PARTRAC

Loch Long Salmon
Nutrient Modelling

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EXECUTIVE SUMMARY

Loch Long Salmon Company are proposing to construct the first semi-closed containment marine salmon farm in Scotland at the Beinn Reithe site, located on Loch Long; a sea loch which extends north-eastward from the Firth of Clyde. A two-dimensional hydrodynamic marine model (coupled with a particle tracking module) has been developed to provide further evidence to support the assessment of regulatory compliance in terms of the potential impact to a shellfish waters protected area located in the vicinity of the proposed development. The model has been validated and calibrated against measured datasets and applied either directly, or via a series of strategic particle tracking simulations, to assess both dissolved and particulate bound nutrients released. The data generated from the study has been interrogated and utilised to:

1. Validate the output of the loch nutrient model used previously to assess nutrient enhancement within the receiving water body via the application of verified input data to the model; and,
2. Provide additional lines of evidence regarding the dispersion potential of particulate bound nutrients (i.e. waste) from the proposed development and the existing finfish farm site.

The calibration and validation of the marine model has demonstrated effective model performance in terms of accuracy, skill and bias and as such the model is deemed ‘fit for purpose’.

The verification of the input values for the loch nutrient model corroborated the findings of the SEPA screening exercise and it was concluded that the original assessment was found to be conservative in its predictions. By reducing the area of assessment to only include for the upper reaches of Loch Long, the ascribed nutrient enhancement index value increases from ‘1’ to ‘2’ for 2 of the options assessed via the loch nutrient model. However, supporting analyses of the flushing time of the upper basin of Loch Long indicated that the predicted flushing time remains highly similar, suggesting that the predicted increase in impact is a function of the reduction in the area of assessment rather than the prevailing hydrodynamic processes. These data, combined with an assessment of the topography/bathymetry, indicate that the upper and lower basins of Loch Long do not act as two separate systems, rather they act as a single, well-connected, water body.

Evidence garnered from simulations designed to support an assessment of the particulate bound nutrients (i.e. waste) predicted a highly localised impact footprint which is a function of the quiescent tidal flow regime, applied settling velocity and shallow water depths. These simulations predicted that no cumulative impacts would occur between fish farm developments.

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Units and Conventions

The following list describes the units and conventions used in this report. Unless stated otherwise, units have been expressed using the SI convention.

- Current direction is expressed in compass points or degrees, relative to true North [°T], and describes the direction towards which the currents are flowing.
- Current speeds are expressed in metres per second [m/s].
- Water levels are expressed in metres [m] relative to Mean Sea Level (MSL).
- Positions are quoted relative to WGS 84 except where stated.
- All times are quoted in Coordinated Universal Time [UTC].

1 Study Context

Loch Long Salmon Company are proposing to construct the first semi-closed containment marine salmon farm in Scotland at the Beinn Reithe site, located on Loch Long; a sea loch which extends north-eastward from the Firth of Clyde. Figure 1 shows the location of the proposed site on a map (Figure 1).

Figure 1. The proposed site (Beinn Reithe – BNRT1), the Loch Long fish farm (FFMC76) and the Shellfish Water Protected Area are marked. Image reproduced from SEPA (2020).

Following a recent screening exercise for the Beinn Reithe site (SEPA, 2020), the following guidance was provided detailing the requirement for, and potential scope of, higher resolution marine modelling at the site. Such modelling is required to provide further supporting evidence for a robust assessment of regulatory compliance in terms of the potential impact to a shellfish waters protected area located in the vicinity of the proposed development. The guidance provided was as follows:

- *Due to the identified risks, 3D marine modelling should be carried out. Models used must be fully calibrated/validated using appropriate field data. For nutrient modelling, this is likely to be substantially more involved than the standard approach.*
- *The marine model should include discharges from Beinn Reithe (BNRT1), Loch Long (FFMC76) and*

the point source outfall from Beinn Reithe (BNRT1).

- *The resolution of the marine model should be relatively fine around the proposed site and identified features at risk. It may also require a high number of vertical layers.*
- *Nutrient modelling of this site and all other significant nutrient inputs into the head of Loch Long will also be required.*

Screening modelling demonstrates sediment discharges from Beinn Reithe (BNRT1) may influence the Shelllfish Protected Area in the upper sections of Loch Long. Although levels of risk associated with this site are difficult to predict without CFD modelling demonstrating realistic levels of waste capture at this site, higher resolution marine modelling will likely be required to ensure risks to protected shellfish waters are low.

Further engagement with SEPA regarding these recommendations indicated that:

1. *There is no requirement for 3D modelling to be performed. Due to the identified risks, 2D marine modelling should be carried out. Models used must fully calibrated/validated using appropriate field data;*
2. *Higher resolution modelling should be performed to validate the previously used ECE model to assess nutrient enhancement within the receiving water body. The marine model should include discharges from Beinn Reithe (BNRT1), Loch Long (FFMC76) and the point source outfall from Beinn Reithe (BNRT1);*
3. *The resolution of the marine model should be relatively fine around the proposed site and identified features at risk; and*
4. *Nutrient modelling of this site and all other significant nutrient inputs into the head of Loch Long will also be required.*

Upon SEPA's request, and to provide a more robust assessment of the potential impact of the proposed development in terms of nutrient enhancement in receiving waters, a two-dimensional hydrodynamic marine model (coupled with a particle tracking module) has been developed.

2 Approach

In line with the SEPA guidance issued, and published key industry guidance (SEPA, 2019), a high resolution two-dimensional marine model, validated and calibrated against measured data, was developed to support assessment of the potential impact of the proposed development in terms of both dissolved and particulate bound nutrients released from the proposed development. Data extracted directly from the model, and from pertinent particle tracking simulations, was employed to:

1. Validate the output of the loch nutrient model used previously to assess nutrient enhancement within the receiving water body via the application of verified input data to the model; and
2. To provide additional lines of evidence regarding the dispersion potential of particulate bound nutrients (i.e. waste) from the proposed development and the existing finfish farm site.

This approach is designed to provide additional data and information which complement associated work streams (e.g. DEPOMOD and CFD modelling simulations) and offers a greater evidence base from which to demonstrate regulatory compliance. Briefly, the report details the following:

- The validation of the loch nutrient model;
- The development, calibration, and validation of the marine model;
- The setup and parameterisation of the particle tracking simulations and their purpose for supporting the wider assessment;
- The results of the particle tracking simulations;
- The application of verified data to the Loch nutrient model and the model outputs; and,
- Discussion and concluding remarks.

3 Validating the Loch Nutrient Model

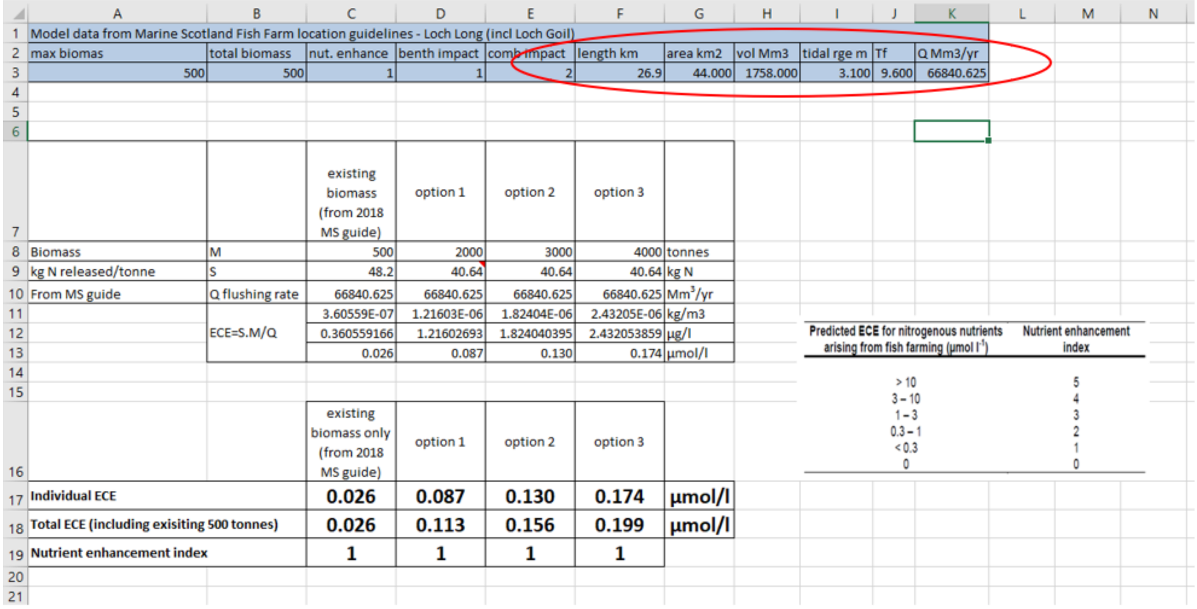
The loch nutrient model is a simple box model that estimates the enhancement of dissolved nitrogen above background levels within a loch system. The box model is known as the Equilibrium Concentration Enhancement (ECE) model. The model uses the following simple equation:

$$ECE = \frac{SM}{Q}$$

1.

Where, ‘S’ is the rate at which nutrient nitrogen is discharged (kg/tonne production/year), ‘M’ is the total maximum consented biomass of all the farms in the loch (tonnes) and ‘Q’ is the flushing rate of the Loch.

‘Q’ is typically calculated from an assessment of the hydrographic characteristics of the loch and assumes nitrogen is only removed from the sea lochs by tidal flushing (Gillibrand *et al.*, 2002). The assumption that tidal exchange forms the core exchange mechanism within sea lochs is justified (Edwards & Sharples, 1986), however the rate of exchange can vary locally due to meteorological influences superimposed on the tide and due to fluctuations in freshwater inputs (e.g.river flow). Figure 2 shows a screenshot of the ECE model user interface.



Model data from Marine Scotland Fish Farm location guidelines - Loch Long (incl Loch Goil)

max biomas	total biomass	nut. enhance	benth impact	comb impact	length km	area km2	vol Mm3	tidal rge m	Tf	Q Mm3/yr
500	500	1	1	2	26.9	44.000	1758.000	3.100	9.600	66840.625

		existing biomass (from 2018 MS guide)	option 1	option 2	option 3	
Biomass	M	500	2000	3000	4000	tonnes
kg N released/tonne	S	48.2	40.64	40.64	40.64	kg N
From MS guide	Q flushing rate	66840.625	66840.625	66840.625	66840.625	Mm³/yr
	ECE=S.M/Q	3.60559E-07	1.21603E-06	1.82404E-06	2.43205E-06	kg/m3
		0.360559166	1.21602693	1.824040395	2.432053859	µg/l
		0.026	0.087	0.130	0.174	µmol/l

	existing biomass only (from 2018 MS guide)	option 1	option 2	option 3	
Individual ECE	**0.026**	**0.087**	**0.130**	**0.174**	**µmol/l**
Total ECE (including exisiting 500 tonnes)	**0.026**	**0.113**	**0.156**	**0.199**	**µmol/l**
Nutrient enhancement index	**1**	**1**	**1**	**1**	

Predicted **ECE** for nitrogenous nutrients arising from fish farming (µmol l^{-1})	Nutrient enhancement index
> 10	5
3 – 10	4
1 – 3	3
0.3 – 1	2
< 0.3	1
0	0

Figure 2. The user interface of the ECE model applied to determine a 'nutrient enhancement index value' for the proposed development. The circled cells indicate where input values can be verified using high resolution marine modelling and strategic particle tracking simulations. N.B. a capture efficiency of 60% is applied and the input values reflect those applied by SEPA as part of the screening assessment (SEPA, 2020).

In more complex loch systems (i.e. in the upper reaches of loch systems where tidal exchange may potentially be reduced) uncertainty exists regarding the validity of the outputs (quantification of the nutrient enhancement index value, see Figure 2) of the oversimplified ECE model, and thus further evidence is required to inform the assessment of compliance. Figure 2 reveals that the input values which influence the determination of ‘Q’, and thus the output of the model, are as follows:

<u>*Area (A) and Volume (V)*</u>

The defined area of the loch, and the volume of water that area contains, significantly influences the determination of ‘Q’. By increasing the area of interest, ‘Q’ is increased which in turn reduces the potential impact of the development, producing a lower nutrient enhancement index value. The opposite of that (i.e. reducing the size of the area of interest) has the opposite effect, increasing the potential impact of the development, producing a higher nutrient enhancement index value.

Tidal Range (R)

The tidal range is defined as the difference between the Lowest Astronomical Tide (LAT) and the Highest Astronomical Tide (HAT)

Flushing time (T_f)

Assuming that exchange is predominantly tidally driven and that water volume is replaced by water entering and leaving a sea loch on each tide (Edwards and Sharples, 1986), the flushing time is given by:

$$Tf = \frac{0.52\,V}{0.7\,A.R}\,days \qquad 2.$$

Where V is volume, A is area and R is the tidal range.

The marine model and strategic particle tracking simulations were applied to assist in the verification of the input values used to determine ‘Q’,

N.B. Based on the initial assessment of the proposed development presented in Figure 2 a nutrient enhancement value of 1 is ascribed.

