Orkney and Shetland Salmon Lice Modelling

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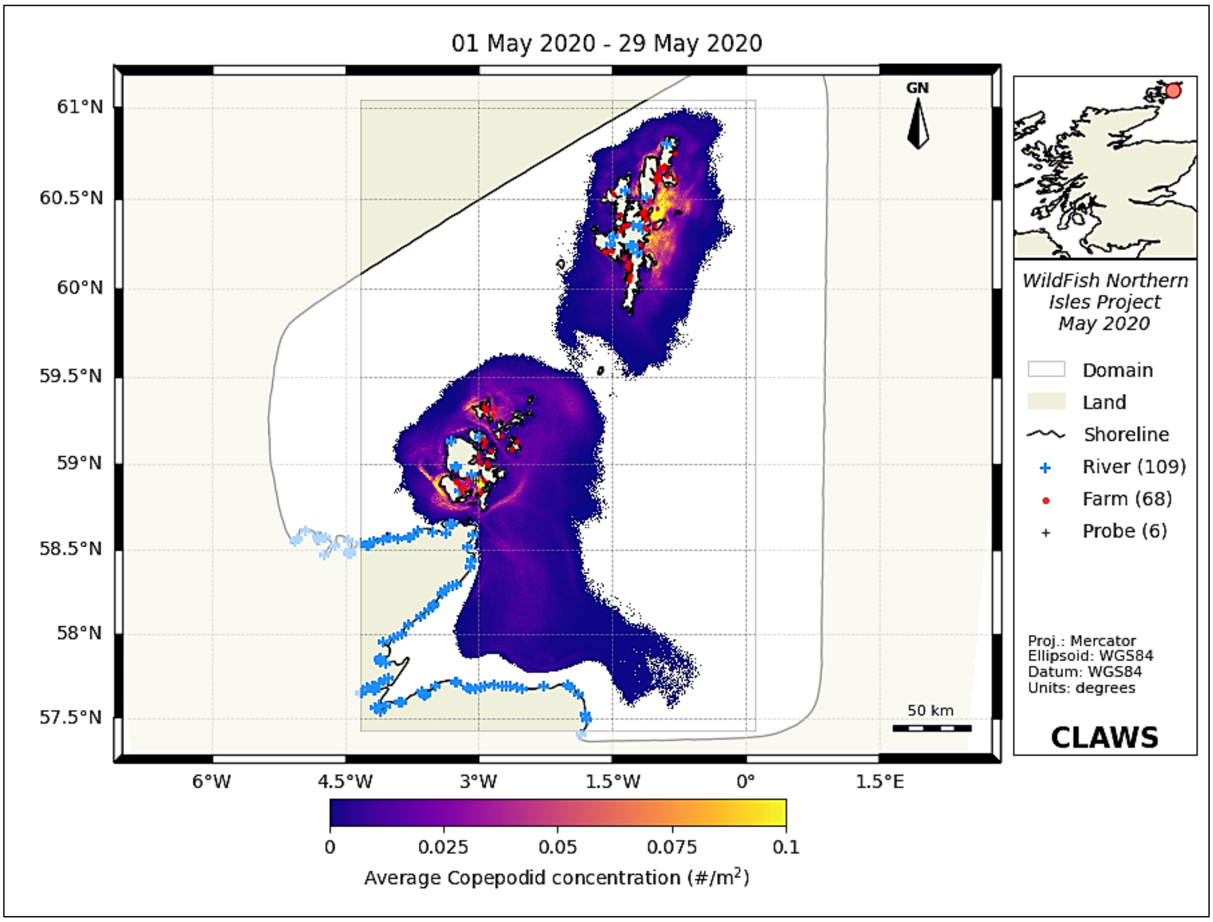

Executive Summary

A biological model of salmon lice (*Lepeophtheirus salmonis*) has been developed in order to assess the risk that wild Atlantic salmon and sea trout will be harmed by lice emanating from salmon farms in the Northern Isles (26 farms on Orkney and 42 farms on Shetland). In order to account for annual variations in the farmed salmon production cycle, hydrodynamic conditions for the years 2019 and 2020 were considered using current farm biomasses (2023-24).

Virtual "lice" particles were released at each farm site and allowed to disperse into the marine environment. Each particle is a "super-individual", representing a number of salmon lice larvae. A simplified lice model has been applied, based on the current SEPA screening approach [SEPA_2024], where the biological effects of salmon lice production, maturity and mortality were included. No lice swimming behaviour was involved in the model and the particles were restricted to be within the top 10 m of the water column [SEPA_2024].

The flow conditions (sea currents) driving the lice particles come from a validated hydrographic model that has been reported elsewhere [MTS_2024] and is not detailed in this document.

When the salmon lice model had developed steady-state conditions, virtual "smolt" particles were modelled swimming through the lice fields. This virtual smolt model predicts the exposure to infective-stage sea lice in lice per m^2-days likely to give rise to harmful levels of mobile lice on wild salmon post-smolts. For a 12.5 cm salmon post-smolt swimming at 1 body-length per second the harmful exposure threshold was set as 0.75 copepodid per m^2-days [SEPA_2024]. Wild salmon post-smolts may spend less than a week in the vicinity of Orkney's and Shetland's salmon farms. Sea trout do not migrate, so their exposure to salmon lice from fish farms is likely to last much longer. The degree of risk to virtual salmon post-smolts therefore is a very conservative minimum indication of the risk of harm to sea trout.

Results for the lice model show that the main salmon lice concentrations on Shetland tend to remain localised along the coastal fringes while for Orkney there is evidence of enhanced dispersion over a wider area. Virtual probe results show that the highest instantaneous lice densities were predicted to occur in Shetland where levels of 2 cop/m^2 can persist over several days.

Snapshots of the instantaneous lice densities show how the salmon lice fields evolve with time and provide evidence of large-scale organised behaviour, often manifesting as long filaments of lice extending over many kilometres. For the extent of the southward copepodid distribution from the Orkney farms it is observed that the lice are channelled southwards from the Pentland Firth to occupy a large portion of the North Sea towards the Moray Firth.

Box-plots from a virtual post-smolt swimming model highlight that the harmful exposure threshold of 0.75 copepodid per m^2-days [SEPA_2024] is likely to be exceeded for certain swim groups. This suggests that there is a likely risk of harmful lice infestation to the virtual post-smolts on these swim routes. Sea trout living in these areas would be at even higher risk of harm than migrating salmon post-smolts.

Other results show that instantaneous peak copepodid values of 9 cop/m^2 are possible and peak lice densities of at least 6 cop/m^2 may persist over a distance on the virtual swim path of approximately 1 km. Finally, a peak cumulative exposure concentration of approximately 1.9 cop/m^2-days was observed for a virtual post-smolt swim route near Shetland.

Comparisons were made between results using the industry-standard value of 0.5 adult female lice per fish compared with the actual value of 0.78 lice per fish, measured across salmon farms on Orkney and Shetland for Q1/2 2024. The higher lice density per fish results in predictions that show a likely increase in the risk of infestation harm.

About the Report Authors

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Tom is a chartered professional engineer with over 25 years' experience in applied computational mechanics. After a first degree in Environmental Engineering at the University of Strathclyde, Tom undertook a Ph.D in Vortex Shedding Flowmeter Pulsating Flow Computational Fluid Dynamics (CFD) Studies at the same university. Subsequently, he was awarded a JM Lessels scholarship from the Royal Society of Edinburgh for a one-year post-doctoral position at the Institute de Mécanique des Fluides de Toulouse, France in the field of numerical oceanography. The IMechE presented Tom with the Alfred Rosling Bennett Premium and Charles S Lake Award in 2003 for CFD in applied aerodynamics. In 2013 Tom returned from an EPSRC-funded sabbatical in the USA, where he carried out fundamental research in rarefied gas dynamics at the University of Michigan and the Lawrence Berkeley Laboratory in California. From 1994-2017 he was a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the University of Strathclyde specialising in heat transfer, fluid mechanics and applied CFD. His work is reported in over 50 refereed journal and conference publications. He is currently a director at the engineering consultancy firm MTS-CFD.

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After a first degree in Aeronautical Engineering at the University of Manchester, Matt worked for BAE Systems (Military Aircraft) at Warton in Lancashire in the Wind Tunnel Department working on projects which included EAP, EFA (Typhoon), Tornado and HOTOL. After leaving BAE in 1990 Matt worked for YARD Consulting Engineers in Glasgow modelling the heat and fluid flows in Advanced Gas Cooled reactors during on-load refuelling. In 1991 Matt accepted a senior lectureship in the Department of Mechanical Engineering at the University of Strathclyde where his research interest covered both experimental and computational heat transfer and fluid dynamics. He was awarded a PhD for his research into 3D imaging and its application to fluid flow visualisation. For his research in the field of experimental and computational fluid dynamics he was awarded the 2003 AR Bennett Premium/CS Lake Award and the 2004 T A Stewart-Dyer Prize/Frederick Harvey Trevithick Prize from the Institute of Mechanical Engineers. In 2022 Matt left the University of Strathclyde to take a directorship with the Engineering consultancy firm MTS-CFD. Matt is a Chartered Engineer and a Fellow of the Institute of Mechanical Engineers. He has published his research in over 100 papers in refereed journal and conference proceedings.

1 Introduction and Motivation

Farmed salmon are hosts for parasitic salmon lice (*Lepeophtheirus salmonis)* which are proven to harm wild salmon and sea trout [Johnsen_2020; Sandvik_2020, ScotGov_2024, SEPA_2024]. In order to assess the risk that wild salmon and sea trout will be harmed by operational farms in the Northern Isles, WildFish has commissioned the development of a detailed hydrodynamic and biological model of the area. The model simulates water levels and flows (i.e., currents and tides), which govern the transport of salmon lice emanating from the fish farms - see [MTS_2024] for further details of the hydrographic model. All operational farms are included in the lice model using up-to-date biomass conditions (2023-24). There were 26 farms on Orkney and 42 farms on Shetland involved in the study.

The use of hydrodynamic modelling to predict salmon lice densities and the risk presented to wild salmonids is increasingly common, particularly in Norway [Johnsen_2020], [Asplin_2020]. Marine Scotland and SEPA [SEPA_2024] are working on similar projects in Scotland. The integrated biological model presented in this report draws on the methods and assumptions used by Scottish and Norwegian modellers working for government agencies, as well as other peer-reviewed research.

In order to represent the salmon lice, virtual “lice” particles were released at each farm site and allowed to disperse into the marine environment. Each particle is a “super-individual”, representing a number of salmon lice larvae based on the farm biomass. A modelling technique based on the current SEPA screening approach [SEPA_2024] has been adopted, where the biological effects of salmon lice production, maturity and mortality were included. No lice swimming behaviour was involved in the model and the particles were restricted to exist in the top 10 m of the water column which is considered a conservative approach [SEPA_2024].

The flow conditions (sea currents) driving the lice particles come from a validated hydrographic model that has been detailed elsewhere [MTS_2024] and is not reported in this document.

The risk of infestation by salmon lice varies according to the density of lice to which the fish are exposed and the duration of that exposure [Johnsen_2020], [ScotGov_2024], [SEPA_2024]. The wild salmon smolt migration may take place across a period of two months, but individual fish are likely to take only a few days to travel through areas adjacent to the Northern Isles, so salmon lice densities averaged over two months do not best represent the risk they face. In this report the model outputs are presented in four ways, to demonstrate how the salmon lice density and therefore the apparent risk vary:

1. Infective lice (copepodid) densities averaged over a 22-day period in May, shown as a heat map.
2. Virtual probes at specific locations to measure how infective lice density varies locally with time.
3. Copepodid densities calculated every hour and shown as an animated series of lice density maps. These are the peak levels that migrating fish are likely to encounter. During their migration journey through the coastal waters, they may pass through multiple areas of high lice density.

4. A virtual post-smolt swimming model to predict the exposure to infective-stage sea lice in lice per m^2-days likely to give rise to harmful levels of mobile lice on wild salmon post-smolts.

Sea trout do not migrate, so they will be exposed to sea lice for longer than salmon post-smolts. They can return to freshwater to rid themselves of sea lice when heavily infested, but not without a physiological cost to the fish.

2 Biomass Data

Farm biomass data are shown in Tables 1-4. The biomasses for the years 2023 and 2024 have been considered in order to represent the annual variability in farm biomass during the salmon production cycle. There were a total of 26 farms on Orkney and 42 farms on Shetland included in the model.

Table 1 *Farm Biomass Data – Orkney, May 2023, Total Biomass = 12,061 tonnes.*

Farm	*Longitude (deg)*	*Latitude (deg)*	*Biomass (tonnes)*
Bay of Holland	-2.6318773	59.087119	245
Bay of Cleat South	-2.9316328	59.306866	0
Bay of Cleat North	-2.9273608	59.311225	173
Kirk Noust	-2.9628277	59.145319	48
East Moclett	-2.8327653	59.320234	1540
Bay of Meil	-2.8988442	58.994963	112
Bay of Vady	-2.9348201	59.132331	850
Carness bay	-2.9228610	59.010556	897
Cava South	-3.1583837	58.871384	1524
Chalmers Hope	-3.2402407	58.893213	650
Eday Sound	-2.7522593	59.16177	0
Wyre Gairsay	-2.9523966	59.110874	247
Lyrawa Bay	-3.2152797	58.87176	0
Mill Bay	-2.5662422	59.130116	245
Ouse Ness	-2.9437070	59.329356	411
Pegal Bay	-3.2083473	58.861945	295
Puldrite Bay	-3.0032261	59.045586	0
Bring Head Hoy	-3.2588189	58.901126	1048
Skelwick Skerry	-2.8368713	59.288569	990
St Margarets Hope	-2.9829022	58.835387	324
Toy Ness	-3.1226207	58.915699	391
Shapinsay Veantrow Bay	-2.8713199	59.076527	112
Vest Ness	-2.9155208	59.326863	891
West Fara	-3.1804705	58.839094	0
Quanterness	-2.9845224	59.008351	579
Westerbister	-2.9516904	58.906311	489
		TOTAL	**12,061**

Table 2 *Farm Biomass Data – Shetland, May 2023, Total Biomass = 30,850 tonnes.*

Farm	*Longitude (deg)*	*Latitude (deg)*	*Biomass (tonnes)*
Balta Island	-0.79834838	60.751186	1369
Bellister	-1.1100008	60.330425	1432
Bastaness	-1.0140021	60.623021	1304
West of Burwick	-1.3152599	60.148351	1379
Burrastow	-1.5913468	60.212845	440
Point of Burkwell	-0.93235249	60.672829	1411
North of Papa	-1.3437334	60.127502	724
Cloudin	-1.5808953	60.211744	1500
Swining Voe	-1.1599061	60.408839	284
Cole Deep	-1.3531129	60.350972	1284
Swarta Skerry	-1.1459899	60.342019	577
East of Langa	-1.3232368	60.137887	1160
Easter Score Holm	-1.3637620	60.174273	1740
Flaeshins	-0.89164344	60.627693	1939
Djuba Wick	-0.98232763	60.620306	1058
Bow of Hascosay	-1.0067761	60.610792	939
Holms Geo	-1.3040464	60.063619	1222
Hogan	-1.5282751	60.209601	106
Lippie Geo	-1.2947949	60.076276	0
Linga	-1.1519962	60.435861	203
South Sound Mangaster	-1.4161779	60.411511	258
Ness of Copister	-1.0862968	60.490971	416
East of Papa Little	-1.3818581	60.344913	836
North Sandwick	-0.9888044	60.645729	881
Olnafirth South	-1.3235427	60.360468	334
Holm	-1.5106580	60.212545	0
Setter Voe	-1.3259868	60.109051	0
Setterness North	-1.1274663	60.429857	491
Setterness South	-1.1441013	60.418957	180
Slocka	-1.4839958	60.527667	55
Stead of Aithness	-1.4191069	60.322490	835
Bight of Foraness	-1.1712948	60.429284	458
Taing of Railsborough	-1.1862134	60.243502	230
Teisti Geo	-1.3111157	60.047628	1221
Uyea Isle	-0.91528857	60.681716	854
Wick of Vatsetter	-1.0253552	60.592558	0
Vee Taing	-0.91490656	60.668047	217
Vidlin North	-1.1229789	60.388049	71
Vidlin Outer	-1.1196841	60.391152	78
North Voe	-1.0246087	60.349374	1117
Wick of Belmont North	-0.97065648	60.679791	265
Wick of Gruting	-0.80155539	60.610961	1982
		TOTAL	**30,850**

Table 3 *Farm Biomass Data – Orkney, May 2024, Total Biomass = 24,585 tonnes.*

Farm	*Longitude (deg)*	*Latitude (deg)*	*Biomass (tonnes)*
Bay of Holland	-2.6318773	59.087119	1977
Bay of Cleat South	-2.9316328	59.306866	52
Bay of Cleat North	-2.9273608	59.311225	899
Kirk Noust	-2.9628277	59.145319	74
East Moclett	-2.8327653	59.320234	3465
Bay of Meil	-2.8988442	58.994963	66
Bay of Vady	-2.9348201	59.132331	882
Carness bay	-2.9228610	59.010556	911
Cava South	-3.1583837	58.871384	297
Chalmers Hope	-3.2402407	58.893213	1550
Eday Sound	-2.7522593	59.16177	899
Wyre Gairsay	-2.9523966	59.110874	704
Lyrawa Bay	-3.2152797	58.87176	381
Mill Bay	-2.5662422	59.130116	1977
Ouse Ness	-2.9437070	59.329356	411
Pegal Bay	-3.2083473	58.861945	0
Puldrite Bay	-3.0032261	59.045586	891
Bring Head Hoy	-3.2588189	58.901126	2500
Skelwick Skerry	-2.8368713	59.288569	2250
St Margarets Hope	-2.9829022	58.835387	773
Toy Ness	-3.1226207	58.915699	1229
Shapinsay Veantrow Bay	-2.8713199	59.076527	907
Vest Ness	-2.9155208	59.326863	127
West Fara	-3.1804705	58.839094	778
Quanterness	-2.9845224	59.008351	585
Westerbister	-2.9516904	58.906311	0
		TOTAL	**24,585**

Table 4 *Farm Biomass Data – Shetland, May 2024, Total Biomass = 26,770 tonnes.*

Farm	*Longitude (deg)*	*Latitude (deg)*	*Biomass (tonnes)*
Balta Island	-0.79834838	60.751186	1720
Bellister	-1.1100008	60.330425	0
Bastaness	-1.0140021	60.623021	1091
West of Burwick	-1.3152599	60.148351	195
Burrastow	-1.5913468	60.212845	0
Point of Burkwell	-0.93235249	60.672829	1264
North of Papa	-1.3437334	60.127502	96
Cloudin	-1.5808953	60.211744	1159
Swining Voe	-1.1599061	60.408839	1697
Cole Deep	-1.3531129	60.350972	0
Swarta Skerry	-1.1459899	60.342019	1158
East of Langa	-1.3232368	60.137887	86
Easter Score Holm	-1.3637620	60.174273	356
Flaeshins	-0.89164344	60.627693	346
Djuba Wick	-0.98232763	60.620306	802
Bow of Hascosay	-1.0067761	60.610792	1061
Holms Geo	-1.3040464	60.063619	0
Hogan	-1.5282751	60.209601	81
Lippie Geo	-1.2947949	60.076276	109
Linga	-1.1519962	60.435861	1876
South Sound Mangaster	-1.4161779	60.411511	148
Ness of Copister	-1.0862968	60.490971	483
East of Papa Little	-1.3818581	60.344913	0
North Sandwick	-0.9888044	60.645729	701
Olnafirth South	-1.3235427	60.360468	0
Holm	-1.5106580	60.212545	360
Setter Voe	-1.3259868	60.109051	67
Setterness North	-1.1274663	60.429857	1398
Setterness South	-1.1441013	60.418957	1545
Slocka	-1.4839958	60.527667	1366
Stead of Aithness	-1.4191069	60.322490	209
Bight of Foraness	-1.1712948	60.429284	1868
Taing of Railsborough	-1.1862134	60.243502	0
Teisti Geo	-1.3111157	60.047628	274
Uyea Isle	-0.91528857	60.681716	904
Wick of Vatsetter	-1.0253552	60.592558	789
Vee Taing	-0.91490656	60.668047	50
Vidlin North	-1.1229789	60.388049	869
Vidlin Outer	-1.1196841	60.391152	917
North Voe	-1.0246087	60.349374	547
Wick of Belmont North	-0.97065648	60.679791	828
Wick of Gruting	-0.80155539	60.610961	350
		TOTAL	**26,770**

3 Salmon Lice Model

The integrated biological model presented in this report draws on the methods and assumptions used by Scottish and Norwegian modellers working for government agencies, as well as other peer-reviewed research [Johnsen_2020], [Asplin_2020], [SEPA_2024]. A methodology based on the current SEPA screening model [SEPA_2024] has been employed. In this approach individual lice "super-particles" are released into the marine environment and advected by sea currents. Each super-particle represents a population of actual lice based on the biomass of each farm with the assumption of an average fish weight of 4.5 kg and 0.5 adult female lice per fish. Each louse is assumed to produce 30 eggs/nauplii per adult female lice per day [Stien_2005].

