Gigha Hydrodynamic modelling

Hydrodynamic model performance

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Approved By	

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List of Abbreviations

2D	Two-dimensional simulations along horizontal plane
3D	Three-dimensional simulations along horizontal and vertical plane
ABS	Agent Based Simulations
ADCP	Acoustic Doppler Current Profiler
AMX	Alphamax bath treatment
BFS	Bakkafrost Scotland Limited.
BODC	British Oceanographic Data Centre
CAR	Controlled Activities Regulations
CD	Chart Datum (local)
CMEMS	Copernicus Marine Emergency Management system
CFS/CFSv2	Climate forecasting system / version 2
COGP	Code of Good Practice
CTD	Conductivity, Temperature, Depth
D*	Dimensionless grain size
D_{50}	Median grain size
DHI	Environmental consultancy and developers of MIKE 3/ECO Lab
DTM	Digital Terrain Model
DTU-10	Oceanographic model computing surge
EmBz	Emamectin Benzoate (SLICE active ingredient)
EQS	Environmental Quality Standard
HD	Hydrodynamics
Hs	Significant wave height
HYCOM	Oceanographic model simulating tidal harmonics
MAE	Mean Absolute error
MLWS	Mean Low Water Springs
MS	Marine Scotland
NB	*Nota Bene:* Note Well
NCEP	National Centres for Environmental Protection
NMPI	National Marine Plan Interactive
MS / MSS	Marine Scotland/ Marine Scotland Science
OS	Ordnance Survey
p_c	Probability of connectivity
PSU	Practical Salinity Unit
Q	Cumec: unit of discharge
r^2	Proportion of the variance for a dependent variable explained by the model
RMSE	Route Mean Squared Error
SDM	Standard Default Method
SEPA	Scottish Environment Protection Agency
SLICE	In-feed treatment containing the active ingredient, EmBz
SSH	Sea Surface Height
T	Tonnes (biomass)
Tp	Peak wave period
U10/V10	u/v vectors at 10m height
u*	Shear velocity
u_z	Roughness Length
UKHO	UK Hydrographic Office
UTM-29	Universal Trans Mercator – 29: Cartesian projected coordinate system

WGS84	Lat/Long Coordinate system
WLLS	Wider Loch Linnhe system (Marine Scotland Model)
μ	Mu; Statistical mean
θ	Theta: Shields parameter
τ_E	Tau-E; Critical resuspension thresholds
σ	Standard deviation

1. Introduction

This report summarises work undertaken by Bakkafrost Scotland (BFS) to construct and validate a 3D hydrodynamic model in the area surrounding the Isle of Gigha, including the larger Sound of Jura, Loch Linnhe, Northern Channel and the Sound of Mull. The model is intended to be applied to review the dispersal of aquaculture related discharges including solid waste, bath treatments and biological discharges from finfish farms operational in the area. The extent of the Hydrodynamic domain, extends from Belfast to Loch Suart and from Malin head to Ailsa Craig with high node definition surrounding existing finfish sites in the domain. The primary are of interest at two existing BFS farms around the Isle of Gigha be seen in Figure 1.1.

It is intended this modelling be used to improve the understanding of hydrodynamic flows in the wider study area (Northern channel, Rathlin Island, Corryvreckan, Sound of Luing and Loch Shuna) and, particularly, within the vicinity of the primary study area (Isle of Gigha and Sound of Jura). This greater understanding will then facilitate the assessment and identification of dominant hydrodynamic regimes within the model domain and their impact on the dispersion of aquaculture related discharges.

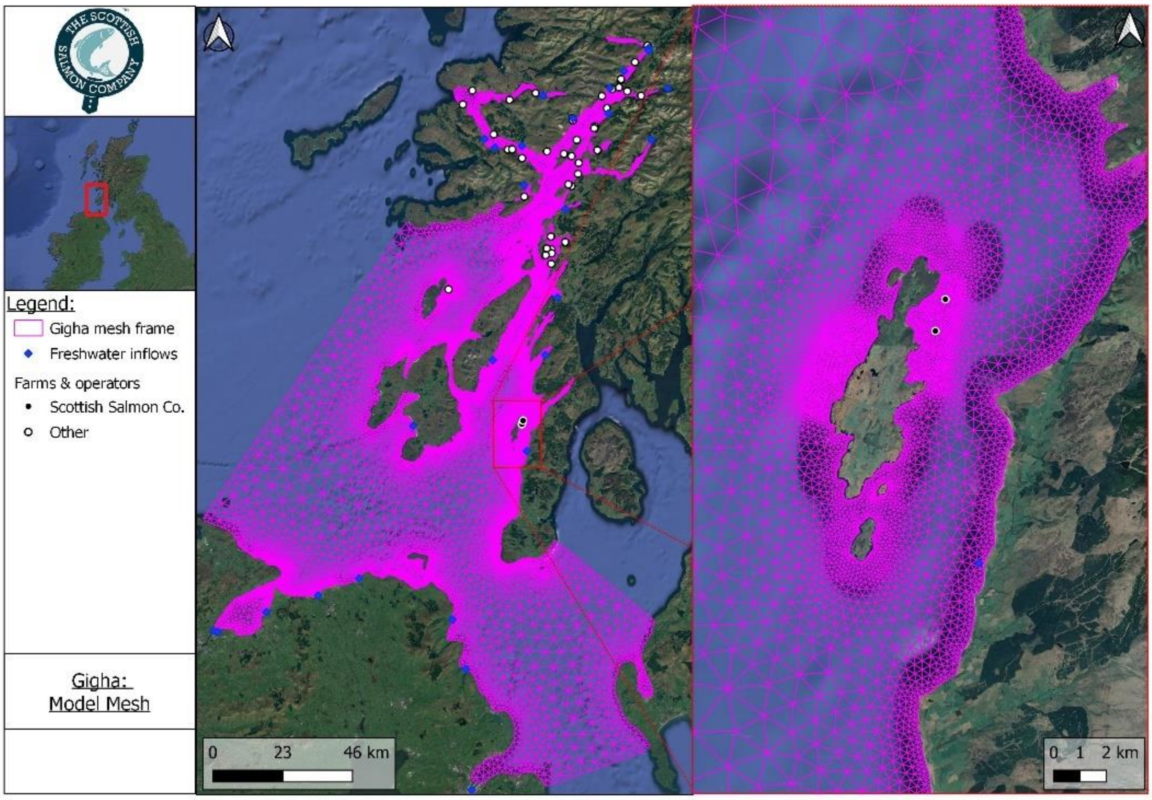

Figure 1.1: Gigha hydrodynamic model mesh and existing CAR licences

1.1 Geographical Context

The primary area of interest of this study is the Island of Gigha, west of the Mull of Kintyre and within the sound of Jura. The assessment incorporates a wider area of interest, reviewing interaction with receptors within the Sound of Jura, Loch Shuna and the wider Loch Linnhe system. These areas are displayed in Figure 1.2. The primary area is considered moderately exposed to significant Atlantic swells from the Malin Sea area and the Irish Sea. The Isle of Gigha does offer significant protection from these Atlantic swells to the existing BFS sites of Druimyeon Bay and East Tarbert Bay. The tidal regime varies significantly within the domain, with an M_2 amphidromic point between Rathlin Island and the Sound of Islay. The tidal regime is semi-diurnal in nature with recorded tidal ranges varying from a 3 m spring range at Bangor, 0.8 m at Gigha/ Port Ellen and 4.3 m at Tobermory. The tidal regime in the primary and wider areas of interest is thus considered complex, with hydrodynamic flows perturbed and exacerbated by complicated geological formations, overwritten by a complex glacial history resulting in deep, narrow fjordic sea lochs, shallow sills[1] and tidal velocities in excess of 5 kts (2.6 m/s) are commonly observed.

Freshwater inflows are significant within the wider area of interest, with freshwater bores observed at the Corran Narrows and high freshwater concentrations observed at the Falls of Lora and within Loch Etive[2]. Significant freshwater inflows are also sourced from the North of Ireland, including Loch Foyle, the River Bush and Bann. It is however likely these freshwater sources will be highly dissipated and not directly interact with farms in the primary area of interest.

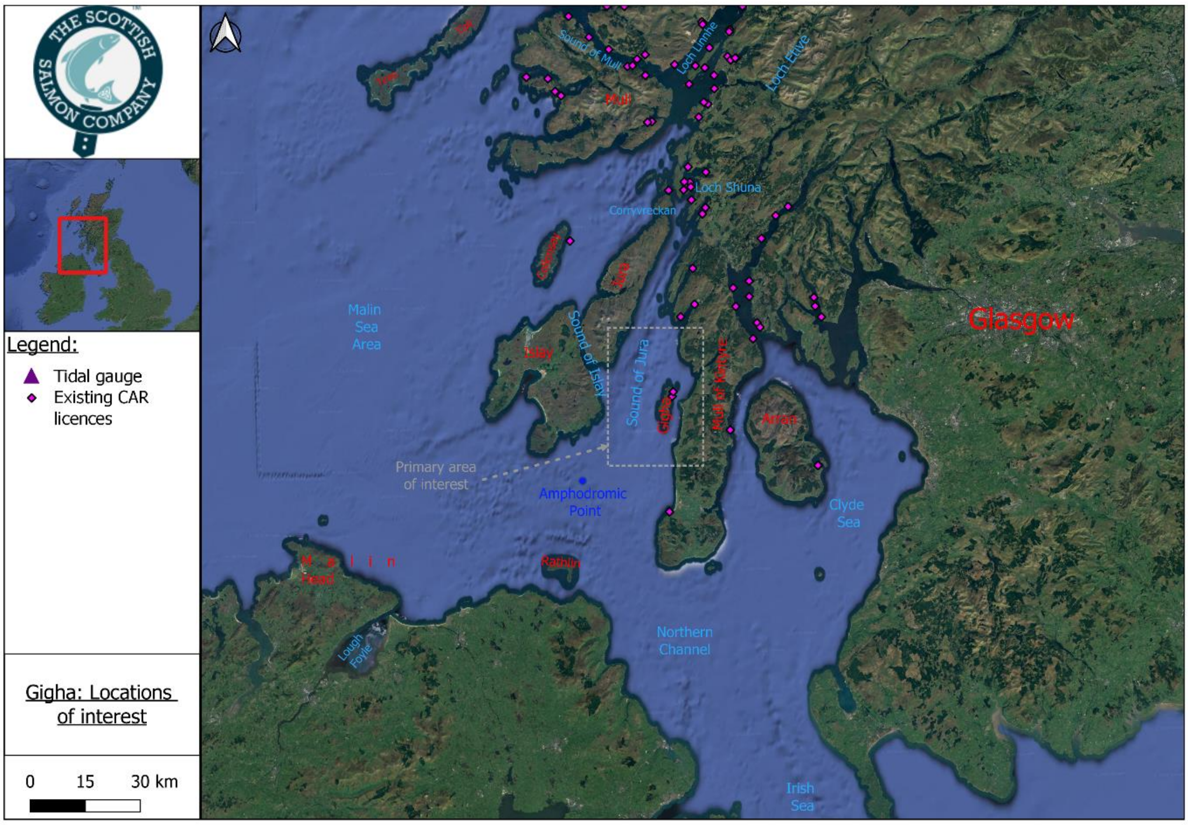

Figure 1.2: Geographical context of the primary area of interest

1.2 Project Aims

The complexity of the oceanography in the study area and its proximity to marine research facilities at Oban and Millport has resulted in extensive marine investigation in the area and its aquatic systems. The larger area also supports significant aquaculture activities, particularly within Loch Shuna and the Loch Linnhe system. However, oceanographic observations and academic study of the circulation patterns in the vicinity of the BFS farms remain spatially sparse and little is known about hydrodynamic circulation and sediment movement patterns and their interaction with local freshwater inputs and the interface of this area with the wider system.

