06 - DEVELOPMENT OF A TIDE, STORM SURGE AND WAVE FORECAST SYSTEM FOR THE SOUTH WEST COAST OF IRELAND

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Abstract
This paper describes the development and results of a TELEMAC-2D hydrodynamic model and SWAN spectral wave model set up to potentially provide an operational forecast of tides, storm surges and waves for Tralee and adjacent bays, in South West (SW) Ireland. The models were set up using the latest bathymetry data including high resolution multibeam and LiDAR data. The TELEMAC model was initially forced with TPXO tidal data and wind and pressure data from ECMWF and Met Éireann and calibrated against available tide gauge and wave data in SW Ireland including Tralee Bay. The SWAN model was driven by forecasts of wave spectra from ECMWF and wind from ECMWF and Met Éireann. Following the first of two trial periods in winter 2018/2019 the TELEMAC model boundary tidal forcing was updated to use FES2014, which resulted in closer agreement with tidal predictions. The second live trial period was subsequently carried out during the Autumn of 2019 which included measurements of waves within Tralee Bay. This paper summarises the setup of the models and preliminary results to date.

1. INTRODUCTION

The Office of Public Works (OPW) in Ireland is investigating the viability of an operational tide, storm surge and wave forecast system for Tralee and adjacent bays in an area of the South West Coast of Ireland (Figure 1). This could potentially supplement an existing operational national storm surge forecast service and a trial regional tide, storm surge and wave forecast system on the East Coast of Ireland.

The area of interest is exposed to storm surges due to strong winds and low atmospheric pressure, as well as waves generated in the Atlantic Ocean that propagate from offshore and those generated more locally within the bays. Whilst the required forecast system does not yet extend to forecasting coastal inundation levels or extents due to high waves and water levels, the system is expected to provide an indication of the potential for coastal flooding.

Two continuous trial periods were carried out to forecast wave conditions, tide and surge levels at 45 points distributed along the coastline of Tralee and the adjacent bays. This paper summarises the tide, storm surge and wave modelling aspects of the development project and presents a selection of comparisons of the forecasts against measured data.

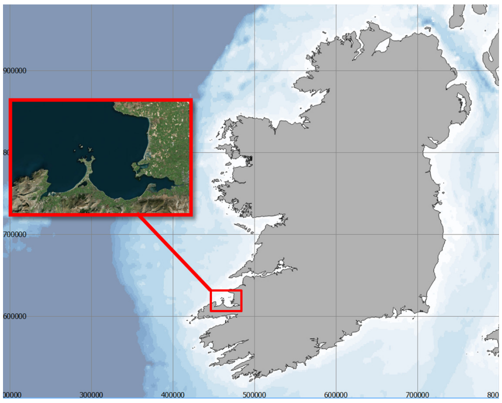


Figure 1: *Location Map (Sources: Google Earth, GSHHS, ETOP01)*

2. THE TELEMAC-2D MODEL

To predict the tide and storm surges a TELEMAC-2D hydrodynamic model (TELEMAC, 2020) was set up and calibrated against available sources of measured water levels and wave conditions in the vicinity of Tralee Bay.

The TELEMAC-2D model was set up to cover an area extending from Blacksod Bay in the North to Bantry Bay in the South and West to the edge of the continental shelf (see Figure 2). The model mesh comprises approximately 200,000 nodes, and close to 400,000 elements. It has a spatial resolution of the order of 10km offshore reducing to 10's of metres in the coastal regions thus providing an accurate representation of the seabed in the shallow coastal waters.

2.1 Bathymetry

The accuracy of the forecasts will depend on several factors including the accuracy of the available source bathymetry, the model resolution and the model boundary conditions comprising forecast winds, surface pressure and water levels. For this pilot study a wide range of sources of bathymetry were obtained and compiled to provide the model seabed depths.

