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EIAR Volume 4: Offshore Infrastructure Technical Appendices
Appendix 4.3.1-4
Spectral Wave Model Calibration and Validation Report

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Dublin Array Offshore Wind Farm

Spectral Wave Model Calibration and Validation Report

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Dublin Array Offshore Wind Farm

Spectral Wave Model Calibration and Validation Report

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Rev No	Date	Reason	Author	Checker	Authoriser
Rev 0	04/06/2020	Original Submission	J Gibson	K McGovern	R Dannatt

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SUMMARY

Intertek Energy and Water Consultancy Services (Intertek) has been commissioned by innogy Renewables Ireland (innogy) to conduct physical process modelling to support the Environmental Impact Assessment (EIA) for the Dublin Array Offshore Wind Farm (OWF) development.

To undertake the physical process study Intertek is building a suite of numerical models, which collectively form The Dublin Array Physical Processes Modelling System (DAPPMS). This includes a Hydrodynamic (HD) model and a Spectral Wave (SW) model, which will be used to assess a range of impacts on the physical environment from the proposed OWF development. This report provides details of the model build, calibration and validation of the DAPPMS SW model. A separate report, P2344_R2968_rev1, provides details of the HD model (Intertek, 2020).

The DAPPMS SW model has been calibrated and validated against field measurements of wave height, period and direction from three data sources. The calibration and validation data include:

- The M2 wave buoy, operated by Foras na mara (Marine Institute);
- JN1163 South, study specific survey data, AQUAFACT International Services Ltd for Saorgus Energy Ltd; and
- Dublin Bay Buoy, operated by Ocean Energy Ireland.

The DAPPMS SW model has three open boundaries, one to the north, east and south. The boundaries are driven by temporally varying timeseries of wave conditions extracted from the Atlantic – Iberian Biscay Irish- Wave Multi-Year Model (IBI_Reanalysis_Wav_005_006) provided by Copernicus[1]. A spatially varying wind field is applied over the model domain, with data taken from European Centre for Medium-Range Weather Forecasts (ECMWF) European Re-Analysis (ERA) Interim winds database, the same data used to drive the IBI_Reanalysis_Wav_005_006 model.

There are no formal guidelines for the assessment of wave model performance as exist for HD models. Therefore, wave model calibration is based on visual analysis, and on modelling and oceanographic experience and expertise.

Five independent storm events were selected from the measured data under which to assess the performance of the model. The events were chosen so that a range of directions of wave approach could be assessed. Once an acceptable calibration was achieved, four independent events were modelled to validate the derived calibration parameters. These events included both storm and less energetic wave conditions.

In general, agreement between modelled and observed wave heights, period and direction are good across the three assessment field measurement locations, and the model is considered fit for use in the Dublin Array physical processes assessment.

[1] Copernicus, previously known as GMES (Global Monitoring for Environment and Security), is the European Programme for the establishment of a European capacity for Earth Observation.

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GLOSSARY

AWAC
Acoustic Wave and Current Profiler

CD
Chart Datum

DAPPMS
Dublin Array Physical Processes Modelling System

DHI
Danish Hydraulic Institute

ECMWF
European Centre for Medium-Range Weather Forecasts

EIA
Environmental Impact Assessment

EMODnet
European Marine Observation and Data Network

ERA
European Re-Analysis

FM
Flexible Mesh

FWR
Foundation for Water Research

HD
Hydrodynamic

H_{m0}
Significant Wave Height

IBI_Reanalysis_Wav_005_006
Atlantic -Iberian Biscay Irish- Wave Multi-Year Model

INFOMAR
Integrated Mapping for the Sustainable Development of Ireland's Marine Resource

innogy
innogy Renewables Ireland

Intertek
Intertek Energy and Water Consultancy Services

MSL
Mean Sea Level

OSI
Ordnance Survey Ireland

OWF
Offshore Wind Farm

SW
Spectral Wave

Tp
Peak Wave Period

UKHO
United Kingdom Hydrographic Office

UTM
Universal Transverse Mercator co-ordinate system

WGS84
World Geodetic System 1984

1. INTRODUCTION

1.1 Project Overview

Intertek Energy and Water Consultancy Services (Intertek) has been commissioned by innogy Renewables Ireland (innogy) to conduct physical process modelling to inform the Environmental Impact Assessment (EIA) for the Dublin Array Offshore Wind Farm (OWF) development.

The physical process modelling includes an assessment of the potential impacts of the Dublin Array Offshore Wind Farm on the local tidal hydrodynamics and wave climate. In addition, the modelling aims to assess likely sediment dispersion and deposition resulting from construction activities associated with the OWF installation. The suite of numerical models developed for the study are collectively termed the Dublin Array Physical Processes Modelling System (DAPPMS), and this includes a Hydrodynamic (HD) model and a Spectral Wave (SW) model.

This document describes the modelling approach, model construction, model calibration, and model validation of the SW modelling element of the DAPPMS. The scope and specification of the DAPPMS is reported in the Assessment Methodology Report (Intertek 2020a), submitted to innogy on 27th January 2020. The HD model calibration and validation are reported in a separate report, P2344_R4968_Rev1 (Intertek, 2020b).

1.2 Study Site

The Dublin Array Offshore Wind Farm project is located on the Kish and Bray banks, approximately 10 km off the east coast of Ireland, south east of Dublin. Dublin Array has a proposed electrical generating capacity of up to 1 GW. The offshore wind farm will be located within an area of 54 km^2, in water depths ranging from 2 to 30 m (Chart Datum (CD)). The variation in water depth causes a spatially varied range of metocean conditions over the site.

1.2.1 Wave Climate

The wave climate at the Dublin Array OWF site is dominated by waves approaching from a south to south easterly direction. These waves approach the site from the Atlantic and are therefore relatively large and exhibit a stronger swell influence[2]. Waves also approach the site from the north, north-east and easterly directions; however, these waves are generally wind generated and smaller and shorter period[3] waves which occur less frequently (see Section 2.2).

1.3 Modelling Approach Overview

The modelling is conducted in the MIKE21 Flexible Mesh (MIKE21 FM) software. The model is two dimensional and built over an unstructured triangular mesh of varied resolution.

The model is built and calibrated using data measured by AQUAFACT International Services Ltd for Saorgus Energy Ltd, Foras na Mara/ Marine Institute and Ocean Energy Ireland supplied to Intertek by innogy, and includes bathymetric, measured wave and measured and modelled wind data.

[2] Swell waves are waves that have moved away from the area where they were generated, are relatively more regular, have longer period and more energy than locally generated wind waves.
[3] Wave period is the time between two consecutive waves.

2. DATA

Various sources of data have been used to build and calibrate the wave modelling component of the DAPPMS. This includes a combination of bathymetric data, wind data and wave data (both measured and modelled). This section of the wave modelling calibration report gives an overview of these data.

Model calibration is the process during which the model performance is compared against field data and systematically improved by modifying model parameters to make the model replicate the observed data as closely as possible. Model validation uses the calibrated model setup (the parameters defined during the calibration process) to compare the model against a set of field data independent of the set used for the calibration comparison. For wave modelling there are no prescribed standards for assessing the performance of the model; therefore, the level of calibration is assessed visually using expert judgement, by looking at wave height, peak wave period and wave direction, and if acceptable the model is considered representative and fit for use. Otherwise, the model calibration continues until an acceptable validation is achieved.

2.1 Bathymetry

Bathymetric data are used to create a representation of the topography of the sea floor. The data are taken from a number of publicly available sources as detailed below.

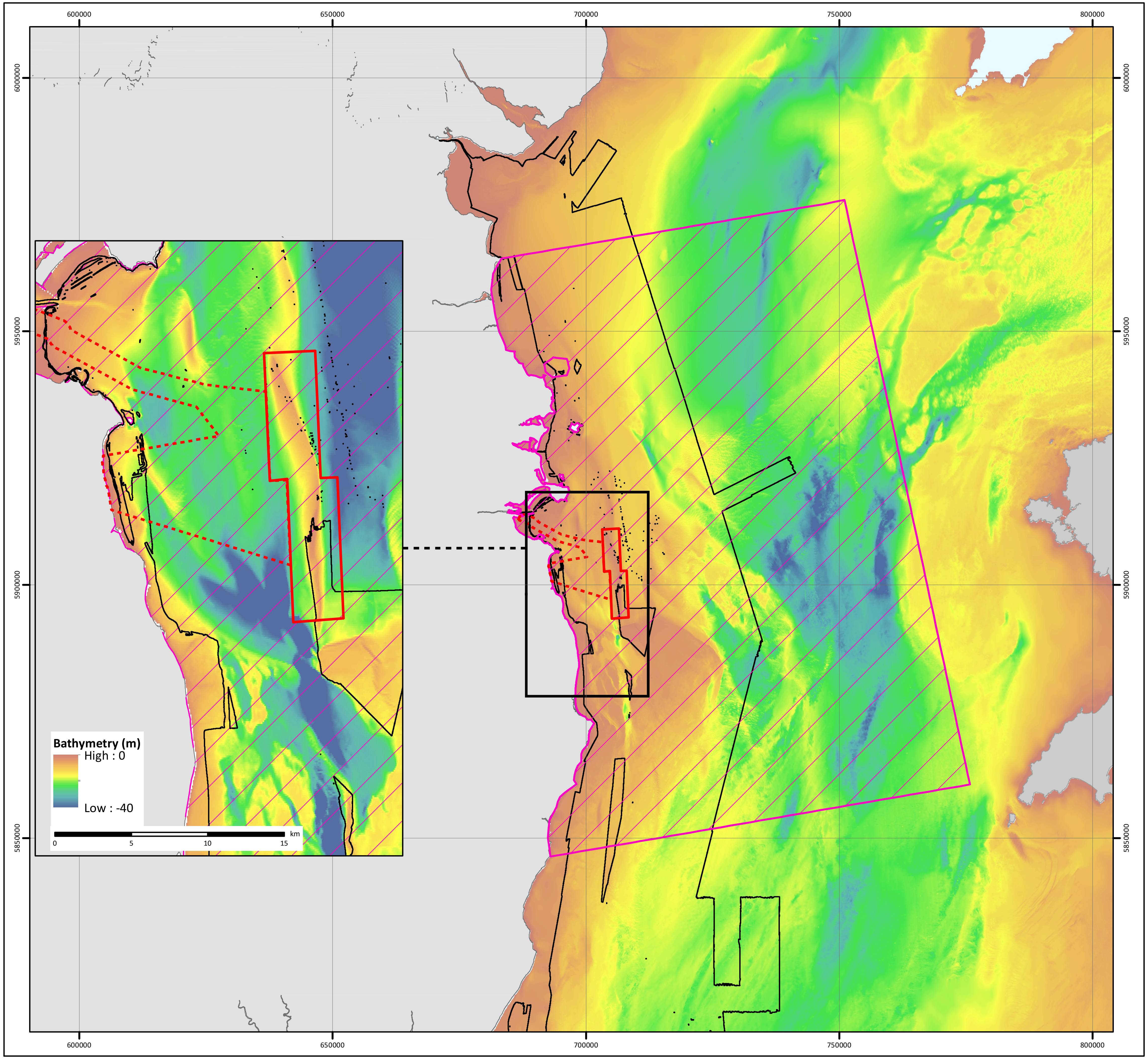
The primary data resource considered for bathymetry was the INFOMAR bathymetry, provided by the Geological Survey, Ireland. The dataset provides a high level of detail at a consistent scale across the majority of the study area. This information was also supplemented by EMODnet bathymetry to enable 100% coverage (EMODnet Bathymetry Consortium, 2018). The land boundary of the model was taken from the Ordnance Survey Ireland National 1:250,000 map (OSI, 2019). A summary of the bathymetric data sources is provided in Table 2-1.

The coverage and resolution of the available data is considered suitable for the purpose of building the DAPPMS SW model and for the purpose of applying the model to undertake the physical processes assessment to inform the Dublin Array OWF EIA.

Table 2-1 Summary of bathymetric data sources

Item	Provider	Parameters	Horizontal resolution (m)
INFOMAR	INFOMAR	Bathymetry	10
EMODnet	EMODnet	Bathymetry	115
Land Boundary	Ordnance Survey Ireland	Land boundary	20

All data sets were reduced to a common vertical datum of Mean Sea Level (MSL), using data published by the UK Hydrographic Office (UKHO) and EMODnet. The coverage of the bathymetric data used for the model construction is shown in Figure 2-1 (P2344-CAL-001) , together with the extents of the model domain. The data used to represent the bathymetry in the MIKE21 SW model is common to the MIKE21 HD modelling also conducted for this study.



DUBLIN ARRAY OFFSHORE WINDFARM PHYSICAL PROCESSES ASSESSMENT

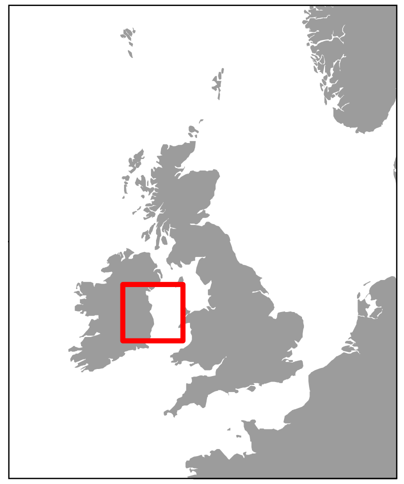
CALIBRATION AND VALIDATION
Model Domain and Bathymetry

P2344-CAL-001	A

Legend

- Dublin Array Proposed Wind Turbine Area
- Export Cable Area of Search
- Model Domain
- Informar Hi-Res Bathymetry Extent

Bathymetry (m)
High : 0
Low : -150



NOTE: Not to be used for Navigation

Date	19 February 2020
Coordinate System	WGS 1984 UTM Zone 29N
Projection	Transverse Mercator
Datum	WGS 1984
Data Source	Informar; EMODNET; EPA; OSI; ESRI
File Reference	J:\P2344\Mxd\04_CAL\ P2344-CAL-001.mxd
Created By	Chris Dawe
Reviewed By	Chris Carroll
Approved By	Emily Perkins

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0 10 20 30 40 km

2.2 Wave

Measured wave data are required to provide reference data against which to calibrate and validate the SW model of the DAPPMS. The wave data used in this study come from surveyed data provided to Intertek by innogy, as well as publicly available data to give wider coverage within the modelling domain. These data characterise the physical metocean environment and provide a basis for model calibration and validation. Details of the data used in the SW model development are given below. Wave conditions are given in terms of Significant Wave Height[4] (H_{m0}), Peak Wave Period[5] (Tp) and Mean Wave Direction[6] in degrees.

