North Gravir Aquaculture Modelling

Sea Lice Assessment Report

Project No 26802148

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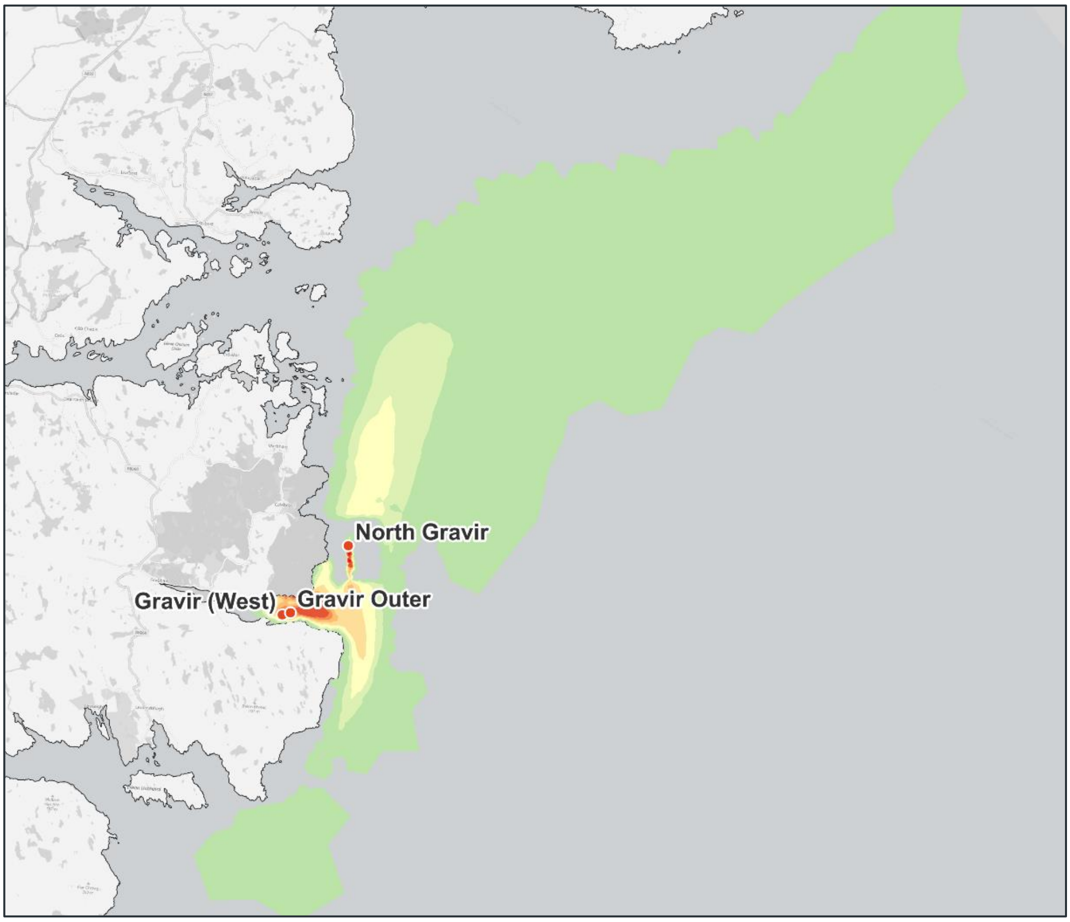

Hydrodynamic modelling for North Gravir Finfish Farm development

Sea Lice Dispersion Assessment Report

Report
Project No 26802148

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NOMENCLATURE

Abbreviations	
ABM	Agent Based Modelling
BFS	Bakkafrost Scotland Ltd
CFSR	Climate Forecast System Reanalysis
ECLH	East Coast Lewis Harris model
FM	Flexible Mesh
HD	Hydrodynamic
km	Kilometre
psu	Practical Salinity Unit
RANS	Reynold-Averaged Navier-Stokes
SAC	Special Area of Conservation
SEPA	Scottish Environment Protection Agency
UK	United Kingdom
3D	Three-dimensional

Variable	Abbrev.	Unit
Atmosphere		
Downward solar radiation flux	SR	W/m^2
Ocean		
Current speed	CS	m/s
Current direction	CD	°N (clockwise
Water temperature	T_{water}	°C
Water Salinity	Salinity	Psu (Practical Salinity Unit)
Water density	ρ_{water}	Kg/m^3

Executive Summary

Bakkafrost Scotland Ltd (BFS), one of the leading producers of farmed Atlantic salmon in Scotland, are assessing the potential dispersal of sea lice from the Proposed Development of North Gravir, the Outer Hebrides, and the various sources (e.g., marine pen fish farm sites) within the region.

The salmon lice (*Lepeophtheirus salmonis*) is a parasite of wild and farmed salmonids. The transmission of an infection occurs in the planktonic stages of the salmon lice life-cycle. Female adults produce eggs which, when hatched, release nauplii larvae that are dispersed in the water by currents. The salmon lice undergo several metamorphoses as they transition into the infectious copepodite stage. Copepodite larvae may attach to the scales or gills of a farmed or wild host salmonid. After attachment the larvae will settle and undergo several further metamorphoses before transitioning into the adult phase and reproducing.

This technical report describes a numerical modelling study that has been performed to identify sea lice dispersal, at the different stages of sea lice evolution, for the proposed North Gravir marine pen fish farm site. The modelling framework comprises of two main components: 1) a hydrodynamic (HD) model, and 2) an agent based biological model (ABM).

A review of existing data and literature has been performed to understand the hydrodynamic setting at the area of North Gravir, the Outer Hebrides. Based on this understanding, a 3-dimensional (3D) hydrodynamic model was constructed that simulates the water level variations and flows in response to a variety of forcing functions in a climatological context [1]. The model has been verified to ensure that it captures the important processes that govern dispersion of salmon lice.

The biological model was designed to simulate the dispersal of planktonic salmon lice larvae. The model configuration is founded upon peer-reviewed scientific literature and describes the development and behaviour of planktonic phases of salmon lice (from the non-infectious through to the infectious stages of its life-cycle). The model captures the behaviour and response of larvae to environmental conditions (such as light intensity, seawater temperature, and salinity), and their mortality due to senescence and predation. The coupled hydrodynamic-biological model can be used to simulate the dispersal of salmon lice from marine pen fish farm sites to identify potential dispersal of infective lice. Salmon lice dispersion is assessed over two (2) seasons: an annual calendar period (January to end of December), and an early to late spring season (April to end May) coinciding with the seasonal peak smolt out-migration. In this way, the sensitivity of the model to different environmental conditions was assessed, providing a more conclusive picture on potential dispersal of salmon lice.

1 Introduction

This report has been prepared for **Bakkafrost Scotland Ltd.** (BFS) by DHI, in relation to hydrodynamic and biological modelling services for aquaculture sites in the Outer Hebrides. Specifically, this report describes the methodology and key results of a coupled hydrodynamic-biological modelling study to **assess dispersal pathways of salmon lice originating from North Gravir in isolation and cumulatively from marine pen fish farms sites** in the waters around North Gravir, the Outer Hebrides.

1.1 Background to the study

The Outer Hebrides, also known as the Western Isles, is an archipelago located off the west coast of mainland Scotland. It consists of a chain of islands, the largest of which are Lewis and Harris, North Uist, South Uist, Barra and Benbecula.

Aquaculture activities play a significant role in the Outer Hebrides' economy and food production. The region's coastal waters offer ideal conditions for aquaculture due to their clean environment. Salmon farming is one of the primary aquaculture activities in the area, with several farms located around the islands. These farms rear Atlantic salmon, providing a sustainable source of high-quality protein.

Aquaculture activities in the Outer Hebrides adhere to strict regulations and sustainability practices to protect the natural environment and maintain the long-term viability of the industry. The industry provides employment opportunities for local communities and contributes to the region's economy while promoting the production of healthy and sustainable seafood.

Figure 1.1 shows the location of the fish farm sites considered within the context of this assessment. Namely, the proposed North Gravir site, and the currently active BFS sites of Gravir (West) and Gravir Outer, and also the MOWI sites of North Shore W, and North Shore E and Tabhaigh. The map includes all sites that are assessed for cumulative input of salmon lice as provided by BFS. Further details on the sites, including their name, operator, and geographical location are summarised in Table 1.1.

The salmon louse is a parasite of wild and farmed salmonids. They are found in the cold and temperate marine waters across Northern Europe, and on all salmonid species: salmon, trout, and char. The parasite feeds on the skin of the fish, resulting in physical damage to its host. This may lead to impaired swimming performance, altered feeding behaviour, reduced growth, or act as a pathway for infection by pathogens.

The management of salmon lice populations is of fundamental importance to the aquaculture sector in Scotland. This project has been initiated to assess the dispersion of salmon lice in the waters around North Gravir, the Outer Hebrides.

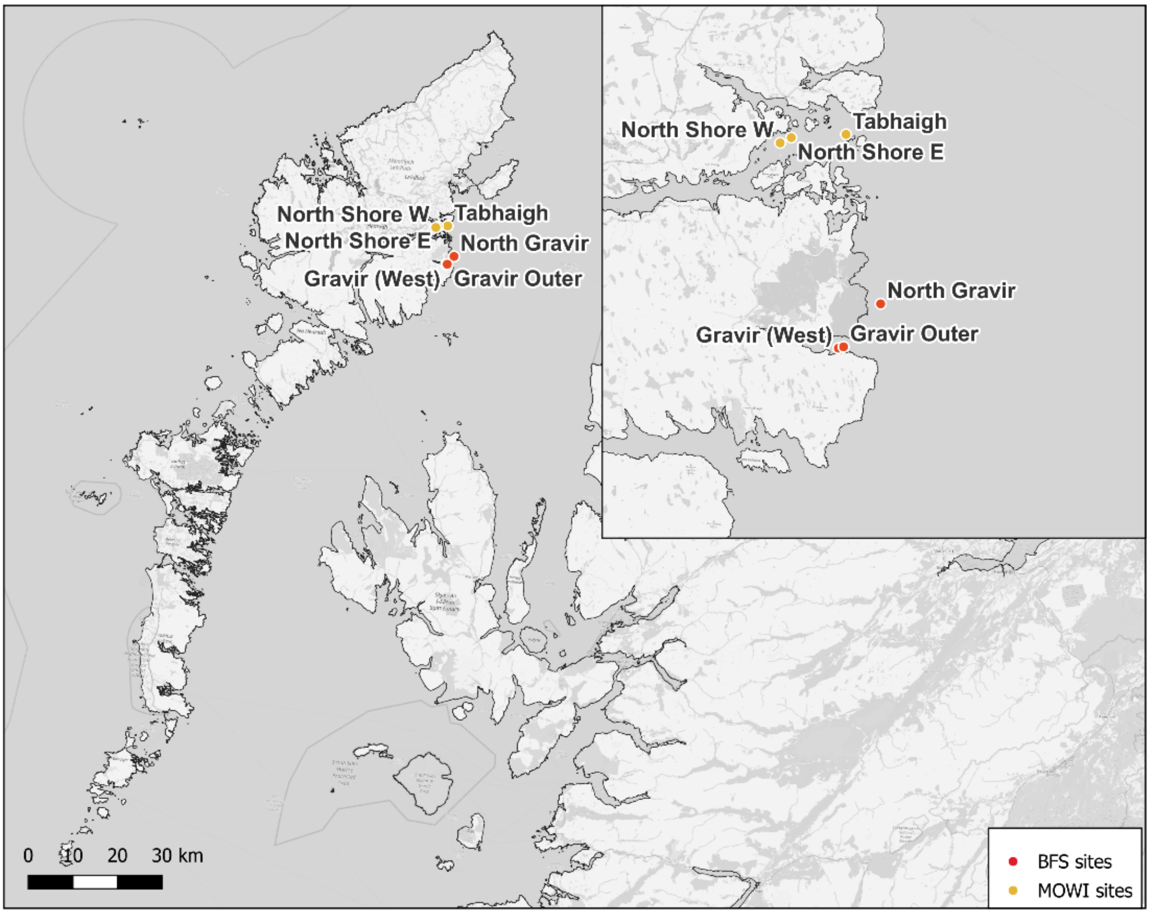

Figure 1.1 Map of Outer Hebrides showing the geographic locations of aquacultures sites considered in the context of this salmon lice assessment, namely North Gravir, Gravir (West) and Gravir Outer (see also Table 1.1). Also shown are the three sites operated by MOWI namely North Shore W, North Shore E and Tabhaigh.

1.2 Aims and objectives

The aim of the present study is to assess the potential dispersal of salmon lice in the waters around the Proposed Development of North Gravir, the Outer Hebrides. The assessment is in line with the Marine Directorate's Scoping Advice for North Gravir.

This aim will be fulfilled via the following objectives:

- Based on peer-reviewed scientific literature, setup a coupled hydrodynamic-biological model that describes the development and behaviour of planktonic phases of salmon lice (from non-infectious through to infectious phases); and
- Use a coupled hydrodynamic-biological model to simulate the dispersal of salmon lice from the proposed North Gravir site, cumulatively from North Gravir and the currently active BFS sites Gravir (West) and Gravir Outer and cumulatively from North Gravir and the currently active BFS sites Gravir (West) and Gravir Outer and the three (3) MOWI sites namely North Shore W, North Shore E and Tabhaigh.

1.3 Layout of this report

The remaining sections of this report are organised as follows:

- Section 2 describes the modelling methodology for the salmon lice assessment;
- Section 3 describes the setup and configuration of the biological models;
- Section 4 presents and discusses the results of the model investigations; and
- Section 5 draws conclusions and provides recommendations.

Table 1.1 Salmon aquaculture farm sites assessed in this study following consultation with **BFS.**

FS ID	Site Name	Operator	Site production in last 3 years	Site coordinates [OSGB36]	
				Easting [m]	Northing [m]
-	North Gravir	BFS	No	143020	916238
FS0242	Gravir (West)	BFS	Yes	141309	914446
FS0242	Gravir Outer	BFS	Yes	141520	914500
FS1033	North Shore W	MOWI	Yes	139405	922953
FS1033	North Shore E	MOWI	Yes	138959	922739
FS1297	Tabhaigh	MOWI	Yes	141621	923083

2 Modelling Methodology

This section describes the modelling framework that was chosen for assessing the salmon lice dispersion and connectivity around North Gravir, the Outer Hebrides.

Many of the aquaculture sites in the waters around the Outer Hebrides are located within environments where vertical stratification (density gradients due to difference in water temperature and salinity) has important implications for vertical mixing and density driven flows. Wind forcing also plays a major role in driving local flow patterns, which is important for surface dispersion. In addition, vertical variation of temperature and salinity determine the development and behaviour of salmon lice; they show an avoidance to low salinity areas and will seek higher water temperature to minimise development time until the infectious stage of their life-cycle.

Taking the abovementioned factors into consideration, a 3D model is considered necessary to capture the important processes [2]. The **MIKE 3 Flow Model FM (Flexible Mesh)** modelling system developed by DHI was chosen for this application, as it includes the simulation tools to model 3D free surface flows and associated transport and water quality processes. The following modules available within MIKE 3 were used during this study.

HD – Hydrodynamics: This module simulates the water level variations and flows in response to a variety of forcing functions. It includes a wide range of hydraulic phenomena in the simulations, and it can be used for any 3D free surface flow. The Flexible Mesh (FM) version, which uses a depth and surface adaptive vertical grid, is particularly suitable in areas with a high tidal range.

MIKE ECO Lab – Ecological and Agent Based Modelling: This is a complete numerical laboratory for water quality and ecological modelling.

The MIKE 3 model used for the present study was version 2023 [3].

The following sections provides a general description of the MIKE 3 Hydrodynamic module (section 2.1) and MIKE ECO Lab (section 2.2).

2.1 MIKE 3 Hydrodynamic module

The hydrodynamic module is the basic computational component of the MIKE 3 Flow Model FM, and has been developed for applications within oceanographic, coastal, and estuarine environments [3]. The hydrodynamic module provides the basis for the other modules such as sand transport, mud transport, particle tracking, and MIKE ECO Lab.

The computational mesh is based on the unstructured grid in the horizontal direction, an approach which gives maximum degree of flexibility when handling problems in complex domains. In the vertical direction, a sigma (s) discretisation is used, meaning that model elements are represented as 3-sided prisms (Figure 2.1)

The MIKE3 modelling system is based on the numerical solution of the 3D incompressible Reynolds Averaged Navier-Stokes (RANS) equations, invoking the assumptions of Boussinesq, and of hydrostatic pressure. Thus, the MIKE 3 flow model consists of continuity, momentum, temperature, salinity, and density equations, which are closed by a turbulent closure scheme. In the horizontal domain both Cartesian and spherical coordinates can be used. The free surface is considered using a sigma-coordinate transformation approach.

The spatial discretisation of the primitive equations is performed using a cell-centred finite volume method. The spatial domain is discretised by sub-division of the continuum into non-overlapping element/cells. In the horizontal plane an unstructured grid is used, while a structured discretisation is adopted in the vertical domain. The elements can be prisms or bricks whose horizontal faces are triangles and quadrilateral elements, respectively. An approximative Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions.

For the time integration a semi-implicit approach is used where the horizontal terms are treated explicitly, and the vertical terms are treated implicitly.