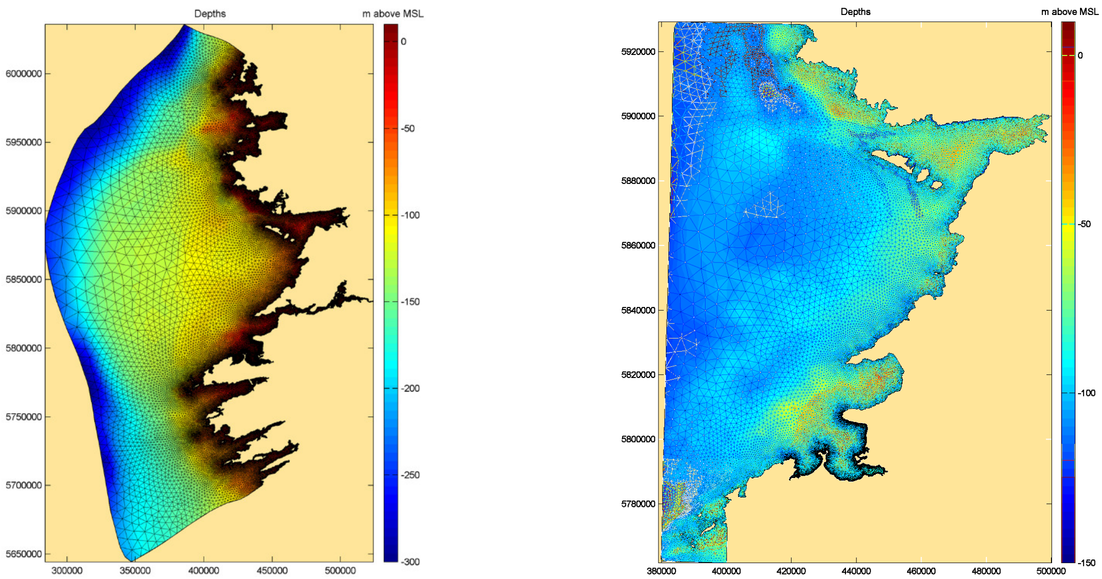


Figure 2: *TELEMAC (left) and SWAN (right) Model extents, meshes and bathymetry*

The main source of bathymetry was obtained from the Geological Survey of Ireland and Marine Institute joint INFOMAR project (GSI and INFOMAR) which hosts an extensive set of bathymetry data around the coast of Ireland compiled from a number of different sources including multibeam survey and LiDAR data. Within Tralee Bay, detailed LiDAR data from OPW, and further offshore beyond the limits of the INFOMAR data, GEBCO_2014 point data, were used. Within parts of Brandon Bay, charted point data was used to improve the seabed map in this area which was not well covered by the above datasets. Tralee Bay includes areas of shallow intertidal saltmarsh, so the LiDAR data was particularly useful in representing these areas in the model. Where necessary the VORF model (2007) was used to transform some of the surveys to a common vertical datum.

2.2 Tidal conditions

The hydrodynamic conditions are dominated by astronomical tidal effects. To represent the tidal effects, the offshore boundary of the model was initially driven by tidal levels extracted from the TPXO satellite altimetry dataset (Egbert et al, 2002 and OSU, 2008). TPXO provides tidal boundary conditions based on 13 tidal harmonic constituents, and has a spatial resolution of 1/12°. As part of model calibration, described below, the tidal forcing subsequently changed to FES2014 (Carrere at al. 2015) which led to greater accuracy. FES2014 has a spatial resolution of 1/16° and provides up to 34 constituents, including several of the important constituents evident from the harmonic analysis of the measurements.

2.3 Atmospheric Conditions

Storm surges are a result of atmospheric wind and pressure effects and can also be influenced by the geometry of the coast and by the tides. Two sources of atmospheric pressure and wind speed and directions were considered in this study:

- The Met Éireann Harmonie model (HIRLAM-Aladin Research in Mesoscale Operational NWP In Euromet) data (Bengtsson, 2017), represents the atmosphere using the fundamental equations of meteorology and produces forecast data for a wide variety of surface parameters such as wind, rain, temperature and precipitation at a horizontal resolution of 2.5 km, with 65 levels in the vertical. A 54-hour forecast with a 1 hour temporal resolution is produced four times a day, at 00Z, 06Z, 12Z and 18Z.
- The European Centre for Medium Range Weather Forecasting (www.ECMWF.int) Operational atmospheric forecast model, is produced at a spatial resolution of 0.1 degrees and provides a 10-day forecast and is also produced four times a day. The ECMWF forecasts are available in hourly timesteps from 0 to 90 hours, 3 hourly from 93 to 144 hours and 6 hourly from 150 to 240 hours.

For the present study the TELEMAC-2D model was forced with the 00Z and 12Z Harmonie forecasts providing a short-range forecast of up to 54 hours using a temporal resolution of 1 hour. The model was also run independently, using the 00Z ECMWF operational forecasts providing a short to medium range forecast, meeting the requirement of a 6-day forecast, using a temporal resolution of 3 hours and spatial resolution of 0.125 degrees available at the time of the study.