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[1] Berx, B. Gallego, A. & Heath, M, (2015). *Loch Linnhe and Firth of Lorne MASTS Case Study Workshop Report.* Scottish Marine and Freshwater Science Vol 6 No 1.

[2] Hicks, N., Brand, T et al., (2016) *Loch Etive: MASTS Case Study Workshop Report* [Accessed online 10/05/2021: http://www.masts.ac.uk/media/36494/loch-etive-workshop-report_final-report.pdf]

The aim of the present study is to review the given hydrodynamic conditions influencing a primary area of interest including two active CAR licences for finfish farms (Druimyeon Bay and East Tarbert Bay), review the potential for site development and apply this simulated data to better understand the dispersal of farm related discharges and risks associated with identified receptors.

The aim will be fulfilled via the following objectives:

- Review existing data and literature to understand the hydrodynamic setting of existing and potential farms around the Isle of Gigha and their potential interaction with the wider environs;
- To setup, calibrate and validate a 3-Dimensional (3D) hydrodynamic, baroclinic model, of the area surrounding the Isle of Gigha that captures the important processes that govern dispersion of farm releases;

The model is intended to be applied to review the dispersion of aquaculture related discharge to the wider environment.

1.3 Oceanographic setting

Given the remit of the modelling, there are three dominant mechanisms that govern flow and exchange within coastal and estuarine environments. These are;

- Tidal forcing;
- Meteorological forcing (wind stress, ambient temperature, precipitation and barometric pressure); and
- Density driven interchange (stimulated by atmospheric interaction and temperature and salinity gradients).

The role of these mechanisms on the area surrounding the Isle of Gigha, the wider Sound of Jura and connected systems are outlined below.

1.3.1 Tidal levels

The tidal environment within the primary area of interest is a micro-tidal, semi-diurnal regime with a mean spring range of 0.8 m. As we move away from this area of interest, the tidal regime varies significantly with a macro tidal regime observed at Bangor/Portpatrack to the south, Malin Head to the west and at Tobermory to the north. The area encompassing the primary area of interest can thus be considered a complex oceanographic environment, with the flood tide generally flooding from south to north, creating intricate flow patterns within the various sounds and fjordic systems and constrained by open inflows from the Irish Sea and the Eastern Atlantic and constrained inflows through the Corryvreckan and the Sound of Luing to the north.

1.3.2 Tidal velocities

Currents within the area of interest are dominated by the tidal conditions, with high velocities elicited regularly with mean observed current speeds of between 0.12 m/s and 0.16 m/s and maximum observed speeds between 0.5 m/s to 0.7 m/s at the surface layers at BFS farms. Event driven velocities are present but are considered largely insignificant in comparison to the tidal component of water velocities. Average (depth and time) velocity roses observed at BFS hydrographic meter deployment locations are displayed in Figure 2.4. The data collected by BFS remains the only known observational data in the primary area of interest.

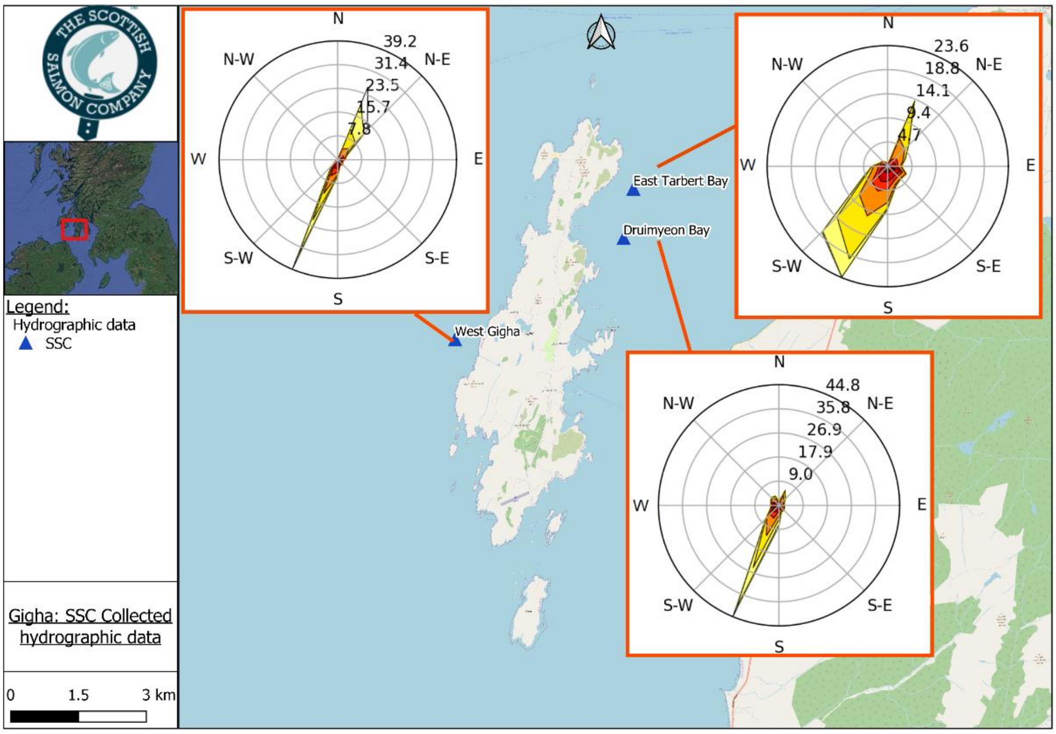


Figure 1.3: Observed current roses at hydrographic meter deployment locations

1.3.3 Wave conditions:

The wave conditions in the area was reviewed using the North-west shelf re-analysis from January 2019 to January 2021[3] and the simulated wave climate for the Mull of Cara (south of the Isle of Gigha) can be seen in Figure 1.4.

The model illustrates a moderate wave climate with the approximate 1 in 1-year Significant Wave Height (*Hs*) of approximately 4 m. It also demonstrates that the dominant wave direction is west-south-westerly originating from the Malin Sea area. The model also demonstrates a small contribution from southerly waves originating from the Irish Sea. The significant proportion of waves from westerly directions and their magnitude result in waves from this origin being considered the dominant wave conditions at the West of Gigha, whilst the BFS sites to the East of Gigha are likely influenced from southerly swells

[3] Tonani, M., Sykes, P., King, R. R., McConnell, N., Péquignet, A. C., O'Dea, E., ... & Siddorn, J. (2019). The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system. *Ocean Science*, *15*(4), 1133-1158.

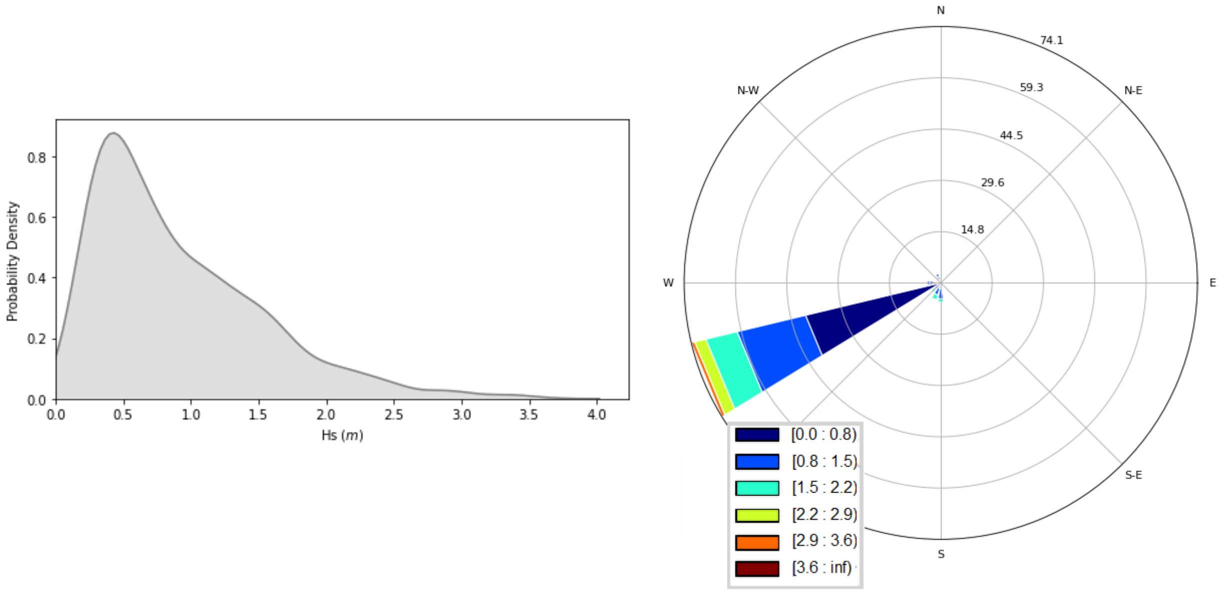


Figure 1.4: Wave conditions for Gigha. Data generated from CMEMS hindcast 2019-2020

1.3.4 Density driven interchange:

As outlined in earlier sections, the larger domain area is considered significantly modified by thermohaline circulatory processes, particulary by the role of local fluvial freshwater inputs. As it is accepted that some lice or other pathogens are sensitive to ambient temperature and salinty for maturation and mortality, whilst abiotic components are influenced by stratification. The influence of these densinity hydrographic conditions have a significant impact on farm operation and the dispersion of farm related discharges.

Few observational datasets exist to review the detail of density driven interchange within the primary area of interest. As a result little is known about the water column salinity and density propertries in the area.

1.4 Modelling approach

The hydrographic complexity of the area of interest represents multiple tidal, hydrographic and bathymetric features of significance further complexified by thermohaline circulation, heat interchange and wind/wave related currents. Full representation of the hydrographic processes associated with these features in contemporary simulation packages, for the extensive time periods (365 days) required for SEPA compliance, requires a prohibitive level of computational resource. Therefore, to permit representation of these features within the modelling framework, simplifications are required. These simplifications are discussed in this document and the framework for modelling simulations are presented below.

1.4.1 Simulation package

The simulation package chosen to simulate the dispersal conditions of BFS sites in the vicinity of the Isle of Gigha is the MIKE suite of model packages, hosted by DHI Consulting. Given the role of three-dimensional (3D) processes in the dispersal of particles from the farms, 3D simulations were considered vital to accurately represent process undertaken. MIKE 3 includes the simulation tools to model 3D free surface flows, density and heat driven interchange and associated sediment, ecology and water quality processes. The following module available within MIKE 3 was used during this study:

- ***HD – Hydrodynamics***: This module simulates the water level variations and flows in response to a variety of forcing function according to the Reynolds averaged Navier-Stokes equations and their simplifications, conserving momentum, temperature, salinity and density. It includes a wide range of hydraulic phenomena in the simulations and provides the basis for simulations performed in subsequent modules. Modern flexible, triangular mesh was used to facilitate the interchange between locations using a semi-implicit simulation approach.

It is intended that model outputs be applied to track particle dispersion in the two packages outlined below (also available in MIKE3):

- ***Particle tracking***: MIKE Particle Tracking module can be run with 2D and 3D simulations and allows particles to be simulated as passive particles, carried within the water column. This module follows a Langrangian computational framework and is less computationally expensive than the alternative Eulerian framework.

- ***ECO Lab***: Ecological and Agent Based Modelling: This is a complete numerical laboratory for water quality and ecological modelling. This module is similar to the Particle Tracking module discussed above but enables the ability to specify how the particles interact with the simulated ambient conditions of the water column. Thus, the representation of a particle's behaviour in the environment can be improved (from traditional advection dispersion characteristics), including interaction with environmental variables that govern a given subject's maturation/decay and movement.

The MIKE 3 Model used for the present study was version 2022.

2. Model Setup

As outlined in Section 1, there are three modelling tasks required to successfully simulate the dispersion of the subject matter (Sea Lice, Feed and Faeces, and Bath treatments). The setup of these conditions are outlined in the following sections.