For the hydrodynamics, a "spin-up" period of 1-month covering April was used to develop the temperature and salinity fields. The solution was then hot-started with salmon lice introduced from the 1st May in a model run lasting until the 28th May for each of the hydrodynamic years 2019 and 2020.

Particles were released every 5 minutes from each farm site over the total length of the model run (12 particles per hour). Initial particle positions were randomly distributed within a volume of radius 19 m and depth 3 m centred at the lat/lon location of the farm.

In addition to transport by sea currents, particles were given a random movement component, both vertically and horizontally at each time increment to represent turbulence on a subgrid scale. Particles were dispersed in the horizontal using a dispersion coefficient of 0.1 m^2/s and dispersed in the vertical using a dispersion coefficient of 0.001 m^2/s. This is considered a conservative vertical mixing approach [SEPA_2024]. The particle integration method used was 4th order Runge-Kutta.

Nauplii maturation to infectivity was driven by the direct interaction of the particles with the water temperature fields. The lice were considered as infective copepodids from 40 to 170 degree-days [Myksvoll_A_2018]. Mortality was parameterized at a constant rate of 17% per day, as estimated by [Stien_2005]. No lice swimming behaviour was included in the model and the particles were restricted to be within to the top 10 m of the water column [SEPA_2024].

When steady-state conditions for the salmon lice population were achieved a cumulative hourly average lice density field (copepodids/m^2) was calculated over the period 6th-28th May. The averaging took place on a sampling mesh with a bin size of 200 m. At steady-state, there was a population of approximately 300 million copepodids in the model system as shown in Figure 1.

In addition to the average copepodid density fields, instantaneous lice densities may be studied quantitatively using virtual probes at specific locations to measure how infective lice density varies locally with time.

Further to this, the transient lice density field may also be interrogated qualitatively by analysing an animated series of copepodid density maps. These are the peak levels that migrating fish are likely to encounter. During their migration journey through the coastal waters, they may pass through multiple areas of high lice density.

Finally, virtual "post-smolt" particles may be modelled swimming through the moving lice fields. This virtual post-smolt swimming model predicts the exposure to infective-stage sea lice in copepodids per m^2-days likely to give rise to harmful levels of mobile lice on wild salmon post-smolts. For a 12.5 cm salmon post-smolt swimming at 1 body-length per second the harmful exposure threshold was taken as 0.75 copepodids per m^2-days [SEPA_2024]. The threshold for harm for similarly sized sea trout is likely to be similar.

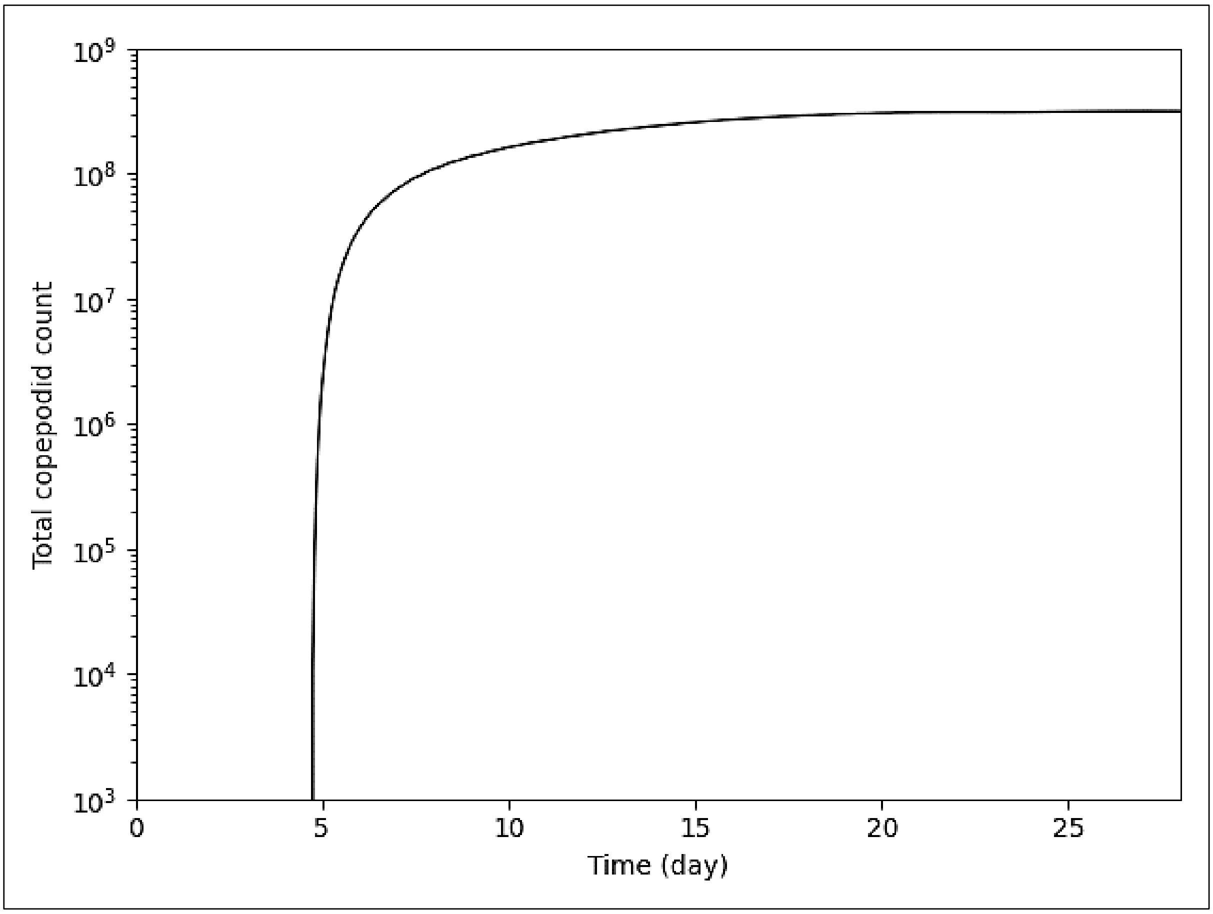

Figure 1 *Total copepodid count for May 2019 showing a population of approximately 300 million in the model system at steady-state conditions. Nauplii particles are released at time t=0 and infective lice begin to appear at maturation after 40 degree-days (approximately 4.6 days).*

Note: In order to assess the effects of no vertical swimming in the lice model a more sophisticated model was run based on the Norwegian LADIM approach [Myskvoll_A_2018], [Myskvoll_B_2018], [Skardhamar_2018]. This model includes lice diel migration due to light attraction and salinity avoidance. No significant changes in lice distribution were observed between the more sophisticated LADIM approach and the no-vertical-swimming SEPA model employed in this study. The level of agreement between the models is likely due to particles being restricted to the upper 10 m of the water column and salinity avoidance being less critical in the well-mixed open seas around the Northern Isles compared with stratified fjordic systems such as those found on the West Coast of Scotland.

4 Results

4.1 *Average copepodid density plots*

Figures 2 and 3 show the average infective lice density plots for May in the hydrodynamic years 2019 and 2020, respectively. Blue crosses on the shorelines represent the mouths of local rivers and burns according to [G2G_2018].

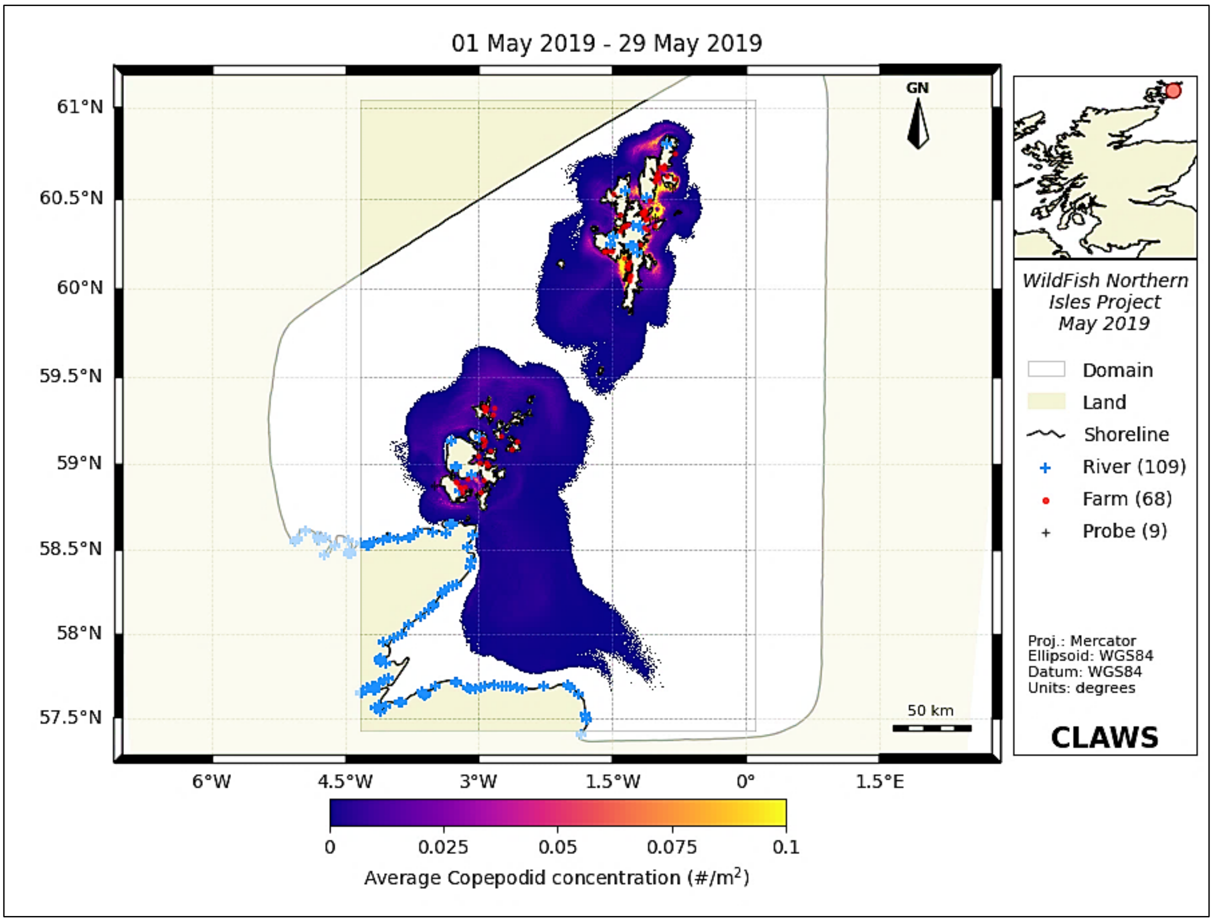

Figure 2 *Heat map of average copepodid density (#/m²) over the hydrodynamic period 6th-28th May 2019 on a sampling mesh of bin size 200 m. The total biomass for the 26 Orkney farms was 12,061 tonnes while the total biomass for the 42 Shetland farms was 30,850 tonnes.*

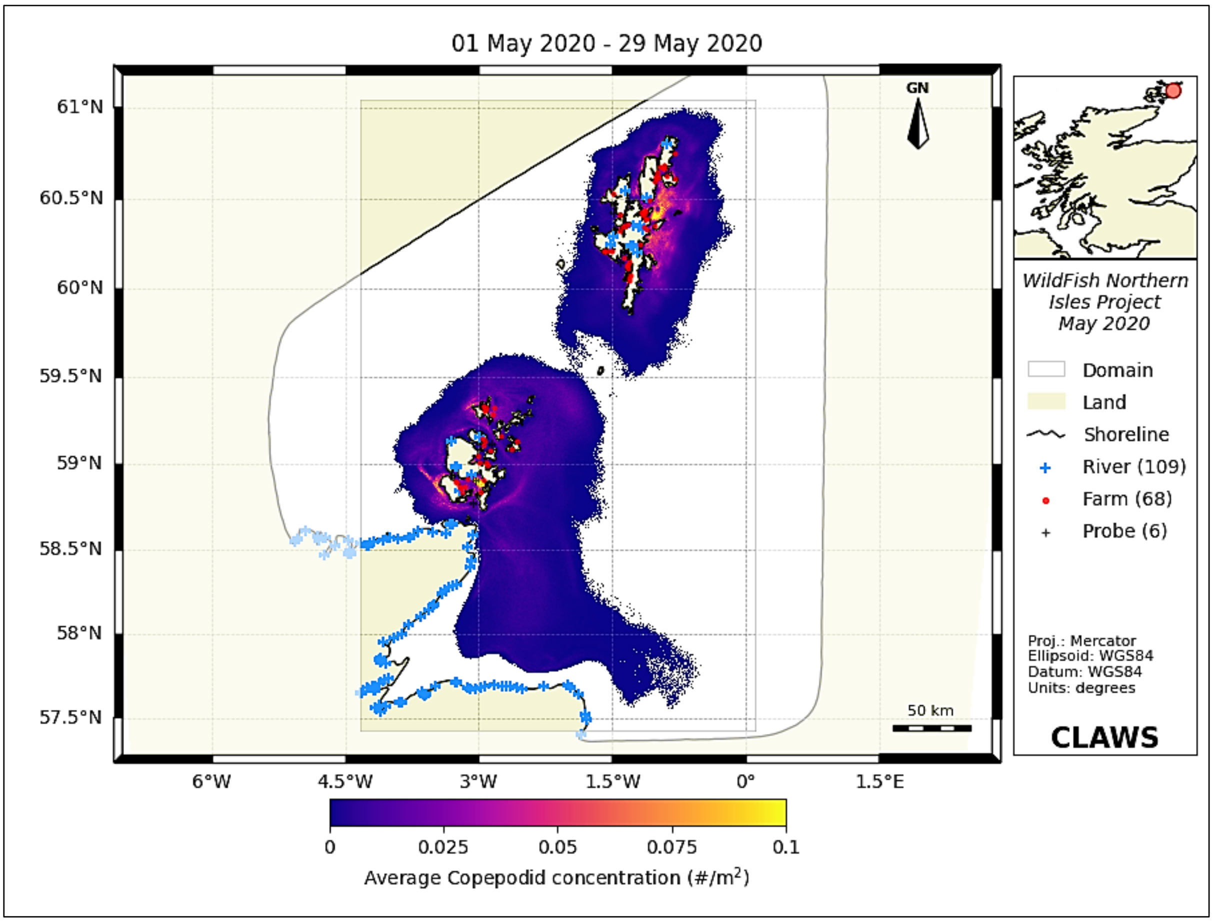

Figure 3 *Heat map of average copepodid density (#/m^2) over the hydrodynamic period 6th-28th May 2020 on a sampling mesh of bin size 200 m. The total biomass for the 26 Orkney farms was 24,585 tonnes while the total biomass for the 42 Shetland farms was 26,770 tonnes.*

Results from the copepodid heat maps indicate that there is little apparent lice interaction between the Orkney and Shetland farms in these particular instances. The main salmon lice concentrations on Shetland tend to remain localised along the coastal fringes while for Orkney there is evidence of enhanced dispersion over a wider area. This is likely due to more energetic tidal flows around Orkney compared with Shetland and closer proximity to the mainland.

The lower copepodid concentration levels around Orkney in the hydrodynamic year 2019 (biomass year 2023) reflects the lower total production biomass of 12,061 tonnes in that year compared with 24,585 tonnes in May 2020 (biomass year 2024). In contrast, Shetland had a more consistent total biomass with 30,850 tonnes in May 2019 (biomass year 2023) and 26,770 tonnes in May 2020 (biomass year 2024).

In terms of lice distribution, it is evident that the lice are channelled southwards from the Pentland Firth to occupy a large portion of the North Sea towards the Moray Firth. The predicted instantaneous copepodid distribution is observed to have a high spatial and temporal variability, constantly dynamic and highly transient in nature. Although the infective lice densities in this southern region are generally lower and more widely-dispersed compared to the Northern Isles coastline, pockets of higher lice densities may exist in the long lice filaments that are seen to form over distances of many kilometres (see Figs. 23-26). Such copepodid accumulations have been found in other studies [SPILLS_2022]. It is possible that food sources relevant to migrating smolts may also form in higher aggregations at these tidally-driven gathering points. Smolts feeding in such areas would possibly be exposed to higher infective lice densities.

4.2 *Virtual Probes*

Figures 4 and 5 show the locations of the 9 virtual probes across the model envelope for the 2019 run. For the 2020 run, Figures 6 and 7 show the locations of the 6 virtual probes used in this model. The probe locations were chosen based on the likely locations of highest average copepodid density (see Figs. 2 and 3).

Figure 4 *Location of virtual probes 1-5 on Orkney for the 2019 model.*

Figure 5 *Location of virtual probes 6-9 on Shetland for the 2019 model.*

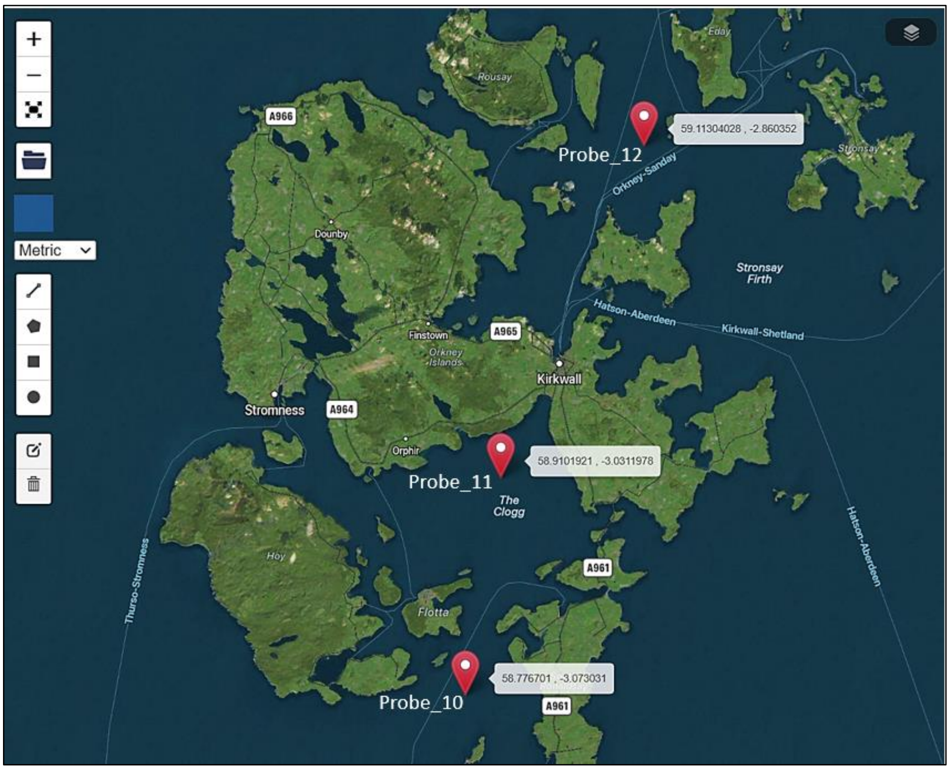

Figure 6 *Location of virtual probes 10-12 on Orkney for the 2020 model.*

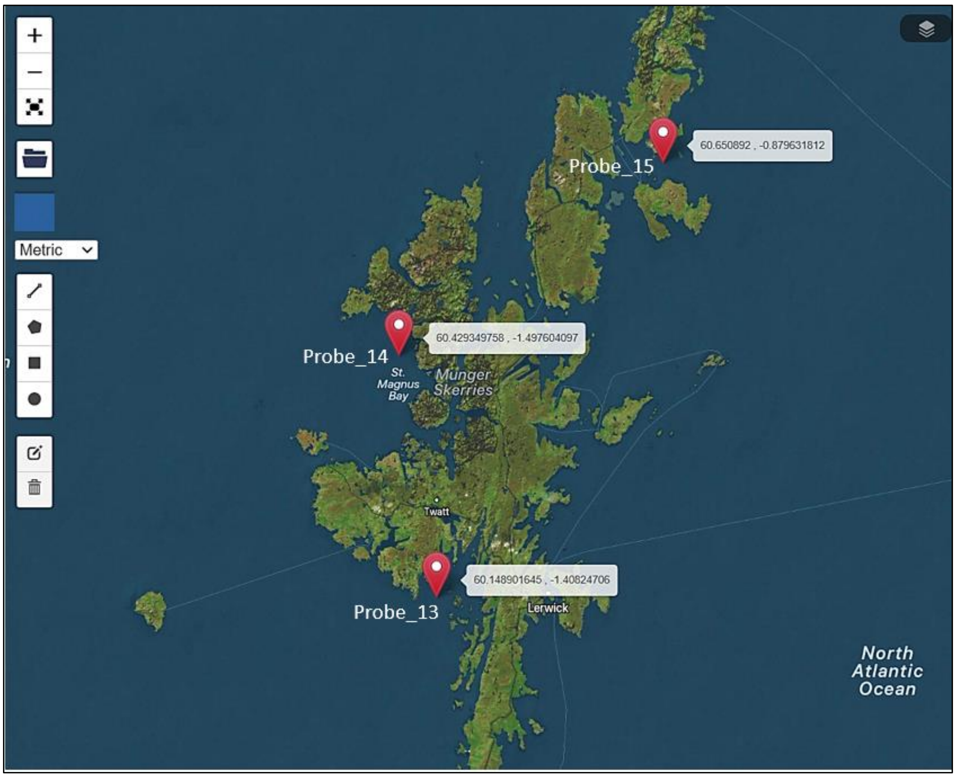

Figure 7 *Location of virtual probes 13-15 on Shetland for the 2020 model.*

Instantaneous values of copepodid density (#/m^2) have been measured at each probe location and the output is shown in Figures 8-22. Note that the y-axis is in a log-scale.