To account for surges at the model outer boundary, tidal elevations imposed were first adjusted for the hydrostatic head due to air pressure i.e. the inverse barometer effect. The coefficient of wind influence, which takes into account to some extent the roughness of the seas and other processes, was calculated following the standard TELEMAC formulation given by the Institute of Oceanographic Sciences in the UK (Flather, 1976).

Two of the main differences between the EMCWF and Harmonie data is the spatial resolution currently available and temporal resolution as used in the present study, so one could expect that the Harmonie data should provide a more accurate representation of the wind fields, particularly any small spatial and temporal scale features such as small intense storms.

2.4 Measured water level data

Relevant observational tide data on the West and SW coast of Ireland are available from the Irish National Tide Gauge Network (INTGN) at Roonagh Pier, Galway Port, Inishmore, Kilrush Lough and Castletownbere Port, and from the OPW Hydrometric Network (www.waterlevel.ie), including Fenit Pier and Blennerville within Tralee Bay. The INTGN data are generally available every 6 minutes (except for Castletownbere Port: every 15 minutes) and are referenced to Ordnance Datum (OD) Malin Head (OSGM15). The OPW data in Tralee Bay are currently available every 5 minutes and are also referenced to OD Malin Head (OSGM15).

Some observational tide gauge stations such as at Roonagh Pier and Kilrush Lough have only been in operation for a relatively short period. It is also worth noting that there can be long interruptions in the data, e.g. when the devices were serviced. This means that not all of the data could be used when performing tidal analysis.

A temporary tide gauge was also installed by the GSI at Brandon Quay, within Brandon Bay (Figure 5), providing a short term record of water levels during the second trial period.

2.5 TELEMAC-2D Model Calibration

An initial model calibration was carried out using TPXO and ERA5 wind and pressure data from ECMWF as a proxy for operational forecast wind and pressure data. ERA5 (Hersbach and Dee, 2016) is a climate reanalysis dataset, available through the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). The initial calibration of the tide only model predictions was based on a spring neap cycle at Fenit Pier from 2008 that is representative of an average spring neap cycle.
For the calibration of the model for tide and surge events, an analysis of the tide gauge data at Fenit Pier was carried out to identify five events between 2013 and 2017 with notable surge residuals, including the highest event recorded at Fenit Pier. It is worth noting that high surge residuals, and some of the events selected, did not necessarily occur with spring tides.

The model calibration included sensitivity tests to the bed friction, tide, and atmospheric forcing.
Model results were subsequently validated against tide gauge data across the area including at Fenit Pier, Kilrush Lough, Galway Port and Inishmore for a representative average spring-neap cycle. The tide only results were in reasonably good agreement with average errors of between 0.02m to 0.1m in elevation and errors of between 9 to 18 minutes in the timing of high waters, but outside the target accuracy set for the system. Following the initial model calibration, a first continuous trial period was carried out during the winter of 2018-2019. Results from this trial at the Fenit Pier tide gauge within Tralee Bay showed relatively small but nevertheless noticeable differences in the tide only predictions.

The differences between the model predictions and synthesised tides, whilst relatively small, appeared in both the phase and amplitude, and therefore were unlikely to be corrected by simple adjustments to the TPXO data, as occasionally required. The synthesised tides were based on a tidal harmonic analysis of the Fenit Pier gauge for the continuous period between February 2016 to July 2017 using T-Tide (Pawlowicz, 2002). A review of the performance of several different global tidal models given in Stammer et al. (2014), concluded that FES2012 and TPXO08 performed best in shelf seas, but with FES2012 having the highest resolution and the lowest errors for the main tidal constituents for shelf seas such as the European Continental shelf. More recently Ray et al. (2019) show that FES2014 improves upon FES2012. A review of the amplitudes of the harmonic constituents from this analysis showed several important constituents were not included in TPXO but were included in FES2014. A hindcast of the first continuous trial period using FES2014 produced a noticeable improvement in model predictions, particularly at high water, and was therefore adopted for the second trial period.

2.6 TELEMAC Model Validation

Model validation was carried out as part of the two continuous forecast trial periods. Following model recalibration after the first trial period, the second continuous trial period was carried out during the months of October to December 2019. During the second trial, as presented in this paper, the model was forced with FES2014 at the boundaries, with wind and pressure forcing from the forecasts provided by ECMWF operational forecast and Met Éireann Harmonie forecast within the model domain. The following sections present a comparison of the model results against observed data at Fenit Pier.