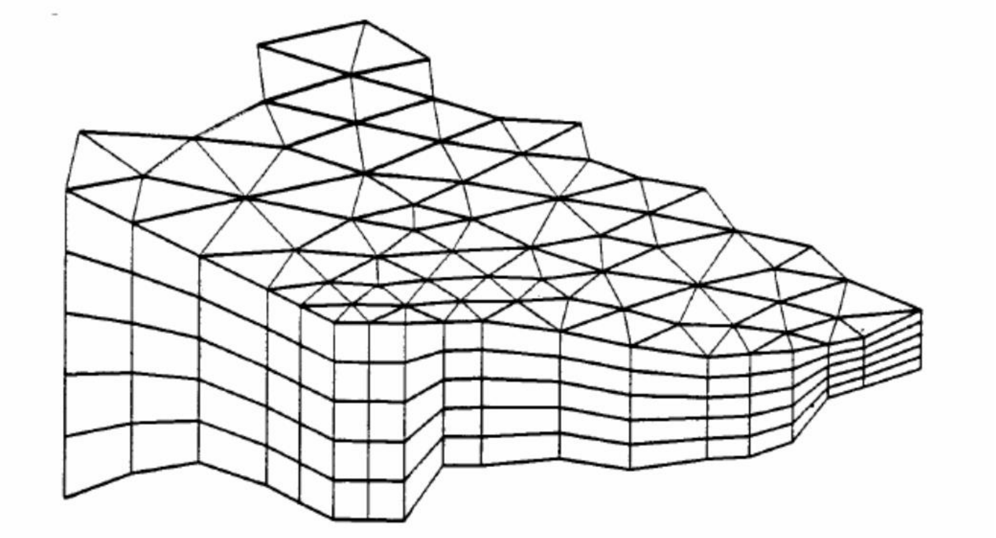

Figure 2.1 Example of an unstructured mesh in MIKE3 with 5 sigma layers.

2.2 MIKE ECO Lab module

MIKE ECO Lab is a numerical laboratory for ecological and ABM developed by DHI [4]. It is an open and generic tool for customising aquatic ecosystem models to predict water quality and ecology. This is achieved by describing and solving important processes using equations which are integrated within DHI's suite of hydrodynamic flow models, including MIKE 3 hydrodynamic module (see Section 2.1).

Some typical examples of MIKE ECO Lab applications include the transport/decay of pollutants, bathing water quality, and aquaculture. The predictions and outputs from MIKE ECO Lab are well-suited for inclusion as part of an Environmental Impact Assessment (EIA).

Aquatic ecosystems are commonly described by process-oriented models which follow the fate of masses or concentrations in the system as they flow between different components. This is a well-established and proven method, and a good choice of tool when simulating dissolved substances or pollutants (i.e., when the fate of the substance is solely determined by passive transport due to the hydrodynamic forcing). However, many phenomena cannot be satisfactorily described by this type of process-oriented model. Marine organisms often show explicit responses to environmental conditions (e.g., light, temperature, and salinity), which can affect their behaviour. For example, planktonic organisms that can migrate vertically though the water column in response to diurnal variations in light intensity (even as they are subject to passive transport by the hydrodynamic conditions).

MIKE ECO Lab can be utilised to setup and run an ABM, which is a model describing the autonomic behaviour and states of agents, objects, or individuals. It is a step forward from advection dispersion modelling since chemical and biological coefficients can be integrated, allowing more complex environmental interactions and feedback to be simulated. The agents are represented through a *Lagrangian* framework that describes all the information on the state, behaviour, and movement of particles. This type of framework is well suited for modelling the planktonic stages of salmon lice larval development.

For more information on MIKE ECO Lab the reader is directed to the description in [4].

3 Model Development

This section describes the setup of the numerical models that form the basis of the analysis of salmon lice dispersion around North Gravir, the Outer Hebrides. This includes regional 3D hydrodynamic climatology models (Section 3.1), and the specification of biological modelling using the MIKE ECO Lab (Section 3.2). In the latter, salmon lice development and behaviour are represented through ABM.

3.1 Hydrodynamic model (HD_{NG_Clima})

DHI have previously established a dedicated regional 3D hydrodynamic climatology of North Gravir using the MIKE 3 hydrodynamic model (HD_{NG_Clima}) [1]. A climatology model offers a simple technique for predicting the mean status of the atmospheric and oceanographic conditions over an annual period. The local North Gravir climatology model is a dynamically down-scaled version of the East Coast and Lewis and Harris (ECLH), developed for and maintained by the Marine Directorate of the Scottish Government, to describe the circulation of the Outer Hebrides [5, 6, 7].

For further details on the setup, configuration, and verification of HD_{NG_Clima}, the reader is directed towards [1].

3.2 MIKE ECO Lab model

A MIKE ECO Lab model was setup to describe the planktonic phases of salmon lice larvae as they transition through different development stages (from non-infectious nauplii to infectious copepodites). Furthermore, the ABM functionality within the MIKE ECO Lab model parameterises the behaviour and response of salmon lice larvae to environmental conditions (i.e., light intensity in the water column, seawater temperature, and salinity) and their mortality (i.e., due to senescence and predation).

The following sub-sections describe the parameterisation of the biological model setup in MIKE ECO Lab. First, a summary of the marine salmon louse life-cycle is provided (Section 3.2.1). This is followed by a description of the processes and behaviours that are included in the salmon lice model (3.2.2).

3.2.1 Overview of the life-cycle of salmon lice

Salmon lice are found in cold and temperate waters across Northern Europe and on all salmonid species: salmon, trout, and char. It is a parasite that feeds on the skin resulting in physical damage to its host. This may lead to impaired swimming performance, altered feeding behaviour and reduced growth, or act as a pathway for infection by pathogens.

Salmon lice exists in marine waters only, so salmon smolts transferred to marine pens from freshwater sites will initially be free from lice. However, after transfer to the sea, fish are susceptible to parasitisation by salmon lice which occur naturally in the marine environment. Salmon lice larvae originate from wild fish, or from other marine pen fish farms, and the attachment to a host occurs in the planktonic stages of the salmon lice life-cycle (Figure 3.1). Female adults produce egg strings which, when hatched, release nauplius larvae that are dispersed in the water column. These larvae can swim horizontally, but this movement is of minor, or no importance compared to passive drift through the water due to currents. They also swim vertically, at an average speed of one body length per second (0.5 mm/s) [8] as a response to various environment forcing. The larvae undergo several metamorphoses as they transition into copepodid larvae (the infectious stage of the salmon lice life-cycle). A copepodid larvae encountering a wild or farmed salmonid has the potential to attach to the scales or gills of a host fish. After attachment, the larvae will settle and undergo several further metamorphoses, before transitioning into the adult phase and reproducing.

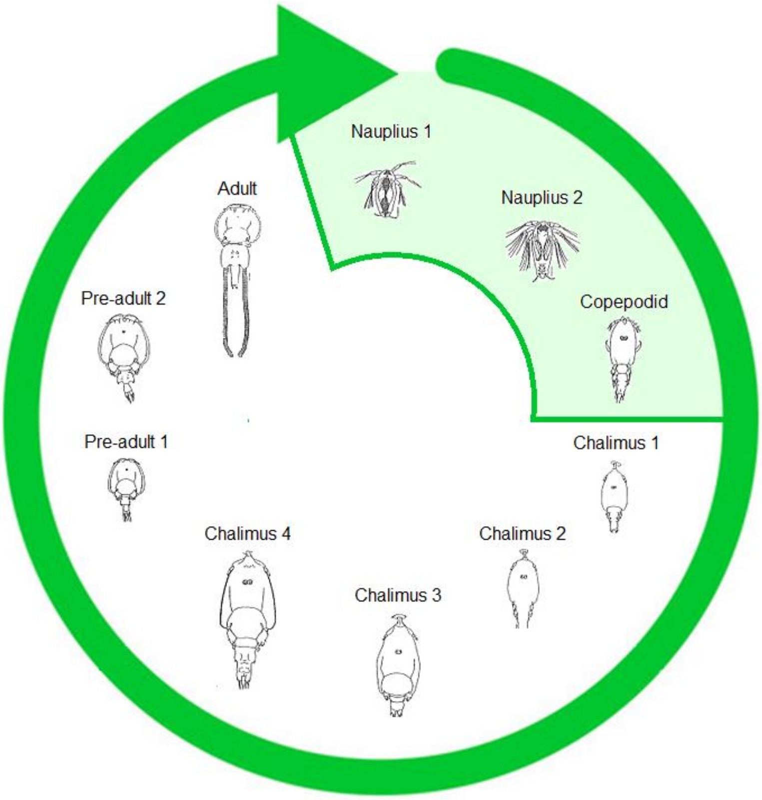

Figure 3.1 **Conceptual model of the life-cycle of the salmon lice. Highlighted area shows the stages modelled as part of this study (Nauplius 1, Nauplius 2, and Copepodid stages).**

3.2.2 Salmon lice ABM model

The objective of the Salmon lice model is to provide a simple ABM class to simulate the planktonic life stages of salmon lice, i.e., the first two non-infective nauplii, plus the infective copepodite stages. The module is used to describe/simulate the planktonic dispersal of salmon lice. The module can be used by its own to simulate dispersal patterns during the planktonic stage, or in combination with a farm/pen ABM class to enable full dynamic simulations of the entire life-cycle. In this study, only the planktonic salmon lice ABM class is used.

3.3 Model design

The biological model utilises the ABM functionality within MIKE ECO Lab by using Lagrangian particles to simulate the dispersal of salmon lice. The particles are dispersed by the hydrodynamic flow field, with a non-passive vertical movement dependent on environmental conditions as modelled in [1]. This means that each entity drifts passively but can moderate its vertical position due to responses to light, temperature, or salinity.

Two periods were assessed:

- An annual period, January to end of December (coinciding with the hydrodynamic climatology as in [1]; and
- An early spring period 13 April to 25 May coinciding with the peak smolt out-migration period [9].

The criteria of using an annual (baseline) simulation period was mainly statistical robustness in representing the full range of environmental conditions that affect salmon lice development through the various life-cycle stages. For example, focusing on oceanic temperature trends, the period from January to May can be considered a 'cool' water temperature period, whilst the period from June to December will be 'warmer', with a distinct effect on temperature dependent sea-lice development. This way, the release scheme provides a conclusive annual coverage, with no bias of salmon lice development representation with regards to its dependence on water temperature.

As the salmon lice larvae develop through various stages of the planktonic life-cycle (see section 3.2.1, they are subject to several environmental forcing factors such as temperature, light intensity, and salinity, with specific responses (i.e., being phototactic) and subsequent growth-related transformations. The number of larvae active during two nauplius stages and one copepodid stage, are represented in two frames of reference: *Lagrangian* (i.e., tracking individual particles moving through space and time, and determining their properties), and *Eulerian* (i.e., examining the number of particles in each element area and/or volume, and calculating the overall change over time).

Larvae are infectious to salmonid fish during the copepodid stage of their life-cycle. At this stage of development populations of copepodites (as number of particles per computational mesh element and/or volume) are used to derive the spatial concentrations of infective lice.

3.3.1 Particle sources and releases

The simulated particles represent salmon lice in a so called 'super-particle' context, where each super-particle represents a larger number of salmon lice individuals. This is an efficient approach for simulating the dispersion of a large population whilst incorporating mortality within reasonable computational demands.

In the biological model twenty (20)[1] super-particles are released every timestep from the designated source location of the North Gravir site with respective input from the additional sources (see Table 3.1 and Figure 1.1). All sources are defined to be at full stock biomass throughout the simulation period. Each super-particle represents 1,000 newly hatched nauplii-I larvae (i.e., the age of the larvae was assumed to be zero); hence, a total of approximately 33,000 larvae individuals are represented per 15 mins from the North Gravir site alone. All particles were released at a depth of 3 m below the water surface. While it is suggested for salmon lice to remain within the first four meters of the water column by performing short swimming bursts [10, 11], diurnal vertical migration seem to be exhibited by copepodites [12].

The number of nauplii larvae released was set based on the weekly average, gravid female lice counts from the adjacent Gravir sites during the smolt migration period. The number of larvae released will vary in time and in space and will be influenced by many factors; the farm biomass; number of egg laying (ovigerous) adult female lice (here same rate among all sources); the egg production rate and the number of egg string batches per louse; number of viable eggs per clutch; treatment and harvesting schedules; and environmental conditions (e.g., water temperature). The assessment of the potential dispersal of the infectious (copepodite) lice presented in this study should, therefore, be interpreted as a conservative approximation given the utilisation of full stock versus operational biomass per source site.

An additional ‘conservative’ scenario of an increased rate of **0.5** ovigerous (gravid) lice per fish for all sources is also being presented.

Thus, scenarios can be summarised as below:

- Two periods:
    - Whole annual period, January to December, coinciding with the climatological hydrodynamic database temporal coverage; and
    - Peak smolt out-migration period (13th of April to 25th of May).

For those periods the following scenarios are presented:

- Prescribed input (BFS) (see also Table 3.1):
- North Gravir as single source based on average salmon lice count during the peak smolt out-migration period over multiple years from the nearby sites of Gravir (West) and Gravir Outer; and
- All BFS designated sources (North Gravir, Gravir (West) and Gravir Outer);
- All BFS designated sources (North Gravir, Gravir (West) and Gravir Outer) plus the MOWI sources (Tabhaigh, North Shore W and North Shore E);
- Conservative input (see also Table 3.2) (only for Copepodid stage);
- All BFS designated sources (North Gravir, Gravir (West) and Gravir Outer) at 0.5 ovigerous lice per fish; and
- All BFS designated sources (North Gravir, Gravir (West) and Gravir Outer) plus the MOWI sources (Tabhaigh, North Shore W and North Shore E) at 0.5 ovigerous lice per fish.

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[1] A release scheme based on 200 super-particles, but same total population, was also examined for sensitivity of output to the particle scheme (not presented herein).

Table 3.1 Input for North Gravir salmon lice assessment based on full stock biomass and average salmon lice count for the North Gravir site and the additional sources as specified by BFS.

North Gravir model							
	Site	**North Gravir**	**Gravir (West)**	**Gravir Outer**	**Tabhaigh**	**North Shore W**	**North Shore E**
	FS ID		FS0242	FS0242	FS1297	FS1033	FS1033
	Based on average salmon lice count (pers. comm. BFS)						
Physical numbers	**Farm biomass [T]**	4680	515.7	2285.2	2500	1650	2400
	Fish mass [kg]	5	5	5	5	5	5
	Number of ovigerous lice per fish (average during peak smolt out-migration period over multiple years)	0.12	0.12	0.12	0.5	0.5	0.5
	Number of eggs per clutch per day	28	28	28	28	28	28
	Number of fish per farm	936000	103140	457040	500000	330000	480000
	Number of larvae per farm per day	3144960	346550.4	1535654.4	7000000	4620000	6720000
Model settings	**Time period [days]**	365	365	365	365	365	365
	Model timesteps [15 mins]	35040	35040	35040	35040	35040	35040
	Number of larvae released in model per timestep	32760	3609.9	15996.4	72916.66667	48125	70000
Model input	**Number of particles released per timestep**	33	4	16	73	48	70
Model output	**Output 'super-particle' representative of released particles**	1000	1000	1000	1000	1000	1000

Table 3.2 Input for North Gravir salmon lice assessment based on full stock biomass and 0.5 ovigerous female lice per fish for the North Gravir site and the additional sources as specified by BFS.

North Gravir model							
	Site	**North Gravir**	**Gravir (West)**	**Gravir Outer**	**Tabhaigh**	**North Shore W**	**North Shore E**
	FS ID		FS0242	FS0242	FS1297	FS1033	FS1033
	Based on 0.5 ovigerous female lice per fish						
Physical numbers	**Farm biomass [T]**	4680	515.7	2285.2	2500	1650	2400
	Fish mass [kg]	5	5	5	5	5	5
	Number of ovigerous lice per fish	0.5	0.5	0.5	0.5	0.5	0.5
	Number of eggs per clutch per day	28	28	28	28	28	28
	Number of fish per farm	936000	103140	457040	500000	330000	480000
	Number of larvae per farm per day	13104000	1443960	6398560	7000000	4620000	6720000
Model settings	**Time period [days]**	365	365	365	365	365	365
	Model timesteps [15 mins]	35040	35040	35040	35040	35040	35040
	Number of larvae released in model per timestep	136500	15041.25	66651.66667	72916.66667	48125	70000
Model input	**Number of particles released per timestep**	137	15	67	73	48	70
Model output	**Output 'super-particle' representative of released particles**	1000	1000	1000	1000	1000	1000

3.3.2 Salmon lice development stages

As mentioned previously in Section 3.2.1, the life-cycle of a salmon louse involves several development stages (see Figure 3.1). In the biological modelling we only considered the planktonic nauplius (nauplii-I and nauplii-II) and copepodite stages of the salmon lice life-cycle.

Salmon lice movement is influenced by light intensity in the water column (phototaxis) [13], and the duration of the nauplius stages (nauplii-I and nauplii-II) decreases with increasing temperature. This means that salmon lice in warmer waters develop faster into the infective copepodid stage. However, larvae in warmer waters use up their internal energy reserves faster, which means that the 'infection window' is also reduced.