The hydrodynamic model is considered the primary driver of the work undertaken and a summary of the development of the process is summarised within this Section. The model was constructed to be run in MIKE 3, with ten vertical sigma layers.

2.1 Model Mesh

The three-dimensional model was setup in MIKE 3 in UTM-29 with a mesh generated in BlueKenue with variable node spacing along the shoreline, with element growth constrained by bathymetry and elevated resolution on the footprints of farms and oceanographic features of interest. A representation of the model mesh can be seen in Figure 2.1.

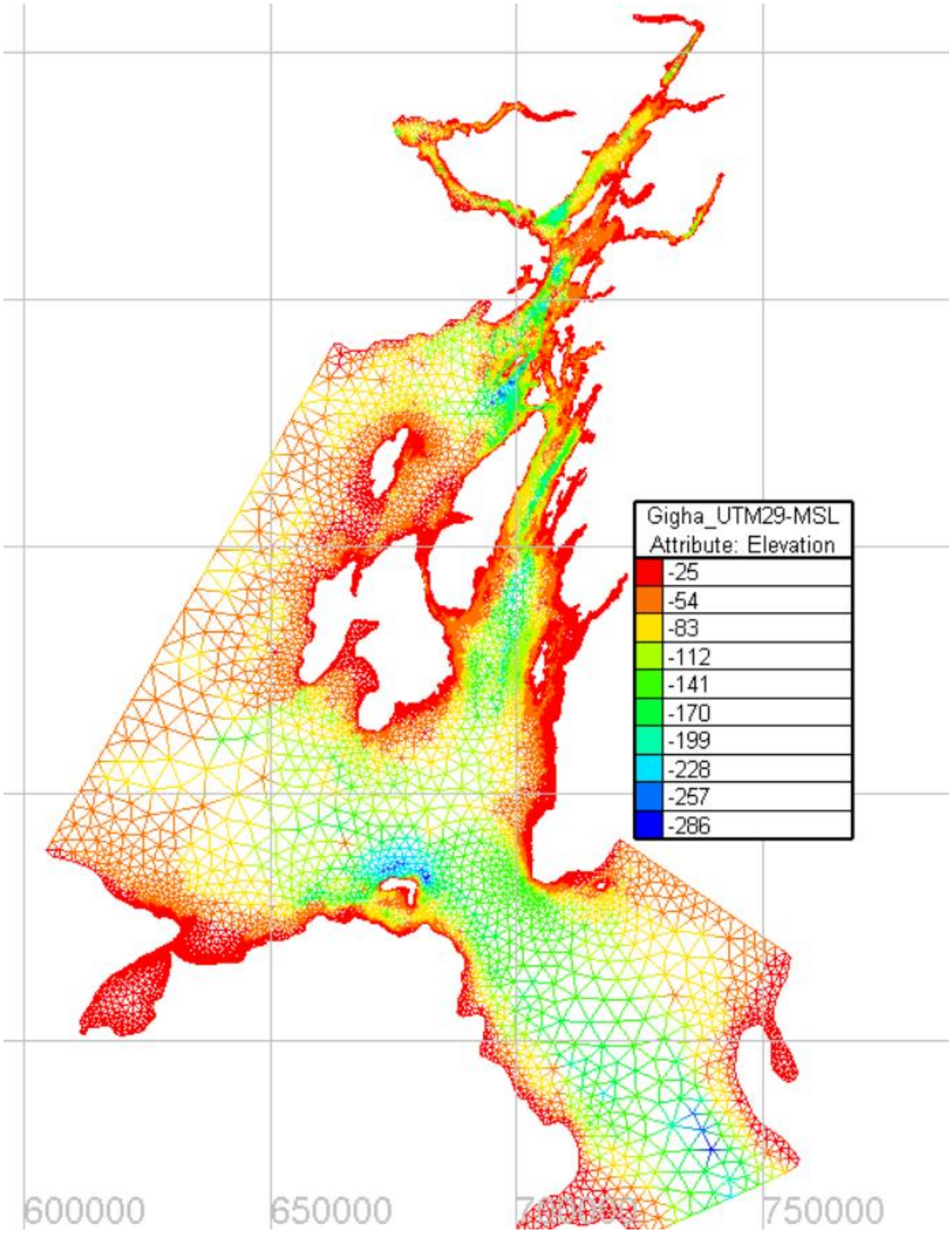
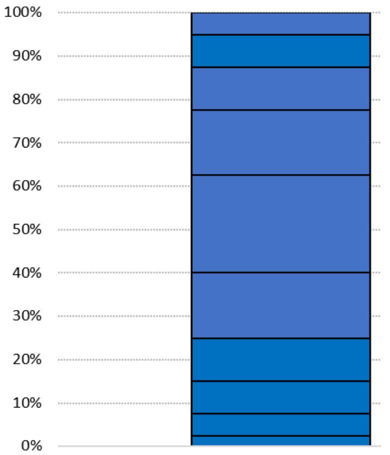


Figure 2.1: Model Mesh used in simulations

The mesh was discretised vertically into 10 variable sigma depth layers to better represent stratification throughout the domain. These divisions can be seen in Table 2.1. Increased resolution of sigma layers was included at the surface and bed layers to better represent interaction with both atmospheric conditions and the friction induced by the bed.

Table 2.1: Vertical discretising in Gigha domain

Layer	% of Water Column
1	0.05
2	0.075
3	0.1
4	0.15
5	0.225
6	0.15
7	0.1
8	0.075
9	0.05
10	0.025



2.2 Reference systems

All model spatial data was made relevant to UTM-29N, WGS84 (ESPG:32629). All bathymetry data was maintained in Chart Datum (mCD) and converted to Mean Sea Level (MSL) based on a conversion of 0.6 m (based on the Admiralty TotalTide conversion at the Sound of Gigha).

It is recognised that the conversion from CD to MSL varies throughout the model domain as the charted surface deviates from reference geoids. However, given the localised area of interest (Gigha) the conversion to MSL was not considered significant and within measurement error of the composite bathymetry used

2.3 Bottom boundary

The bottom boundary of the model was defined using established third-party datasets and includes the definition of model bathymetry and bed roughness. The genesis of the bottom boundary conditions used in the model are outlined below.

2.3.1 Bathymetry

Bathymetry was applied from multiple public sources presented below, in order of priority. This priority list was devised based on the source accuracy of the data, the degree of interpolation in the spatial DTMs and resolution of the data

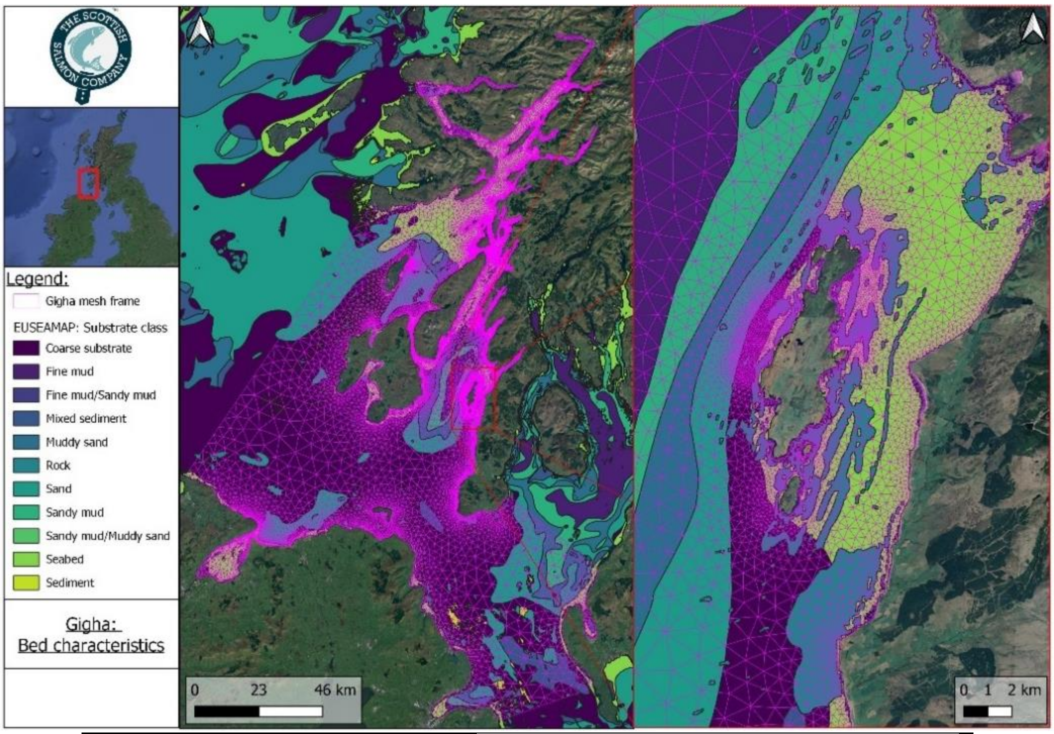
- UKHO /Admiralty online bathymetry portal (Crown copyright)
- EMODnet DTM
- OS Mean High Water Springs (MHWS) polyline
- GEBCO DTM

It should be noted that GEBCO data was used solely in the vicinity of the shoreline, where alternative data was not available. Due to the poor accuracy of this data (as assessed against BFS spot-depths and Admiralty DTMs) and the absence of suitable terrestrial datasets (LiDAR), areas of GEBCO data were manually reviewed to assess the suitability of nearshore areas not covered by high quality EMODnet or UKHO bathymetry.

BFS holds additional, localised single-beam bathymetry survey in the area, however this data was not included in the modelling as all datasets reviewed overlapped the extent and coverage of UKHO data, which is considered of greater accuracy and consistent with large areas of the domain.

2.3.2 Bed roughness

Bed roughness was defined using the parameter "roughness length" (z_0), described as; the distance above the bed where velocity equals zero. This parameter was varied throughout the domain based on the *EMODnet Seabed Habitat – substrate type*[4] and, where no value was available the model default value of 0.05m was applied. The substrate classes can be seen in Figure 2.2.



Substrate classification	*z_0 (m)*
Fine Mud	0.02
Muddy Sand	0.03
Sandy Mud	0.04
Sand	0.05
Mixed	0.05
Coarse Sediment	0.063
Rock	0.07

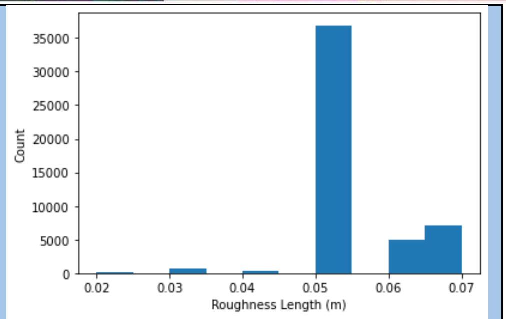


Figure 2.2: EUSeaMap substrate classification.

At the time of writing, no guidance exists on the classification of substrate z_0, as exists with Mannings '*n*' for terrestrial and 2D applications. Work undertaken by Partrac[5] outlines that z_0, estimated from 15 observations of the boundary layers at seven aquaculture sites around the Scottish coastline fluctuates between 0.0025 m and 0.0688 m along this stretch of coastline. A loose approximation can be derived from this dataset of a positive correlation between z_0 and D_{90} ($r^2 = 0.25$). In addition, it is also recognised that z_0 is greater where substrate surface is uneven. Therefore, z_0 was increased as the D_{50} associated with each substrate class was increased to a maximum value of 0.07 m, as can be seen in the table above (Figure 2.3).

[4] EMODnet (2021) EMODnet Broad-scale Seabed habitat for Europe (EUSeaMap). [Accessed online 15/01/2021 - https://portal.emodnet-bathymetry.eu/
[5] Black, K., Carpenter, T., Berkeley, A., Black, K. S., & Amos, C. L. (2016). Refining sea-bed process models for aquaculture. Scottish Association for Marine Science.