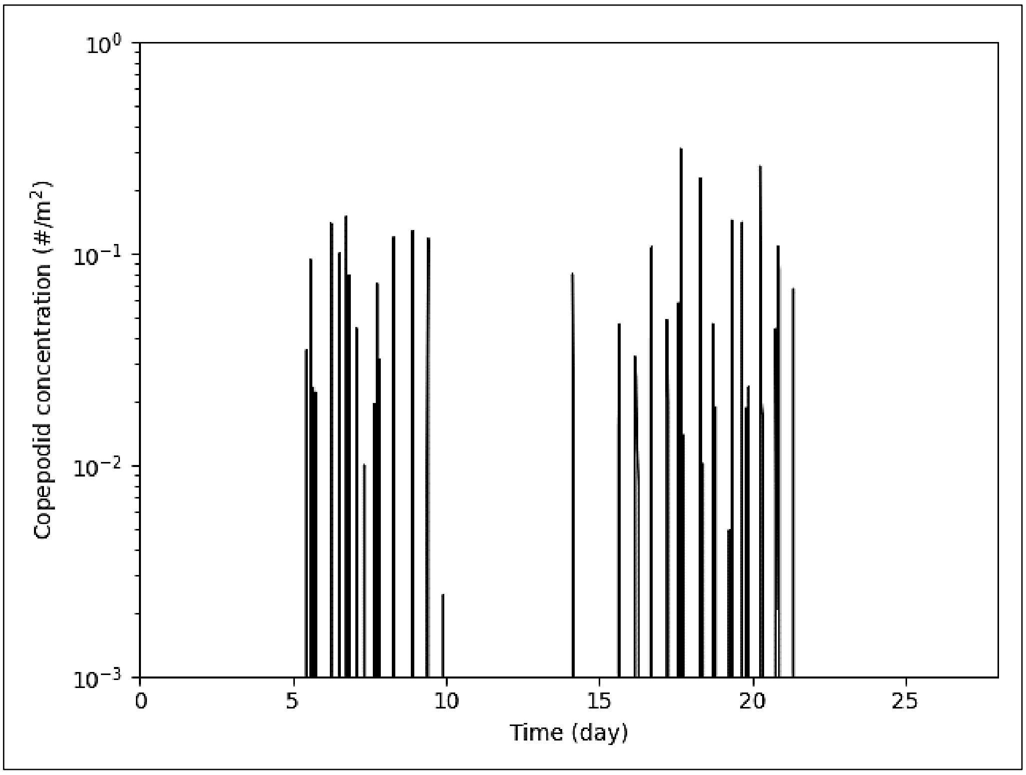

Figure 8 *Probe 1 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2019.*

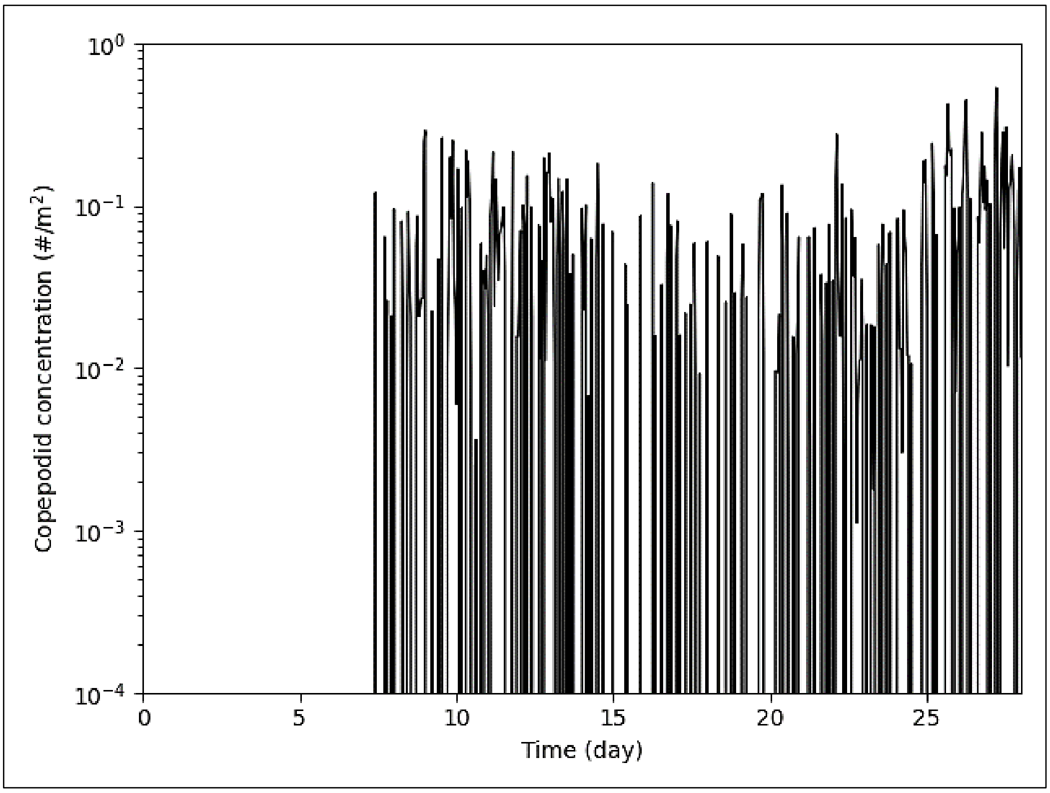

Figure 9 *Probe 2 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2019.*

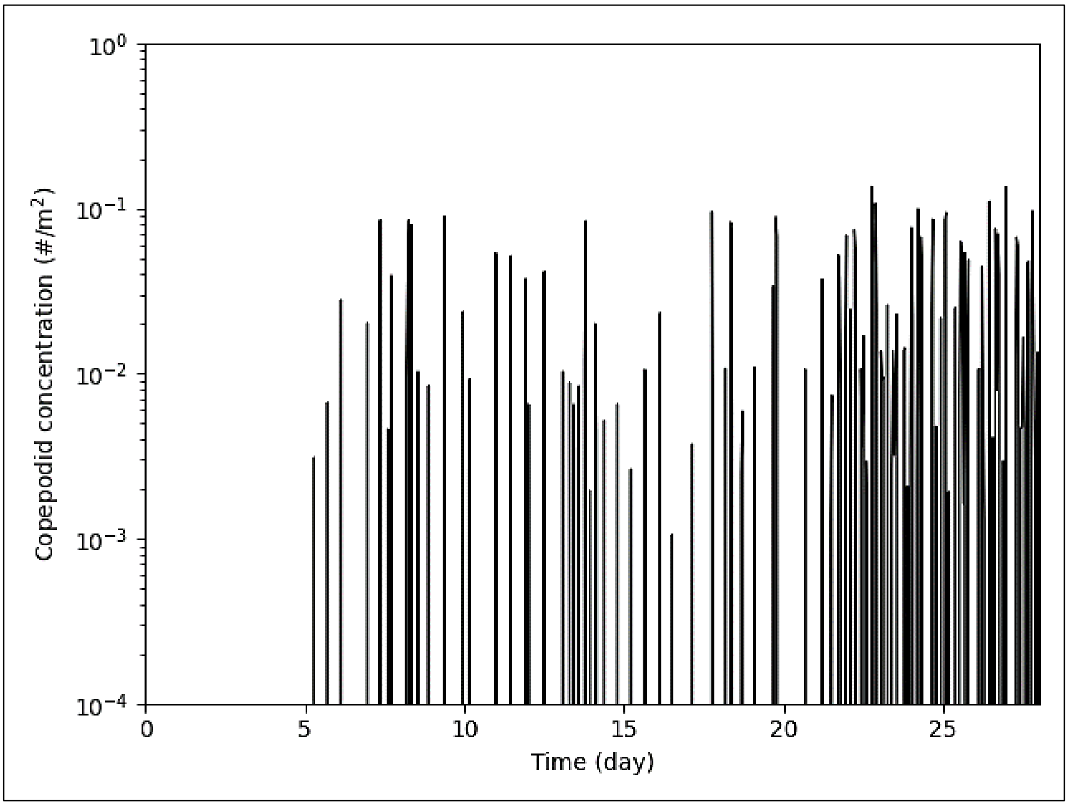

Figure 10 *Probe 3 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2019.*

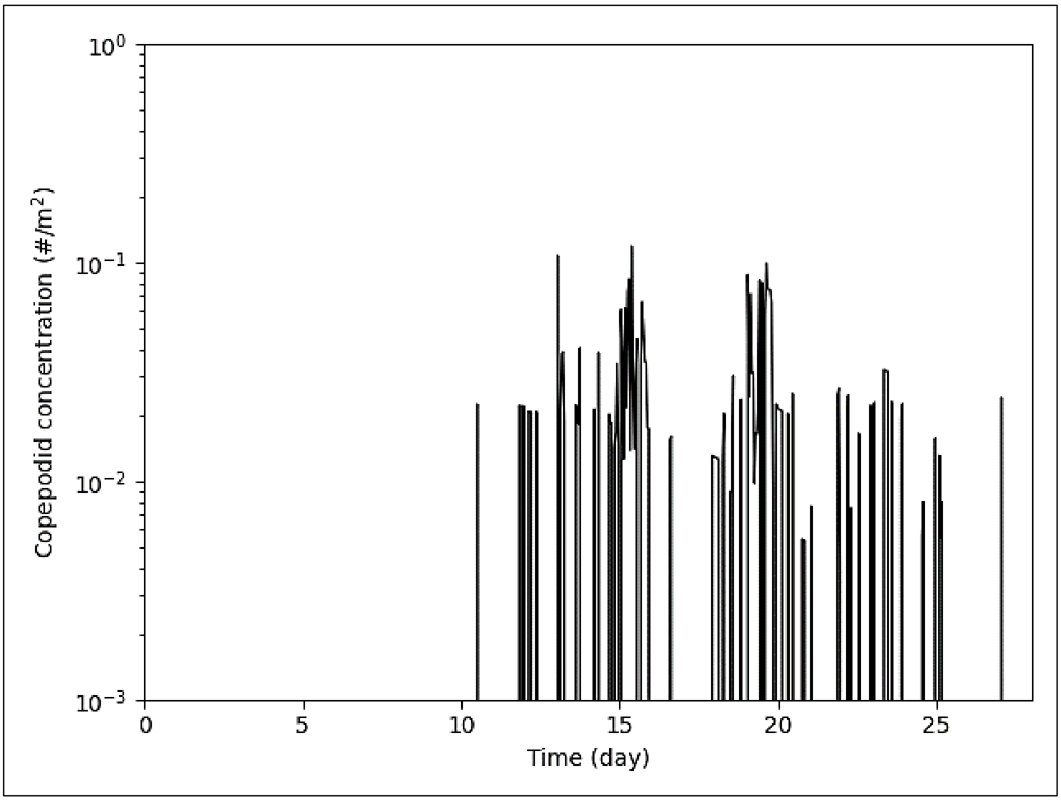

Figure 11 *Probe 4 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2019.*

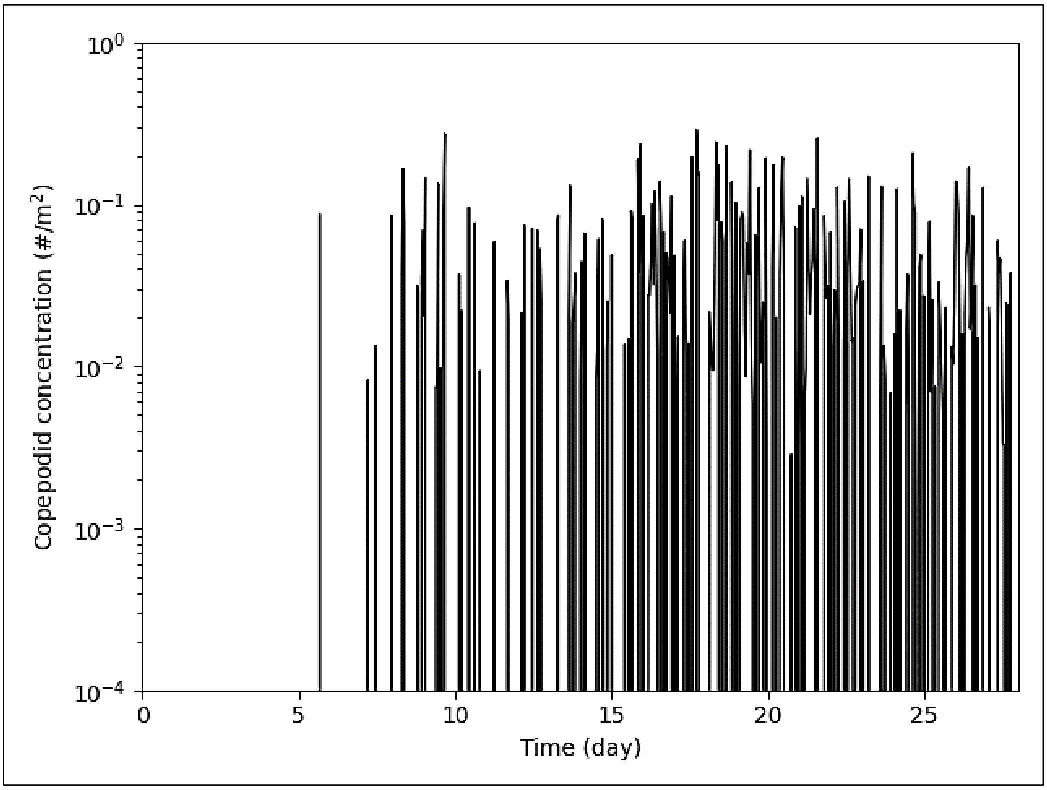

Figure 12 *Probe 5 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2019.*

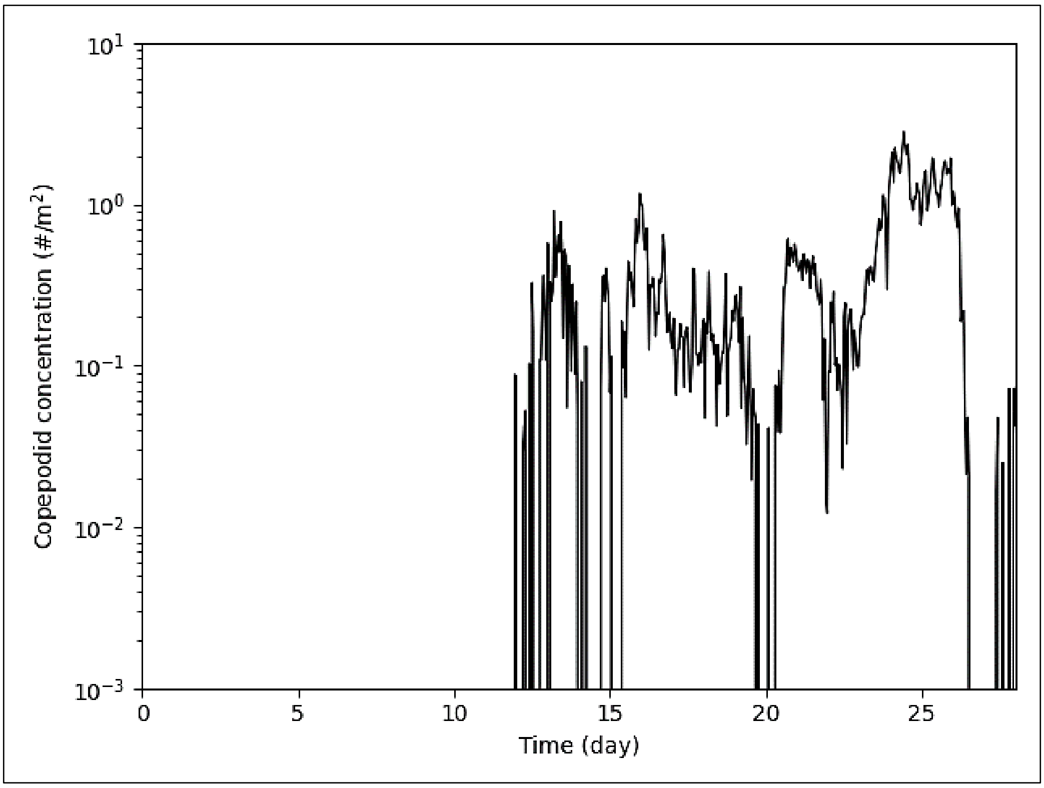

Figure 13 *Probe 6 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2019.*

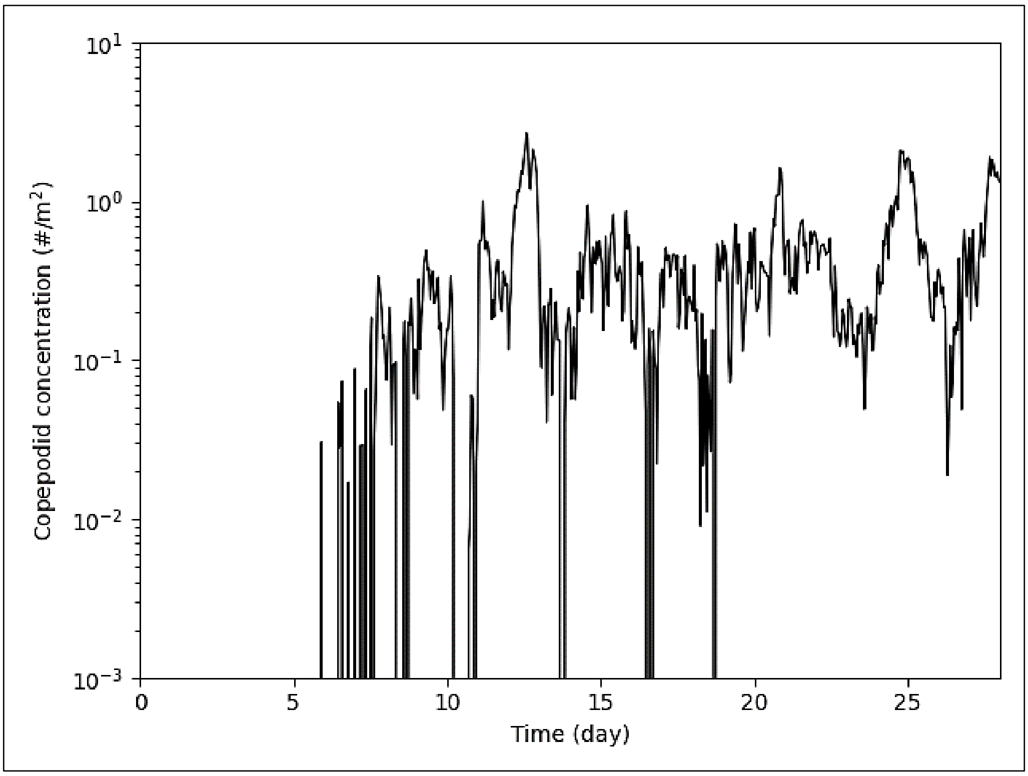

Figure 14 *Probe 7 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2019.*

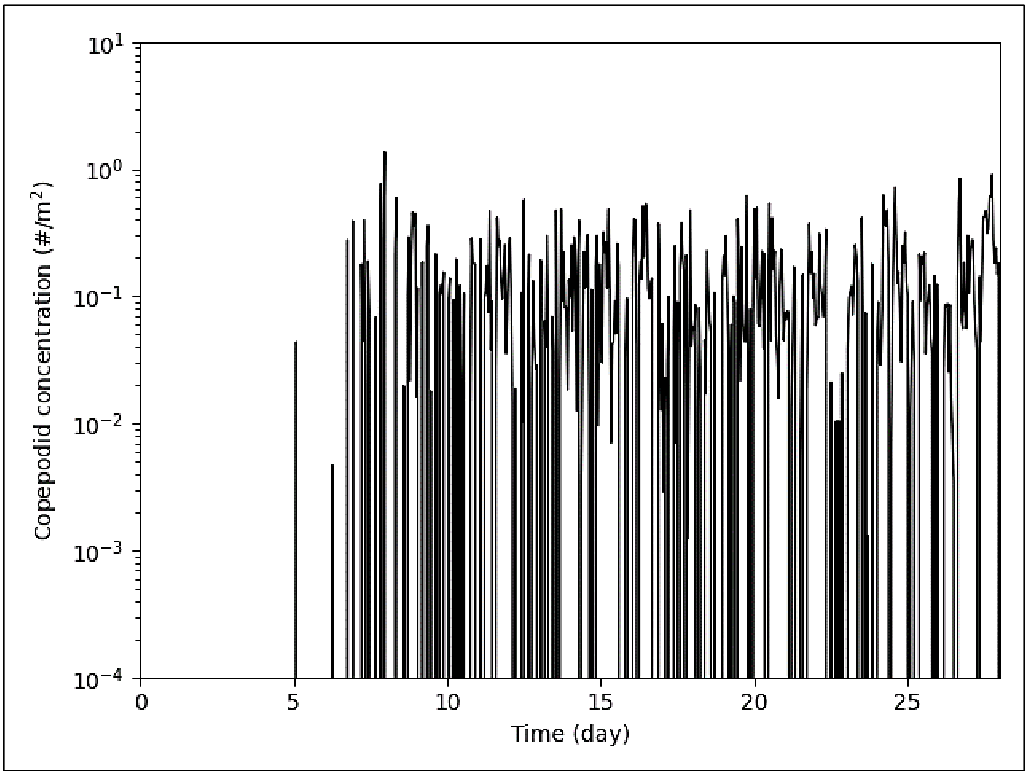

Figure 15 *Probe 8 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2019.*

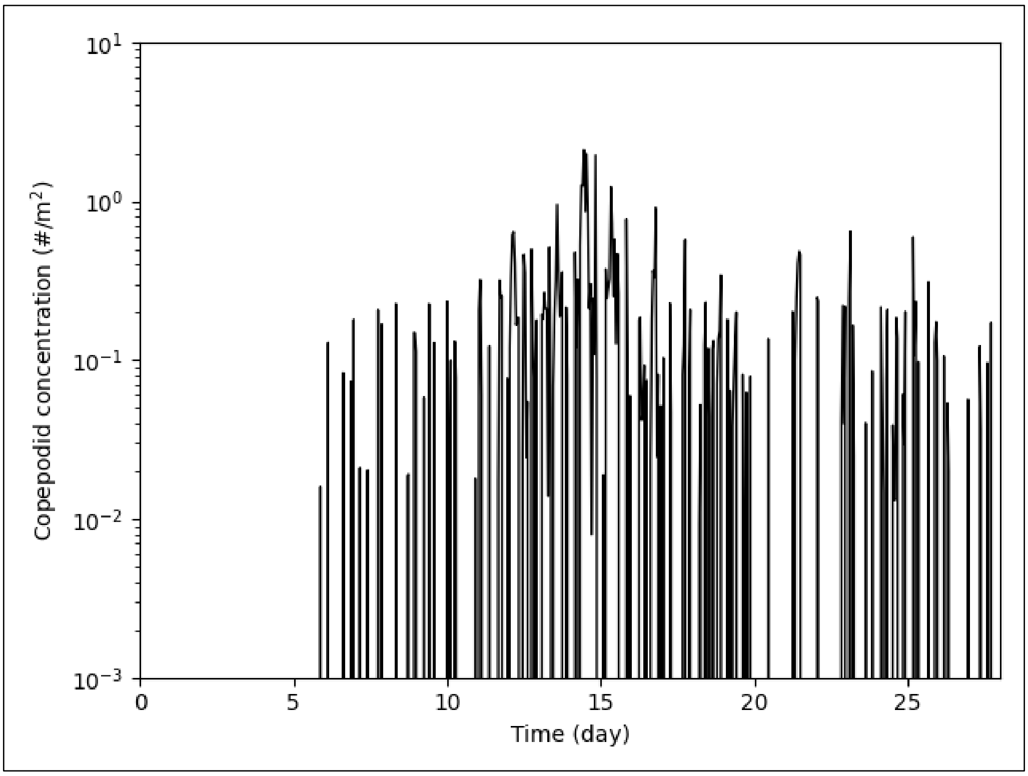

Figure 16 *Probe 9 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2019.*

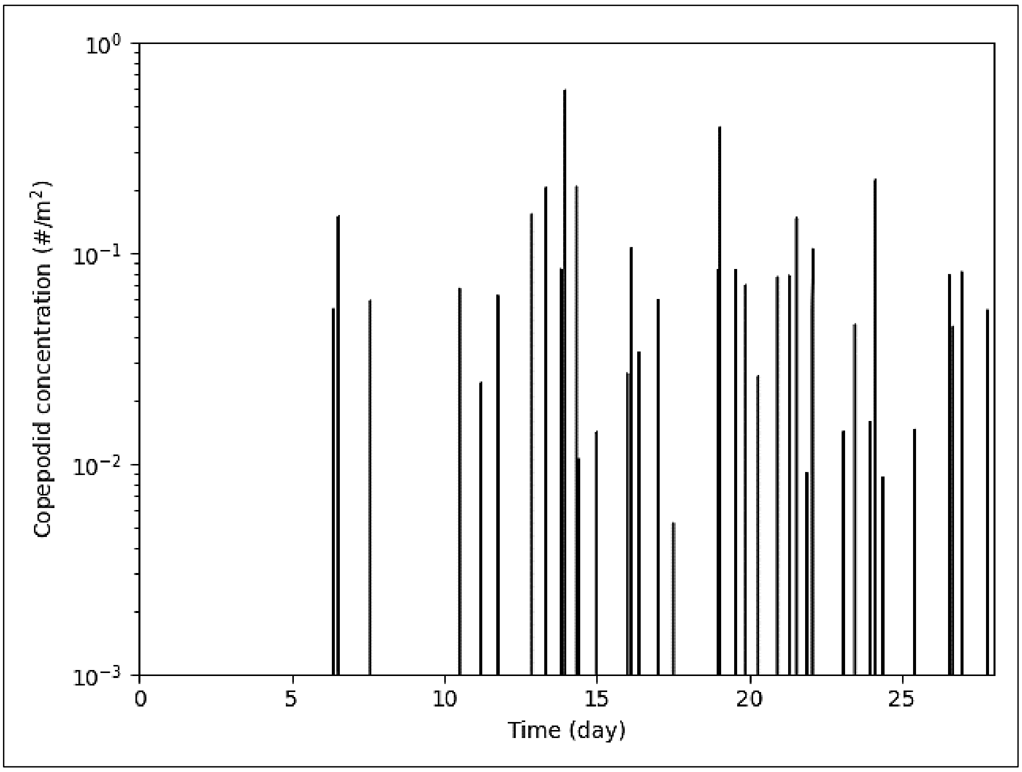

Figure 17 *Probe 10 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2020.*

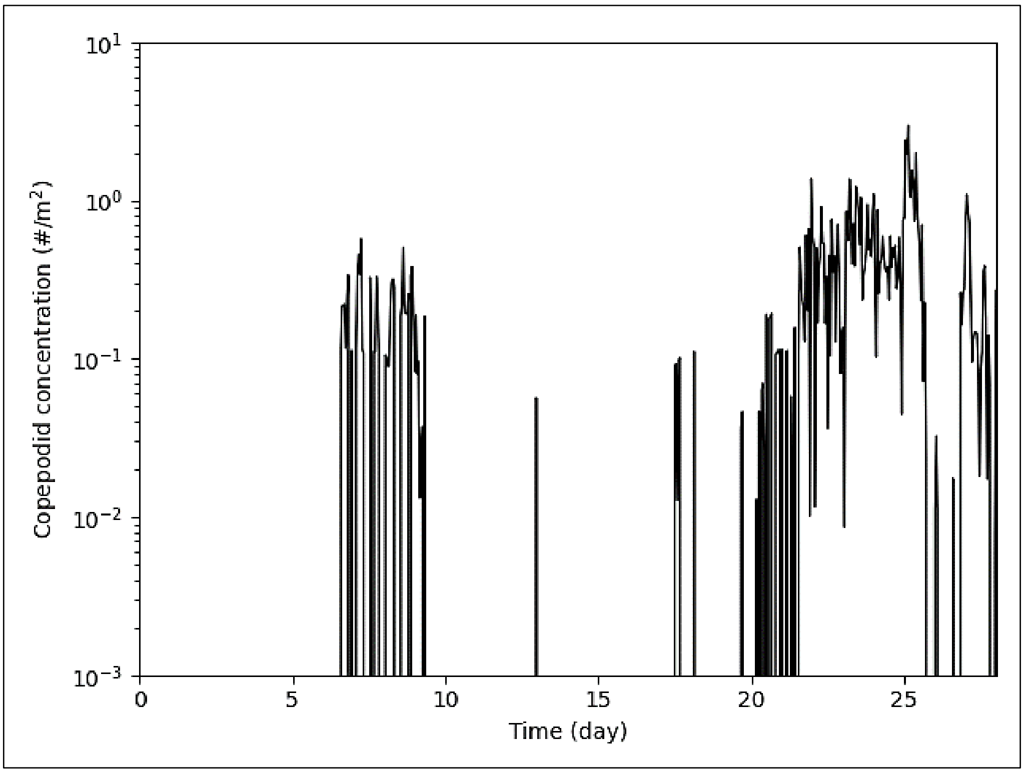

Figure 18 *Probe 11 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2020.*

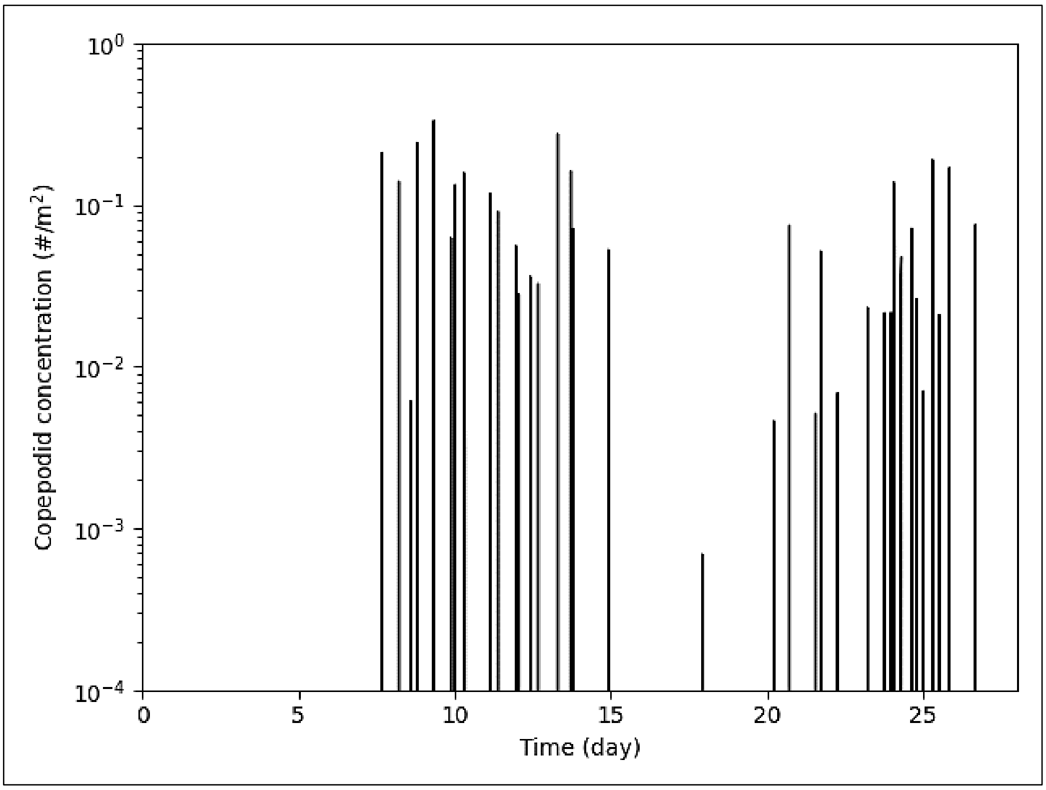

Figure 19 *Probe 12 (Orkney) instantaneous values of copepodid density (#/m^2) for May 2020.*

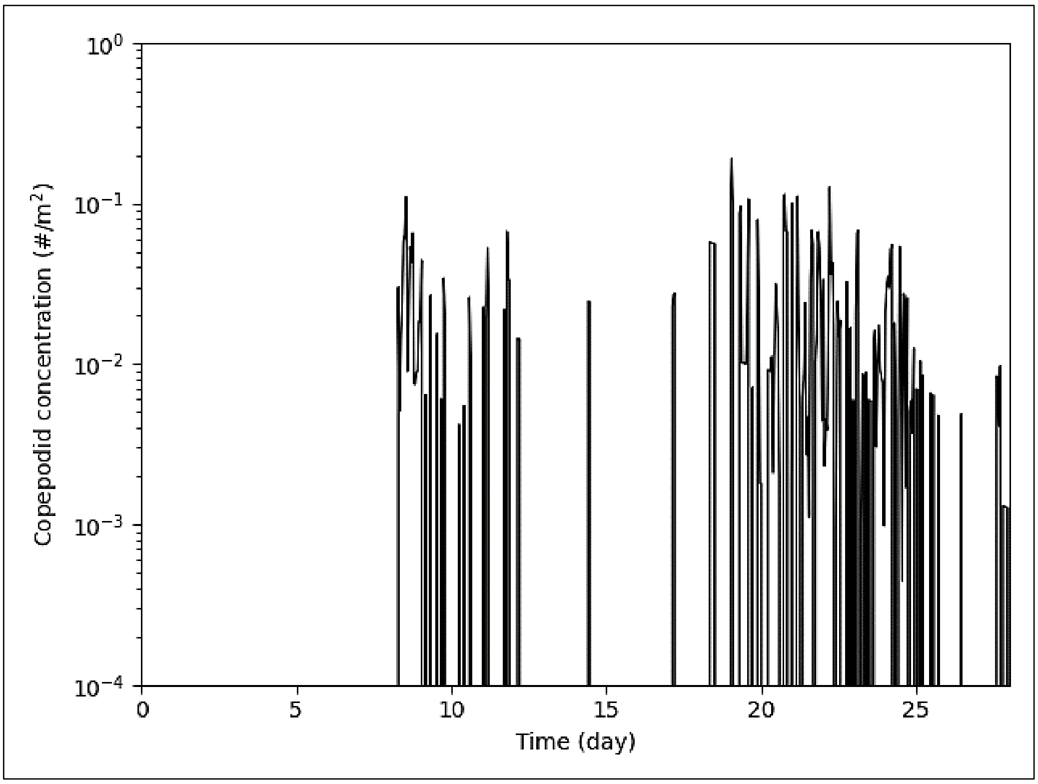

Figure 20 *Probe 13 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2020.*