The M2 wave buoy, operated by Foras na Mara/Marine Institute is a surface buoy moored in deep water (approximately 95 mCD) and is located approximately 35 km off the Irish Coast. The buoy collects a range of metocean data including wave and wind parameters, making this a key dataset for use in this study. The data available at the M2 Wave Buoy site span approximately eight years, from August 2010 to June 2018.

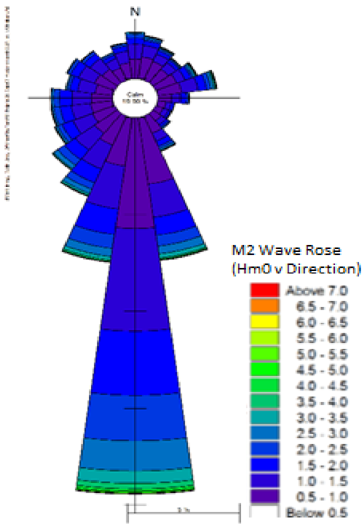
Figure 2-2 shows the wave climate at the M2 Wave Buoy over the eight year period. The figure shows a dominance in wave conditions from a southerly direction, with a maximum H_{m0} of over 7 m.

Dublin Bay Buoy is located within Dublin Harbour and operated by the Commissioner of Irish Lights. The buoy is located between Howth and Dun Laoghaire. The water depth at this site is approximately 15 mCD. Analysis of these data has shown numerous data spikes where unbelievable wave heights are reported, periods where these spikes were identified were discounted from the assessment. Intertek has conducted further analysis on these data and conducted numerous sensitivity tests during the model calibration process, details of which are provided in Section 2.3.

- Acoustic Wave and Current (AWAC) measurements at the JN1136 South site are project specific surveyed data collected during previous investigations in 2012 conducted by AQUAFACT International Services Ltd for Saorgus Energy Ltd. These data are of a fairly short duration of approximately 27 days. The JN1136 wave buoy is located in approximately 14 mCD on the western side of the Bray sandbank.

The details of wave data are presented in Table 2-2, with Figure 2-3 showing their location.

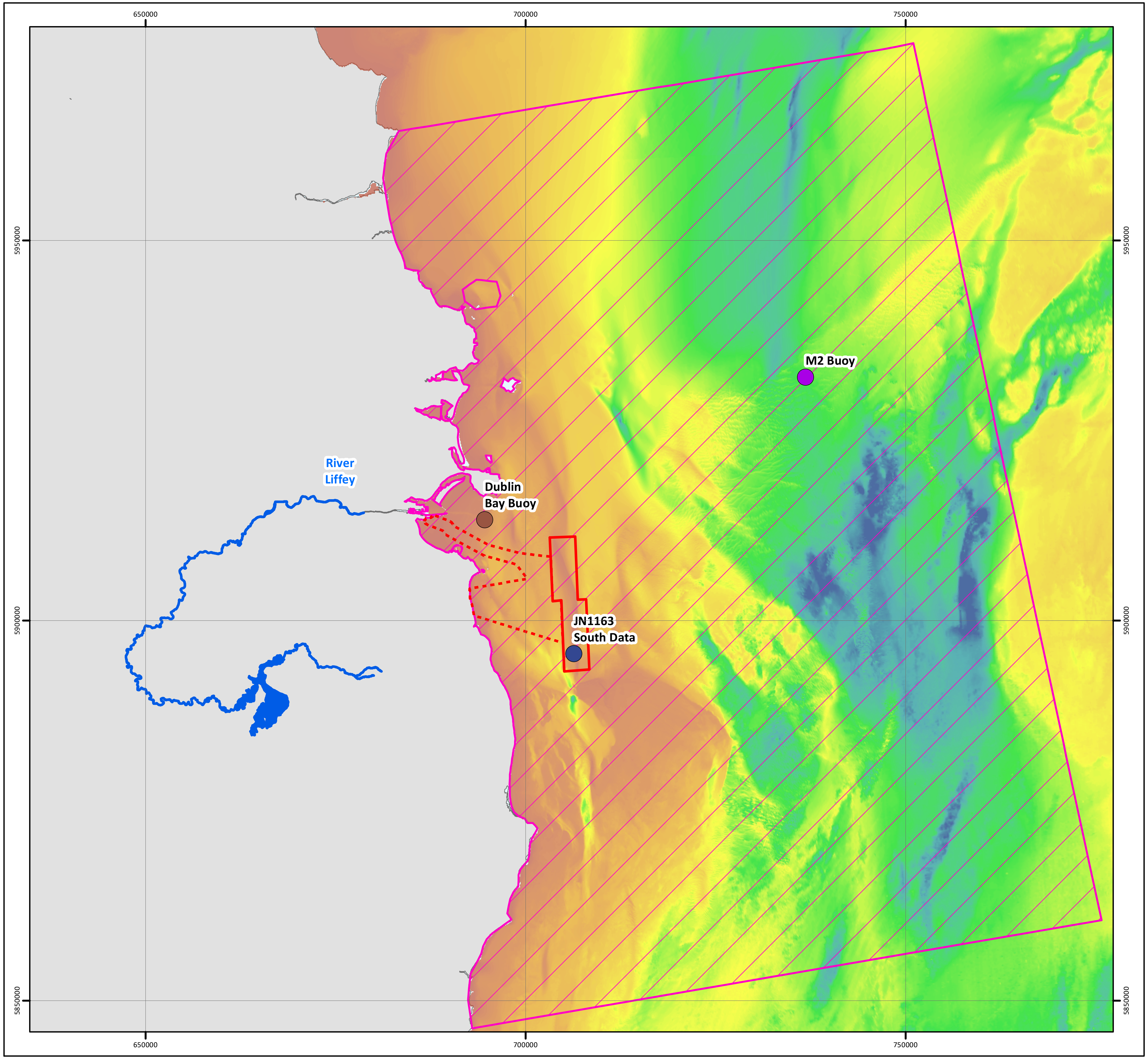
Figure 2-2 Offshore wave climate at M2 Buoy



4 Significant Wave Height is the average height of the highest one-third of all waves with a given time.
5 Peak Wave Period is the wave period associated with the most energetic waves.
6 Mean Wave Direction is the mean of all individual wave directions in a time series.

Table 2-2 Summary of wind and wave data sources

Item	Provider	Parameters	Latitude (WGS84)	Longitude (WGS84)	Start time	End time	Duration (days)	Comment
JN1163 South	innogy	Hs, Tp, Wave Dir	53.1698	-5.9128	23/08/2012	19/09/2012	26.94	Shallow water observation, short duration which may not capture storm events
M2 Wave Buoy	Foras na Mara/ Marine Institute	Hs, Tp, Wave Dir & Wind	53.4836	-5.4302	09/08/2010	25/06/2018	2,877	Deep water wave buoy, useful for assessing appropriateness of offshore boundary, long duration dataset.
Dublin Bay Buoy	Ocean Energy Ireland	Hs, Tp	53.3325	-6.0774	07/02/2014	14/05/2019	1,922	Shallow water observation, long duration dataset. Data show some data spikes and some questionable wave height values, also no wave direction and erroneous reporting of wave period.



DUBLIN ARRAY OFFSHORE WINDFARM PHYSICAL PROCESSES ASSESSMENT

CALIBRATION & VALIDATION

Wave Data Source Locations

P2344-CAL-004	A

Legend

- Dublin Bay Buoy
- JN1163 South Data
- M2 Buoy
- River Liffey
- Dublin Array Proposed Wind Turbine Area
- Export Cable Area of Search
- Model Domain

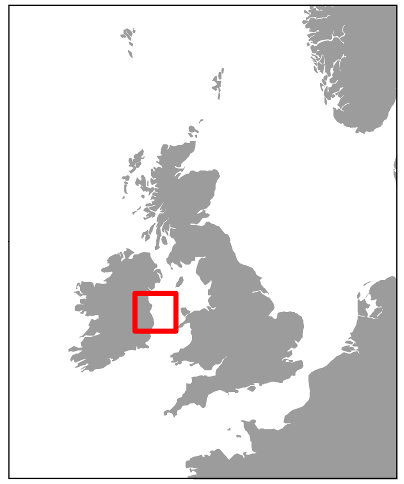
Bathymetry (m)

Value

High : 0

Low : -150

N W E S



NOTE: Not to be used for Navigation

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Projection	Transverse Mercator
Datum	WGS 1984
Data Source	EMODNET; EPA; ESRI; Innogy
File Reference	\\EGBRLHKNAS001\gis\P2344\Mxd\04_CAL\ P2344-CAL-004.mxd
Created By	Chris Dawe
Reviewed By	Emma Langley
Approved By	Josh Gibson

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0 7.5 15 22.5 30 km

The bathymetric metadata and Digital Terrain Model data products have been derived from the EMODnet Bathymetry portal - http://www.emodnet-bathymetry.eu.; Data from EPA under Creative Commons Attribution license 4.0; ©Esri

2.3 Data Quality Review

The data used in the model build and calibration are predominantly as documented in the Metocean Data Review (Intertek, 2019). Initial assessment of the data during the Metocean Data Review identified the suitability of the data for conducting the physical process modelling. Through the model build, calibration and validation process additional analysis of the data was undertaken. The key findings of the data review relevant to the calibration and validation of the SW model are outlined below.

2.3.1 Bathymetry Data

The bathymetry datasets provide good vertical and spatial resolution across the entire study area. The EMODnet and INFOMAR datasets are compiled from various previous surveys, so cover a range of time periods. As such, it is possible that the seabed level may have changed between, and since, the individual surveys. However, these datasets are the best available source and these changes are unlikely to affect the general morphology or sedimentary regime of the area.

2.3.2 Spatial Distribution of Wave Data

The three data points available for the assessment of the SW model performance provide a limited means by which to assess the performance of the SW model. The M2 wave buoy is situated offshore near the eastern model boundary, providing a location with deep water where unattenuated waves can be assessed, and also provides a suitable site for identification of storm conditions to derive calibration scenarios. The JN1136 South buoy is located within the OWF array field, so presents an opportunity for assessment of the SW model's ability to transform waves from the offshore boundaries to the study site. Likewise, the Dublin Bay Buoy provides data by which wave transformation can be assessed in relatively shallow water.

2.3.3 Analysis of Wave Data

The M2 wave buoy provides long-term wave measurements (approximately eight years). Waves predominately approach from a southerly direction at this location. Of significance to the Dublin Array site are waves approaching from the east and north, as they will be able to approach the site relatively unattenuated. There are instances within the dataset where data were not recorded.

JN1163 South is located in very shallow water at approximately 8 mCD, but also in the lee of the crest of Bray Bank which is around 3 mCD. The likelihood is that large waves from the east moving over the bank would break before reaching JN1163 South and the crest of the bank would likely provide some sheltering. This is a short deployment of approximately 1 month, through the month of August 2012, providing limited opportunity to capture storm events owing the relatively less energetic wave conditions compared to winter conditions.

The Dublin Bay Buoy provides long time series of wave observations inshore of Kish and Bray banks. It is partly sheltered from the north and south by adjacent headlands. This is a more recent deployment than JN1163 South and provides a separate opportunity to correlate wave transformation with observations from the offshore model boundary and the M2 Buoy over a long-time interval.

The summary conclusion of the Metocean Data Review is that there are limited wave data for model calibration; however, they are deemed adequate to deliver a representative model.

3. MODEL BUILD

3.1 Modelling Software

The DAPPMS was built using the MIKE21 Flexible Mesh (FM) modelling system. This software has international recognition as an appropriate platform for model development and is specifically identified in the COWRIE best practice guidance as being suitable for the purpose of EIA studies for Offshore Wind Farm developments (Lambkin et al., 2009).

The MIKE21 FM modelling system comprises a suite of modules that cover the range of processes under consideration, including Hydrodynamics, Waves and Particle Tracking (for sediments).

Specifically, for the wave modelling element of the modelling, the MIKE21 Spectral Wave (SW) model has been utilised. MIKE21 SW is a state-of-the-art third generation spectral wind-wave model capable of simulating the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas.

3.2 Model Mesh and Bathymetry

3.2.1 Coordinate System

The following horizontal and vertical coordinate system has been adopted throughout the DAPPMS:

Horizontal Datum: All work used the Universal Transverse Mercator Co-ordinate system (UTM), applied to the World Geodetic System 1984 (WGS84) ellipsoid. The proposed Dublin Array Offshore Wind Farm lies within UTM Zone 29N [EPSG 32629], and as such, model orientation is referenced to UTM29N Grid North.

Vertical Datum: Water depth is given as metres below Mean Sea Level (MSL) and as a negative value.

3.2.2 Model Mesh

MIKE21 FM utilises an unstructured mesh of irregular triangular elements, allowing the model resolution to vary throughout the domain. This approach provides the greatest flexibility for resolving environmental conditions throughout the study areas. The mesh resolution was optimised during the model development process with the following horizontal resolutions in different parts of the model domain (see Table 3-1).

Table 3-1 Mesh resolution

Location	Mesh element area (m^2)	Mesh element triangle base length (m)
Array Field	Approx. 5,000	Approx. 110
Cable Route	Approx. 5,000	Approx. 110
Sensitive Receptors	Approx. 50,000	Approx. 340
Coastal regions	Approx. 125,000	Approx. 540
Offshore region	Approx. 500,000	Approx. 1,100

These resolutions are considered appropriate and robust for undertaking such a study. The resolution near the offshore boundaries is coarser than the areas of interest since high resolution is not required here (to understand the potential changes in the wave conditions through the presence of the proposed development) and the proposed approach reduces model run times and potential instabilities. The model contains approximately 117,000 elements. Figure 3-1 shows the model mesh over the entire domain. Figure 3-2 shows the model mesh near to the study area.

3.2.3 Model Bathymetry

A linear interpolation technique was adopted to generate the DAPPMS SW model bathymetry. Figure 3-3 shows the bathymetry over the entire model domain whilst Figure 3-4 provides details of the model bathymetry in the vicinity of the study area.

