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EIAR Volume 4: Offshore Infrastructure Technical Appendices
Appendix 4.3.1-3 Hydrodynamic Calibration and Validation Report

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Dublin Array Offshore Wind Farm

Hydrodynamic Calibration and Validation Report

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Dublin Array Offshore Wind Farm

Hydrodynamic Calibration and Validation Report

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Rev No	Date	Reason	Author	Checker	Authoriser
Rev 0	12/02/2020	Original Submission	E Perkins	P Taylor	P Taylor
Rev 1	24/02/2020	Revised following client comments	E Perkins	J Gibson	P Taylor

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 are 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 potential impacts on the physical environment from the proposed OWF development. This report provides details of the model build, calibration and validation of the DAPPMS HD model. A separate report, P2344_R2984_rev0, provides details of the SW model (Intertek, 2020).

The DAPPMS HD model has been calibrated and validated against field measurements of water level and current velocity from a variety of sources. The calibration and validation data include:

- water level and velocity from bed mounted Acoustic Doppler Current Profiler (ADCP) deployments undertaken in 2012 at the array site;
- water level data from the Irish Tide Gauge network;
- water level data from the Admiralty Tide Tables;
- velocity data from the British Oceanographic Data Centre (BODC) for the outer part of the model domain; and
- velocity data from tidal diamonds from Admiralty charts.

The Foundation for Water Research (FWR) guidelines were used to assess the performance of the HD model. In general, agreement between modelled and observed water levels and current velocities are good across the model domain, and the model is considered fit for the purpose of the assessment.

It is noted there are differences in the phasing of the tide across the model domain. These are due to a combination of issues, including uncertainty in the timing of the field data. These phase differences are not considered to be an issue for the purpose of applying the model to undertake the physical processes assessment to inform the Dublin Array OWF Environmental Impact Assessment (EIA).

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

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GLOSSARY

ADCP
Acoustic Doppler Current Profiler

BODC
British Oceanographic Data Centre

DAPPMS
Dublin Array Physical Processes Modelling System

DHI
Danish Hydraulic Institute

EIA
Environmental Impact Assessment

EMODnet
European Marine Observation and Data Network

FM
Flexible Mesh

FWR
Foundation for Water Research

HD
Hydrodynamic

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

UKHO
United Kingdom Hydrographic Office

UTM
Universal Transverse Mercator co-ordinate system

WGS84
World Geodic 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 Process 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 HD modelling element of the DAPPMS. The scope and specification of the DAPPMS is reported in the Assessment Methodology Report (Intertek 2020), submitted to innogy on 27th January 2020. The SW model calibration and validation are reported in a separate report, P2344_R4984_Rev0 (Intertek, 2020).

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, immediately south 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). The variation in water depth causes a spatially varying range of metocean conditions over the site.

1.2.1 Oceanographic Description

The hydrodynamics of the area are tidally-dominated, and the tidal regime is semi-diurnal with a mean spring and neap tidal range of 3.4 m and 1.9 m respectively at Dublin Port (Admiralty, 2019). The tidal currents have peak speeds of 1.9 m/s during spring tides and 1.1 m/s during neap tides. The flood tide is slightly stronger than the ebb. The tidal streams run parallel to the Irish coast, ebbing southwards (Admiralty, 1974).

1.3 Modelling Approach Overview

The model has been developed using the MIKE21 Flexible Mesh (MIKE21 FM) software. The model is two dimensional (depth-averaged) and built over an unstructured triangular mesh of varying resolution.

The model is built and calibrated using data supplied to Intertek by innogy, including bathymetric and measured tidal data.

2. DATA

The tidal hydrodynamic modelling element of the DAPPMS was conducted using a variety of data that were made available by innogy. This section of the report details the data used in the model build, calibration and validation. Model calibration is the process during which the model parameters are compared against field data and altered to make the model more similar. The model performance is assessed both visually and statistically (see section 4 for further details). Model validation uses the calibrated model setup to compare the model against a set of field data independent of the set used for the calibration comparison. The model performance is assessed visually and statistically again and if acceptable the model is considered fit for purpose. Otherwise, the model calibration continues until an acceptable validation is achieved.

2.1 Bathymetry

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

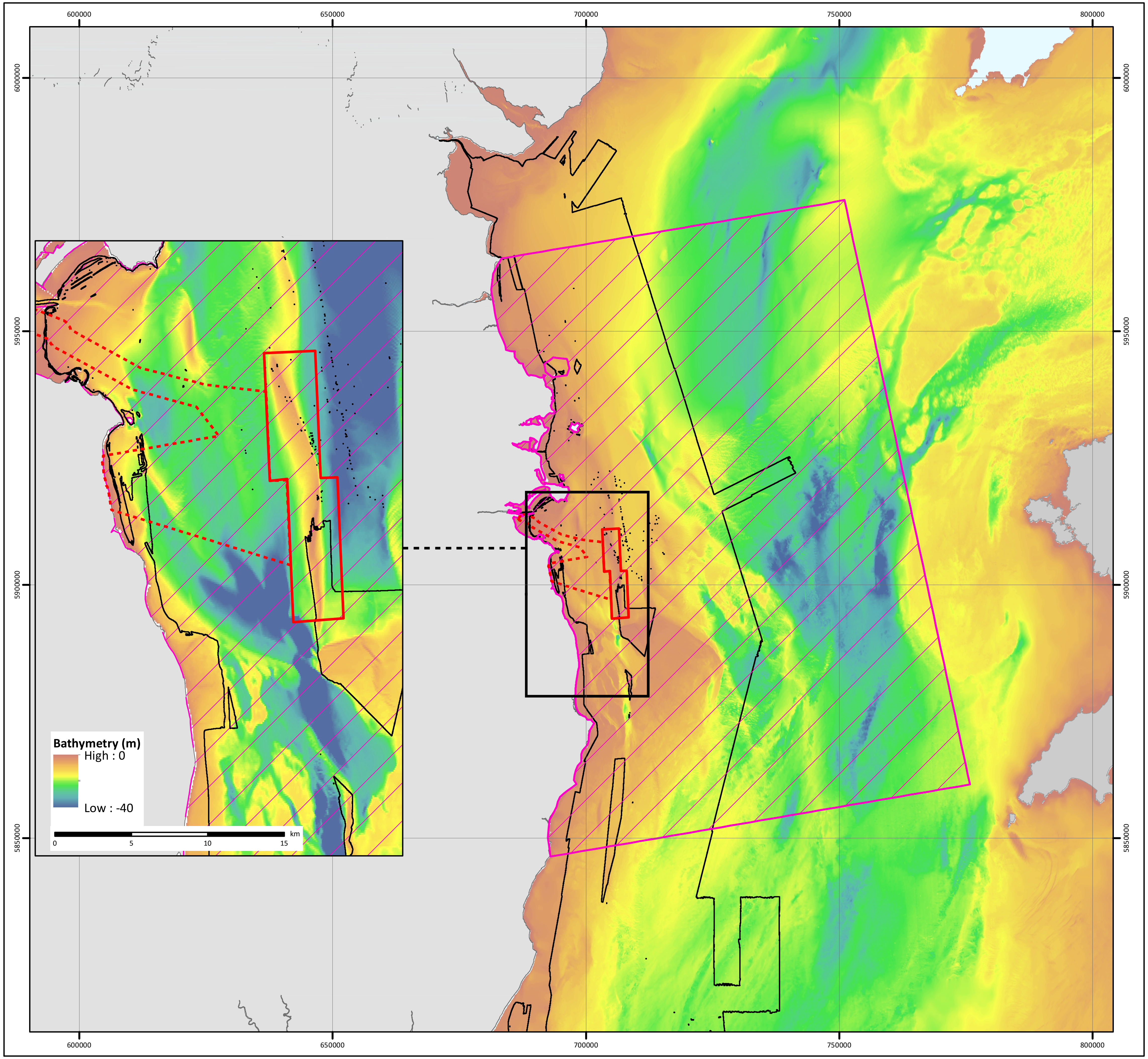
The primary data resource considered for bathymetry was the INFOMAR bathymetry, provided by the Geological Survey, Ireland. The dataset provides a high level of detail at a consistent scale across the majority of the study area. This information was also supplemented by EMODnet bathymetry to enable 100% 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 HD 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.



DUBLIN ARRAY OFFSHORE WINDFARM PHYSICAL PROCESSES ASSESSMENT

CALIBRATION AND VALIDATION
Model Domain and Bathymetry

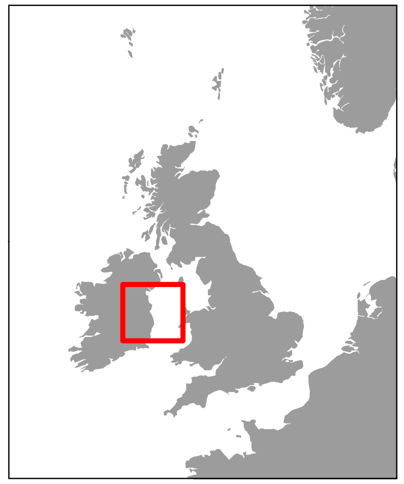
P2344-CAL-001	A

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

N
W
E
S



NOTE: Not to be used for Navigation

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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

innogy intertek

0 10 20 30 40 km

2.2 Tidal hydrodynamics

Tidal hydrodynamic data is required to provide measured reference data against which to calibrate and validate the HD model of the DAPPMS. The tidal data used in this study comes from several sources including surveyed data provided to Intertek by innogy, as well as other freely available data to give wider coverage within the modelling domain. This data characterises the physical metocean environment and provides a basis for model calibration and validation. Details of the data used in the HD model development are given below.

A 2012 survey of the Kish Bank undertaken by AQUAFACT International Services Ltd for Saorgus Energy Ltd provided the primary data resource for calibration and validation of the hydrodynamic model. The survey was undertaken to support the initial EIA in 2012. The survey consisted of two bed-mounted Acoustic Doppler Current Profiler (ADCP) deployments at the northern and southern ends of the bank (one month duration) and two ADCP deployments (day long duration) near the middle of the bank. These deployments produced water level and current velocity data which was utilised for model calibration. The month-long deployments were harmonically analysed to remove noise and atmospheric effects from timeseries. This is standard practice to remove transient effects on hydrodynamic datasets as the water movements due to tides are more important in a physical processes assessment.

The Irish National Tide Gauge Network, operated by Foras na Mara/Marine Institute, provided water levels at the Kish Bank Lighthouse, Dublin Port and Howth Harbour. Information from the UK Hydrographic Office (UKHO) provided additional water level estimates at a number of ports along the coast. Water levels at these sites were generated using the four constituents and two shallow water corrections published in the UKHO Admiralty Tide Tables (2019).

Additionally, British Oceanographic Data Centre (BODC) current meters and UKHO tidal diamonds were used to provide velocity data in the outer part of the model domain. Tidal diamonds were also used to provide a wider spatial coverage of velocity data through the domain. The tidal diamonds are a relatively coarse indicator of currents due to their low resolution which are published to the nearest hour and 0.1 knots. This equates to a possible error of up to approximately 30 mins for time and 0.05 knots (0.03 m/s) for speed. In addition, they have other uncertainties in the measurement and analysis of data from the tidal diamonds, including whether current speeds and directions are for surface or depth-averaged currents and the length and age of the originating dataset result in Tidal Diamond data being variable in quality. These data were therefore used for additional qualitative validation of the model, with due consideration of their limitations.

A summary of the tidal hydrodynamic data sources is provided in Table 2-2 and in Figure 2-2 (P2344-CAL-002). The coverage and resolution of the available data is considered suitable for the purpose of calibrating and validating the hydrodynamic element of the DAPPMS.

Table 2-2 Summary of tidal hydrodynamic data sources

Item	Provider	Parameters	Latitude (WGS84)	Longitude (WGS84)	Start time	End time	Duration (days)	Harmonic analysis?	Comment
JN1163 South	innogy	Levels, velocities	53.170	-5.913	23/08/2012	19/09/2012	26.9	Yes	Phasing very similar to JN1163 North. Successfully harmonically analysed.
JN1163 North			53.284	-5.936	23/08/2012	20/09/2012	27.9	Yes	1.5 hour phase difference in water levels from Kish Bank Lighthouse, 3.2 km north. Successfully harmonically analysed.
JN1163 C1		Velocities	53.233	-5.921	19/09/2012 14:30	20/09/2012 14:00	1.0	No	Phasing very similar to JN1163 North – i.e. ~1.5 hour difference in phase compared with nearby Kish Bank Lighthouse Dataset too short to harmonically analyse
JN1163 C2			53.234	-5.908	19/09/2012 15:00	20/09/2012 11:50	0.9	No	
Dublin Port	Foras na Mara/ Marine Institute	Levels	53.346	-6.222	13/02/2007	25/10/2019 (active gauge)	4637.0	Yes	Water level record for Dublin Port with some data gaps. However, successfully harmonically analysed.
Howth Harbour			53.392	-6.068	24/10/2006	25/10/2019 (active gauge)	4374.0	Yes	Water level record for Howth Harbour with some data gaps. However, successfully harmonically analysed.
Kish Bank Lighthouse			53.311	-5.926	28/07/2006	17/03/2015 (inactive gauge)	3154.0	No	Tide gauge does not accurately record the water levels below -1.6 mMSL. As this is above the water level during a typical spring tide, the gauge has not captured the entire range of low waters throughout the spring-neap tidal cycle. As such, the timeseries is not suitable for harmonic analysis. There are also periods of significant noise in the field data. 1.5 hour phase difference in water levels from JN1163 North, 3.2 km south. The data can still be used for qualitative model calibration.
Arklow	UKHO	Levels	52.800	-6.133	Harmonic constituents			n/a	4 main constituents and 2 shallow water correction factors provided, which are used to generate a reasonable prediction of water levels.
Dun Laoghaire			53.300	-6.133					
Malahide			53.450	-6.150					
River Boyne Bar			53.717	-6.233					
Wicklow			52.983	-6.033					1/6th diurnal correction factor is missing owing to lack of data.
B014751	BODC	Velocities	53.350	-5.550	06/09/1972	10/10/1972	33.9	Yes	Good record of speeds and directions in the middle of the water column, with minimal noise. Successfully harmonically analysed.
B014738			53.433	-5.367	06/09/1972	10/10/1972	34.0	Yes	
SN061C	UKHO		52.895	-5.842			0.5	n/a	

