model was calibrated and validated against field data obtained during the COAST3D project. In this section a brief explanation of the calibration and validation is given, but a more detailed description is given in SIEGLE *et al*. (in prep.).

There is no standard procedure for model calibration and verification in the modelling literature (CHENG *et al*., 1991). Typically, calibration or validation is accomplished by qualitative comparison of short time-series of water level or velocity produced by the numerical model with field data for the same location and for the same period of time (CHENG *et al*., 1993). The COAST3D datasets provide an excellent database for the calibration and validation of coastal area models (SUTHERLAND, 2001; WALSTRA *et al*., 2001a). These data include accurate bathymetric surveys and a spatially dense array of instruments measuring neap/spring tides and calm/storm conditions.

After the sensitivity tests were carried out with varying eddy viscosity and resistance values, the model was calibrated through comparisons (measured against calculated) of water level and velocity time series for different eddy viscosity and bed resistance values. Two spring tide periods were chosen for the model calibration, including calm conditions (25-29/10/1999) and storm conditions (10-14/11/1999).

Time series of measured data and modelled results were compared and a more objective analysis of the results was also carried out using linear regression analysis and the Relative Mean Absolute Error (RMAE) (WALSTRA *et al*., 2001b). The best agreement between measured and calculated data was obtained with the use of depth varying resistance coefficients (Chezy numbers) as given in Table 1.

Time series comparison of calculated water level and the measured data for the pier (offshore) and harbour (in the estuary) for both calibration periods, show that the model predicts accurately the water level, with maximum residuals of about 5 cm offshore and 15 cm in the estuary at high water. The RMAE values of 0.009 and 0.016 (pier) and 0.036 and 0.097 (harbour), for each calibration period respectively, indicate an excellent agreement. Figure 3 compares measured and calculated water level time series for the second calibration period, during which the experiments presented in this paper were carried out. As shown in SIEGLE *et al*. (in prep.), velocities are also well predicted by the model, reproducing most of the rapid variations in the measured tidal currents. To validate the model, it was successfully applied at different periods, which present different tide and wave conditions from those of the calibration period.

Table 1. Depth varying Chezy numbers.

Depth (m)	Chezy numbers (m– s^{-1})
H < -3	40
-3 < H < -1	34
-1 < H < 1	32
1 < H	31

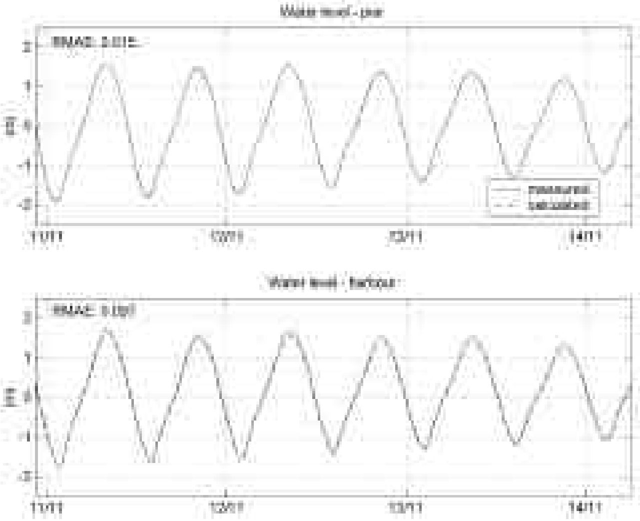

Figure 3. Measured and calculated water level time series for the second calibration period (pier and harbour tide gauge positions).

WATER SURFACE TOPOGRAPHY

Water surface topography is defined as the spatial water level distribution over the area of interest, and is quantified through the analysis of water level deviations in relation to a fixed water level reference point. The reference point used for Teignmouth is the position of the pressure sensor at the Teignmouth pier (Figure 1).