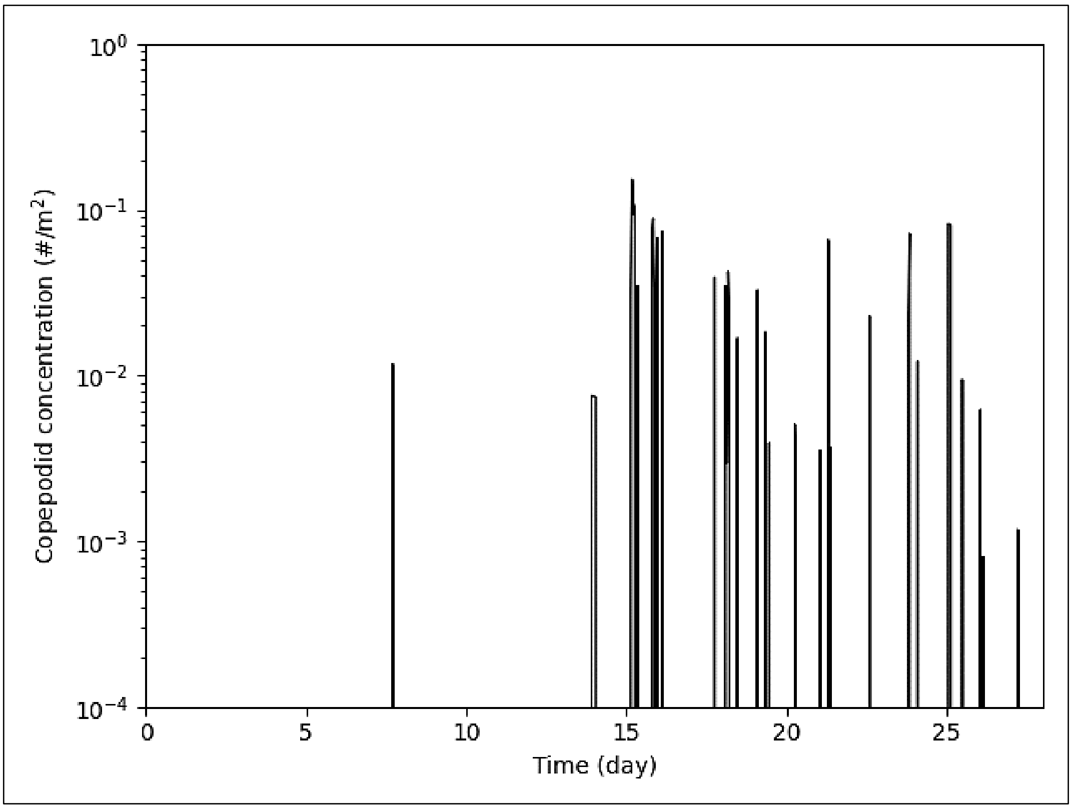

Figure 21 *Probe 14 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2020.*

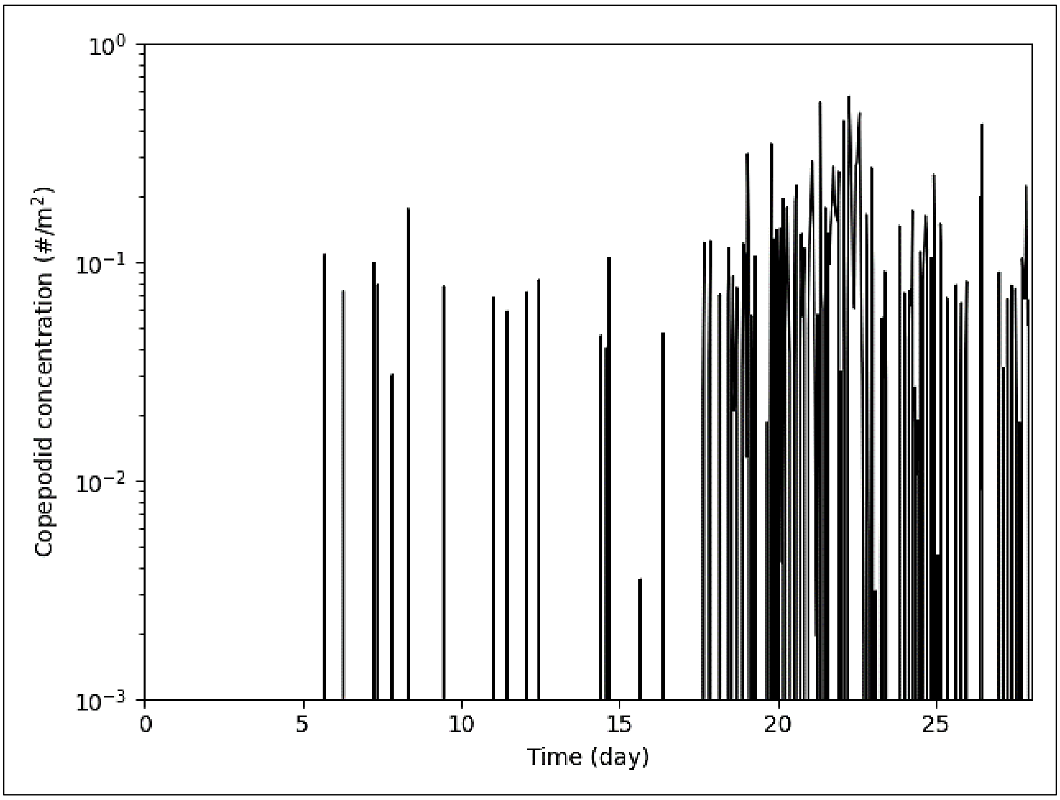

Figure 22 *Probe 15 (Shetland) instantaneous values of copepodid density (#/m^2) for May 2020.*

The probe results show that the highest instantaneous lice densities are predicted to occur in Shetland in May 2019 at probe locations 6, 7, 8 and 9 where levels of 2 cop/m^2 can persist over several days (see Figs 13-16). In addition, for Orkney in May 2020, lice density levels approaching 1 cop/m^2 are likely to occur and be maintained over several days at Probe 11 in Scapa Flow (see Fig. 18).

4.3 *Lice Distribution Snapshots*

4.3.1 *Northern Isles Distribution*

In addition to the instantaneous quantitative data provided by the virtual probes, copepodid densities calculated every hour may be shown as an animated series of lice density maps. These are the peak levels that migrating fish are likely to encounter. During their migration journey through the coastal waters, they may pass through multiple areas of high lice density.

This qualitative data demonstrates how the salmon lice fields evolve with time and provides evidence of large-scale organised behaviour, often manifesting as long filaments of lice extending over many kilometres.

Figures 23-26 show sample snapshots of the instantaneous copepodid density fields (#/m^2) around the Northern Isles for the hydrodynamic May 2019 and 2020 runs. Lice animations are also available as part of this study.