Figure 3-1 Spectral wave model domain and mesh

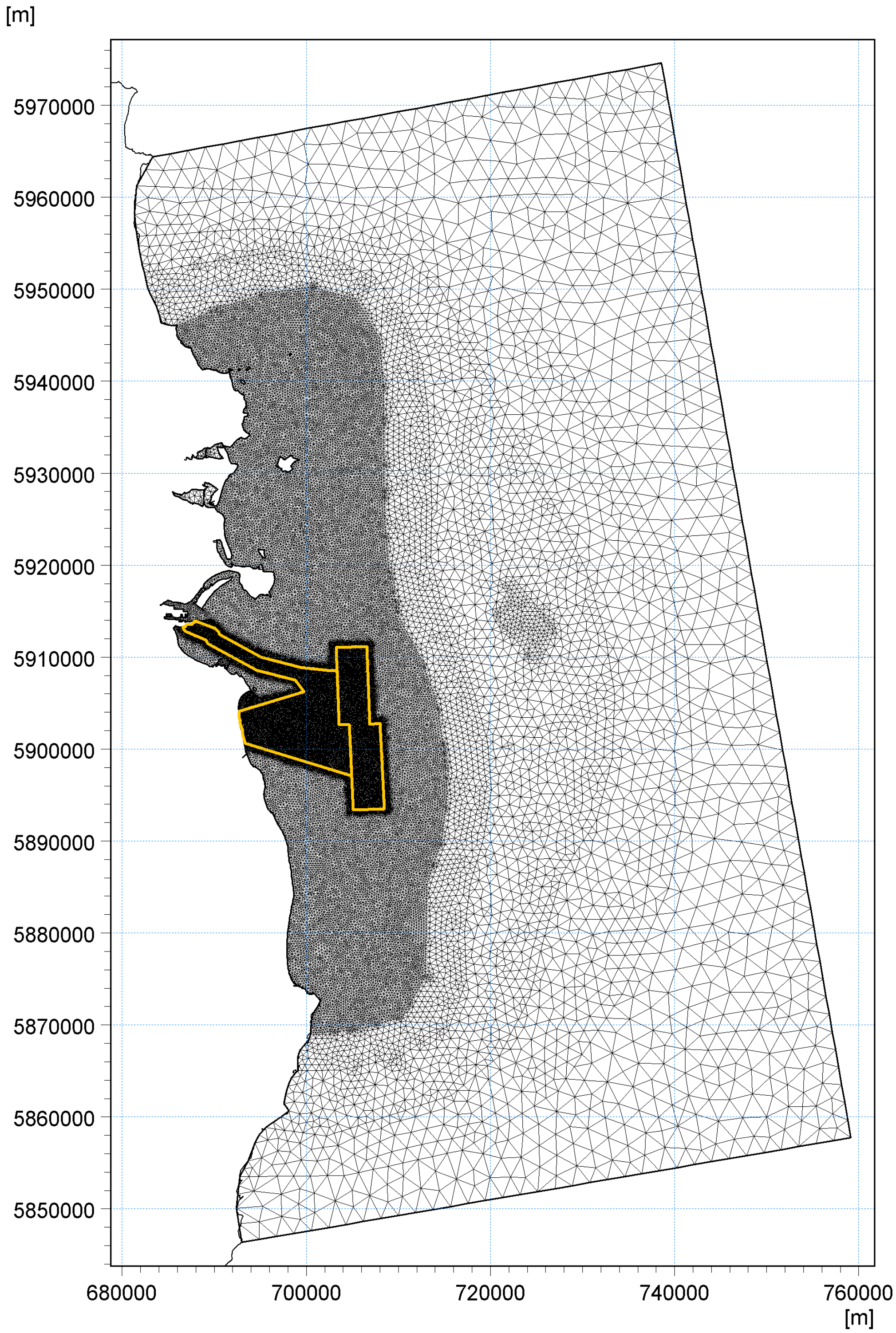


Figure 3-2 Spectral wave model mesh – array field and export corridors

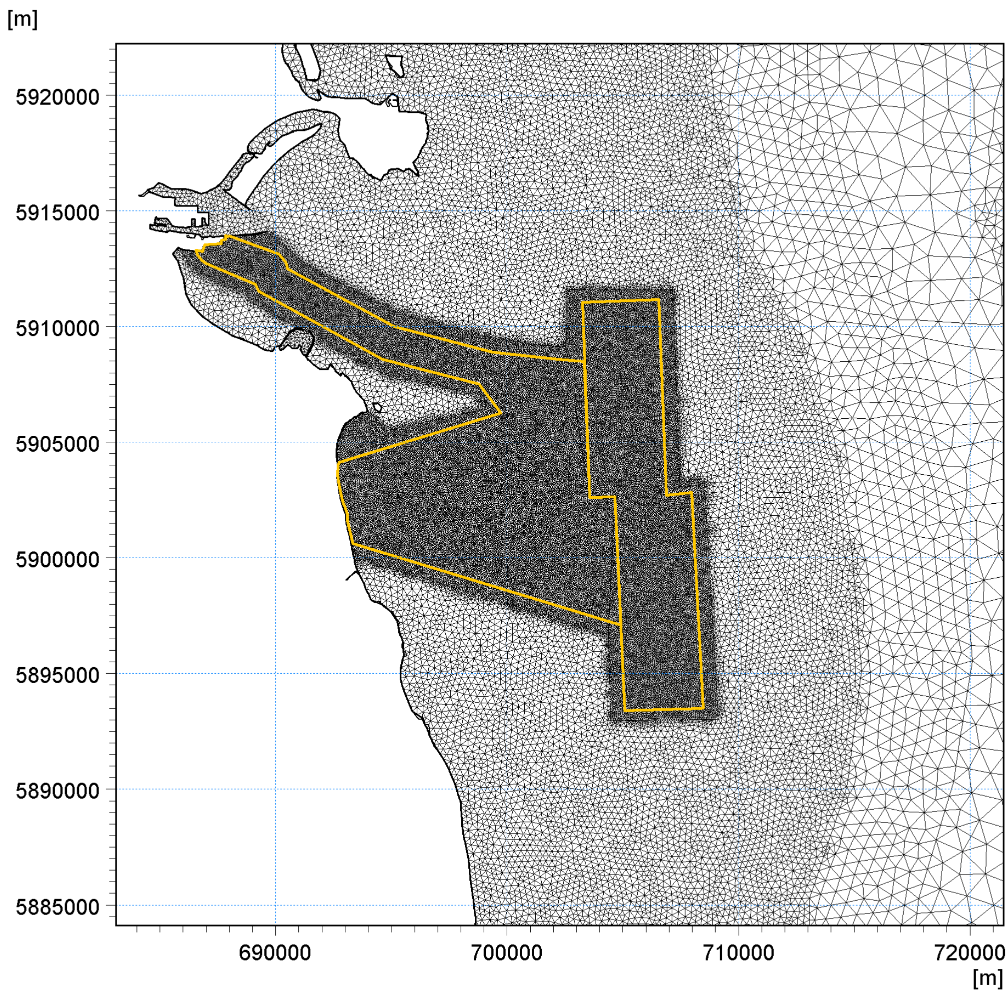


Figure 3-3 Spectral wave model bathymetry

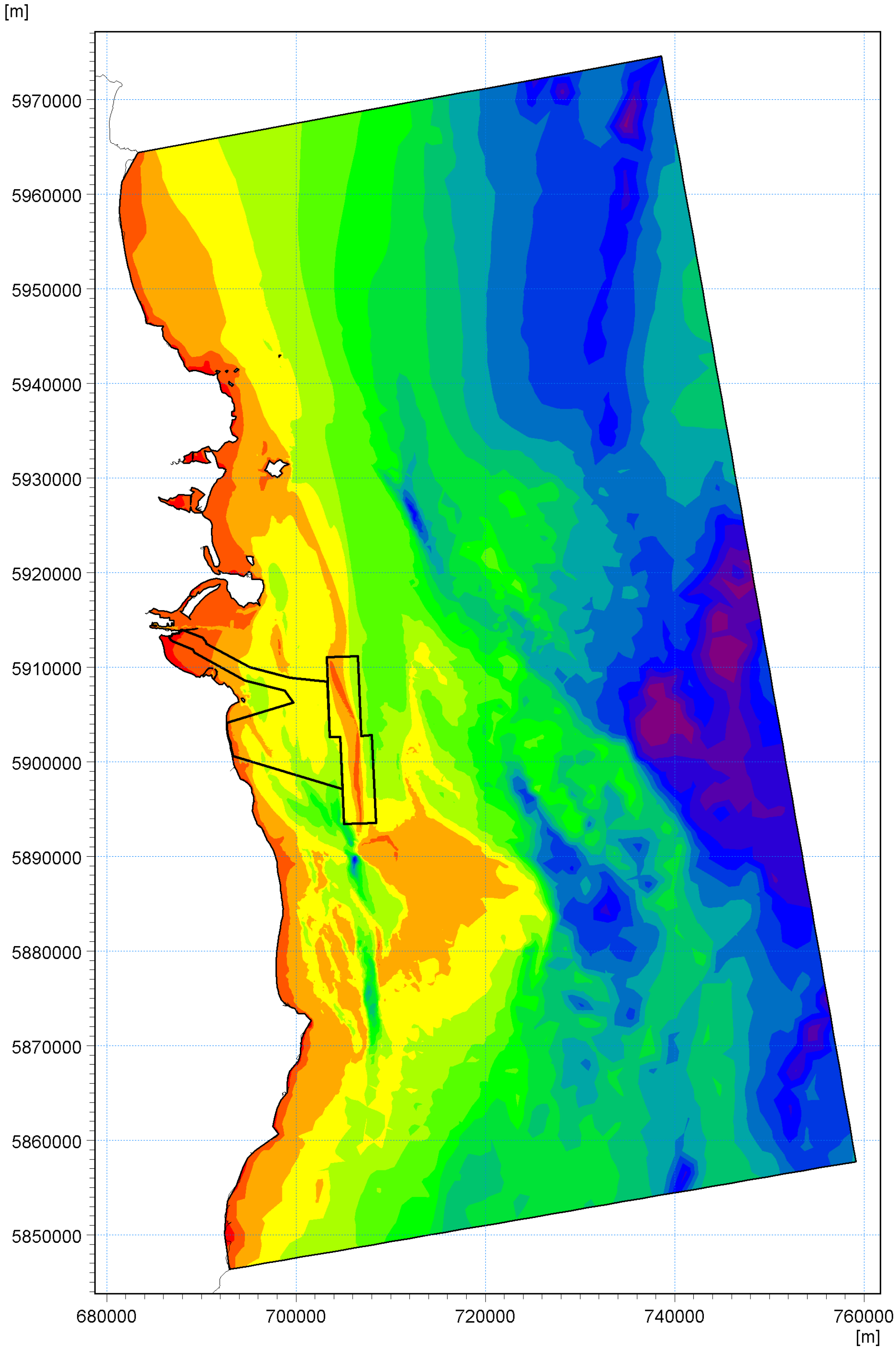
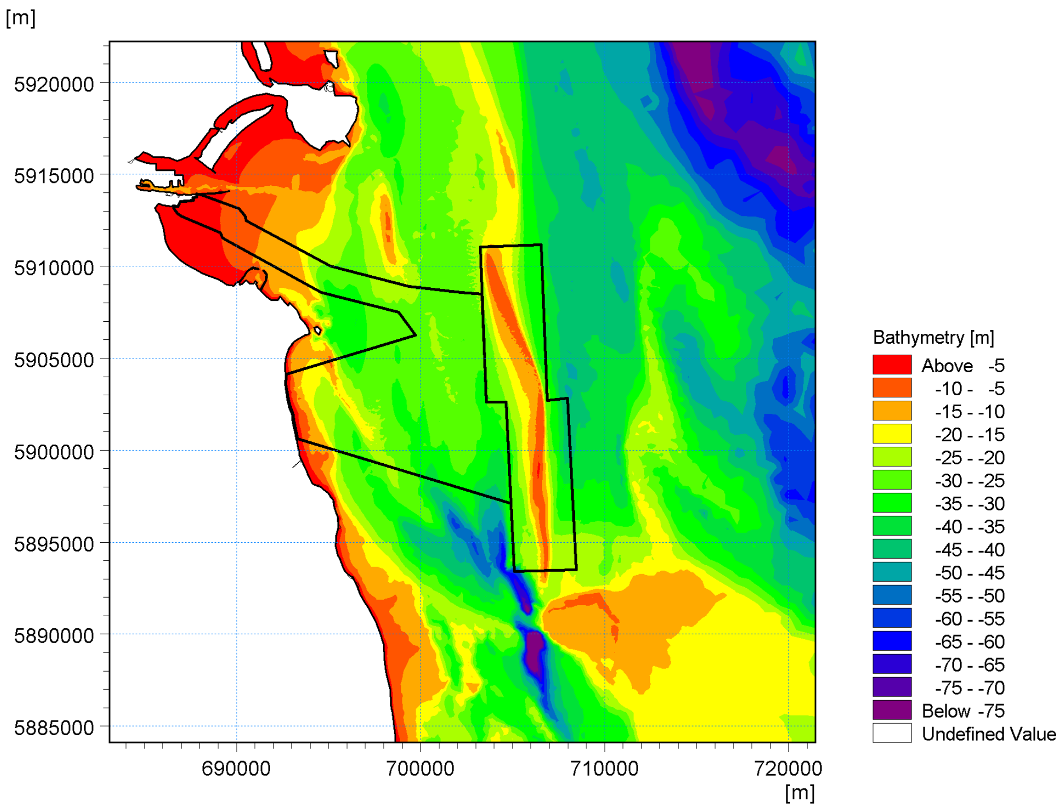


Figure 3-4 Spectral Wave model bathymetry – array field and export corridors



3.3 Model Input and Setup Parameters

3.3.1 Model Open Boundaries

The DAPPMS SW model is driven by temporally varying wave conditions along its northern, eastern and southern boundaries. These boundaries were located sufficiently far from the area of interest to eliminate potentially erroneous boundary effects that may occur within numerical models.