2.4 Model forcing

Model forcing was available from a multitude of providers including DHI, NOAA and Marine Scotland Science (MSS). These datasets were required to stimulate appropriate model function to elicit appropriate representation of sea lice migration and dispersion.

2.4.1 Hydrodynamic forcing

Open-source conditions available from CMEMS. The Northwest Shelf Reanalysis (NWSR) model[6,7 & 8]. This 3D large scale marine hydrodynamic model is generated and updated by the UK Met Office and hosted on the Copernicus Marine service simulating oceanographic conditions from 04/05/2019 to a seven-day forecast. The model simulates hydrodynamics in a 0.014 x 0.03 degree cell size (~1,950 x 1,550 m in the area of interest) in 33 z-level vertical layers. The following variables were used to drive the model:

1. Sea Surface Height (SSH) (15-min timestep)
2. z-layer UV velocity vectors (hourly timestep)
3. z-layer Temperature (hourly timestep)
4. z-layer Salinity (hourly timestep)

The parent model is coupled with a wave model facilitating wave related feedback in the surface layer which is driven by WaveWatch IIIv4 and ECMWF-IFS-HRES for atmospheric conditions. Model hydrodynamics consists of 11 tidal constituents with boundary forcing from the Met Office's North Atlantic 1/12 model and the Baltic Sea Analysis forecast. Major freshwater inflows exist, generated from observations provided by relevant UK environmental agencies and the NFRA.

NWSR model outputs were extracted at each boundary node to develop high-definition boundary conditions to better resolve the complex flow regime of the North Channel and eastern Atlantic. A 15-minute timestep was only available for SSH and Sea Surface Currents. All other variables were applied at respective depths along the four boundaries displayed in Figure 2.3.

[6] Tonani, M., Sykes, P., King, R.R., McConnell, N., Péquignet A-C., O'Dea, E., Graham, J.A., Polton, J., Siddorn, J.: The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system], Ocean Sci., '''15''', 1133–1158, 2019. https://doi.org/10.5194/os-15-1133-2019

7 Lewis, H., Castillo Sanchez, J. M., Siddorn, J., King, R., Tonani, M., Saulter, A., Sykes, P., Péquignet, A.-C., Weedon, G., Palmer, T., Staneva, J., and Bricheno, L.: Can wave coupling improve operational regional ocean forecasts for the North-West European Shelf], Ocean Sci., '''15''', 669–690. https://doi.org/10.5194/os-15-669-2019

8 Crocker, R., Maksymczuk, J., Mittermaier, M., Tonani, M., and Péquignet A-C.: An approach to the verification of high-resolution ocean models using spatial methods], Ocean Sci., '''16''', 831–845, 2020. https://doi.org/10.5194/os-16-831-2020

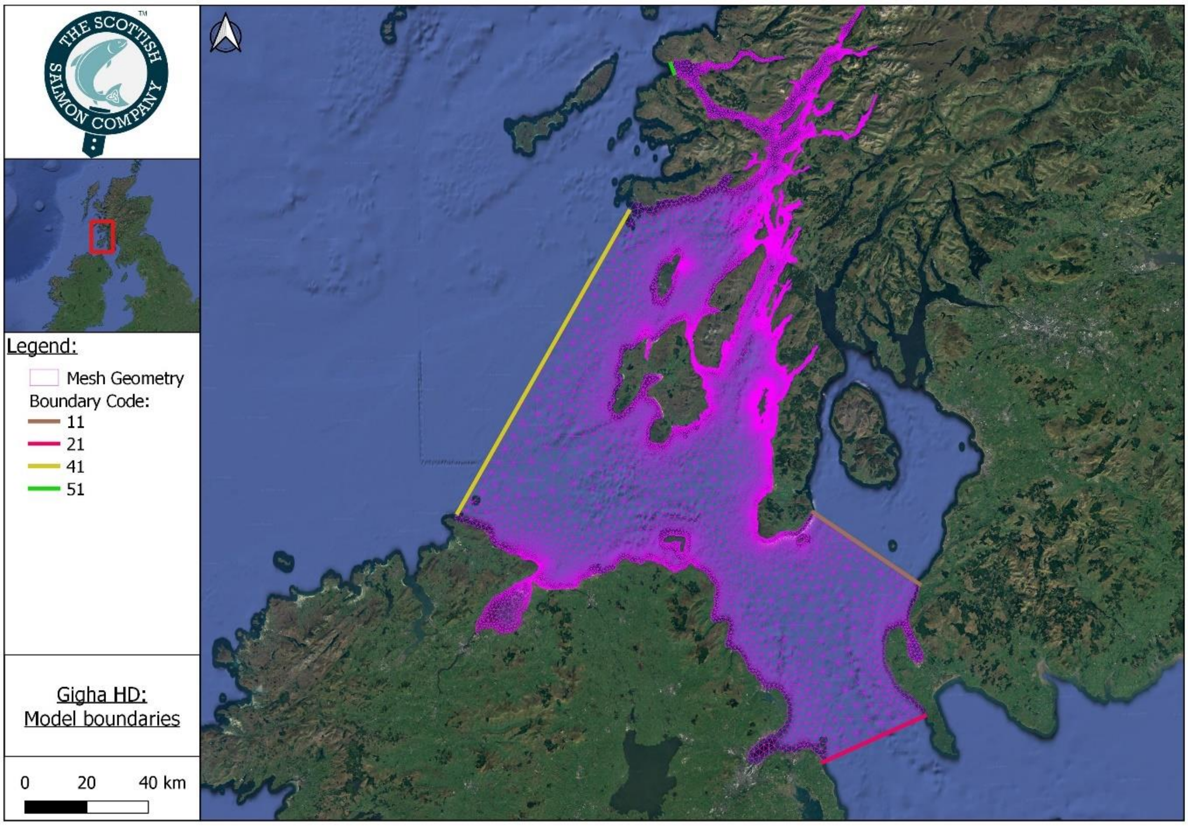


Figure 2.3: Mesh geometry and MIKE 3 code values

2.4.2 Meterogloical forcing

Meteorological conditions were derived from the CFSv2 reanalysis, three-hourly, 0.25 arc second dataset[9] available from NCAR online repository. The following parameters were input directly to the Gigha domain on the CFSv2 cartesian domain:

Wind parameters at 10 m height (U_{10} and V_{10})

- Pressure reduced to MSL
- Precipitation at 0 m
- Cloud cover (total), converted to Clearness Coefficient
- Relative humidity at 2 m
- Short wave radiation at 2 m

2.4.3 Temperature & Heat exchange

A representation of heat exchange was integrated into the temperature and salinity module within model simulations. All model defaults were retained with the MIKE default empirical function of Short & Long wave radiation. Ambient Temperature was integrated as spatially and temporally varying from CFSv2 forecasts, 2 m above the surface (from same dataset as that described in the “Met Forcing” section above).

For design runs, simulated conditions from CFSv2 will be applied for Short wave radiation, Clearness coefficient (transformed from cloud cover) and Relative humidity will be drawn from the 0.5˚ grid of the

[9] Saha, S., et al. (2021), NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products. Research Data Archive at the National Centre for Atmospheric Research, Computational and Information Systems Laboratory. [accessed 20/02/2021: https://doi.org/10.5065/D6N877VB]

CFSv2 model from the UCAR repository. The file drawn for application is held in the boundary conditions section of the model.

2.4.3 Fresh Water forcing

27 fresh water sources in Scotland and Ireland selected based on average daily discharge and a representation of inflows applied for all model runs. The watercourses used can be seen in Table 2.2 and their location can be seen in Figure 2.4.

Given the location of the calibration sites relative to these freshwater inputs and the low estimated discharge of the Allt Beachaire and other small rivers on Islay, Jura and the Mull of Kintyre, these daily averaged conditions were considered relevant to have minimal impact on model calibration/validation process. However given that subsequent modelling of particles is known to be sensitive to salinity, an extensive list of freshwater influxes were integrated based on a scaling factor derived from daily averaged freshwater inflows from Marine Scotland's Scottish Shelf Model (SSM)[10].

Table 2.2: Freshwater inflows for design runs

Watercourse Name	SSM average daily discharge (Q)
River Bann	113.478
River Lochy	109.860
River Etive	98.468
River Foyle	87.010
River Leven	24.449
River Aline	10.268
River Roe	10.090
River Lagan	9.518
Strontian	9.037
River Euchar	8.907
River Faughan	7.715
River Bush	7.599
Inbhir Scaddle	7.256
River Add	6.815
River Duror	5.960
Lussa River	4.992
Allt Baile Bhoidhich	3.818
River Forsa	3.465
River Nevis	3.169
Abhainn Na Coinnich	2.753
River Gour	2.735
Allt Beachaire	2.709
Glenarm River	2.476
Marhrie River	2.242
Abhainn a' Gharbh-achaidh	2.227
Cushendun River	2.149
Aros River	2.110

[10] Wolf J., Yates N., A Brereton A., Buckland H., De Dominicis M., Gallego. A, O'Hara Murray, R. (2016). The Scottish Shelf Model. Part 1: Shelf-Wide Domain. Scottish Marine and Freshwater Science Vol 7 No 3, 151pp.

For design runs, measured conditions were available within the lower courses of the Aline, Lochy, Strontian and Nevis from CEH NFRA[11]. Observed discharge rates were not available for the remainder of the 23 sites for the design periods simulated. To address this, hydrographs were derived based on the ratio of seasonal peak discharge for each watercourse to the River Lochy (identified as the primary hydrographic dataset, with the largest catchment). Therefore, observations of discharge volumes from the River Lochy were scaled, based on relative summer/winter maximum discharge of the SSM using the equation below for each timestep.

$$(\hat{s}/\hat{p})O = MQ$$

Where:

$\hat{p}$ = Mean of seasonal discharge at primary river (River Lochy)

$\hat{s}$ = Mean of seasonal discharge at secondary river

O = Observed Discharge of River Lochy at a given timestep

MQ = Modified discharge at secondary river

Figure 2.4: Freshwater inflows and BFS farms

It is recognised that the design river flows for the rivers without records are unlikely to be accurate. However, the application of scaled flows will approximate the magnitude of discharge and the daily variability well. Whilst this extrapolation is highly uncertain, it is considered significantly more representative than the SSM 'annual averaged' conditions and allows significant freshwater events to be adequately represented in simulations.

Observed river temperatures were available from the lower course of the River Aline for 2016 and 2018 from MSS[12]. This data was averaged and used to define a daily average freshwater temperature for each timestep (day of the year). In the absence of supplementary data from other water courses, these average temperatures were extrapolated to all other freshwater inflows for design runs. Again, this is

[11] CEH (2021) National River Flows Archive: Data search [Accessed 10/02/2021: https://nrfa.ceh.ac.uk/data/search]

[12] MSS (2021) Marine Scotland Science: Scotland River Temperature Monitoring Network © Crown copyright 2021

considered a better representation of source water temperature and its variability than a constant 10˚C temperature. Salinity values of all freshwater inflows were set to a constant value of 0 PSU.

2.5 Initial Conditions

Initial SSH, salinity and temperature conditions within the domain were extracted and interpolated to the Gigha model domain from the WESTCOMS[13] model domain. The WESTCOMS model is an FVCOM based hydrodynamic model of the wester Scottish coastline and Hebrides and is visible in Figure 2.5

A spin-up time of five days from these initial conditions was determined appropriate for the stabilisation flow-fields and water-levels. A further 30 days was required for the stabilisation of thermohaline circulatory processes and density due to a large deviation between the WESTCOMS initial conditions, forcing conditions and observed bed temperatures.