4 Development of the Marine Model

A hydrodynamic model for the Loch Long region, forced by a wider regional model (Firth of Clyde (FOC) model), was developed. This section presents details of the model set-up and configuration and provides information on calibration and validation procedures. Model performance is assessed by comparing the modelled conditions (water level and tidal flows) with measured data (water level and current speeds) derived from a recent measurement campaign conducted at the site, and other available datasets provided by SEPA (2020a). The following sections specifically detail the following aspects of the modelling process:

- Model configuration and boundary forcing;

- Setup of the model grid and implementation of the bathymetry across the local and regional domains; and,
- Calibration-validation and model performance.

The approach adopted in the setup, calibration and validation of the model closely follows the modelling guidelines published by SEPA (SEPA, 2019).

4.1 Software

The model has been developed using the MIKE21 software platform (developed and operated by the Danish Hydraulic Institute [DHI]). The MIKE 21 Flow Model is a comprehensive modelling system of two-dimensional (2D) free-surface flows using an unstructured flexible mesh grid. MIKE21 software is ideally suited for modelling a wide range of hydraulic and environmental phenomena in aqueous environments. The unstructured mesh approach provides an optimal degree of flexibility in the representation of complex geometries and enables smooth representations of boundaries (i.e. small mesh elements are used in the local areas around sites of interest where greater detail is required). The hydrodynamic module simulates water level variations and flows in response to a variety of forcing functions, these include:

- Bottom shear stress;
- Wind shear stress;
- Barometric pressure gradient;
- Coriolis force;
- Momentum dispersion;
- Sources and sinks;
- Flooding and Drying; and,
- Wave radiation stresses.

4.2 Configuration

The Firth of Clyde (FOC) model used at the screening stage (SEPA, 2020) forms the regional model in this study. The regional model is a fully baroclinic model, including tidal and meteorological forcing and freshwater runoff inputs. It covers the western Scottish shelf, from the Isle of Mull to the Isle of Man (Figure 3). The FOC output consists of a year-long simulation of the amplitudes, and phases, of eleven tidal constituents (MM, MF, O_1, K_1, Q_1, P_1, M_2, S_2, N_2, K_2, M_4). Historically, the FOC model has compared favourably against various current meter data, indicating that the model provides a reasonable description of the hydrodynamic regime in the region.

Outputs from the regional model were provided to us by SEPA and these were used to force the local model[1] which is nested within the regional model domain. The local model extends from broadly the Isle of Arran to the west of Loch Long (Figure 4). The resolution of the local model grid increases from *circa* 200m at the outer boundaries, to *circa* 20 m along the shoreline. Typically, a nodal resolution of circa 25-30 m is achieved in the near-shore waters within Loch Goil, Holy Loch and Upper Loch Long (Figure 5).

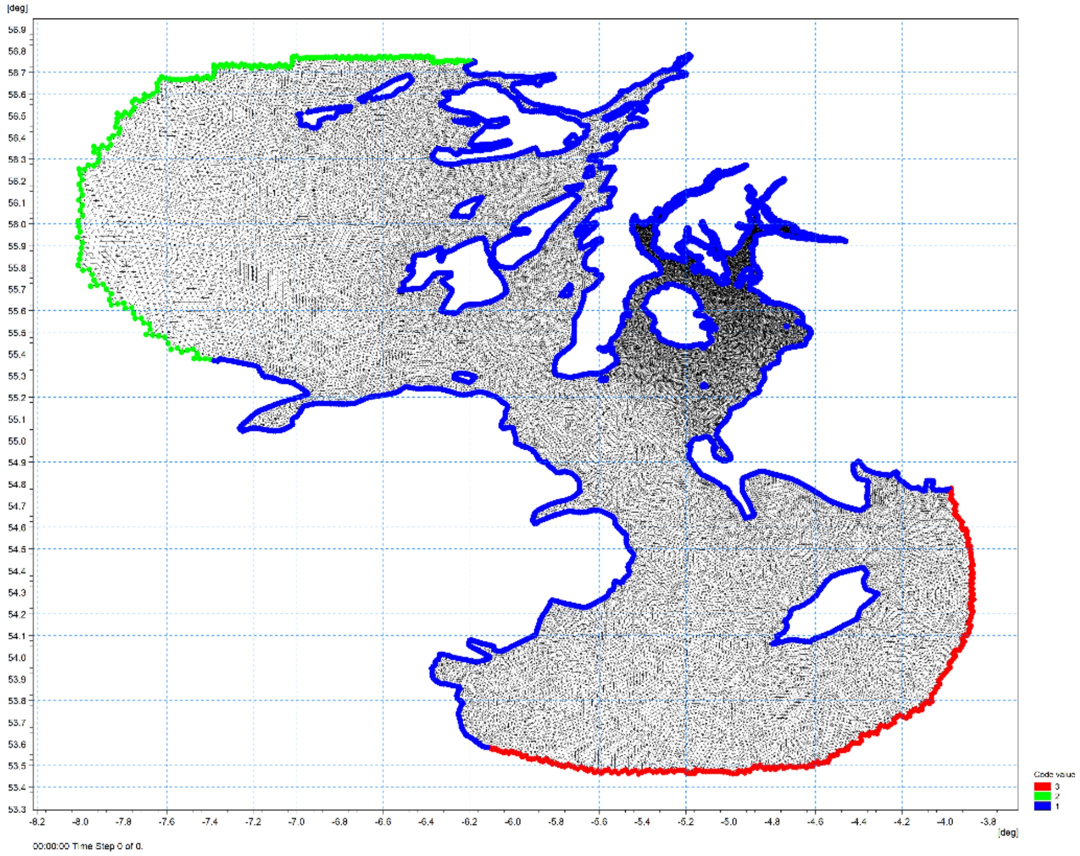


Figure 3. The regional FOC model domain. Data source: SEPA (2020a).

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[1] The local area model was forced from water level elevation not tidal flow velocity.

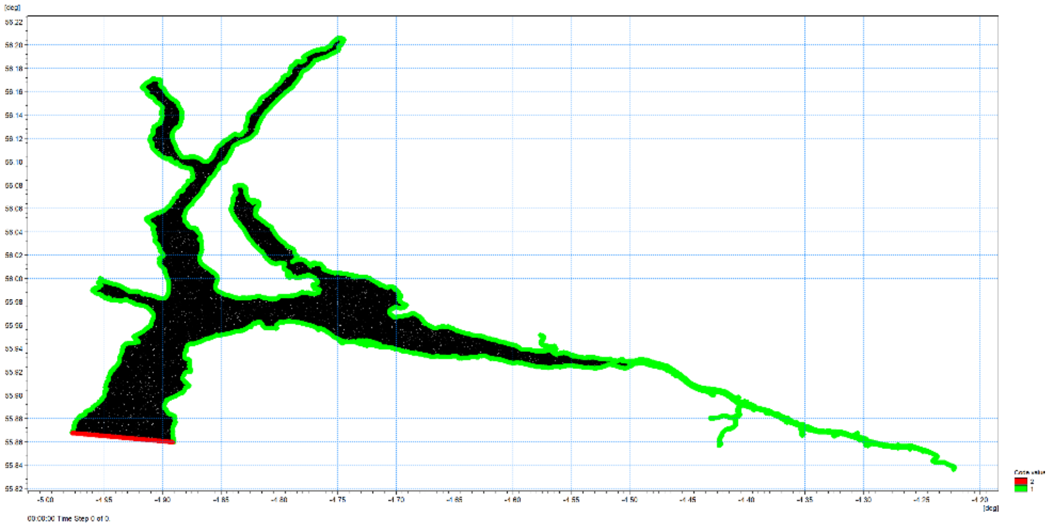

Figure 4. The local model mesh. N. B. The green boundary represents the shoreline, and the red boundary is the driving conditions being water elevation extracted from the FOC model.

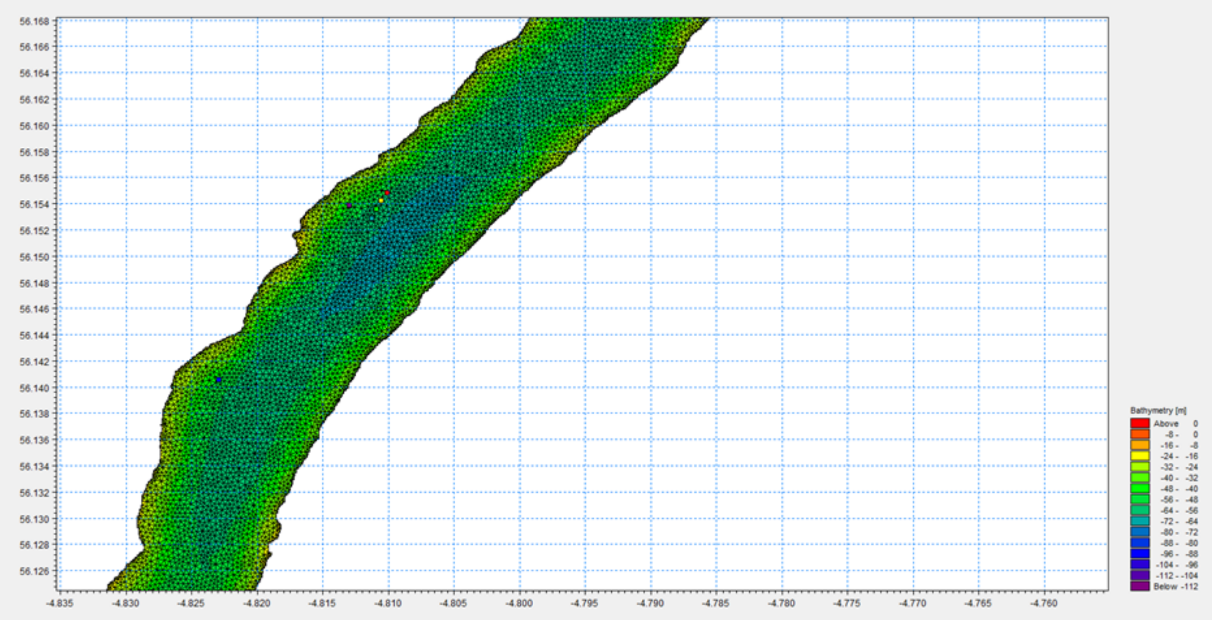

Figure 5. The unstructured mesh in the upper reaches of Loch Long. The location of the proposed development (BNRT1) and the existing fish farm (FFMC76) are overlain the model mesh.

4.3 Bathymetry

Local bathymetry was derived from three main sources:

- The FOC model (SEPA, 2020)[2];
- The European Marine Observation and Data network (EMODnet) bathymetry data (https://portal.emodnet-bathymetry.eu); and,
- United Kingdom Hydrograhic Office (UKHO) INSPIRE bathymetry data (https://datahub.admiralty.co.uk/portal/apps/webappviewer/).

Following a review of data quality, these data were merged and converted into a single topographic dataset (water depths relative to Mean Sea Level [MSL]) and carefully inspected for discontinuity. The shoreline was derived from Satellite EMODnet shoreline data, relative to MSL. The bathymetry implemented within the local model is displayed in Figure 6.

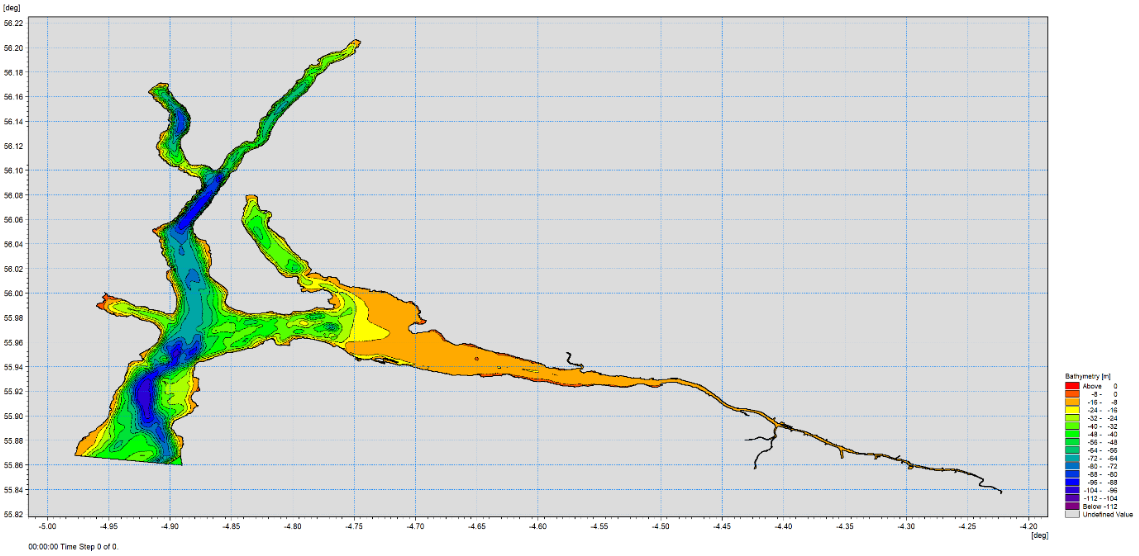

Figure 6. Bathymetry implemented in the local model. Water depths are presented relative to MSL.

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[2] A quantitative comparison of the more up to data derived from the UKHO and data provided by SEPA (2020a) revealed differences in water depths ranged from -1.8 m to 2.6 m. This equates to approximatley 5 % of averaged water depths across the area.

4.4 Fluvial and Local Wind Inputs

The modelling package provided by SEPA included 213 fluvial sources. In total 12 rivers/streams discharge to waters within the local model domain (Figure 7). Fluvial inputs are mostly limited to small streams; the largest averaged input observed within the data record is from source 76, however this has a negligible influence on the hydrodynamic regime within the area of interest (Figure 7). An averaged year-long flow record for these sources is presented in Figure 8.