The calculation of the water surface topography from MIKE21 water depths model results involves the following steps: (1) subtraction of the bathymetric data of the water depth grid, resulting in a surface elevation grid file; and (2) the subtraction of the correspondent reference water levels for each time step of interest. Additional steps include the exclusion of dried area data from the emerged sandbars and the extraction of water level residual time series and profile series at points of interest.

Using the calibrated model a series of experiments were conducted aiming to quantify the relative importance of tidal range, wave conditions and river discharge on the water level topography. A sensitivity analysis of the response of the main processes was carried out to define the design of each modelling experiment. Model tests were focused on the spring tidal phase since maximum variability in water surface topography was observed during this period. It is also during spring tide conditions that the coastline extraction from video images is more important as this permits shoreline detection over a wider area.

Tidal Range

To test the water surface topography distribution in relation to different tidal ranges, the analysis of two runs was carried out, one at neap tide and the other at spring tide conditions. Each test period covers 25 hours (two tidal cycles). During the neap tide period (16/11 – 17/11/1999) the tidal range was 1.6 m and conditions were calm, with significant wave heights (H_{sig}) of about 0.1 m. During the spring tide tests (11/11 – 12/11/1999) the tidal range was approximately 4 m, with H_{sig} varying from 0.7 to 1.4 m. As described below, over the spring tide period, tests with a range of wave conditions were carried out, allowing the analysis the influence of waves to be separated from that of the tidal range.

Wave Conditions

Wave set-up and run-up at the beach are usually included in the techniques to extract morphology from video images (e.g. DAVIDSON *et al*., 1997; KINGSTON *et al*., submitted). The aim of this experiment is to quantify the wave effects causing an overall increase in the water level residuals (e.g. in the inlet channels) and also to assess their relative influence across the area. This was carried out during the modelled spring tide period.

Sensitivity tests showed that the most important wave parameter for the water surface topography distribution is Hsig, with the wave period having no significant effect. For this reason, only the Hsig was changed for each run, varying from no waves (0.0 m) to 1.8 m. The period and direction were maintained constant with values of 6.6 s and 115o respectively, as they were the averaged values over the modelled period.

MIKE21 NSWwas run for each wave condition using the same parameters as for the calibration period. The parameters governing wave breaking were set as suggested by HOLTHUIJSEN *et al*. (1989): =1.0 (maximum steepness parameter), =0.8 (maximum H/d parameter; H is wave height and d is water depth) and =1.0 (adjustable constant).

River Discharge

Different values of river discharge were also defined for model runs over the spring tide period, evaluating its importance to the water surface topography at the inlet and adjacent coast. As shown before, the Teign river discharge varies significantly during the year (from less than 20 $m^3 s^{-1}$ to 100 $m^3 s^{-1}$). During the modelled spring tide period, the measured river discharge was of about 7 $m^3 s^{-1}$, but for the experiment purpose the discharge was incremented gradually to up to 100 $m^3 s^{-1}$.

RESULTS AND DISCUSSION

Analysis of extracted time series and profile series at different locations around the area of interest, at the positions shown in Figure 1, allows the quantification and assessment of the relative importance of each of the studied processes. Results are described and discussed for each of the processes analysed during the modelling experiments.