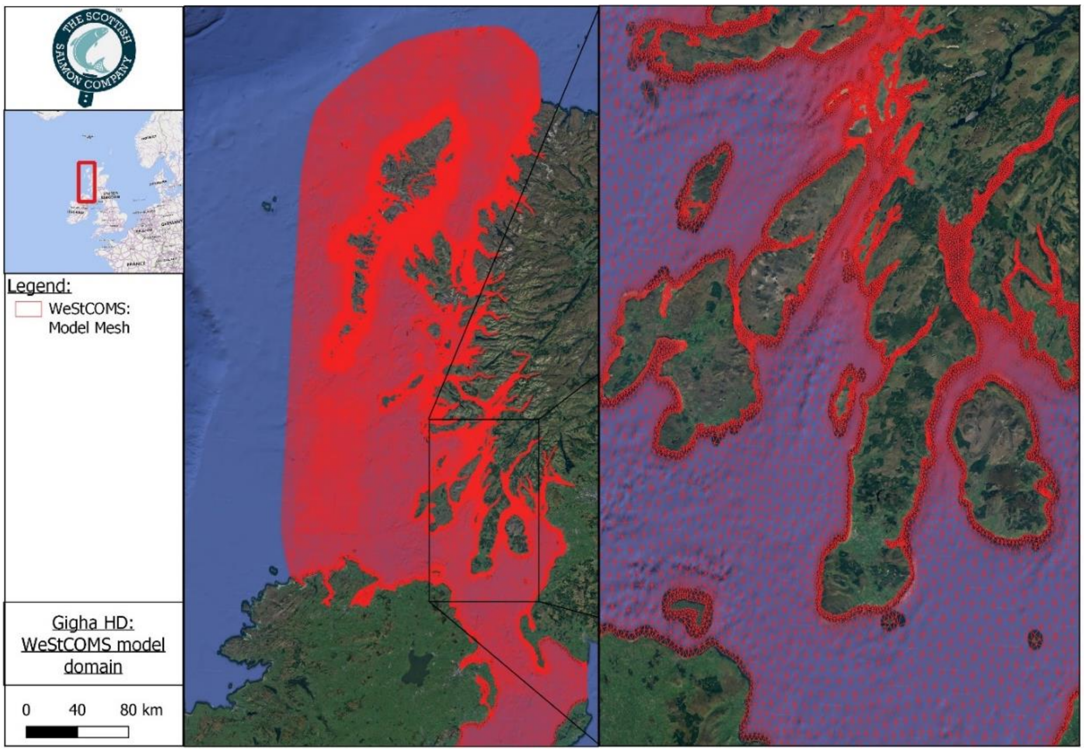


Figure 2.5:WESTCOMS model domain in the area of interest

2.6 Observed oceanographic data

Data observations were available from multiple sources within the primary area of interest and the wider area. This data is presented in the sections below.

Four BODC A-Class gauges exist within the domain, congruent with the simulation period. These public datasets hold records of observed water level records as well as isolate the residual water level component associated with surge events. These records are continuous since early 1990 and were reviewed over the simulated period. Six additional ADCP/RDCP records were collected by BFS (outlined below), these hold records of water level, water vectors at 1 m vertical intervals throughout the water column and water temperature at the bed throughout deployment periods.

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The NWSR simulated conditions are available from 04/05/2019 and, as a result, direct validation against East Tarbert Bay and Druimyeon Bay (existing BFS site) datasets was not possible (with appropriate model spin-up). In lieu of this, the simulation period used for validation spanned from 08/04/2021 to 30/09/2021, covering the entire dataset collected at West Gigha (allowing direct calibration with this dataset). The descriptive statistics of the velocity and water level at the locations of the East Tarbert Bay and Druimyeon Bay datasets were reviewed with reference to the observed conditions at these locations, allowing the skill of the model at these sites to be estimated. BODC water level datasets were reviewed for the entire simulation period (post spin-up).

Table 2.3: Hydrographic deployments within primary area of interest

Site	Data Recorded	End Date	Record Length
East Tarbert Bay -1	ADCP	03/03/2019	33 days
Druimyeon Bay - 1	ADCP	24/03/2019	38 days
Druimyeon Bay - 2	ADCP	12/05/2019	48 days
East Tarbert Bay - 2	ADCP	12/05/2019	48 days
West Gigha - 1	ADCP	06/05/2021	50 days
West Gigha - 2	ADCP	16/06/2021	40 days
BODC: Tobermory	Tide gauge	31/08/2021	10 + years
BODC: Portpatrick	Tide gauge	31/08/2021	10 + years
BODC: Bangor	Tide gauge	31/08/2021	10 + years
BODC: Portrush	Tide gauge	31/08/2021	10 + years

Figure 2.6: Hydrographic deployment locations

All BFS deployments held temperature observations at the bed during the deployment which allows the validation of bed temperature and salinity. Additionally, as part of BFS's ongoing monitoring, surface temperatures are collected at feed barges of active farms and CTD casts are collected, congruent with hydrographic deployments/checks. As the spatial and temporal resolution of stratification observations become more prevalent, it is intended the model skill in predicting this stratification be reviewed when data becomes available.

2.7 Model tuning / calibration

During model development, the model mesh and setup went through an informal model calibration process to generate greater agreement between modelled and observed water levels and currents. The model was calibrated based on water level records and the observed velocity distribution collected by the ADCP/RDCP deployments in the vicinity of the Isle of Gigha. To optimise the model performance the following model/mesh parameters were varied:

1. Node output was reviewed within three model nodes of the recorded deployment location and the model node with most similar hydrographic conditions to the observed was chosen. This is considered appropriate given the known inaccuracies in the absolute location of the deployments and assumptions made in the interpolation of bathymetry.
2. Boundary condition forcing: Applying surface currents, Water Column average, or velocities from a specified depth.
3. Bed roughness: varied between uniform, scaled variable parameters and localised variation.
4. Model bathymetry: localised edits in the vicinity of the shoreline.
5. Format of heat exchange characteristics: review of forcing conditions, between Long-wave radiation, clearness coefficient and inclusion of precipitation

Once calibrated, this model was validated against longer observational periods to review model skill. This process is outlined in Section 3.

Two general model setups were applied to review the dispersal of the four simulated particles releases. These releases were simulated based on the output flow vectors and stratification properties generated from hydrodynamic simulations reviewed by model developers DHI. Some minor modifications were undertaken to increase the suitability of the model and to improve the simulation approach, bringing the methodology in line with regulatory requirements. Selected significant modifications are outlined briefly in Table 3.3 along with selected parameters applied in the particle tracking module.

Table 2.4: General particle tracking model setup

Parameter	Modification
Mesh	Mesh developed and applied in the BFS Gigha domain for 3D HD simulations was refined, yielding an average cell size of 1,250m^2 (equivalent to an 35x35 m cartesian grid), within the vicinity of the farm.
Horizontal diffusion	Distribution of vertical sigma layers increases the resolution at the surface and bed.
Horizontal diffusion	Set to 0.1 m^2/s. *
Vertical diffusion	Set to 0.001 m^2/s.

3. Model Performance

3.1 Water level validation

The long-term water level validation records at the four BODC A-Class gauges are within the model domain. These records show good geographical spread throughout the domain with the Tobermory, Bangor and Portpartick gauges situated close to boundary conditions. These were considered the primary method of the validation of the water level within the wider study area. The 90 days of combined water level data at West Gigha is situated close to the amphidromic point and displays a micro tidal range. Subsequently, this was considered sensitive to variability of water-levels within the domain and this observation record is applied to validate the water level validation in the primary site of interest.

The model performance is outlined in the following sections with the observed conditions coloured red, and the simulated conditions coloured blue.

3.1.1 Tobermory: BODC, A-Class gauge

The water level observations at the BODC A-class gauge at Tobermory were reviewed against the simulated conditions throughout the study period and are displayed in **Figure 3.1**. The Q-Q plot below shows good agreement between the simulated conditions and the observed. The modelled density plot below demonstrates the simulated conditions exhibit less variability than the observed conditions, leading to a lower occurrence of simulated extreme conditions. The modelling is however considered to accurately replicate the observed conditions, given that the RMSE is less than 10% of the tidal range.

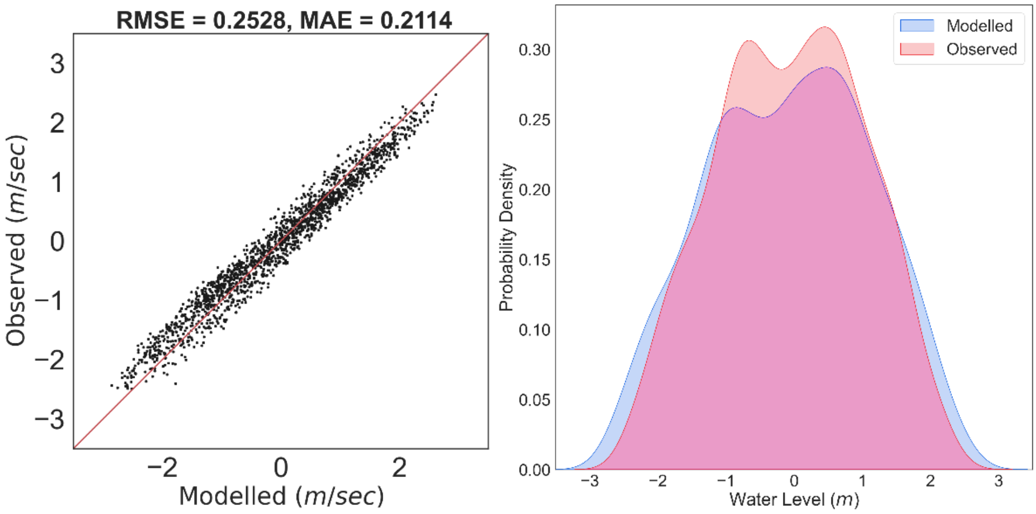


Figure 3.1: Water level validation at Tobermory

3.1.2 Portpatrick: BODC, A-Class gauge

The BODC gauge at Portpatrick was also used to review the skill of the model close to its southern boundary. The Q-Q and Density plots are shown in Figure 3.2. These show a consistent MAE between the simulated and observed conditions of ~0.30 m. The simulated conditions follow the distribution and the corrected magnitude for the location and replicate the timing of water levels.

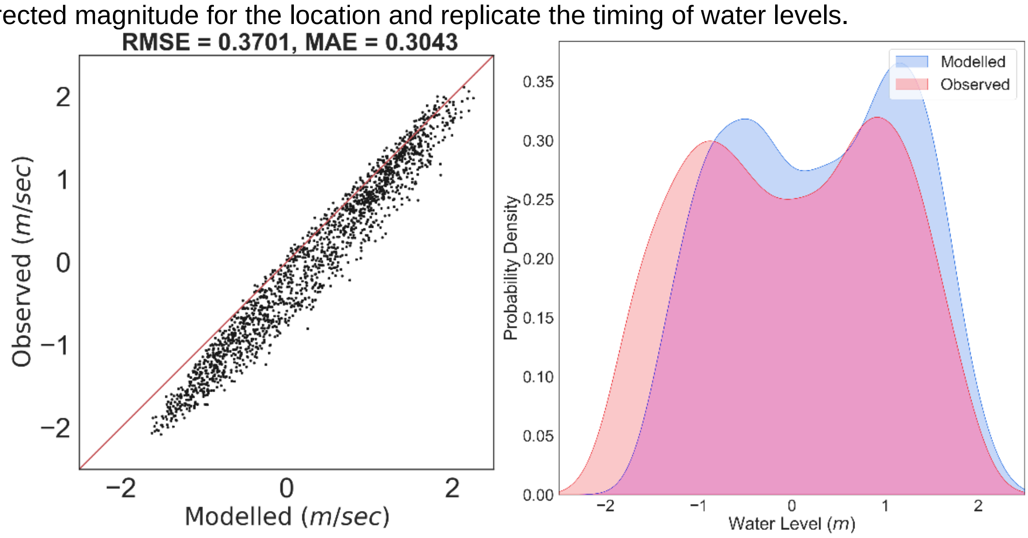


Figure 3.2: Water level validation at Portpatrick

3.1.3 Bangor: BODC, A-Class gauge

The model performance of water-level prediction at Bangor is displayed in Figure 3.3. The bias noted at Portpatrick is not as marked with closer agreement between the simulated and observed, reinforced by a decrease in RMSE of ~ 25%. The modelled conditions replicate the spread of water levels observed at the gauge and the simulation is considered appropriate.

