Storm surge hind- and forecasting using Mike21FM - Simulation of surges around the Irish Coast

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Abstract
This paper presents details on an Irish Sea Tidal and Surge Model which has been developed as part of the Irish Coastal Protection Strategy commissioned by the Office of Public Works (OPW). The main objective was to utilise the model in deriving extreme water levels to quantify the risk from coastal flooding. Initially the model was envisaged to be used for the Irish Sea alone; however due to the flexible mesh capability in MIKE 21 HDFM, it was possible to develop a single model which would allow the transformation of surges from the continental shelf around the entire coast of Ireland. As a result the model has been used, with a number of modifications, for large sections of the Irish Coastline for a wide range of applications.

The model uses a flexible mesh with cell sizes ranging from several kilometres at the western Atlantic boundaries to tens of metres in certain coastal areas. It is driven by water level boundaries which are defined by a series of harmonics, including seasonal and annual components depending on the application. The wind and pressure field applied is derived from reanalysis or operational atmospheric data sets provided by the European Centre for Medium-range Weather Forecasts (ECMWF). The model has been calibrated against an extensive dataset comprising tide gauges and tidal stream data.

More recently the model has been used as forecasting tool on an operational basis for the winter months, providing Irish authorities with estimates on likely flood risk at coastal locations. The model has also been ported to the ICHEC (Irish Centre for High End Computing) and future development includes fully operational forecasting in collaboration with Met Eireann and the Office of Public Works.

Introduction

In 2004 RPS Consulting Engineers were commissioned to undertake a pilot study under the Irish Coastal Protection Strategy. The key objective of this study was to derive extreme coastal water levels and erosion risks along the South East Coast of Ireland from Dalkey Island to Carnsore Point. Following assessment of the available tide gauge data and historic records the project team decided to develop a tidal and surge model for the Irish Sea. Initially it was envisaged to build a local model of the Irish Sea driven by larger scale models such as the POLCOMS based CS20 model. This opened the possibility of simulating historic storm surges for specific storm events and thus hindcasting water levels along the coast. The following sections
describe the set-up and forcing of this model and also highlight some of the issues encountered in the set-up and simulation process.

**Model setup**

The model bathymetry was derived from a range of sources. The majority of the bathymetric data for the original models was derived from the MIKE tool C_Map; however in some areas of the Irish Sea this can date back to the mid 1800’s therefore additional data was provided. A number of surveys previously commissioned by RPS were used to replace chart information. In some areas such as shallow banks and mudflats this was important as often charts do not provide sufficient details in flooding and drying areas. The Irish National Seabed Survey (INSS) was also used in the first models since this time the model has been updated with bathymetry from more recent Irish survey campaigns such as the Joint Irish Bathymetric Survey (JIBS) and INFOMAR. All data was converted to mean sea level using a large set of data points as shown in Figure 1, using a custom made routine in Matlab.

![Figure 1: Mean sea level correction values, locations (red cross) and interpolated surface](image-url)

The mesh of the model was developed based on the bathymetric information; the mesh size being manually adjusted in areas with abrupt changes in bathymetry such as the edge of the continental shelf and near banks and channels. In an iterative process the model was refined further at banks and in channel sections to obtain similarity between the simulated flow and full scale. The flexible mesh allows this refinement without significant increase in cell numbers compared to rectangular mesh models. The targeting of cells in the areas of rapid change is illustrated in Figure 2 at the Kish Bank, offshore from Dublin.

The use of the quadrangular meshing option has also been utilised in the model. Areas where narrow channels exist would normally require large numbers of triangular cells in order to describe the bathymetry and provide the required flow volumes however quadrilateral cells are more computationally efficient. Figure 3 shows how, in Cork these cells have been applied.
Figure 2: Mesh detail at Codling bank in the Irish Sea

Figure 3: Mesh detail at Cork Harbour using quadrangular cells
The number of computational cells has varied between the different model versions and initially was around 50,000 cells. In more recent versions the model features over 60,000 cells with targeted high resolution areas. Cell sizes are 36’ as the maximum resolution in the deeper parts of the Atlantic, a cell size of 12’ along the open boundary and reducing to less than 100 metres at locations near the shore or in inlets.

The computational performance of different versions of the model has been governed by the relationship between cell size and water depth in terms of overall runtime; with the latest models having a reduced run time despite their increased cell numbers. The CFL number and thus the computational time step in the more detailed areas has played a pivotal role. Inshore and near shore areas with depths of 20 – 40metre and locations with deeper areas close to shore such as Tuskar Rock in the entrance to the St Georges Channels and Rathlin Island in the North Channel are two examples where a balance between cell size and runtime had to be found. Performance improvements in the order of 20 – 30% have been possible following a modification of the initially derived mesh, without a significant decrease in the number of cells at the same time. Similar observations have been made by (Lambkin 2007).