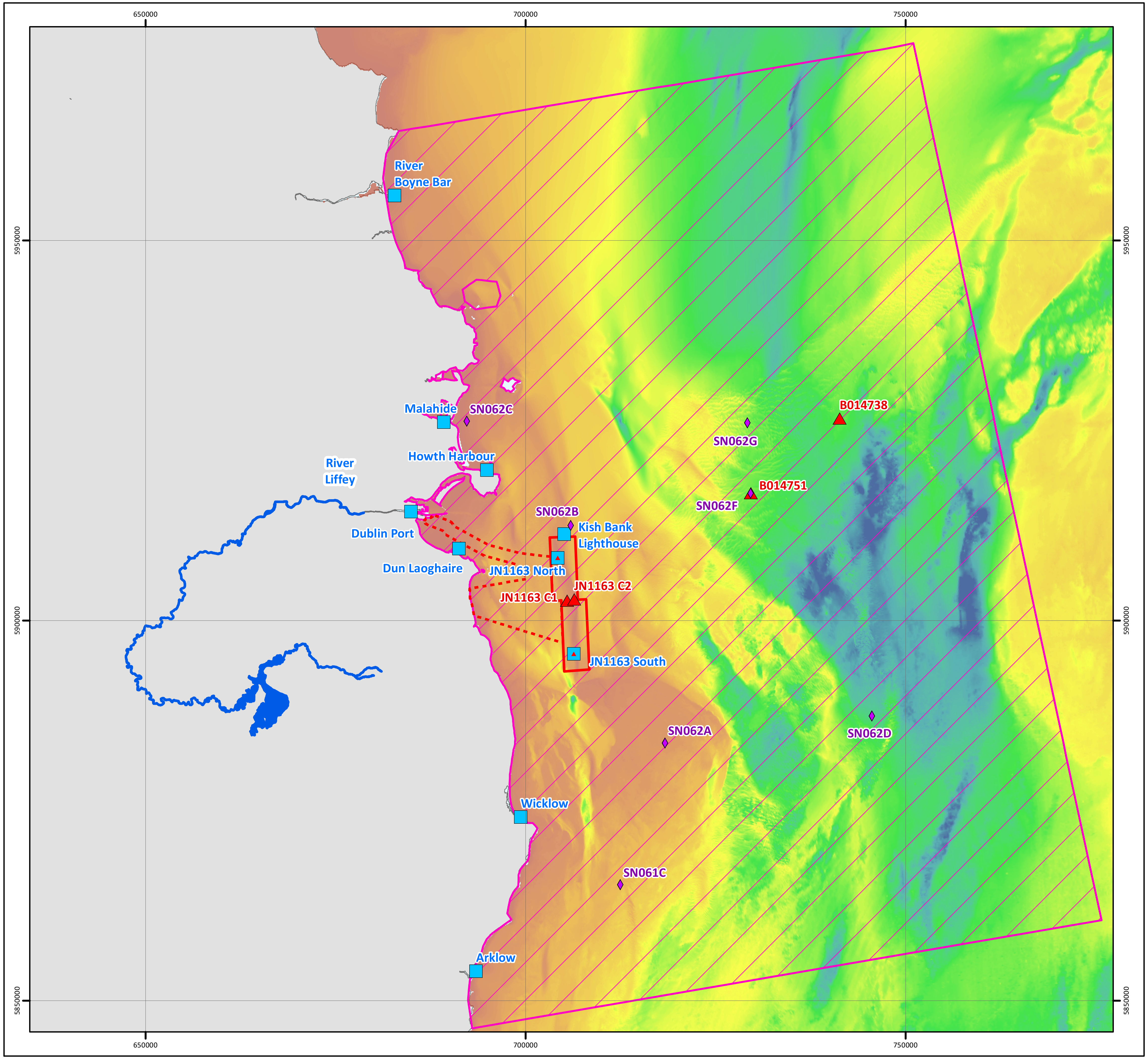
Item	Provider	Parameters	Latitude (WGS84)	Longitude (WGS84)	Start time	End time	Duration (days)	Harmonic analysis?	Comment
SN062A		Velocities (tidal diamond)	53.060	-5.742	12 hours of hourly speeds and directions for a mean spring and a mean neap tide				Good spatial coverage. SN062B is the closest tidal diamond to the study site.
SN062B			53.322	-5.908					
SN062C			53.450	-6.105					
SN062D			53.080	-5.333					
SN062F			53.350	-5.550					
SN062G			53.433	-5.550					

DUBLIN ARRAY OFFSHORE WINDFARM PHYSICAL PROCESSES ASSESSMENT

CALIBRATION & VALIDATION

HD Model Calibration and Validation Locations

P2344-CAL-002	A



Legend

HD Calibration & Validation Location

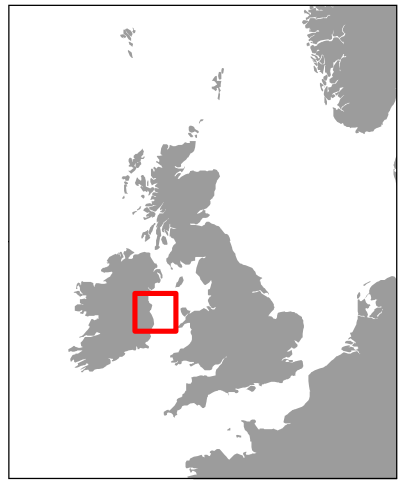
- Levels
- Levels & Velocities
- Velocities
- Velocities (Tidal Diamond)
- River Liffey
- Dublin Array Proposed Wind Turbine Area
- Export Cable Area of Search
- Model Domain

Bathymetry (m)

High : 0

Low : -150

N W E S



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-002.mxd
Created By	Chris Dawe
Reviewed By	Chris Carroll
Approved By	Emily Perkins

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0 7.5 15 22.5 30 km

2.3 Data quality review

The data used in the model build and calibration is predominantly as documented in the Metocean Data Review (Intertek, 2019), with additional calibration sites acquired as needed. 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 HD 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 general morphology or sedimentary regime of the area.

2.3.2 Spatial Distribution of Hydrodynamic Data

There is a good spatial distribution of water level and current sites with dataset periods that are long enough for harmonic analysis. There are three sites near the study site: JN1163 North, JN1163 South and Kish Bank Lighthouse. Dublin Port and Dun Laoghaire are also near the cable export route. The water level sites also provide good coverage of the coastal and nearshore areas throughout the model domain. There is a good spread of shorter duration current datasets such as JN1163 C1, JN1163 C2 and the UKHO tidal diamonds near the study area and the wider model domain. These shorter duration datasets cannot be harmonically analysed (see section 2.3.4 for additional information).

2.3.3 Duration of Hydrodynamic Field Data

There are seven datasets with a duration sufficiently long to be harmonically analysed. These are JN1163 North and JN1163 South near the study site, two BODC current meters in the outer part of the model and three tide gauges.

The water levels at Kish Bank Lighthouse and JN1163 North, approximately 3.2 km from each other, are 1.5 hours apart in phase. This difference in phase over such a short distance is unrealistic and it can be concluded that there is a timing error in the measured datasets. Model calibration is therefore undertaken with due consideration of this error.. However, as the purpose of the model is to assess changes to physical processes and impacts from the proposed OWF, the key model outputs are water levels and current velocities. The phasing of the tide is less important, especially as the model will be used to assess relative differences between the baseline and subsequent 'impact' scenarios.

2.3.4 Harmonic Analysis of Hydrodynamic Field Data Results

The longer the data series, the more robust the harmonic analysis performed on that data series. One or two months of data is generally considered a long enough series to obtain sufficient set of tidal constituents for most applications. 15 days is the minimum length of time series required to produce a reasonably robust set of tidal constituents that capture spring-neap tidal variation. Harmonic analysis of shorter time series is possible using more advanced techniques (e.g. inferred constituents based on nearby donor sites), but these approaches are likely to introduce their own errors into the analysis and are considered to bring little additional value to an assessment. Very short time series – several days or less – cannot reasonably be harmonically analysed by any method since it is not possible to separate out the tidal and non-tidal components. As such, both JN1163 North and JN1163 South were harmonically analysed.

The harmonic analysis of JN1163 North and JN1163 South produced harmonic constituents such that the predictions generated will be to MSL. This removes the issue that the vertical datum of the measured water level timeseries was not given and is not known. Harmonic analysis also removes non-tidal components of the recorded signal such as atmospheric effects on water level. However, large non-tidal influences, and/or particularly 'noisy' signals sometimes cannot be accurately harmonically analysed, and the harmonic analysis must be checked against the raw measured data.

It is noted that the current data at JN1163 South exhibits a large degree of "noise" in its tidal signal, as can be seen in Figure A24. This suggests some interference in the instrumentation measurement from a non-tidal force or instrumentation error. As such the ability to correctly harmonically analyse the data is limited, and the re-predicted data may be unreliable.

Whilst there can be seasonal variation in the mean water level, the variation is negligible for the Admiralty ports within the study area during the model calibration and validation period.

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 sediment plume dynamics).

Specifically, for the tidal element of the modelling, the MIKE21 Hydrodynamic (HD) model has been utilised. MIKE21 HD simulates unsteady flow considering density variations, bathymetry and external forcing to give accurate representations of water levels, current speed and direction.

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), acting from the World Geodetic System 1984 Datum (WGS84). The proposed Dublin Array Offshore Wind Farm lies within UTM area 29N [EPSG 32629] as such orientation shall be 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 Mesh Development

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 addressing 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	Area (m^2)	Triangle base length (m)
Array Field	5,000	Approx. 110
Cable Route	5,000	Approx. 110
Sensitive Receptors	50,000	Approx. 340
Coastal regions	125,000	Approx. 540
Offshore region	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 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 areas.

3.2.3 Model Bathymetry

A linear interpolation technique was adopted to generate the DAPPMS HD 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 Hydrodynamic Model Domain and Mesh