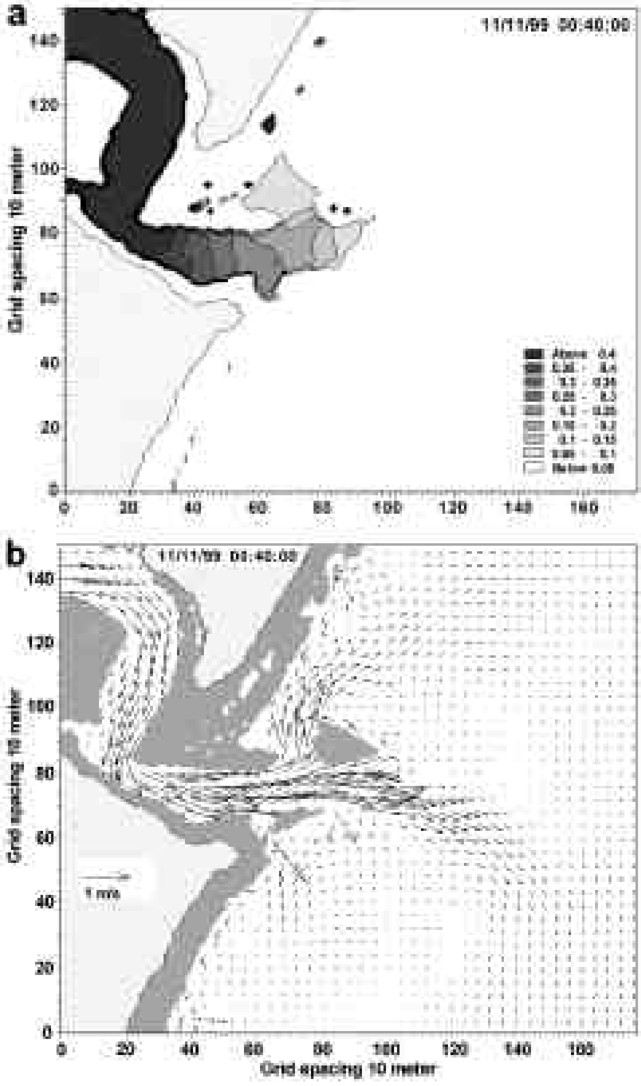

Figure 4. Contour plot of the water surface topography (a) and velocity vector plot (b) at maximum water level residuals (11/11/99 00:40:00).