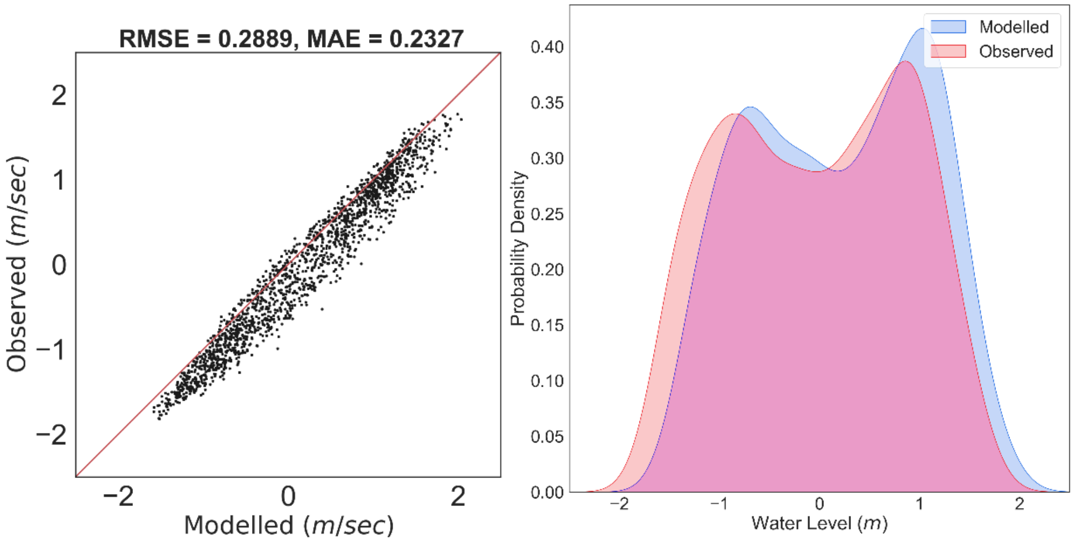


Figure 3.3: Water level validation at Bangor

3.1.4 Portrush: BODC, A-Class gauge

Model performance at Portrush was reviewed and is displayed in Figure 3.4. The Q-Q plot below shows good general agreement between simulated and observed conditions, with exceptional agreement at lower water levels but as water level increases, so too does the error between the modelled and the observed conditions. The error does not become significant with the average RMSE ~0.2 m. The distribution plot also demonstrates good agreement with the observed, with simulated conditions exhibiting a smaller range than the observed and a higher frequency of water levels of >0 m.

The model is considered to replicate the conditions well at the Portrush water level gauge.

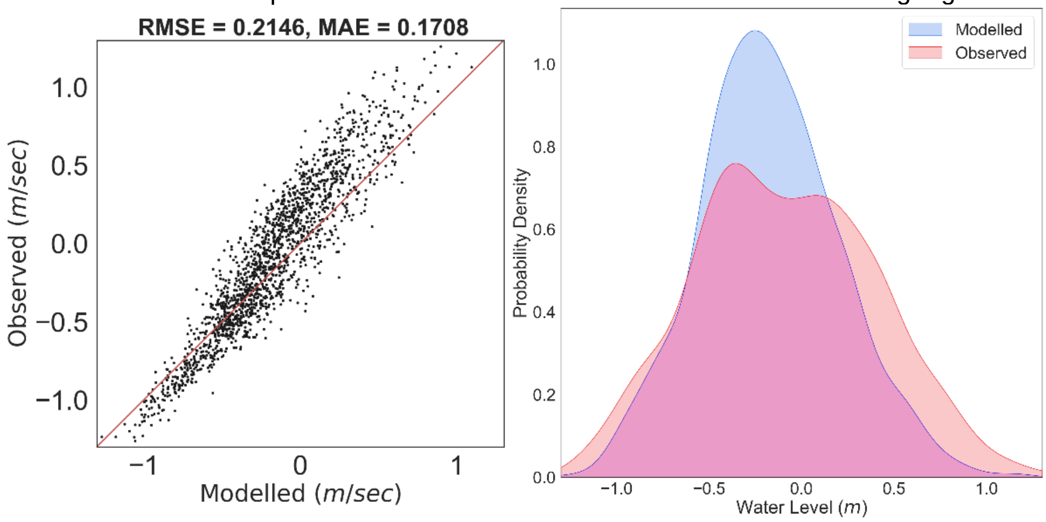


Figure 3.4: Water level validation at Portrush

3.1.4 West Gigha: Two ADCP deployments

The water-level at West Gigha was reviewed at 20-minute intervals throughout each of the two deployment windows.

Figure 3.5 displays the model's ability to replicate observed water-levels from 06/05/2021 for 50 days. The simulated water level replicates variability in observed conditions well, whilst consistently underpredicting conditions by circa

0.19 m. The Q-Q plot adjacent demonstrates the influence of surge events predicted in the modelling but not observed. These events are also observed in the timeseries plot circa 09/04/2021 and 04/05/20221 when the modelled conditions exceed the observed conditions. The modelled water level predicts the timing of high water well in this micro-tidal environment. The influence of these surge conditions is more pronounced here than at the four locations outlined earlier due to the smaller tidal range observed here.

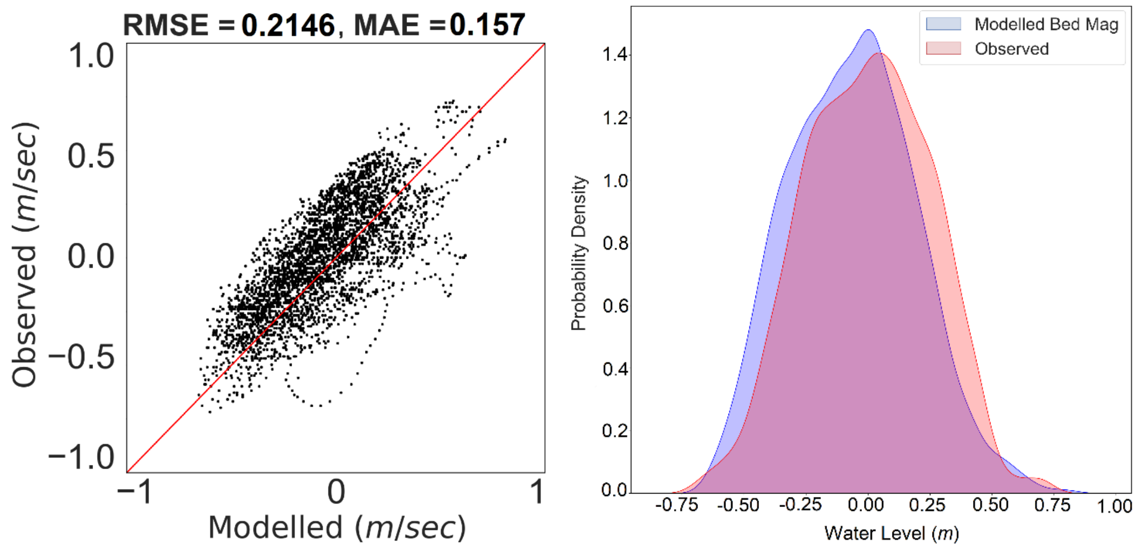


Figure 3.5: Water level validation West Gigha, Deployment 1

The plots comparing the simulated and observed conditions at the site for the second deployment are displayed in Figure 3.6 below. They demonstrate that the model approximates the timing and the variation between High and Low water well. However, given the low tidal range here, the surge conditions inherited from the boundary have a significant impact on the conditions at the site, producing a systematic bias in water levels and a greater range than observed. This is well demonstrated in the time series plot below when elevated water levels shift the mean water level ~0.25 m at the start of the observation period before it reverts to the observed conditions at the 17/05/2021 before another bias is introduced on the 23/05/2021.

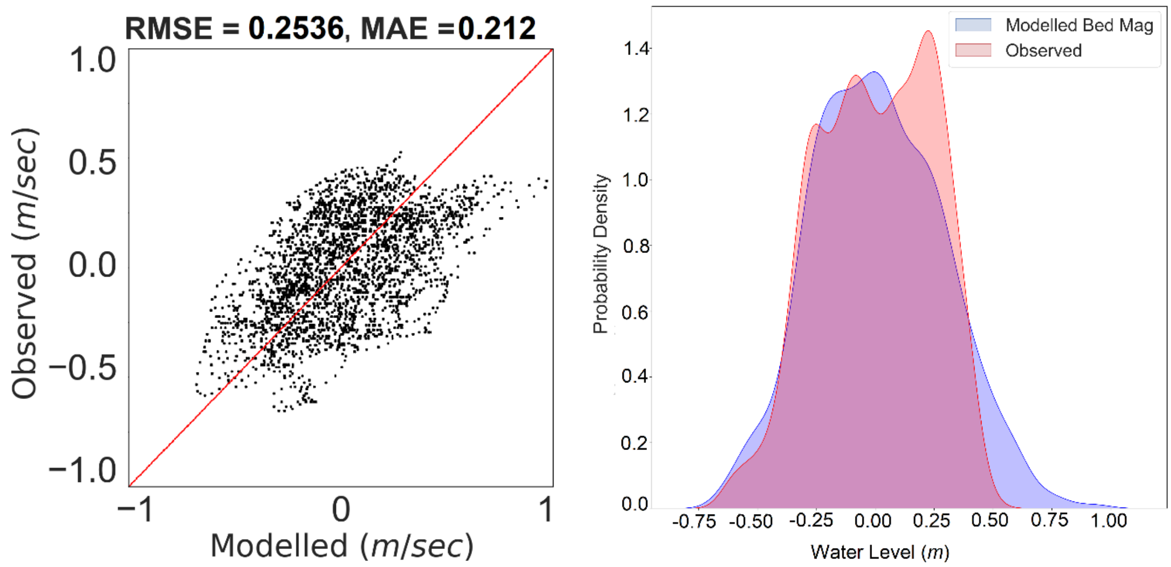


Figure 3.6: Water level validation West Gigha, Deployment 2

3.2 Velocity validation

Comparisons of the average velocity profiles and the velocity distributions at the surface and bed for each site can be seen in Table 3.1. The datasets can be coarsely split into two categories, which are discussed in greater detail in following sections

1. Direct calibration: These deployments were simulated directly within the model framework, applying congruent atmospheric and oceanographic forcing conditions.
2. Indirect validation: These deployments were not simulated directly within the model and the water column summary statistics are presented to review model skill.

3.2.1 Direct validation

Two datasets were available for direct validation at West Gigha with 90 days in total. These datasets are both situated to the west of the Isle of Gigha, as displayed in Figure 2.6. The model performance at these two sites is considered good and performance metrics are outlined in Table 3.1. The figures demonstrate that the model replicates observed velocities well throughout the water column, particularly at the surface where the mean and interquartile range of velocity speeds are very similar.

At the bed, the model underestimates observed velocities by 0.05 m/s (mean bed velocity of 0.13 m/s compared to 0.18 m/s observed) and reproduces approximately half the variability (σ = 0.045 compared to 0.09 m/s observed). However, the model-data comparison produces a good match, capturing the bed current axis within 15 degrees and producing a RMSE of 0.1 m/s and MAE of 0.08 m/s (for reference, the surface comparison produces a RMSE of 0.15 and MAE of 0.13 m/s).
The underprediction of variability at both the surface and bed is not unexpected considering the temporal discretisation of model forcing, spatial discretisation of the model grid (node spacing at the location of the observations is on the order of 100 m) and simplified conditions at the bed, all tending to reduce simulated variability. We conclude that the model sufficiently represents the local flow characteristics, noting that the simulation underestimates bed velocities by approximately 28 %. The model results will therefore represent a conservative estimate of local deposition.