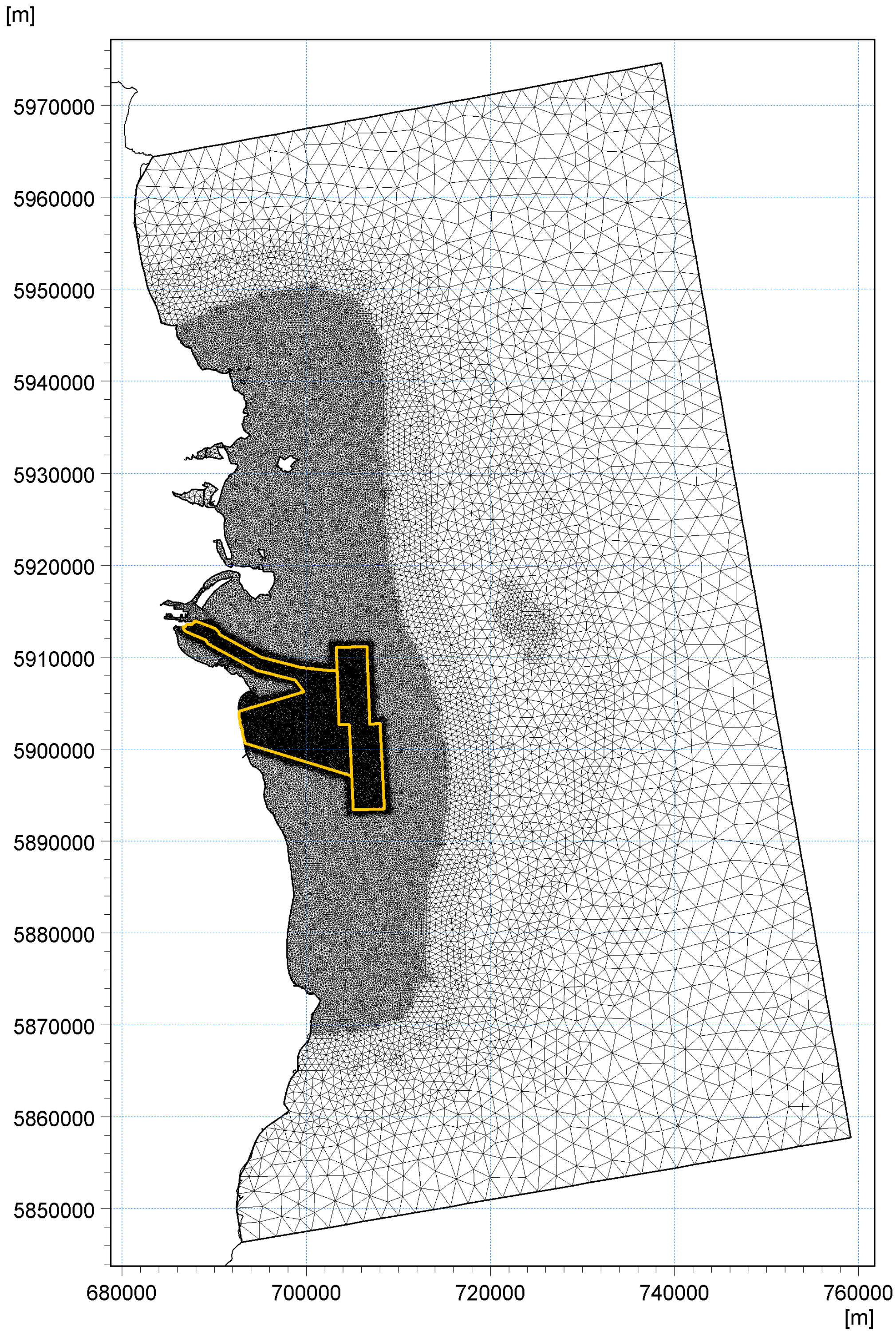


Figure 3-2 Hydrodynamic Model Domain and Mesh – proposed wind turbine area

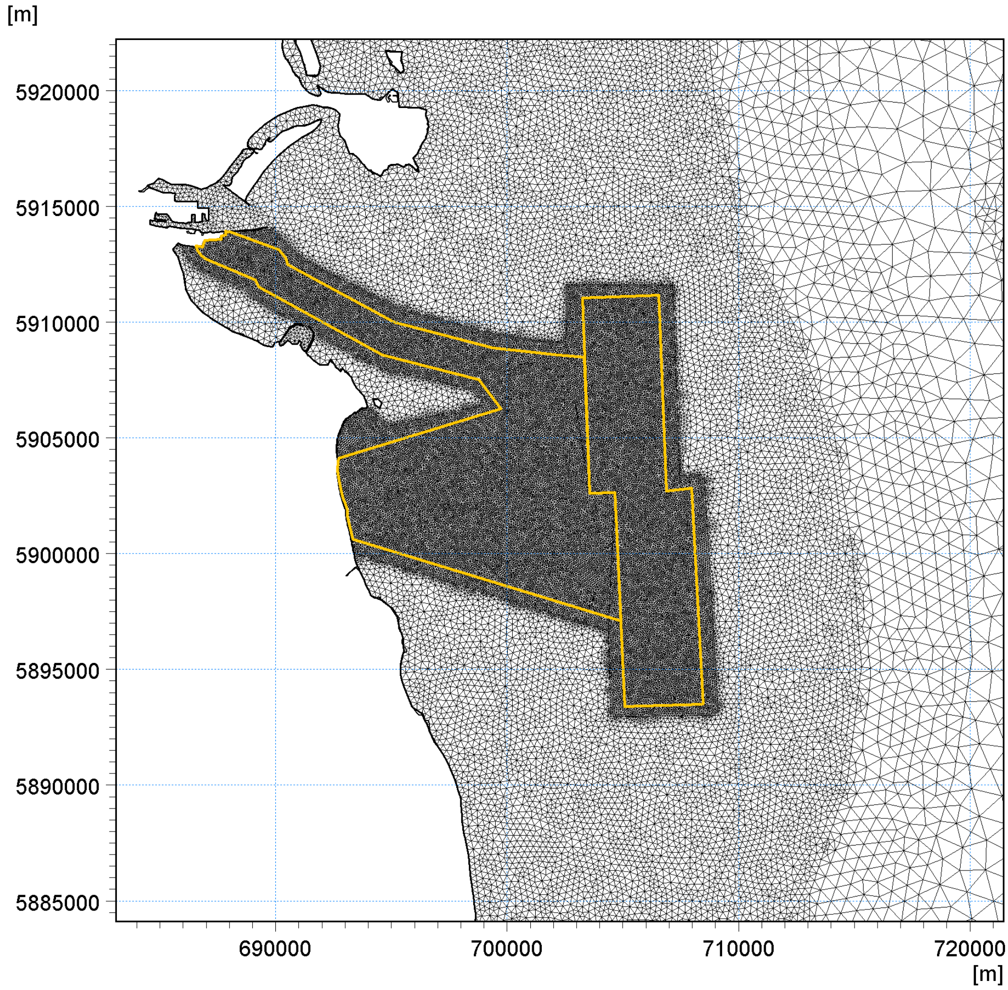


Figure 3-3 Hydrodynamic Model Bathymetry

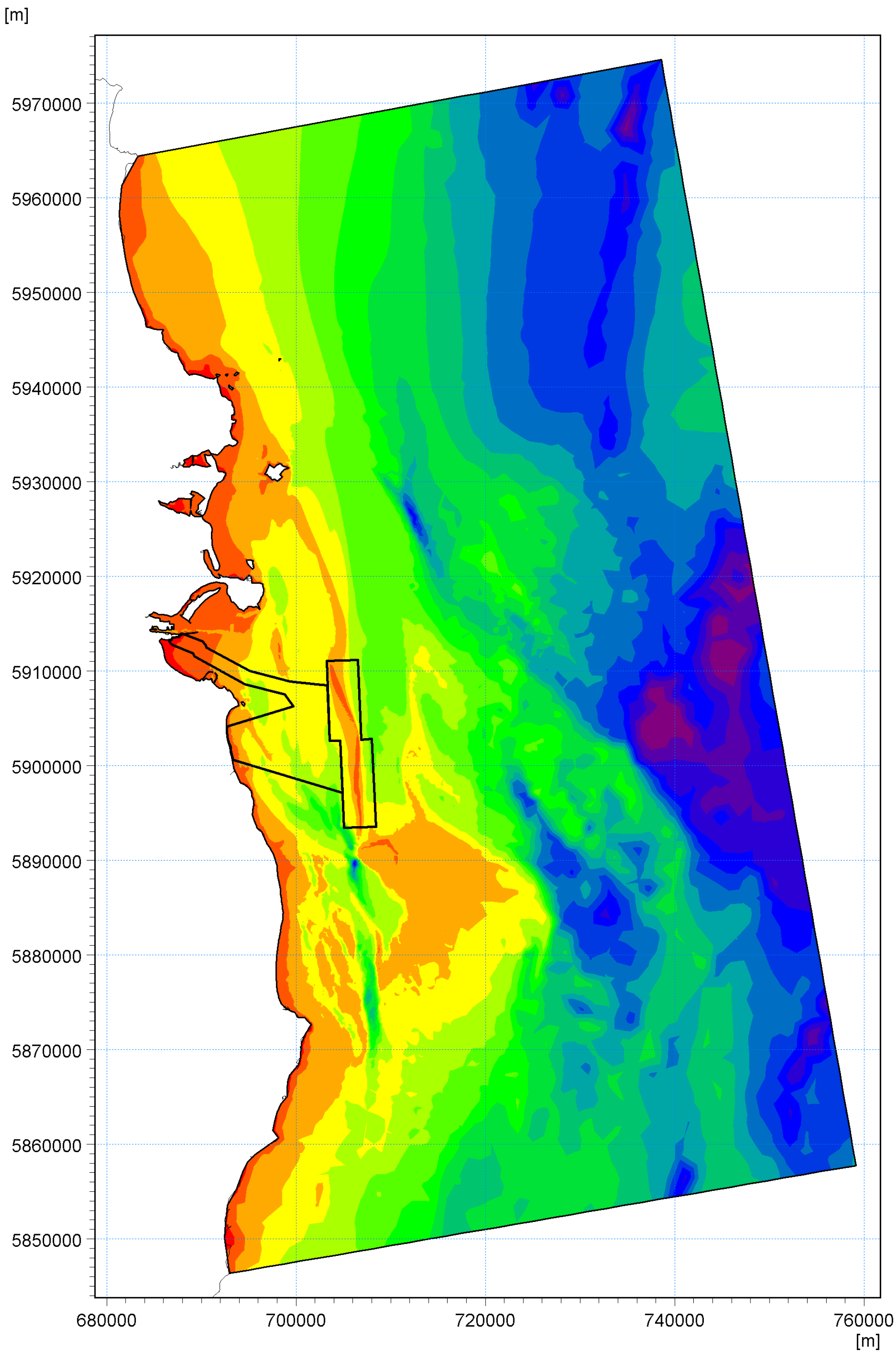
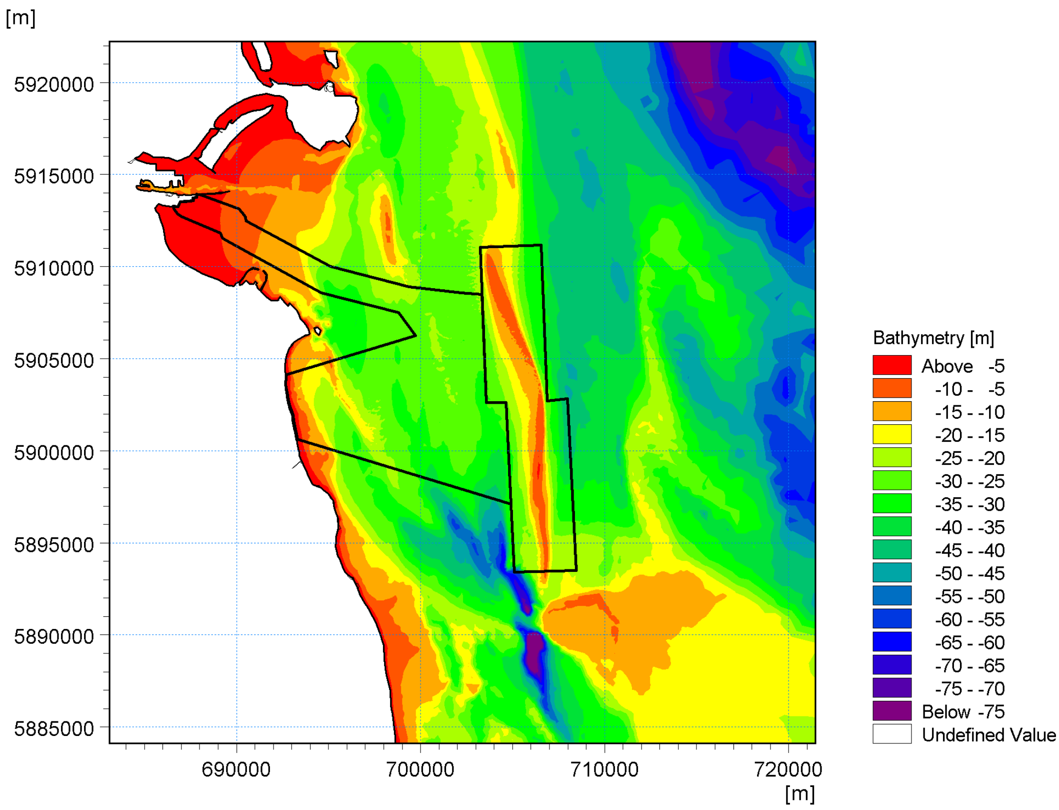


Figure 3-4 Hydrodynamic Model Bathymetry – proposed wind turbine area



3.3 Model Boundaries

3.3.1 Model Open Boundaries

The DAPPMS HD model is driven by spatially and temporally varying water level boundaries along its northern, eastern and southern edges. The land boundary has a zero normal velocity condition allowing water movement parallel to the coast. These offshore boundaries were located sufficiently far from the area of interest to eliminate potentially erroneous boundary effects that may occur within numerical models. No Coriolis forcing was applied within the model as its inclusion presented model instabilities at the model boundary. However, this still produces a robust model owing to the fact that this is a local model domain and not a wider body of water where Coriolis has more pertinence.

The source for boundary conditions for the DAPPMS HD model is DHI's MIKE21 Global Tidal Model. This has a horizontal resolution of 0.125° x 0.125°. The model includes the ten tidal constituents: M2, S2, K2, N2, S1, K1, O1, P1, Q1 and M4 (DHI, 2019), and is considered appropriate for providing boundary conditions for the DAPPMS HD model.

3.4 Model Parameters

3.4.1 Model Timestep

The flexible mesh model utilises a dynamically varying time step technique to optimise model run speed and model stability. A maximum time step of 30 seconds is used in the model, and a critical Courant-Friedrich-Levy number of 0.8 is applied to maintain the stability of the model.

All model runs are given an initial warm up period of at least 12 hours to allow water levels and current flow fields to stabilise.

3.4.2 Wind Forcing

The DAPPMS HD model was calibrated and validated for calm conditions, without applying wind forcing due to the HD model producing a purely tidal signal.

3.4.3 Eddy Viscosity

Eddy viscosity in the model is represented using a Smagorinsky formulation, a sub-grid scale eddy viscosity model. A typical Smagorinsky coefficient of 0.28 was adopted in the model (DHI, 2019).

3.4.4 River Flows

The River Liffey is the only river within the study area that could be hydrodynamically significant. Its mouth is also close to one of the potential cable landing sites, so it was included in the hydrodynamic model. The mean flow and a typical riverine velocity were used.

Table 3-2 River parameters

Parameter	Value
Name	River Liffey
Location of mouth	53.346, -6.229 (Latitude, Longitude)
Mean flow (m^3/s)	18 (OSPAR Commission,2004)
Velocity (m/s)	0.5

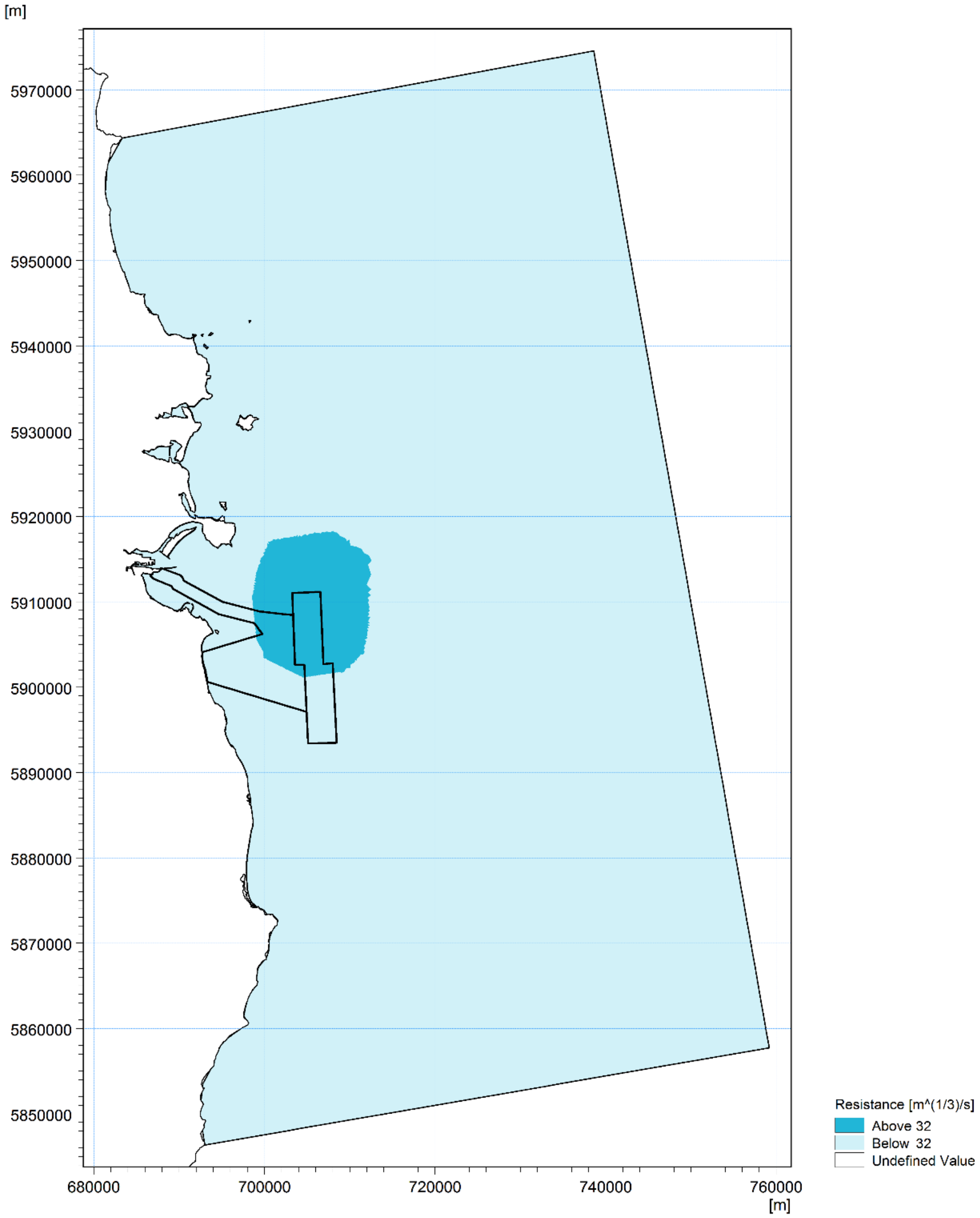
3.4.5 Bed Resistance

Bed resistance is one of the major factors that influence the hydrodynamics of a water body. This is represented in the hydrodynamic model by the Manning number, M ($m^{1/3}/s$) which is the inverse of the Manning coefficient, n. The Manning number may be entered as a single value over the entire model area, or as a bed resistance map corresponding to the model mesh.

Model calibration has been undertaken by fine tuning model parameters, to produce the optimum model performance when compared against field data. The primary means of HD calibration was by adjusting the bed resistance, as is standard practice. Results were compared with field data, taking note of differences in the magnitude and phasing of tidal height, current speed and direction. Successive iterations allowed the optimum bed resistance within the model mesh to be determined.

Figure 3-5 shows the final calibrated Manning number map of the DAPPMS HD model. A Manning number of 32 $m^{1/3}/s$ was used throughout the domain except for an area around the north of the Kish Bank. This area uses a Manning number of 40 $m^{1/3}/s$ to reduce the bed resistance, as current speeds in the area were underpredicted when compared to the field data otherwise.

Figure 3-5 Hydrodynamic Model Resistance map



4. MODEL CALIBRATION AND VALIDATION

4.1 Model Calibration and Validation Method

The hydrodynamic modelling component was calibrated and validated using metocean data identified in the data review and as outlined in Table 2-1 (See section 2).

Calibration of the HD model was undertaken by comparison of model predictions against measured field data for mean spring tidal conditions, between 18/09/2012 and 21/09/2012 with the afternoon of 20/09/2012 used as the most representative mean spring tide. Validation of the model was then undertaken against mean neap tidal conditions, occurring between 23/09/2012 to 26/09/2012, with the morning of the 25/09/2012 used as the most representative mean neap tide. Once the model has been calibrated and validated, it can be run for different time periods based on the same model parameters.

4.1.1 Calibration and Validation Metrics

Calibration was achieved by fitting the model output to the observed data by varying the calibration coefficients (such as bed resistance). The degree of fit between model and observations determined the level of model calibration; poor fit suggested poor calibration; good fit suggested good calibration. The degree of fit varies from location to location, depending on local conditions and how well these can be represented in the model.

Model fit to field data was assessed in two ways:

- visual comparison of the model output against observed data: the shape, trend, range and limits of model output and observed data;
- statistical comparison of the difference between observations and the model outputs to determine the frequency with which the model fits the measured data within defined limits, e.g. 80% of the model predictions are within 0.1 units or 10% of the observed value.

In practice both methods should be used, as no single method provides a full assessment of model performance.

Intertek assesses HD model performance using an approach developed from guidelines set out in the Foundation for Water Research Framework (FWR, 1993). The guidelines provide a good basis for assessing model performance statistically. However, Intertek's experience, gained from calibrating a wide range of models over many years, has shown that the statistical guidelines can sometimes be too prescriptive, particularly in situations of low tidal flow (<0.2 m/s) where:

- guidelines are either too easily achieved (if an absolute criterion, e.g. ± 0.1 m/s, is applied), or unachievable (if a relative criterion, e.g. ± 10% of observed speed, is applied);
- guideline error may be lower than the accuracy of the survey instrumentation (a 10% error would equate to 0.02 m/s or less, which is close to the resolution of most current meters);
- natural background noise and instrument noise may partially, or completely, mask the tidal signature in the observed data, in which case there is no reasonable way to determine if the model is calibrated (other than through the general observation that it predicts the low current speeds indicated by measurements).

It is generally very difficult to meet a current direction standard of <15°, particularly in coarser mesh areas or where instruments and measuring techniques cannot resolve direction to this level of accuracy. A directional range of ± 30° is considered more appropriate.

Phase difference is a measure of the timing between the measured and modelled data. It is calculated by assessing whether the modelled data is leading (positive phase error) or lagging (negative phase error). Under certain conditions, models can meet statistical calibration standards, but, on visual inspection, appear to perform poorly. Conversely, seemingly accurate models can fall short of the statistical guidelines. Guidelines alone should not be used when assessing the overall performance and acceptability of the model, and it is necessary for experienced modellers/oceanographers to offer a critical assessment of model performance taking all the available information into account.

The DAPPMS HD model performance was measured against the FWR metrics given in Table 4-1 (FWR, 1993).