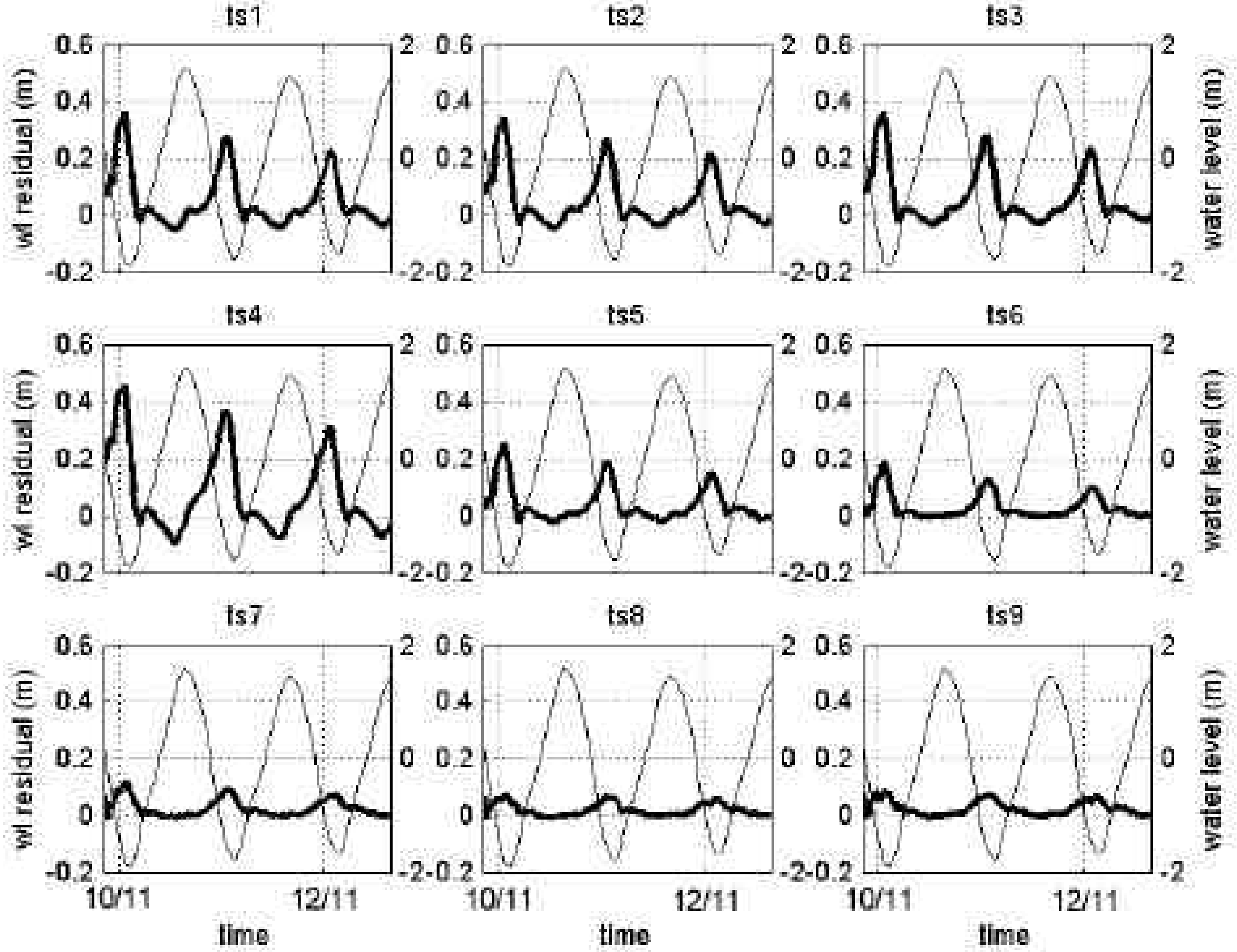

Figure 5. Time series of water level residuals (thick line) and water level (thin line) for each of the extracted locations (TS1 to TS9).

Tidal Range

Water surface topography is directly related to the tidal range, with highest water level residuals during spring tide periods. During the modelled neap tide period, only small changes in water surface topography are registered, with a virtually flat surface around the area. Maximum residual elevations in relation to the pier reference point are less than 5 cm. Conversely, water surface topography varies significantly during spring tide conditions, with maximum and minimum water level residuals in the inlet channel of 0.4 and -0.2 m, respectively. The emerged sandbars at low water spring tide periods play an important role in the funnelling and friction effects of the channel. This is clearly seen in the analysis of a sequence of contour plots of water surface topography over the modelled spring tide period, as shown in Figure 4 for the time of maximum residuals (final stages of ebb tide). During the early stages of the ebb tide, the deeper water column and wider channel reduce these funnelling and friction effects in the channel. This is also seen in time series of water level residuals at different locations (Figure 5). The extracted time series show that maximum residuals are registered at approximately local LW – 1 hour and minimum values at local HW – 1 hour, coinciding with ebb and flood peak currents. Figure 6 shows how the channel current velocities are phase locked with the water level residuals, a response to the pressure gradient forces created by the difference in water level in the estuary and offshore.

The water surface slope between the estuary and the open sea is shown at its maximum gradient in Figure 7a for Profile 1, in the middle of the channel. Figures 7b and 7c

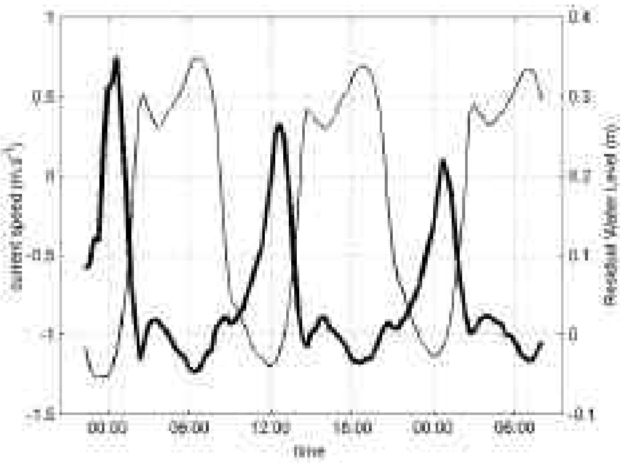

Figure 6. Current speed (thin line) and residual water level (thick line) in the middle of the channel (TS2).

