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EXTREME TIDAL SURGE MODELLING IN THE RIVER THAMES USING A COUPLED MODELLING APPROACH

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Surge tides originating from North Sea have been presenting a serious risk of flooding to the Thames Estuary region and to the City of London for centuries. Tidal surge forecasts and the prediction of their impact in the River Thames have been studied utilizing a coupled modeling system using a storm surge forecasting model and a hydrodynamic model. The storm surge model was developed using multiple-input single-output transfer function models whereas the hydrodynamic model was built in MIKE11. The models structure, calibration and validation processes are presented including the sensitivity analysis. Within the sensitivity analysis, the tide level at Southend was considered as the most important influence on determining the peak water levels along the tidal corridor. Subsequently, the influence of the wind during the simulation was studied in order to examine the impact of the wind factor in this model. The model results indicated that the wind direction was a primary parameter. Ensemble forecast water levels at Thamesmead were used as a boundary condition by the validated model and the potential of the model to simulate a variety of scenarios was investigated. The results suggested that the MIKE11 based model could be applied to the simulation and forecasting of the tidal level along the Thames and that further improvement could be made depending on the availability of additional information on the operation of control structures along the river corridor.

1. INTRODUCTION

Central London is home to millions of residents and if the region were to be flooded, the consequences would affect not only the entire UK economy but also many lives. Flooding in the Thames estuary may be due to a combination of meteorological and environmental factors such as high tides coupled with storm surges, as well as sea level rise due to the melting polar ice caps and the geological tilting of the UK. The oceanic tide is conformed by the astronomical component, which depends on the interaction of the sun and moon with the earth, shape of the coastline and the bathymetry (sea depth); and the meteorological component (known as storm surge), which depends on the meteorological conditions such as wind speed and atmospheric pressure. Storm surges are the result of low/high atmospheric pressure centers coupled with strong winds and they can increase/decrease the tidal level depending on the atmospheric conditions. A low-pressure centre can increase the sea level by several meters. If this increase is in phase with the peak of the tide, it may have disastrous consequences. The propagation of tides and storm surges in the North Sea follow an anti-clockwise direction, moving down the East coast of Great Britain and reaching the Thames Estuary.

During 1953, London experienced one of the most serious flooding events with a storm surge traveling down the east coast of England, and causing widespread damage from Yorkshire to the Thames Estuary. This lead to the construction of the Thames barrier, which became operational in 1984. However, to provide enough time for this barrier to be operated, the prediction of storm surges in the Thames Estuary is extremely important. Therefore, this paper is focused on the forecasting of water levels along the river Thames using a coupled modeling approach (See Figure 1).

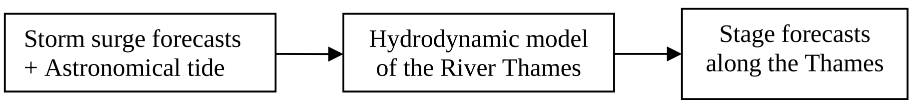

Figure 1. Whole systems modelling of water levels in the Thames River

2. STORM SURGE FORECASTING IN THE THAMES ESTUARY

The Proudman Oceanographic Laboratory (POL) has developed a software tool (POLTIPS-3) to accurately predict the astronomical tide around the British Isles [1]. The continental shelf model CS3 developed by POL is the operational model developed to forecast storm surges in the UK with a resolution of approximately 12 km [2]. The CS3 model runs twice a day and it is completely driven by atmospheric forecasts from the UK Meteorological Office mesoscale model. An ensemble of storm surge forecasts can then be generated by using an ensemble of atmospheric forecasts in order to quantify the uncertainty in the surge prediction. A different approach to forecast storm surges is the use of data-driven models such are neural networks [3-4] and Fuzzy Bayesian methods [5]. These models take storm surge water level (residual) measurements down the North Sea to forecast the storm surge water level at Sheerness, which is the lower boundary condition of the hydrodynamic model for the River Thames.

Randon *et al*. [5] concluded that residuals down from Whitby (See Figure 2) can be used to forecast residuals at Sheerness. However, the use of more than one location and additional meteorological data such as wind speed and atmospheric pressure may help to improve the forecasts. Therefore, we propose to use not only residuals at Whitby, but also at Cromer, as well as measurements of wind speed and atmospheric pressure at Whitby, Cromer and Sheerness. The residual data were downloaded through BODC (British Oceanographic Data Centre – www.bodc.ac.uk) whereas the meteorological data were downloaded through BADC (British Atmospheric Data Centre - badc.nerc.ac.uk). Residual data were obtained with a time interval of 15 min, which were averaged to produce hourly data. The wind speed and atmospheric pressure data were directly obtained as hourly data. Seven years of data from 1st January 2000 to 31st December 2007 were downloaded to calibrate and validate the following model.