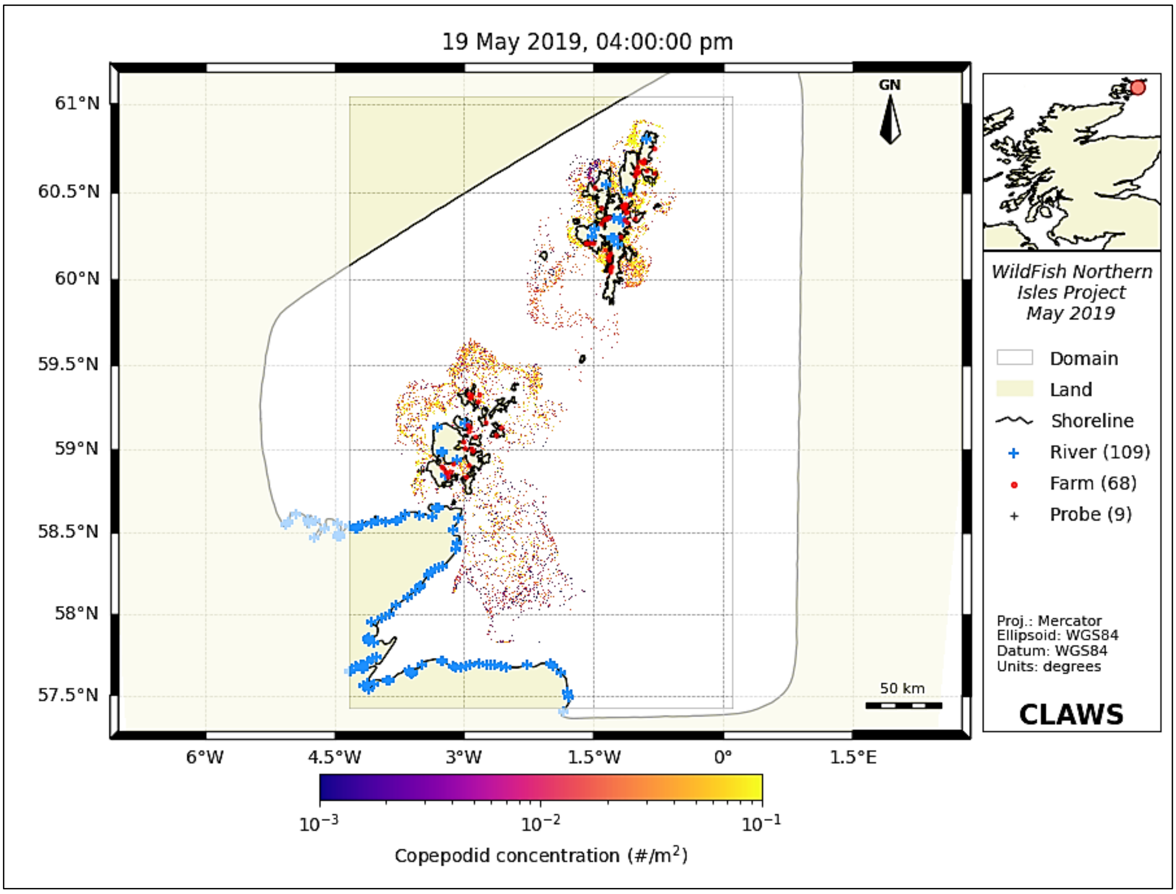

Figure 23 *Snapshot of instantaneous copepodid density (#/m^2) on the 19th May 2019.*

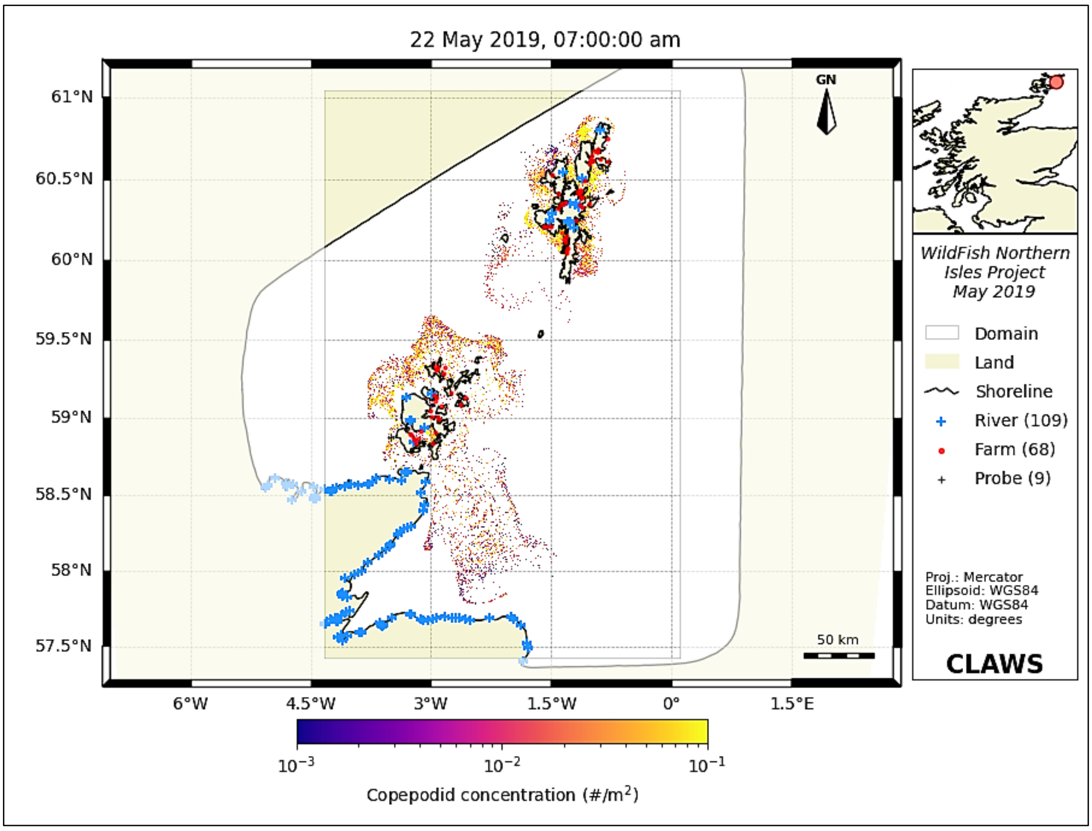

Figure 24 *Snapshot of instantaneous copepodid density (#/m^2) on the 22nd May 2019.*

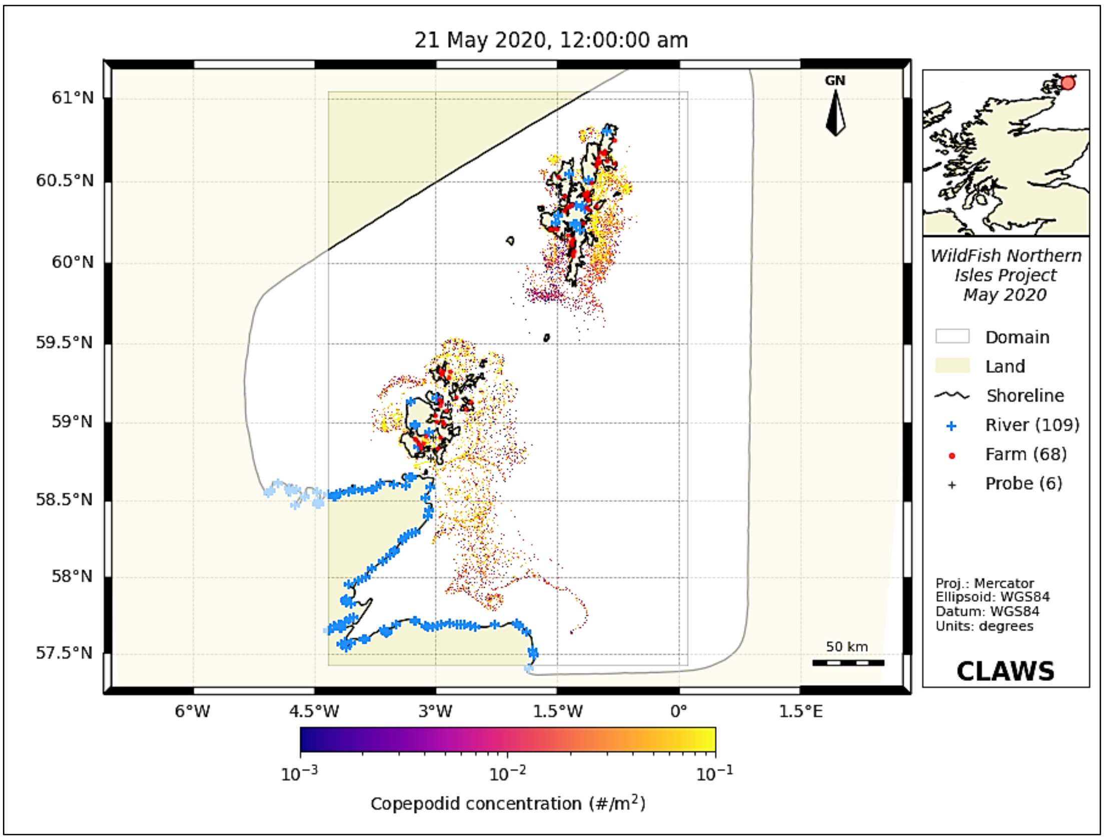

Figure 25 *Snapshot of instantaneous copepodid density (#/m^2) on the 21st May 2020.*

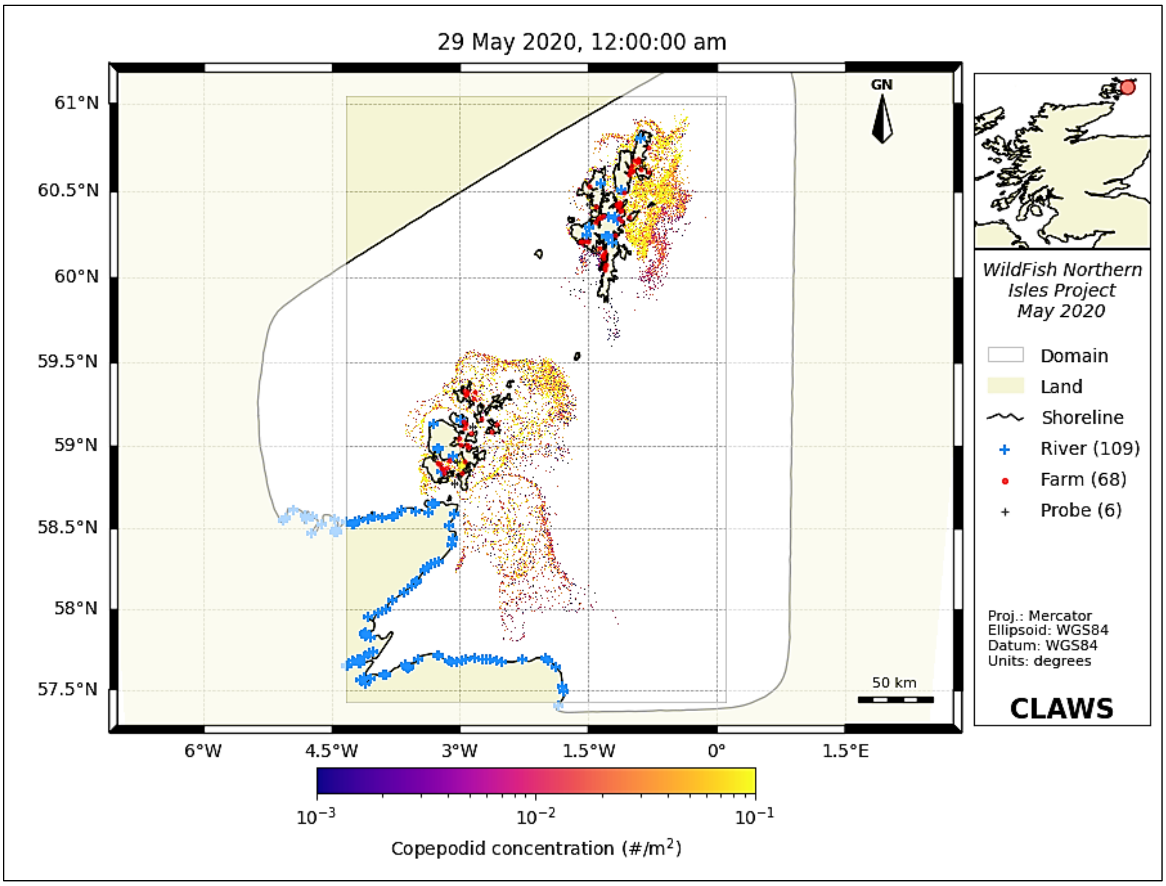

Figure 26 *Snapshot of instantaneous copepodid density (#/m^2) on the 29th May 2020.*

4.4 *Virtual Post-Smolt Model*

When the salmon lice model has developed steady-state conditions (i.e. approximately, from the 6th May – see Fig. 1), virtual "post-smolt" particles were modelled swimming through the instantaneous lice fields. This virtual smolt model predicts the exposure to infective-stage sea lice in lice per m^2-days likely to give rise to harmful levels of mobile lice on wild salmon post-smolts. Wild sea trout in the same areas would experience a higher level of exposure to sea lice, as they do not migrate far, so the exposure indicated by passing virtual salmon post-smolts through the model for a few days gives a very conservative indicator of the minimum level of risk for resident sea trout. For a 12.5 cm salmon post-smolt swimming at 1 body-length per second the harmful exposure threshold was set as 0.75 copepodid per m^2-days [SEPA_2024]. For specific swimming paths, an assessment may then be made regarding risk of harmful lice infestation to the virtual post-smolts.

Virtual post-smolt particles were released on an hourly basis and followed a user-specified swim path. The swim paths were chosen such that the smolts would pass through areas of high average lice density (see Figs. 2 and 3) in an attempt to replicate a worst-case scenario for the migrating fish. Figures 27-30 show the post-smolt swim paths for the May 2019 and 2020 runs.