To account for the temperature dependent development of larvae in the model, the age of the particles is calculated in degree-Days (°Days, the integrated temperature over time). The particles become infective when their age attains an integrated value of 50°Days, chosen based on the values from previous studies for reference temperatures of 7-10°C [13, 14, 15] .The maximum age of planktonic salmon lice was set at an integrated particle age of 150°Days [13, 16, 17]. Beyond this time, it is assumed that lice have died through starvation or senescence (the larvae are sustained by their internal yolk reserves, and if the copepodites fail to attach to a host, they will not be able to mature into reproducing adult larvae). The stage durations used in the biological model are summarised in Table 3.3

Figure 3.2 shows an example of the temperature dependent development of a salmon louse based on, a typical, water temperature time-series for Scottish waters. Based on these temperatures, a louse will develop into an infectious copepodid larvae after approximately 5.6 days and die after 12 to 14 days. This gives a total infection window for this example of ~7-10 days, during which time significant transport and dispersion by currents may have occurred [18].

Table 3.3 Stage duration [°Days] for salmon louse development as used in the production of the salmon lice ABM model (after [8]).

Stage	Stage duration [°Days]
	Production model
1: nauplii-I	30
2: nauplii-II	20
3: copepodid	100

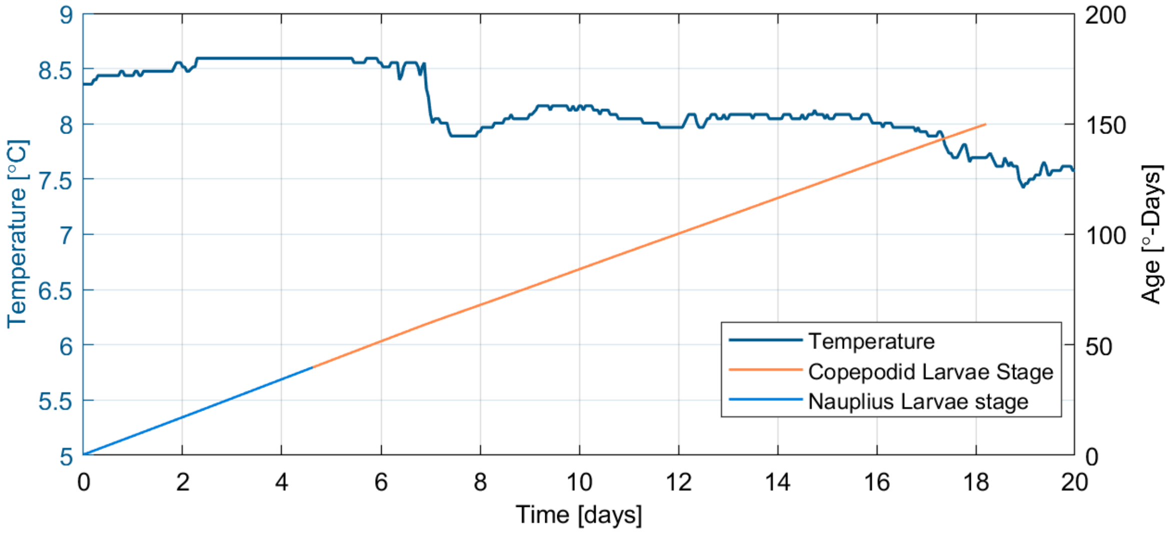

Figure 3.2 Example of larval development as a function of temperature for typical conditions in the waters around Scotland.

Mortality

The model accounts for mortality of salmon lice during the simulations. Mortality can be specified as either a constant rate or as a salinity dependent value.

Constant mortality rate

A sensitivity run on constant mortality rates has been examined. A constant mortality rate of 0.17 per day has frequently been applied in modelling studies for salmon lice [13, 16, 17]. It is somewhat common to represent mortality by a constant rate that varies during each stage of the larval life-cycle as summarised in Table 3.4. These values taken from the [8], which were based on previous work by [19]. Figure 3.3 shows an example of the decrease in abundance of larvae (from an initial starting population of 1,000 individuals), subject to mortality rates for the different life stages.

Table 3.4 Mortality rates (constant) per development stage used herein.

Stage	Mortality rate [per day]
1: nauplii-I	0.17
2: nauplii-II	0.17
3: copepodid	0.22

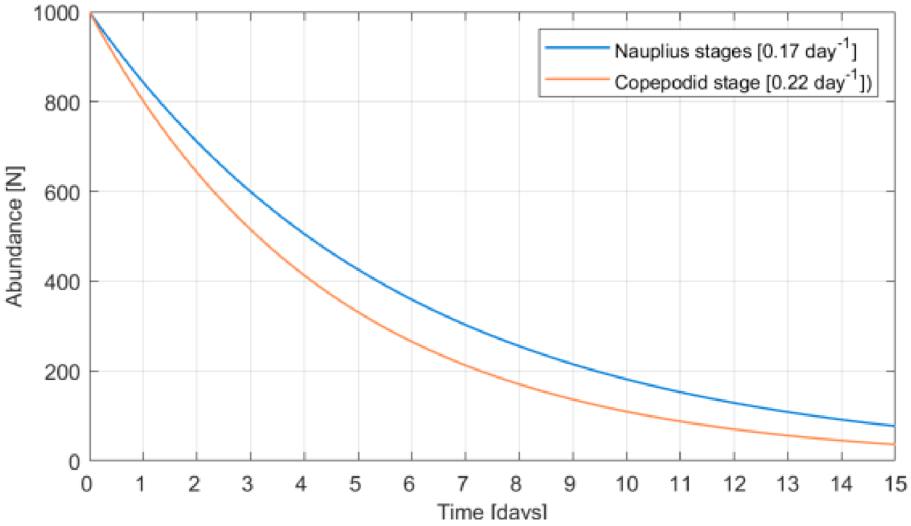

Figure 3.3 **Mortality rates of salmon lice larvae over time for different development stages.**

Salinity dependent mortality rate

All model runs were performed with a salinity dependent mortality based on equation (3.1), which was proposed in [20]:

$$MortalityRate_{salinity} = 0.2112 + max(0.0, 10.5696 - 0.3562 \cdot Salinity) \quad \textbf{(3.1)}$$

Figure 3.4 shows an example of the decrease in abundance of larvae (again from an initial starting population of 1,000), as a function of time subject to mortality rates for the different salinity levels in [20]. It is clear from equation (3.1) that in oceanic environments (i.e., with salinity >32), mortality rate due to salinity is effectively zero and defaults to the background mortality of 0.2112 d^{-1}. Here the background mortality of 0.2112 d^{-1} corresponds well with the fixed mortality rates for the copepodid stage (0.22 per day as in Table 3.4) as given by [19] mostly because the same data source [21] was used by the authors of both works.

Total mortality rate

Total mortality rate (μ) is then calculated as the mortality rate (salinity dependent, in this study) plus the Predation Mortality, defined as the product of a grazing rate per day (set at 0.1), corrected by the grazing tendency due to temperature variations, applied as the power on a grazing constant ($\theta = 1.05$).

$$\mu = MortalityRate \quad + GrazingRate * \theta^{(Temperature-20)} \quad \textbf{(3.2)}$$

Figure 3.5 shows the total mortality rate of nauplii and copepodid salmon lice larvae for different water temperatures, based on a constant mortality rate from Table 3.4.

Converting the mortality rate in a risk probability

The total mortality rate is converted into a per time step probability (time step duration *dt* [sec]) for each particle:

$$P(death) = 1 - e^{\left(\frac{-\mu * dt}{86400}\right)} \qquad (3.3)$$

This probability has been tested against a standard uniform random number ([0, 1]) with the conditional criterion being to remove a particle if the random number is less than the dying probability as described by equation (3.3). Additionally, individuals leaving the copepodid stage are removed from the simulations.

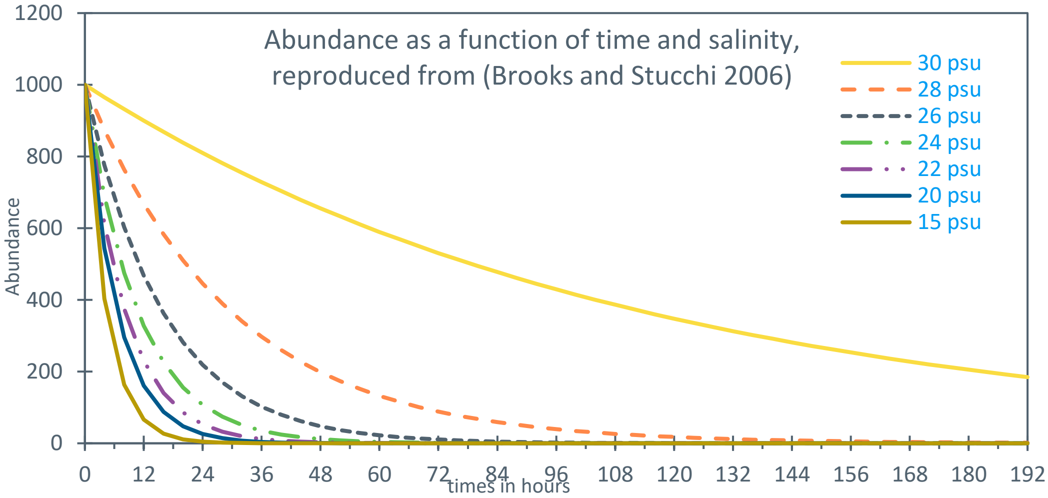

Figure 3.4 **Abundance of salmon lice entities as a function of time and salinity (after [20]).**

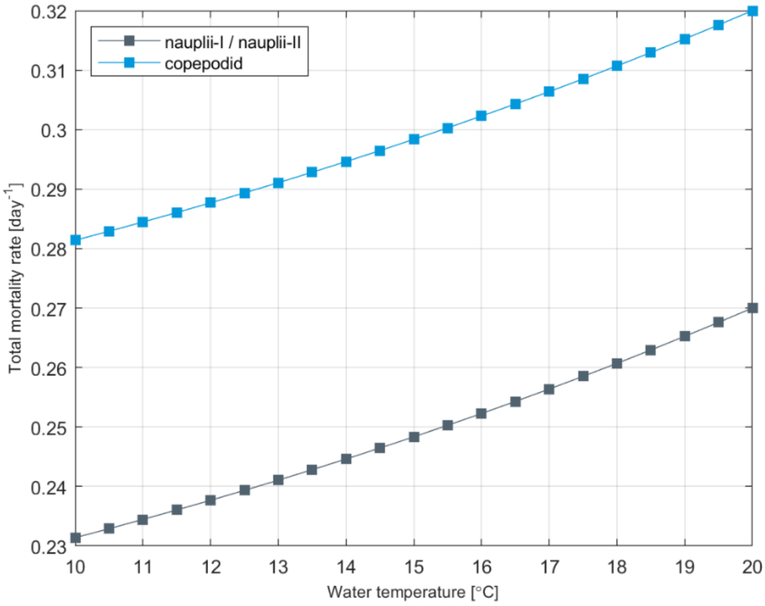

Figure 3.5 **Total mortality rate [day^{-1}] of nauplii and copepodid salmon lice at different water temperatures [°C]. The total mortality rate is calculated via equation (3.2), with constant mortality rates per development stage (see Table 3.4).**

Movement

The salmon lice ABM uses passive drifting particles to simulate the dispersal/distribution of entities representing the planktonic life stages of salmon lice. Entities can move vertically in the water column, based on a hierarchical response to salinity, light and temperature.

Horizontal Movement

The modelled salmon lice larvae cannot swim horizontally in the model. Salmon lice larvae are subject to passive transport by the flow field (including random walk properties, see section 3.3, *Dispersion*). Thus, horizontal swimming by salmon lice larvae, herein, is considered insignificant in comparison to the random horizontal diffusion. The horizontal movement of particles is therefore set by the local current conditions which are provided by a hydrodynamic model (Section 3.1 and [1]) with the addition of a stochastic diffusion process translated as a particle random walk.

Particles that leave the domain through the offshore boundaries were excluded from the remainder of the simulation.

Vertical Movement

The modelled salmon lice particles were given the ability to swim vertically through the water column based on certain hierarchical responses to salinity (i.e., particles sink to avoid unfavourable fresh surface waters), and temperature (i.e., particles seek higher temperatures to optimise development time). A constant vertical swimming speed of 0.5 mm/s was set for all development stages. This value is used in other model studies [17] and roughly corresponds to about 1 body length per second [8]. An additional ground avoidance response is adopted to prevent particles becoming stranded on the seafloor. The thresholds for some of the movement cues are dependent on the development stage (stage dependent thresholds).

The particle response to light intensity, salinity, temperature, and seafloor followed the following logic:

1. If the salinity drops below a threshold, then the particle will swim downwards. Salmon lice show an avoidance to low salinity areas in laboratory experiments [14], and exhibit aggregation under or at the halocline. Estimates for the threshold for low salinity avoidance for salmon lice vary, but a value of 20 psu was adopted in accordance with the method used by [8].
2. If light intensity increases above a threshold, then the particle will swim upwards. Salmon lice exhibit cues of positive phototaxis, and, in the absence of vigorous surface water mixing, are expected to show higher concentrations in upper water masses [12]. The light threshold movement response for the nauplii and copepodid planktonic life stages have been set to 0.39 and 2.06×10^{-5} [μmol photons $m^{-2}s^{-1}$], respectively.

   NOTE: the solar net heat flux used in this study is computed from a climatology meteorological forcing from the global Climate Forecast System Reanalysis (CFSR) model[2]. The regional climatology model (HD_{NG_Clima}) is not considering the shortwave and longwave radiation fluxes [1]. Additionally, the value used in the ECLH climatology represents an average daily flux with long-term seasonal characteristics, but no diurnal variation. Thus, the level of light intensity from the ECLH climatology is such that it is always above the threshold value; hence, all lice, regardless of the stage of development, will swim upwards. To remedy this fact, a CFSR based solar net heat flux climatology was computed for the years 1993-2014 with the inclusion of a diurnal signal. The diurnal signal was constructed

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[2] Climate Forecast System Reanalysis (CFSR) | Climate Data Guide (ucar.edu)

on the assumption of stationarity in terms of intensity for the respective calendar months (i.e., intensity for the respective calendar months does not exhibit a trend over the years).

3. If a vertical temperature gradient exists, then a particle will seek higher temperature water. Evidence from field studies suggests that planktonic salmon lice larvae seek higher water temperatures to minimise development time to infectious stages [15]. Modelled particles can sense the water temperature in adjacent vertical model layers (above and below). This is based on a temporally smoothed history of the temperature and vertical position. If the temperature is below the smoothed history reference, entities may move to adjacent vertical model layers (either above or below).
4. Particles avoid the seafloor. If the depth of a particle is detected less than 1 m from the seafloor, then the particle will swim upwards to avoid contact with the seafloor.

Vertical distribution of particles, as a response to the environmental parameters, at all salmon lice life-cycle stages, can be seen in Figure 3.6.

Objectives

Particles have no direct objectives. Implicit a short development time is an objective.

Prediction

There is no prediction of any states or process into the future. All reactions/decisions occur on the base of current and past/historic information.

Sensing

Particles can sense the local flow field (current direction and speed) as well as local environmental parameters (light, salinity, temperature) directly.

Interaction

There are no interactions with other entities of the planktonic life stages.

Stochasticity

A random variable (uniform) is used to test if an entity dies within a time step. Apart from this, each entity may see slightly varying environmental factors (in the form of local flow conditions), dependent on the selected dispersion scheme. This will cause a standard, uncorrelated random walk component in the horizontal/and or vertical.

Dispersion

Dispersion describes the transport of particles due to molecular diffusion and non-resolved turbulence or eddies. In coastal areas dispersion due to non-resolved turbulence is normally by far the most important factor. It is important to distinguish between horizontal dispersion (e.g., due to non-resolved eddies), and vertical dispersion (e.g., due to bed generated turbulence). Hence, dispersion in horizontal and vertical directions is specified separately. The process of dispersion is implemented as a likelihood to move in a random direction.

Following SEPA's interim guidance the horizontal and vertical dispersion coefficients were set as 0.1 m^2s^{-1} and 0.001 m^2s^{-1}, respectively.

Generic outputs

The output of the ABM simulations is the spatial/temporal variation of planktonic salmon lice life stages based on the hydrodynamic flow field, and the vertical movement that is dependent on the development stage. The distribution of particles during the infective copepodite life stage has been of primary interest, and it was used to create maps of potential dispersal of salmon lice originating from the Proposed

Development of the North Gravir site and active BFS (and MOWI) sites nearby the North Gravir site.