The boundary data are taken from the Atlantic –Iberian Biscay Irish- Wave Multi-Year Model (IBI_Reanalysis_Wav_005_006) which is an open source hindcast wave model. This wave model is provided by the Copernicus Marine Environment Monitoring Service (Copernicus), covering the period 1992-2018 with hourly data. The model extent is from 26.0°N to 56.0°N and 19.0°W to 5.0°E and is provided on a 0.1° longitude/latitude grid. The use of this hindcast model was validated by analysis of the model output with measured data at the M2 and M5 wave buoys, and reported in document P2344_BN4950_Rev0 (Intertek 2020). For each boundary, data were extracted from the IBI_Reanalysis_Wav_005_006 model at the location which presented the largest fetch from each boundary that might approach the OWF array.

3.3.2 Wind Forcing

Wind forcing is applied to capture the growth of wave climate over the model domain. A sensitivity analysis was conducted applying spatially uniform and spatially varying wind fields. The uniform wind field was taken from measured data at the M2 wave buoy location, with the same wind condition being applied over the whole domain. The spatially varying wind field was sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) European Re-Analysis (ERA) Interim winds. These are the same winds that were applied to drive wave growth of the IBI_Reanalysis_Wav_005_006 wave model. This wind field comprises 6-hourly data and has a spatial resolution of approximately

0.7°. To assess the validity of the wind data a comparison was made against measured wind data from the M2 Wave Buoy location. Figures 3-5 and 3-6 show the degree of correlation between measured wind speed and wind direction respectively. The excellent fit between the measured and modelled data shows their use is valid for this study.

Figure 3-5 Comparison of measured (M2 Wave Buoy) and ECMWF wind speed (m/s)

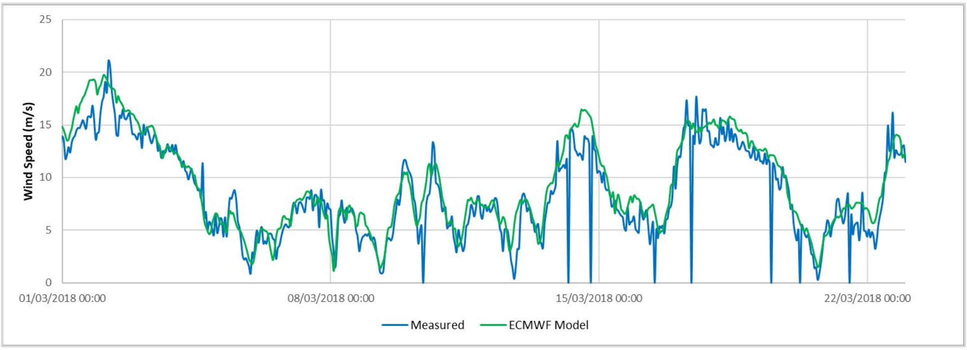
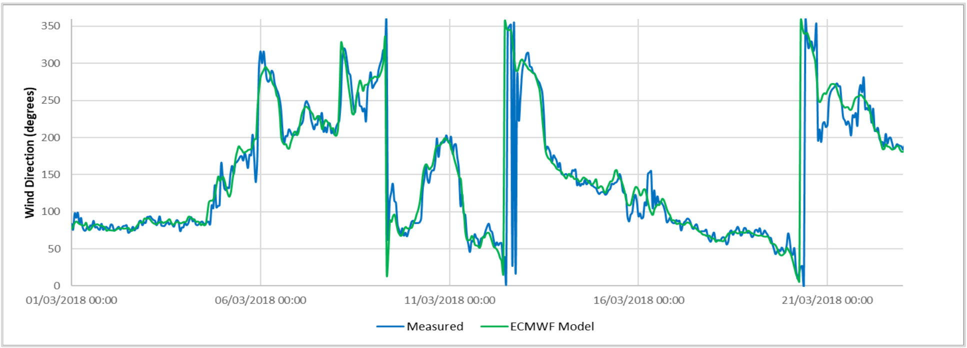


Figure 3-6 Comparison of measured (M2 Wave Buoy) and ECMWF wind direction (degrees)



3.3.3 Bottom Friction

Bottom friction for wave modelling is represented using the Nikuradse roughness parameter [7]applied as a constant across the model domain.

Model sensitivity to the Nikuradse roughness parameter was checked, and it was found that the SW model is not particularly sensitive to the parameter. Therefore, a typical Nikuradse roughness of 0.002 m was adopted in the model.

3.3.4 White Capping

Energy dissipation due to white capping [8]is included in the model by specifying two dissipation coefficients, Cdis and DELTAdis.

The Cdis and DELTAdis are dimensionless coefficients applied as a constant across the domain. Model sensitivity to both coefficients was checked and it was found that the model performed best with a Cdis value of 2.5 and a DELTAdis value of 0.1.

[7] Nikuradse roughness parameter is a dimensionless calibration parameter that parameterises the roughness of the seabed.
[8] White Capping is a process of wave breaking induced when the wave reaches a critical steepness.

3.4 Model Calibration and Validation

The spectral wave model was calibrated by comparing the model output against the field data at the M2, Dublin Bay and JN1163 South wave buoys. To ensure that the model was able to accurately replicate the wave climate within the model domain five different scenarios were modelled, from varying directions of approach, which are coincident with the measured wave data. These scenarios include storm conditions but also less energetic wave conditions, to demonstrate that the model performs well under both a high and low energy wave climate.

Table 3-2 details the scenarios that were selected to calibrate the SW model.

Table 3-2 Wave model calibration scenarios

Scenario	Start	Finish	Direction	Notes
Run 1	26/08/2012 00:00	29/08/2012 00:00	Northerly changing to Southerly	Storm condition from a southerly direction with up to 3.5 m H_{m0}.
Run 2	26/12/2015 12:00	29/08/2012 12:00	Southerly	Energetic wave climate with an offshore H_{m0} of approximately 3 m.
Run 3	16/10/2016 00:00	19/10/2016 10:00	Southerly to Westerly	Storm condition with initial wave height of about 3 m H_{m0}. Wave direction moves gradually from a southerly to westerly direction, indicating the later part of the period are wind waves.
Run 4	01/03/2018 00:00	04/03/2018 00:00	North Easterly	Storm condition from a north easterly direction with up to 6 m H_{m0}.
Run 5	01/03/2017 00:00	04/03/2017 10:00	North Westerly to Southerly	Storm condition from a north direction moving to north easterly anticlockwise, with up to 3 m H_{m0}.

Note: description of wave climate is from measured data at the M2 wave buoy location.

The primary means of model calibration was by the adjustment of the white capping parameters (Cdis and DELTAdis). Model predictions were compared with the field data, taking note of the differences in the magnitude and phasing of H_{m0}, Tp and mean wave direction. Successive iteration allowed the optimum white capping conditions to be determined.

It should be noted that there are no widely-accepted formal (e.g. statistical) guidelines for the assessment of wave model performance as exist for hydrodynamic models. Assessment is therefore based on visual analysis, on modelling and oceanographic expertise, and on the identified requirements of the resultant EIA study.

Spectral wave model validation was undertaken against four independent scenarios. Adopting the same calibration parameters, the model was validated for independent storm events and benign conditions to demonstrate the model is performing well under all scenarios, and is not biased to the calibration events.

Table 3-3 details the scenarios that were selected to validate the model.

Table 3-3 Wave Model validation scenarios

Scenario	Start	Finish	Direction	Notes
Run 6	16/03/2017 12:00	19/03/2016 12:00	Easterly	Up to 2.0 m H_{m0} .
Run 7	11/03/2016 00:00	14/03/2016 00:00	Southerly	Up to 1.5 m H_{m0} , dropping to low wave height of below 0.5 m H_{m0}.
Run 8	16/07/2017 12:00	19/07/2017 12:00	Southerly	Wave direction moving from westerly direction of approach to southerly and then north easterly.
Run 9	24/07/2016 12:00	27/07/2016 12:00	Southerly	Westerly turning to northerly. Small wave of height of approximately 1 m H_{m0} for duration of calibration period.

Note: description of wave climate is from measured data at the M2 wave buoy location.

3.5 Calibration Results

The spectral wave model results were compared with field data, taking note of the difference in the magnitude and phasing of H_{m0}, Tp and mean wave direction. The results for the five calibration periods are presented in Appendix A.1 with a synopsis of the results descried in Table 3-4.

Table 3-4 Summary of spectral wave model fit with calibration data

Location	Figure	H_{m0}	Tp	Dir	Overall Fit/Comment
Run 1					
M2 Wave Buoy	A-1,A-2, A-3	Good	Very Good	Excellent	Model overpredicts the peak H_{m0} and Tp. However generally good agreement.
JN1136 South	A-16,A-17, A-18	Excellent	Very Good	Good	Overall very good fit, model direction slightly more southerly than measured.
Run 2					
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-4, A-5, A-6	Reasonable	Poor [1]	Excellent	Model overpredicts the peak H_{m0} and particularly Tp. However generally acceptable agreement.
Dublin Bay Buoy	A-19, A-20	Excellent	Suspect measurements [1]	No data	H_{m0} in agreement with measured data. Measured Tp appears incorrect [1].
Run 3					
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-7, A-8, A-9	Good	Poor [1]	Excellent	Model overpredicts the peak H_{m0} and particularly Tp. However generally acceptable agreement.
Dublin Bay Buoy	A-21, A-22	Excellent	Suspect measurements [1]	No data	H_{m0} in agreement with measured data. Measured Tp appears incorrect [1].
Run 4					
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-10,A-11,A-12	Very Good	Excellent	Excellent	Overall excellent fit
Dublin Bay Buoy	n/a	No data	No data	No data	n/a
Run 5					
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-13, A-14, A-15	Excellent	Excellent [1]	Excellent	Overall excellent fit
Dublin Bay Buoy	A-23, A-24	Excellent	Suspect measurements [1]	n/a	H_{m0} in agreement with measured data. Measured Tp appears incorrect [1].

[1] See discussion in Section 4.1.

The results show that the SW model achieves a generally good calibration against the three measured datasets. They also show that the model is able to replicate wave conditions approaching from differing directions under both storm and more benign conditions. The results show that there is a mismatch in the wave period for certain scenarios; this is discussed in Section 4.1.

3.6 Validation Results

The spectral wave model results were compared with field data, taking note of the difference in the magnitude and phasing of H_{m0}, Tp and mean wave direction. The results for the four validation periods are presented in Appendix A.2 with a synopsis of the results descried in Table 3-5.

Table 3-5 Summary of spectral wave model fit with validation data

			Run 6		
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-25, A-26, A-27	Excellent	Very Good	Excellent	Overall excellent fit
Dublin Bay Buoy	A-37	Very Good	discounted due to suspect measurements.	No data	Model slightly underpredicts peak H_{m0}.
			Run 7		
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-28, A-29, A-30	Excellent	Excellent [1]	Excellent	Overall excellent fit
Dublin Bay Buoy	A-38, A-39	Excellent	Very Good [1]	No data	Overall excellent fit for H_{m0}.
			Run 8		
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-31, A-32, A-33	Excellent	Discounted [1]	Very Good	Overall excellent fit
Dublin Bay Buoy	A-40	Excellent	Discounted due to suspect measurements	No data	Low energy wave climate, well represented by the model.
			Run 9		
Location	**Figure**	**H_{m0}**	**Tp**	**Dir**	**Overall Fit/Comment**
M2 Wave Buoy	A-34, A-35, A-36	Excellent	Excellent	Excellent	Overall excellent fit
Dublin Bay Buoy	A-41	Excellent	Discounted due to suspect measurements	No data	Low energy wave climate, well represented by the model.

[1] See discussion in Section 4.1.

The validation scenarios show that the calibration adopted in the SW DAPPMS are valid for other the selected time periods based on the fit of the model to the M2 wave buoy and Dublin Bay Buoy data.

4. DISCUSSIONS AND CONCLUSIONS

4.1 Discussion

Through the calibration process it is evident that the DAPPMS SW model achieves generally good agreement with the measured data at the M2 wave buoy, Dublin Bay Buoy and JN1136 South Buoy.

As the M2 wave buoy and Dublin Bay Buoy have coincident measured data it was possible to assess the model performance at both sites for the same event. Based on the presented results it shows that the DAPPMS SW model accurately replicates the wave transformation processes from the offshore to the nearshore, including the transition from deep water to shallow water as waves pass the Kish and Bray Banks into Dublin Bay.

A single scenario was chosen to assess the model performance at the JN1136 wave buoy, due to the limited length of measured data here. This was a scenario were the wave direction moves from a northerly to a southerly direction. The model performs well, replicating the measured data in wave height, phasing and direction. This indicates that the model performs well over the OWF array location.

Based on the degree of calibration achieved it can be inferred that the data used to drive the model boundaries are appropriate to inform the forthcoming EIA, albeit with some limitations as described below. Copernicus wave data were proven to be an appropriate source of wave data to represent the wave climate at the north, east and southern model boundaries. Through the calibration process, the importance of applying an appropriate wind field was evident, so that wave growth could be replicated over the selected storm events. Applying a spatially varying wind field over the model domain was shown to be appropriate, owing to the size of the model domain and distance of the calibration points from the model boundary.

During the model calibration a range of conditions were selected to assess the model's performance under both storm and more benign wave conditions and also for waves approaching from differing directions. The predominant angle of approach is from a southerly direction; this is also the direction with the largest storm events and a combination of swell and wind-sea conditions. Other conditions modelled are from westerly and easterly directions, both of which present wind-sea wave climates.

The results demonstrate that the model is able to replicate the wave climate from each direction of wave approach. The calibration results show that the model achieves a good degree of fit in terms of phase and magnitude of the wave climate. Wave directions are also well matched in the calibration runs.

The most marked discrepancies between measured data and model predictions are seen in some of the wave period (Tp) plots. In some of these plots the predicted period matches the measurements well, while in others there is a generally poor match (with the model often over-predicting), or the performance flips between good and poor over time. This issue has been carefully investigated during the calibration process and is believed to reflect the following two issues:

- Wave periods measured at the Dublin Bay buoy are believed to be frequently erroneous. There are numerous occasions in the recorded data set when the measured period appears far too short for the coincident wave height. We believe this may reflect a chronic problem with the measurement of wave period by the buoy. For completeness and openness Intertek has included all of the calibration and validation plots where a poor Tp fit occurs at the Dublin Bay buoy, although have not shown plots where Tp was measured and analysis was discounted. However, we believe these discrepancies do not indicate a fundamental problem with the SW model that generally suitably replicates Tp.