Open Boundaries and model extent

In the initial phase the location of the open boundaries was examined. In the first model set-up the most western boundary was placed between Porcubine Bank and Ireland at 12°W. This was however relocated to 16°W to include Rockall and Porcubine Bank and also extended further north. The model also initially had an open boundary into Lands End however this was found to result in significant instability and poor correlation at nearby tidal locations. The model was therefore extended further south and incorporates a land boundary near Isle d’Ouessant and includes the entire English Channel, as illustrated in Figure 4.
The offshore boundary definition for the tidal forcing was derived from the KMS global tidal model originally with a 0.5° resolution (Andersen 1994, Andersen, Woodworth et al. 1995, Andersen 1995). This model is now part of the tidal prediction package in the Mike 21 Toolbox and has been improved to 1/4° resolution. It provides 8 harmonics (M2, S2, K2, N2, O1, P1, Q1 & K1) of diurnal and semidiurnal nature, though the values of the P1 and Q1 constituents are of small magnitude in the open area. This data set was initially compared against the data provided by the Permanent Service for Mean Sea Level (PSMSL). From the analysis it was determined that the KMS tidal predictions should be supplemented with values for the L2 and NU2 constituent (Zetler 1980).

An overview of the GLOUP data available in the vicinity of the model domain is shown in Figure 4. Additional data was included to account for seasonal changes in water level (annual and monthly harmonics – 6 in total) and harmonics relevant to the sections where the model joins the coastline (3 harmonics) totalling 19 constituent which are now available for the generation of boundary conditions. The tidal analysis of any relevant time series data was undertaken using the MIKE21 tidal toolbox and Matlab code, t_tide (Pawlowicz, Beardsley et al. 2002).
Figure 5: Global Undersea Pressure (GLOUP) data set available from PSMSL within the model domain

Model Calibration

The model was calibrated against a large set of locations with tidal predictions, illustrated in Figure 6. In most instances the tidal records were obtained and analysed to determine a set of harmonic coefficients. High quality data sets are available for a large range of ports and coastal locations for England, Wales and Scotland through the National Tidal Sea Level Facility. However in Ireland, good tide gauge data is limited and as a result the Marine Institute has now developed a similar service, collating tide gauge data from a large range of providers.

During the calibration process it became apparent that a thorough examination of the quality of tide gauge data used is essential. Often tidal predictions are taken “as-is” with little question as to their accuracy. In the calibration process a good correlation to most open water locations outside the Irish Sea was achieved at a very early stage. Good correlation was also obtained at locations such as Fishguard and Holyhead, yet Dublin and Rosslare showed a much worse match with the model data. Closer examination of the recorded tides at Rosslare indicated a difference of predicted and observed high water of between 20 and 30 minutes in 2004. More details on predictions used for example by Proudman Oceanographic Laboratory, the UK Hydrographic Office and others were obtained (including the predictions included in CMap). From these it became apparent that due to the short duration of the records, the number of harmonics used in the predictions can be limited and in some instances less than is used along the open boundaries of the model.

As a result of this finding, the calibration process only used those locations with good quality data sets of one year or more and tidal predictions of less quality were only included for reference. In the model validation process data sets over two full lunar cycles were used; these included average neaps and spring cycles in addition to a particularly large spring and small neap. This gave the full range of tidal levels experienced at each location.
Good correlation with tidal ports along Atlantic coast, the southern Irish Coast and entrance to Bristol Channel and English Channels was achieved. Similar locations in the Hebrides and along the North coast correspond well with the predictions. Further validation has shown a good match of tides in the Irish Sea e.g. Fishguard, Holyhead, Port Erin and Portpatrick, however there is a persistent under prediction of tides for events with high waters larger than MHWS at Dublin (up to 0.2m). This may be due, in part, to the tide gauge recording seiching within the harbour. It should be noted that no internal tidal forcing is currently used as it was found to give rise to only small changes in surface elevation, yet large changes in runtime for the model. Two sample data sets are given in Figure 7 & Figure 8 with Dublin being based on a good quality data set and Courtown (close to the degraded amphidromic point) of less quality.

Figure 7: Comparison of predicted tide and simulated tide at Dublin Port, prediction based on good quality data set
Initially the primary purpose of the model was the simulation of extreme surge events. At a very early stage, it was questioned if the model extended sufficiently seawards to simulate the development and progression of a surge. The Northern Atlantic Oscillation is often mentioned in this context and is considered as an indicator for the occurrence of large storm events and surges. However in the deeper parts of the Atlantic the flow of water caused by the wind shear is counterbalanced by a backflow at greater depth, thus giving rise to only small increase in surface elevation.