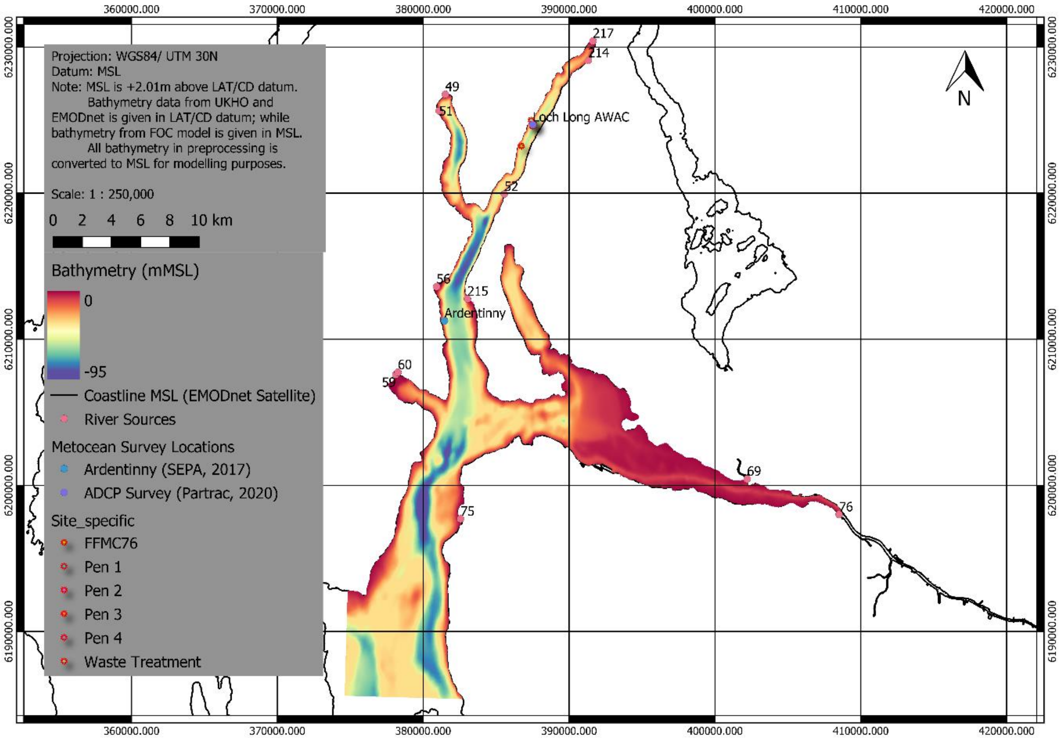

Figure 7. The fluvial sources which input to the local model domain. The proposed fish farm site location and the location of ADCP deployments, used to support model validation, are also included for reference.

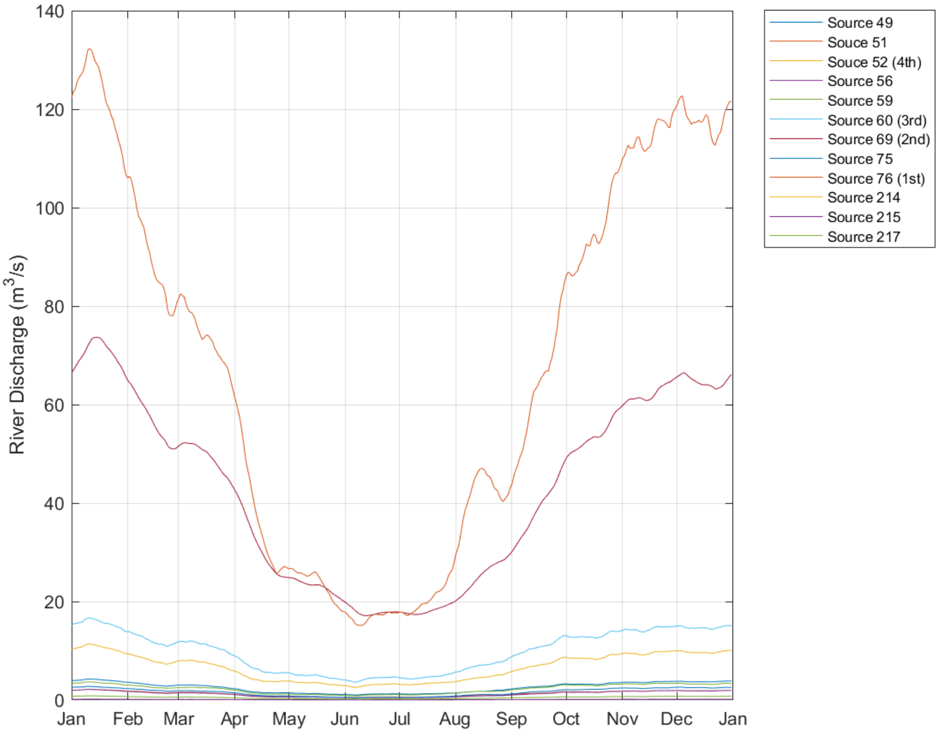

Figure 8. Averaged daily flows from the 12 fluvial inputs which discharge to the local model domain (top four river sources shown).

Wind forcing contributes towards the development of non-tidal flow fields. The model was run with and without local wind forcing applied to the local area model. Hourly wind speed, direction, and air pressure data from the Met Office meteorological station at Paisley were used as source data.

N.B. for the purpose of model calibration-validation, simulations were performed without any wind forcing (in line with SEPA guidance (SEPA, 2019)).

4.5 Model Calibration

The local area model was calibrated using water level and current data measured by an Acoustic Doppler Current Profiler (ADCP) deployed on the loch bed at Ardentinny (located approximately 15 km from the proposed fish farm site, see Figure 7). The calibration exercise first investigated and compared the water surface elevation, as measured by the ADCP pressure sensor, and secondly the current speed and the north and east components of flow velocity. Model predictions are compared with the measured data record to assess model performance. The location and measurement duration data used to calibrate the model are detailed in Table 1.

Table 1. Location and measurement duration data of the ADCP deployment used for model calibration.

Site	Longitude	Latitude	Start Time	End Time	Duration (days)
Ardentinny	-4.902397	56.03187	05/10/2017	10/01/2018	97

The calibration was performed following industry standard techniques (e.g. Lambkin *et al*. 2009, Pye *et al*., 2017 and SEPA, 2019). Simulations were run for the same period as the observations and the modelled tidal elevation and velocity at the site evaluated against the observed data[3]. The bed friction and diffusion/dispersion coefficients were adjusted to obtain the best fit against the observed water surface level and current velocity data. The results of the calibration exercise are presented in Figure 9 to Figure 13. The performance statistics are shown in Table 2. The performance of the model during the calibration exercise can be summarised as follows:

- Water levels at Ardentinny were reasonably accurately modelled; the model slightly under – predicted the tidal range during the neap tidal phase and slightly over predicted the range during the spring tidal phase (see Figure 9 and Table 2).
- The model effectively simulated the dominant features of the observed flow field within the upper loch with flow velocity and direction strongly replicated (see Figure 10, Figure 13 and Table 2).
- North and east components of depth-averaged flow velocity were satisfactorily reproduced by the model. The model slightly under-predicted the eastward flow component during the neap tidal phase but slightly over-predicted during the spring tidal phase (see Figure 11). It should be noted that due to the dominant direction of flow being observed along the north-south axis, the eastward component was reduced which likely increased the error. The northward components of modelled current closely matched those of the observed currents, with reasonable agreement during the neap tidal phase. The northward flow component was slightly over-predicted during the spring tidal phase (see Figure 12).

The performance of the hydrodynamic model during model calibration exceeds target standards published in SEPA guidance (SEPA, 2019) (see Table 2).

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[3] Observed tidal elevations and velocities were extracted from the observational data using classical tidal harmonic analysis tool T_TIDE (R. Pawlowicz *et al*., 2002). Boundary conditions and flow data, were taken from the FOC model, coincident with the time of year of the observations (i.e. November – December for Ardentinny and June – July for the AWAC deployed at the proposed development site).

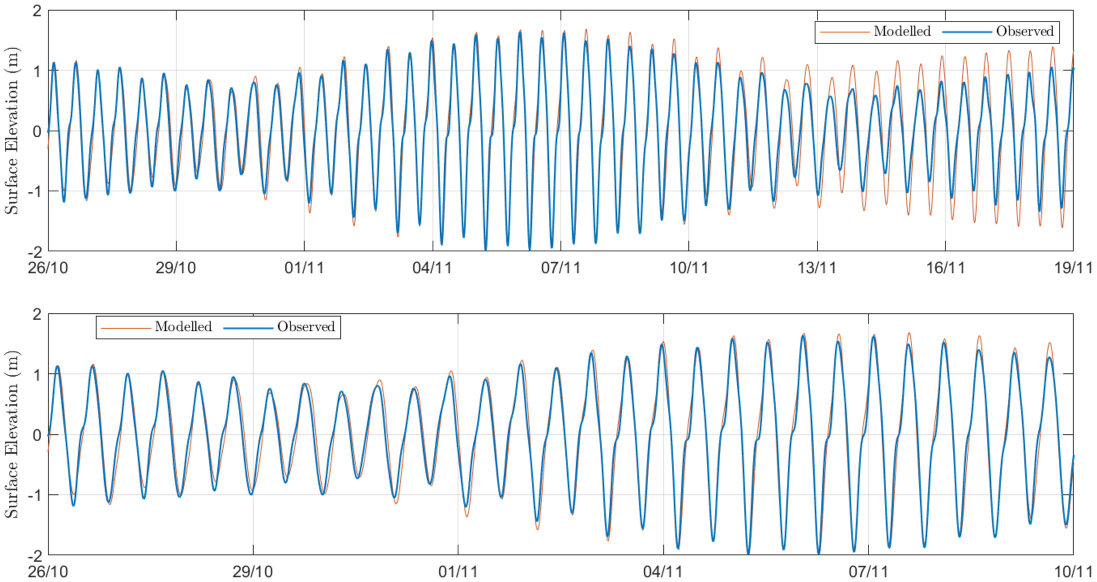

Figure 9. Time series showing the comparison between observed and modelled water surface elevation. The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a zoomed in subset 15-day record.

Figure 10. Time series showing the comparison between observed and modelled current speed. The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15-day record.

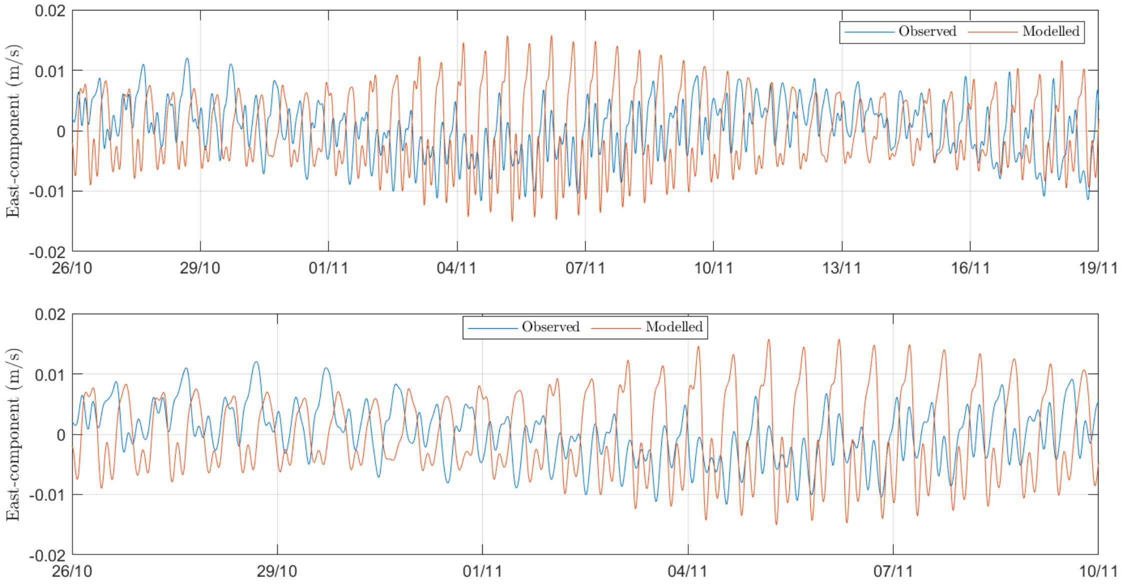

Figure 11. Time series showing the comparison between observed and modelled current velocities from the east component. The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15-day record.