- In addition to the above, the SW model calibration and validation has also been somewhat limited in the availability of data to drive the model. The selected source of boundary data – the Atlantic -Iberian Biscay Irish- Wave Multi-Year Model – is believed to be the most suitable available, and has been demonstrated (Intertek 2020) to provide a good fit against measurements at both the M2 and M5 wave buoys. However, the data available from this model do not distinguish between the local wind-sea and swell wave components of the wave field. Typically, in oceanographic models, the total wave height is calculated as the square root of the wind-sea wave height squared and the swell wave height squared. The wave period, however, may just be taken from the highest of the two wave components – wind-sea or swell. We believe this is evident in the SW model boundary conditions, where period sometimes rapidly switches from short period (typical of local wind-sea waves) to longer period (typical of swell waves) – presumably when the swell wave height rises above the wind-sea wave height and vice versa. Since this reflects a mathematical simplification rather than a true physical process, it is not captured in any of the calibration or validation data sets.

These two limitations combine to make some of the Tp calibration and validation plots look poor. However, we do not consider this to impact the overall performance of the SW model, since:

- The most likely sources of the discrepancy have been identified and arise from two issues which are understood.
- These issues will not come into play during the EIA supporting studies, for which the SW model will be run under a set of scenarios derived through statistical analysis of the long time series hindcast data at the model boundary. From this data timeseries known statistical relationships between Hm0 and Tp will be used to derive specific wave conditions to assess the impact of the development.
- For calibration and validation scenarios where Tp does not experience these issues the SW model shows good performance and accurately represents Tp.

Following the calibration, four independent validation scenarios were modelled. These runs were conducted as additional checks of the model performance. As for the calibration scenarios, the validation results show that the model achieves a good degree of fit in terms of wave height, period and direction.

4.2 Limitations

Through the course of the SW model calibration a number of limitations have been identified. These are summarised as follows:

- There are three locations within the model domain where measured data are available for calibration and validation. Whilst this provides a limited means to assess the model performance over the wider model area including at key receptors the data is considered sufficient.
- A key data set for model calibration is the JN1136 South wave buoy data. This data set has a relatively short duration, and therefore only limited potential for model calibration. However the model performance at this location is good, and this calibration adds value to the calibration achieved at the M2 wave buoy and Dublin Bay Buoy locations.
- The wind field is given at six-hourly intervals. For this reason the model is sometimes unable to capture short-duration peaks that are identified in the measured data. However, this is not considered to be a limitation in terms of the ultimate use of the model to support the EIA since it will be run for selected representative wave events rather than a time series that is dependent on the wind field.
- The input wave field (at the model boundaries) does not differentiate between wind sea and swell wave conditions; therefore, it is not possible to capture this distinction effectively in the SW model.

For this reason, a mismatch can sometimes be seen to occur when assessing the wave period, which reflects the rapid switching between wind-sea and swell wave periods at the model boundaries. However, this will not be a problem when using the SW model to support the Dublin Array EIA since Intertek will be modelling a limited number of wave scenarios for which we will specify precisely the input height, period and direction.

4.3 Conclusions

The Dublin Array Physical Processes Modelling System has been constructed to undertake a physical processes study as part of the EIA of the proposed Dublin Array Offshore Wind Farm. This report provides details of the calibration and validation of the DAPPMS SW model.

The DAPPMS SW model has been calibrated and validated against field measurements of wave data at three sites within the model domain. The calibration and validation data include:

- Wave measurements at the M2 Wave Buoy;
- Wave measurements at the Dublin Bay Wave Buoy; and
- Wave measurements at the JN1136 South Wave Buoy.

Overall, the model achieves a good level of calibration and validation. There is generally very good agreement between measured and modelled wave height and direction. There is also good agreement between measured and modelled wave period other than in some scenarios where either the measured data or the model boundary conditions experience known quality issues.

Overall the model is considered fit for use for informing the physical processes assessment for the EIA of the Dublin Array OWF.

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2 Intertek, 2019. *'Dublin Array Offshore Windfarm: Metocean Data Review'.* R2344_R4865_Rev0.

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4 Intertek, 2020b. *'Acquisition and processing of offshore boundary data for wave model' Report.* R2344_BN4950_Rev0.

5 Lambkin, Harris, Cooper and Coates 2009.' Coastal Process Modelling for Offshore Wind Farm Environmental Impact Assessment: Best Practise Guide'. *COWRIE.*

6 OSI, 2019. Coast – OSI National 250k Map of Ireland https://data.gov.ie/dataset/coast-osi-national-250k-map-of-ireland.