3.2.1 Indirect validation

In addition to the validation at West Gigha, the model was validated with conditions at four alternative conditions to the east of the Isle of Gigha, as displayed in Figure 2.6. The collection of this data was incongruent with the simulation time period and boundary conditions from the NWSR was not available to cover the observational period at the time of writing. As the datasets and simulations are not contemporary, direct validation was not possible. In lieu of this, the water column velocity magnitude was taken to approximate validation. Model performance metrics are outlined in
Table **3.1** and discussed in the following sections.

Druimyeon Bay

The model overestimates vertical shear and average velocity at both Druimyeon Bay deployments overpredicting mean velocities by 0.02-0.04 m/s. The directions of the vectors vary slightly from the observed conditions with the simulated conditions producing asymmetrical tidal lobes where asymmetric lobes were observed. This is not considered significant due to the incongruence in model forcing over the time period.

Whilst some of the variability may be due to the non-contemporary timeseries comparison, some may be due to a smoothing of a thin dyke feature tracking north from Ardminish point and several small islands (>30 m long) in the bathymetric interpolation. This feature is likely to have an impact on velocities at Druimyeon Bay, slowing currents in the area. However, the best available bathymetry was used in the generation (from the UKHO/Admiralty) and the representation of flows at Druimyeon Bay is considered appropriate for the review of particle dispersal.

East Tarbert Bay

The simulated conditions at East Tarbert Bay closely replicate the conditions observed throughout both deployments and a total of 96 days. As with Druimyeon Bay, the model slightly overpredicts simulated velocities but at lower magnitudes (0.005 and 0.009 m/s, respectively). The model also approximates the velocity shear throughout the water column and well estimates the deviation of currents from the mean with a similar inter-quartile range to the observed.

The simulated velocity vectors are demonstrated to mimic the observed velocity vectors with less variability than the observed. The velocity vectors also predict the dominant southerly lobe at this location.

The modelling is considered to appropriately replicate the observed hydrographic conditions at East Tarbert Bay. Despite the non-contemporary observations and simulations, the model accurately replicates the observed hydrographic summary statistics within anticipated variability.

3.3 Temperature and Salinity validation

The deployments at West Gigha hold records of observed bed temperature conditions. The model was found to well replicate the bed temperature conditions following an extended model spin-up (as visible in the initial deployment in Figure 3.7, D1). This extended spin-up period is attributed to dissonance between the NWSR forcing conditions and the WESTCOMS initial conditions. Following this stabilisation period of 28 days (since model commencement) the modelled conditions are seen to closely follow the trend of observed temperatures with reduced variability with the modelled bed temperature producing diurnal oscillations of similar magnitude to the observed.

The model is considered to well replicate the bed temperature conditions at the West Gigha sites.

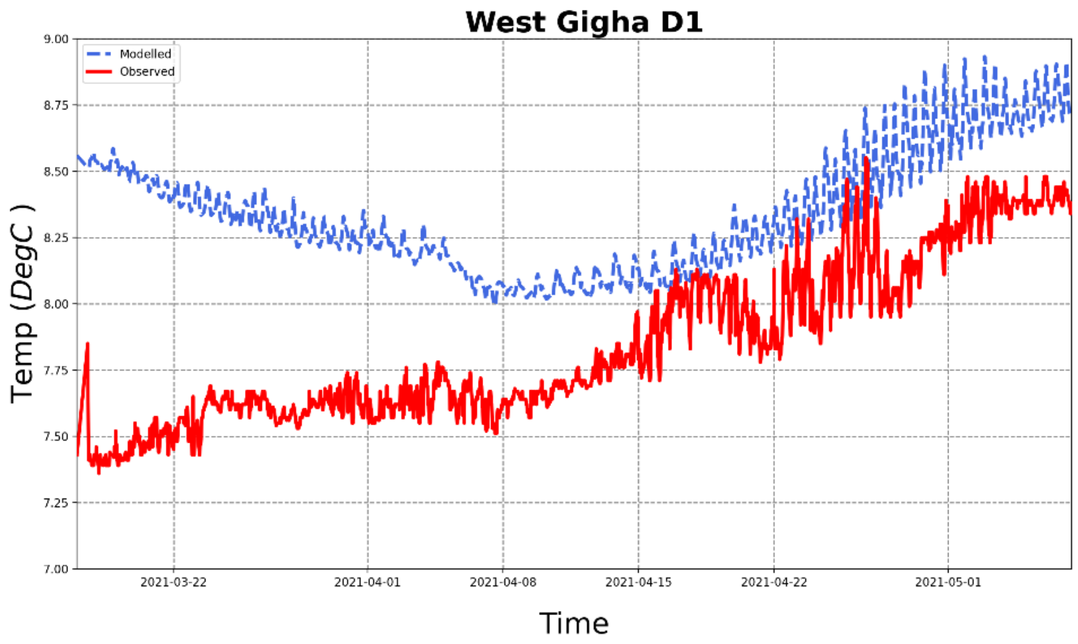
3.4 Combined model performance

The model is considered to accurately replicate the hydrographic conditions (water level, velocity and bed temperature) at the West Gigha deployments and well approximate the non-contemporary observed water column velocities at the four remaining deployments on the east of Gigha. This localised review of model performance outlines that the model is suitable for the review of hydrographic processes in the primary area of interest.

In the wider domain, the scarcity of hydrographic observations available makes validation in this wider area difficult. However the four water-level observations demonstrate a good geographical spread throughout the domain and the model performance in replicating hydrographic conditions at these locations with a consistent RMSE value of circa 0.2 m outlines that the model appropriately replicated water level conditions in the wider domain.

The model is therefore considered highly skilled in the replication of hydrographic conditions within the model domain and particularly within the primary area of interest, in the vicinity of West Gigha.

The impact of bath treatments will be reviewed in combination with congruent releases from existing BFS farms at Druimyeon Bay and East Tarbert Bay. The existing sites will be simulated based on previous releases of bath treatments at BFS farms.



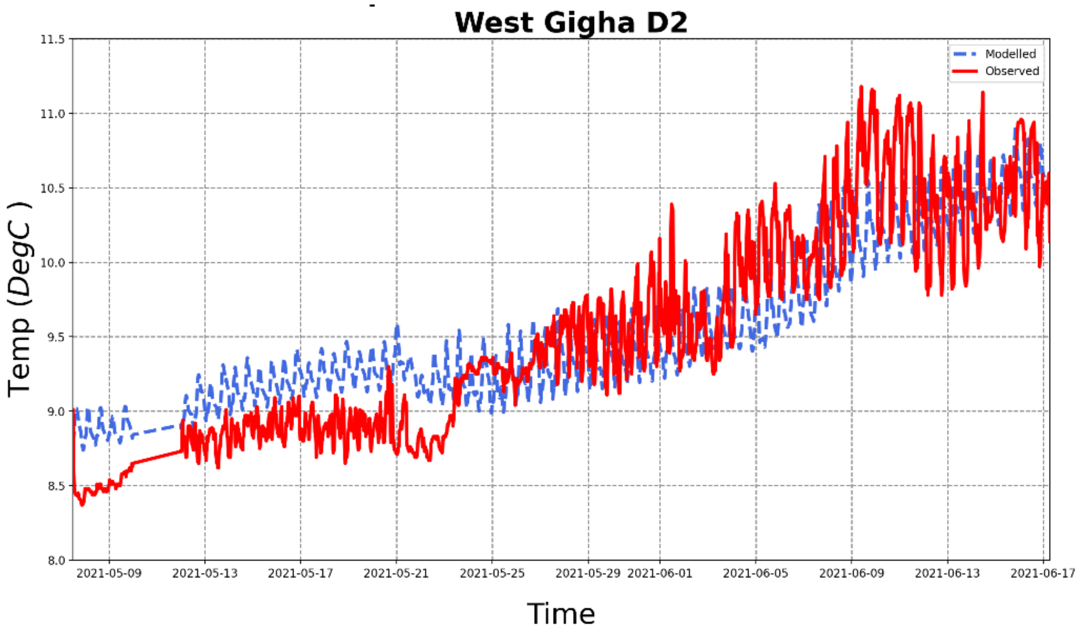
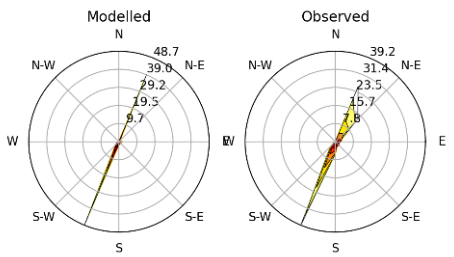
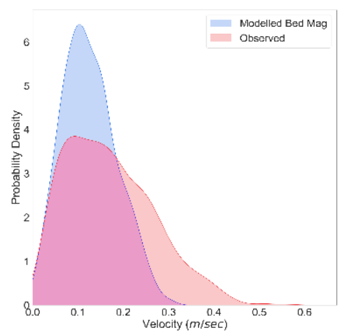
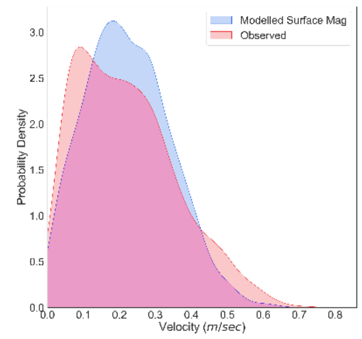
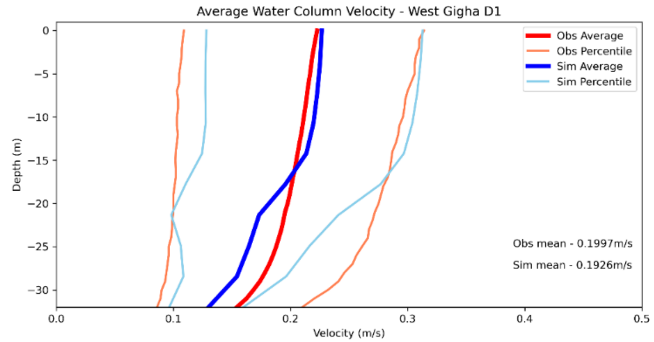
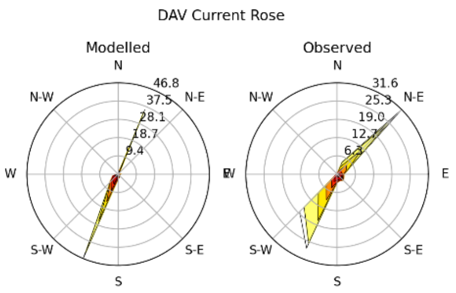
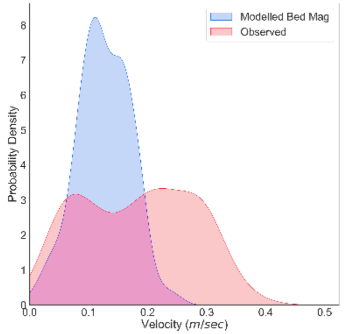
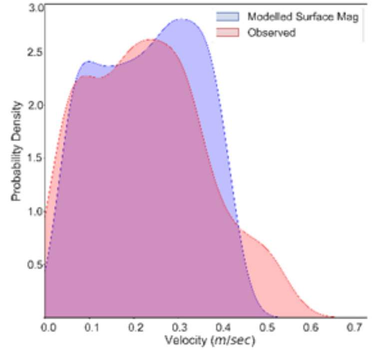
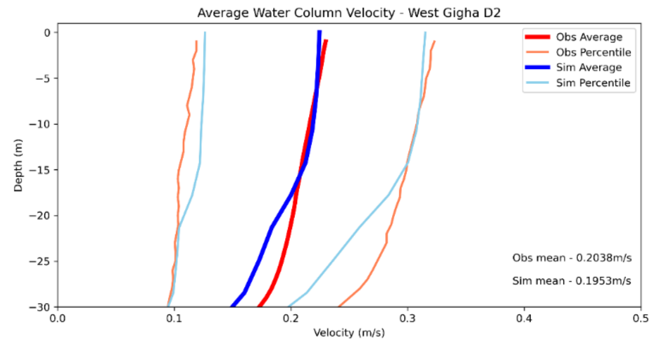
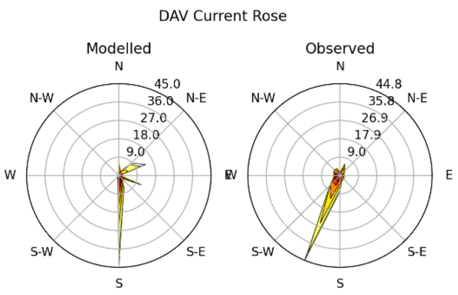
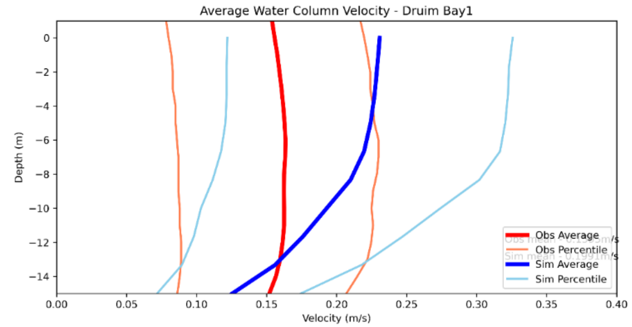
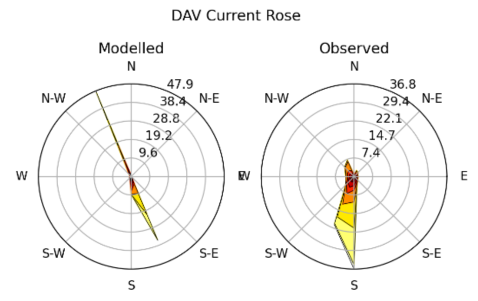
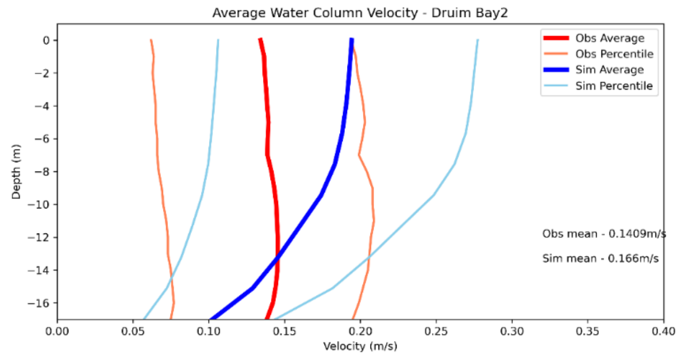
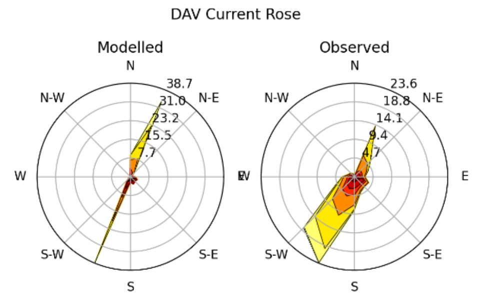
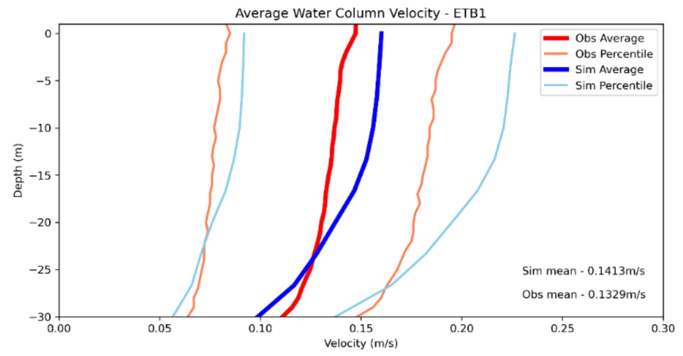
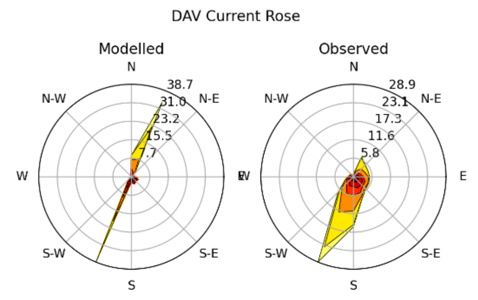
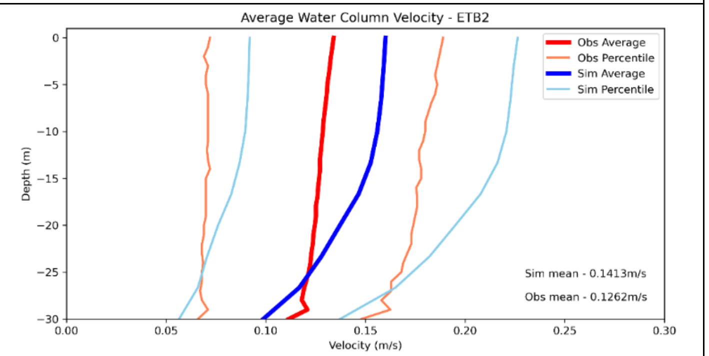