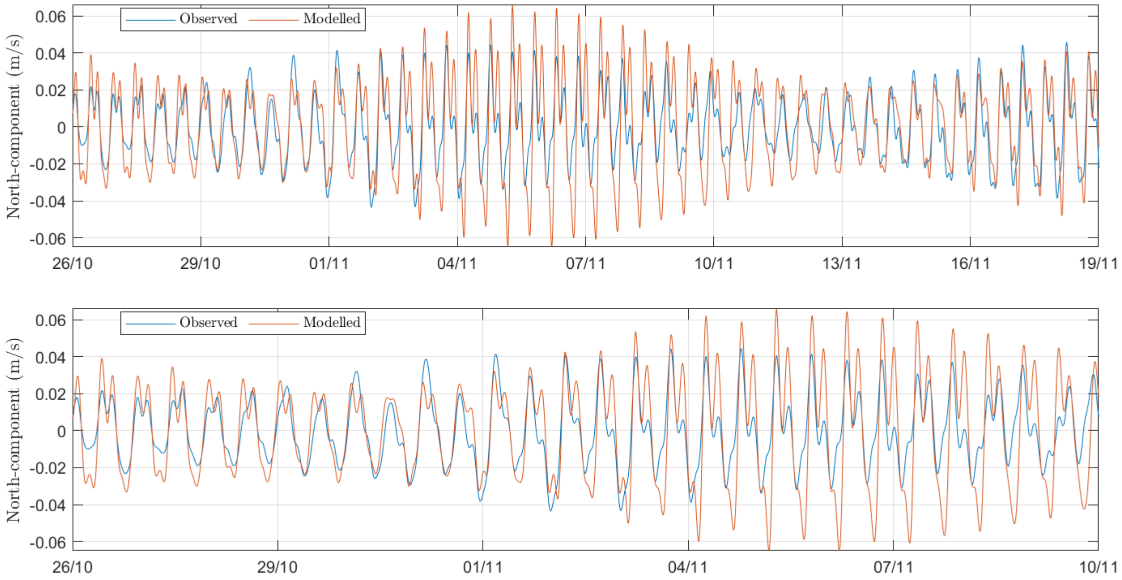

Figure 12. Time series showing the comparison between observed and modelled current velocities from the north component. The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15-day record.

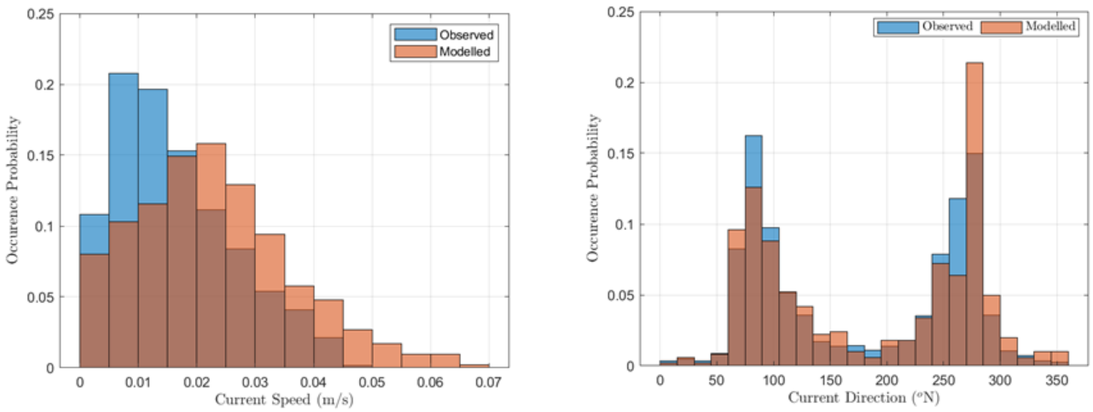

Figure 13. Histogram plots showing measured and modelled current speed (left) and flow direction (right). N.B. The orange colour shows where observed and modelled data overlap.

Table 2. Model performance statistics when compared to the Ardentinny ADCP data.

Parameters	Skill Score	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)	Mean Percentage Error (MPE)	Calibration / Validation Standard (SEPA, 2019)	
					Absolute	Percentage
Water Level (m)	0.91	0.19 m	0.26 m	7.5% springs 9.3% neaps	± 0.1 m	± 10 % springs ± 15 % neaps
High Water Phase (mins)	-	4 min	5 mins	-	± 15 min	
Current Speed (m/s)	0.78	0.01 m/s	0.01 m/s	14.4%	± 0.1 m/s	± 10 - 20 %
Current Direction (degrees)		15°	20°		± 30°	

4.6 Model Validation

The model validation was performed against data from an ADCP deployment at the proposed fish farm site (BNRT1, see Figure 7 for the frame location). The ADCP data were measured from mid-June to the end of July 2020. Table 3 shows the location and measurement duration data for the deployment. The validation exercise first investigated the water surface elevation, as measured by the ADCP pressure sensor, and secondly the depth averaged current speed and north and east components of flow velocity.

Table 3. Location and measurement duration data of the ADCP deployment used for model validation.

Site	Longitude	Latitude	Start Time	End Time	Duration (days)
Loch Long AWAC	-4.811033	56.153917	18/06/2020	30/07/2020	42

The results of the validation exercise are presented in Figure 14 to Figure 18. The performance statistics are presented in Table 4. The performance of the model during the validation exercise can be summarised as follows:

- Overall, the agreement between modelled and measured data is reasonable (see Figure 14 to Figure 18 and Table 4).
- The modelled tidal phase showed a phase lag of *circa* 30 mins compared to the observed data. This is thought to be due to internal wave activity which slightly modifies the phase of observed currents. Although the phase of the flow was not quite captured by the model, the magnitude of current speed and water surface elevation was broadly similar to the measured data observations.
- Histograms of the current velocity at the site demonstrate that the model broadly captures the orientation and magnitude of the observed flow (see Figure 18). The model slightly under-predicts the observed flows, particularly at the maximum observed speeds. This is likely a function of the salinity and stratification through the water column; the effects of which are not fully captured by the model.

The performance of the hydrodynamic model during model validation exceeds target standards published in the SEPA guidance (SEPA, 2019) (see Table 4), and thereby we consider it is acceptable for the present purpose.

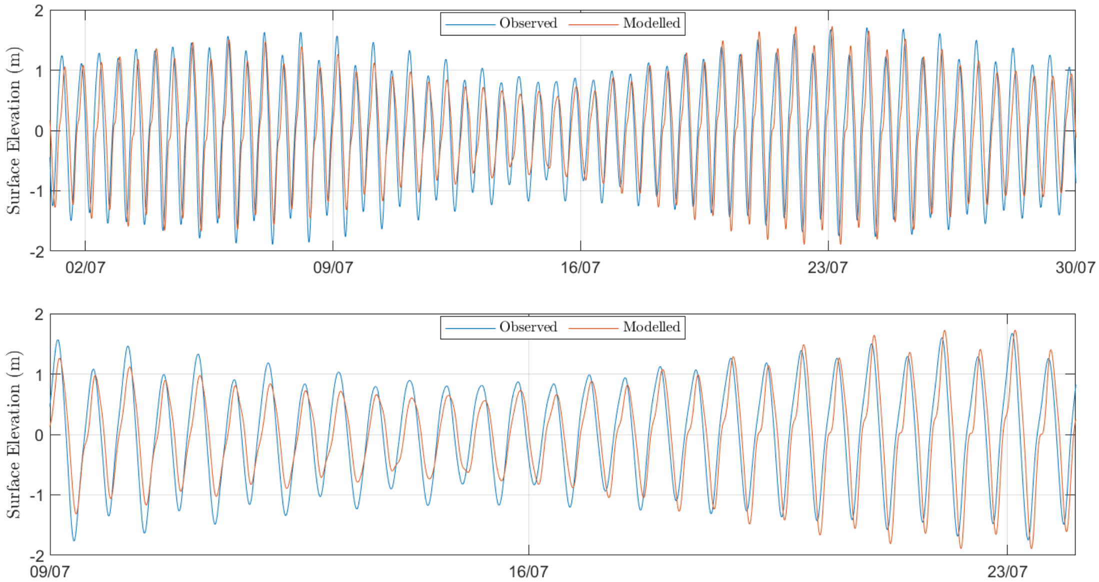

Figure 14. Time series showing a comparison between observed and modelled water surface elevation at the proposed fish farm site (BNRT1). The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15-day record.

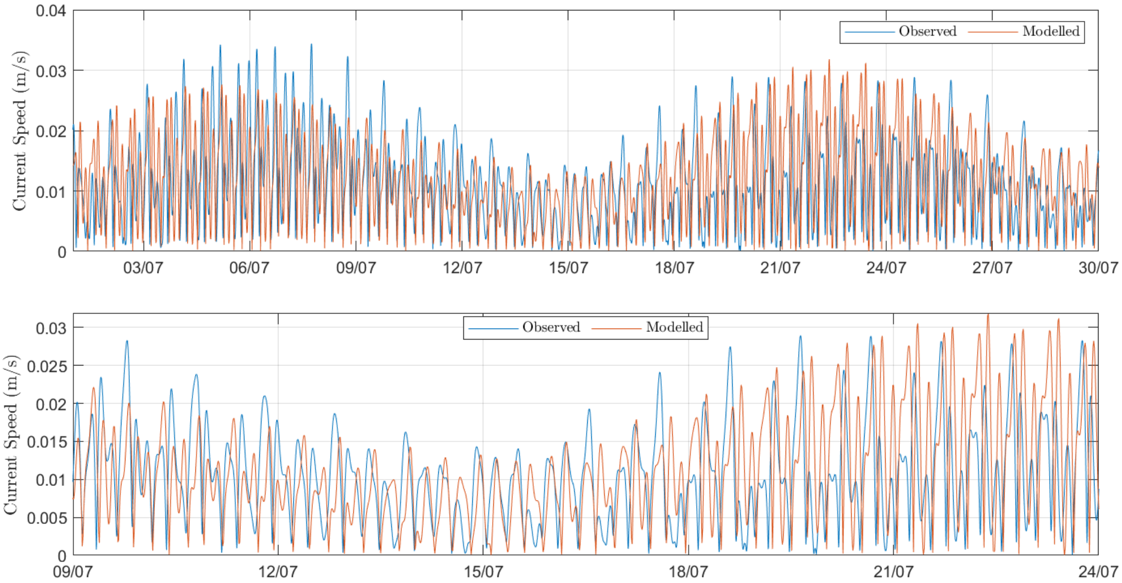

Figure 15. Time series showing a comparison between observed and modelled current speed at the proposed fish farm site (BNRT1). The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15-day record.

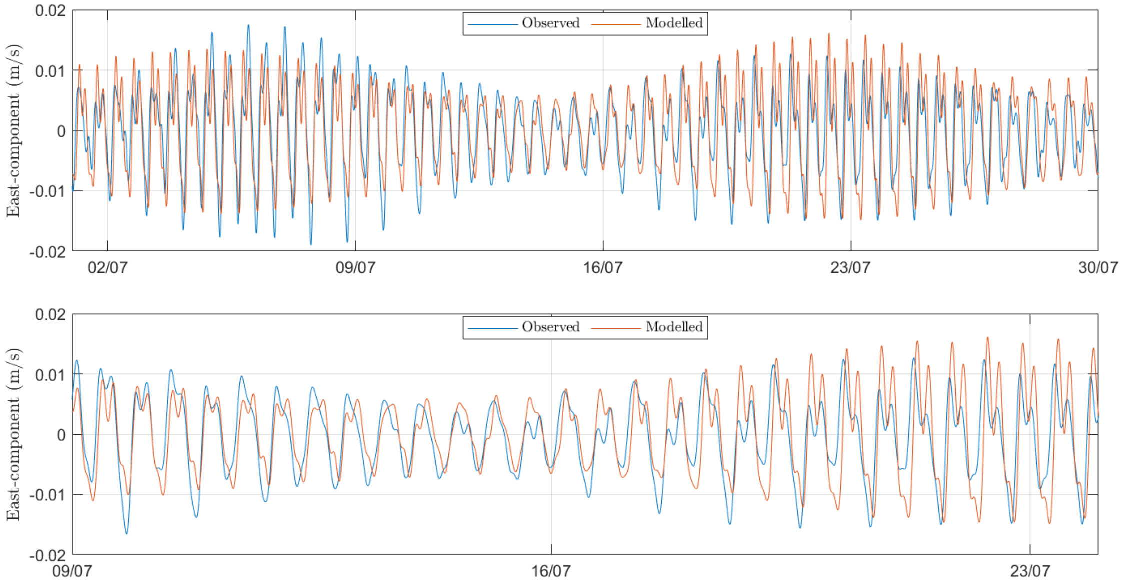

Figure 16. Time series showing a comparison between observed and modelled east component of flow velocity at the proposed fish farm site (BNRT1). The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15 day record.

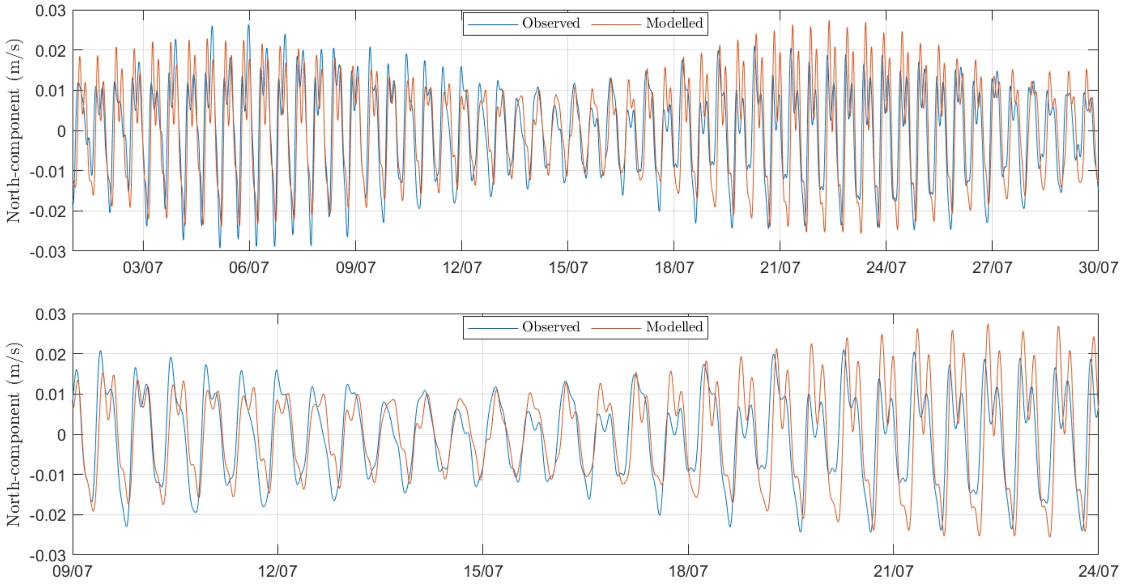

Figure 17. Time series showing a comparison between observed and modelled north component of flow velocity at the proposed fish farm site (BNRT1). The top plot shows the full data recorded by the ADCP at Ardentinny whilst the bottom plot provides a subset 15-day record.