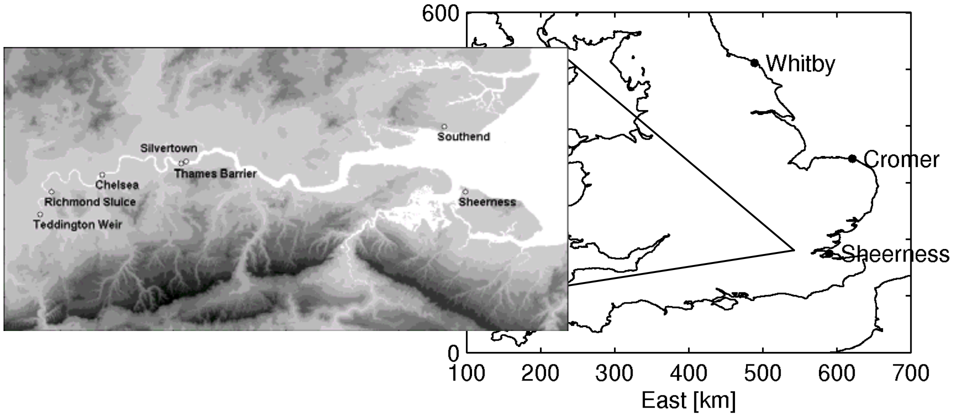

Figure 2. The River Thames and location of the water level gauges.

The forecasting of storm surges can be carried out using Transfer Function (TF) models. TF models are also data-driven models that can be calibrated using time series data. TF models are easier to implement when compared to neural networks and fuzzy Bayesian methods. TF models have been widely used in rainfall-runoff modeling coupled with Kalman filters [6]. The most basic structure known as SISO (Single-Input Single-Output) TF model requires one input and one output time series. TF models known as MISO (Multiple-Input Single-Output) require more than one input time series to produce the output. Given the input time series *u(t)*, and *v(t)* and the output time series *y(t)*, a MISO TF model can be represented by a linear combination of inputs and output by:

$$\begin{aligned} & y(t)+a_1 y(t-1)+a_2 y(t-2)+\cdots+a_{na} y(t-na)= \\ & b_1 u(t-nkb)+b_2 u(t-nkb-1)+\cdots+b_{nb} u(t-nkb-nb+1)+ \\ & c_1 v(t-nkc)+c_2 v(t-nkc-1)+\cdots+c_{nc} v(t-nkc-nc+1) \end{aligned} \quad (1)$$

where a_{na}, b_{nb}, and c_{nc} are the model parameters, *nkb* and *nkc* are the time delays that are related to the forecasting time, and *na*, *nb* and *nc* repesent the order of the model. *t* represents the current time step, whereas *t-1* represents the previous time step. The time delays and model order represent the structure of the TF model. For a given model structure, the parameters of the TF model can be calculated using either recursive least square methods or prediction error/maximum likelihood approaches (e.g. using the 'armax' function in Matlab). If the parameters and model structure are known, then the output *y(t)* of the TF model can be calculated using Equation 1. It is clear that the output *y(t)* is a linear combination of past inputs and past outputs and therefore the TF models are known to be linear models. Equation 1 can be extended if more than two inputs are available.

The calibration time period was selected from 01/01/2000 to 01/03/2000 and the rest of the 7 years of data were selected as validation. Longer calibration periods produced unstable TF models. The best model was produced using values for $na = nb = \ldots = 2$. The time delays were chosen to be 6 hr to produce 6hr forecasts. The input data were wind speed and atmospheric pressure at Whitby, Cromer and Sheerness, and residual data at Whitby and Cromer. The output was the residual data at Sheerness. The results showed that the inclusion of wind speed and atmospheric pressure reduce the error compared with a model than only employs residual data as inputs. The results are shown in Figure 3.