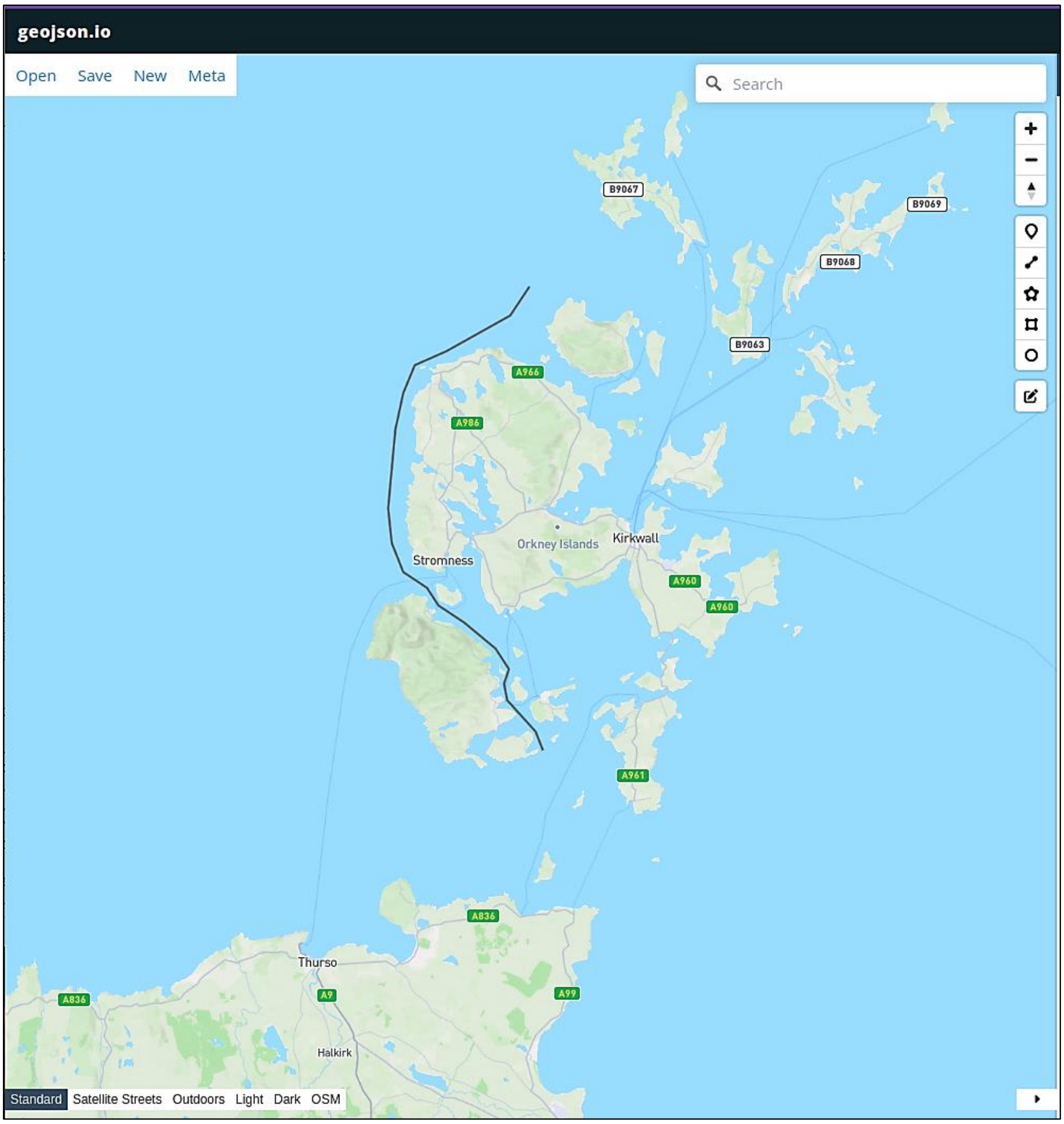

Figure 27 *Virtual Post-Smolt Swim Route – ~60 km, Orkney, May 2019 run.*

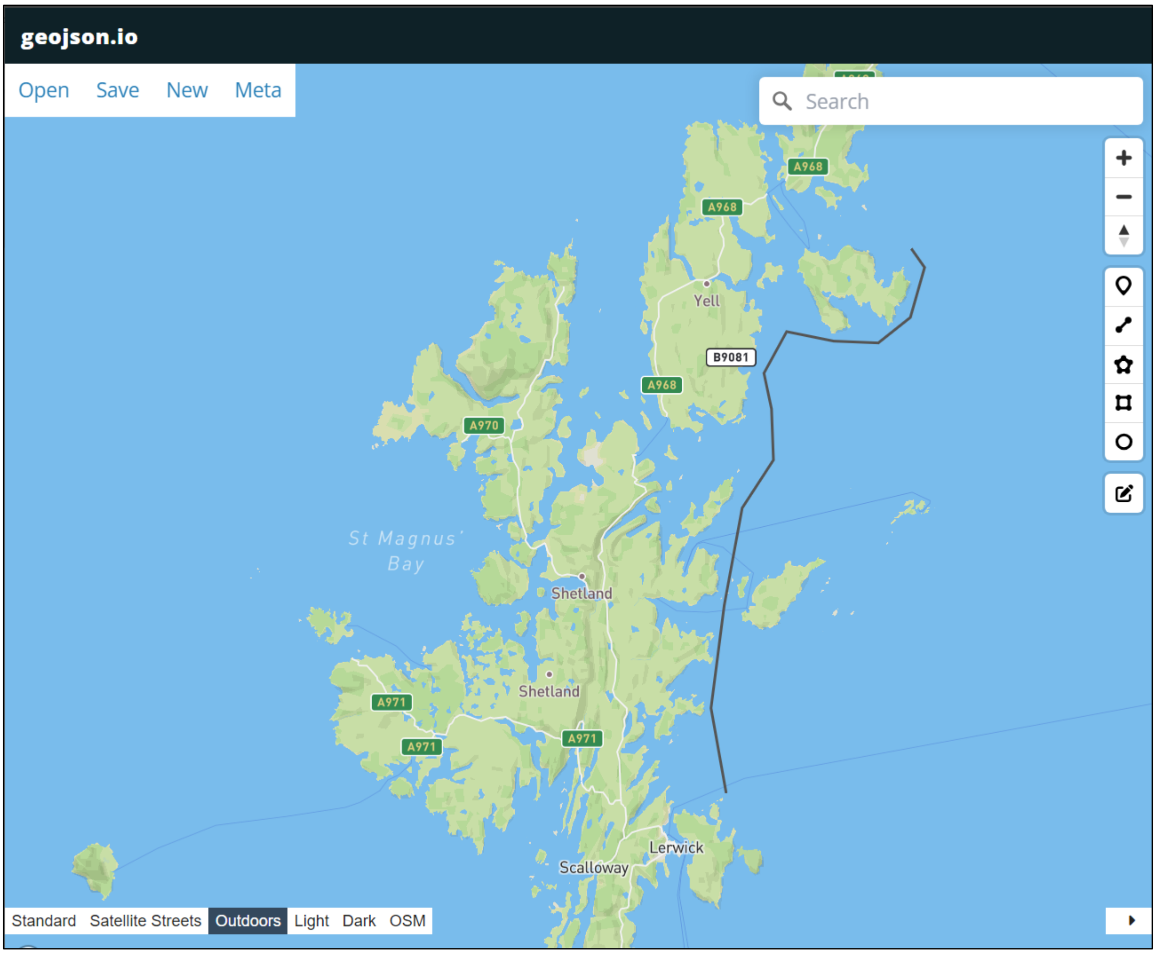

Figure 28 *Virtual Post-Smolt Swim Route – ~60 km, Shetland, May 2019 run.*

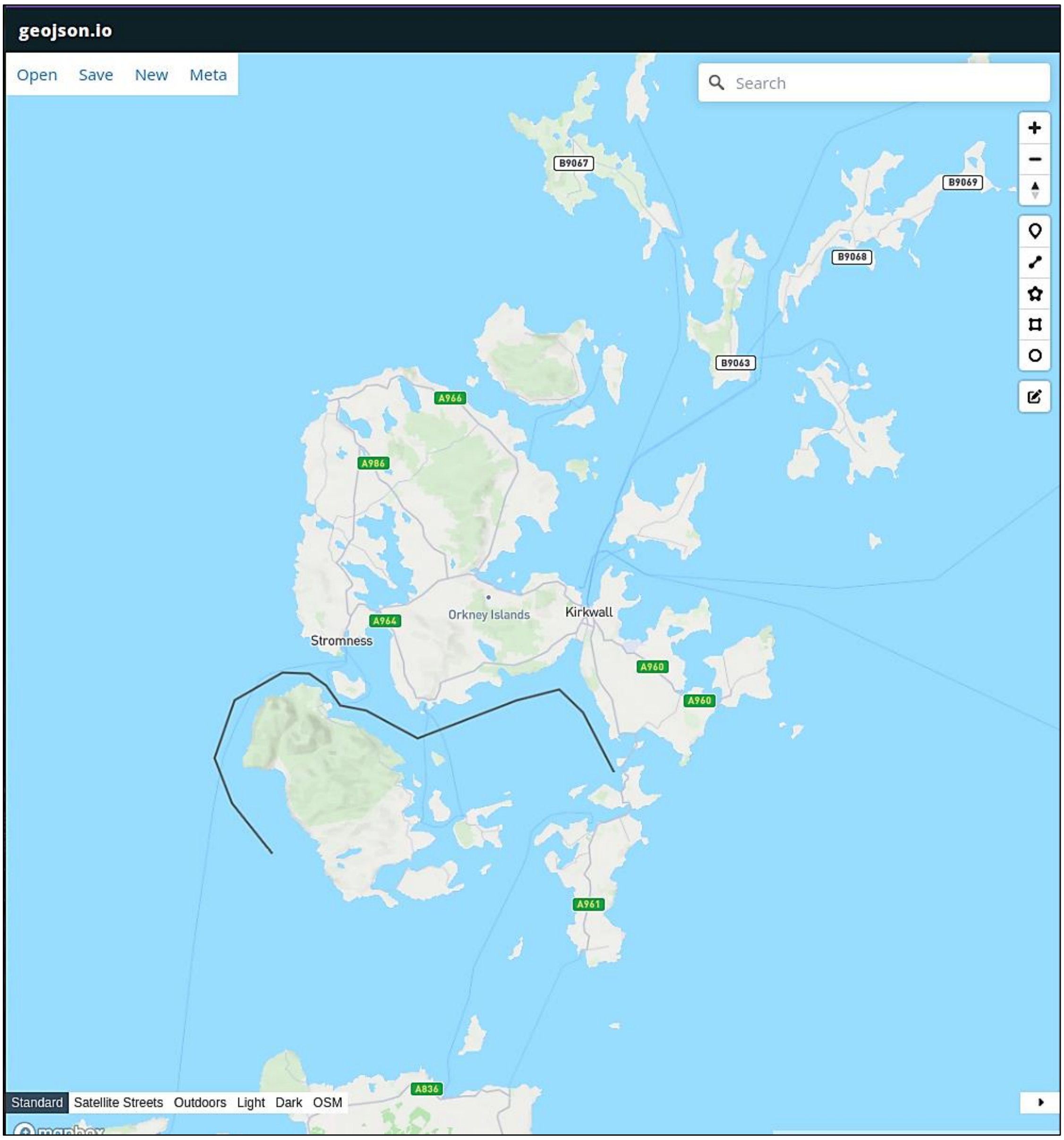

Figure 29 *Virtual Post-Smolt Swim Route – ~50 km, Orkney, May 2020 run.*

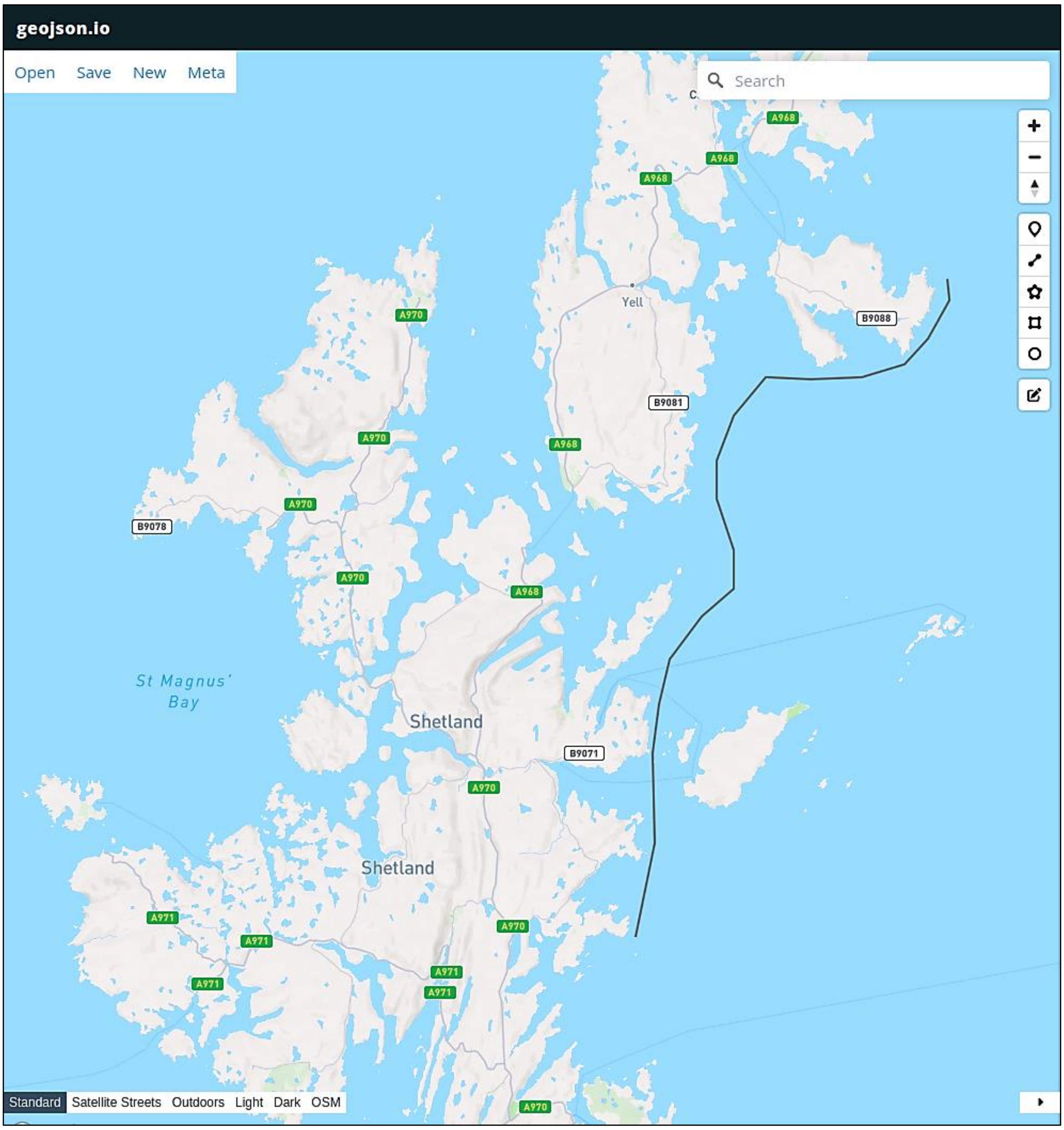

Figure 30 *Virtual Post-Smolt Swim Route – ~50 km, Shetland, May 2020 run.*

Figures 31-34 show the box-plot results of the cumulative exposure to infective-stage sea lice in lice per m^2-days. In order to optimise the amount of data on each graph, virtual swim particles are binned based on their release time into at most 20 evenly-populated groups. The box-plots show the standard results of mean, median, Q1 and Q3 along with whiskers showing the minimum and maximum exposure values.

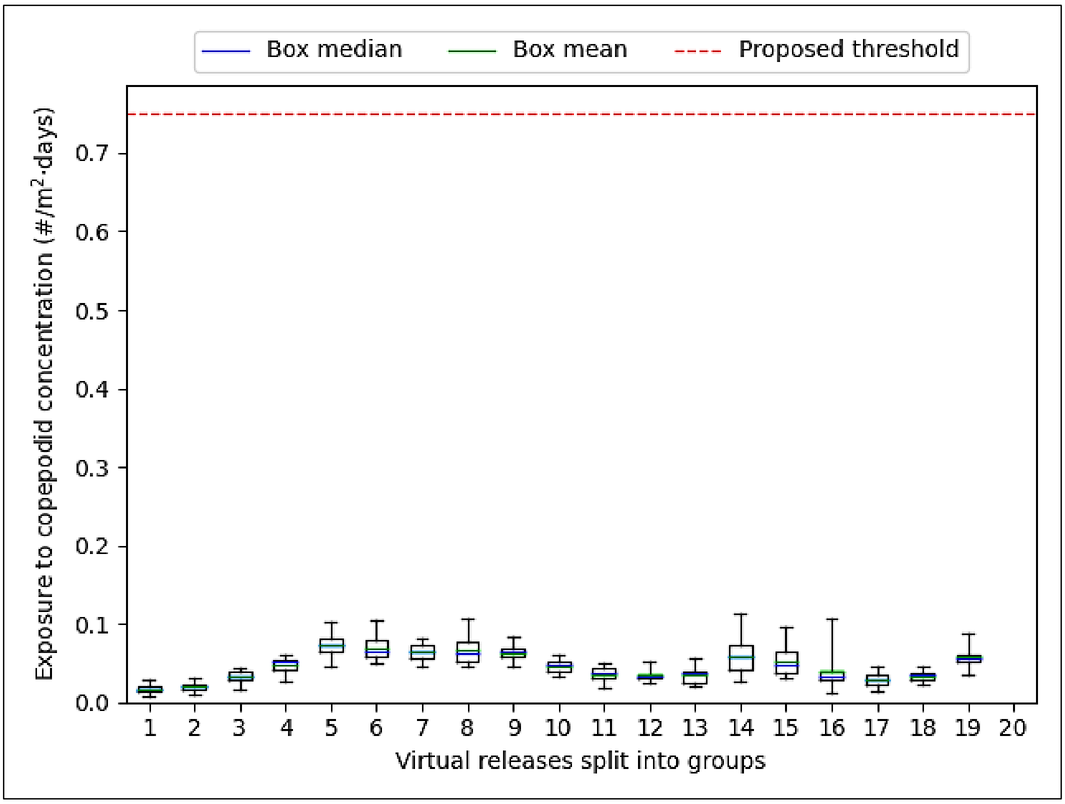

Figure 31 *Box-plot of exposure to infective-stage sea lice for the May 2019 Orkney swim path shown in Figure 27.*

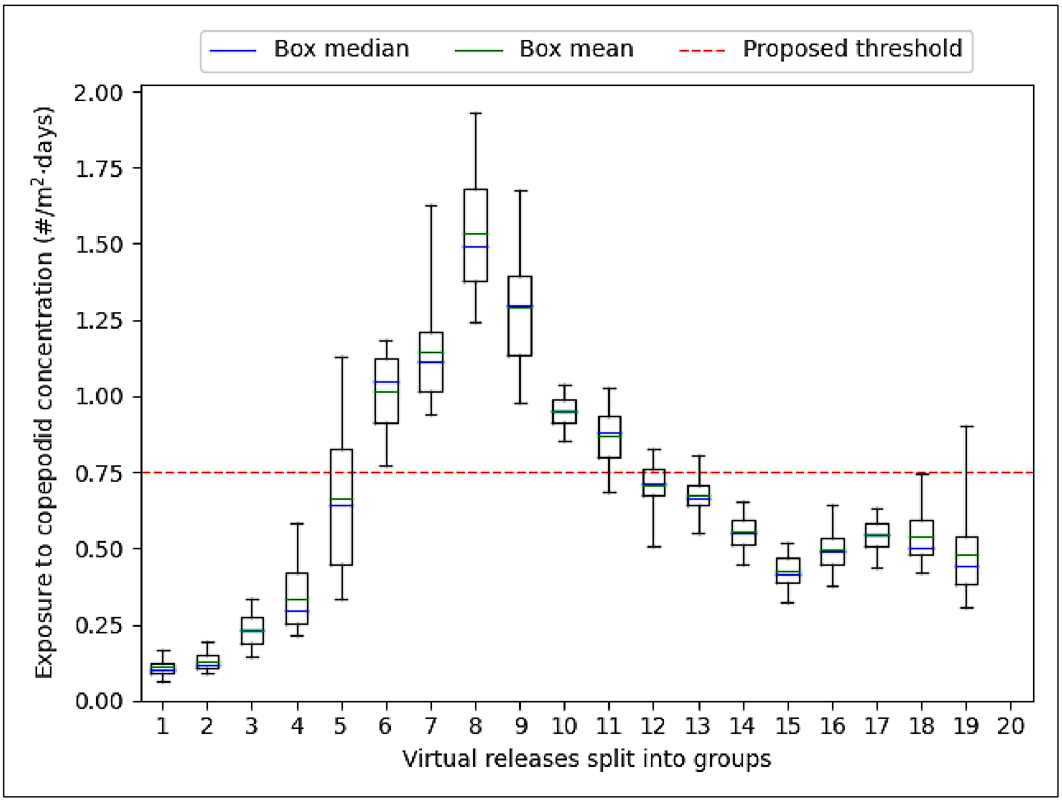

Figure 32 *Box-plot of exposure to infective-stage sea lice for the May 2019 Shetland swim path shown in Figure 28.*

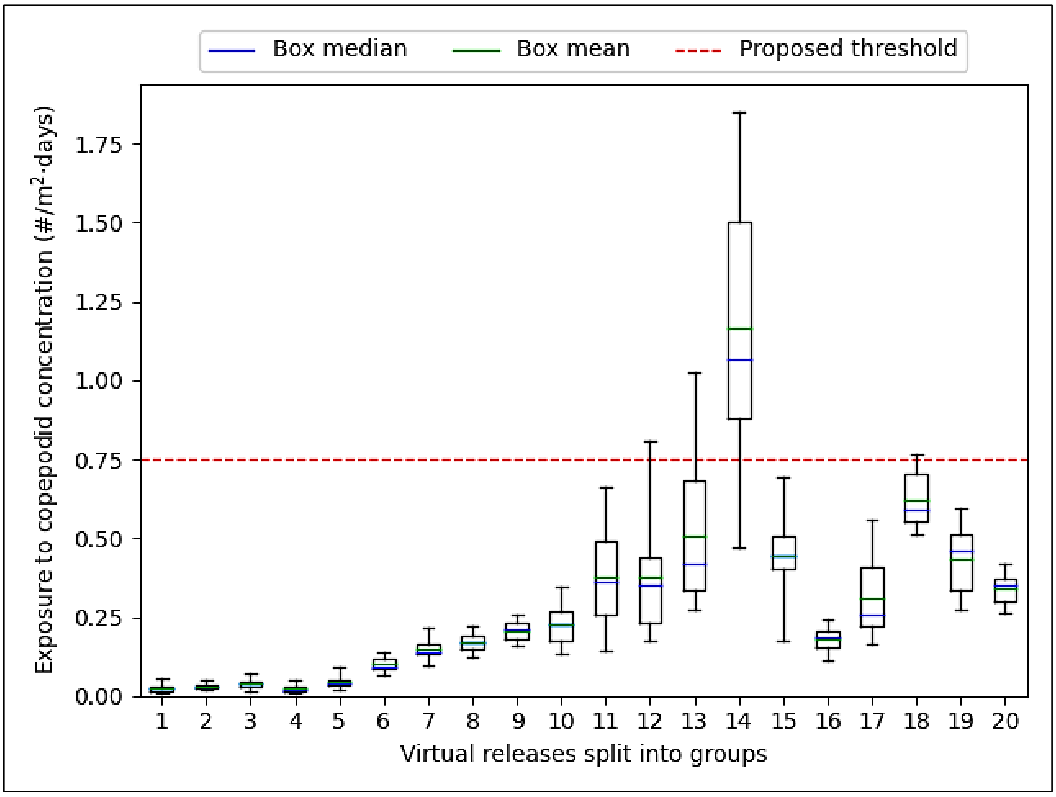

Figure 33 *Box-plot of exposure to infective-stage sea lice for the May 2020 Orkney swim path shown in Figure 29.*

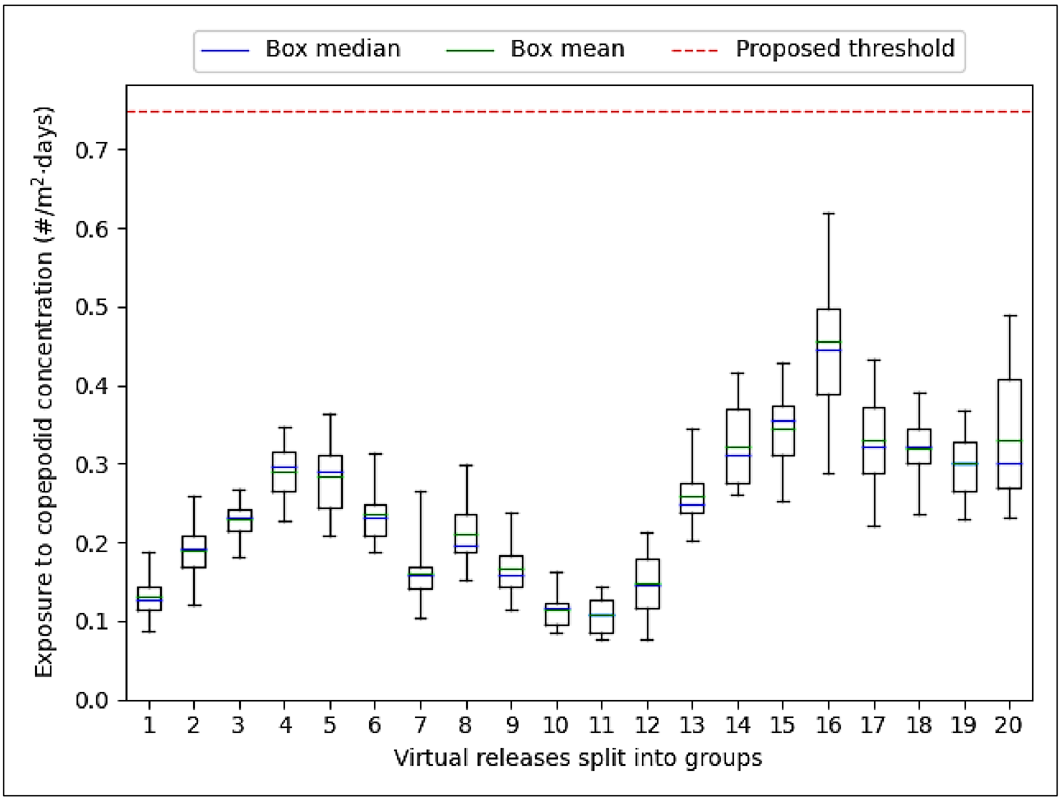

Figure 34 *Box-plot of exposure to infective-stage sea lice for the May 2020 Shetland swim path shown in Figure 30.*

The box-plots results show that the harmful exposure threshold of 0.75 copepodid per m^2-days [SEPA_2024] is likely to be exceeded for certain swim groups during the May 2019 Shetland swim (Fig. 28) and the May 2020 Orkney swim (Fig. 29). This means that there is a likely risk of harmful lice infestation to the virtual post-smolts on these swim routes.

It should be noted that the lice exposure results focus on possible swim paths for migrating wild salmon post-smolts, however, sea-trout populations are also likely to be affected as they would normally rest in closer proximity to local spawning burns along the coastline.

In addition to the box-plot cumulative exposure results, Figures 35-38 show the values of instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases.