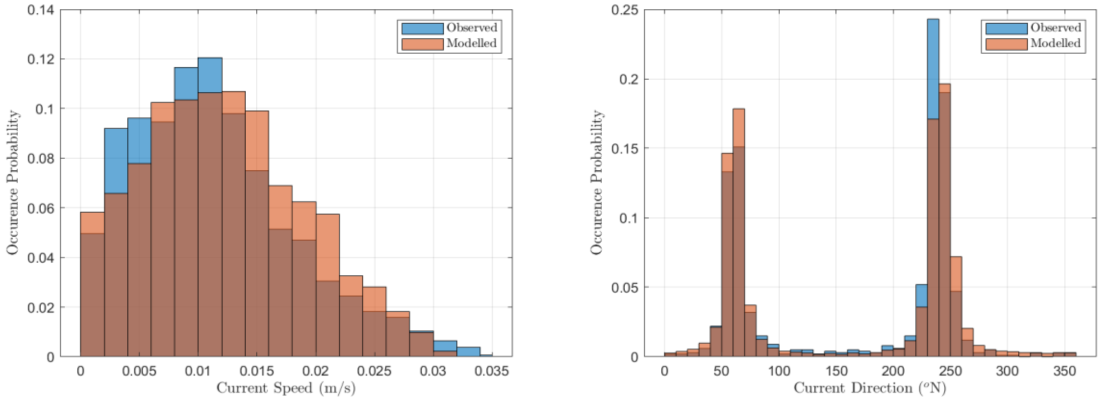

Figure 18. Histogram plots showing measured and modelled current speed (left) and flow direction (right). N.B. The orange colour shows where observed and modelled data overlap.

Table 4. Model performance statistics during model validation.

Parameters	Skill Score	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)	Mean Percentage Error (MPE)	Calibration / Validation Standard (SEPA, 2019)	
					Absolute	Percentage
Water Level (m)	0.97	0.12 m	0.15	8% springs 9% neaps	± 0.1 m	± 10 % springs ± 15 % neaps
High Water Phase (mins)	-	15 mins	21 mins	-	± 15 min	
Current Speed (m/s)	0.88	0.01 m/s	0.01 m/s	12 %	± 0.1 m/s	± 10 -20 %
Current Direction (degrees)	-	12°	15°	-	± 30°	

5 Particle Tracking Simulations

To garner robust predictions of potential nutrient enhancement due to both soluble and particulate bound nutrients, a series of particle tracking simulations were run as part of this study. To run these simulations, a particle tracking module within the DHI suite was coupled with the validated hydrodynamic model. The aim of undertaking these simulations was to:

Simulation 1: Assess the flushing time of Loch Long, and the upper basin, to directly verify the input values to be applied within the ECE model; and,
Simulation 2: Determine the transport trajectory (transport pathways), and impact footprint, of particulate bound nitrogen in the upper loch using a Lagrangian approach.

Sensitivity cases were run to examine the influence of seasonality on model predictions. Thus, for the two simulations, two cases were run over a period of 30 days reflecting typical winter and summer conditions (e.g. enhanced fluvial and wind conditions). The two cases were setup as follows:

1. *Typical winter conditions*: Particles to be released on the 1st January coincident with the period of typically strongest wind forcing and highest river flow rate.

2. *Typical summer conditions*: Particles to be released on the 1st June coincident with the period of typically lowest wind forcing and lowest river flow rate.

5.1 Simulation 1

The computation of flushing time assumes that a waterbody functions as a continuously stirred tank reactor (CSTR), so that flushing time can be estimated from observations of outflow concentration over time. Using particle tracking simulations to verify the flushing time of the loch system therefore relies on a coincidental release of neutrally buoyant particles at each grid node, across the model domain. The flushing time is then defined as the point in time where only 37% of particles released remain within the model domain (Thoman & Mueller, 1987; Monsen et al., 2002).

Across the model domain the simulation was initiated with a uniform distribution of initial particles (~ one particle at each cell). Through time, the number of particles remaining inside the local model domain during the simulation period was determined. Recognising that releasing particles into the model domain may be influenced by both the tidal phase (timing) and seasonal effects, cases were initiated at different tidal phases (i.e. Mean Sea Level [MSL], Mean High Water Spring [MHWS], Mean Low Water Spring [MLWS], Mean High Water Neap [MHWN] and Mean Low Water Neap [MLWN]). In total, 10 cases were run as part of the simulation.

For this simulation, three geographical configurations were developed, one which included Loch Long and Loch Goil, the second comprising the upper basin of Loch Long with Loch Goil, and the third comprising solely the upper basinof Loch Long. The rationale behind including Loch Goil in the bounded area is to be consistent with (and thus allow comparability with) with the SEPA screening model approach. Furthermore, assessment of just the upper basin of Loch Long affords us the opportunity to interrogate the influence of ‘A’ and ‘V’ on the outputs of the ECE model.

5.2 Simulation 2

To investigate the transport trajectory, spatio-temporal distribution and ‘impact footprint’ of particulate bound nutrients released in the upper regions of the loch further simulations were run. To support the assessment of regulatory compliance, the ‘worst-case scenario’ was adopted for the modelling. Again, to investigate seasonal effects, cases were run under ‘typical’ summer and winter conditions (detailed previously). For the two proposed cases, particles were released from three fixed point locations (i.e. BNRT1, the waste treatment plant and FFMC76) as a continuous discharge. Figure 19 shows the release locations on a map. The simulations were parameterised using empirical values derived from the relevant literature (e.g. Cromey *et al.*, 2002; Jiang *et al.*, 2017; Ali *et al.*, 2011; Remen *et al.*, 2016) and SEPA-recommended values. Finally, the solid waste input was derived from the licensed total biomass (N.B. waste feed was assumed to amount to 3% of the feed supplied and faecal waste was estimated as 15% of feed supplied). Table 5 to Table 7 detail the input values used for the simulations from each point source.

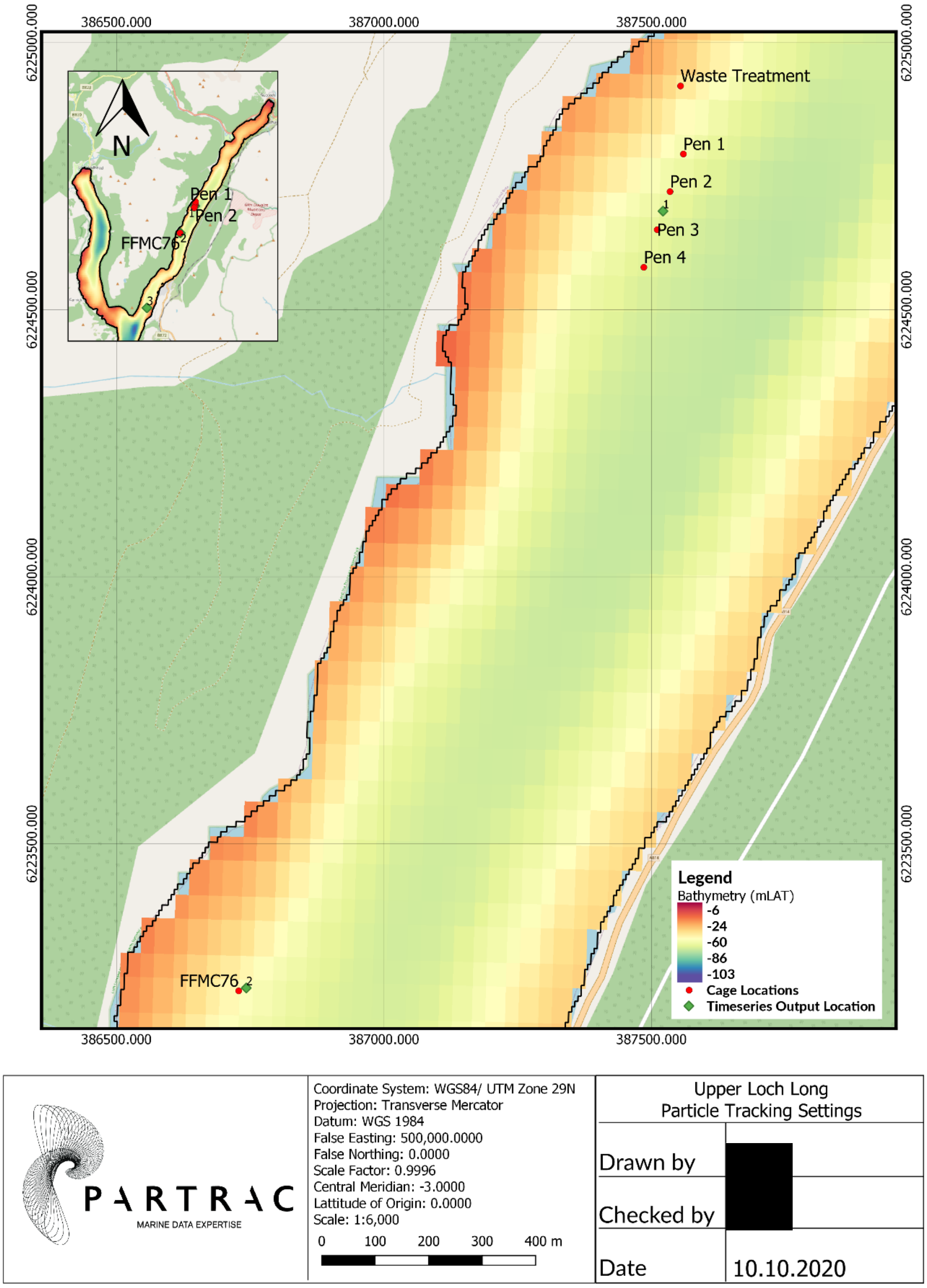

Figure 19. Fixed Point Sources where particles were released within the model domain.

Table 5. The particulate bound nutrients released from the BNRT1 site during each simulation. The mass input is determined based on a peak biomass of 1000 tonnes, per pen and a pen capture efficiency rate of 60%[4].

Site	Longitude	Latitude	Depth of release (relative to MSL)	Mass input (kg N/day)	Particles released per 30 s time step
Pen 1	4.8102223° W	56.154867° N	-30m	24.48	10
Pen 2	4.8105944° W	56.154229° N	-30m	24.48	10
Pen 3	4.8109498° W	56.153583° N	-30m	24.48	10
Pen 4	4.8113220° W	56.152945° N	-30m	24.48	10

Table 6. The particulate bound nutrients to be released from the FFMC76 site during each simulation. The mass input is determined based on a peak biomass of 500 tonnes[5].

Site	Longitude	Latitude	Depth of release (relative to MSL)	Mass input (kg N/day)	Particles released per 30 s time step
FFMC76	4.8229290° W	56.140600° N	-25m	32.96	10

---

[4] The mass input is calculated via the predicted feeding intake. Thus, nitrogen waste discharge mass = 1000 x 10^3 (Max biomass cap) * 0.01 (1% of biomass as daily feed intake) * 0.18 (15% from faeces and 3% from feed waste) * 0.40 (40% remaining of waste treatment) * 0.034 (3.4% of waste is nitrogen).

[5] The nitrogen waste of cod versus salmon farms ratio is ~1.077. Thus, nitrogen waste discharge mass = 500 x 10^3 (Max biomass cap) * 0.01 * 0.18 * 0.034 * 1.077.

Table 7. The particulate bound nutrients released from the waste treatment plant during each simulation. The mass input is based upon a 5% discharge rate and peak biomass of 1000 tonnes per pen and a pen capture efficiency rate of 60%)[6].

Site	Longitude	Latitude	Depth of release (relative to MSL)	Mass input (kg N/day)	Particles released per 30 s time step
BNRT1 Waste Discharge	4.8115567° W	56.1556930° N	-5m	7.34	3

6 Results

6.1 Verification of the ECE Model Input Values

Utilising the validated marine model, our Geographical Information System (GIS) toolbox and the data generated from the targeted particle tracking simulations ('Simulation 1'), the input values ('V', 'A', 'R' and T_f) of the ECE model can be verified and the outputs of the model updated.

6.1.1 Verification of 'V', 'A' and 'R'

These input values for the ECE model were derived directly from the validated marine model and calculated using the GIS toolbox. The area (A) and volume of the water body assessed (V) were calculated using the bathymetric data implemented in the model (relative to MSL), the tidal range (R) was extracted directly from the marine model and was predicted to range between 3.5 and 3.6 m (see Table 8).