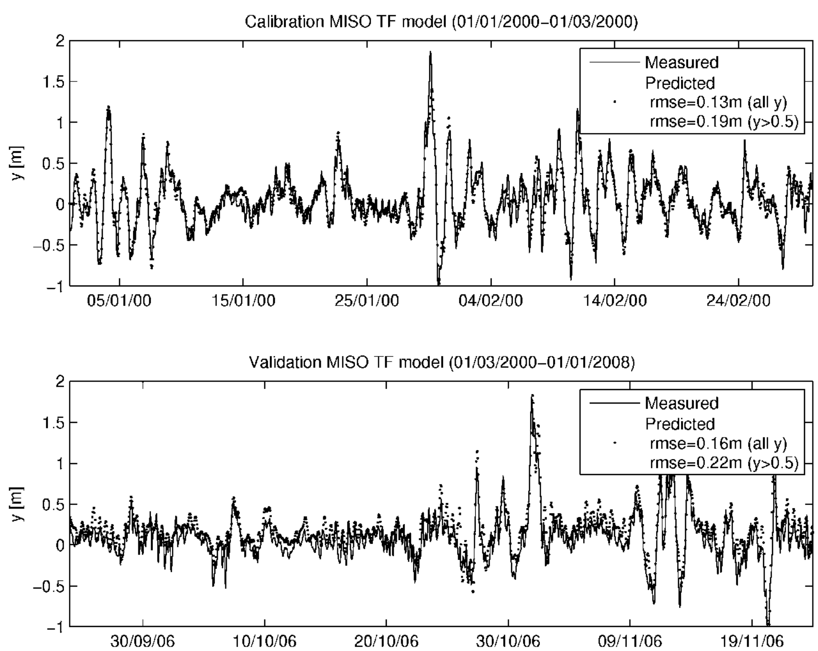

Figure 3. Calibration and validation of the TF model to forecast residuals at Sheerness.

3. MODELING OF WATER LEVELS ALONG THE THAMES RIVER

MIKE11 software was developed by DHI water and environment, and it is a fully-dynamic, one dimensional modeling program, which can be used for simulating steady and unsteady flows, water levels, sediment transport and water quality in both simple and complex river and channel systems [7]. The implicit, finite difference scheme is employed in the computation to model the interaction of the fluvial flow and tide through solving the Saint-Venant equation [8]. This software was used to build the 1D hydrodynamic model of the river Thames using cross-section data. The original model was built by Halcrow in ISIS, but the model did not take into account wind effects. The impact on tide levels along the Thamesmead from wind factors could be varied depends on the wind speed and wind directions in Thames Estuary, where is the crucial setting for Thames Gateway, the London Olympics and offshore wind farms. Therefore, the model was rebuilt in MIKE11 to account for wind effects.

In MIKE11 tide surge model, the river channel was digitized based on the 1:2500 digital map data (Ordnance Survey Landline Plus) from EDINA in UK. The morphology data (94 surveyed cross-sections and its related roughness parameters) and hydrodynamic data were converted directly from the existing ISIS flow model built by Halcrow. Along the River Thames, three main hydraulic structures were described in the original ISIS model, of which were Teddington Weir, Richmond Sluice and Thames Barrier (See Figure 2). As there was limited information of the real operation of these hydraulic structures, the three hydraulic structures were assumed to be open in the MIKE11 model. The upstream boundary was inflow in Teddington Weir, while the downstream boundary was tidal circle in the Southend.

There were 27 events recorded from 1996 to 1999 including 52 tide cycles, which include 9 events with the Thames Barrier being closed. From the remaining 18 events (with the Thames Barrier being opened), 6 of them were selected for calibration and validation of the hydrodynamic model. The selection criterion was the occurrence of the high tide at Southend. Each event had two days to set as the initial condition in the model. The uniformed river channel roughness was the only parameter to be calibrated, which ranged from 0.01-0.05 $s/m^{1/3}$ [9]. Two sites were selected to be served for the calibration and validation in this study, one of them is at Silvertown, located around the Thames Barrier, and the other one is at Chelsea, situated upstream of the barrier (see Figure 2).

The Root Mean Squared Error (RMSE) and Correlation Coefficient (CC) were employed to measure the performance of the model. The calibration showed that the optimal value for the channel roughness was 0.028 $s/m^{1/3}$. The results of calibration and validation are shown in Figures 4 and 5 respectively.