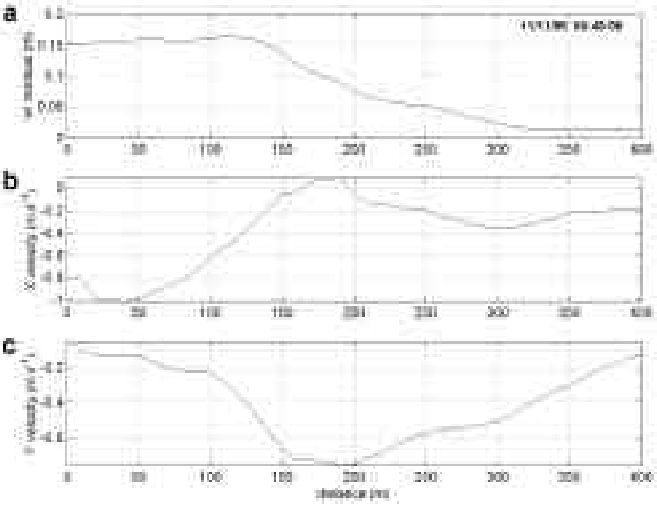

Figure 8. Water slope (a), x-velocity (b) and y-velocity (c) along Profile 2 (P2 = 0 m; P2’= 400 m).

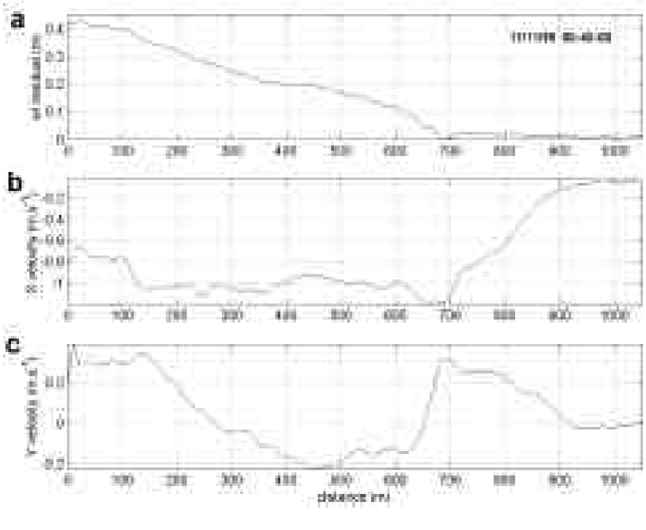

Figure 7. Water slope (a), x-velocity (b) and y-velocity (c) along Profile 1 (P1 = 0 m; P1’= 1050 m).

present the cross and longshore velocities along the same profile, illustrating the relation between them and the surface slope. It shows the dominant cross-shore velocities (x) in the funnelled channel associated with higher water level residuals that generate the slope. When it reaches the end of the channel, the flow spreads out and the slope reaches its end, with values of water level residuals close to zero. This is followed by a decrease in the cross-shore velocity and a slight increase in the longshore velocity as the flow turns to the south as it leaves the channel. Similar behaviour is observed for the longshore slope (Profile 2), from the channel crossing in between the sandbars (Figure 8). Figure 8a shows high residuals inside the channel (up to 140 m from the start of the profile), associated with high cross-shore velocities (Figure 8b). When the secondary flow is channelled northwards through the sandbars, residuals are still significant, with values of about 0.1 m, associated with the high longshore current velocities (Figure 8c). The cross-shore and longshore slopes cycles, from flat surface to the maximum slope and back to flat surface takes of about 5 hours of the ebb tide period.

The interaction between the tidal phase and the sandbar morphology, which defines the velocity field in the channels, has a major influence on the water surface topography distribution across the region. The funnelled flow during ebb tide results in high current velocities and maximum pressure gradient forces between the estuary and the offshore region.