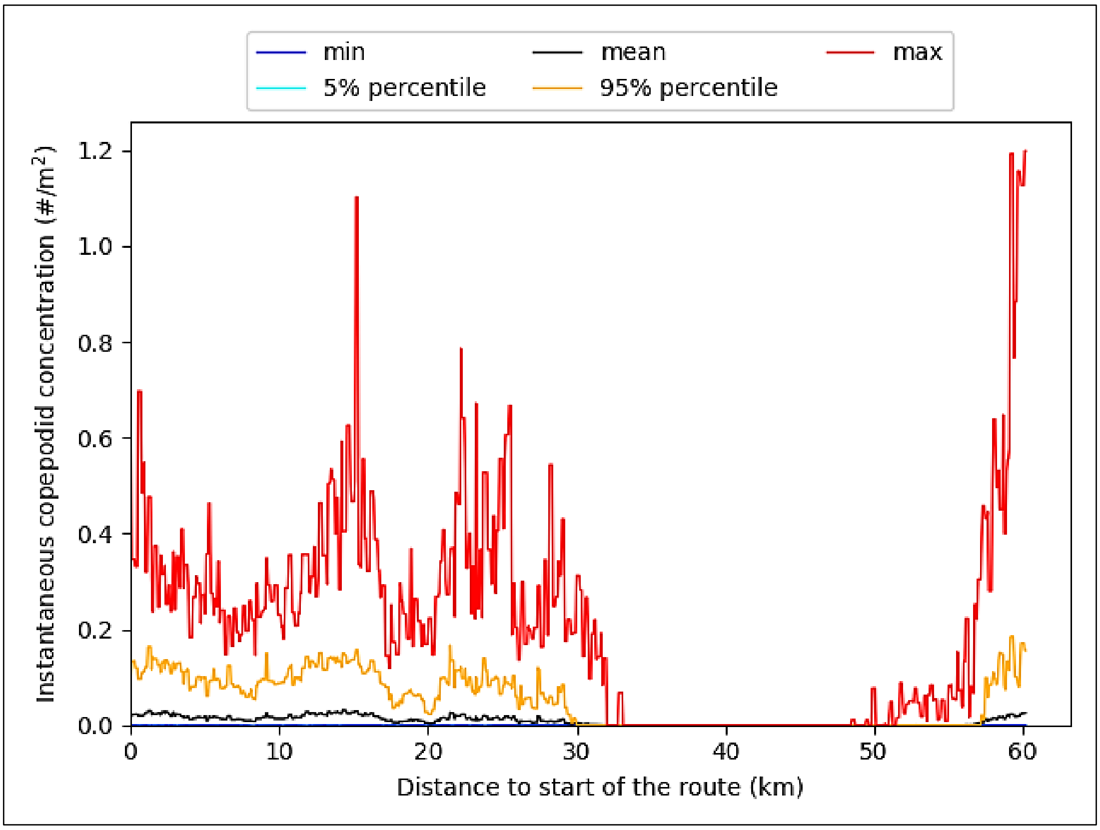

Figure 35 *Instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases, for the May 2019 Orkney swim path shown in Figure 27.*

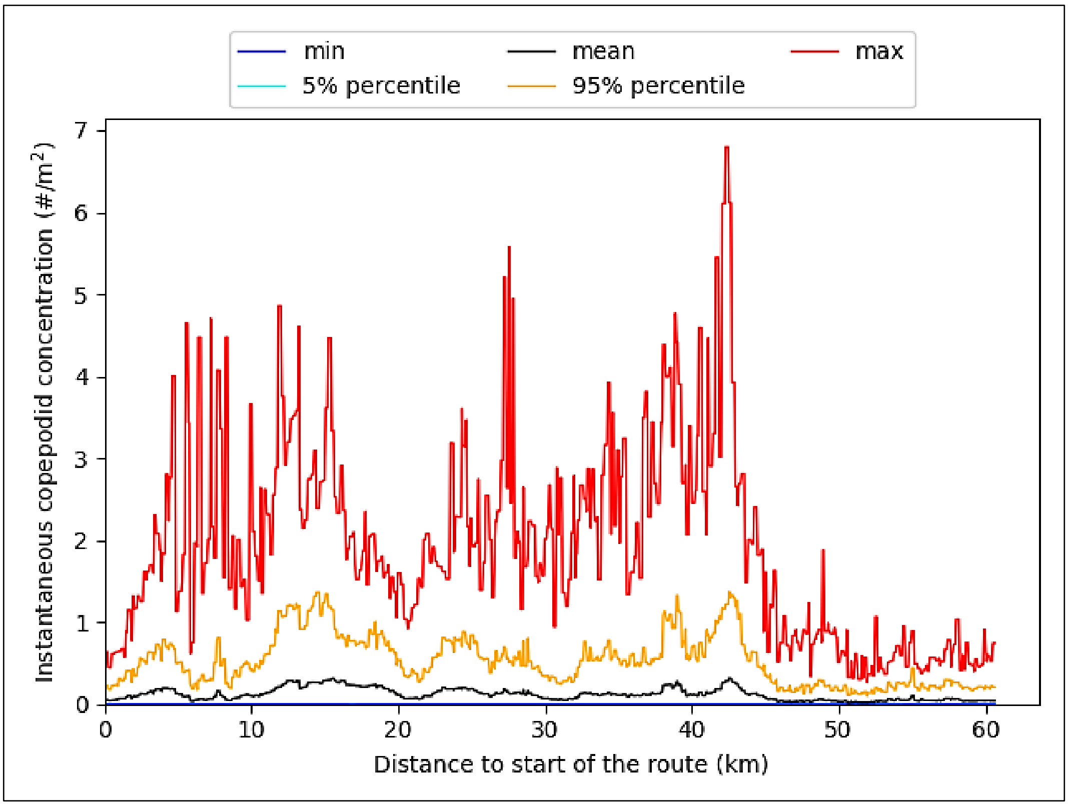

Figure 36 *Instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases, for the May 2019 Shetland swim path shown in Figure 28.*

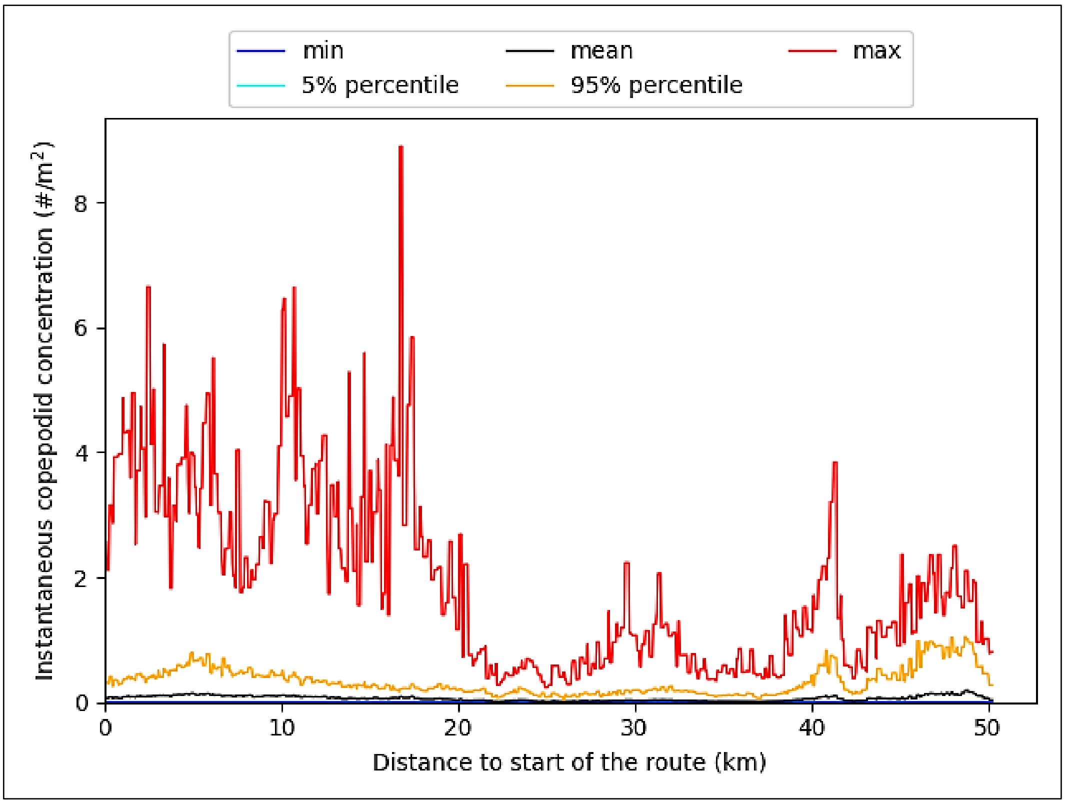

Figure 37 *Instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases, for the May 2020 Orkney swim path shown in Figure 29.*

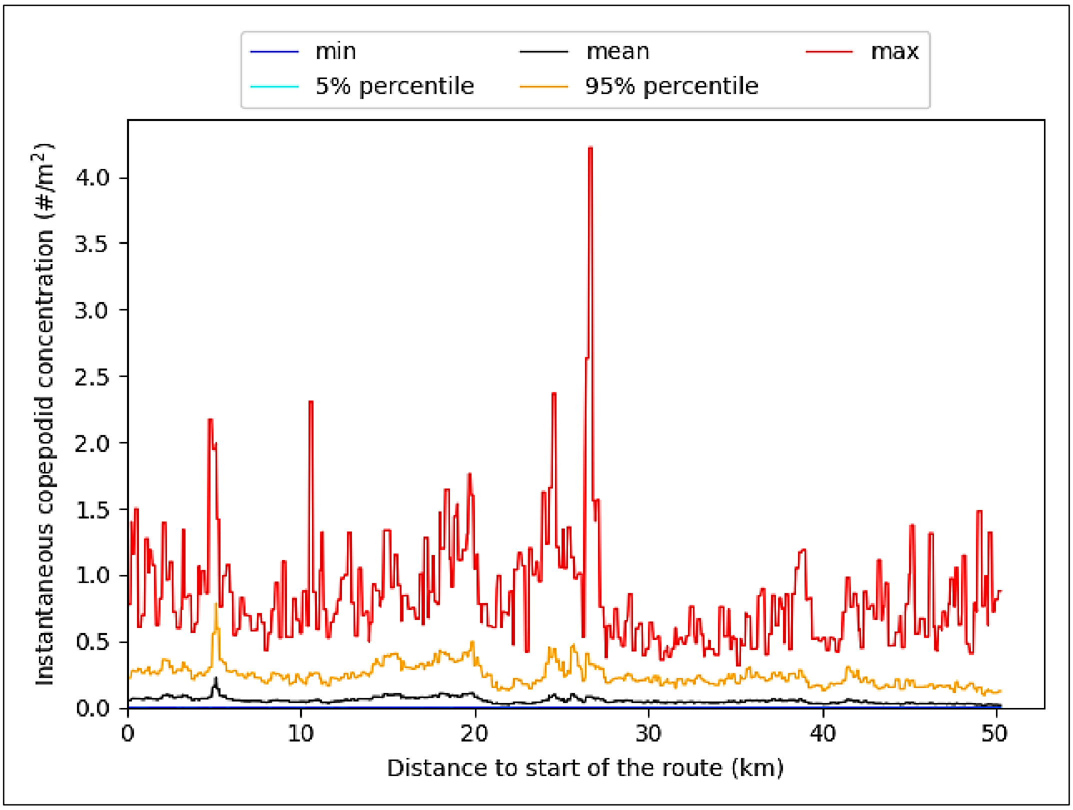

Figure 38 *Instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases, for the May 2020 Shetland swim path shown in Figure 30.*

The results show that instantaneous peak copepodid values of 9 cop/m^2 are possible (Fig. 37) and peak lice densities of at least 6 cop/m^2 may exist over a distance on the swim path of approximately 1 km (Fig. 36).

Finally, Figures 39-42 show the cumulative lice exposure results (#/m^2-days) against time for all virtual post-smolt releases. The results are colour-coded such that bluer shades correspond to earlier releases and redder shades to later ones. The virtual smolts take around 5.5 days to cover a distance of 60 km at 12.5 cm/s. A peak cumulative exposure concentration of approximately 1.9 cop/m^2-days was observed for the May 2019 Shetland swim path shown in Fig.28 - (Fig. 40).

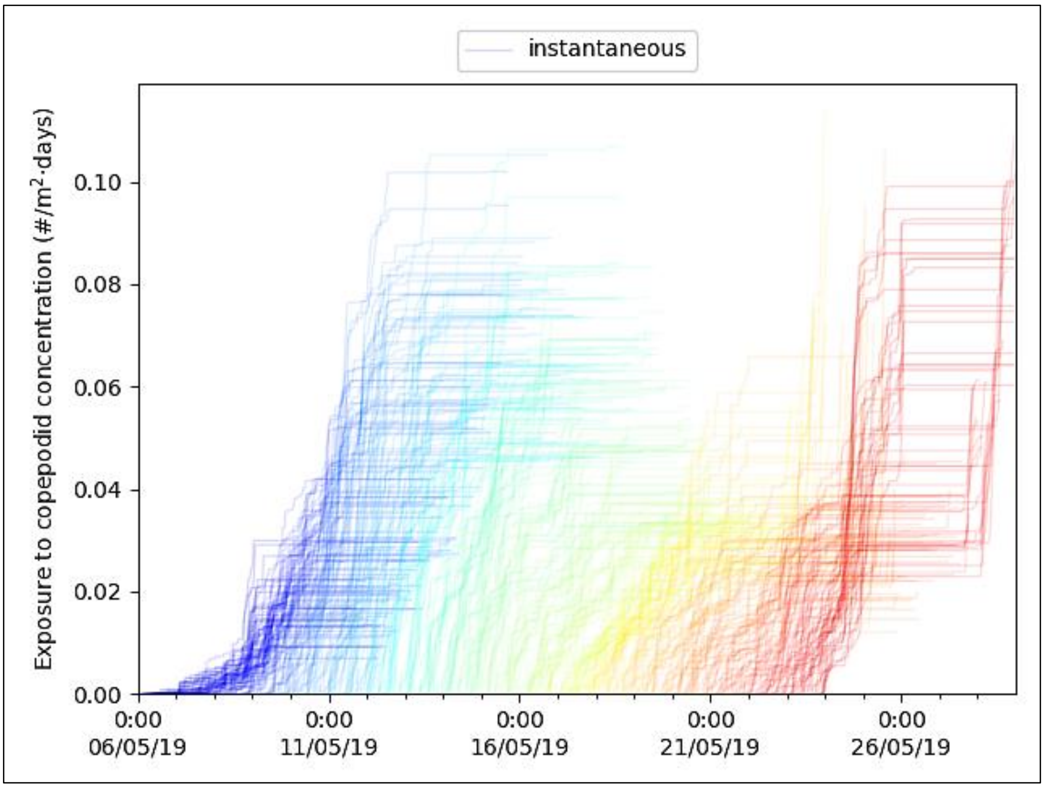

Figure 39 *Cumulative infective lice exposure (#/m^2-days) against time for all virtual post-smolt releases. May 2019 Orkney swim path shown in Figure 27.*

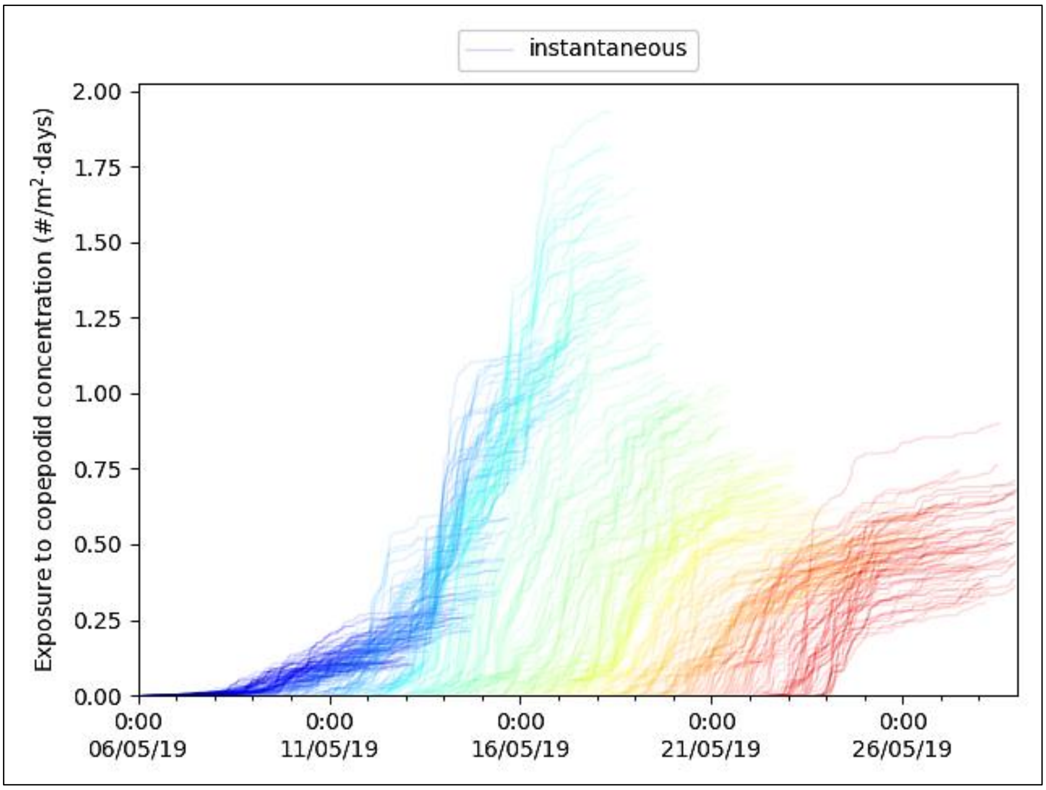

Figure 40 *Cumulative infective lice exposure (#/m^2-days) against time for all virtual post-smolt releases. May 2019 Shetland swim path shown in Figure 28.*

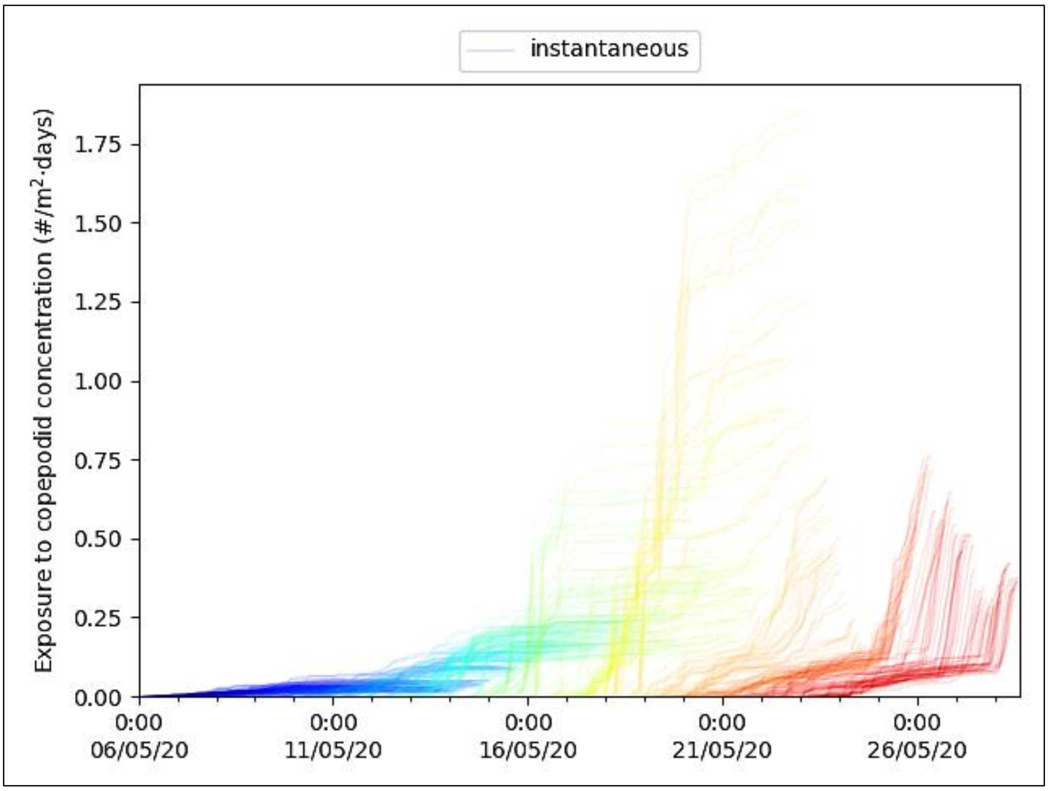

Figure 41 *Cumulative infective lice exposure (#/m^2-days) against time for all virtual post-smolt releases. May 2020 Orkney swim path shown in Figure 29.*

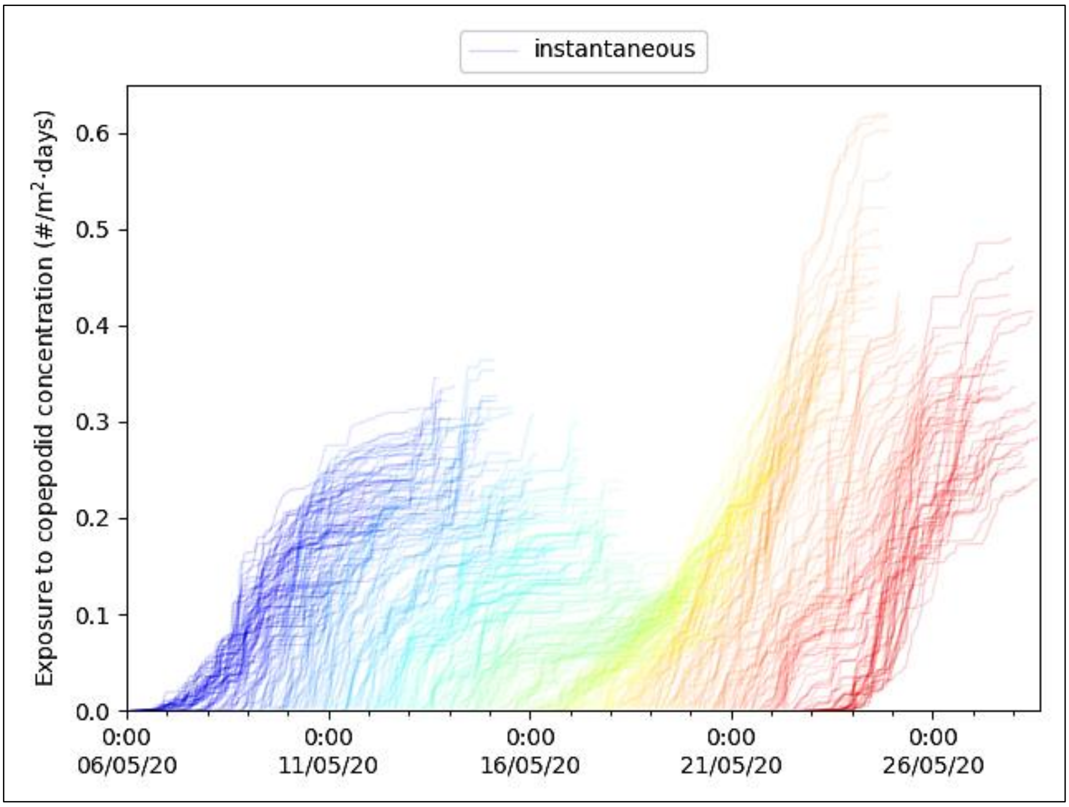

Figure 42 *Cumulative infective lice exposure (#/m^2-days) against time for all virtual post-smolt releases. May 2020 Shetland swim path shown in Figure 30.*

4.4.1 *New sea lice average study*

The work presented thus far has been on the basis of an industry-average figure of 0.5 adult female lice per farmed salmon. Further modelling work has now been undertaken using the actual average measured value from the salmon farms on Orkney and Shetland for Q1/2 2024. This value has been determined as 0.78 lice per fish [WildFish_2024].