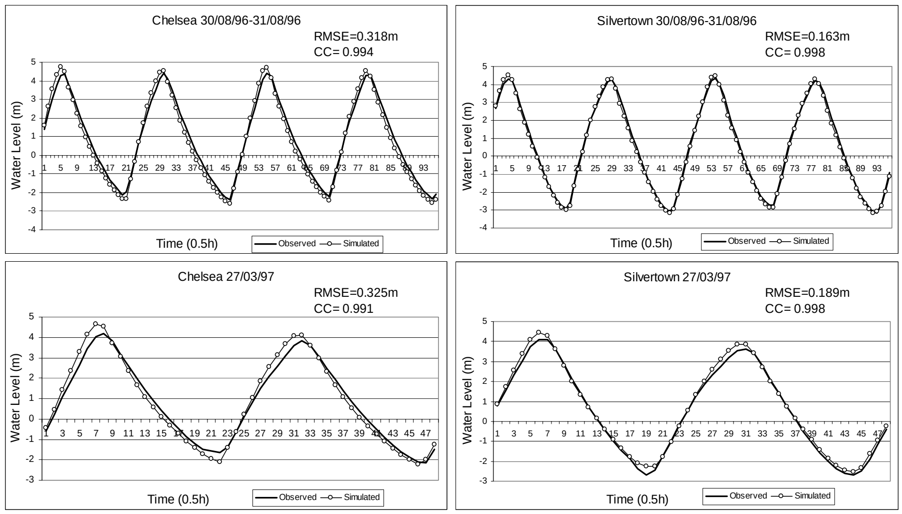

Figure 4. MIKE11 model calibration at Chelsea and Silvertown.

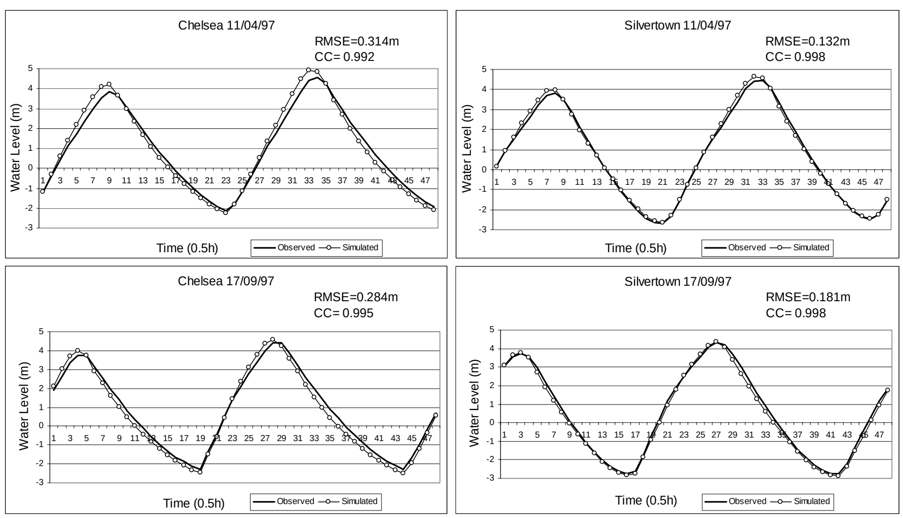

Figure 5. MIKE11 model validations at Chelsea and Silvertown.

4. MIKE-11 MODEL SENSITIVITY ANALYSIS

In order to analyze the model performance with the variations of boundary conditions at Teddington and Southend, a particular event was selected (May 18, 1999). Firstly, constant inflow at Teddington with different return periods (calculated from FEH [10]) was input in the upstream boundary condition, whereas the astronomical tide was input in the and the downstream boundary condition. Secondly, different water levels were input into the downstream boundary (Southend), while the upstream boundary was keep with a constant inflow with a 5-year return period. The results are shown in Tables 1 and 2. Table 1 shows that the inflow at Teddington has little effect in the water levels along the river Thames, being the tide the major contributor. In this case, the peaks at Chelsea and Silvertown only increased around 2.2% on average compared to the inflow with 5yrs return period. However, Table 2 shows that the water level along the river Thames is very sensitive to the tide level at Southend, as the enhancement of tidal peak level at Chelsea and Silvertown were close to the increase of the tidal peaks at Southend.