Wave Conditions

The experiments with different modelled wave conditions show their distinct influence across the area of interest. To assess wave influence on the water level residuals, the average values of the extracted time series for each position were used to apply a polynomial regression analysis (Figure 9). The curves fitted present an r squared value higher than 0.99 for all positions. The range in water level residual values shown in Figure 9 also shows the relative increase in wave influence in the region outside the main inlet channel (increasing from TS7, TS8 reaching the maximum influence at TS9, behind the outer Pole sandbar). This region behind

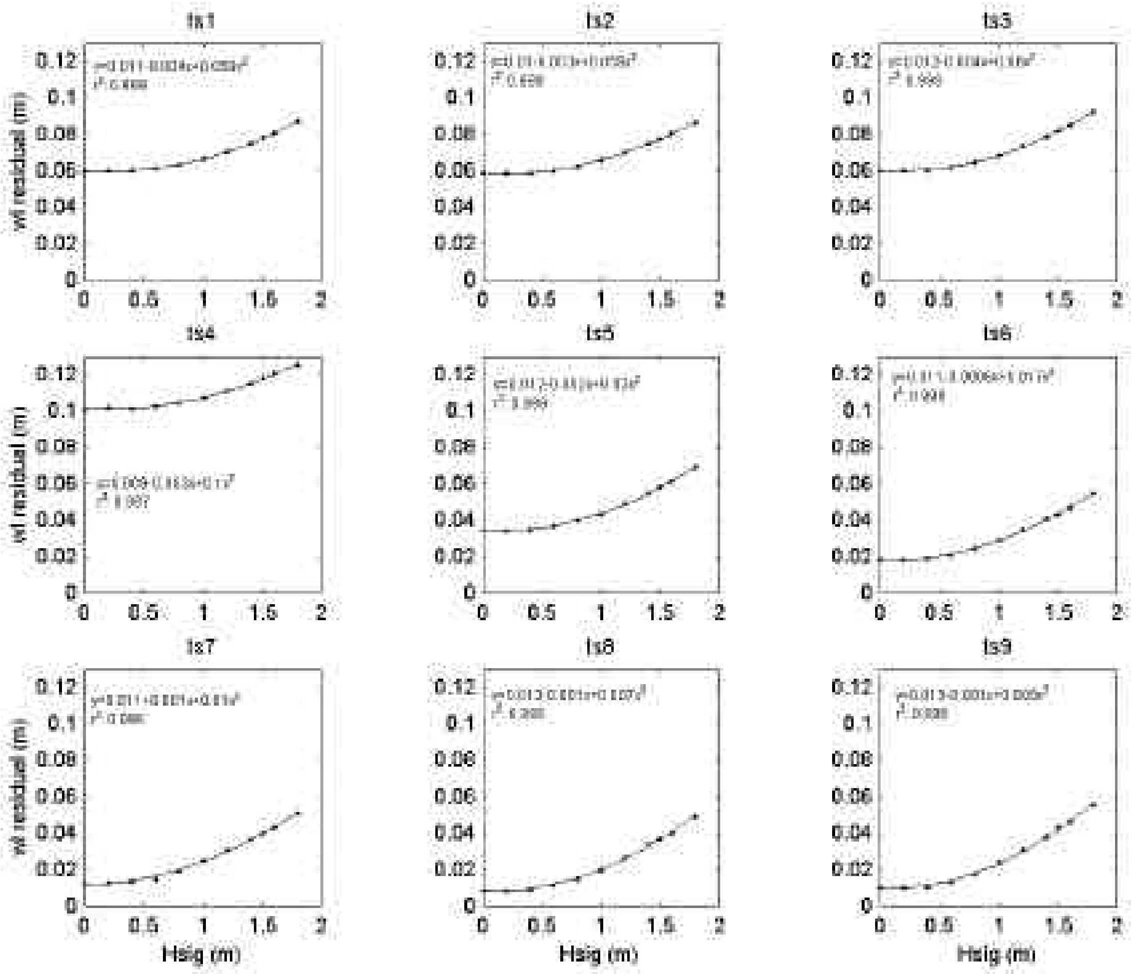

Figure 9. Polynomial regression analysis of the wave induced water level residuals for each of the extracted locations (TS1 to TS9).