APPENDIX A

Spectral Wave Model Calibration and Validation Plots

A.1 WAVE MODELLING CALIBRATION PLOTS

A.1.1 Wave Calibration Plots, M2 Wave Buoy

Figure A-1 Run 1 Model calibration, Wave Height: M2 Wave Buoy

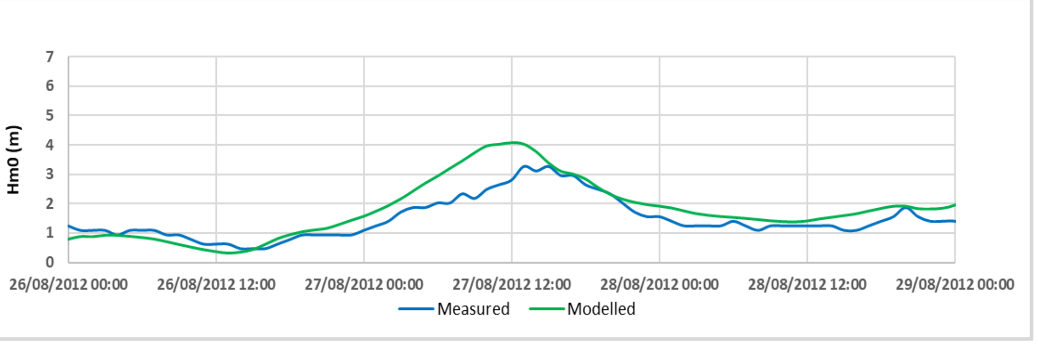


Figure A-2 Run 1 Model calibration, Wave Period: M2 Wave Buoy

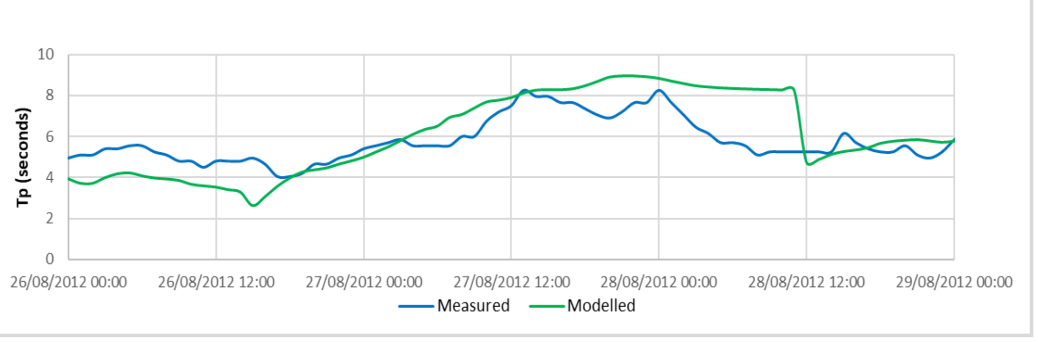


Figure A-3 Run 1 Model calibration, Wave Direction: M2 Wave Buoy

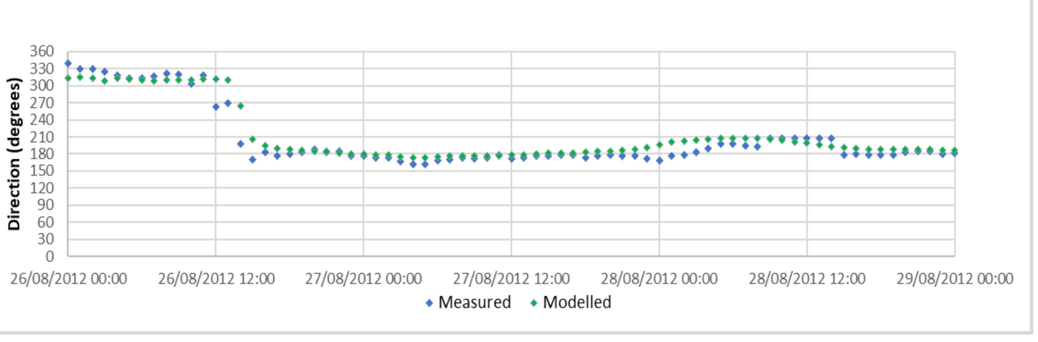


Figure A-4 Run 2 Model calibration, Wave Height: M2 Wave Buoy

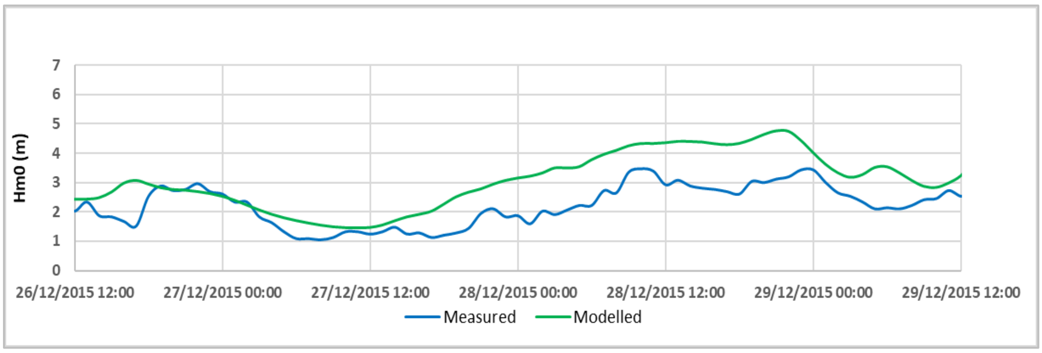


Figure A-5 Run 2 Model calibration, Wave Period: M2 Wave Buoy

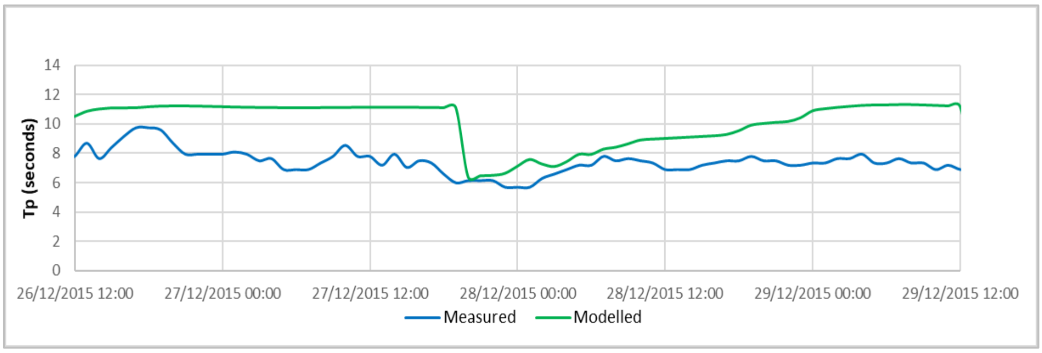


Figure A-6 Run 2 Model calibration, Wave Direction: M2 Wave Buoy

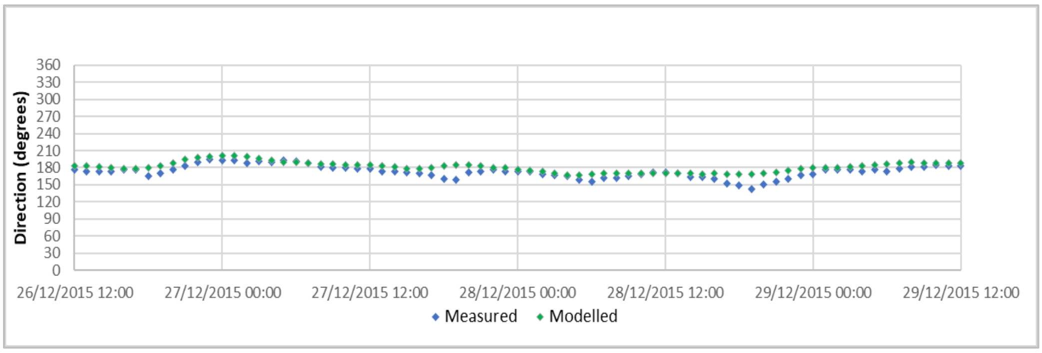


Figure A-7 Run 3 Model calibration, Wave Height: M2 Wave Buoy

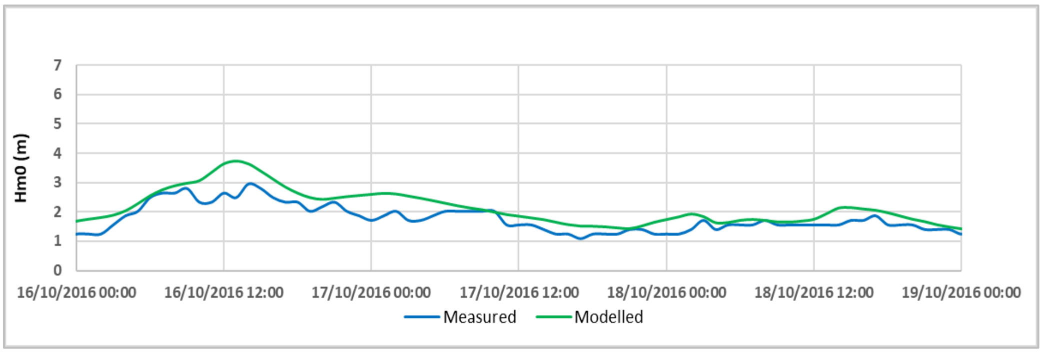


Figure A-8 Run 3 Model calibration, Wave Period: M2 Wave Buoy

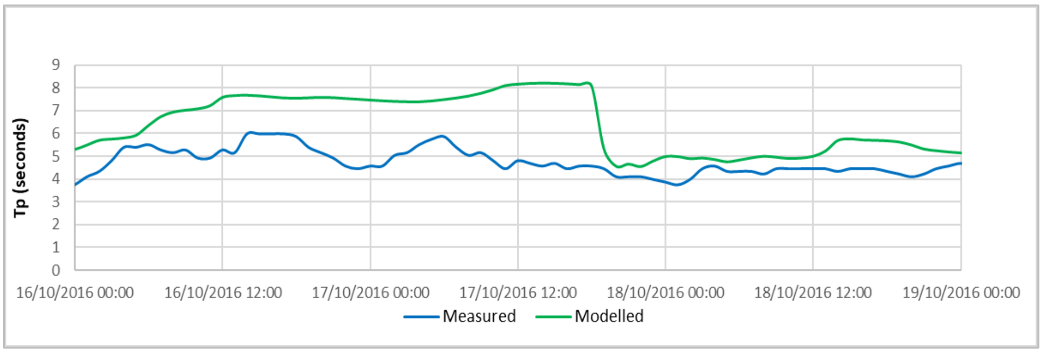


Figure A-9 Run 3 Model calibration, Wave Direction: M2 Wave Buoy

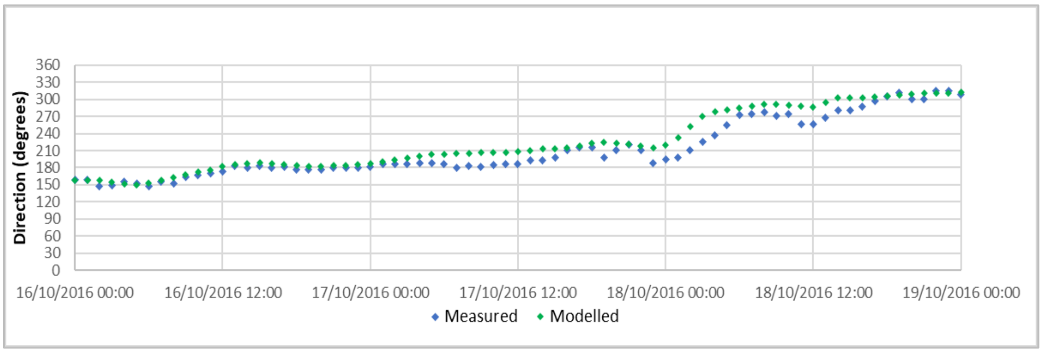


Figure A-10 Run 4 Model calibration, Wave Height: M2 Wave Buoy

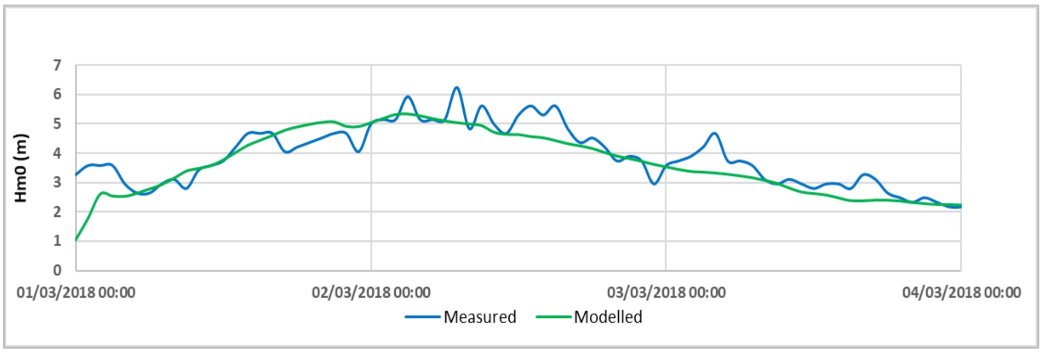


Figure A-11 Run 4 Model calibration, Wave Period: M2 Wave Buoy

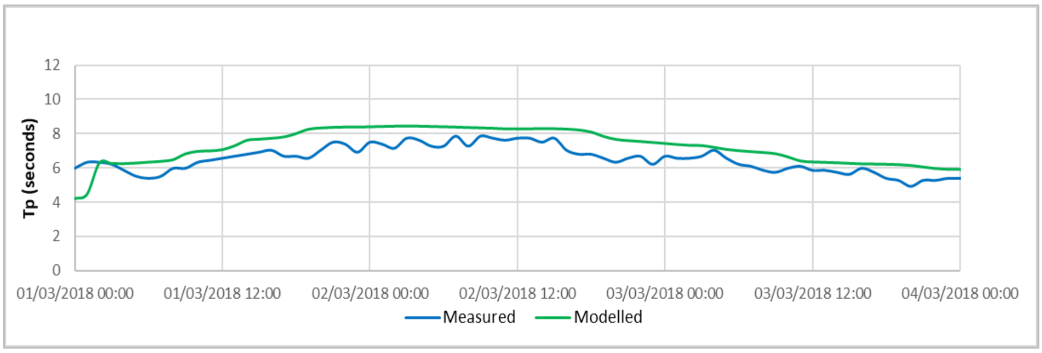


Figure A-12 Run 4 Model calibration, Wave Direction: M2 Wave Buoy

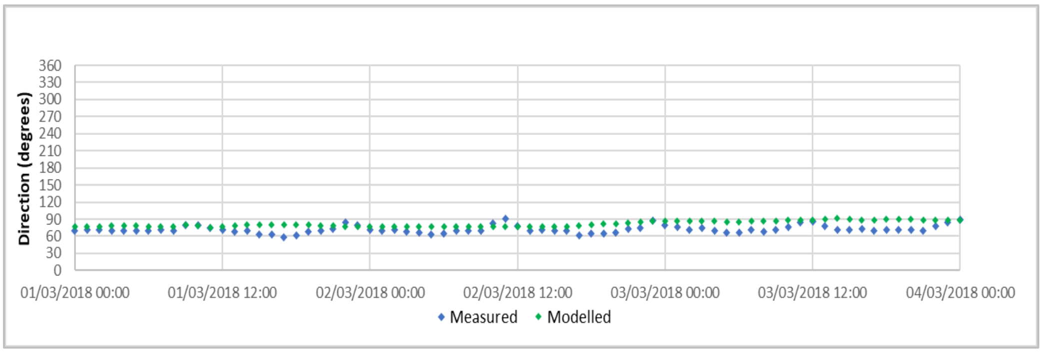


Figure A-13 Run 5 Model calibration, Wave Height: M2 Wave Buoy

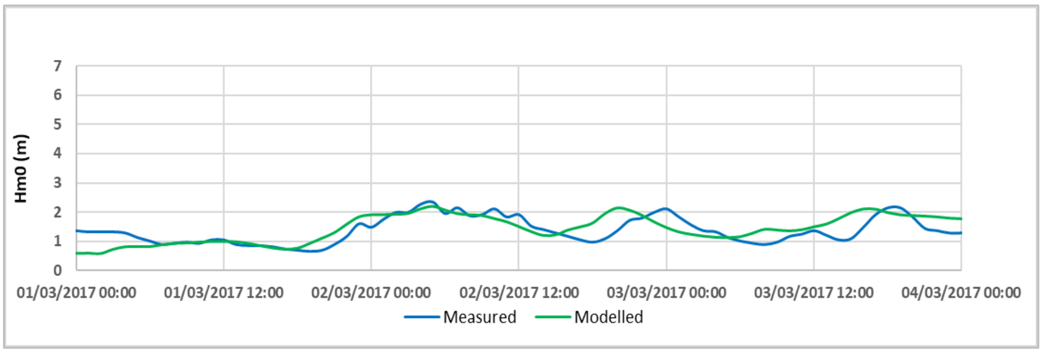
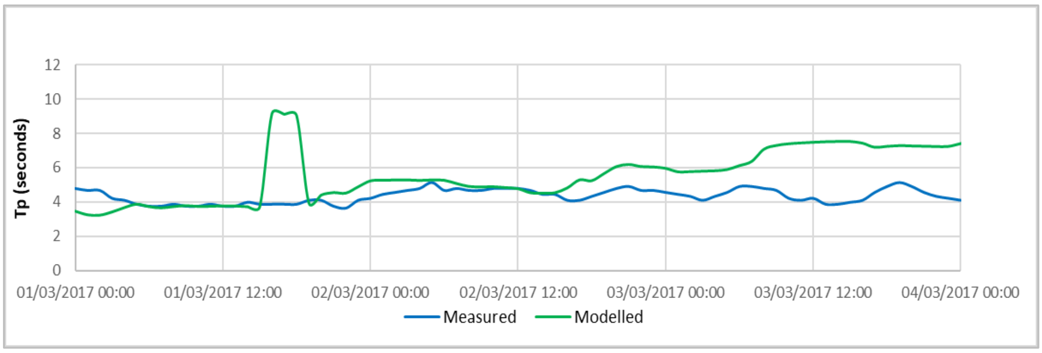
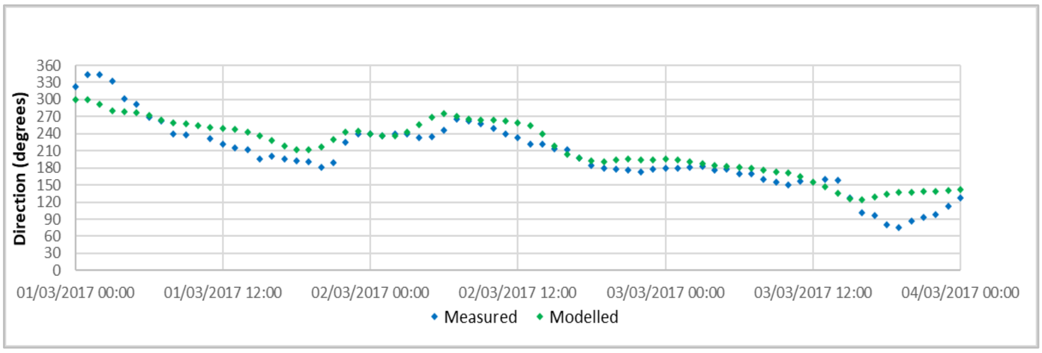


Figure A-14 Run 5 Model calibration, Wave Period: M2 Wave Buoy



Note: the peak in the modelled timeseries is due to the switch from wind to swell conditions described in Section 4.2.

Figure A-15 Run 5 Model calibration, Wave Direction: M2 Wave Buoy



A.1.2 Wave Calibration Plots, JN1136 Wave Buoy

Figure A-16 Run 1 Model calibration, Wave Height: JN1136 Buoy

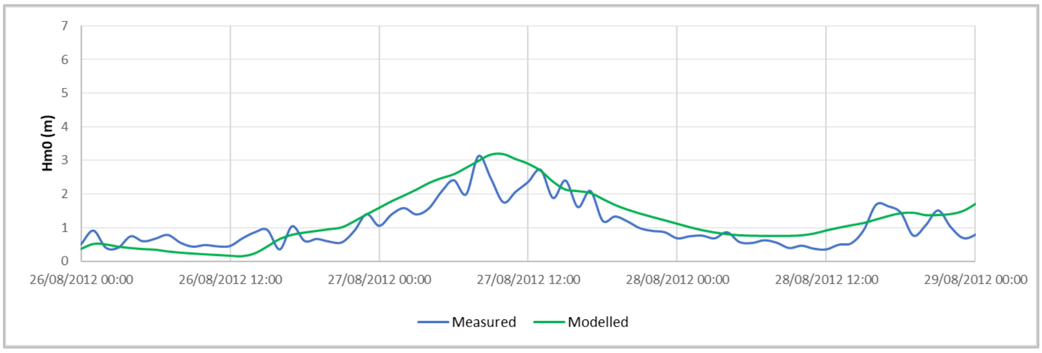


Figure A-17 Run 1 Model calibration, Wave Period: JN1136 Buoy

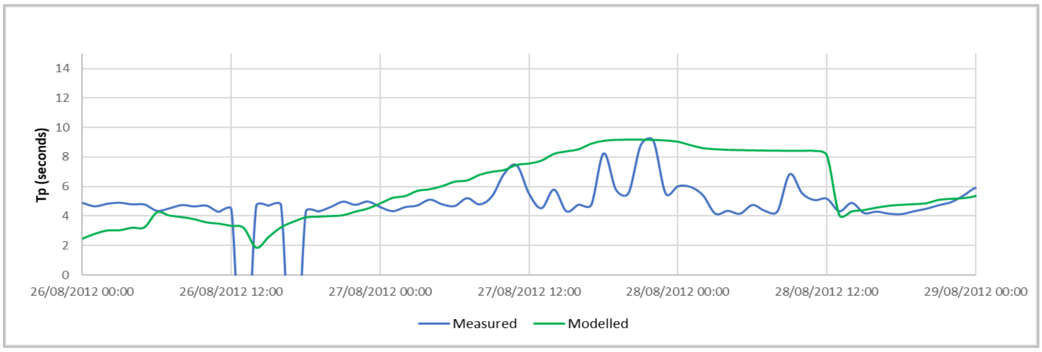
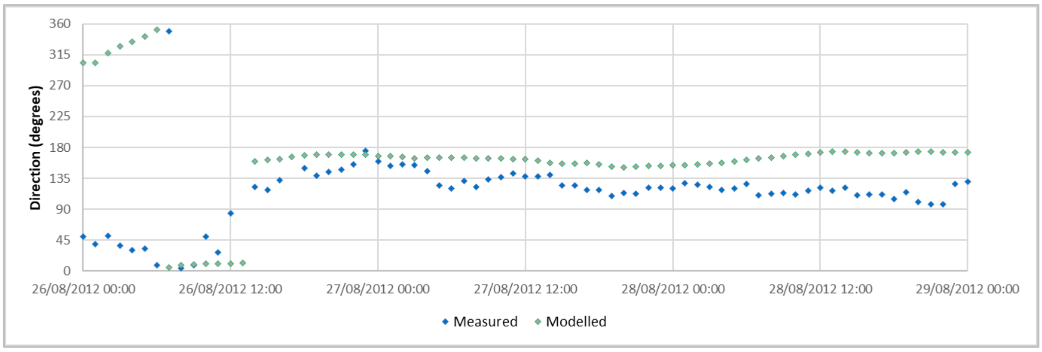