Table 4-1 Metrics for DAPPMS HD Model Calibration and Validation

Parameter	Tolerance Applied	
	Absolute	Relative
Water Level	± 0.1 m	± 10-15%
Current Speed	± 0.1 m/s in coastal areas or ± 0.2 m/s in estuaries	± 20%
Current Direction	± 30°	N/A

A statistical analysis of model fit requires that the tolerances in Table 4-1 are achieved over the majority of the calibration or validation period. If either the absolute or the relative tolerance is achieved, the model is considered to meet the performance criteria. It is unlikely that these tolerances will be achieved throughout the entire calibration or validation period, as there will inevitably be some factors that cannot be fully accounted for in the model numerical scheme, input data and calibration coefficients, particularly in shallow coastal waters. However, model calibration and validation should seek to achieve these tolerances over the majority of the position/time combinations evaluated. In an effort to qualify the level of calibration or validation, and allow comparison between sites, a qualitative scale of model-to-data fit is adopted. This comparative scale is based on the frequency with which tolerance criteria are achieved (see Table 4-2).

Table 4-2 Goodness of Fit for HD Calibration and Validation

Goodness of Fit	% of time tolerance is achieved
Excellent	>90%
Very Good	>80%
Good	>70%
Reasonable	>60%

4.2 Model Calibration and Validation Results

4.2.1 Water Level Results

The DAPPMS HD model has been calibrated against tidal water level data collected during surveys at the Kish Bank and at tidal gauges and Admiralty ports at sites along the western edge of the Irish Sea. The locations of the tidal gauges are shown in Figure 2-2 in Section 2.2. Water level data under spring tides in 2012 have been used to evaluate the fitness of the model.

Comparison plots between model predictions and field data are given in section A.1.1 in Appendix A. The figures show the model calibration performance against water levels under spring tides. A summary of the statistical analysis of model fit and visual analysis of the calibration plots is provided in Table 4-3. Percentage fit is presented after the reported phase difference has been accounted for. The results of the water level calibration are discussed in Section 5.1.

Table 4-3 Summary of model fit with calibration data: water level

Location	Figure Number	Phase difference (min)	% Fit	Evaluation
Arklow	A-1	6	73%	Excellent fit visually for tidal water levels and phase for mid tide and below. Good statistical fit. Model over-predicts high water levels, potentially due to additional constituents being required to resolve the unusual tidal curve in the area. NB. This location is close to the model boundary and not close to the main area of interest.
Dublin Port	A-2	-36	100%	Excellent fit visually and statistically, with tidal range and phase being well predicted by the model.
Dun Laoghaire	A-3	-41	100%	Good fit visually, with tidal range being well predicted by the model. Excellent statistical fit.
Howth Harbour	A-4	-20	100%	Excellent fit statistically and visually, with tidal range and phase being well predicted by the model.
JN1163 North	A-5	-105	87%	Reasonable fit visually and very good statistical fit. Model over-predicts tidal range. Phase difference of approximately 1.5 hours.
JN1163 South	A-6	-96	100%	Good fit visually and excellent statistical fit, with tidal range well predicted. Phase difference of approximately 1.5 hours
Kish Bank Lighthouse	A-7	16	99%	Excellent fit visually and statistically, with tidal range and phase being well predicted by the model. NB. Kish Bank Lighthouse is very close to JN1163 North but the observational data at these two locations are not in phase.
Malahide	A-8	-47	100%	Good fit visually and excellent statistical fit, with tidal range being well predicted by the model.
River Boyne Bar	A-9	-4	100%	Excellent fit visually and statistically, with tidal range and phase being well predicted by the model.
Wicklow	A-10	-47	77%	Good fit visually and good statistical fit with tidal range and phase. Model over-predicts tidal range and has increased asymmetry than the harmonic prediction.

After the completion of model calibration, the calibrated DAPPMS HD model was validated against tidal water level data under neap tides, at the same sites as used for the model calibration (see Figure 2-2 for locations). Comparison plots between model predictions and field data are given in Section A.1.2 in Appendix A. The figures show the model validation performance against water level during neap tides.

A summary of the statistical analysis of model fit and visual analysis of the validation plots is provided in Table 4-4. Percentage fit is presented after the reported phase difference. The results of the water level validation are discussed in Section 5.1.

Table 4-4 Summary of model fit with validation data: tidal water level

Location	Figure Number	Phase difference (min)	% Fit	Evaluation
Arklow	A-11	-25	81%	Very good statistical fit. Reasonable fit visually with tidal range and phase. Model tidal curve is more asymmetric than the harmonic prediction.
Dublin Port	A-12	-43	100%	Excellent statistical fit. Reasonable fit visually with tidal range and phase. Model under-predicts tidal range.

Location	Figure Number	Phase difference (min)	% Fit	Evaluation
Dun Laoghaire	A-13	-54	100%	Excellent statistical fit. Good fit visually, with tidal range being well -predicted by the model.
Howth Harbour	A-14	-28	100%	Excellent statistical fit. Good fit visually, with tidal range and phase being well -predicted by the model.
JN1163 North	A-15	-103	97%	Excellent statistical fit. Reasonable fit visually. Model over-predicts tidal range. Phase difference of approximately 1.5 hours.
JN1163 South	A-16	-100	96%	Excellent statistical fit. Good fit visually with tidal range. Phase difference of approximately 1.5 hours.
Kish Bank Lighthouse	A-17	-4	70%	Good fit visually, with tidal range and phase being well -predicted by the model. Reasonable statistical fit. Period of over-prediction by the model coincides with a period of increased variability in the field data.
Malahide	A-18	-49	100%	Good fit visually, with tidal range being well -predicted by the model. Excellent statistical fit.
River Boyne Bar	A-19	-11	100%	Excellent fit visually and statistically, with tidal range and phase being well predicted by the model.
Wicklow	A-20	-69	98%	Good fit visually, with tidal range being well -predicted by the model. Excellent statistical fit.

4.2.2 Current Speed and Direction Results

The DAPPMS HD model has been calibrated against current data collected during surveys at the Kish Bank and at sites in the Irish Sea. The locations of the current meters are shown in Figure 2-2 in Section 2.2. Current data under spring tides in 2012 have been used to evaluate the fitness of the model.

Comparison plots between model predictions and field data are given in section A.2.1 in Appendix A. The figures show the model calibration performance against current speed (top) and current direction (bottom) under spring tides.

A summary of the statistical analysis of model fit and visual analysis of the calibration plots is provided in Table 4-5. Percentage fit is presented after the reported phase difference has been accounted for. The results of the current speed and direction calibration are discussed in Section 5.2.

Table 4-5 Summary of model fit with calibration data: current speed and direction

Location	Figure Number	Phase difference (min)	% Fit		Comments
			Speed	Direction	
B014751	A-21	-4	59%	81%	Good fit visually for speeds and directions, and phasing. Model over-predicts speeds during the flood. Very good statistical fit for directions. Borderline reasonable statistical fit for speeds.
B014738	A-22	-12	59%	80%	Good fit visually for speeds and directions and phasing. Model over-predicts speeds during the flood. Very good statistical fit for directions. Borderline reasonable statistical fit for speeds.
JN1163 North	A-23	-78	68%	60%	Reasonable fit visually and statistically for speeds, ebb/flood asymmetry is mirrored. Directions are reasonable during periods of increased current speeds, but the model rotates in the opposite direction to the harmonic prediction during the turn of the tide. Phase difference of approximately 1.5 hours.
JN1163 South	A-24	-119	57%	78%	Reasonable fit visually for speeds despite slight over-prediction by model. Good fit visually and statistically for directions. Poor statistical fit for

Location	Figure Number	Phase difference (min)	% Fit		Comments
			Speed	Direction	
					speeds. Phase difference of approximately 1.5 hours. See note on data quality in Section 2.3.4.

After the completion of model calibration, the calibrated DAPPMS HD model was validated against current data during neap tides, at the same sites as used for the model calibration (see Figure 2-2 for locations). Comparison plots between model predictions and field data are given in Section A.1.2 in Appendix A. The figures show the model validation performance against current speed (top) and current direction (bottom) during neap tides.

A summary of the statistical analysis of model fit and visual analysis of the validation plots is provided in Table 4-6. Percentage fit is presented after the reported phase difference has been accounted for. The results of the current speed and direction validation are discussed in Section 5.2.

Table 4-6 Summary of model fit with validation data: current speed and direction

Location	Figure Number	Phase difference (min)	% Fit		Comments
			Speed	Direction	
B014751	A-25	-14	81%	88%	Good fit visually with speeds and phasing well-predicted by the model. Very good statistical fit. The model directions are inaccurate at low speeds.
B014738	A-26	-26	69%	81%	Good fit visually with speeds well-predicted by the model. Very good statistical fit for directions. Reasonable statistical fit for speeds. The model directions are inaccurate at low speeds.
JN1163 North	A-27	-27	61%	61%	Reasonable fit visually and statistically for speeds despite slight over-prediction by model. Directions are ok during periods of increased current speeds, but the model rotates in the opposite direction to the harmonic prediction during the turn of the tide.
JN1163 South	A-28	-54	59%	88%	Reasonable fit visually for speeds despite slight over-prediction by model. Good fit visually and statistically for directions. Borderline reasonable statistical fit for speeds.

4.2.3 Additional Current Validation

Additional validation of the performance of the currents in the HD model was undertaken at JN1163 C1 and C2 and at the tidal diamonds specified in section 2.2. A statistical analysis was not performed on these datasets owing to the short duration of the datasets and for the tidal diamonds in particular, uncertainty in the precision of the dataset (See Section 2.2).

A summary of the visual analysis of the model performance during the calibration period is provided in Table 4-7. The phase difference at the tidal diamonds is given to the nearest 15 minutes due to the precision of the dataset. The closest tidal diamond to the OWF site is SN062B. The results of the current speed and direction validation are discussed in Section 5.2.

Table 4-7 Summary of model fit during calibration period: tidal diamonds

Location	Figure Number	Phase difference (min)	Comments
JN1163 C1	A-29	-87	Good fit visually and statistically for speeds and directions. Phase difference of approximately 1.5 hours.

Location	Figure Number	Phase difference (min)	Comments
JN1163 C2	A-30	-108	Reasonable fit visually for speeds and directions. Tidal asymmetry is not as pronounced in the model. Phase difference of approximately 1.5 hours.
SN061C	A-31	-60	Reasonable fit on current speeds, with the model under-predicting peak current speeds by 0.3m/s. Good fit on directions. The model predicts a more circular motion than the tidal diamond, including not recreating the slack waters predicted.
SN062A	A-32	-45	Poor fit for current speeds, with the model under-predicting the peaks by up to 0.7m/s. Good fit for directions with the model motion slightly more circular than the tidal diamond.
SN062B	A-33	45	Reasonable fit for current speeds. Model has more pronounced tidal asymmetry than the tidal diamond. Excellent fit for directions.
SN062C	A-34	0	Excellent fit for speeds and directions.
SN062D	A-35	30	Reasonable fit for current speeds, with the model producing a more pronounced ebb/flood inequality than the tidal diamond. Excellent fit for directions.
SN062F	A-36	15	Good fit for current speeds with the model over-predicting by 0.3m/s on the flood tide. Excellent fit for directions.
SN062G	A-37	30	Good fit for current speeds with the model over-predicting by 0.3m/s on the flood tide. Good fit for directions.

A summary of the visual analysis of the model performance at the tidal diamonds during the validation period is provided in Table 4-8.

Table 4-8 Summary of model fit during validation period: tidal diamonds

Location	Figure Number	Phase difference (min)	Comments
SN061C	A-38	-75	Good fit for current speeds and directions. The model predicts a more circular motion than the tidal diamond, not recreating the slack waters indicated by the tidal diamond.
SN062A	A-39	-60	Good fit for current speeds and directions. The model motion is slightly more circular than the tidal diamond.
SN062B	A-40	15	Good fit for current speeds. Model has more pronounced tidal asymmetry than the tidal diamond. Excellent fit for directions.
SN062C	A-41	-60	Excellent fit for speeds and directions.
SN062D	A-42	-30	Reasonable fit for current speeds, with the model producing a more pronounced ebb/flood inequality than the tidal diamond. Excellent fit for directions.
SN062F	A-43	0	Good fit for current speeds with the model over-predicting by 0.3m/s on the flood tide. Excellent fit for directions.
SN062G	A-44	0	Good fit for current speeds with the model over-predicting by 0.3m/s on the flood tide. Good fit for directions.

5. DISCUSSION

The statistical analysis and visual inspection of the model performance of tidal water levels and current velocities shows good agreement with measured data at most sites. This indicates that the fundamental hydrodynamics of the area are generally well represented by the model.

The model has a good fit and phasing at Arklow, the River Boyne Bar and the Kish Bank Lighthouse. These sites are near the southern and northern boundaries and in the middle of the domain near the study site respectively, so provide a good indication that the model is working acceptably in these areas and between them. Whilst the model is 1.5 hours out of phase at JN1163 North and South, it is in phase at the Kish Bank Lighthouse, 3.2 km away. Given the uncertainty in the field data for the JN1163 sites, it is likely some of this phase difference relates to that. In general, whilst there are varying phase differences across the model domain, phase is not a key output from the model for assessing physical processes. Therefore, the model is considered an appropriate and robust tool to inform the EIA.

5.1 Water levels

The majority of the water level sites show good model performance, with a good level of calibration and validation across the model domain. The magnitude and shape of the tidal curve is well represented at all sites. However, as noted above, there are varying phase differences at many of the sites, in particular at the four JN1163 sites. The cause of these is likely to be associated with the timing of the field data (all was assumed to be in GMT in absence of any other information). However, the exact phase of the modelled tide is much less important for a physical processes assessment as part of an EIA than the magnitude and shape of the tidal range. As such, the tidal wave being up to two hours early in the model is not considered to impair the modelling assessment.

The differences between the field data and model at Kish Bank Lighthouse during the validation period are mostly due to issues with the field data, which shows a very noisy signal, indicating a potential issue with the instrument, or other non-tidal signal. However, the general shape, magnitude and phasing of the modelled predictions are in good agreement. There is a significant non-tidal signal and increased noise in the field data during this period. Usually these would be removed during harmonic analysis of the dataset but the tide gauge at the lighthouse does not accurately record water level below -1.6 mMSL so the dataset cannot be harmonically analysed. As there is an excellent fit at the lighthouse during the calibration period when the field data is of better quality, the performance of the model at the site is considered suitable for the requirements of the EIA.

5.2 Currents

Whilst a number of the sites have a reasonable fit under the statistical analysis, visual inspection shows that the range of current speeds is generally good. The model does overestimate the tidal asymmetry in the area. The sites in the outer part of the model domain tend to be over-estimated during the flooding northwards flow by 0.2-0.3 m/s. However, the key sites near the array (e.g. JN1163 North, South, C1 and C2) have a reasonable fit for both speeds and directions. Visually, the range of current speeds is within the range of the field data. These key sites have a similar percentage fit for directions as well. As such, the model is considered to have a reasonable calibration in this area.

Whilst the currents at the sites on the bank rotate in the opposite direction to the field data during the calibration period, the majority rotate in the same direction as the field data during the validation period. This difference occurs during periods of low current speeds, which only occur for around one fifth of the tidal cycle. It is not expected to noticeably affect the transport of sediment and, as such, is not considered to impair the performance of the model for the purpose of the EIA physical processes assessment.

At the two sites on the bank, JN1163 North and South, there are different phase differences for currents and for water levels. This means that the peak tidal currents in the model occur at a different time relative to high and low water than in the field data. . However, the difference in phase differences is fairly minor and tidal phase is not a significant parameter for physical process modelling anyway. There is a reasonable fit, however, for the key parameters of water level, current speed and current direction.

As the precision of the tidal diamonds is within 30 minutes, the majority of the phase differences for the calibration and validation at these sites fall within the tolerance of the dataset so are negligible. There is a good fit for current speed, direction and phase at the tidal diamond nearest the site.

6. CONCLUSION

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

The DAPPMS HD model has been calibrated and validated against field measurements of water level and current velocity from a variety of sources. The calibration and validation data include:

- water level and velocity from bed mounted ADCP deployments undertaken in 2012 at the array site;
- water level data from the Irish Tide Gauge network;
- water level data from the Admiralty Tide Tables;
- velocity data from BODC for the outer part of the model domain; and
- velocity data from tidal diamonds from Admiralty charts.

Overall, the model achieves a reasonable level of calibration and validation. There is generally a good agreement between measured and modelled water levels and currents.