Figure 3.7: Modelled and observed bed temperature at West Gigha deployments (Deployment 1: top, Deployment 2: bottom)

Table 3.1: Simulated vs. Observed velocity performance.

Site	Velocity Vectors: Modelled & observed	Bed Velocity distribution	Surface Velocity distribution	Velocity profiles
West Gigha 1				
West Gigha 2				
Druimyeon Bay 1		Non congruent dataset, velocity magnitude density not reported		

Site	Velocity Vectors: Modelled & observed	Bed Velocity distribution	Surface Velocity distribution	Velocity profiles
Druimyeon Bay 2		Non congruent dataset, velocity magnitude density not reported		
East Tarbert Bay 1		Non congruent dataset, velocity magnitude density not reported		
East Tarbert Bay 2		Non congruent dataset, velocity magnitude density not reported		

3.5 Hydrodynamic sensitivity

The MIKE 3 suite is known to be sensitive to modeller decisions, in other work packages, undertaken by BFS. Models with similar architecture have been found to be sensitive to boundary conditions, atmospheric forcing and domain extent and insensitive to bed roughness length. An additional sensitivity test was undertaken to review model sensitivity to grid resolution in the vicinity of the West Gigha farm. This test is outlined below.

3.5.1 Mesh geometry & resolution

Mesh geometry was reviewed in the vicinity of the proposed West Gigha farm where there are observations congruent to the simulation period. The mesh resolution was reviewed and reduced in area was refined to have elements with a maximum area of 10,000 m^2 using the MIKE mesh builder and the bathymetry re-interpolated. This uniform spatial distribution varies slightly from the growth in BlueKenue with a mean spacing of ~100 to 125 m and an element area of circa 8,000 m^2. The observed velocity profile with the chosen mesh resolution and the modified mesh resolution are presented below.

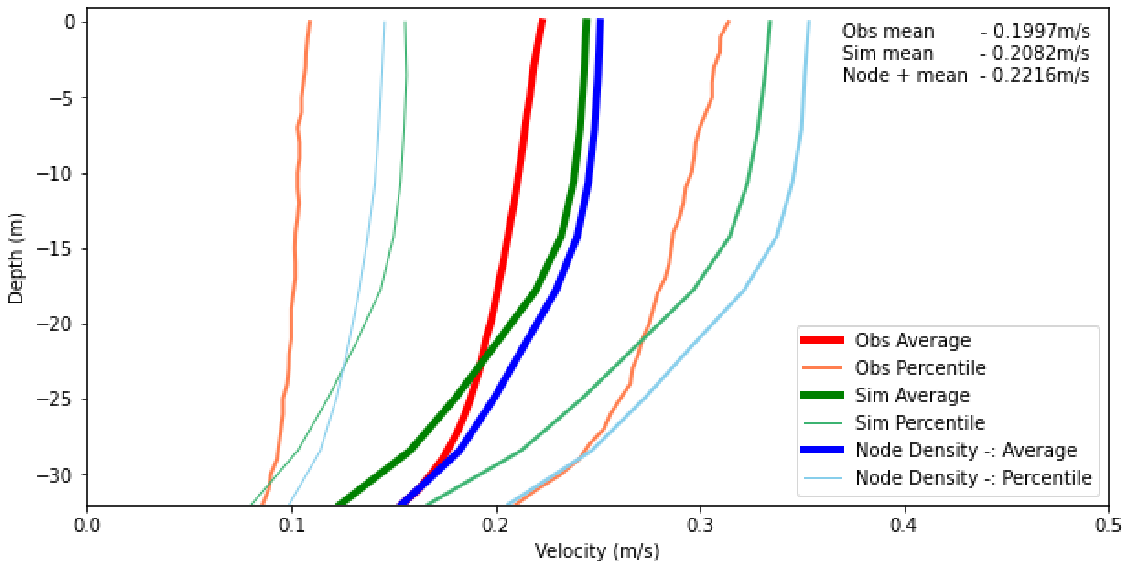


Figure 3.8: Model Sensitivity: Mesh resolution at West Gigha

The velocity profile above outlines the simulated velocities are sensitive to the mesh resolution in the vicinity of the hydrographic deployment at West Gigha. It is anticipated the increased bathymetry resolution in the standard mesh resolution better represents the undulation in the bed and facilitates the best possible definition of the features. Whilst the reduced mesh definition has a closer mean velocity to the observed conditions, the chosen mesh resolution is considered to approximate the conditions at the site well with increased representation of bathymetric features and horizontal velocity shear. The modelled velocity was deemed sensitive to mesh resolution. The same sensitivity was not noted in bed temperature and water level.

3.6 Third party review

The hydrodynamic model was reviewed by software developers at DHI Consulting, reviewing the model setup, performance and suitability for the proposed application for the review of dispersal of aquaculture related discharge within the model domain. DHI's summary of the hydrodynamic modelling package is presented below:

> *"As a final note, from DHI's perspective modelling of a complex area, as this is, it is most of the times difficult to achieve perfect model skill on every single available validation point. As long as the model skill is not considered unrealistic and the general circulation patterns are observed and replicated consistently it should, depending on scope, to be sufficient for risk-based assessments. Focusing on West Gigha site especially, the validation presented in the accompanying document* [1] *is on overall considered very good for risk-based assessments at the vicinity of the development area."* C.Mitsis (DHI), 2022

The model is therefore considered appropriate for the proposed application in reviewing particle dispersal from farms within the area surrounding the Isle of Gigha.

4. Conclusion

The Isle of Gigha is located within a highly complex hydrographic environment, a short distance from an amphidromic point and influenced from water bodies in the Inner Hebrides, the Irish sea and the Malin Sea area. Replicating the observed conditions over the six validation periods is considered problematic and complex. The validation of model capabilities outlined in this report, particularly of bed temperature at West Gigha, is thus considered high. Subsequently, the model is considered appropriate to simulate the dispersion of aquaculture related discharges (bath treatments, solid and lice dispersal) at West Gigha, Druimyeon Bay and East Tarbert Bay as the model accurately replicates observed water levels, velocity vectors and temperature for each dataset assessed.

This large scale, 3D baroclinic model is therefore appropriate to assess the dispersal of aquaculture related by-products from locations surrounding the six ADCP datasets and four long term water level observation record available at the time of writing. This extensive validation process is of high quality both spatially and temporally and is intended to give greater confidence in the accuracy of simulated hydrographic processes.