Figure A-18 Run 1 Model calibration, Wave Direction: JN1136 Buoy



A.1.3 Wave Calibration Plots, Dublin Bay Wave Buoy

Figure A-19 Run 2 Model calibration performance, Wave Height: DUBLIN Wave Buoy

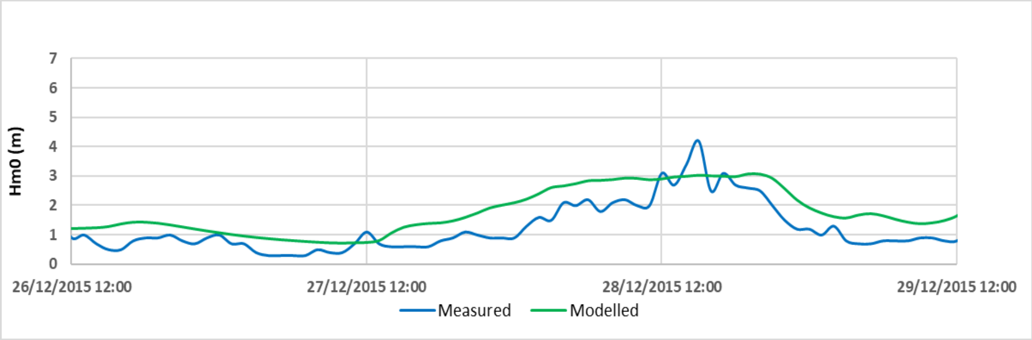


Figure A-20 Run 2 Model calibration performance, Wave Period: DUBLIN Wave Buoy

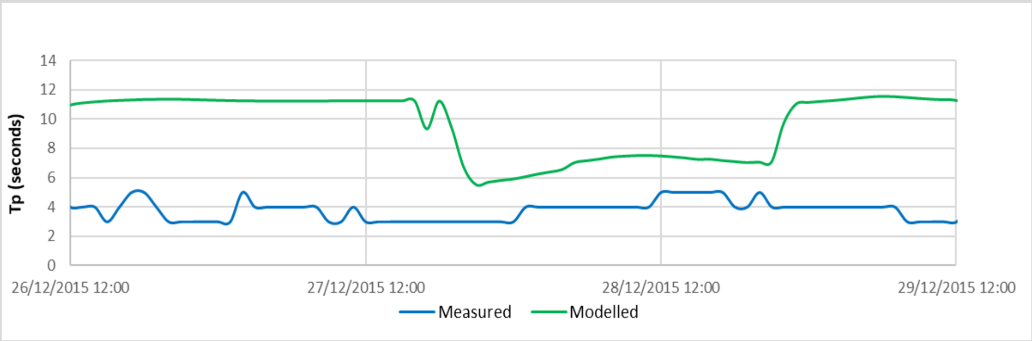


Figure A-21 Run 3 Model calibration performance, Wave Height: DUBLIN Wave Buoy

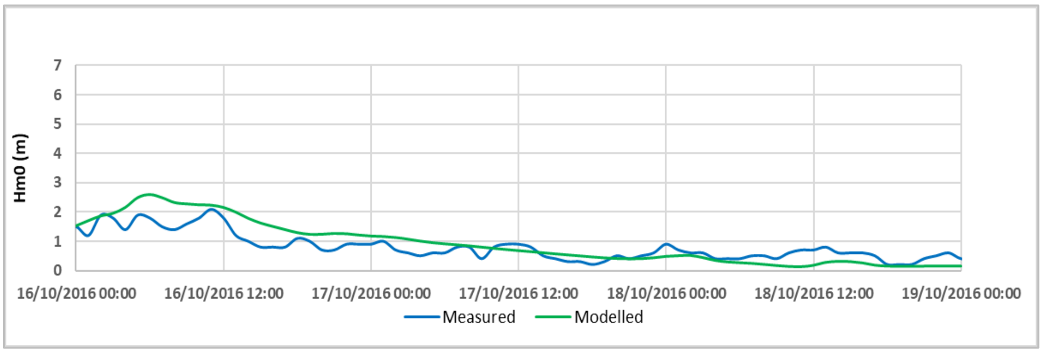


Figure A-22 Run 3 Model calibration, Wave Period: DUBLIN Wave Buoy

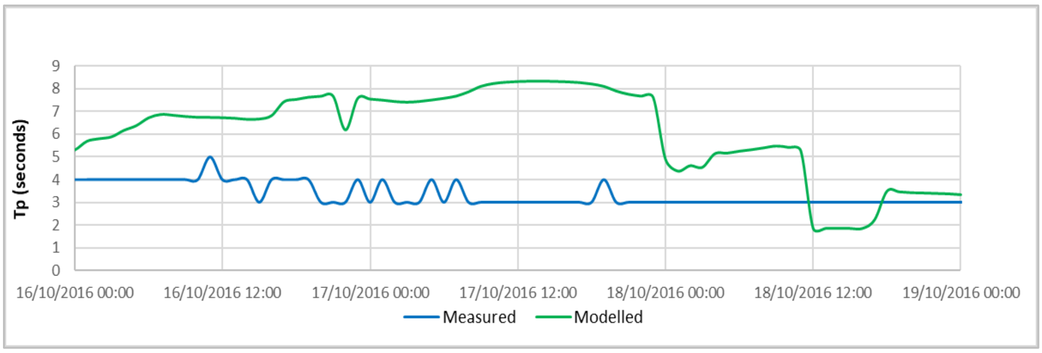


Figure A-23 Run 5 Model calibration, Wave Height: DUBLIN Wave Buoy

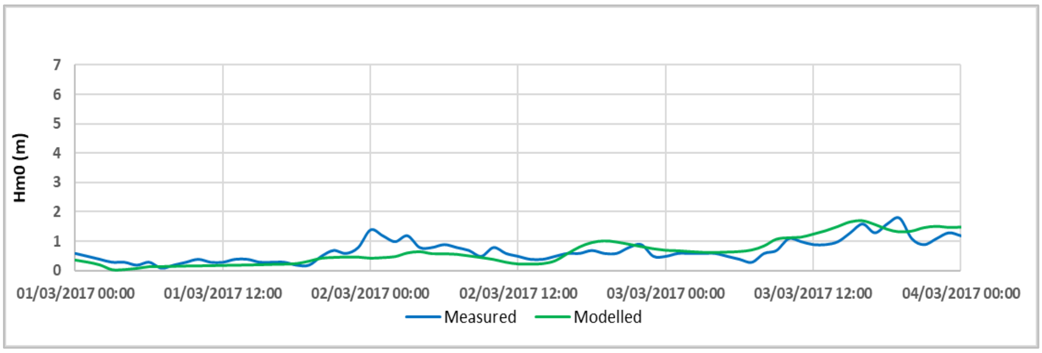
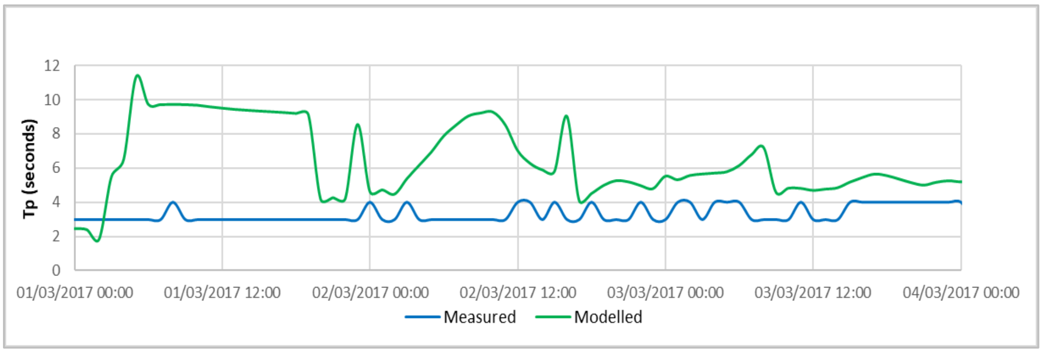