For the sites on the bank, the currents rotate the opposite way at some states of the tide and at some locations when compared to the observed data. However, the difference in current direction (between the model and field data) only occur at low speeds, and so a short period of the tidal cycle. Therefore, this difference is not anticipated to affect the performance of the model in terms of replicating the tidal currents and the associated transport of materials. Whilst there are varying phase differences across the model domain, phase is not considered a key output from the model as the proposed use of the model (i.e. assessing the potential impacts from the OWF and associated activities) does not rely on it. The phase differences are due to a combination of issues, including potentially uncertainty in timing of the field data.

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

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APPENDIX A

Hydrodynamic Model Calibration and Validation Plots

A.1 WATER LEVEL CALIBRATION AND VALIDATION PLOTS

A.1.1 Water Level Calibration Plots

Figure A-1 Model calibration performance against water level: Arklow

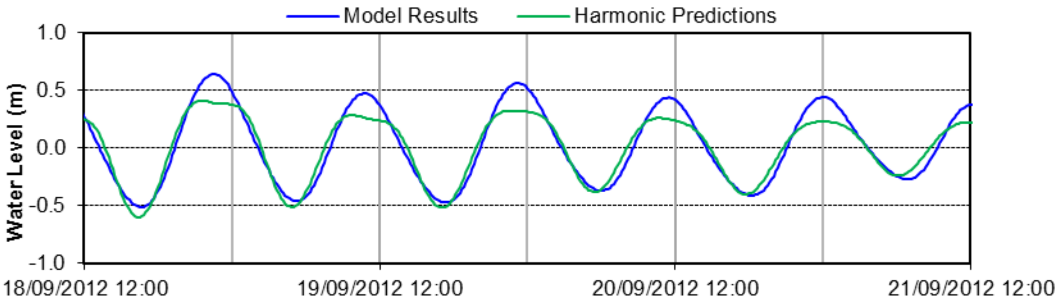


Figure A-2 Model calibration performance against water level: Dublin Port

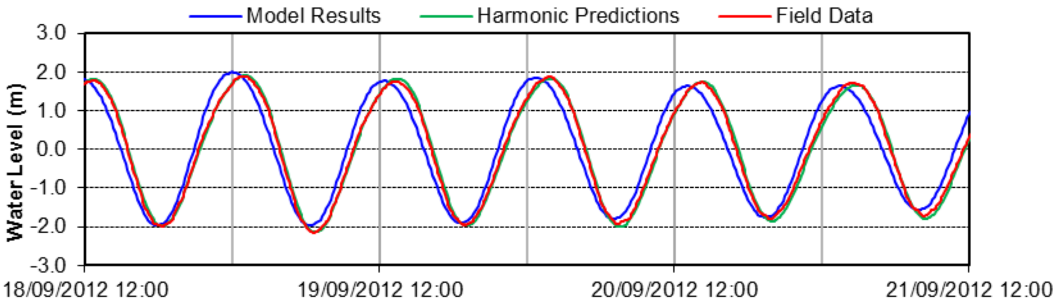


Figure A-3 Model calibration performance against water level: Dun Laoghaire

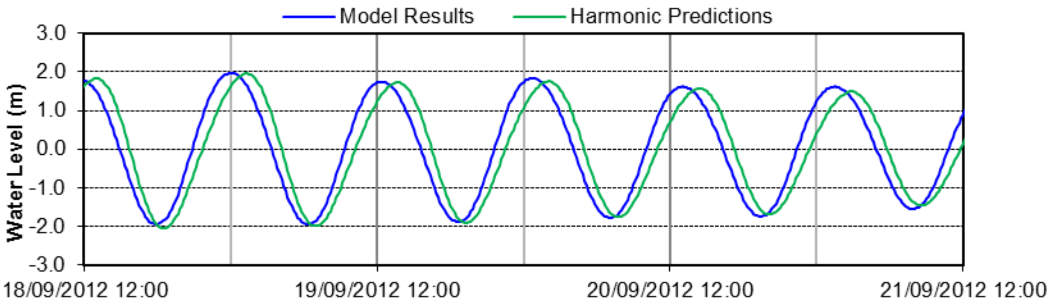


Figure A-4 Model calibration performance against water level: Howth Harbour

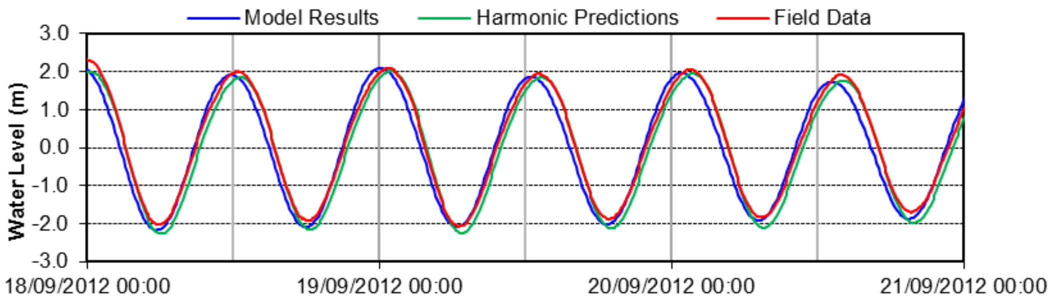
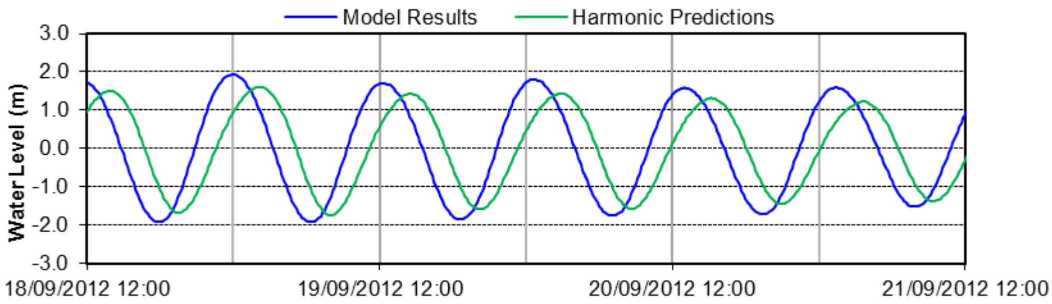
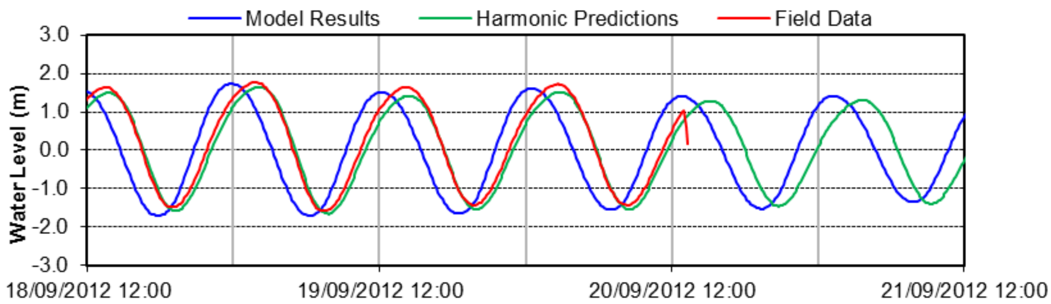


Figure A-5 Model calibration performance against water level: JN1163 North



Note: The phase difference between the model and the harmonic prediction is discussed in Section 2.3.

Figure A-6 Model calibration performance against water level: JN1163 South



Note: The phase difference between the model and the harmonic prediction is discussed in Section 2.3.

Figure A-7 Model calibration performance against water level: Kish Bank Lighthouse

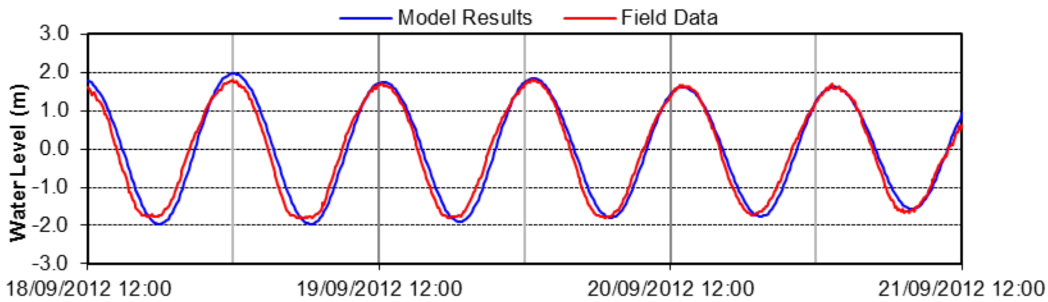


Figure A-8 Model calibration performance against water level: Malahide

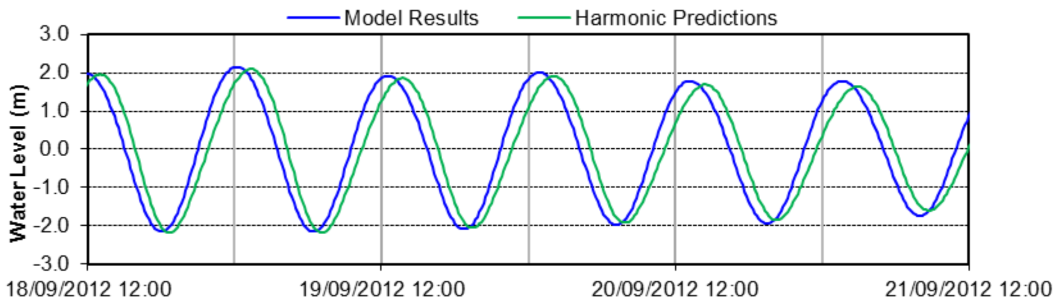


Figure A-9 Model calibration performance against water level: River Boyne Bar

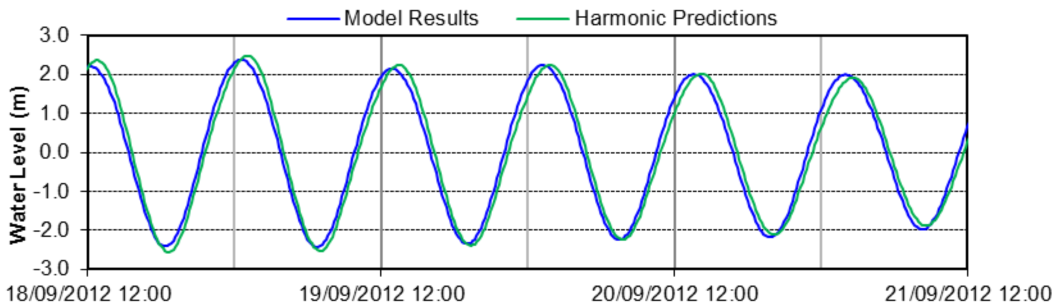
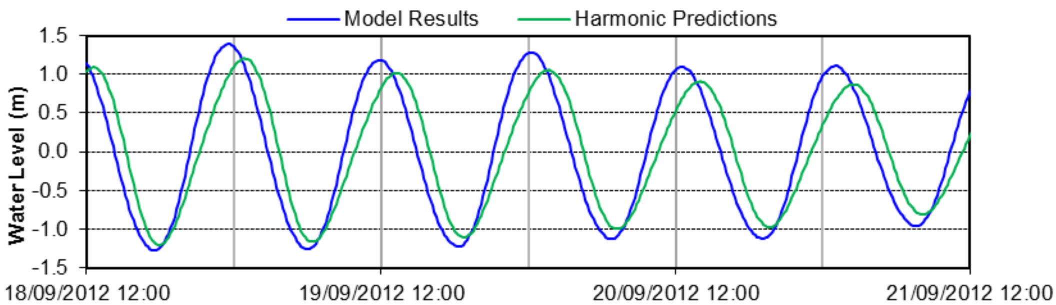


Figure A-10 Model calibration performance against water level: Wicklow



Note: The phase difference between the model and the harmonic prediction is discussed in Section 2.3.

A.1.2 Water Level Validation Plots

Figure A-11 Model validation performance against water level: Arklow

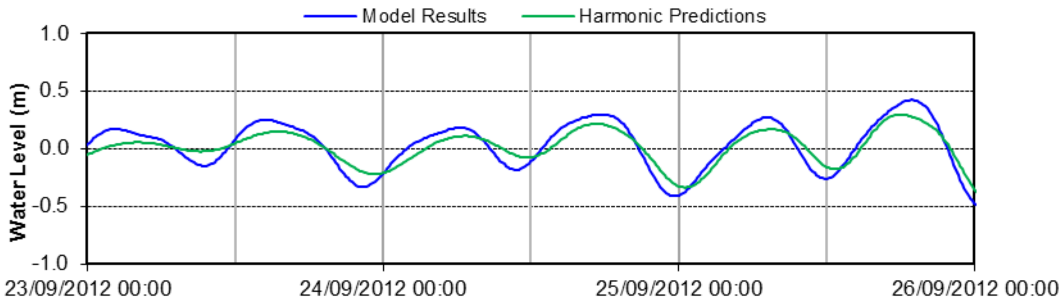


Figure A-12 Model validation performance against water level: Dublin Port

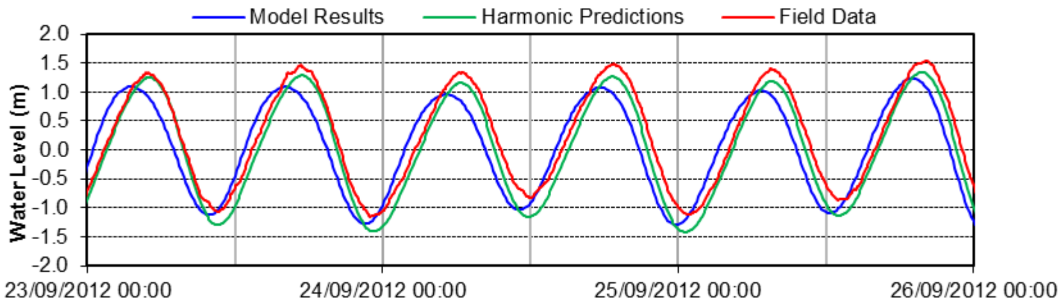


Figure A-13 Model validation performance against water level: Dun Laoghaire

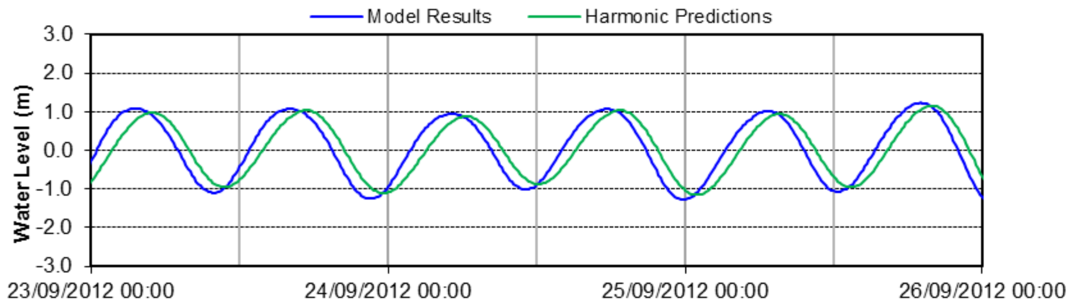


Figure A-14 Model validation performance against water level: Howth Harbour

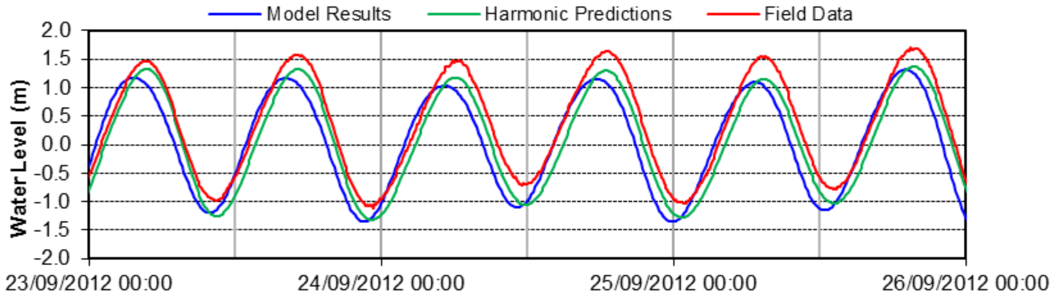
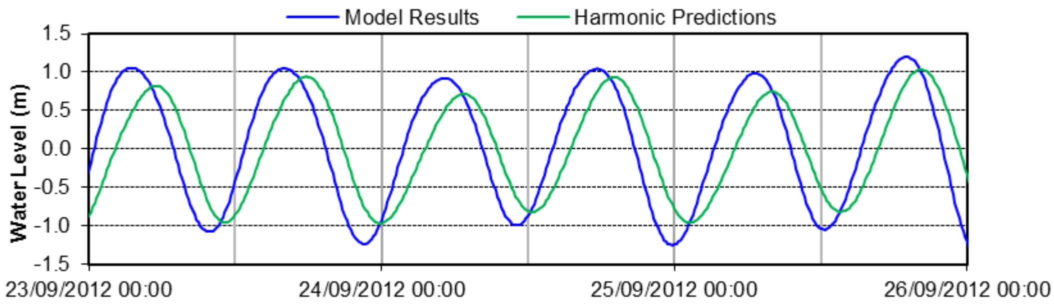
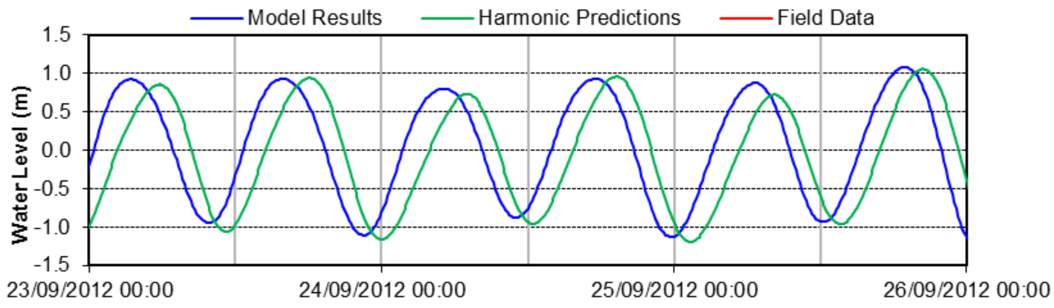