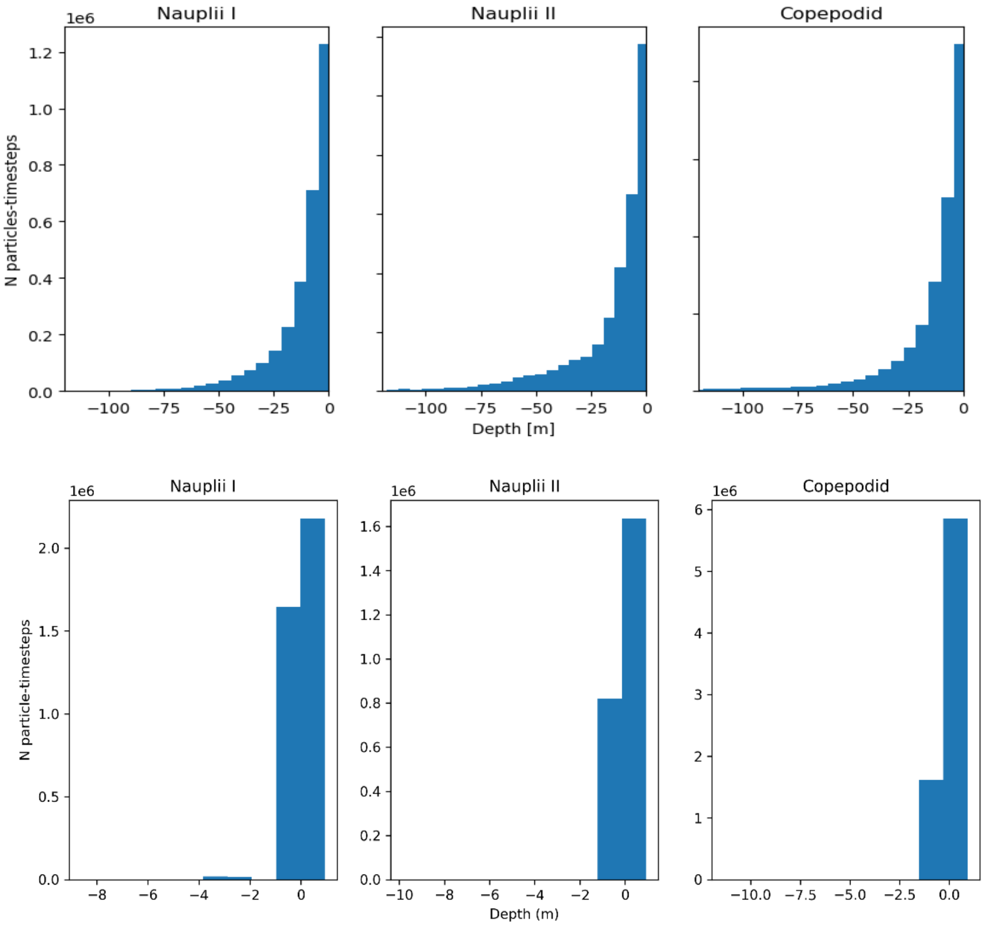

Figure 3.6 **Vertical distribution for the different salmon lice life-cycle stages associated with salmon lice model parameters affecting vertical movement when using the climatological light intensity forcing with diurnal variation (top) vs using climatological light intensity with no diurnal variation (bottom). In the latter case, all particles' positions are recorded to surface layers as light intensity is above threshold throughout simulation time.**

4 Model Results

In this section, the outputs of the coupled hydrodynamic-biological salmon lice model described in Section 3.1 and Section 3.2 are used to identify potential dispersal patterns from salmon lice originating from the Proposed Development of North Gravir and cumulatively from active BFS (and MOWI) sites around North Gravir, the Outer Hebrides.

4.1 Salmon lice development

The spatial-temporal variation of salmon lice, during planktonic life stages, is a function of the dispersion through the hydrodynamic flow field, and the vertical movement that is dependent on the development stage (see section 3.3.2), which is controlled by taxation on environmental factors such as light intensity, temperature, and salinity conditions in the water column. This can be used to provide insight on the dispersal patterns for different sources of salmon lice/particles.

Salmon lice dispersion was determined for particles released from:

- the Proposed Development of North Gravir as a single source;
- three (3) source locations representing designated BFS aquaculture sites in the waters around the North Gravir site, namely North Gravir, Gravir (West), and Gravir Outer (see also Table 1.1), as a cumulative input.
- The above three (3) source locations representing designated BFS aquaculture sites in the waters around the North Gravir site and three (3) MOWI active sites, namely North Shore W, North Shore E and Tabhaigh, (see also Table 1.1), as a cumulative input.

The development time for simulated salmon lice to transition into the infectious copepodite stage was illustrated for a single particle in Figure 3.2, which represents the development progress of 1,000 newly hatched nauplii-I larvae. The influence of mortality on the lice numbers can also be observed in Figure 3.5.

For the final (production) run, a salinity dependent mortality rate was used as described in section 3.3.2, with the overall survival rate at the transition to the copepodid stage being 54% and 71% for the peak smolt out-migration and annual periods, respectively. The applied stage duration of 150°days at copepodid stage results in a mean infectious window of 3.7 -5.1 days. A constant-based mortality rate (see section 3.3.2) was also adopted for the model sensitivity runs, leading to an average of 0.05 day^{-1} rate during the copepodite stage.

The development time to copepodite of lice is summarised in Table 4.1. The larvae development time did not vary significantly between source locations. However, comparing the results between two seasonal periods (January to June and June to December), it can be noted that:

- There is an increase in survival rate to the copepodite stage from ~48% (January to June) to ~88% (June to December), see the column titles "Survival Rate at Copepodid stage transition"[3] in Table 4.1;

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[3] The survival rate at the transition to the copepodite life stage is defined as the average of the maxima recorded individuals copepodites population per super particle over all released particles, following the assumption that the copepodites population will follow the prescribed decrease rate with time.

- A decrease in the development time from ~5.0 days (January to June) to ~3.5 days (June to December), reflecting the increasing water temperatures during the latter period;
- The infectious period decreases from ~5.1 days (January to June) to ~3.7 days (June to December). Both are considered consistent to relevant salmon lice studies as referenced herein, and, therefore, the particle dataset is a representative basis with which to assess potential dispersal patterns of salmon lice.

Table 4.1 Copepodite life-cycle stage for repeated releases for the whole annual period and the shorter peak smolt out-migration period for the North Gravir release location as in Table 1.1.

Whole annual period	*Period to infective stage [days]*	*Infectious window [days]*	*Survival Rate at transition to Copepodid stage [%]*	*Particle maximum age [days]*	*Particle Minimum age [days]*
Jan2Dec	4.1	4.2	71	13.9	2.1
Jan2Jun	5.0	5.1	48	13.9	2.6
Jun2Dec	3.5	3.7	88	10.5	2.1
Peak smolt out-migration period	***Period to infective stage [days]***	***Infectious window [days]***	***Survival Rate at transition to Copepodid stage [%]***	***Particle maximum age [days]***	***Particle Minimum age [days]***
13April - 25May	4.8	4.2	54	13.1	2.9

4.2 Spatial distributions of infective salmon lice

The spatial distributions of infective salmon lice were determined based on the horizontal and vertical positions of particles, integrated in time, and for releases originating from the Proposed Development of North Gravir and cumulatively from all active BFS sites around North Gravir. These results are based:

- on the whole annual period, running from January to December (inclusive) and coinciding with the climatological hydrodynamic database, and
- during the peak smolt out-migration[4] period, running from 13 April to 25 May.

In general, the spatial distribution is consistent with the advection capacity and net circulation of the background advection field from HD_{NG_Clima} as shown in Figure 7.1 in [1]. For example, sources located within a high-capacity advection regime[5] have the potential to travel through a variety of locations with different dispersion dynamics and thus exhibit a wider spatial footprint.

It should be noted that particles originating from sources located within narrow straits and inlets are likely to be locally under-represented by the regional hydrodynamic climatology model (HD_{NG_Clima}) due to the necessary simplifications of the mesh resolution, and the representation of circulation in those locations. As such, the underlying hydrodynamic model may not always be adequate to resolve coastal features and small islands.

The mesh used for the salmon lice dispersion exercise is the same as for the HD_{NG_Clima} database. This means that the nearby area of North Gravir site is spatially resolved down to 25-40 m.

With regards to sensitivity due to the assessed period (section 3.3), there are some discernible differences in the spatial extent of the infectious salmon lice (for example see Figure 4.3 versus Figure 4.6). This is well justified when considering the salmon lice development characteristics and their dependence on light intensity and temperature (range of salinity variations has significantly less impact to salmon lice development due to the seasonal variations of oceanic freshwater content within the Outer Hebrides latitudinal extent [22, 23]). Nonetheless, the salmon lice concentration during infectious stage is in general **below** a value of **0.2 individuals per m^2**. This is even when considering all sources as also under a conservative ratio of 0.5 ovigerous lice per fish and at peak biomass (see Figure 4.10). The exceptions are **isolated** spots[6] along the coastline (see for example Figure 4.17 and Figure 4.20, red spots) where concentration of infectious lice exceeds 10 individuals per m^2**.**

Below, results for salmon lice dispersion during the various life-cycle stages of Nauplii-I, and -II and the infectious Copepodid stage are presented. Results are presented separately for the Proposed Development of the North Gravir site and when considering the cumulative input from all active BFS sites around North Gravir as in Table 3.1.

Results are also split into two different assessment periods:

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[4] Peak smolt out-migration period was selected from 13 April to 25 May [9].

[5] A hydrodynamic field that has a strong advection component.

[6] While there is no allowance for particle sedimentation in the salmon lice dispersion model herein, and any stranded particles are removed from the overall budget of “live” particles, there are still locations in small inlets along the coastline which will act as particle “sinks”. This is partly because of underrepresented hydrodynamic conditions due to the computational mesh coarseness at these locations. The result is weak recirculation dynamics and has the overall effect of increased particle concentrations on those coastal computational cells.

- over the peak smolt out-migration period; and
- for the whole simulation period of January to December.

The increased ratio of **0.5 ovigerous lice per fish** is **only** presented for the **cumulative sources**, as in Table 3.2, and assessed **only** for the **peak smolt out-migration period and the Copepodid stage**.

For all results the 0.5 quantile is presented for the salmon lice mappings for all three (3) life-cycle stages (i.e., Nauplii-I, Nauplii-II and Copepodid).

On the following sections, a description of potential dispersal of salmon lice is presented, first for the Proposed Development of the North Gravir site, and then for the cumulative input from all active BFS (and MOWI) sites including the Proposed Development of the North Gravir site.

4.2.1 North Gravir as a single source

Figure 4.1 to Figure 4.3 illustrate dispersal of salmon lice from the North Gravir site during the peak smolt out-migration period. The number of ovigerous lice per fish is calculated as an average during the peak smolt out-migration period over multiple years from the nearby active BFS sites

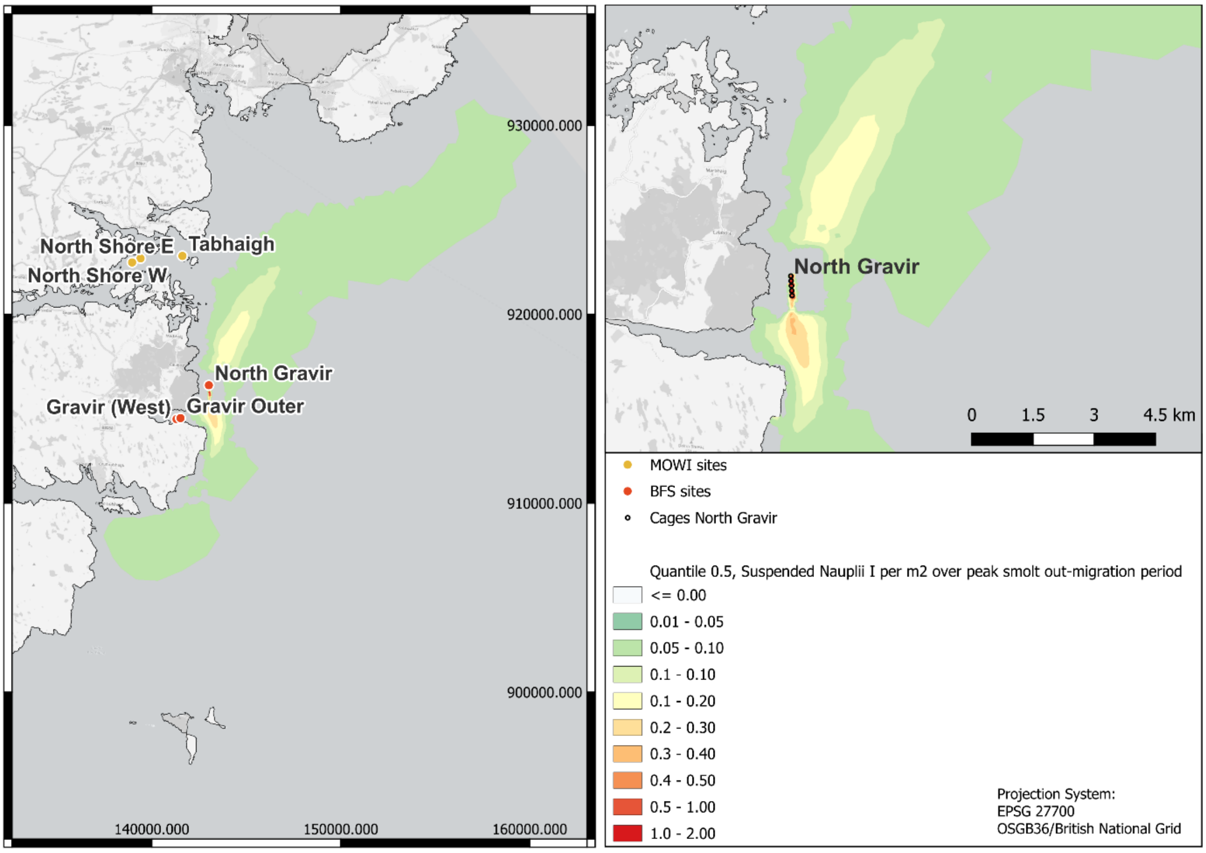

Figure 4.1 **Spatial extent (0.5 quantile) of particles, at Nauplii-I salmon lice stage, originating only from the North Gravir site during the peak smolt out-migration period (13 April to 25 May).**

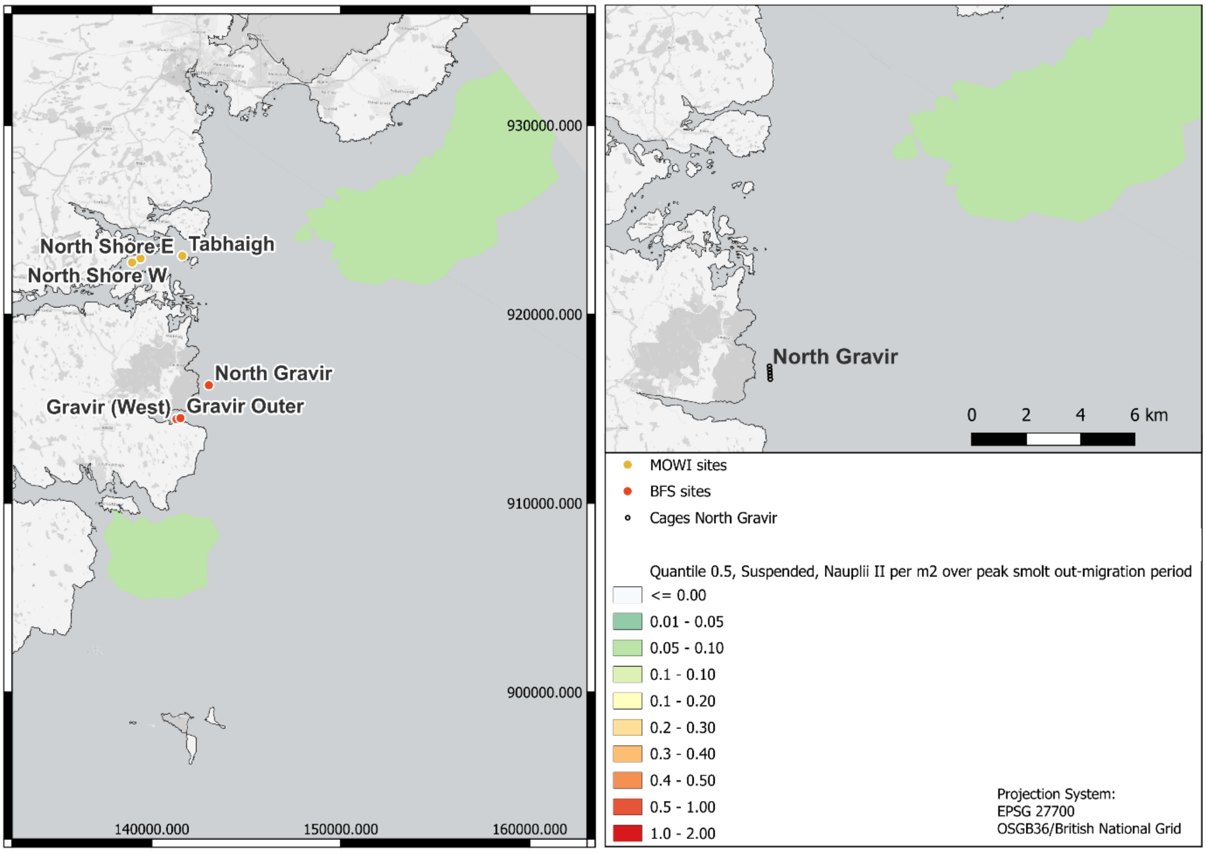

Figure 4.2 Spatial extent (0.5 quantile) of particles, at Nauplii-II salmon lice stage, originating only from the North Gravir site during the peak smolt out-migration period (13 April to 25 May).