The theoretical description of the Ekman layer gives details on the effect of wind shear on a free surface in deep water. Based on the equation defined originally by Ekman and confirmed through experimental data by Ralph and Niiler (Stewart 2004) the depth of the Ekman layer was calculated. For high wind speeds (~20m/s) it can be found that the depth at which the velocity has the opposite direction to the velocity at surface is in the order of 170m. Significant changes to the surface elevation near the continental ledge and in deeper water are therefore primarily due to atmospheric pressure, as the resulting flow is small in terms of momentum equation. Based on this analysis the location of boundaries was considered adequate.

Once the atmospheric boundary is applied the tidal variation in surface elevation is adjusted along the boundary taking account of the mean sea level pressure. A number of sources were considered for the atmospheric boundary data. The wind and pressure fields used in the Irish Coastal Protection Strategy were obtained from the European Centre of Medium Range Weather Forecast (ECMWF) using the ERA 40 reanalysis (Uppala, Kallberg et al. 2005) and the operational atmospheric model. The data for both products is available in 6 hourly intervals with resolutions of 1.125° (ERA40) and 0.5° (operational model until 2008, 0.25° more recently). Following initial testing it was found that the time step of the data set is too course, as depressions can travel too fast in 6 hours giving a transient core pressure in the centre of the depression. This is due to the interpolation of the atmospheric condition by the model. As a result the atmospheric data set was supplemented using the first guess (pre-run) and +3h forecast to fill intermediate time steps to a resolution of 3 hours. The atmospheric data sets are supplied in the typical meteorological GrIB format, which are read using Matlab code and converted to dfs2 files with correct time axis. During this operation the bias correction is applied and intermediate time steps included.
Another issue emerged while validating storm surge events in the Irish Sea; from the analysis of the surge residuals it became apparent that the strength of the wind field in the Irish Sea is underestimated. Further analysis showed that the atmospheric data set has only one or two grid points in parts of the Irish Sea in the longitudinal direction, which are not on the land mask. From a description of the atmospheric model an advection term in the model combined with interpolation of the data set caused this bias. The interpolation takes place when the computational data from the reduced Gaussian grid is transferred to the regular Gaussian grid used for dissemination and archiving. The comparison with recorded wind speeds showed significant decrease in mean hourly wind speed in ECMWF in the Irish Sea - by up to 20%. This was attributed to an underestimation of the thinning of the atmospheric boundary layer over water. Treatment of this bias was considered in two ways:

- Adjusting the friction value for the wind fields, which however lead to overestimation of the wind induced shear in offshore regions or
- Bias correction of the wind strength in the near shore region and in particular in the Irish Sea, which produced acceptable results.

In order to establish the accuracy of the model in terms of surges, the surge residuals for a selection of events were derived. Surge residuals are obtained by subtracting the predicted tidal levels from the observed surface elevation or in case of the model the simulated water levels of the astronomic tides from the total water levels. The observed surge residual can then be assessed in relation to the simulated surge residual. Two examples of such a comparison are given below. These are surge residuals for the same event observed and simulated at Holyhead and Dublin respectively (Figure 9 & Figure 10).

**Figure 9: Observed (blue) versus simulated (red) surge residual at Holyhead, Wales**

**Figure 10: Observed (blue) versus simulated (red) surge residual at Dublin, RoI**
The surge residual in Figure 10 shows significant higher frequency oscillations which are due to seiching in Dublin Bay. This phenomenon can result in variations in water level of typically 0.25m under strong wind conditions. Due to the time averaged wind field used in the model it is however not reproduced in this case. In a separate simulation however it could be shown that, if wind conditions with fluctuations in speed and direction are applied to the model, similar oscillations can be generated.

In order to derive the extreme tides for the selected coastline a peak over threshold analysis on the surge residuals for a selection of historic tide gauge records was undertaken. From these records extreme events were selected and simulated to gain a full coverage of extreme surge water levels along the entire length of the coast.

Model performance

Initially runtime of the model was of significant concern. The first simulations had run times of 7:1 (7 days of tidal predictions in 1 day of computation) on a high performance desktop PCs (∼3sec computational time step). Following further refinement of the mesh and changes in the MIKE21FM code to adaptive time stepping this improved to 12:1. Currently the model is run on a multi processor license in the 2009 version with four cores on a 64bit platform which (despite an ever increasing number of cells) reaches run times of 60:1 or higher. Unfortunately this does give the modeller less excuse for project delays!

Model Output

A range of model outputs are commonly produced. For surge simulations in general two separate simulations are run. Firstly, a simulation for the duration of the start-up and the event period applying astronomic boundaries and Coriolis forcing is run. The second simulation uses the first model set-up with the addition of the wind and pressure fields. As a basic output total water levels and u-/v-velocities are generated to allow hot start of further simulations. In a separate file surface elevations and wind and pressure field as applied to the model are recorded.