Figure A-15 Model validation performance against water level: JN1163 North



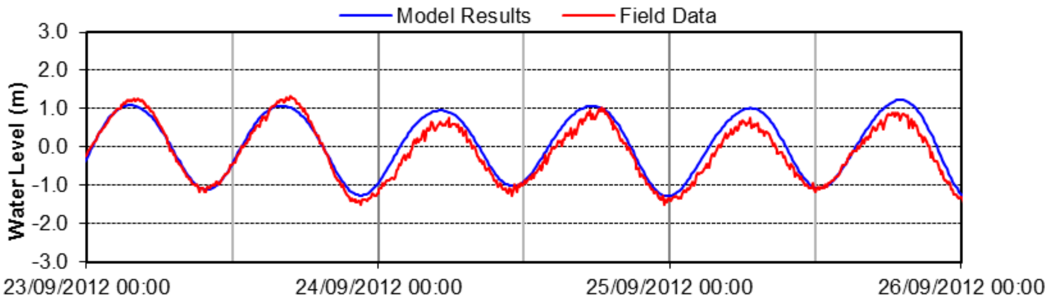
Note: The phase difference between the model and the harmonic prediction is discussed in Section 2.3.

Figure A-16 Model validation performance against water level: JN1163 South



Note: The phase difference between the model and the harmonic prediction is discussed in Section 2.3.

Figure A-17 Model validation performance against water level: Kish Bank Lighthouse



Note: The noise in the field data is discussed in Section 2.3.

Figure A-18 Model validation performance against water level: Malahide

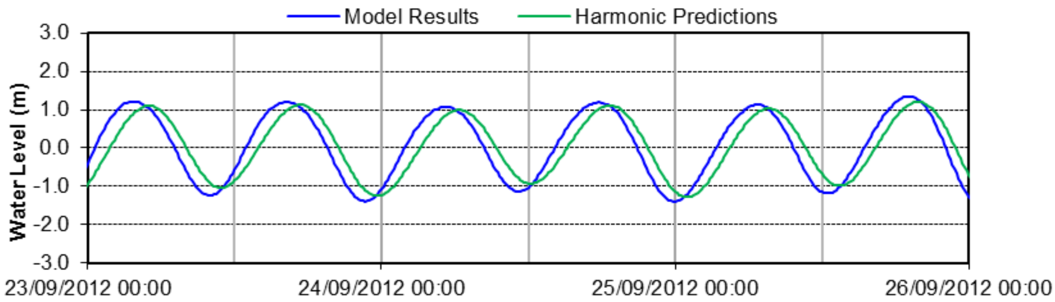


Figure A-19 Model validation performance against water level: River Boyne Bar

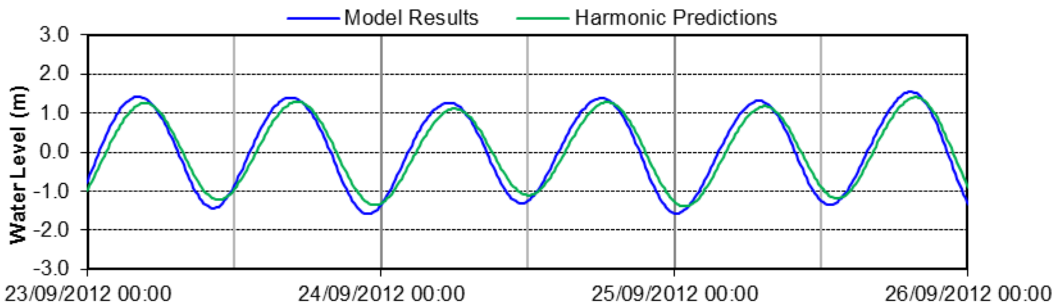
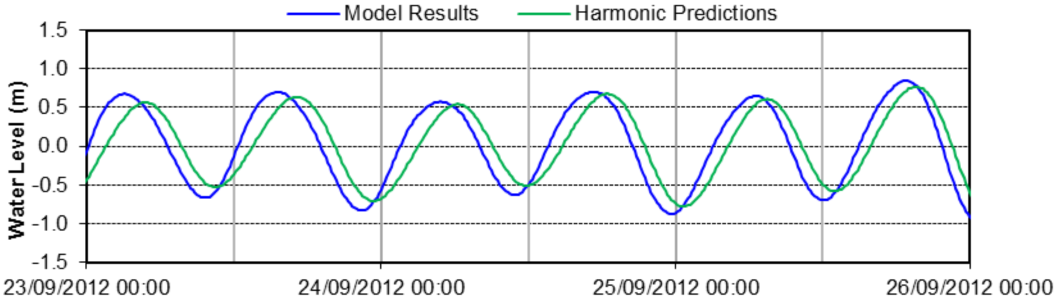


Figure A-20 Model validation performance against water level: Wicklow



A.2 CURRENTS CALIBRATION AND VALIDATION PLOTS

A.2.1 Current calibration plots

Figure A-21 Model calibration against current data: B014751

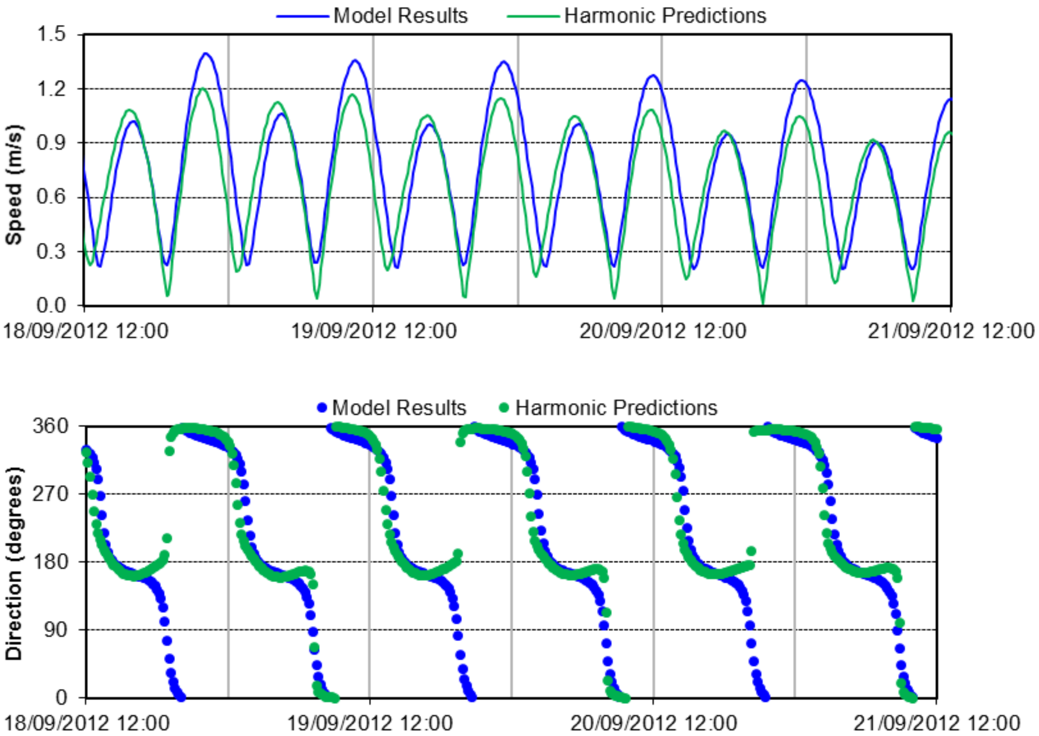


Figure A-22 Model calibration against current data: B014738

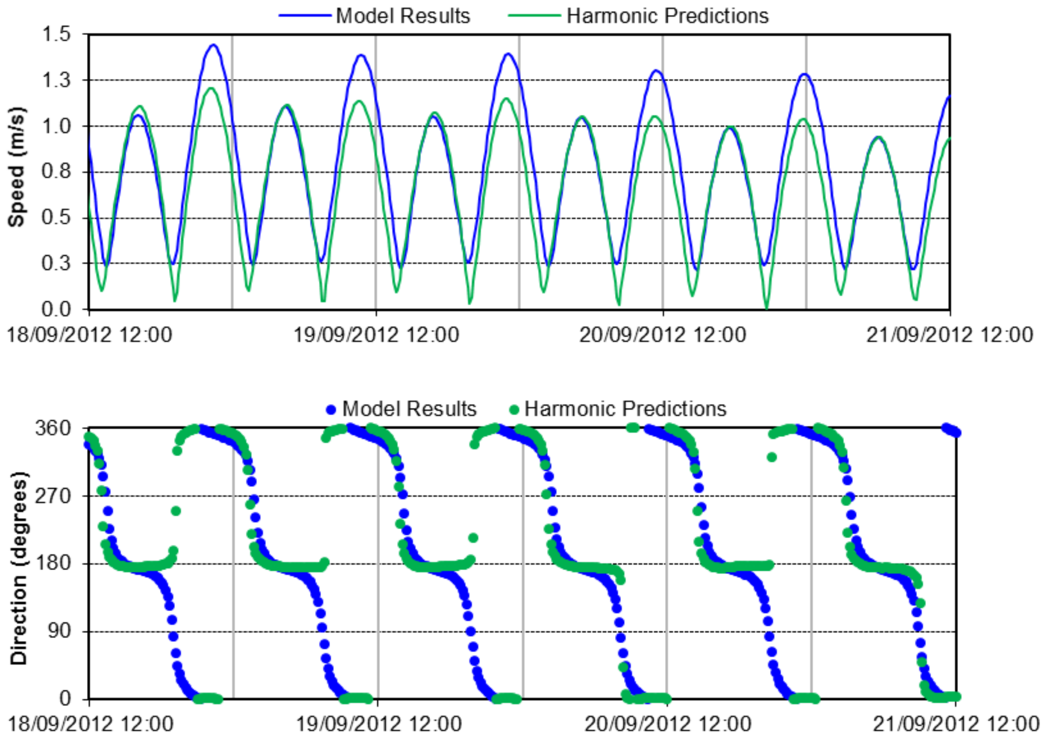
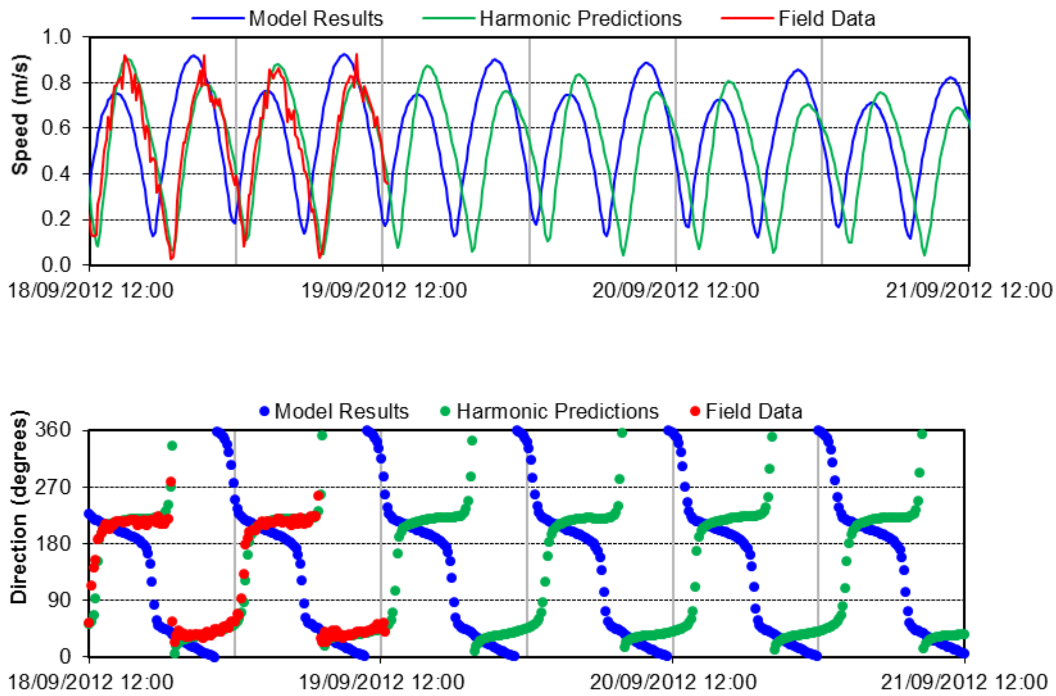
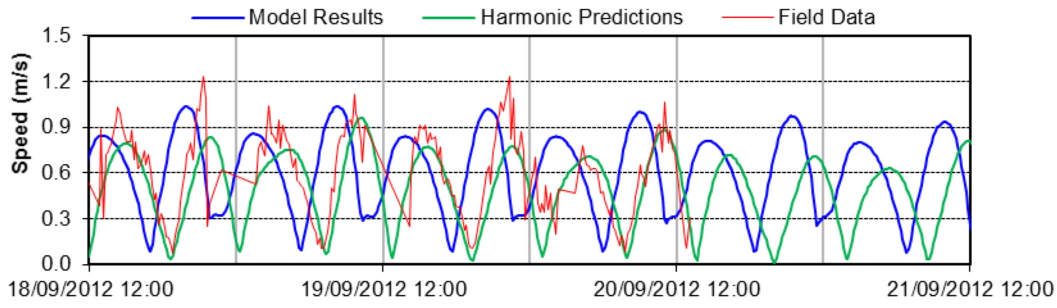


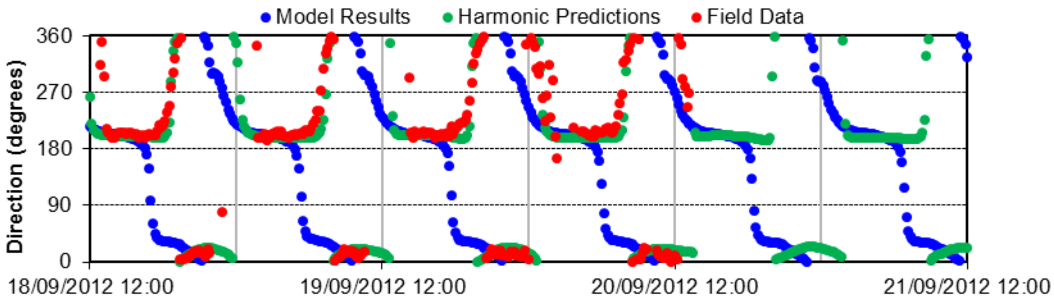
Figure A-23 Model calibration against current data: JN1163 North



Note: The phase and direction differences between the model and the harmonic prediction are discussed in Section 2.3.