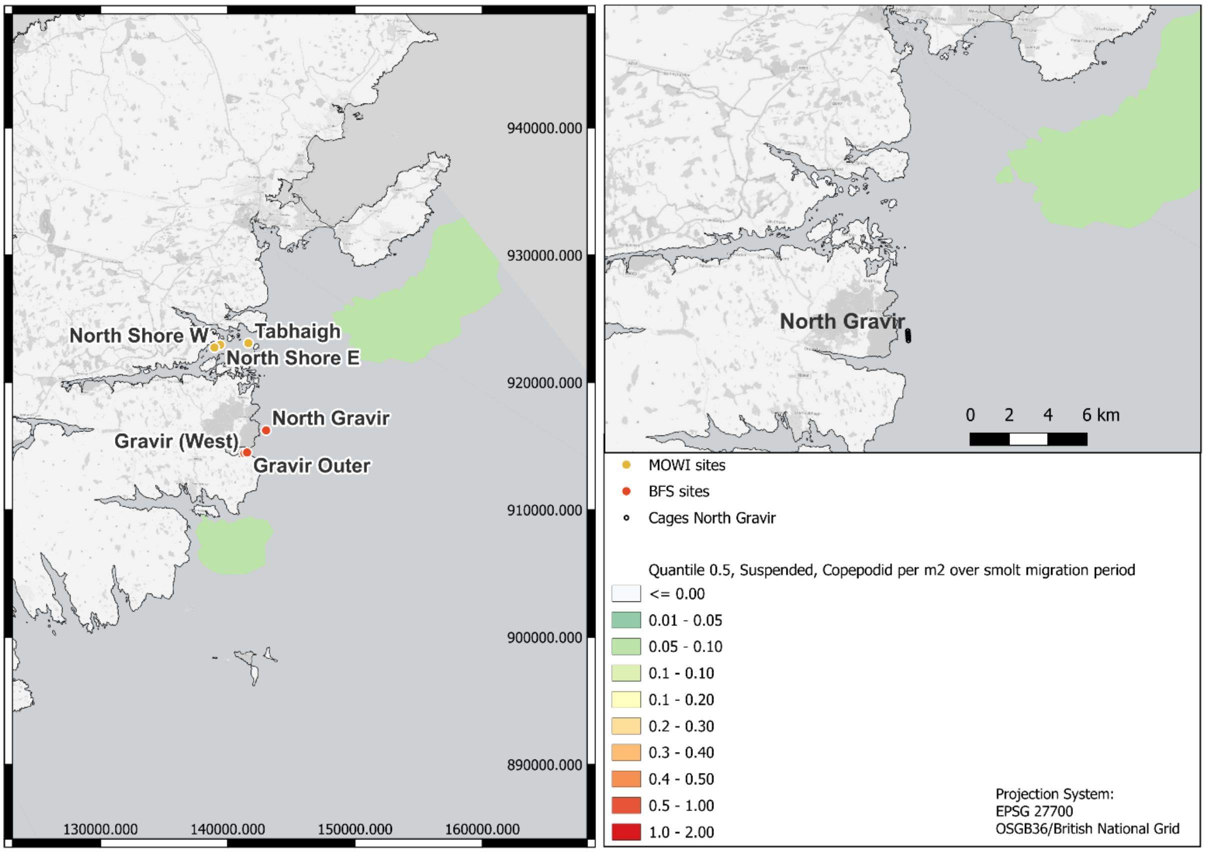

Figure 4.3 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating only from the North Gravir site during the peak smolt out-migration period (13 April to 25 May).

Figure 4.4 to Figure 4.6 illustrate dispersal of salmon lice from the North Gravir site from January to December (inclusive). The number of ovigerous lice per fish is calculated as an average during the peak smolt out-migration period over multiple years from the nearby active BFS sites

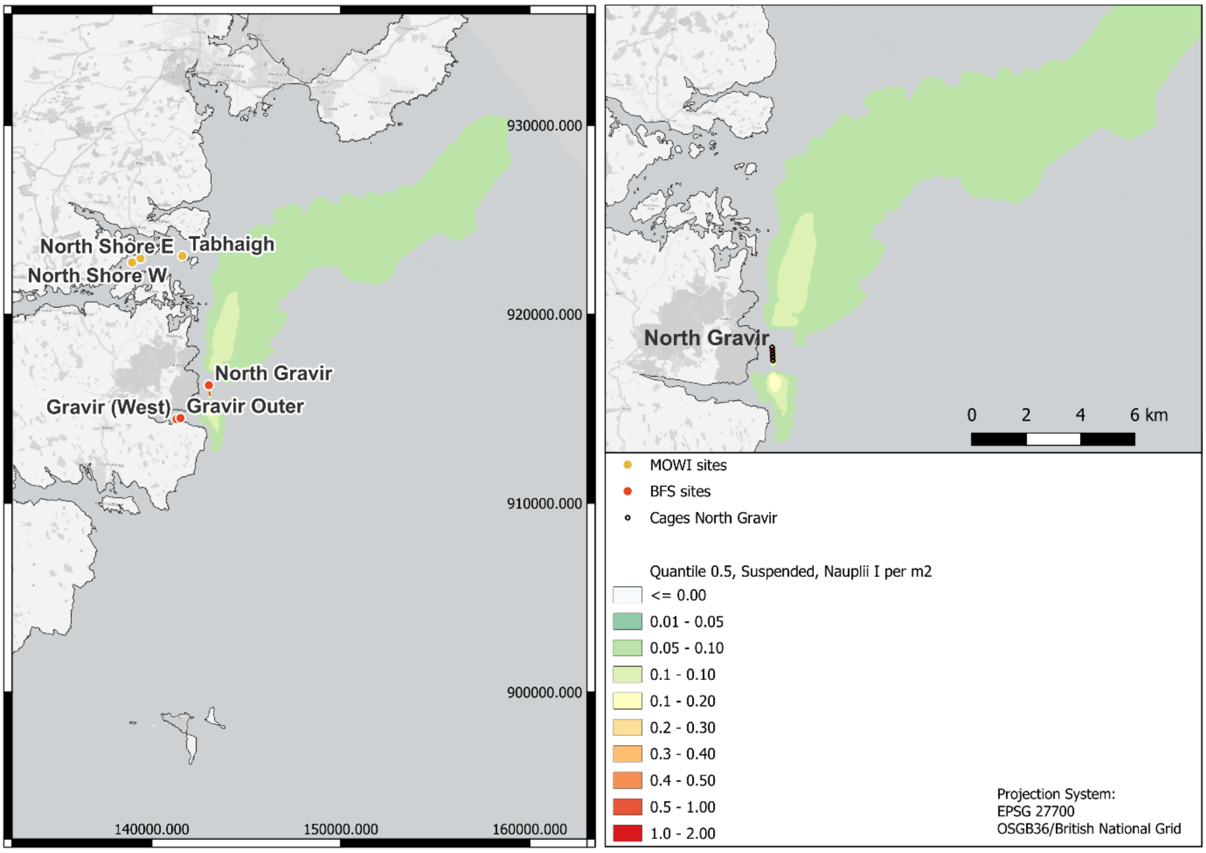

Figure 4.4 Spatial extent (0.5 quantile) of particles, at Nauplii-I salmon lice stage, originating only from the North Gravir site for the whole annual climatological period (January to December).

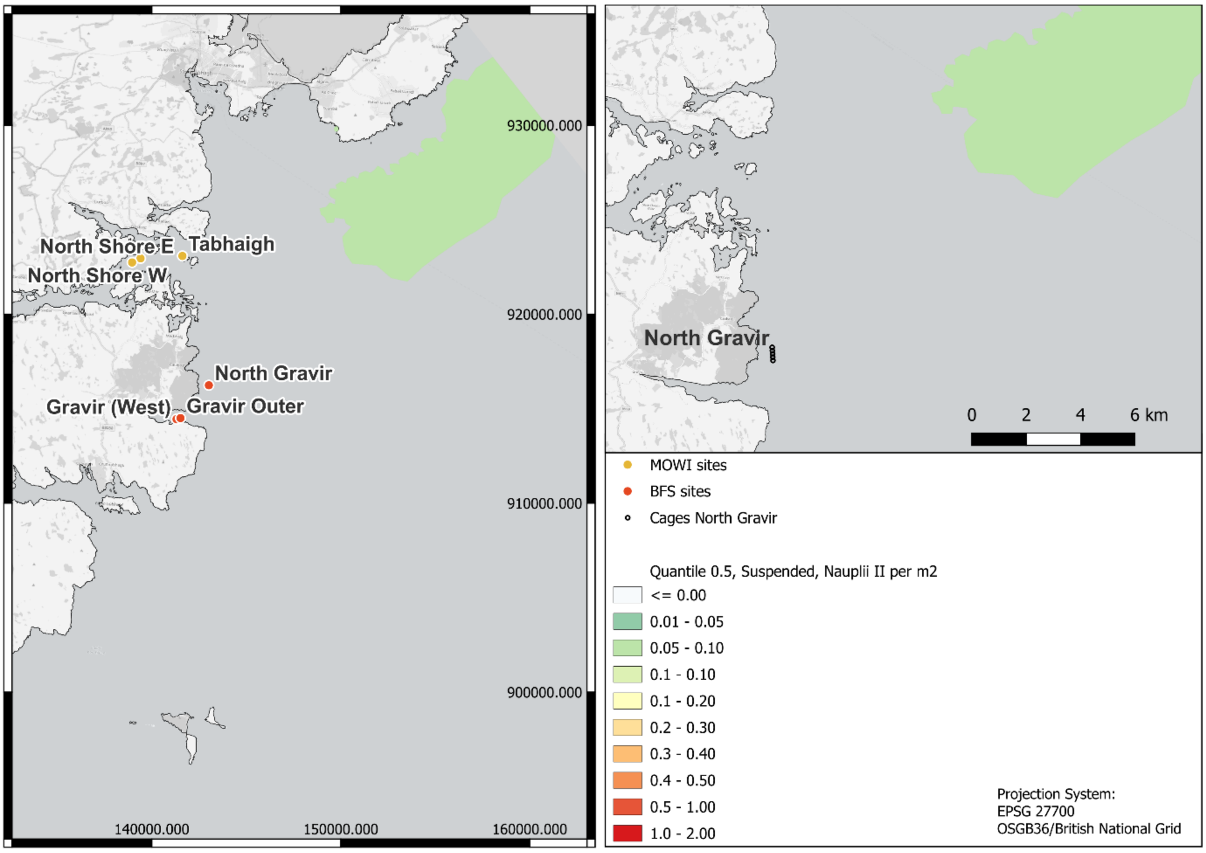

Figure 4.5 **Spatial extent (0.5 quantile) of particles, at Nauplii-II salmon lice stage, originating only from the North Gravir site for the whole annual climatological period (January to December).**

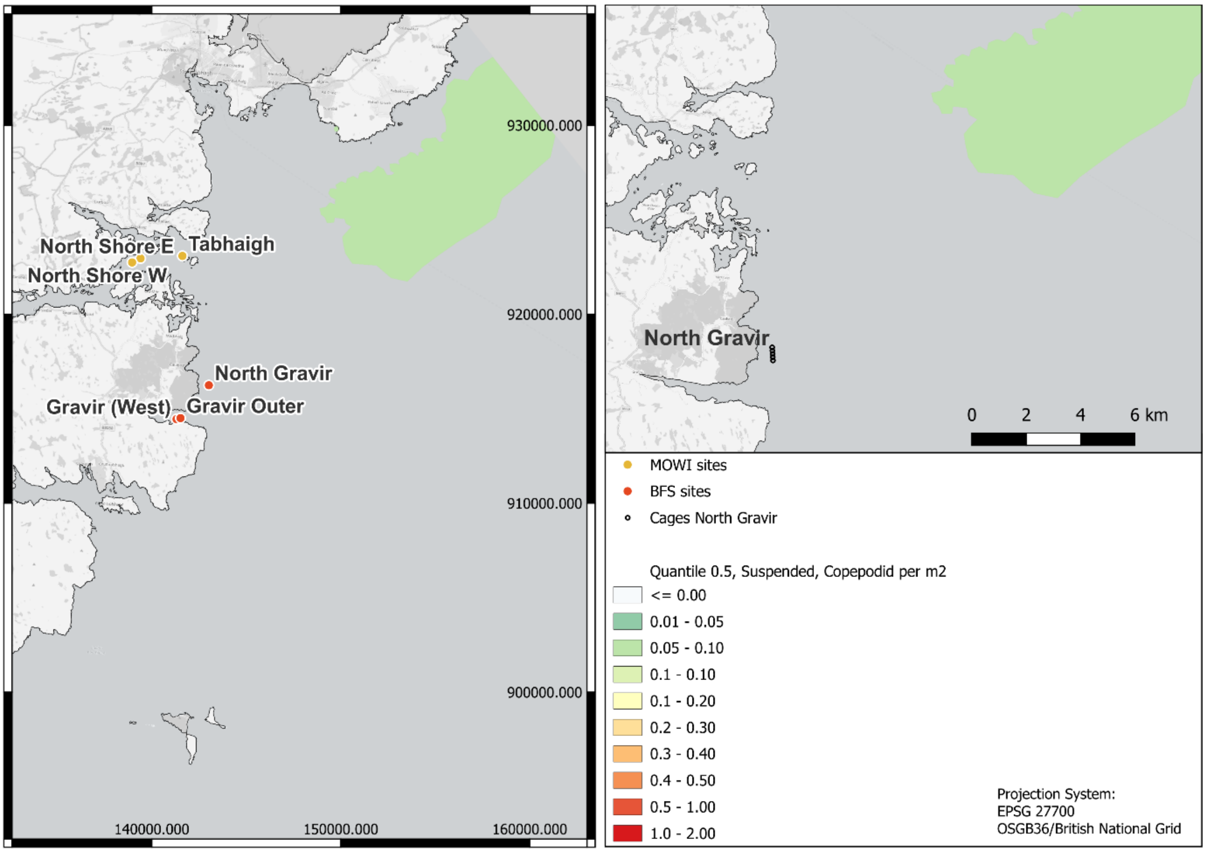

Figure 4.6 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating only from the North Gravir site for the whole annual climatological period (January to December).

4.2.2 All BFS designated sources as in Table 3.1

Figure 4.7 to Figure 4.9 illustrate the dispersal of salmon lice from all nearby active BFS sites and the Proposed Development of the North Gravir site during the peak smolt out-migration period. The number of ovigerous lice per fish is calculated as an average during the peak smolt out-migration period over multiple years from the nearby active BFS sites

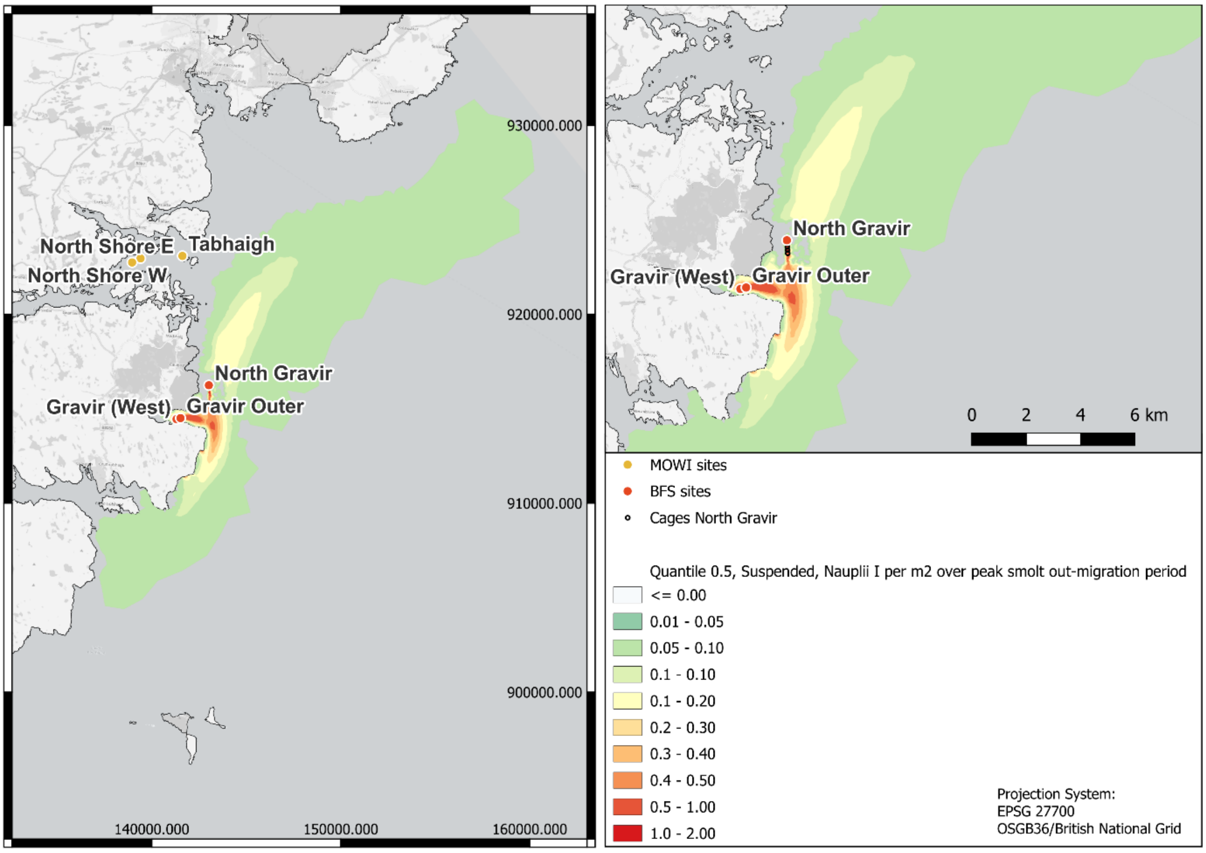

Figure 4.7 **Spatial extent (0.5 quantile) of particles, at Nauplii-I salmon lice stage, originating from all BFS designated sites during the peak smolt out-migration period (13 April to 25 May).**