the outer Pole sandbar is a region were the waves cause a piling up of the water due to refraction effects around the sandbar. The profile shown in Figure 10 is a cross-shore profile at low tide over the sandbars (Profile 4 in Figure 1). Water level residuals for different wave conditions are plotted showing the significant increase in water residuals mainly behind the outer sandbar. At the outside of the outer sandbar, the waves generate an increase in water level residual after breaking. As only shallow water wave breaking is being considered, the maximum wave height is taken from $H_m =$ d (JOHNSON, 1998).

An increase in wave height also causes an increase in the time of occurrence of the residual, and this also becomes more important when we move to lower tidal range periods. This is illustrated in Figure 11, which is a plot of water level residuals for the extreme experiments (without waves and with H_{sig} of 1.8 m) and the tide elevation.

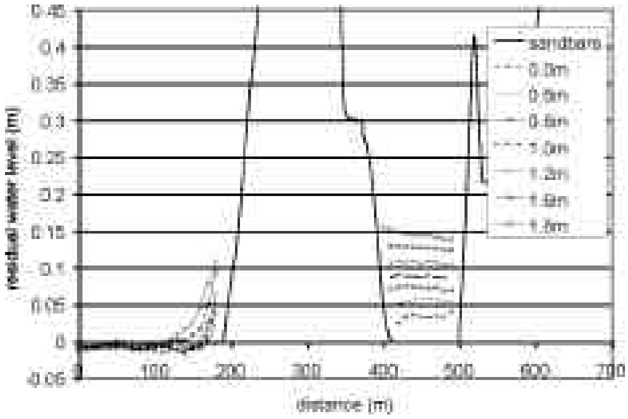

Figure 10. Wave condition effects along the Profile 3 (P3 = 0 m; P3'= 700 m).

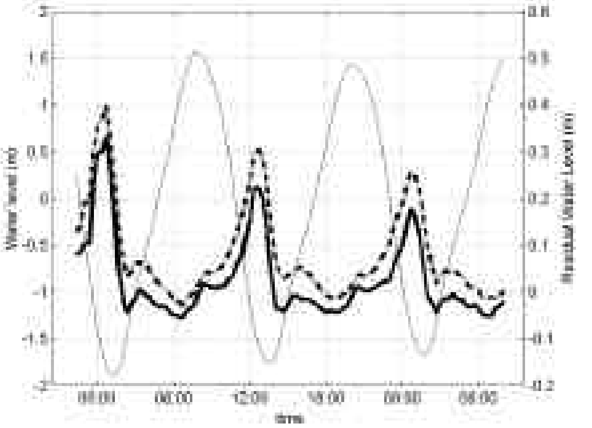

Figure 11. Water levels (thin line) and water level residuals for $H_{sig} = 0.0$ m (solid thick line) and for $H_{sig} = 1.8$ m (dashed thick line) in the middle of the channel (TS2).

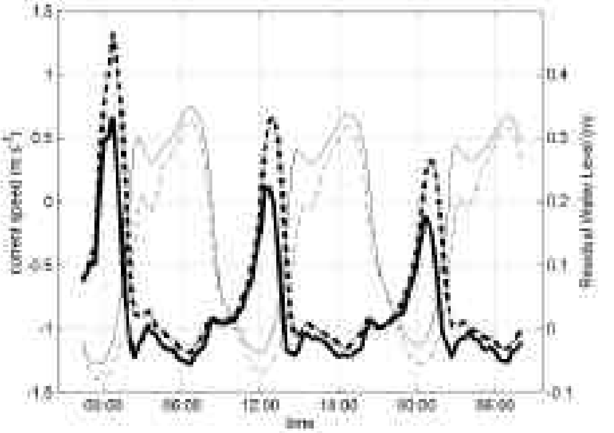

Figure 12. Mid-channel (TS2) current speed (thin lines) and related water level residuals (thick lines) for real condition discharge (solid lines) and for 100 $m^3 s^{-1}$ discharge (dashed lines).