Figure A-24 Model calibration against current data: JN1163 South

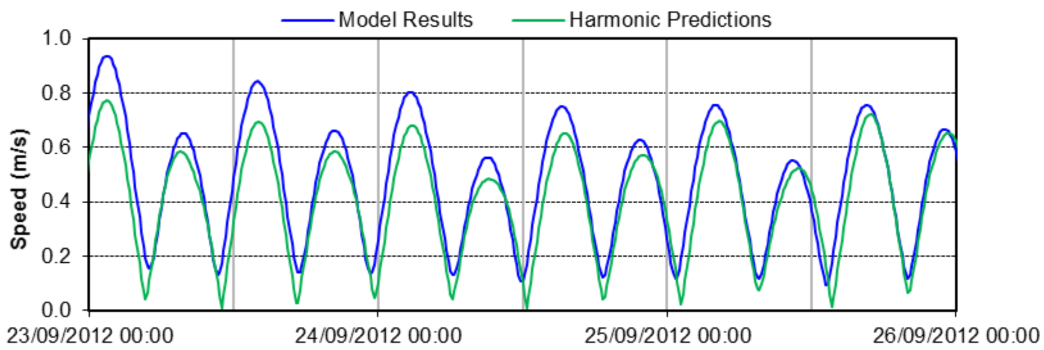




Note: The phase and direction differences between the model and the harmonic prediction are discussed in Section 2.3.

A.2.2 Current Validation Plots

Figure A-25 Model validation against current data: B014751



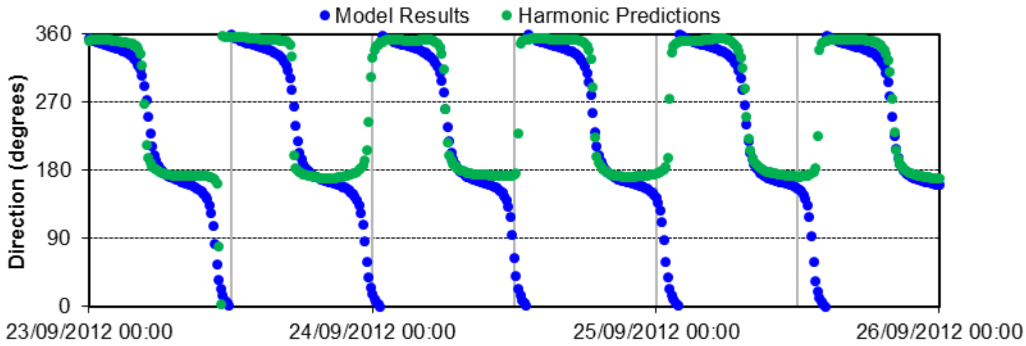
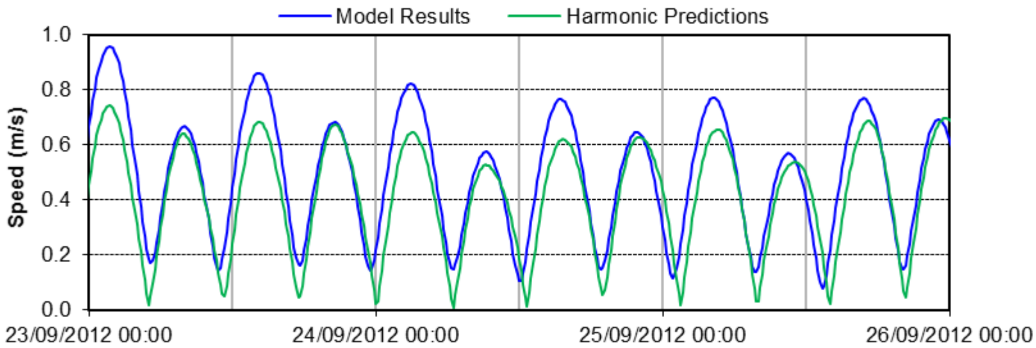


Figure A-26 Model validation against current data: B014738



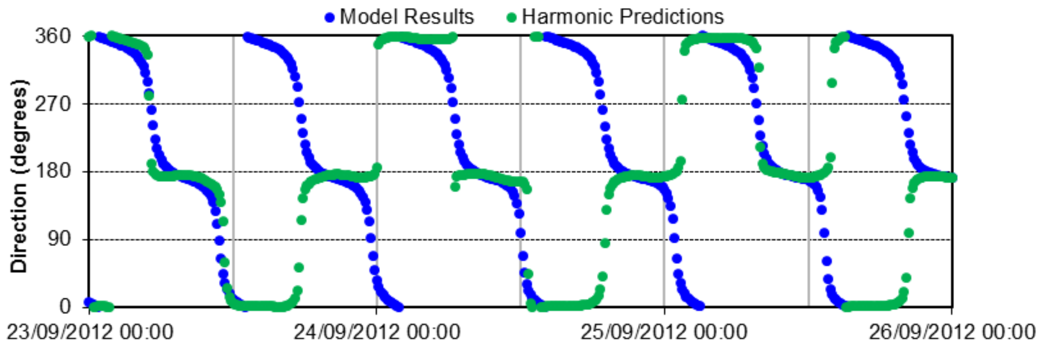
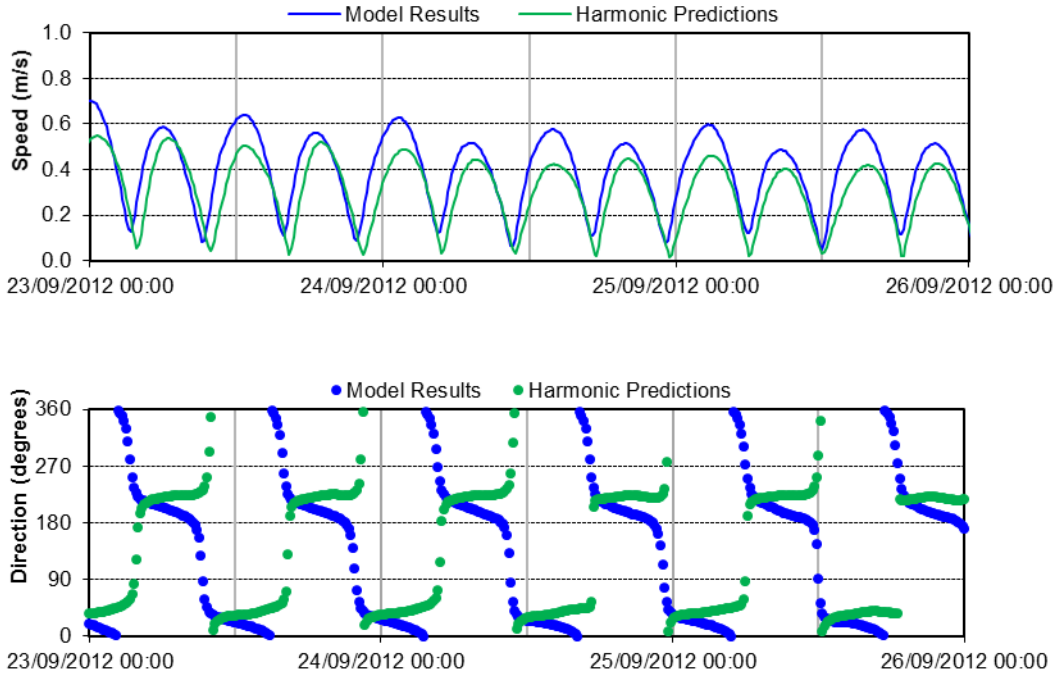
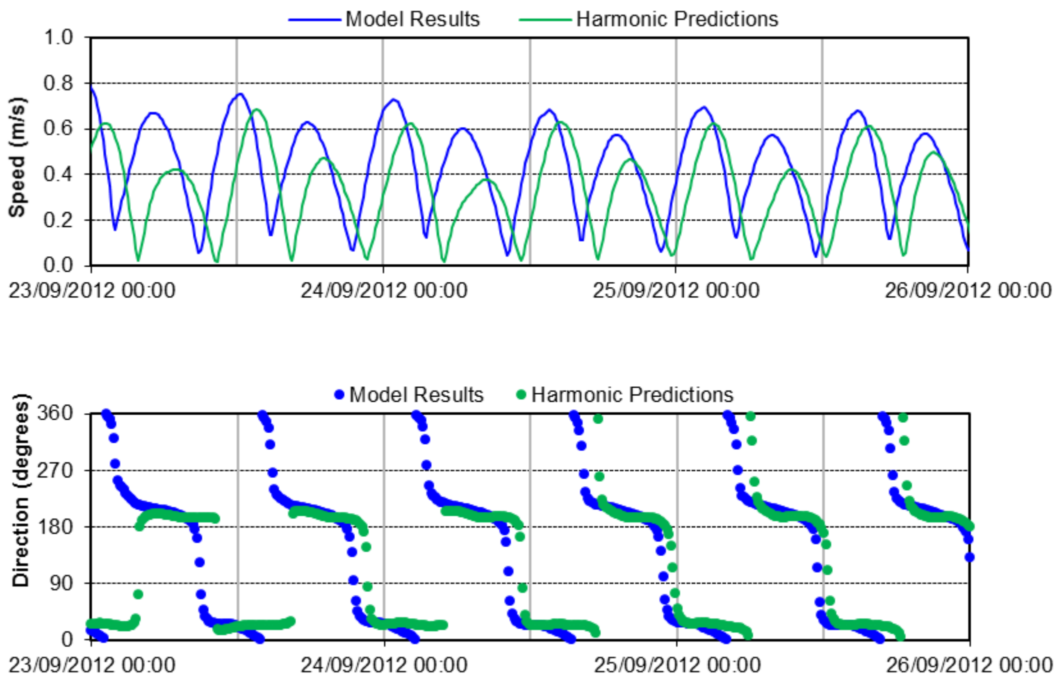


Figure A-27 Model validation against current data: JN1163 North



Note: The phase and direction differences between the model and the harmonic prediction are discussed in Section 2.3.

Figure A-28 Model validation against current data: JN1163 South



Note: The phase and direction differences between the model and the harmonic prediction are discussed in Section 2.3.