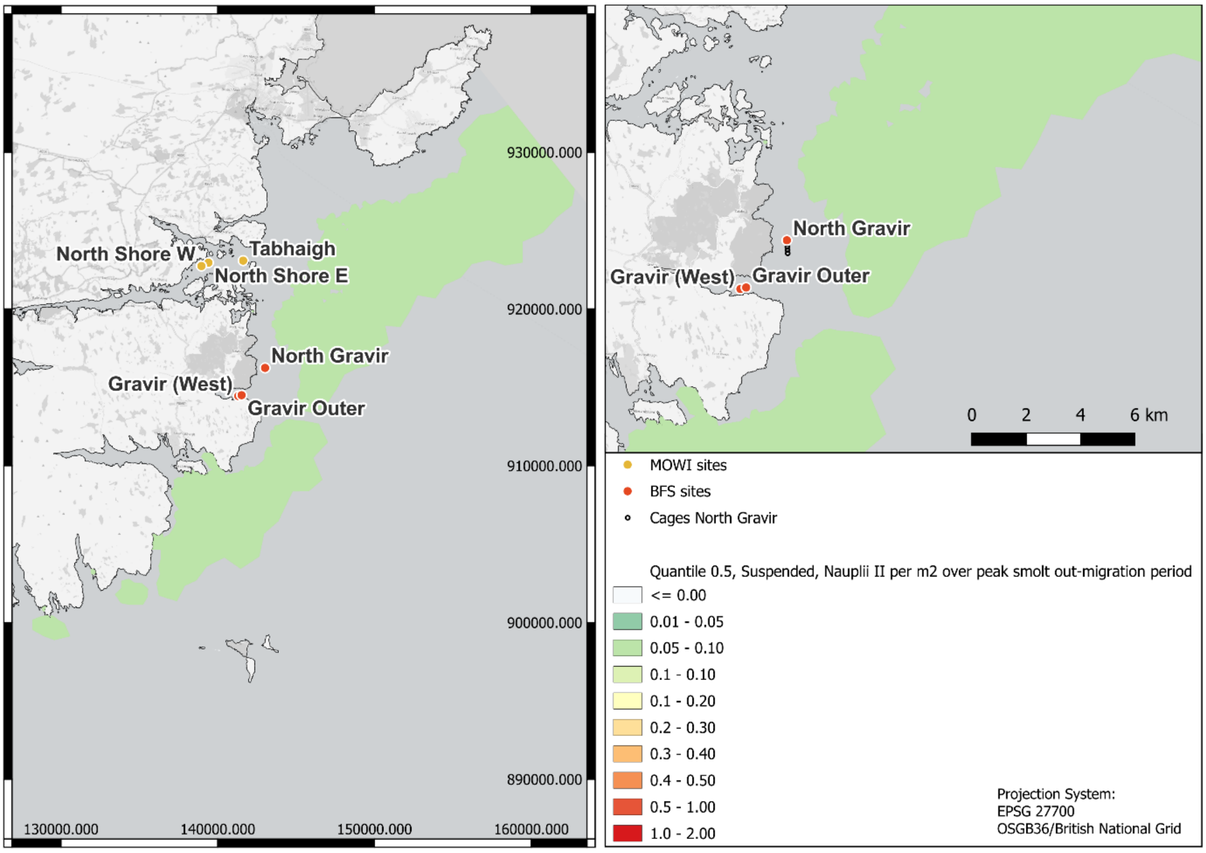

Figure 4.8 Spatial extent (0.5 quantile) of particles, at Nauplii-II salmon lice stage, originating from all BFS designated sites during the peak smolt out-migration period (13 April to 25 May).

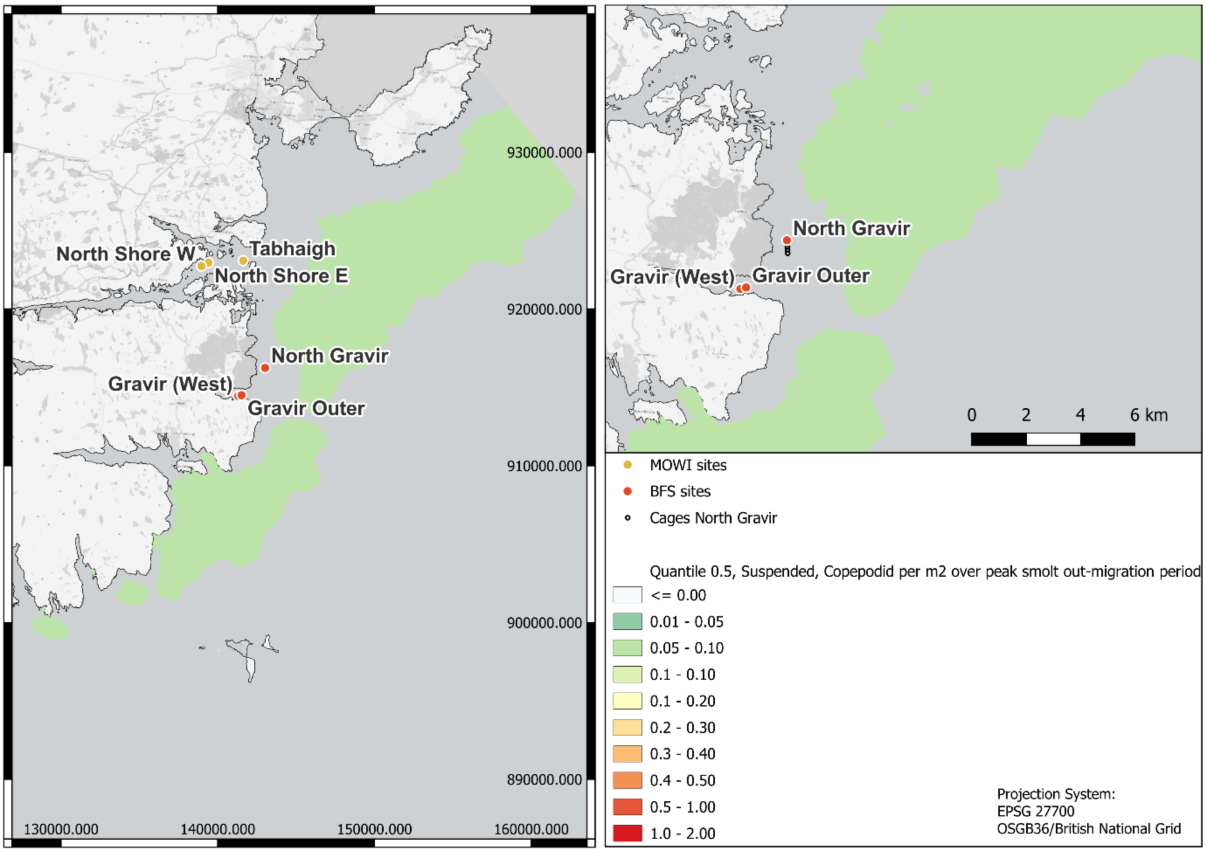

Figure 4.9 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating from all BFS designated sites during the peak smolt out-migration period (13 April to 25 May).

Figure 4.10 illustrate the dispersal of salmon lice (only for the Copepodid stage) from all nearby active BFS sites and the Proposed Development of the North Gravir site during the peak smolt out-migration period. The number of ovigerous lice per fish is set to 0.5 – (only Copepodid stage)

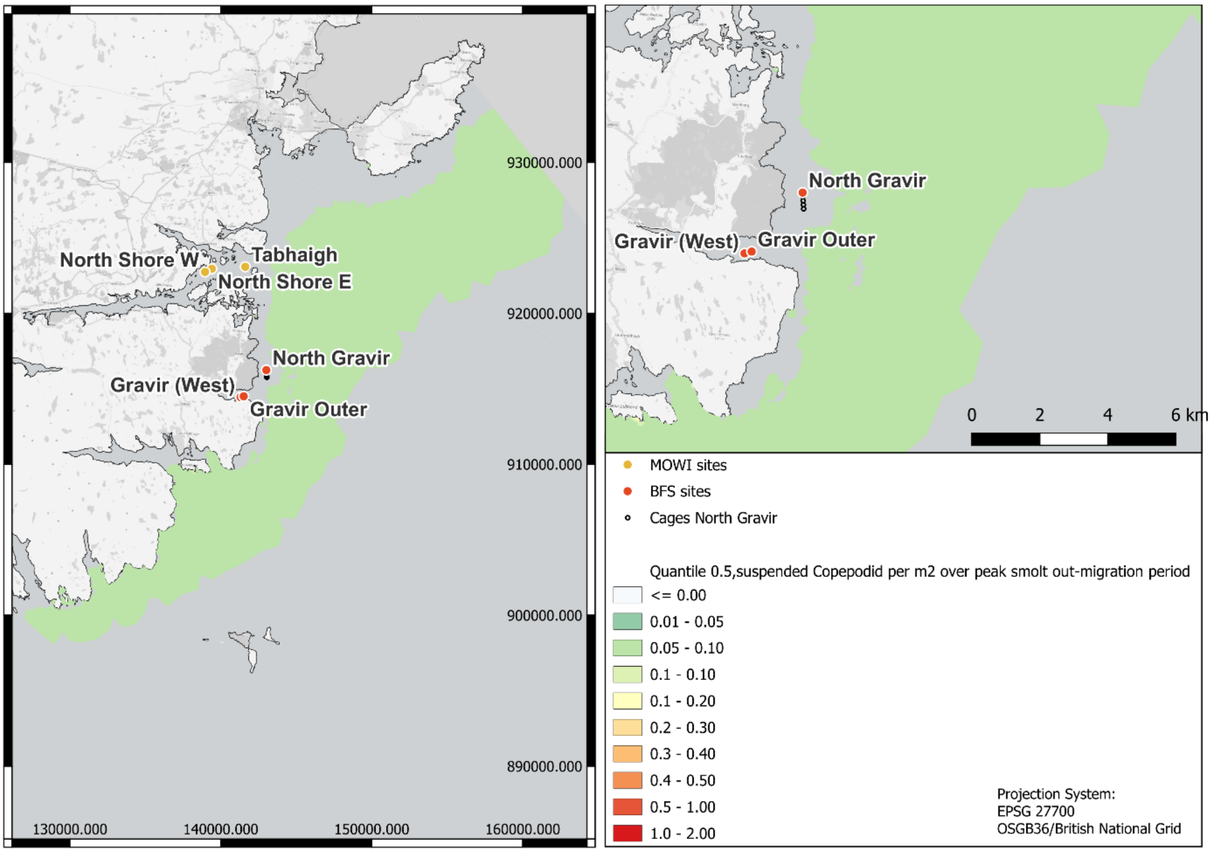

Figure 4.10 **Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating from all BFS designated sites as in Table 3.1 during the peak smolt out-migration period (13 April to 25 May). Ratio of lice per fish is set to 0.5 ovigerous lice per fish for all sources.**

Figure 4.11 to Figure 4.13 illustrate the dispersal of salmon lice from all active BFS sites around North Gravir and the Proposed Development of the North Gravir site from January to December (inclusive). The number of ovigerous lice per fish is calculated as an average during the peak smolt out-migration period over multiple years from nearby active BFS sites

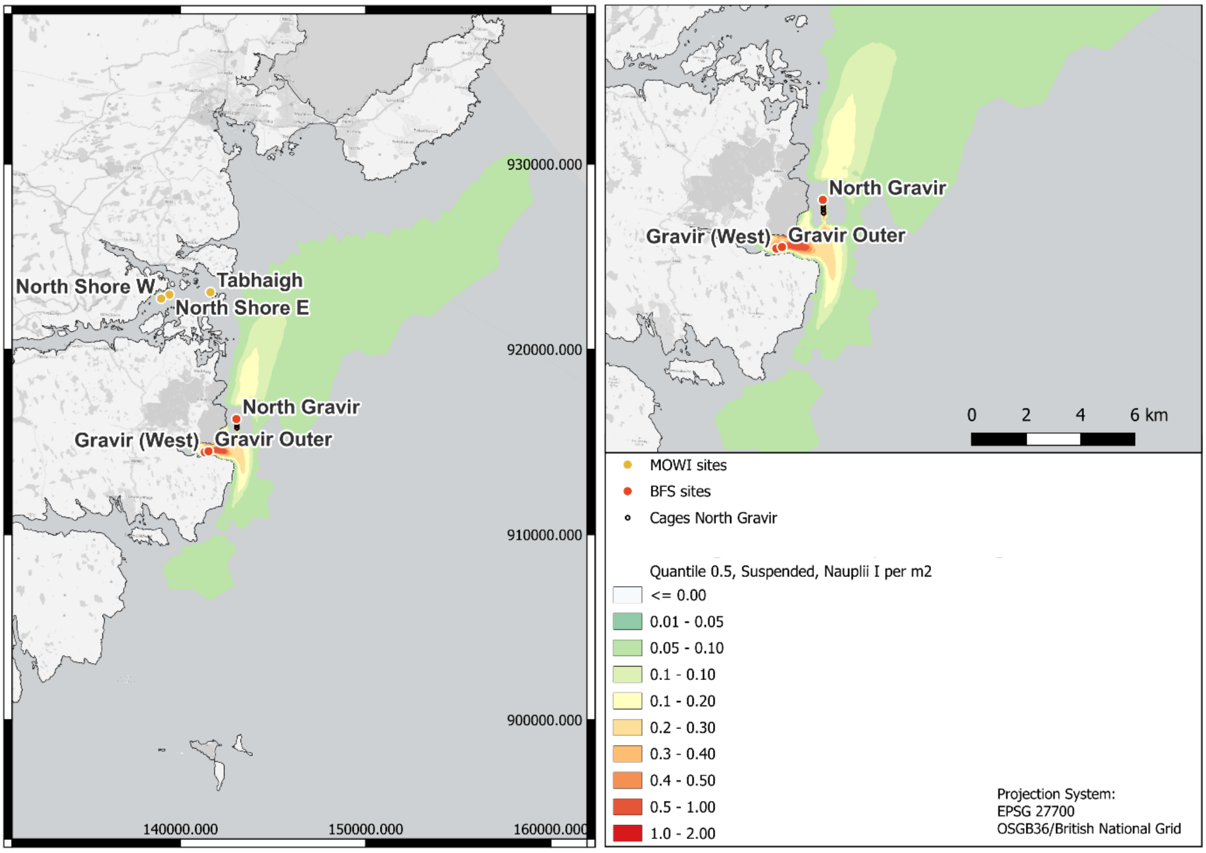

Figure 4.11 **Spatial extent (0.5 quantile) of particles, at Nauplii-I salmon lice stage, originating only from all BFS designated sites for the whole annual climatological period (January to December).**

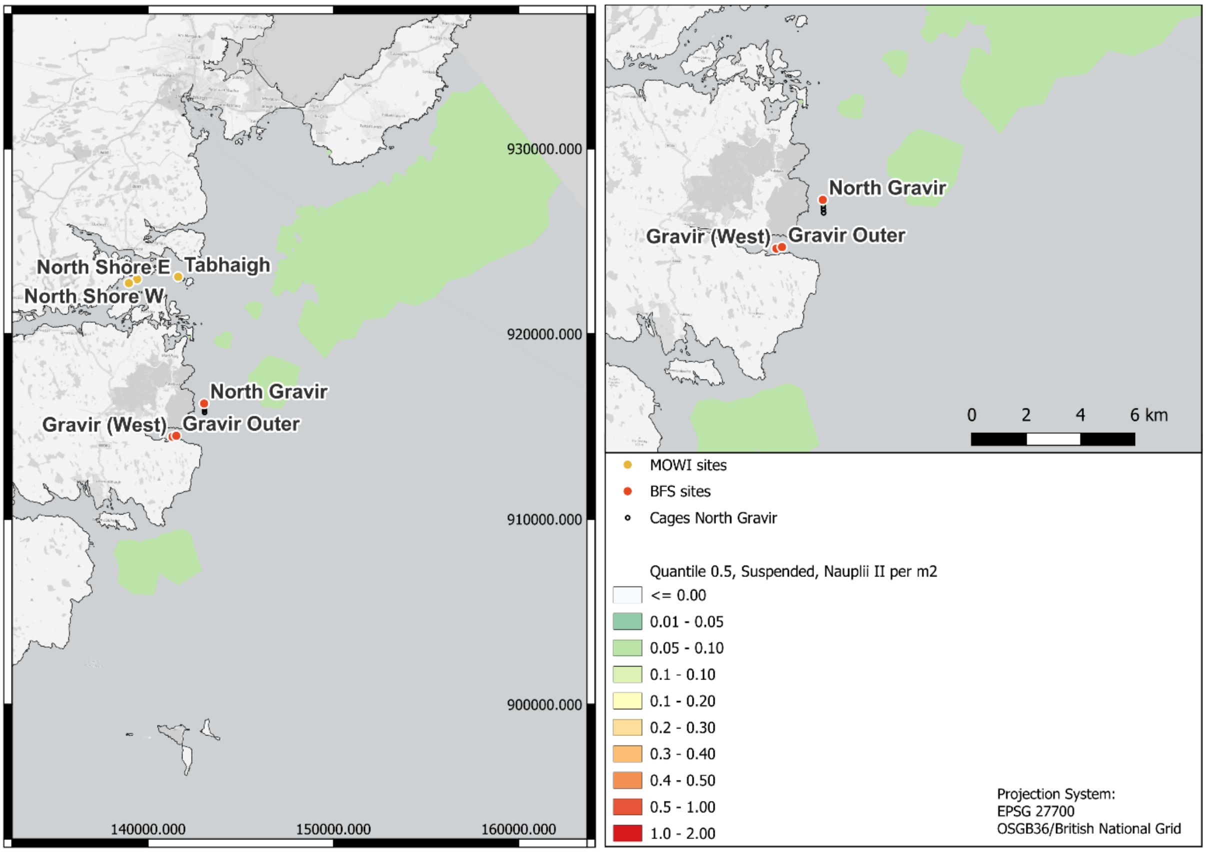

Figure 4.12 Spatial extent (0.5 quantile) of particles, at Nauplii-II salmon lice stage, originating only from all BFS designated sites for the whole annual climatological period (January to December).