Tide Only

The model results for the tide only component are presented first. These results were generated by running the model with tide only forcing, i.e. using only FES2014 and comparing the results against the synthesised tide levels.

The model was run once a day as part of the operational forecast system to produce a 6-day tide-only prediction, i.e. without meteorological forcing. The main aim of running the tide only model was to be able to quote surge residuals at all the forecast points within Tralee and adjacent bays. The model results are presented in Figure 3 as a timeseries of water elevations for a two-day sample period during the second two month trial period to illustrate the model predictions, when there was a noticeable surge event. Scatter plots of all high-water predictions during the trial period are also given in Figure 3 together with the associated error statistics quoted in Table 1. The error bars in Figure 3 are +/- 0.15m, which was the target accuracy for the tide only component of the model.
The time series shows the model is in close agreement with the synthesised tide levels. Figure 3 shows that the model predictions of all high tide levels during the trial period are generally within the target accuracy, with a few high waters slightly underpredicted. The error statistics quoted in Table 1 show that the model predictions meet the target accuracy for 89% of all high waters, and for the higher high waters above Mean High Water Spring (MHWS) the target accuracy is met 100% of the time. MHWS at Fenit Pier is estimated from our tidal analysis of the gauge data to be 2.22m above Mean Sea Level (MSL). Mean errors quoted in Table 1, show a small positive bias of 1cm for all high waters and 6cm for high waters above MHWS.

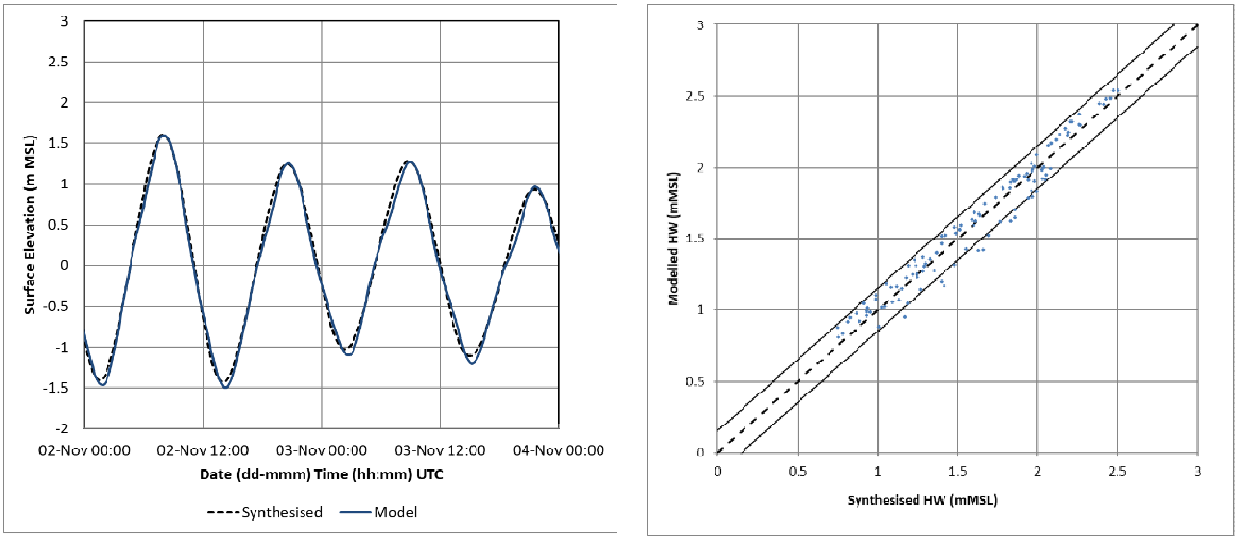


Figure 3: *Tide only synthesised and model predictions at Fenit Pier (left). High tide levels model vs. Synthesised (right).*

Table 1: *Tide only Error Statistics*

	Mean Error (m)	Mean Absolute Error (m)	Error range (m)		Target (m)	Events within target (%)
High Waters	0.01	0.08	-0.25	0.13	+/-0.15	89
High waters above MHWS	0.06	0.06	0.03	0.11	+/-0.15	100

Tide and Surge

The tide and surge model results presented are the first 12 or 24 hours of each forecast, based on the Harmonie or ECMWF forced model runs, respectively. The model results are presented in Figure 4 as a sample 2-day time series of the surface elevation. A scatter plot of all the high water (HW) predictions during the trial period are shown in Figure 4, with associated error statistics quoted in Table 2. The error bars in the scatter plot is the target accuracy measure of 0.25m.