Table 8. The maximum tidal range at three locations within Loch Long. The data was derived directly from the marine model.

Location	Maximum Tidal Range (m)
Loch Long (upper basin)	3.56
Loch Goil	3.53
Ardentinny	3.50

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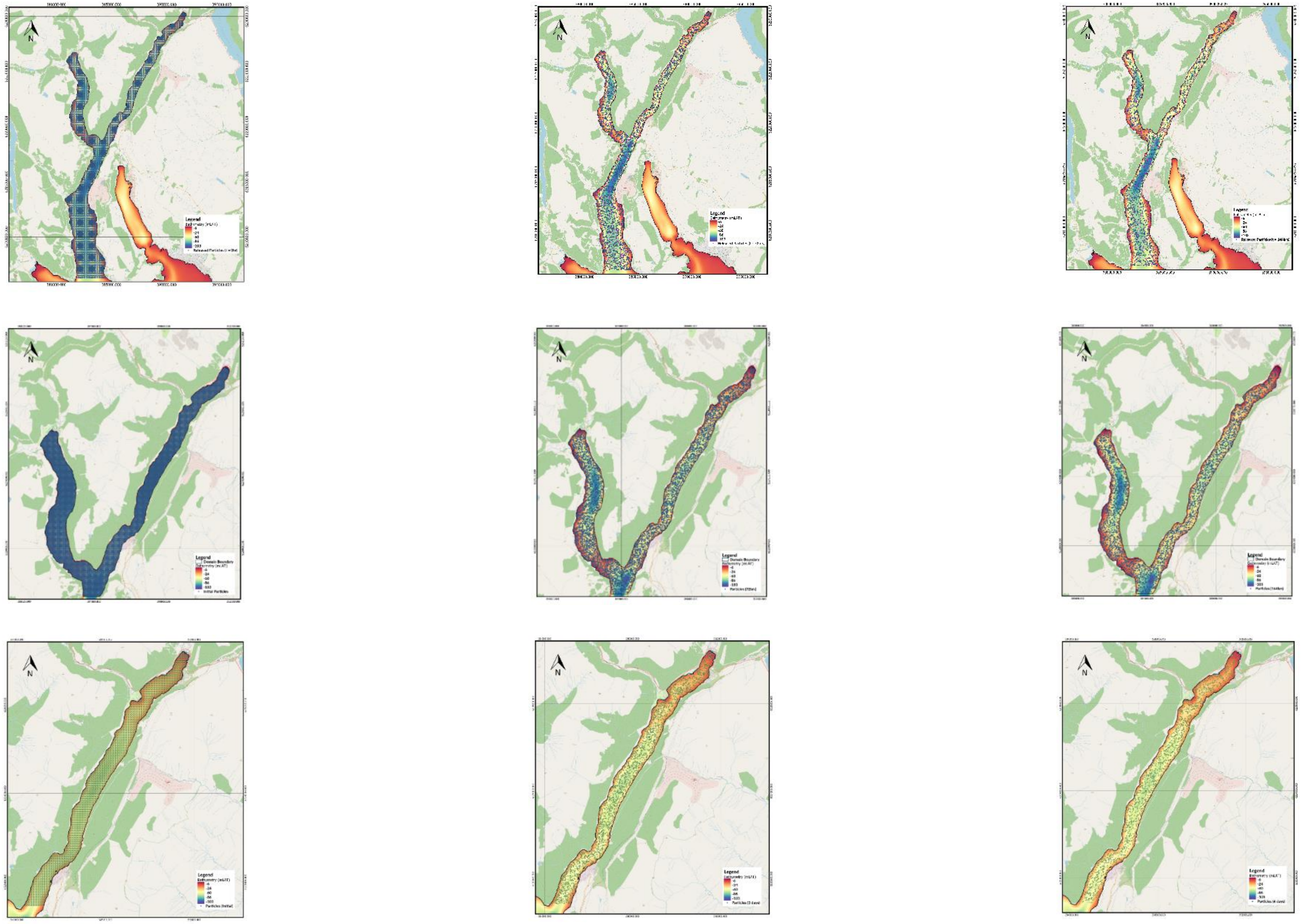
[6] Thus, nitrogen waste discharge mass = 4000 x 10^3 (Max biomass cap) * 0.01 (1% of biomass as daily feed intake) * 0.15 (15% faecal waste) * 0.60 (60% capture of waste treatment) * 0.034 (3.4% of waste is nitrogen) * 0.05 (5% returning to loch).

6.1.2 Verification of T_f

The purpose of the first particle tracking simulation performed was to quantify T_f. The spatiotemporal distribution of particles following release for bounded areas including Loch Long and Loch Goil, the upper basin of Loch Long and Loch Goil and the upper basin are presented in Figure 20.



t = 0 t = 3 days t = 6 days

Figure 20. Particle locations through time during the winter simulation. Particles were released at MSL..The case was run to cover the bounded area of Loch Long including Loch Goil (top), the Loch Long upper basin including Loch Goil (middle) and the upper basin of Loch Long only (bottom) .

Data extracted from the 10 cases performed (see Section 5.1) are presented as the range of particle counts on a time series plot in Figure 21, Figure 22 and Figure 23 which includes for Loch Long including Loch Goil, the upper basin of Loch Long including Loch Goil and the upper basin of Loch Long, respectively. A linear regression analysis of these data produces the best linear fitting lines (R^2 = 0.895, 0.998 and 0.987, see Figure 21, Figure 22 and Figure 23), which once solved, yields mean values for T_f of 218 hours (~ 9.10 days), 186 hours (~7.75 days) and 188 hours (~7.82 days) including for Loch Long including Loch Goil, the upper basin of Loch Long including Loch Goil and the upper basin of Loch Long, respectively.

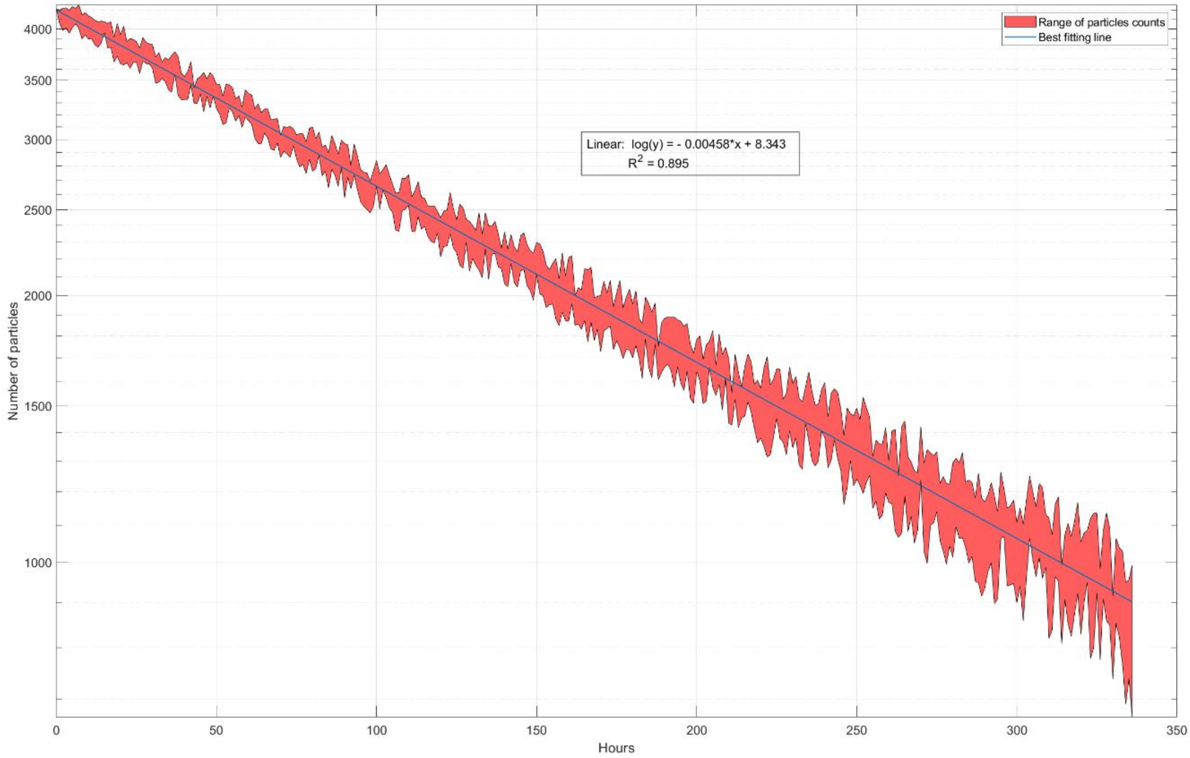


Figure 21. Linear Regression analysis of cases run as part of Simulation 1 including for Loch Long and Loch Goil.

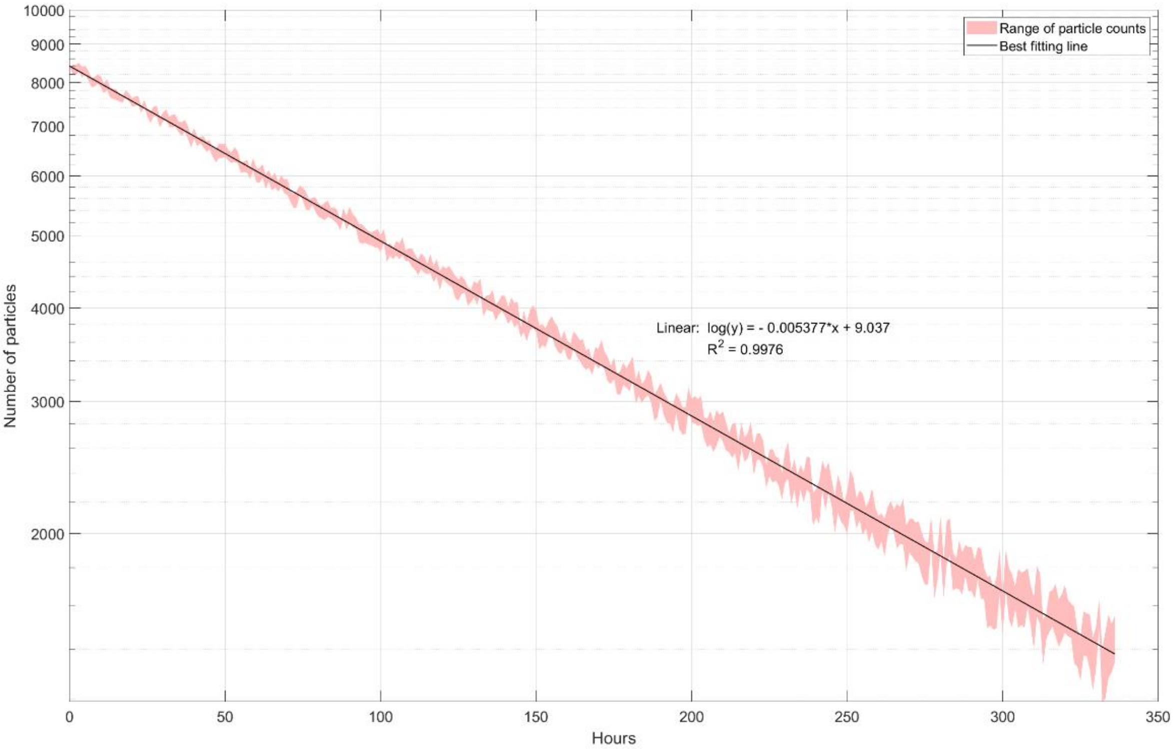


Figure 22: Linear Regression analysis of cases run as part of Simulation 1 including for the upper basin of Loch Long including for Loch Goil.