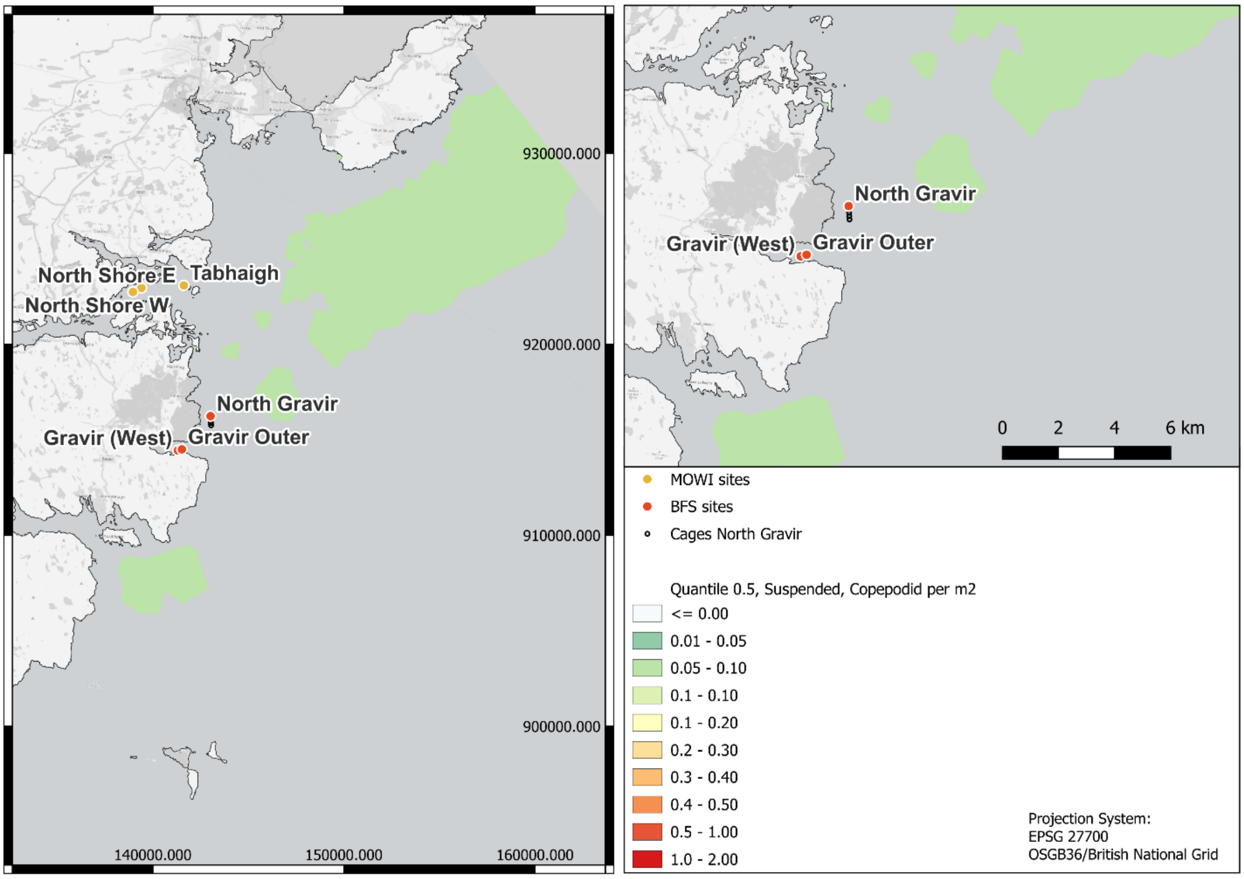

Figure 4.13 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating only from all BFS designated sites for the whole annual climatological period (January to December).

4.2.3 All BFS plus MOWI designated sources as in Table 3.1

Figure 4.14 to Figure 4.3 illustrate dispersal of salmon lice from the Proposed Development of the North Gravir site, all nearby BFS active sites and the MOWI sites as in Table 3.1, during the peak smolt out-migration period. The number of ovigerous lice per fish is calculated as an average during the peak smolt out-migration period over multiple years from the nearby active BFS sites. MOWI sites are modelled with the number of ovigerous lice per fish at 0.5.

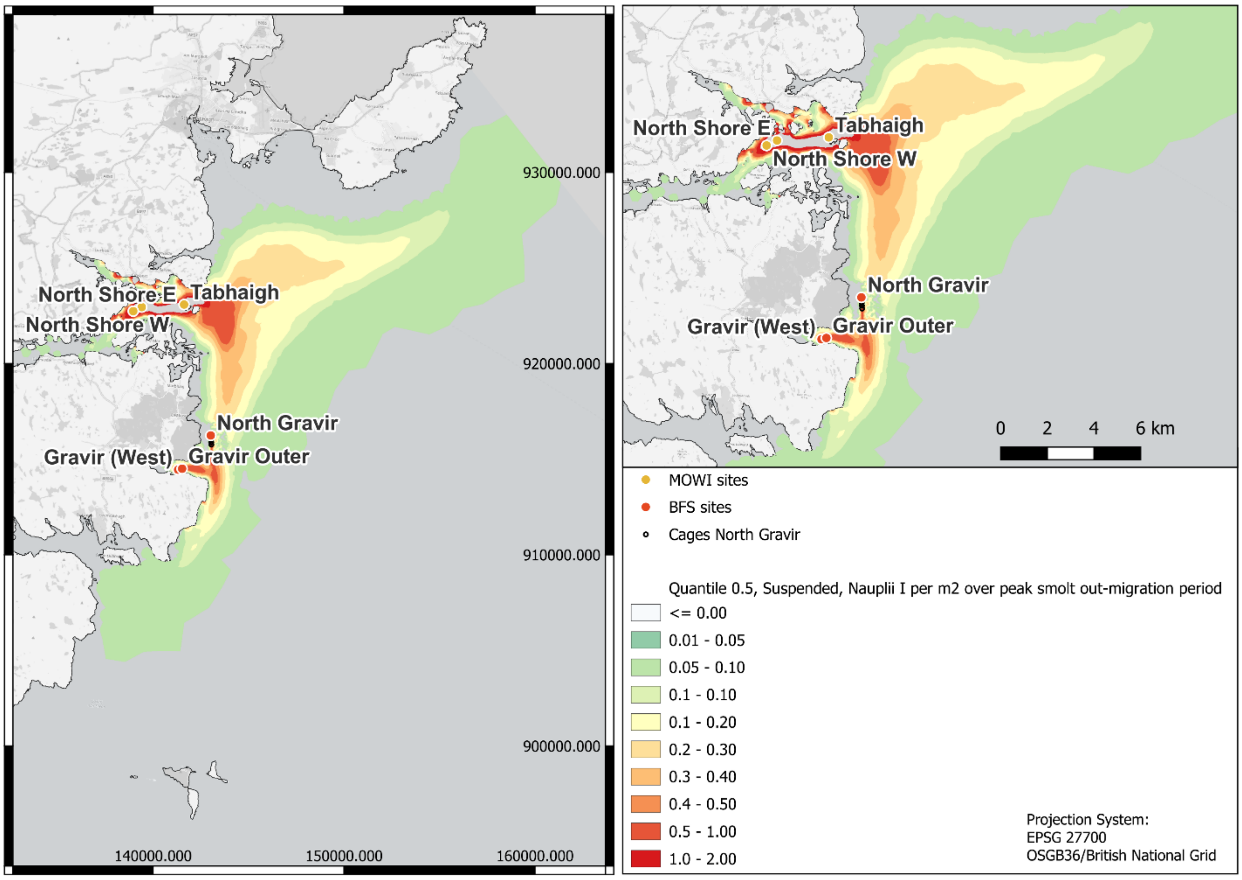

Figure 4.14 **Spatial extent (0.5 quantile) of particles, at Nauplii-I salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites during the peak smolt out-migration period (13 April to 25 May).**

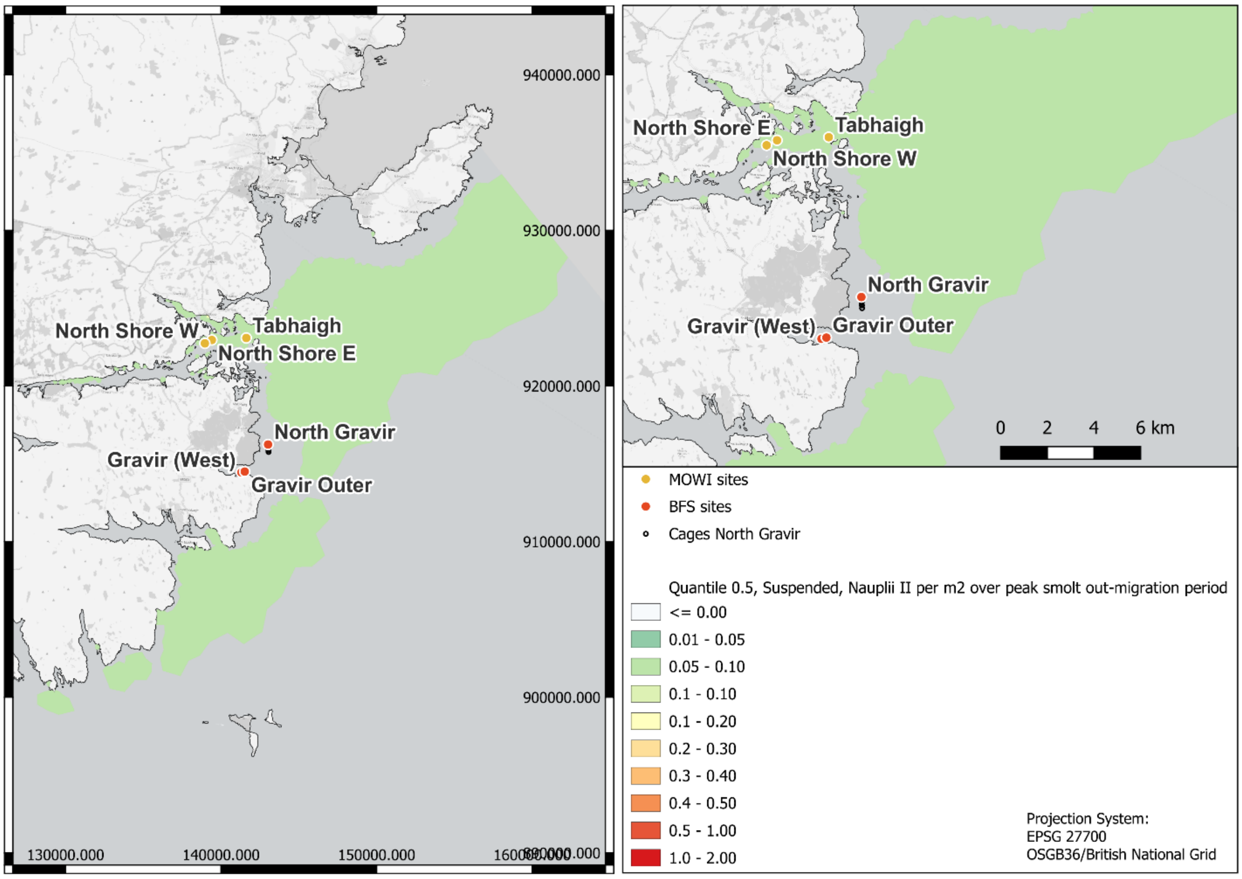

Figure 4.15 Spatial extent (0.5 quantile) of particles, at Nauplii-II salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites during the peak smolt out-migration period (13 April to 25 May).

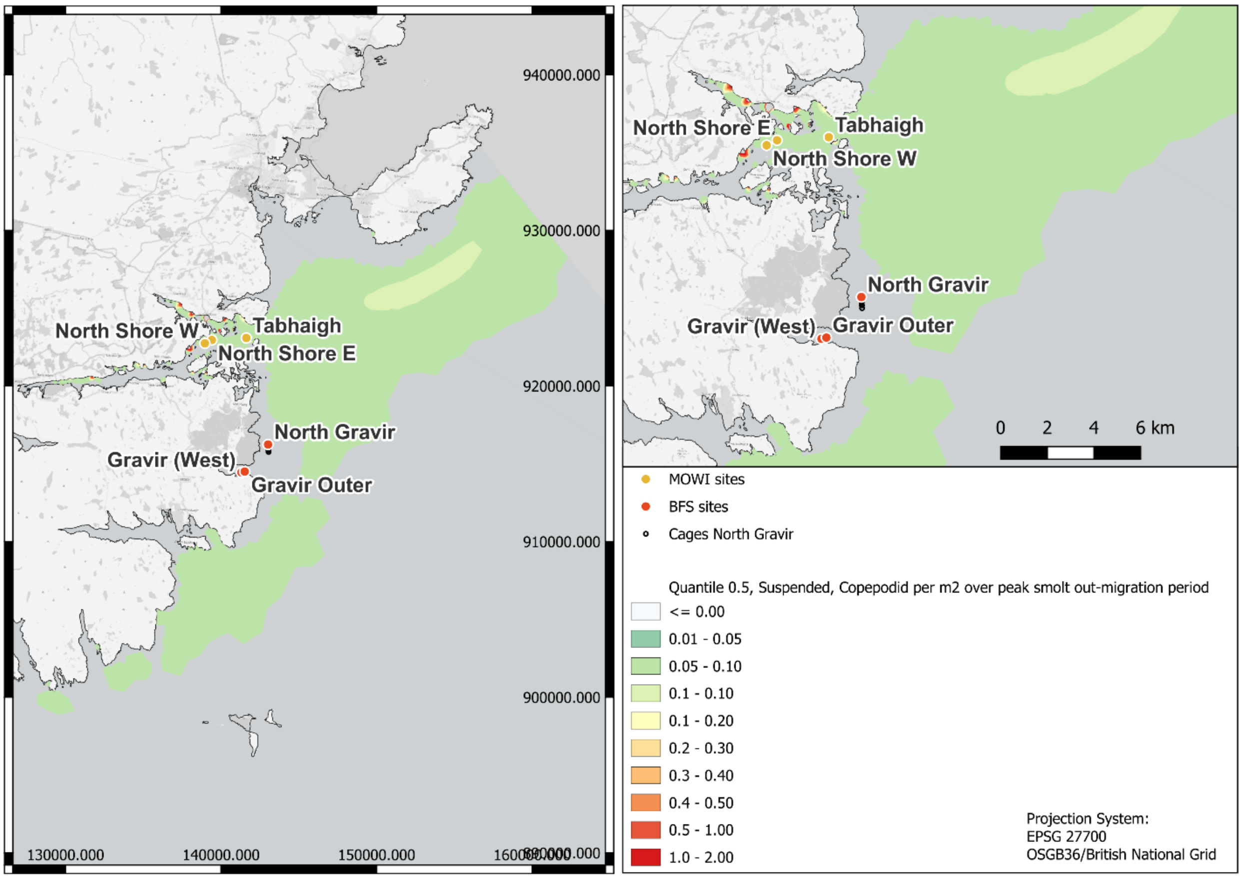

Figure 4.16 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites during the peak smolt out-migration period (13 April to 25 May).