The time series plot in Figure 4 covers the same period as in Figure 3. Figure 4 shows that the models are in reasonably good agreement with the observations. Furthermore, there is little visible difference between the model forced by either ECMWF or Harmonie for this period.

The scatter plot in Figure 4 shows the model predictions of all high waters during the second trial period, plotted against the observed high waters. This plot shows that the model is generally well within the target accuracy of +/-0.25m with only a few high waters slightly underpredicted.

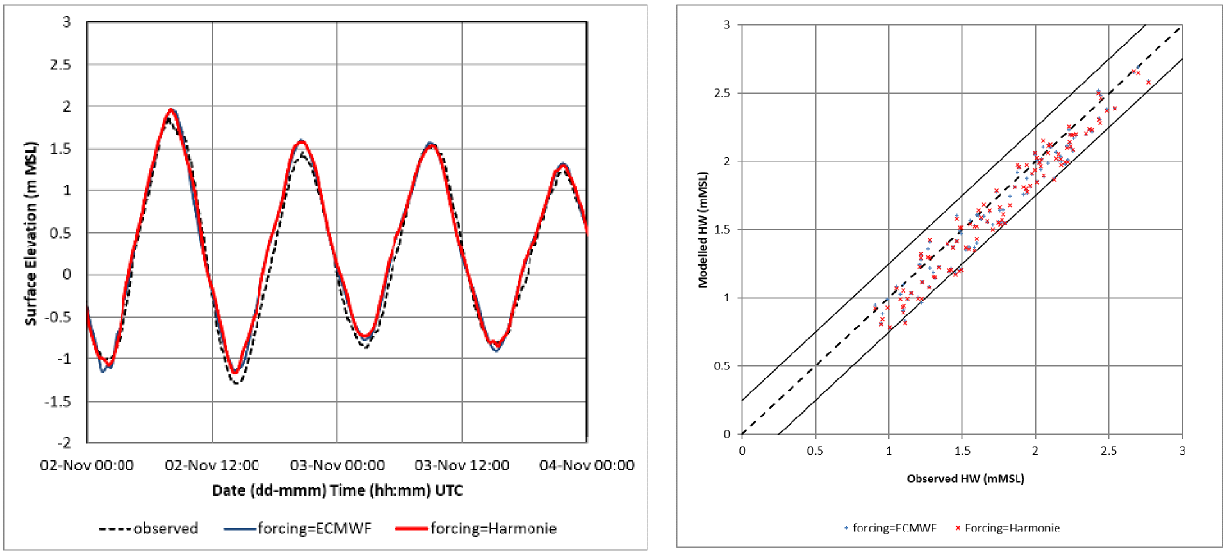


Figure 4: *Tide and surge model predictions and observations at Fenit Pier **(left).** High total water levels: Model vs. Observed (right).*

Table 2 summarise the error statistics of the model, forced using ECMWF and Harmonie, for all high waters and all high waters above MHWS, respectively. These tables show that there is very little difference between the model forced by Harmonie compared with ECMWF.

The scatter plot and error statistics show a small negative mean error of -9cm and -10cm for all high waters and all high waters above MHWS, respectively. It is expected that this negative bias can be corrected through small adjustments to the wind and pressure forecasts, and would be best performed and confirmed after a longer term of model simulations e.g. one year or more, in case there are inter-annual effects.

Table 2: *Tide and Surge Error Statistics*

Forcing	Mean Error (m)	MAE (m)	Error range (m)		Target (m)	Events within target (%)
All high waters						
Harmonie	-0.09	0.11	-0.30	0.14	+/-0.25	96%
ECMWF	-0.09	0.11	-0.28	0.14	+/-0.25	95%
High waters above MHWS						
Harmonie	-0.10	0.11	-0.22	0.07	+/-0.25	100%
ECMWF	-0.10	0.11	-0.22	0.09	+/-0.25	100%

3. THE SWAN SPECTRAL WAVE MODEL

To forecast wave conditions within the area of interest the open source phase average 3rd generation spectral wave model SWAN was used (Booij et al., 1996). This model simulates the transformation of random directional waves representing the processes of wave shoaling, wave refraction, depth-induced breaking, bottom friction and whitecapping, wave growth due to the wind, wave-wave non-linear interactions, wave-current interactions, wave diffraction, and partial and full wave reflection.