Table 1. Sensitivity analysis of various inflows at Teddington

Return Period	1:5yrs	1:50yrs	1:100yrs	1:500yrs
Inflow (m^3/s)	350	600	700	1000
1st Tidal Peak (m) at Chelsea	4.52	4.61	4.62	4.65
2nd Tidal Peak (m) at Chelsea	5.18	5.32	5.36	5.38
1st Tidal Peak (m) at Silvertown	4.09	4.13	4.14	4.14
2nd Tidal Peak (m) at Silvertown	4.74	4.79	4.80	4.81

Table 2. Sensitivity analysis of various tide level enhancements at Southend

1st Tide peak level (m)	+0.1	+0.5	+1	+1.5
1st Tidal peak at Chelsea (m)	+0.025	+0.584	+1.036	+1.339
1st Tidal peak at Silvertown (m)	+0.032	+0.512	+0.977	+1.307
2nd Tide peak level (m)	+0.1	+0.5	+1	+1.5
2nd Tidal peak at Chelsea (m)	+0.017	+0.571	+1.054	+1.39
2nd Tidal peak at Silvertown (m)	+0.02	+0.5	+1.006	+1.357

The following analysis addresses the impact of local wind on the propagation of the tide from the estuary mouth to upstream. A series of simulations have been undertaken for different wind conditions to examine the impact of wind speed and wind direction on the peak on the tide. Wind friction on the water surface can be accounted for in MIKE11 by the inclusion of the wind shear stress in the momentum equation, acting as an additional force. The wind shear stress is expressed by $\tau_w = t_{\text{fac}} C_w \rho_\alpha V_{10}^2$, where C_w represents wind friction coefficient ($3.24*10^{-6}$), t_{fac} depends on the surrounding topography (1.0 for open water and tends to be lower at locations which are sheltered from the wind), V_{10} is the wind speed 10m above the water surface and ρ_α is the density of air. The wind force projection in the length direction of the channel is included in the momentum equation in each Q-point. The time series of wind speed and direction are setup as boundary conditions for different locations. The direction of the wind is in degrees in clock wise direction from north. The topographical factor (t_{fac}) was assumed to be 1.0. Several wind speed/directions were selected: wind speed (m/s): 0, 10, 15, 20, 25, and 30, which were assumed to be constant for the wind duration; and wind direction (degrees): 0, 30, 60, 90, 120, 150, 180, which were also assumed to be constant for the wind duration. Tide residuals were extracted to evaluate the impact of wind factor on tide level, which is defined as the tide level affected by the wind minus the astronomical tide level.

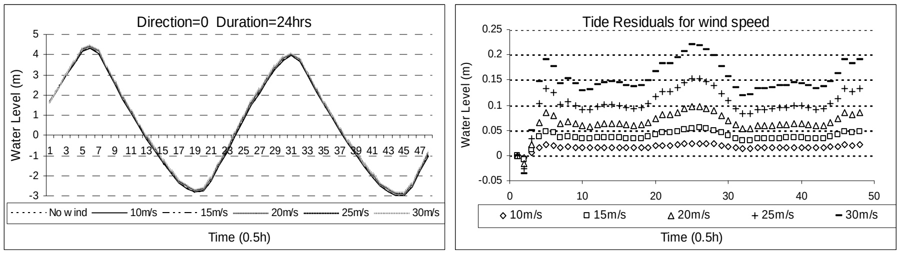

Figure 6 Tide residuals produced by varying the wind speed (Silvertown).

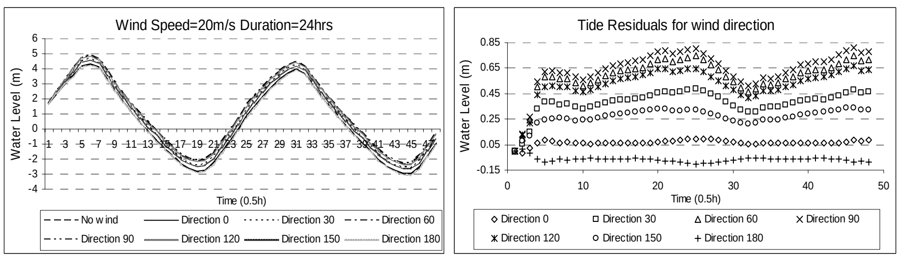

Figure 7 Tide residuals produced by varying the wind direction (Silvertown).

The results are shown in Figures 6 and 7, which demonstrate that both wind speed and wind direction have considerable impact on the residuals in the River Thames, and they can be propagated all the way up to Thamesmead. The influence of the topography however, may produce slightly lower residuals (in this case it was assumed open water).