Figure 4.17 illustrates the dispersal of salmon lice from the Proposed Development of the North Gravir site, all the nearby BFS active sites and the MOWI sites as in Table 3.1, during the peak smolt out-migration period. The number of ovigerous lice per fish is set to 0.5 – (only Copepodid stage)

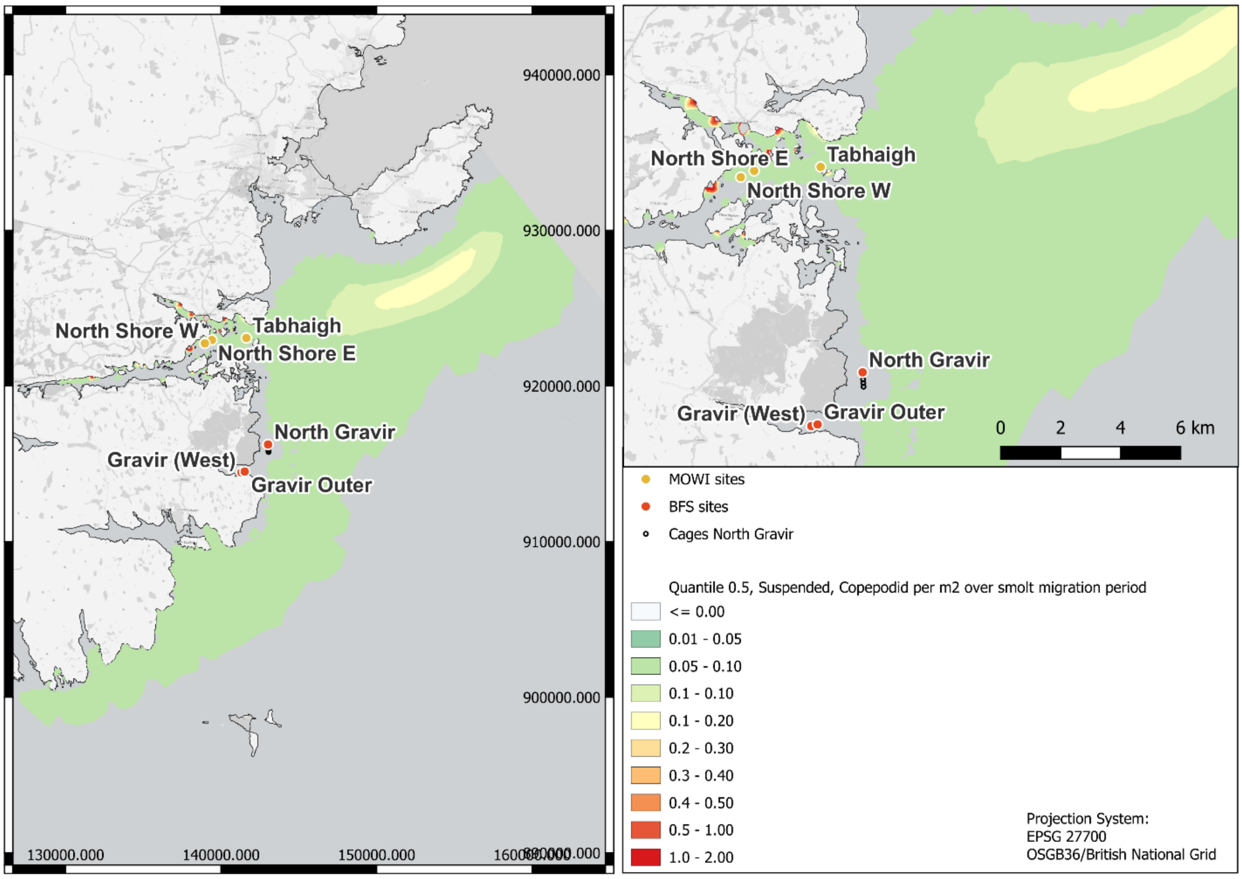

Figure 4.17 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites during the peak smolt out-migration period (13 April to 25 May). Ratio of lice per fish is set to 0.5 ovigerous lice per fish for all sources.

Figure 4.18 to Figure 4.20 illustrate the dispersal of salmon lice from the Proposed Development of the North Gravir site, all nearby BFS active sites and the MOWI sites as in Table 3.1, from January to December (inclusive). The number of ovigerous lice per fish is calculated as an average during the peak smolt out-migration period over multiple years from nearby active BFS sites. MOWI sites are modelled with a ratio of 0.5 ovigerous lice per fish

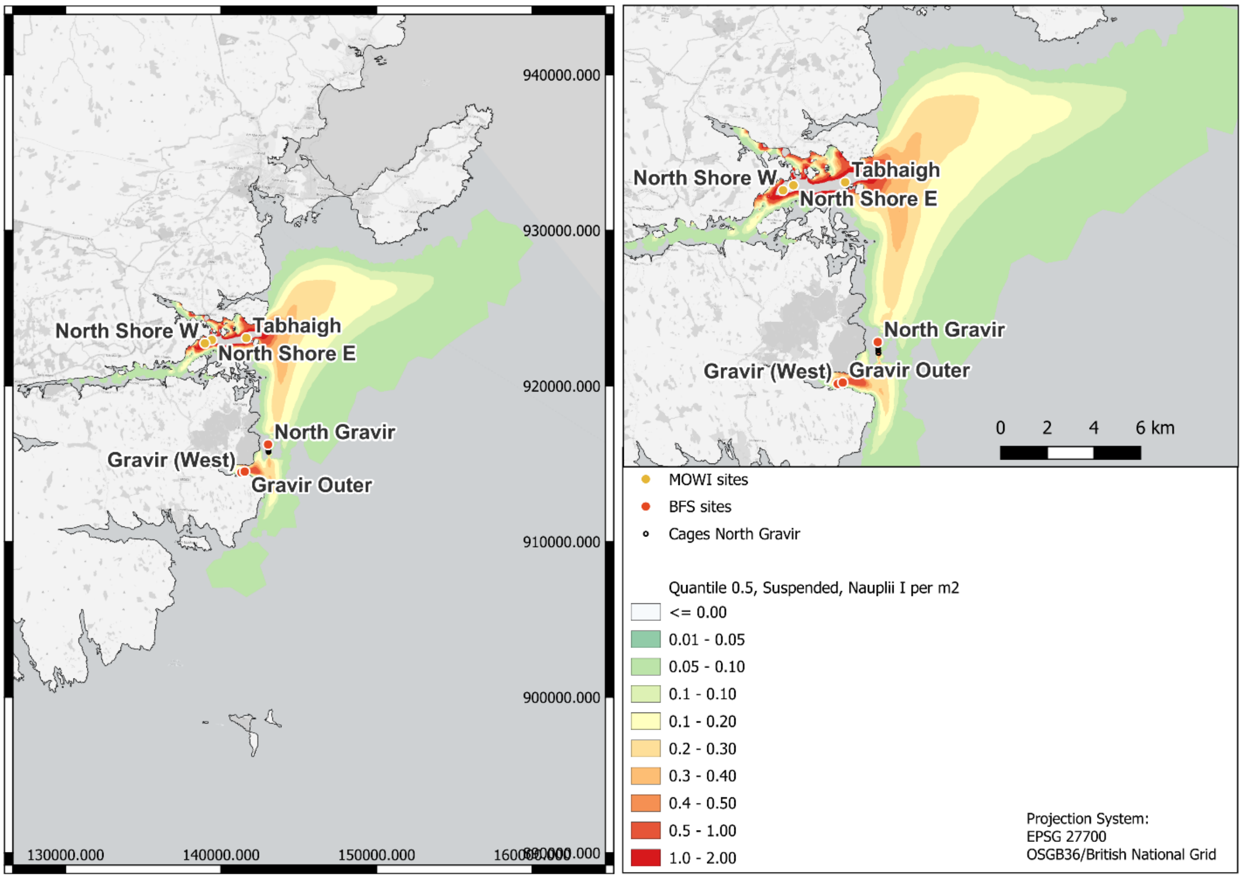

Figure 4.18 Spatial extent (0.5 quantile) of particles, at Nauplii-I salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites for January to December (inclusive).

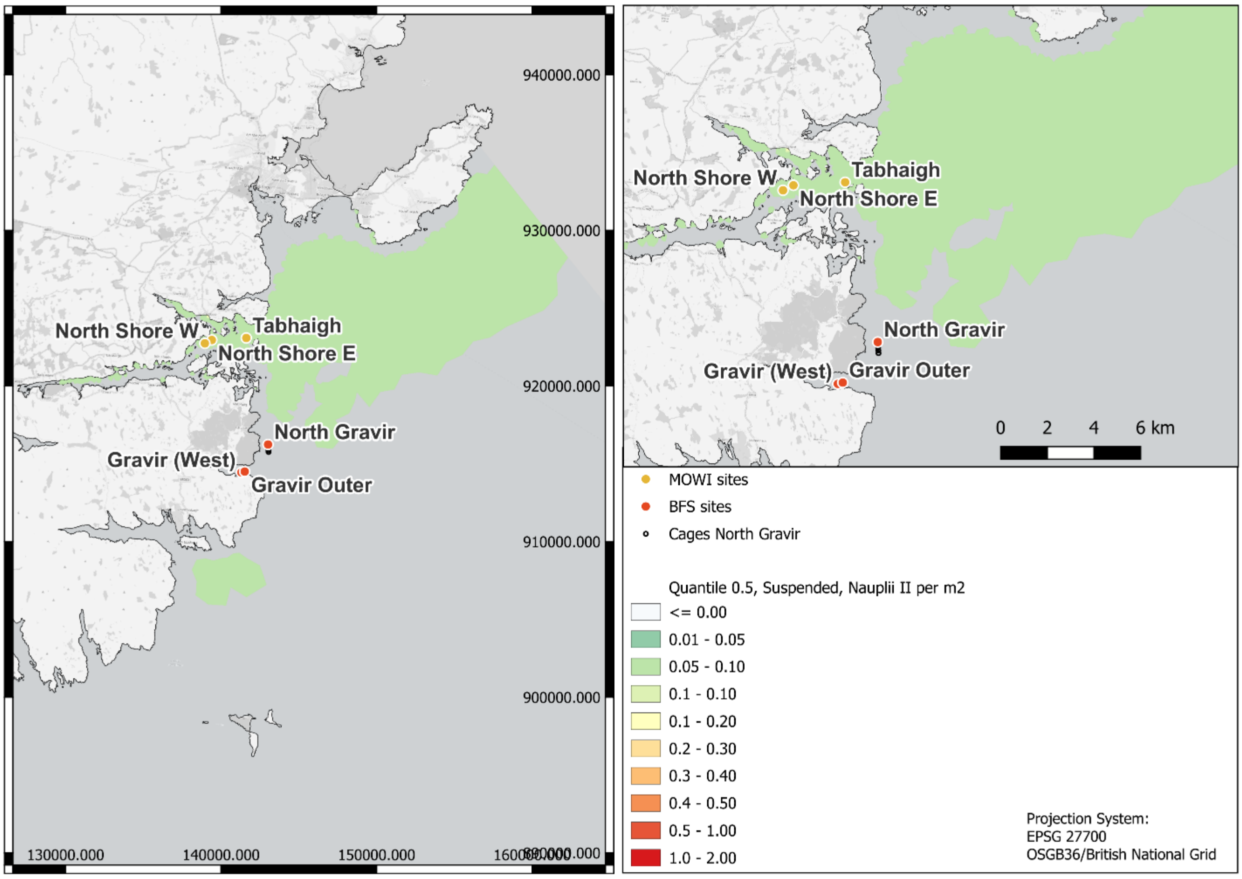

Figure 4.19 Spatial extent (0.5 quantile) of particles, at Nauplii-II salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites for January to December (inclusive).

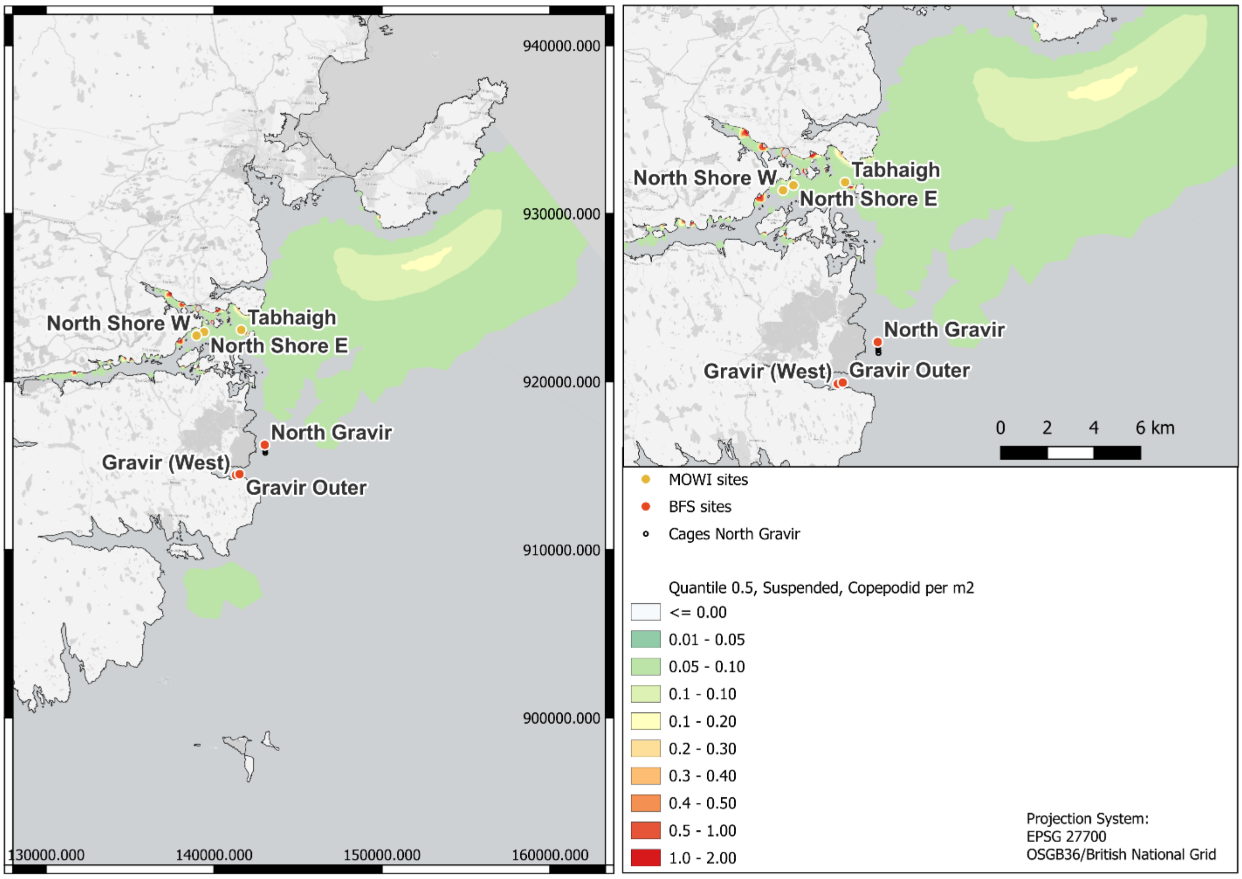

Figure 4.20 Spatial extent (0.5 quantile) of particles, at Copepodid salmon lice stage, originating from the Proposed Development of the North Gravir site and all the nearby active BFS and MOWI sites for January to December (inclusive).

5 Conclusions

A coupled hydrodynamic-biological modelling framework has been used to simulate the dispersal of salmon lice from aquaculture sites in the water around North Gravir, Outer Hebrides and identify pathways for infective lice to reach potential receptors. The model results are used to assess the risk derived from connectivity vectors between designated sources (aquacultures sites as defined Table 1.1). Spatial mappings of dispersed infectious salmon lice aim quantify infection pressure for active and/or prospective sites under different scenarios.

The particle releases are considered conclusive in terms of coverage of temporal variability, populations assessed, and spatial distributions with regards to the designated sources. Two periods were examined based on salmon lice development, and response to environmental factors including light intensity, sea water temperature, and salinity.

Apart from the various environmental factors affecting salmon lice development, the potential dispersal patterns of salmon lice originating from a specific aquaculture site is a function of both its geographic location, the production cycle, and the number of fish on site. This assessment did not examine when releases occur within the production cycle. The assessment though, assumes that the farms maintain full stock biomass throughout the whole year (see Table 3.1). In this context, the derived outputs are unbiased since releases occur every 15 mins for a continuous period of 11.5-months.

As expected, the spatial extent of infectious lice is largest for combined sources during both the whole year assessment and the peak smolt out-migration period. This is mainly due to the increased numbers of particles introduced in the marine environment from the respective sources and the dispersive character of the background hydrodynamic flow field.

Sensitivity due to periods assessed show some discernible differences in the spatial extent of the dispersed infectious salmon lice. There is greater spatial extent during the peak smolt out-migration period for both single and cumulative input (see Figure 4.3 versus Figure 4.6 and Figure 4.9 versus Figure 4.13). This is even greater when considering the cumulative input with the conservative ratio of 0.5 ovigerous lice per fish (see Figure 4.10).

On summary, salmon lice dispersion originating from the Proposed Development of the North Gravir site results, on average, to concentrations of infectious lice **lesser than 0.2 individuals per m^2**. This is consistent for all scenarios examined within this exercise. There are isolated hotspots with concentrations higher than 5-10 individuals per m^2, which are consistently identified at all spatial mappings of suspended Copepodid along the coastlines of Loch Liurboist and Eireasort (see also Figure 4.17 Figure 4.20). These are locations in small inlets along the coastline with shallow bathymetry which act as particle “traps”. This is partly because of underrepresented hydrodynamic conditions due to the computational mesh coarseness at these locations. The result is weak recirculation dynamics and has the overall effect of increased particle concentrations on those coastal computational cells.

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