A.2.3 Additional Current Validation Plots

Figure A-29 Model fit during calibration period: JN1163 C1

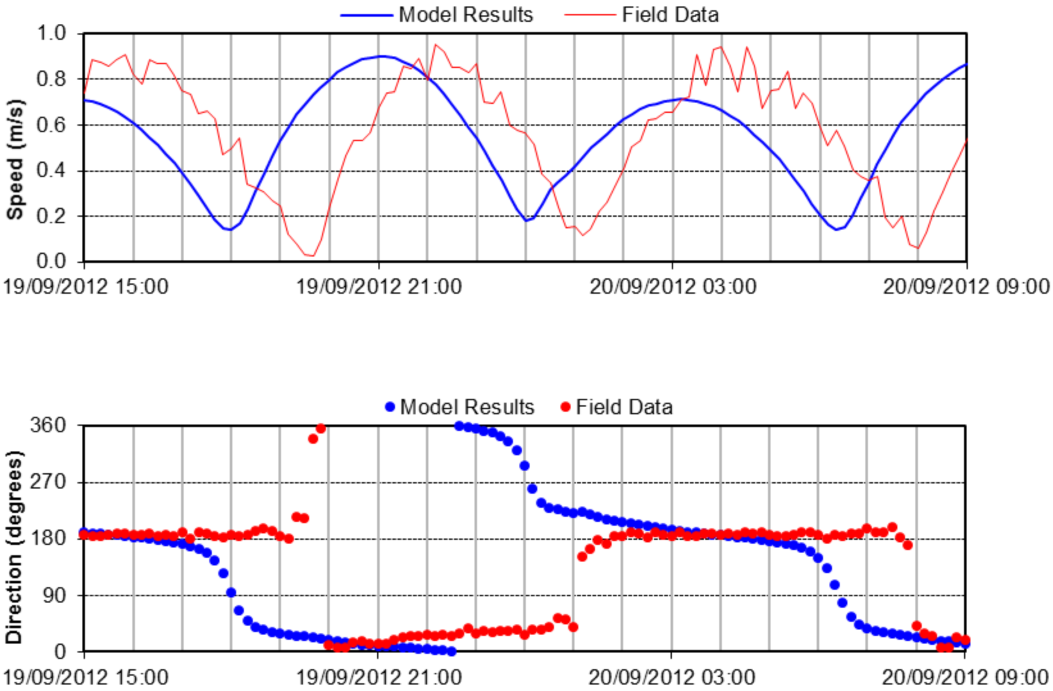


Figure A-30 Model fit during calibration period: JN1163 C2

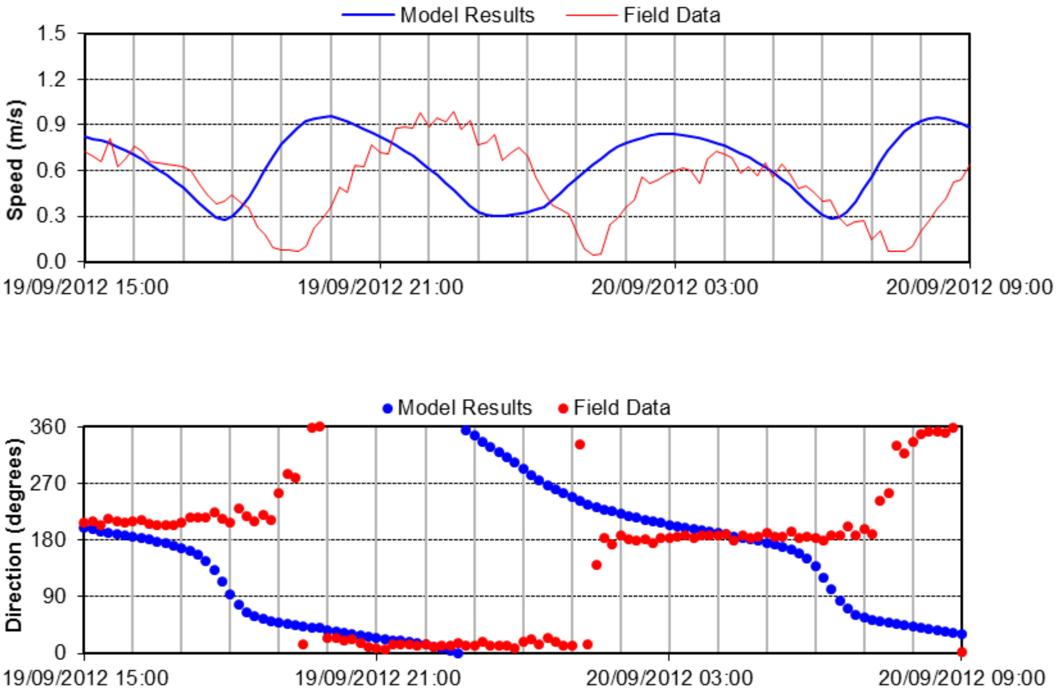


Figure A-31 Model fit during calibration period: SN061C

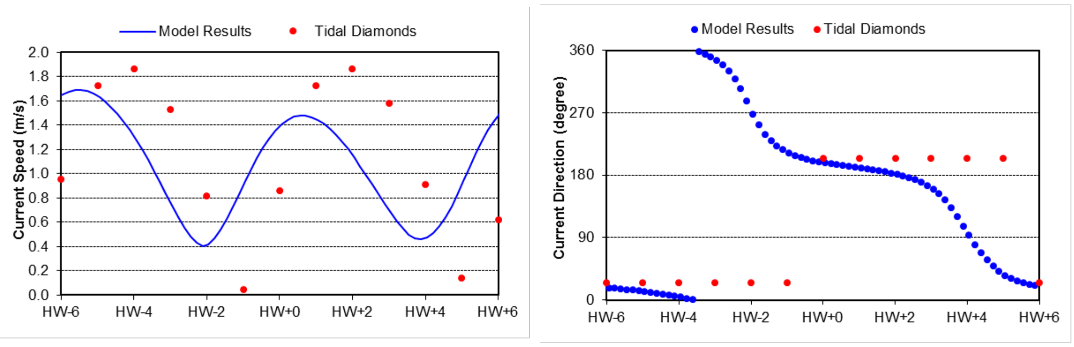


Figure A-32 Model fit during calibration period: SN062A

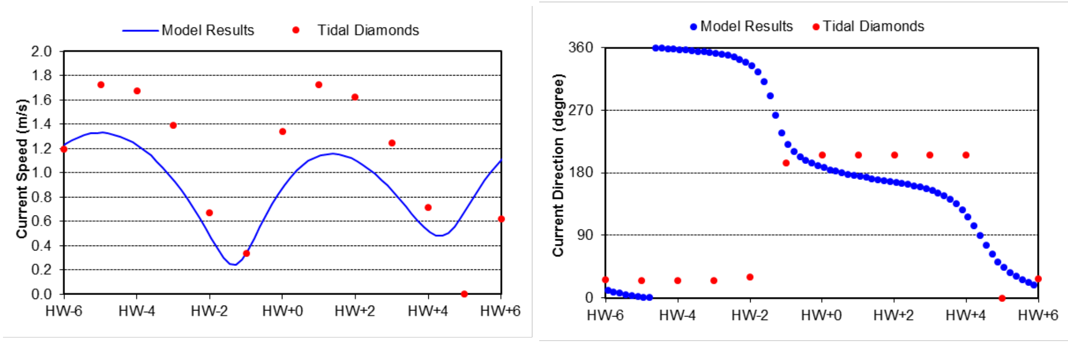


Figure A-33 Model fit during calibration period: SN062B

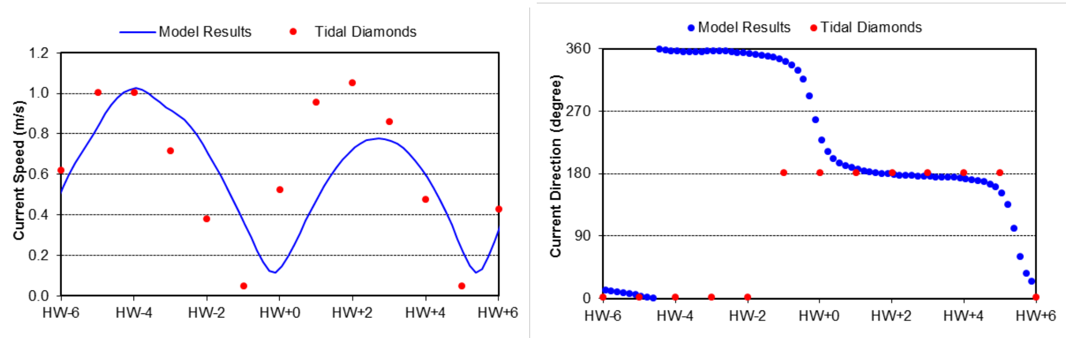


Figure A-34 Model fit during calibration period: SN062C

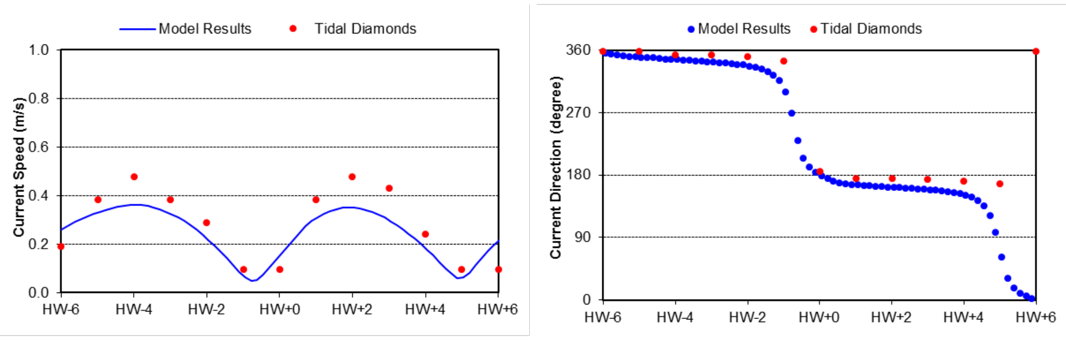


Figure A-35 Model fit during calibration period: SN062D

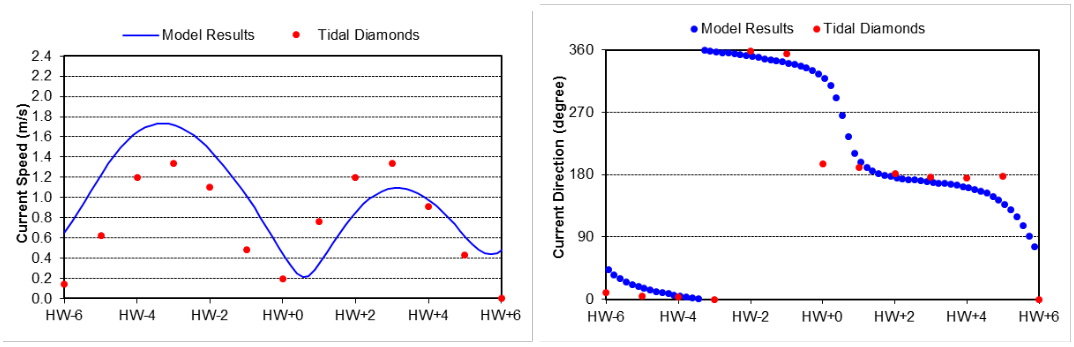


Figure A-36 Model fit during calibration period: SN062F

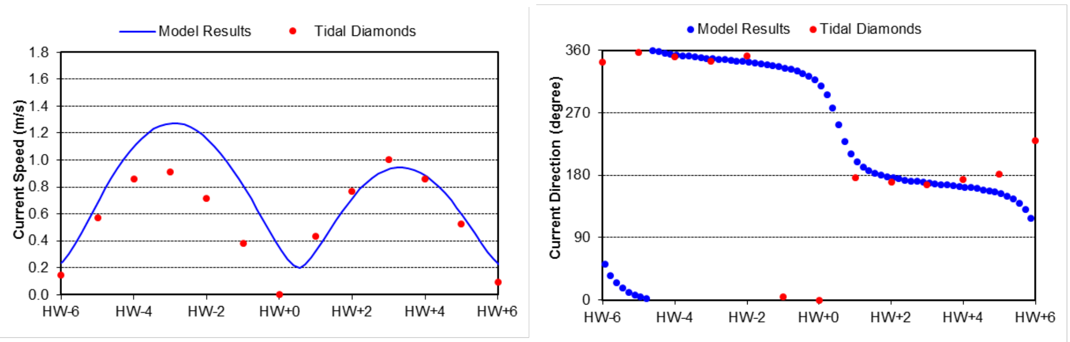


Figure A-37 Model fit during calibration period: SN062G

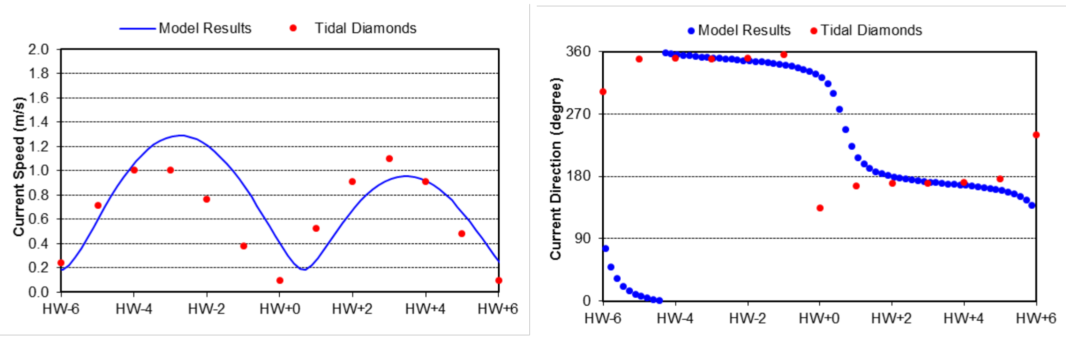


Figure A-38 Model fit during validation period: SN061C

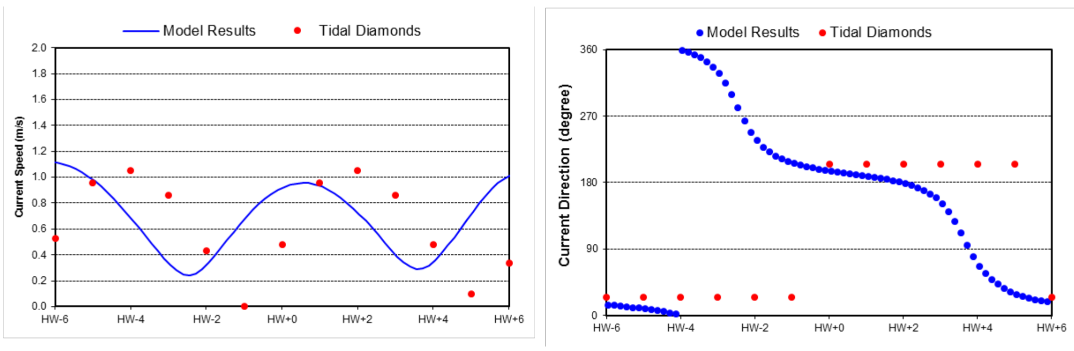


Figure A-39 Model fit during validation period: SN062A

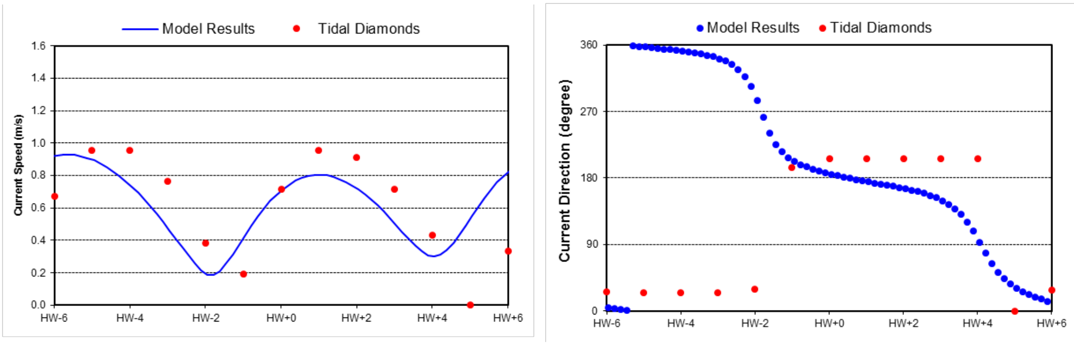


Figure A-40 Model fit during validation period: SN062B

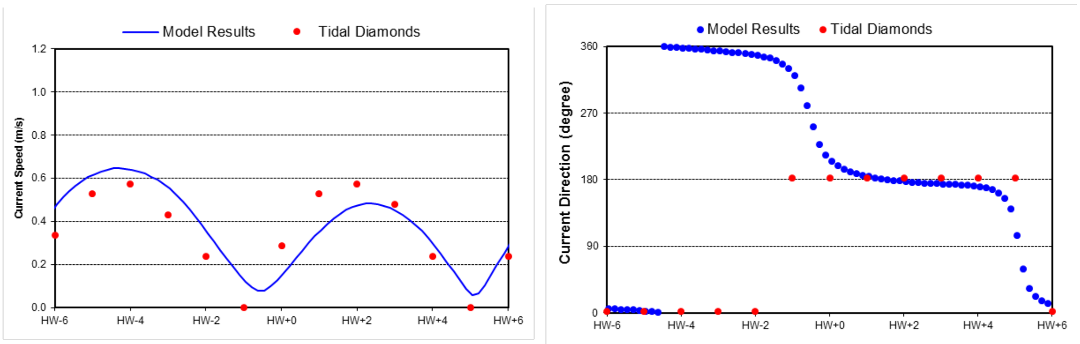


Figure A-41 Model fit during validation period: SN062C

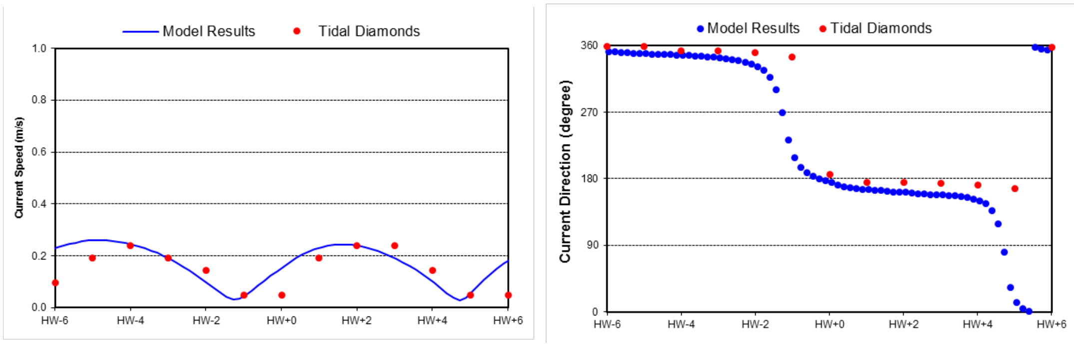


Figure A-42 Model fit during validation period: SN062D

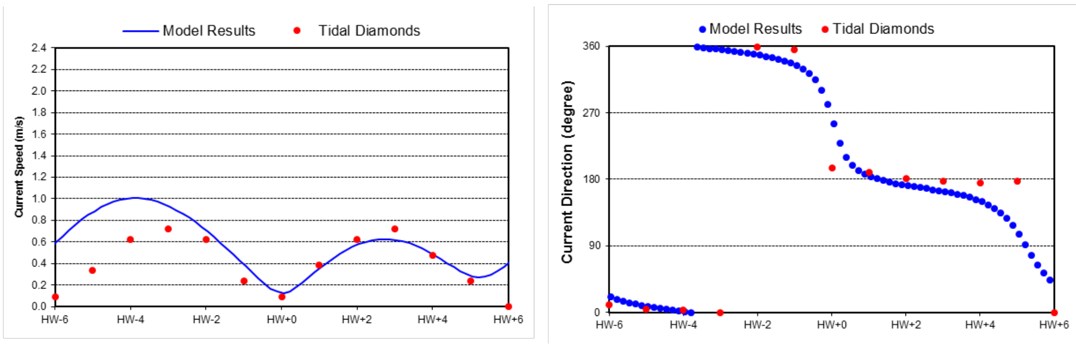


Figure A-43 Model fit during validation period: SN062F

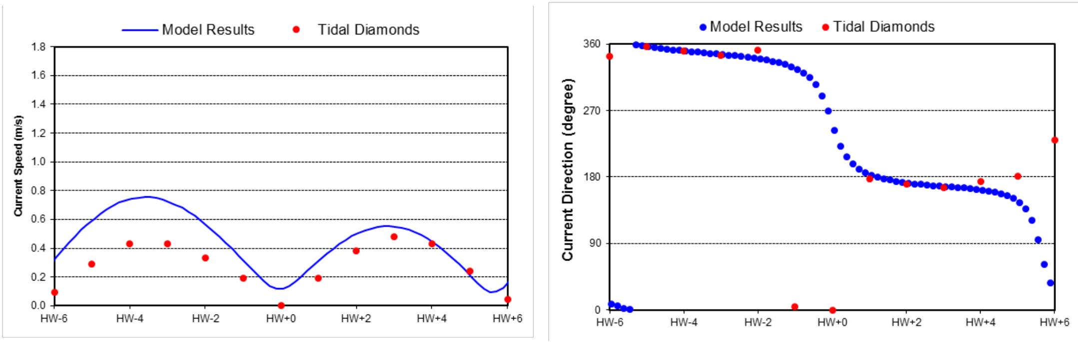


Figure A-44 Model fit during validation period: SN062G