The SWAN model developed used an unstructured triangular mesh and covers a slightly reduced area compared with the TELEMAC-2D Model and has slightly coarser mesh size close to the coast. The SWAN model depths are based upon the same bathymetry as used in the TELEMAC-2D flow model. Figure 2 shows the model mesh and Bathymetry for the Swan model. In Tralee Bay, the mesh resolution reduces to around 50 m, with the resolution at the coast in other areas around 200 m, i.e. still relatively high resolution. The model mesh comprises 53084 nodes and 101028 elements. The model spectra was discretised into 24 directions and 42 frequencies and a 5 minute time step was used throughout.

3.1 Boundary wind, wave and water levels

The model was run in non-stationary mode, with spatially and time varying water levels including the predicted surge levels provided by model runs of TELEMAC-2D. Hotstart files from the previous forecast run were used to initialise each forecast model run.

During the initial SWAN model calibration against measurements at four sites on the west coast of Ireland, the SWAN model was forced with offshore wave spectra and winds from ERA5. During the two live validation trial periods the model was forced with offshore wave spectra based on the ECMWF operational forecast model and wind forecasts from ECMWF and Met Éireann. These provide a source of spatially varying and time varying offshore waves and wind conditions, with minimal loss of information between models.

3.3 Measured wave data

There are a number of sources of wave measurements on the West coast of Ireland (see Figure 5), but, until this study, none within Tralee Bay. These include measurements at the WestWave wave energy demonstration site near Killard off the coast of County Clare and at Galway (http://www.digitalocean.ie). WestWave is in open water, whereas Galway is partly protected by the Aran Islands. Wave measurements are also available north of Tralee from the Commissioners of Irish Lights at Ballybunnion, off the west coast of Kerry, and at Finnis, situated by the Finnis Rock to the east of Inisheer on the Aran Islands.

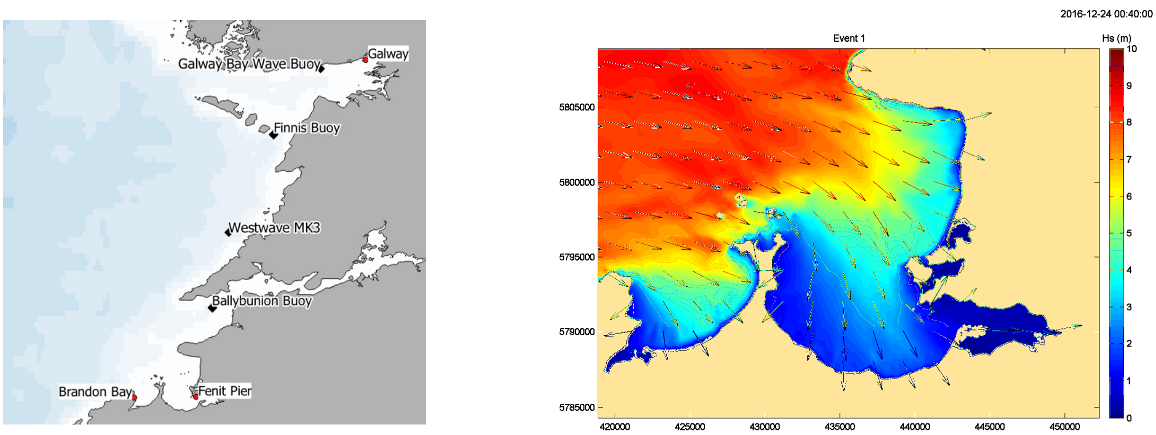


Figure 5: *Available measurements of waves prior to second live trial period (left). Example SWAN model output for initial calibration model run (right).*

3.4 SWAN Model Calibration and Validation

The SWAN model was initially calibrated for a limited set of storm events measured at the four locations on the West coast of Ireland. Figure 5 shows the predicted significant wave height and mean wave directions within the area of interest for one storm event on the 24 December 2016. Generally, the model compared reasonably well with the measurements at the four locations, and subsequently the first of two live trial validation periods was completed. This trial covered the period 24 November 2018 to 22 February 2019.

Model results from the first trial period were primarily compared against measurements at the nearest location to Tralee Bay at WestWave. Figure 6 shows scatter plots of predicted wave conditions, given in terms of significant wave height (Hs), peak wave period, and mean wave direction. In these plots the short range forecasts which are based on Harmonie winds are based on the first 12 hours of each forecast, with forecasts issued twice daily. The medium range forecasts use ECMWF forecast winds and are based on the first 24 hours of each forecast, with forecasts issued once a day. The lighter symbols represent the full time series predictions, and the darker symbols represent the event peaks. Corresponding error statistics are presented in Table 3.