Figure A-24 Run 5 Model calibration, Wave Period: DUBLIN Wave Buoy



A.2 WAVE MODELLING VALIDATION PLOTS

A.2.1 Wave Validation Plots, M2 Wave Buoy

Figure A-25 Run 6 Model validation, Wave Height: M2 Wave Buoy

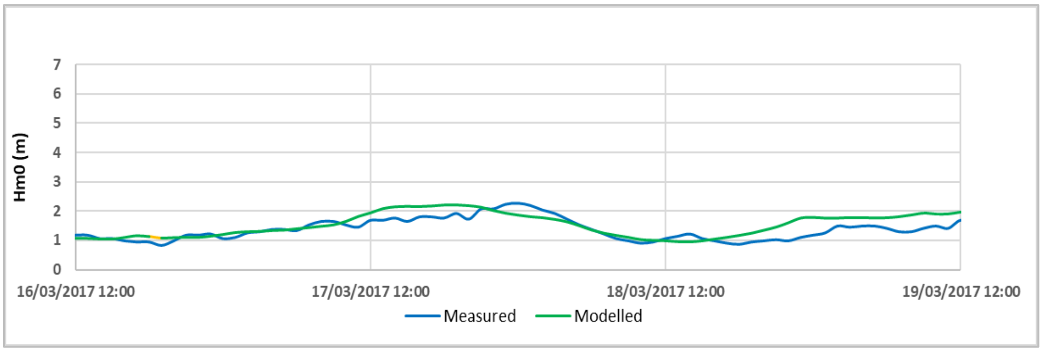


Figure A-26 Run 6 Model validation, Wave Period: M2 Wave Buoy

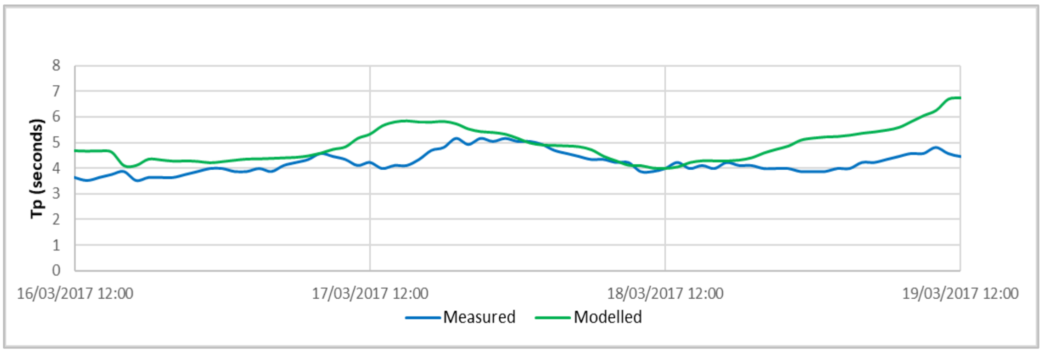


Figure A-27 Run 6 Model validation, Wave Direction: M2 Wave Buoy

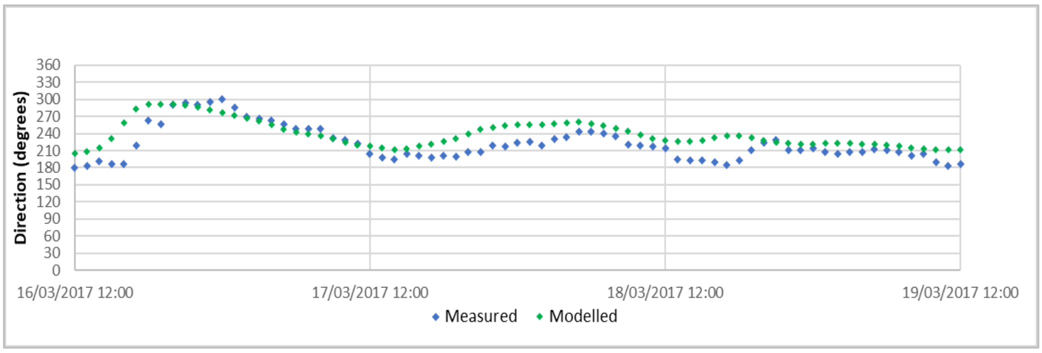


Figure A-28 Run 7 Model validation, Wave Height: M2 Wave Buoy

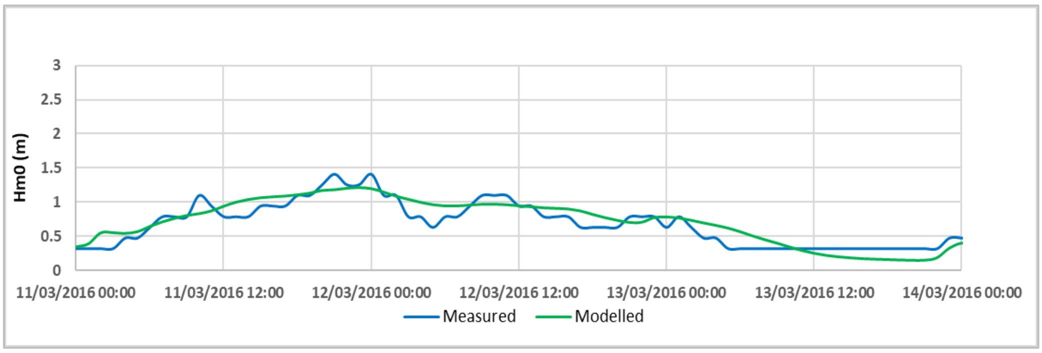


Figure A-29 Run 7 Model validation, Wave Period: M2 Wave Buoy

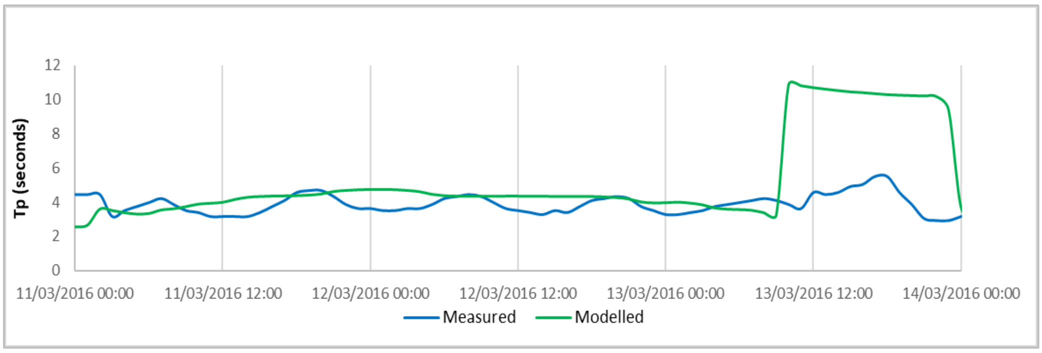


Figure A-30 Run 7 Model validation, Wave Direction: M2 Wave Buoy

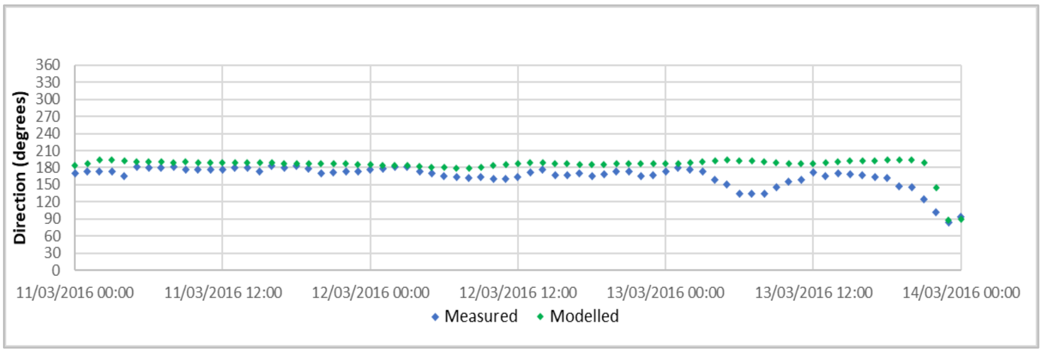


Figure A-31 Run 8 Model validation, Wave Height: M2 Wave Buoy

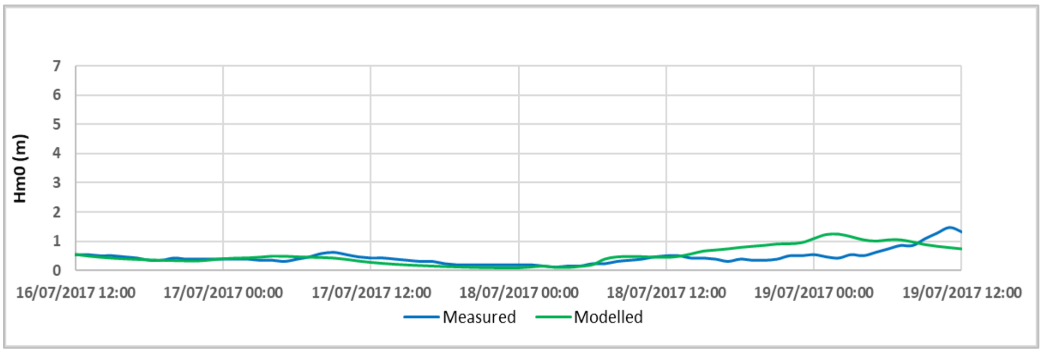


Figure A-32 Run 8 Model validation, Wave Period: M2 Wave Buoy

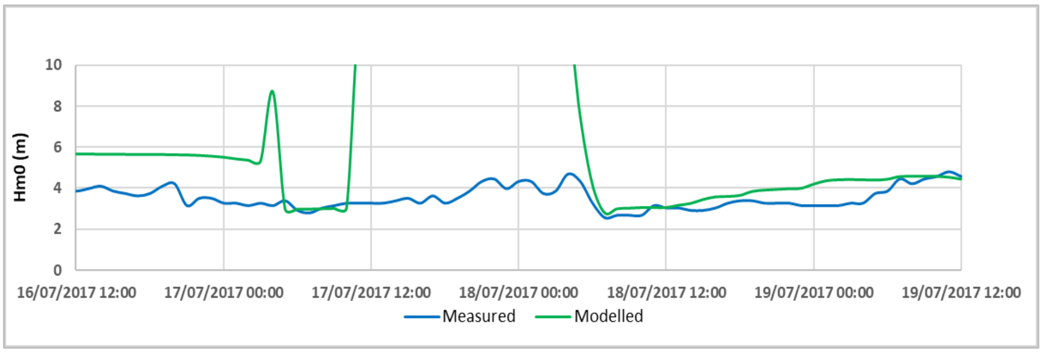


Figure A-33 Run 8 Model validation, Wave Direction: M2 Wave Buoy

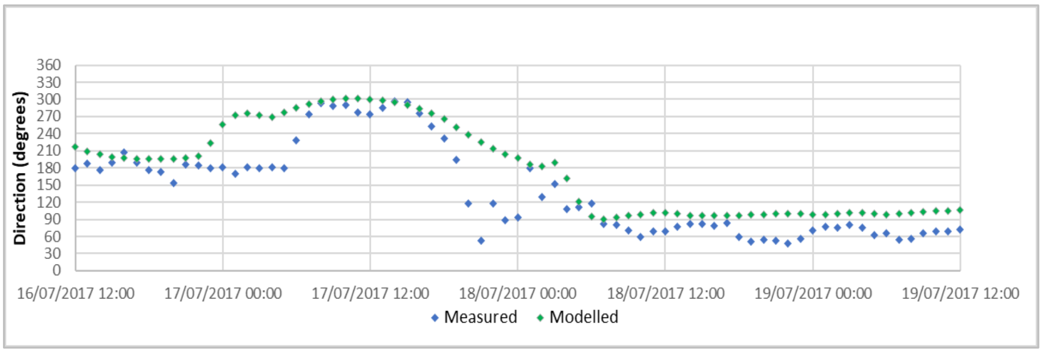


Figure A-34 Run 9 Model validation, Wave Height: M2 Wave Buoy

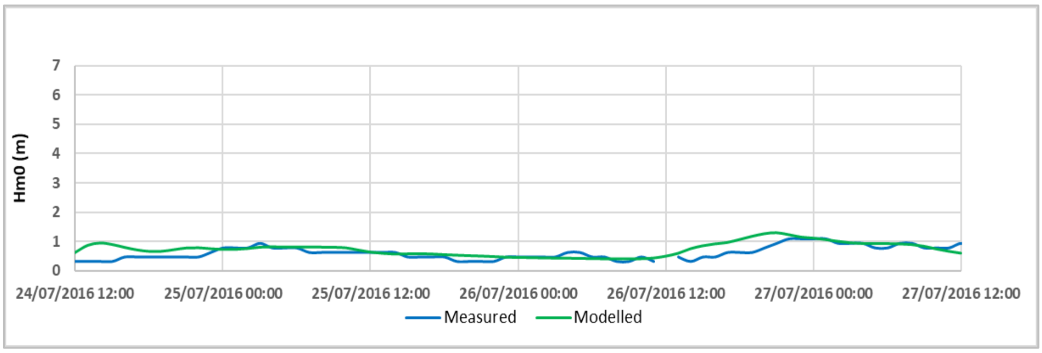


Figure A-35 Run 9 Model validation, Wave Period: M2 Wave Buoy

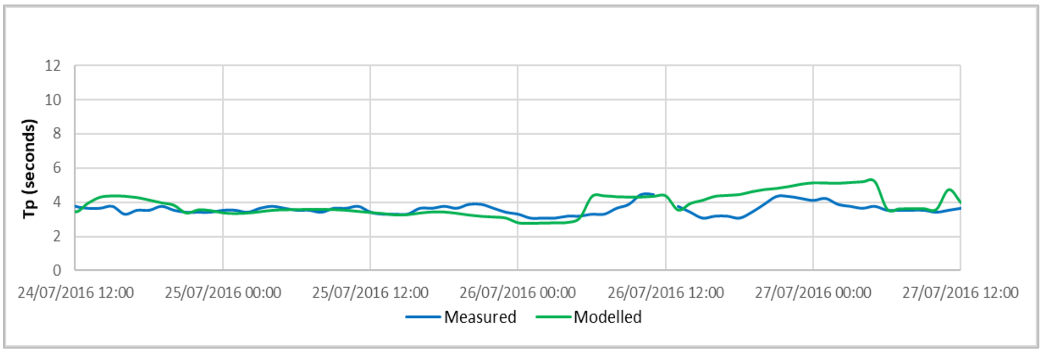
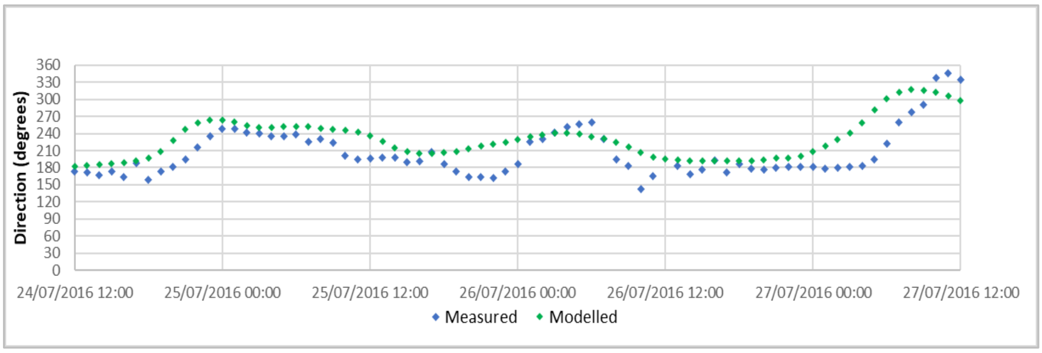


Figure A-36 Run 9 Model validation, Wave Direction: M2 Wave Buoy



A.2.2 Wave Validation Plots, Dublin Bay Wave Buoy

Figure A-37 Run 6 Model validation, Wave Height: DUBLIN Wave Buoy

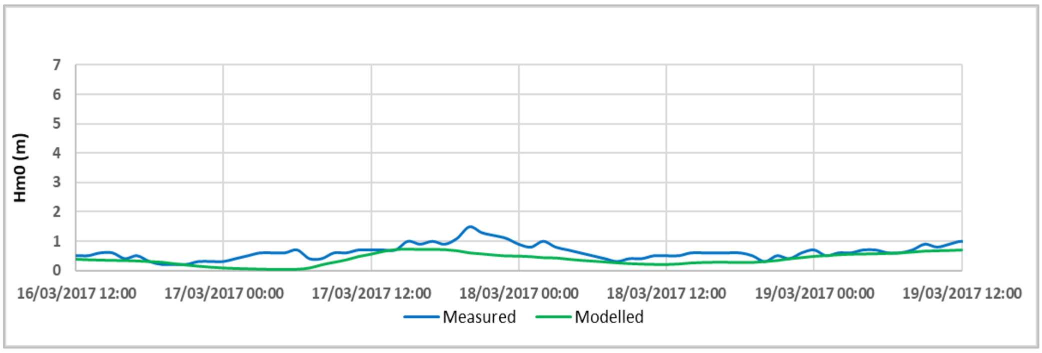


Figure A-38 Run 7 Model validation, Wave Height: DUBLIN Wave Buoy

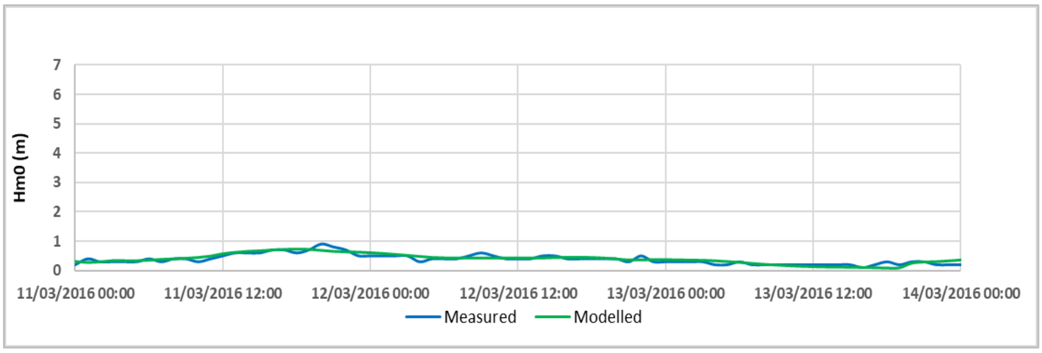


Figure A-39 Run 7 Model validation, Wave Period: DUBLIN Wave Buoy

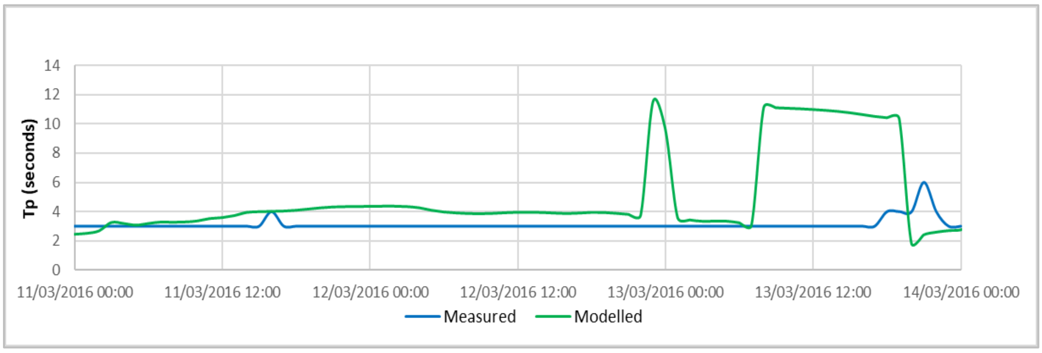


Figure A-40 Run 8 Model validation, Wave Height: DUBLIN Wave Buoy

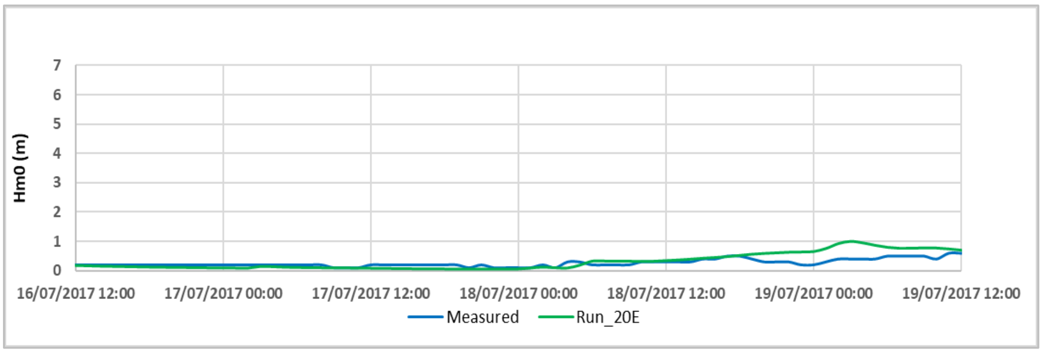


Figure A-41 Run 9 Model validation, Wave Height: DUBLIN Wave Buoy