5. WHOLE SYSTEMS MODELLING

The idea of whole systems modeling is to integrate and couple the outputs of the different models to reach a final goal. An example of this system was shown in Figure 1. It is clear that the storm surge 6h forecasts at Sheerness are driven by different observations at different locations in the East coast of England (wind speed, atmospheric pressure and water level). The storm surge model is coupled with the deterministic astronomical tide and this becomes the lower boundary condition of the hydrodynamic model of the river Thames.

The Flood Risk Management Research Consortium's (FRMRC) first co-location workshop was focused on a hypothetical extreme storm event affecting the Thames Estuary using the concept of whole systems modeling. This event provided the opportunity to generate ensemble tidal surge forecasts at different points in the East coast of England. A storm surge event that occurred on 20051125 0100GMT on the Thames estuary was analyzed. The event occurred during a period of neap tides and it did not cause any problem. However, to make the modeling interesting, the surge was superimposed with the peak of the largest tide to occur in the next coming years. Measured water level data and an ensemble of 24 members from the output of the CS3 model at Whitby, Cromer and Sheerness were available (See Figure 8). The rationale of 'ensemble forecasting' is to represent the uncertainty in the forecasts. The storm surge forecasts were routed through the MIKE11 model and the results shown in Figure 9. This shows the ensemble water level forecasts at Sheerness and the relative forecasted water levels at the Thames Barrier.

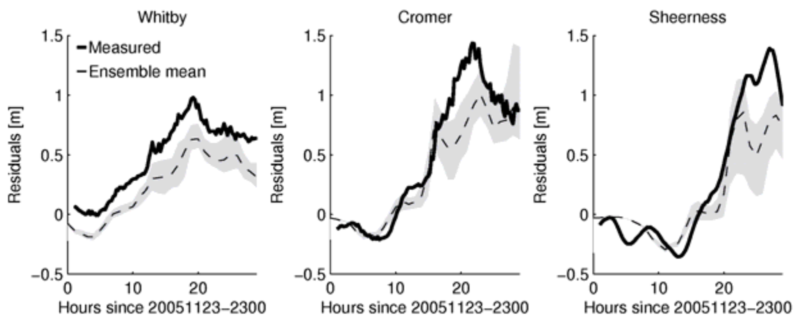

Figure 8. Ensemble storm surge forecasts from the CS3 model. The shaded area shows the ensemble spread with quantiles $q(0.1)$ and $q(0.9)$.

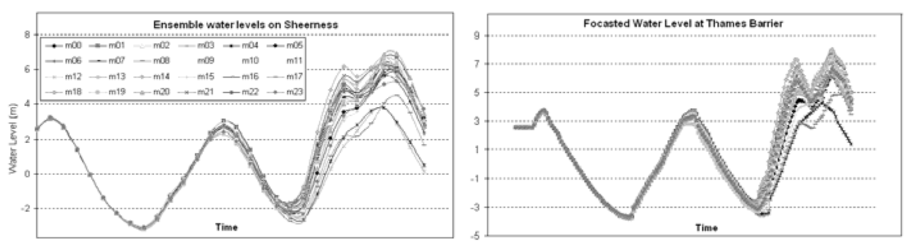

Figure 9. Ensemble water levels at Sheerness provided by POL and Met Office and forecasted water level at Thames Barrier using the MIKE 11 model.

The hydrodynamic model of the river Thames represents a mean to explore a number of potential scenarios using storm surge forecasts either from the CS3 model or the MISO TF model proposed in section 2. The most important and potential practical use of the hydrodynamic model is to propagate the uncertainty and simulate the relative water level at various points all the way up to Thamesmead and to provide the crucial real-time data to support the flood management system under extreme weather conditions.

6. CONCLUSIONS

This paper presented a robust model to forecast storm surges at Sheerness with a lead time of 6 hr. The results showed that the error of this model is about 0.22m assuming water levels above 0.5m only. The storm surge model was coupled with a hydrodynamic model of the river Thames to forecast water levels in any part of the river.

The hydrodynamic model of the river Thames was built using cross-section data of the river channel in the MIKE11 software. The calibration of this model allowed adjusting the channel roughness. It was shown that the water levels along the river Thames are highly dependent on the variations of the water levels at Sheerness. However, the inflow at the upstream boundary condition showed little effect in the results.

ACKNOWLEDGEMENTS

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