From these data sets the surges at given locations can be derived, by subtracting the tidal component (derived in the first simulation) from the total water level (derived in the second). It should be noted that surge residuals provide the effect the surge has on the total water levels. This includes current-surge interaction due to currents driven by astronomic tides, which could accelerated or decelerate the progression of a surge depending on the tidal stage, even though the actual astronomic water level is excluded. Due to the separation of the two components it is possible to improve the accuracy of the water level predictions by applying calibration factors derived during model testing.

Results

Since the initial development the model has been applied to a number of projects and it is beyond the scope of this paper to present these all in detail. A small selection is therefore discussed here. During the simulation of extreme storm events a number of observations were made; in general it can be said that surges have large spatial extent and compared to astronomic tides they have relatively small variations along the coast. Figure 11 to Figure 14 show examples of two selected storm events, in each case the storm track and the resulting maximum
surge residual is presented. Figure 15 shows the spatial water level changes due to the tide.

Extreme surges, in particular along the East coast of Ireland, are mostly a combination of low pressure in conjunction with wind shear causing variation in water level. This can be in part explained as a result of the Coriolis forcing, which deflects north going currents along the Irish East coast towards the East resulting in higher water level in eastern parts of the Irish Sea when compared to the Western side. This can be the case even with easterly wind components and thus extreme wind conditions on their own are unlikely to give large surges along the East coast of Ireland. The analysis of tide gauge data has also shown that extreme surge events are relatively frequent along this coast, with heights of 0.7metre around Dublin as the annual event. However often these coincide with low astronomic water levels thus pass unnoticed. The paths of the strongest surges along the east coast of Ireland differ significantly, although a depression of 960hPa or lower is common.

Figure 11: Centre of depression from 15/12/89 - 18/12/89 plotted at 3 hourly intervals, resulting in maximum surge level of 0.94m in Dublin Bay and 0.87m at Rosslare (simulated)
Figure 12: Maximum surge residual during simulation period for surge event December 1989

Figure 13: Centre of depression from 31/01/02 - 02/02/02 plotted at 3 hourly intervals, resulting in maximum surge level of 0.91m in Dublin Bay and 0.62m at Rosslare (simulated)
Figure 14: Maximum surge residual during simulation period for surge event February 2002

Figure 15: Large spring tidal level relative to mean sea level in domain, note the different scale compared to Figure 12 & Figure 14

Other uses of the model
The original purpose of the model was to establish extreme water levels for south east coast of Ireland. Using the flexible mesh technique offers the opportunity to change the resolution in certain areas depending on purpose of model. This meant that the model could be utilised for different applications without a complete rebuild of the domain. The model can therefore be used for tidal resource studies or as source for generation of boundaries for more detailed local models.
Storm surge forecasting for Ireland
The computational efficiency of the Irish Seas model was exploited to develop the storm surge forecasting service on behalf of the OPW. The model continues to utilise meteorological forecast data from ECMWF in concert with predicted tidal levels to provide a real-time forecast of water levels due to storm surges.

The system provides two short-range and one longer range forecast each day; this data is made available to all the relevant public bodies via a secure website (Figure 16). The three forecasts per day are based on the meteorological forecasts generated by ECMWF. The short range forecasts provide predicted levels for a period of 72 hours using 3 hourly interval data on wind speed and pressure, whilst the longer range forecast uses 6 hourly data to provide a 6 day forecast. The first 72 hour simulation commences at 07:00UT, as soon as the meteorological data is available, with the results being uploaded to the web portal when the simulation is complete, generally before 09:00UT. The 144 hour simulation is immediately initiated following the 72 hour model termination, with the results being made available around mid-day. The 72 hour evening forecast proceeds in a similar fashion to the morning forecast.

Figure 16: Web interface for access of surge forecast

The operation of the forecast system is fully automated, from the download and transfer of GriB meteorological files to MIKE format, through the simulation itself to the post-processing and web page generation. Currently a MatLab interface is used to trigger and control the system. The data is offered as both graphical plots and ASCII files accessible for downloading (Figure 17 & Figure 18 respectively). In addition, areas which are sensitive or prone to coastal flooding, such as Cork and Wexford, are modelled at higher resolution and a number of prediction points are provided at these locations.
Figure 17: Graphical output of surge, total water level and predicted tide for sample location including estimate of uncertainty

Figure 18: Tabular output of surge, total water level and predicted tide for sample location
Conclusions

The development, calibration and validation of the Irish Seas Tide and Surge model has demonstrated how the advantages of the flexible mesh technology can be harnessed in order to provide computationally efficient models for a variety of purposes. Mesh adaptation and the concentrating of cells in areas where the greatest resolution is required allows for increased model accuracy without sacrificing run-time; so much so that real-time forecasting becomes possible. The model is also ideally suited for providing boundary data in terms of both water levels and fluxes for independent or pre-existing models which utilise either flexible or rectangular meshes.

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References