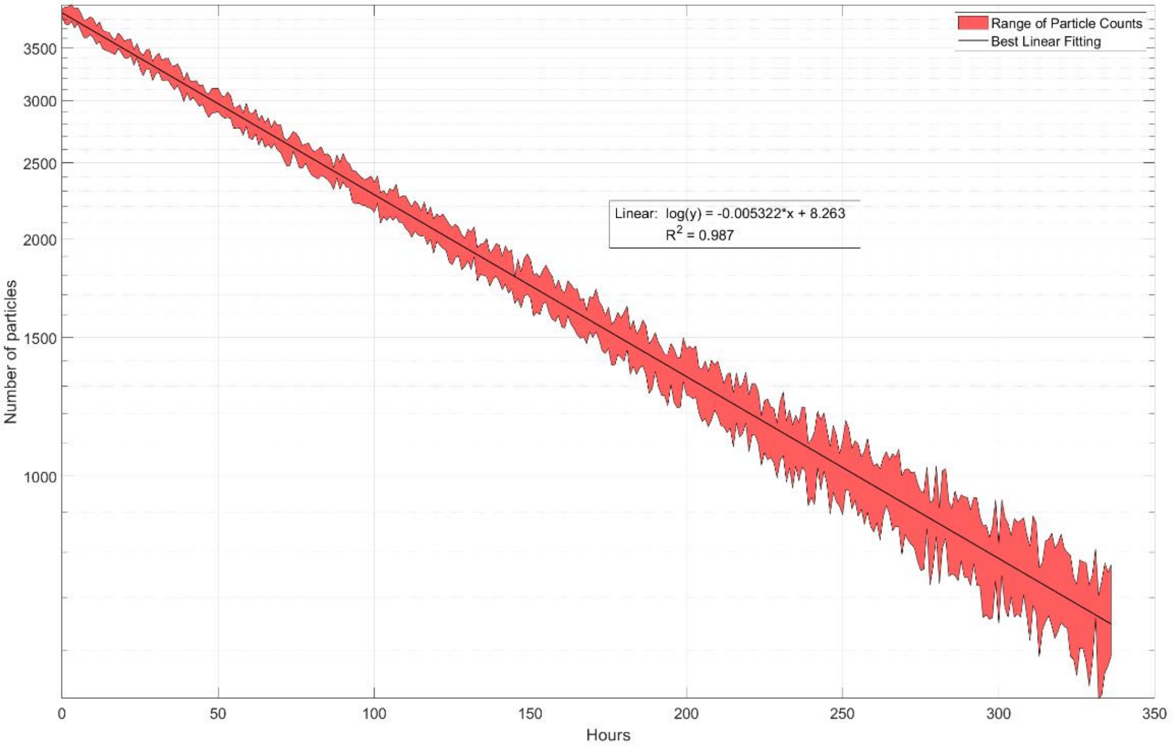
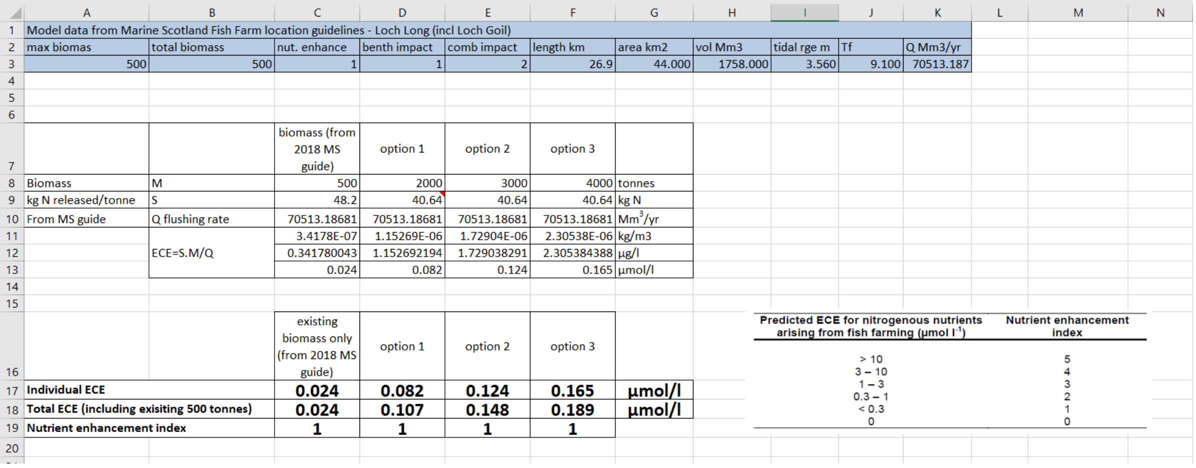


Figure 23: Linear Regression analysis of cases run as part of Simulation 1 including for the upper basin of Loch Long.

6.1.3 Verifying the ECE Model Outputs

Utilising the data garnered from the marine model and the strategic particle tracking simulations the ECE model was updated using the verified values for ‘R’ and ‘T_f’ where the model included for Loch Long and Loch Goil (Figure 24) and ‘A’, ‘V’, ‘R’ and ‘T_f’ where the model included for just the upper basin of Loch Long (Figure 25). For the verified model of the upper basin, the ascribed nutrient enhancement index value changes to ‘2’ for ‘option ‘2 and 3’ (Figure 25).



Model data from Marine Scotland Fish Farm location guidelines - Loch Long (incl Loch Goil)

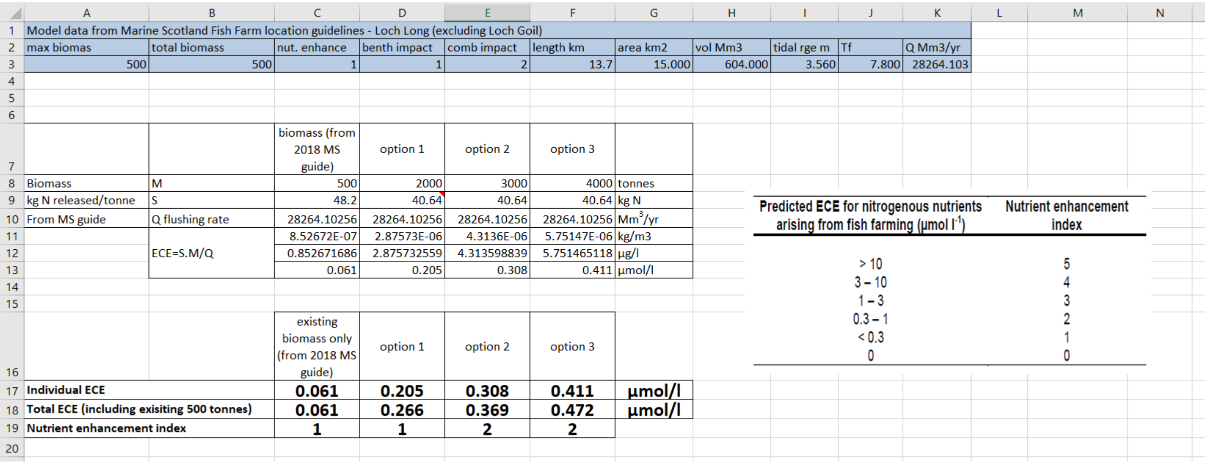
max biomas	total biomass	nut. enhance	benth impact	comb impact	length km	area km2	vol Mm3	tidal rge m	Tf	Q Mm3/yr
500	500	1	1	2	26.9	44.000	1758.000	3.560	9.100	70513.187

		biomass (from 2018 MS guide)	option 1	option 2	option 3	
Biomass	M	500	2000	3000	4000	tonnes
kg N released/tonne	S	48.2	40.64	40.64	40.64	kg N
From MS guide	Q flushing rate	70513.18681	70513.18681	70513.18681	70513.18681	Mm^3/yr
		3.4178E-07	1.15269E-06	1.72904E-06	2.30538E-06	kg/m3
	ECE=S.M/Q	0.341780043	1.152692194	1.729038291	2.305384388	µg/l
		0.024	0.082	0.124	0.165	µmol/l

	existing biomass only (from 2018 MS guide)	option 1	option 2	option 3	
Individual ECE	**0.024**	**0.082**	**0.124**	**0.165**	**µmol/l**
Total ECE (including exisiting 500 tonnes)	**0.024**	**0.107**	**0.148**	**0.189**	**µmol/l**
Nutrient enhancement index	**1**	**1**	**1**	**1**	

Predicted ECE for nitrogenous nutrients arising from fish farming (µmol l^{-1})	**Nutrient enhancement index**
> 10	5
3 – 10	4
1 – 3	3
0.3 – 1	2
< 0.3	1
0	0

Figure 24. The user interface of the ECE model applied to determine a ‘nutrient enhancement index value’ for the proposed development. The input values for ‘R’ and ‘T_f’’, now verified, have been updated. N.B. this model includes for Loch Long and Loch Goil, and a capture efficiency of 60% is applied.



Model data from Marine Scotland Fish Farm location guidelines - Loch Long (excluding Loch Goil)

max biomas	total biomass	nut. enhance	benth impact	comb impact	length km	area km2	vol Mm3	tidal rge m	Tf	Q Mm3/yr
500	500	1	1	2	13.7	15.000	604.000	3.560	7.800	28264.103

		biomass (from 2018 MS guide)	option 1	option 2	option 3	
Biomass	M	500	2000	3000	4000	tonnes
kg N released/tonne	S	48.2	40.64	40.64	40.64	kg N
From MS guide	Q flushing rate	28264.10256	28264.10256	28264.10256	28264.10256	Mm^3/yr
		8.52672E-07	2.87573E-06	4.3136E-06	5.75147E-06	kg/m3
	ECE=S.M/Q	0.852671686	2.875732559	4.313598839	5.751465118	µg/l
		0.061	0.205	0.308	0.411	µmol/l

	existing biomass only (from 2018 MS guide)	option 1	option 2	option 3	
Individual ECE	**0.061**	**0.205**	**0.308**	**0.411**	**µmol/l**
Total ECE (including exisiting 500 tonnes)	**0.061**	**0.266**	**0.369**	**0.472**	**µmol/l**
Nutrient enhancement index	**1**	**1**	**2**	**2**	

Predicted ECE for nitrogenous nutrients arising from fish farming (µmol l^{-1})	**Nutrient enhancement index**
> 10	5
3 – 10	4
1 – 3	3
0.3 – 1	2
< 0.3	1
0	0

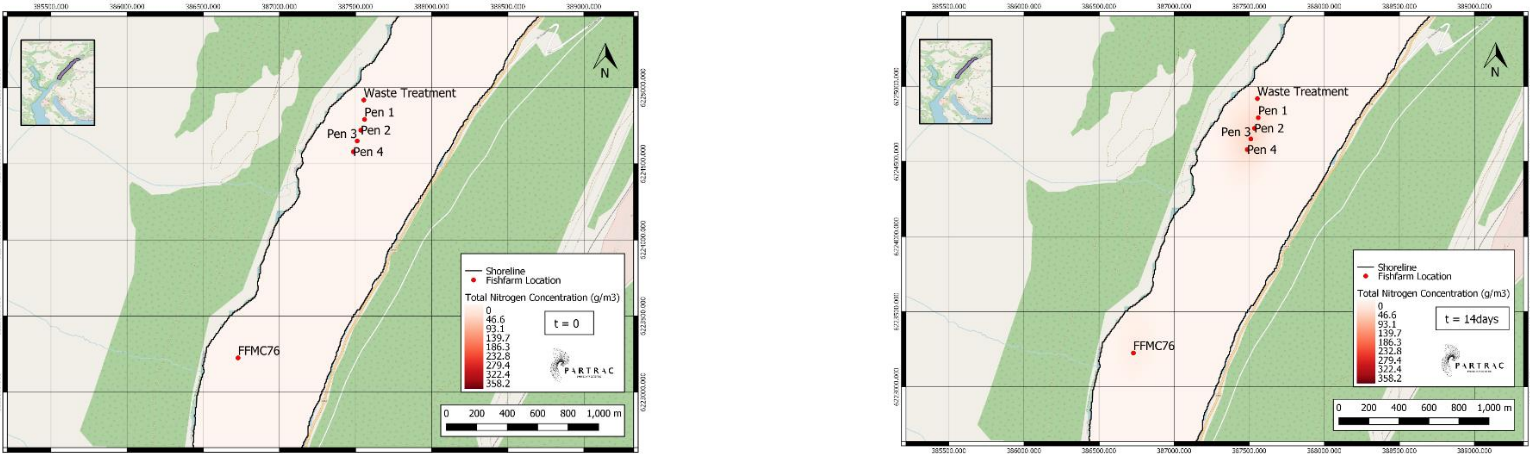
Figure 25. The user interface of the ECE model applied to determine a ‘nutrient enhancement index value’ for the proposed development. The input values for ‘A’, ‘V’ ‘R’ and ‘Tf’’, now verified, have been updated. N.B. this model includes for the upper basin of Loch Long only? and a capture efficiency of 60% is applied.

6.2 Particulate Bound Nutrients (Waste)

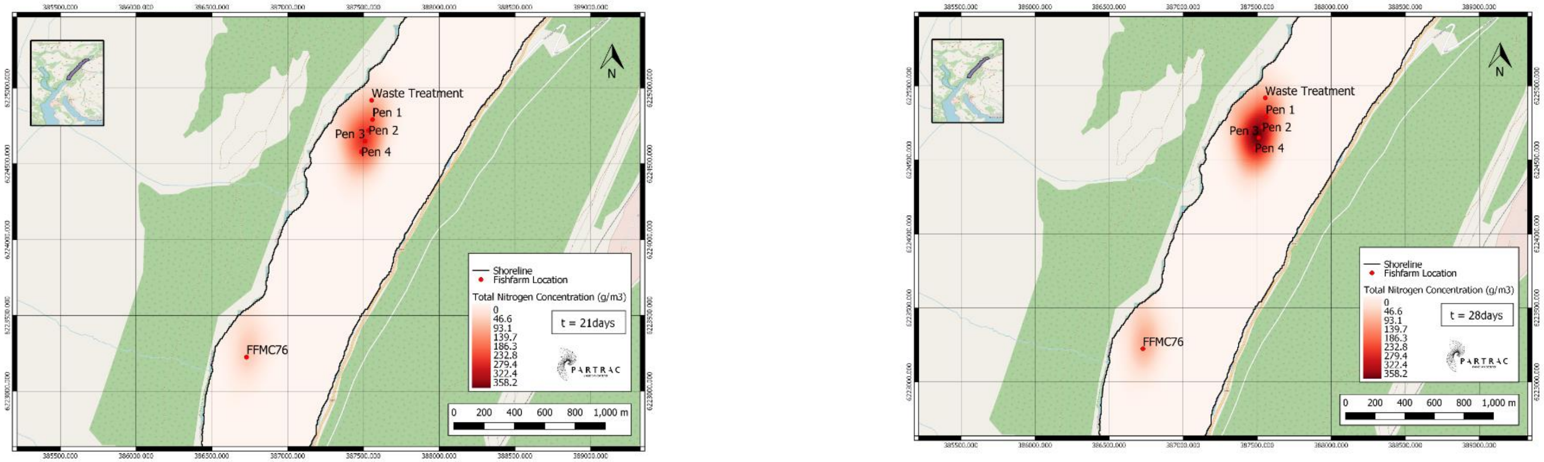
The determined quality of receiving waters, and the relative health of benthic communities, is also influenced by the release of waste from finfish farms. Of particular concern in the upper reaches of Loch Long is the potential cumulative effects of the proposed development, the associated waste discharge outfall and the existing farms in the region. Simulating particulate waste releases from these locations enables a quantitative assessment of the potential interaction of, and cumulative impacts, in the region. These analyses provide further supporting evidence from which to assess compliance. As an example, Figure 26 presents a series of spatial plots showing the predicted total nitrogen concentration through time for the simulation conducted under typical winter conditions. The corresponding time series data extracted from the centre of the pens in the proposed development and the existing fish farm site are presented in Figure 27.