River Discharge

River discharge values varying between the real conditions (of about 7 $m^3 s^{-1}$) during the modelled period and 100 $m^3 s^{-1}$ caused a maximum increase of about 12 cm coincident with the peak ebb tide currents (Figure 12). Average values over the 25 hour period for high discharge show an increase of about 5 cm compared to low discharge periods. The opposite is verified for the minimum residuals (negative), since the flood currents are reduced due to the residual flow during high discharge periods (Figure 12). This causes the water level residuals during high discharge events to be closer to zero at flood periods, while for low discharge events the residuals become negative in relation to the pier reference point.

The water surface slope gradient in the inlet channel also shows an increase in residual water level during high discharge events. Figure 13 illustrates this for the slope along the Profile 1 for high and low river discharge. The slope gradient is significantly increased at high discharge, but the offshore end of the slope is the same for both conditions, being defined by the channel morphology. The channel and sandbar morphology defines the maximum extend of the water surface deviations across the area of interest. This highlights the importance of the channels and sandbar morphology for the water surface topography variability and distribution. The water surface slopes shown in Figure 13 also show a flattening of the slopes at around 400 m, which is coincident with the secondary channel that guides the flow northwards. This allows part of the flow to spread before it is funnelled again in the final part of the main channel.

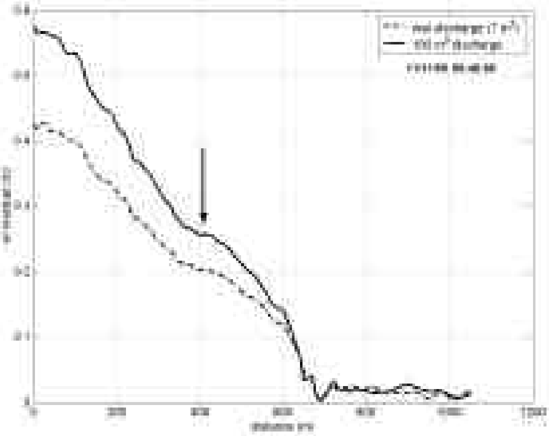

Figure 13. Water slope along Profile 1 for real discharge and for 100 $m^3 s^{-1}$ discharge conditions. The arrow indicates the flattening in the curve at around 400 m distance (P1 = 0 m; P1'= 1050 m).

CONCLUSIONS

A calibrated and validated numerical model (MIKE21 HD, NSW) has been used to model the water surface topography at the complex estuarine inlet system at Teignmouth. The water surface topography at the inlet and adjacent coast presents high spatial and temporal variability, mainly related to the tidal phase. The interaction between tidal phase and sandbar morphology, defines the velocity field in the channels, and drives the water surface topography distribution across the region. Maximum pressure gradient forces between the estuary and the offshore region occur when the flow is funnelled in the channels during ebb tide. The water surface slope presents its maximum gradient at this stage, with its shape directly related to the channel morphology.

The effects of waves increase gradually in the regions outside the main channel, where refraction processes cause water to pile up. River discharge plays an important role in the water surface topography since it is directly related to the velocities in the channel. The higher the river discharges, the higher are the velocities in the channel, and hence the higher are the water level residuals.

This study demonstrates the importance of the water surface topography variations in the coastal region, where a small difference in water level may result in significant deviations of the horizontal shoreline position. As video-imaging techniques to define the coastline rely on water elevation, the knowledge of water surface topography distribution will increase its accuracy.

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