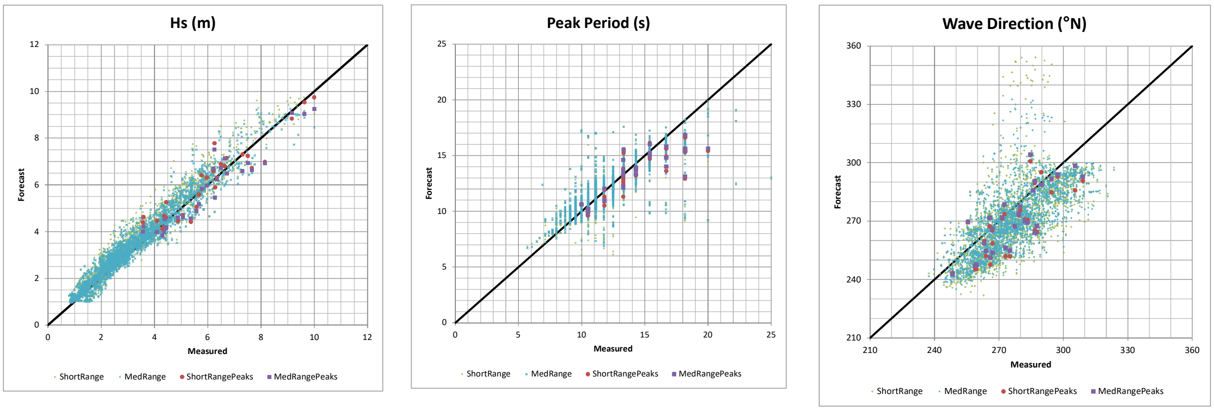


Figure 6: *Wave forecast vs. measured scatter plots*

The error statistics are quoted for all data at the measurement time steps and at storm peaks, where the storms are defined as events with significant wave height exceeding 4m in either the measured data or model predictions. The model forecast mean direction is compared against the quoted measured peak wave direction as the model resolution is 15°. The error statistics quoted are: the mean absolute error (MAE) and the relative MAE. The MAE represents the average unsigned error between model and observations and is given by:

$$\mathrm{MAE} = \overline{|e|} = \overline{|m - o|}$$

where *m* is the model prediction, and *o* is the observation. The MAE is always positive and represents the average absolute error. The relative MAE is the MAE divided by the mean of the observations and provides a normalised measure of the error in the forecast.

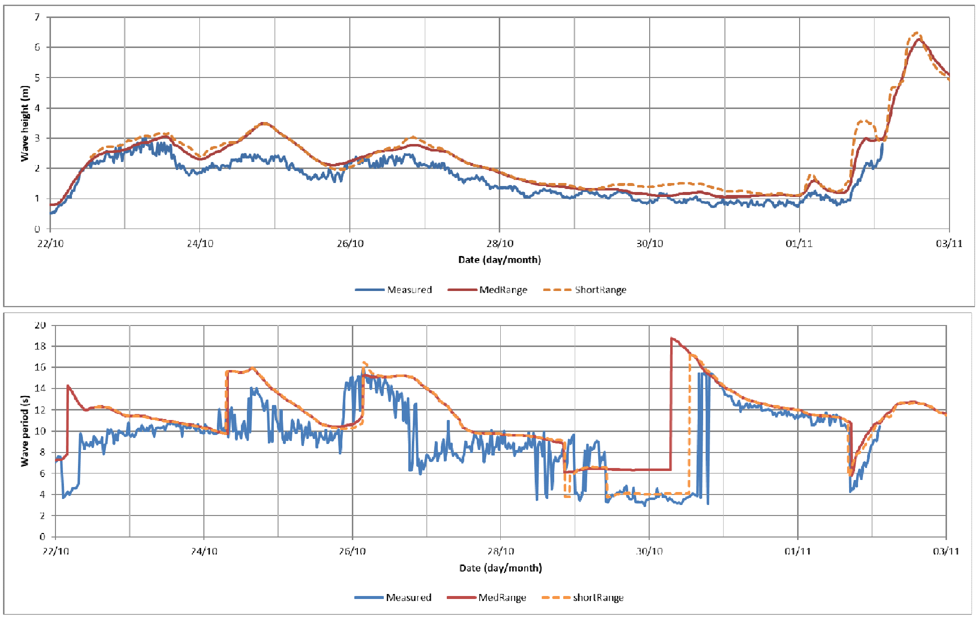
Table 3 shows that both the short and medium range models are in good agreement with the measured waves at WestWave during the first trial period, close to meeting the target accuracy of the system.