Interrogation of the cases run as part of the assessment of particulate bound nutrients is summarised as follows:

- Through time, a gradual increase in the total nitrogen concentration surrounding each source is apparent as a result of the continuous discharge of particulates from each source to the receiving water body. N.B. Nutrient decay was not included in the simulations.
- The predicted impact footprint of the proposed development is highly localised around the location of the farm pens and is a function of quiescent tidal flow conditions in the upper reaches of Loch Long.
- The difference between the concentration of the deposited and suspended load varies with the tidal phase (i.e. during the spring tidal phase, greater suspended load is predicted to occur due to enhanced flow speeds). Regardless, the dispersion of particulate bound nutrients across space, through time, is limited (see Figure 26 and Appendix 1).
- Seasonal variation is observed with the maximum total nitrogen concentration predicted to be enhanced in typical summer conditions compared to those conditions typically experienced in winter, which is a function of the slightly more energetic conditions during the winter months.
- At no time, in any simulation, does the predicted impact footprint of the proposed development and existing finfish farms interact (see Appendix 1), resulting in negligible cumulative effects in terms of particulate bound nutrients.



t = 0 days t = 14 days



t = 21 days t = 28 days

Figure 26. Spatial plot showing the total Nitrogen concentration through time during the 1-month simulation for typical winter conditions.

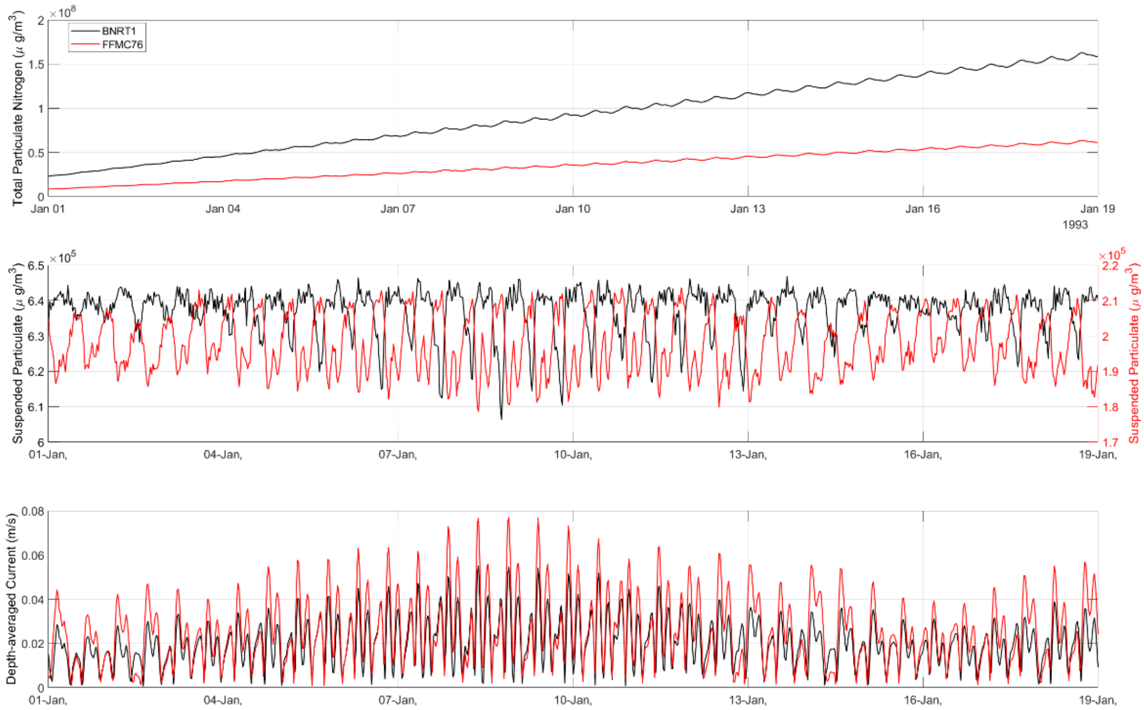


Figure 27: Timeseries of particulate nitrogen concentration and tidal currents at two farms during summer (top) and winter (bottom). The black line shows data extracted from the proposed development (BNRT1) and the red line shows data extracted from the other finfish farm located in the upper reaches of Loch Long (FFMC76).

7 Discussion

The development of the marine model and supporting strategic particle tracking simulations supports the verification of the ECE model. In the ECE model, the flushing rate (Q) is function of the Loch hydrodynamics (i.e. tidal range), topography (i.e. area and volume of the basin) and the flushing time. The results indicate that the original assessment performed by SEPA as part of the screening exercise was conservative, with the input values for 'R' and 'T_f', providing a more conservative estimate of nutrient enhancement than those values verified by the marine model (see Section 3 and Section 6.1.3). Of particular note was the results of the assessment of the influence of 'A' and 'V'. The outputs of the ECE model are highly skewed to the total area, and thus volume, of the area of interest. As such, by simply increasing (or decreasing) the area of interest the model in turn predicts a reduction (or increase) in the potential nutrient enhancement index for the proposed development. To investigate this further we ran two cases, one which included for Loch Long and Loch Goil and one which only included the upper basin of Loch Long. The particle tracking simulations yielded a mean flushing time of ~9 days and ~7-8 days, for the system and just the upper basin, respectively. These evidence suggest that the hydrodynamic characteristics of the lower, and upper, basin are highly similar supporting the hypothesis that the upper and lower basins of Loch Long act as a single, well-connected system in term of tidal exchange. An examination of the topography/bathymetry of upper Loch Long and Loch Goil corroborate these findings and indicate that the upper and lower basin of Loch Long do not act as two independent hydrodynamic systems. Interrogation of these data show that the upper basin of Loch Long is characterised by a deep sill feature, in comparison Loch Goil has a pronounced [shallow] sill where it connects to Loch Long. The sill between Loch Long and Loch Goil shallows to ~16m between Roinn Diomhain and Carraig na Maraig before deepening to over 79m in the main basin of the loch; a topography which may influence and impede the tidal exchange between Loch Goil and Loch Long. However, the area of water between the lower and upper basin of Loch long is deeper, with a less pronounced sill feature (circa. 35-40 m deep), which is likely to only have much lesser influence on tidal exchange. This evidence supports the hypothesis that the potential impact in terms of nutrient enhancement of the proposed development located in the upper basin of Loch Long would be of the same scale of magnitude (from a hydrodynamic perspective and not considering total biomass, capture efficiency etc.) as the existing consented farm in Loch Long (FFCM76).

The second round of simulations were designed to assess the potential impact footprint of the proposed development including for discharges from the proposed development (BNRT1), the existing fish farm (FFCM76) and the waste outfall. These simulations enabled an assessment of the cumulative effects of particulate waste discharge on the receiving waters. Throughout the month-long simulations, at no point did the model predict any interaction/overlap between the impact footprints of the proposed development and the existing finfish farm. As such, no cumulative impacts are predicted in the receiving waters. This provides further supporting evidence in terms of the potential impact footprint due to particulate waste. It should be noted that no decay factor was applied within the model simulations and thus the total nitrogen concentration presented in Figure 26 and Figure 27 are potentially arbitrary and do not reflect reality where biological degradation processes would reduce the organic matter concentration accumulation on, and within, bottom sediments.

8 Concluding Remarks

A high-resolution marine model was developed to provide a more robust assessment of the potential impact of the proposed fish farm development for the review and consideration of SEPA. The calibration and validation exercise clearly demonstrated effective model performance. Model performance, in terms of accuracy, skill and bias, was considered to be good; with all performance metrics exceeding those published in the SEPA guidelines (SEPA, 2019). As such, the model was considered a suitable tool to validate / verify the ECE model outputs, and to provide further lines of evidence to support the assessment of nutrient impact in the upper basin of Loch Long.

The verification of the input values for the Loch nutrient model corroborated the findings of the SEPA screening exercise. By verifying the input values and replicating the area (and thus volume) assessed in the screening exercise, the original assessment was found to be conservative in its predictions. By reducing the area of assessment, the ascribed nutrient enhancement index value increases from '1' to '2' for 2 of the options assessed by the model. However, supporting analyses of the flushing time of the upper basin of Loch Long indicate that the predicted flushing time remains highly similar, indicating that the predicted increase in impact is a function of the reduction in the area of assessment rather than the prevailing hydrodynamic processes. These data, combined with an examination of the topography/bathymetry, indicate that the upper and lower basins of Loch Long do not act as two independent hydrodynamic systems, rather the hydrodynamic regime reflects that of a well-connected water body.

Evidence garnered from simulations designed to support an assessment of the particulate bound nutrients (i.e. waste) predicted a highly localised impact footprint which is a function of the quiescent tidal flow regime, applied settling velocity and shallow water depths. These simulations predicted that no cumulative impacts would occur between developments.

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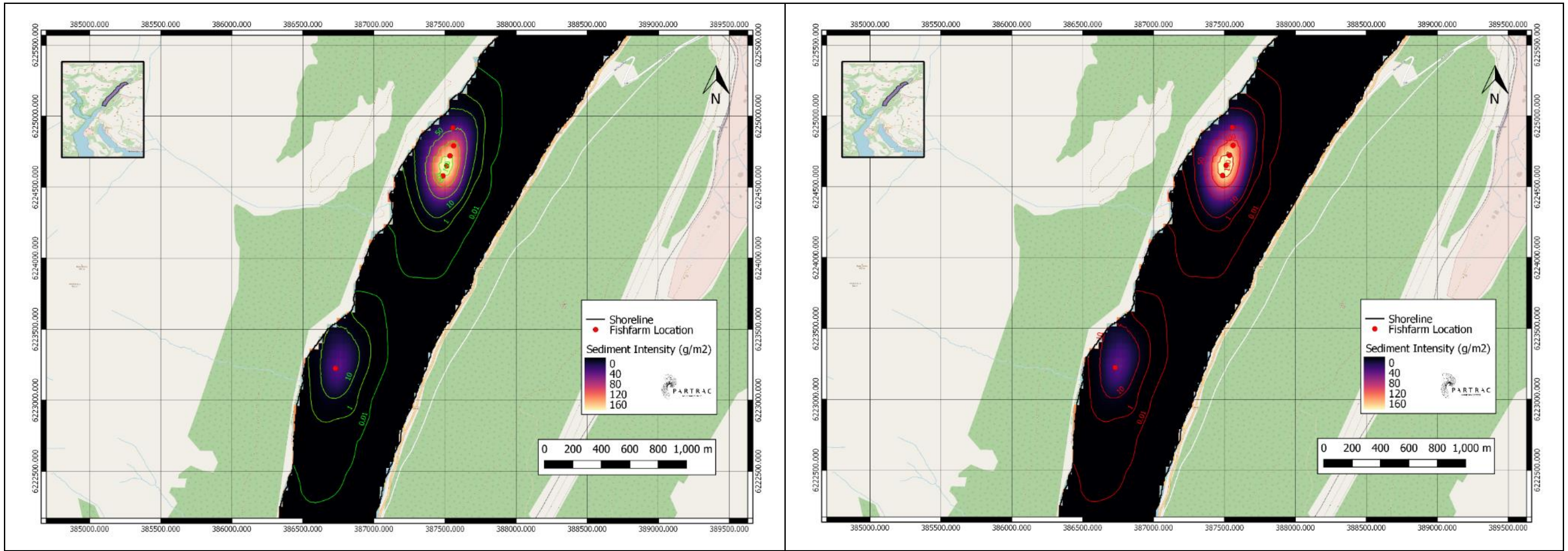
Appendix 1 Sediment Intensity Plots

The mean particulate nitrogen concentration predicted to occur over a 30-day simulation is presented in the form of contoured total nitrogen content maps for both typical summer and typical winter conditions (Figure 28). The predicted extent of the impact footprint of the proposed development and of the existing farm is presented in Table 9.

Table 9: Areas of total nitrogen content for six discrete concentration thresholds.

Total Nitrogen Content (g/m^2)	Predicted extent of impact footprint from Proposed Development (BNRT1)		Predicted extent of impact footprint from Existing Farm (FFMC76)	
	Summer (km$^{2)}$	Winter (km$^{2)}$	Summer (km^2)	Winter (km^2)
0.01	0.706	0.707	0.621	0.621
1	0.369	0.369	0.247	0.248
10	0.254	0.255	0.112	0.114
50	0.107	0.110	-	-
100	0.046	0.051	-	-
150	0.010	0.014	-	-



Typical Summer Conditions

Typical Winter Conditions

Figure 28.Maps showing the total nitrogen content during summer (left) and winter (right) conditions.

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