Table 3: *Wave Forecast Error Statistics – First Trial Period*

Variable	All data (time for time)		Storm Peaks (where Hs> 4m)		Target tolerance
	MAE	RelativeMAE	MAE	RelativeMAE	
Short Range					
Sig wave height	0.40m	12%	0.47m	8%	+/-10%
Peak wave period	0.87s	7%	1.37s	10%	+/-10%
Wave direction	11.7°	N/A	10.6°	N/A	+/-10°
Medium Range					
Sig wave height	0.34m	10%	0.49m	8%	+/-10%
Peak wave period	0.79s	6%	1.22s	9%	+/-10%
Wave direction	10.7°	N/A	9.6°	N/A	+/-10°

The second live trial validation covered the period 8 October 2019 to 9 December 2019. Measurements at WestWave were not available during the second trial period. However, waves were measured using bed mounted AWAC devices at three locations between the approaches to Tralee Bay and further within the bay close to Fenit Island. Preliminary model results are presented below at the outer measurement location (52.3569°N,10.0337°W) in the approaches to Tralee Bay in a still water depth of approximately 21m.

Figure 7 shows that the short and medium range forecasts are in reasonable agreement with the measurements at this location. However, at the measurement locations further into Tralee Bay the agreement was not as good with noticeably large discrepancies at the middle and inner locations and is currently the subject of further investigation.



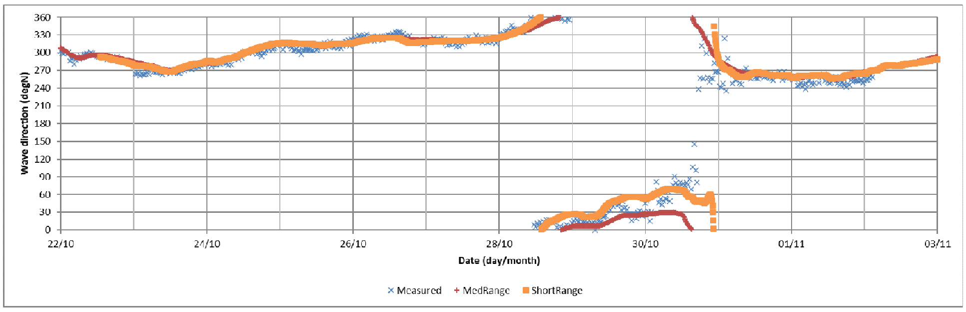


Figure 7: *Time series of wave forecasts (medium range and short range) and measured within Tralee Bay.*

4. CONCLUSIONS

A TELEMAC-2D hydrodynamic model and SWAN spectral wave model have been developed to forecast tide, storm surge and wave conditions on the South West coast of Ireland. The models form part of a real time forecast system under development to provide short to medium range forecasts of up to 6 days. The TELEMAC-2D model was forced with boundary tide levels from FES2014 and wind and pressure forecasts (within the model domain) from the ECMWF and Met Éireann's Harmonie models. The SWAN model was forced with offshore wave spectra forecasts from ECMWF and wind forecasts from the ECMWF and Met Éireann's Harmonie models.

The TELEMAC model has been calibrated and validated against astronomical tide levels synthesised from observed gauge data and total water levels i.e. also accounting for storm surges. The model has been shown to be in good agreement with the observations, generally meeting the target accuracy required of the system. Further improvement to the total water levels could be made by correcting for biases in the surge predictions which could be based on the data from the two trial periods.

For the trial periods modelled to date there was little visible difference between the surge model results when forced by the ECMWF and Met Éireann's higher resolution Harmonie models. Further simulations are recommended for extreme storm events for which the higher resolution Harmonie model is expected to provide a more detailed and accurate forecast of the wind conditions.

The SWAN spectral wave model has been shown to agree well with measurements at WestWave County Clare available during the first live validation trial period, meeting the target accuracy required of the system using either ECMWF or Harmonie wind forecasts. During the second live validation trial period wave measurements were carried out at three locations within Tralee Bay. The SWAN model forecasts were in reasonably good agreement at the outer location. However, at the other locations the agreement was not as good and is currently the subject of further investigation.

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