Figure 43 shows the average infective lice density plots for May in the hydrodynamic year 2020 with the new value of 0.78 lice per fish activated.

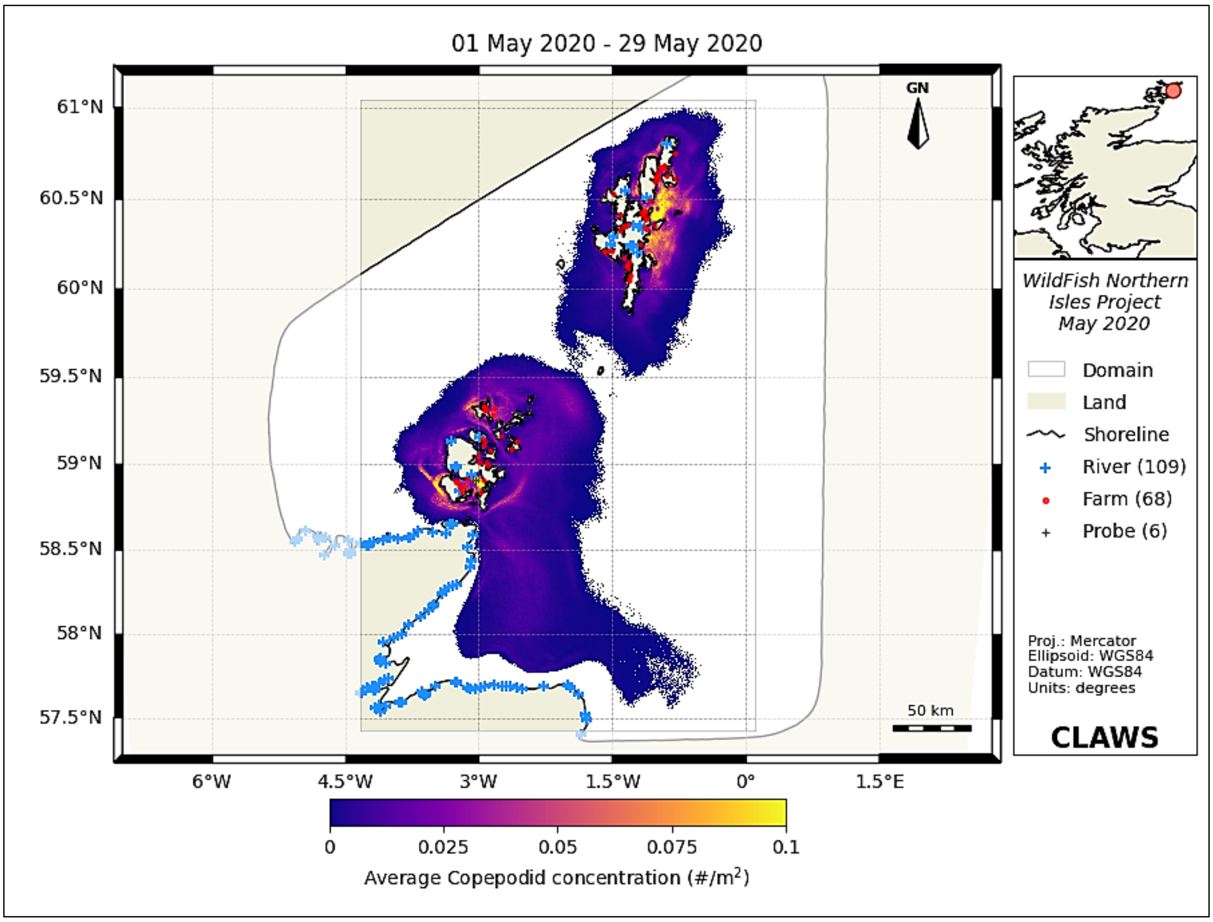

Figure 43 *Heat map of average copepodid density (#/m^2) over the hydrodynamic period 6th-28th May 2020 on a sampling mesh of bin size 200 m. An average value of* ***0.78*** *adult female lice per farmed salmon was employed. The total biomass for the 26 Orkney farms was 24,585 tonnes while the total biomass for the 42 Shetland farms was 26,770 tonnes.*

The general lice distribution pattern is similar to that found with the industry-average 0.5 lice per fish (see Fig.3), however, higher lice concentrations are evident as highlighted by the enhanced areas of yellow on the heat map, indicating average values of 0.1 lice/m^2 or greater.

Figures 44 and 45 show the box-plot results of the cumulative exposure to infective-stage sea lice in lice per m^2-days for post-smolt swim routes around Orkney and Shetland, respectively.

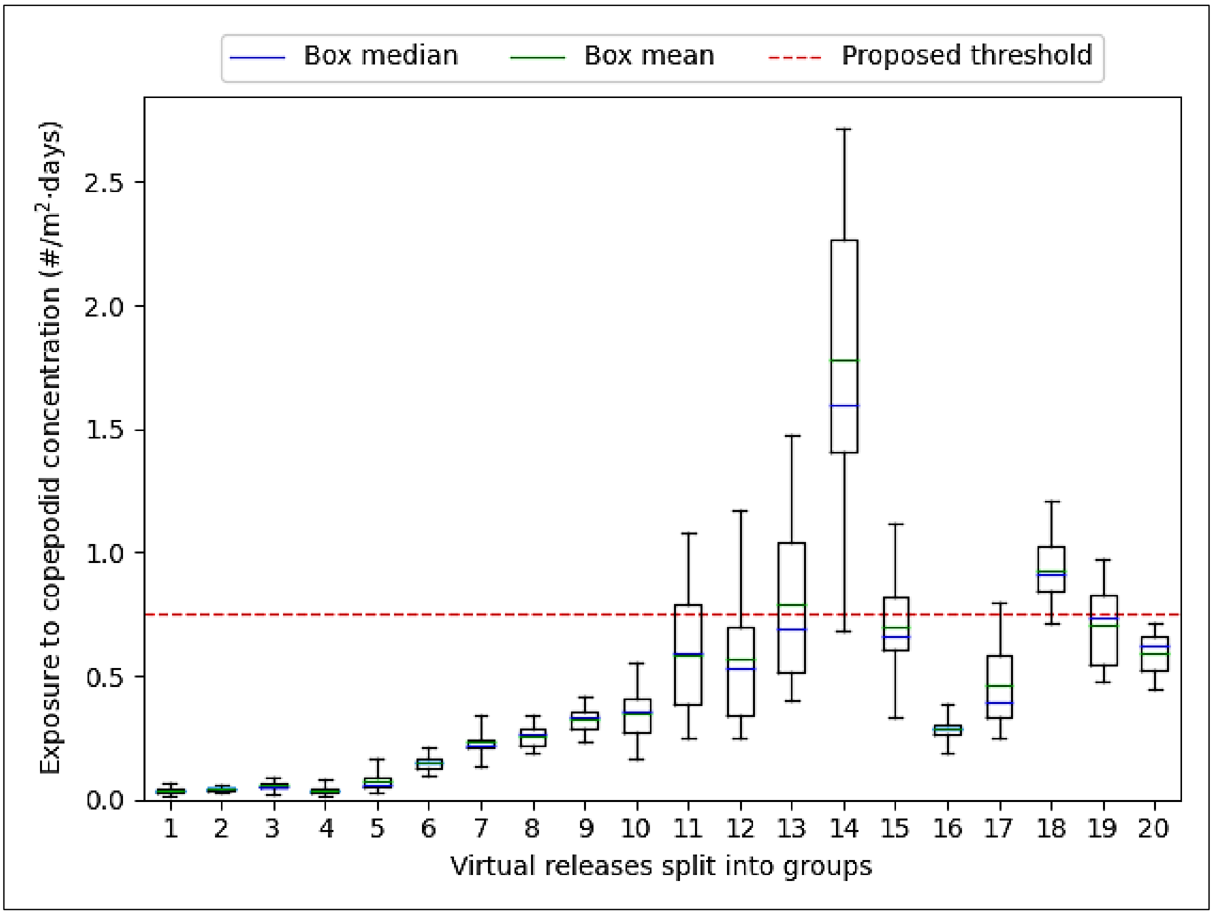

Figure 44 *Box-plot of exposure to infective-stage sea lice for the May 2020 Orkney swim path shown in Figure 29. An average value of **0.78** adult female lice per farmed salmon was employed.*

In comparison with the box-plot results of 0.5 lice per fish (Fig. 33), the new results of Fig. 44 show that the harmful exposure threshold of 0.75 copepodid per m^2-days [SEPA_2024] is predicted to be exceeded for a greater number of swim groups. This means that there is a likely higher risk of harmful lice infestation to the virtual post-smolts on these swim routes.

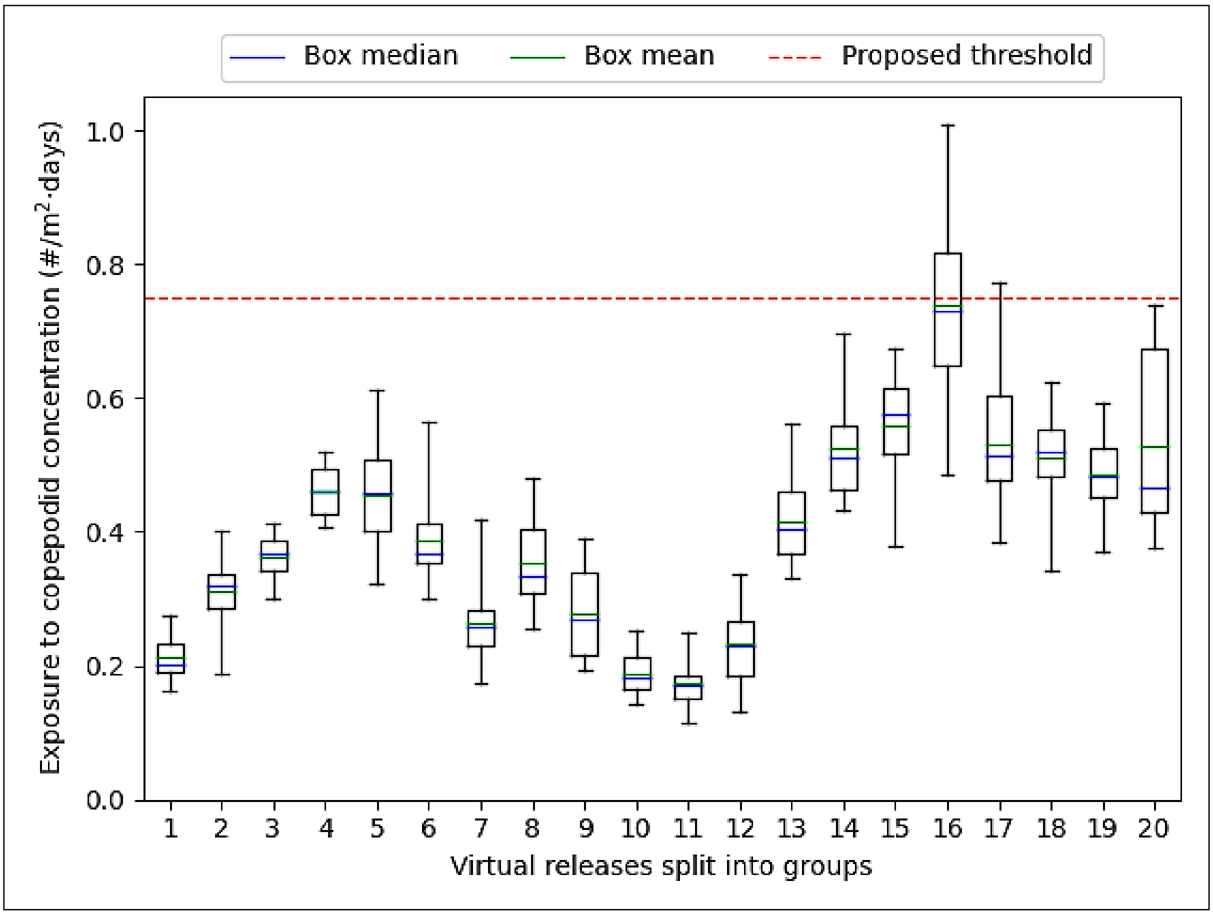

Figure 45 *Box-plot of exposure to infective-stage sea lice for the May 2020 Shetland swim path shown in Figure 30. An average value of* ***0.78*** *adult female lice per farmed salmon was employed.*

Compared with the box-plot results of 0.5 lice per fish (Fig. 34), the new results of Fig.45 show that the harmful exposure threshold of 0.75 copepodid per m^2-days [SEPA_2024] is now predicted to be exceeded for certain swim groups. This means that there is a likely higher risk of harmful lice infestation to the virtual post-smolts on these swim routes.

In addition to the box-plot cumulative exposure results, Figures 46 and 47 show the values of instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases.

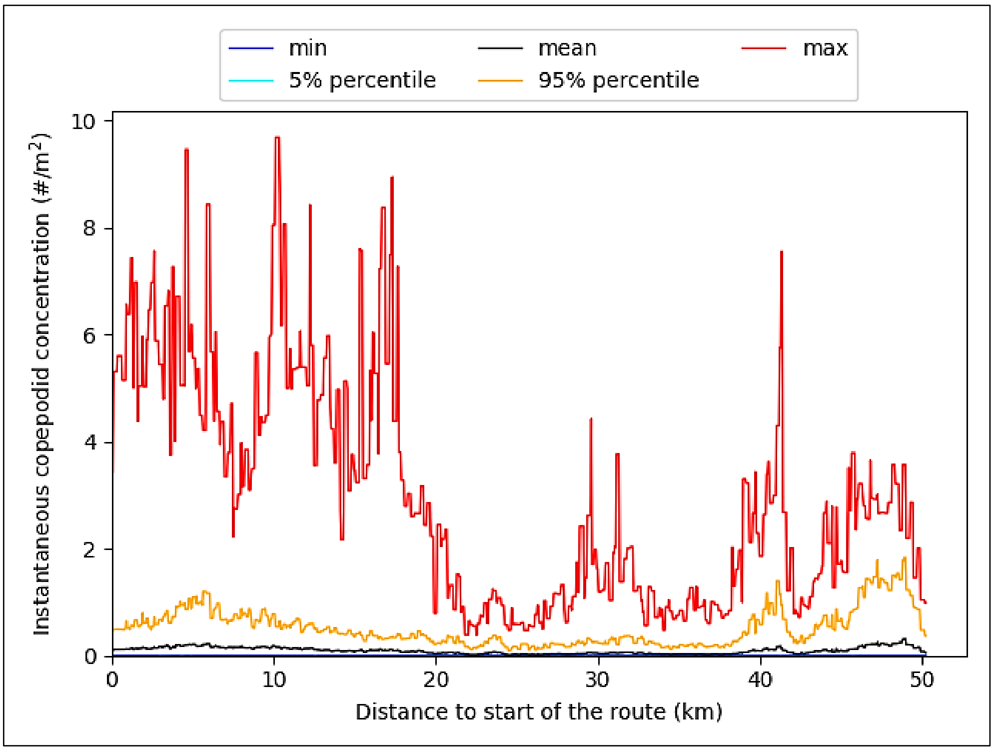

Figure 46 *Instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases, for the May 2020 Orkney swim path shown in Figure 29. An average value of **0.78** adult female lice per farmed salmon was employed.*

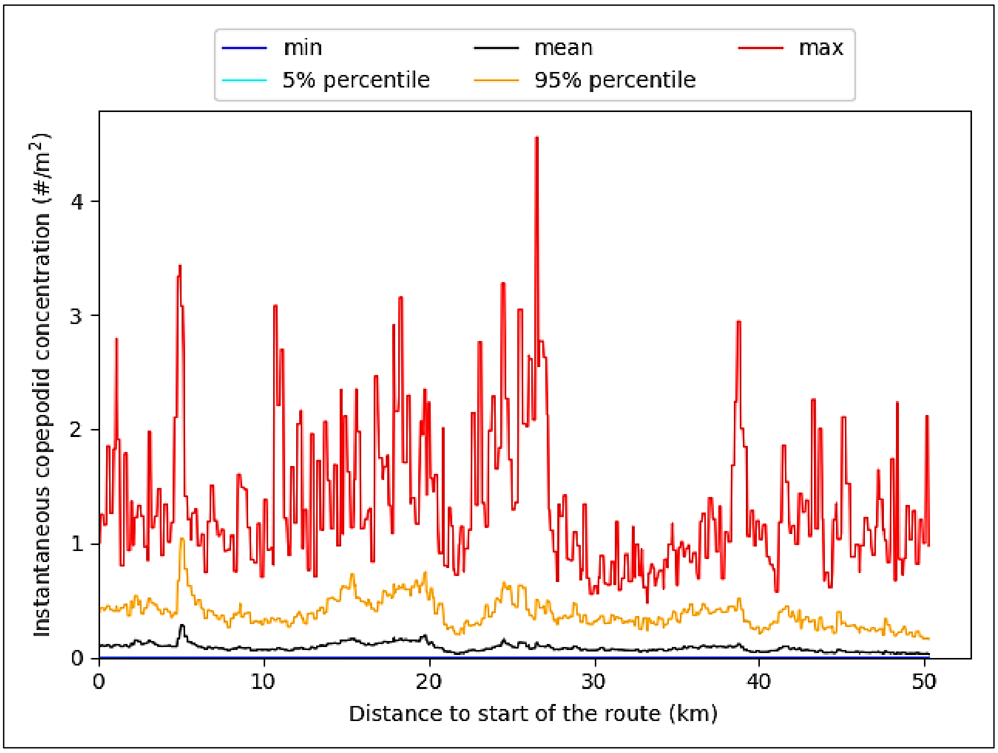

Figure 47 *Instantaneous copepodid concentration (#/m^2), averaged over all virtual post-smolt releases, for the May 2020 Shetland swim path shown in Figure 30. An average value of **0.78** adult female lice per farmed salmon was employed.*

The results show that instantaneous peak copepodid values approaching 10 cop/m^2 are possible (Fig. 46) and peak lice densities of at least 6 cop/m^2 may exist over a distance on the swim path of approximately 2 km (Fig. 46).

Finally, Figures 48 and 49 show the cumulative lice exposure results (#/m^2-days) against time for all virtual post-smolt releases. The results are colour-coded such that bluer shades correspond to earlier releases and redder shades to later ones. The virtual smolts take around 5.5 days to cover a distance of 60 km at 12.5 cm/s. A peak cumulative exposure concentration of approximately 2.7 cop/m^2-days was predicted for the May 2020 Orkney swim path shown in Fig.29 - (Fig. 48).

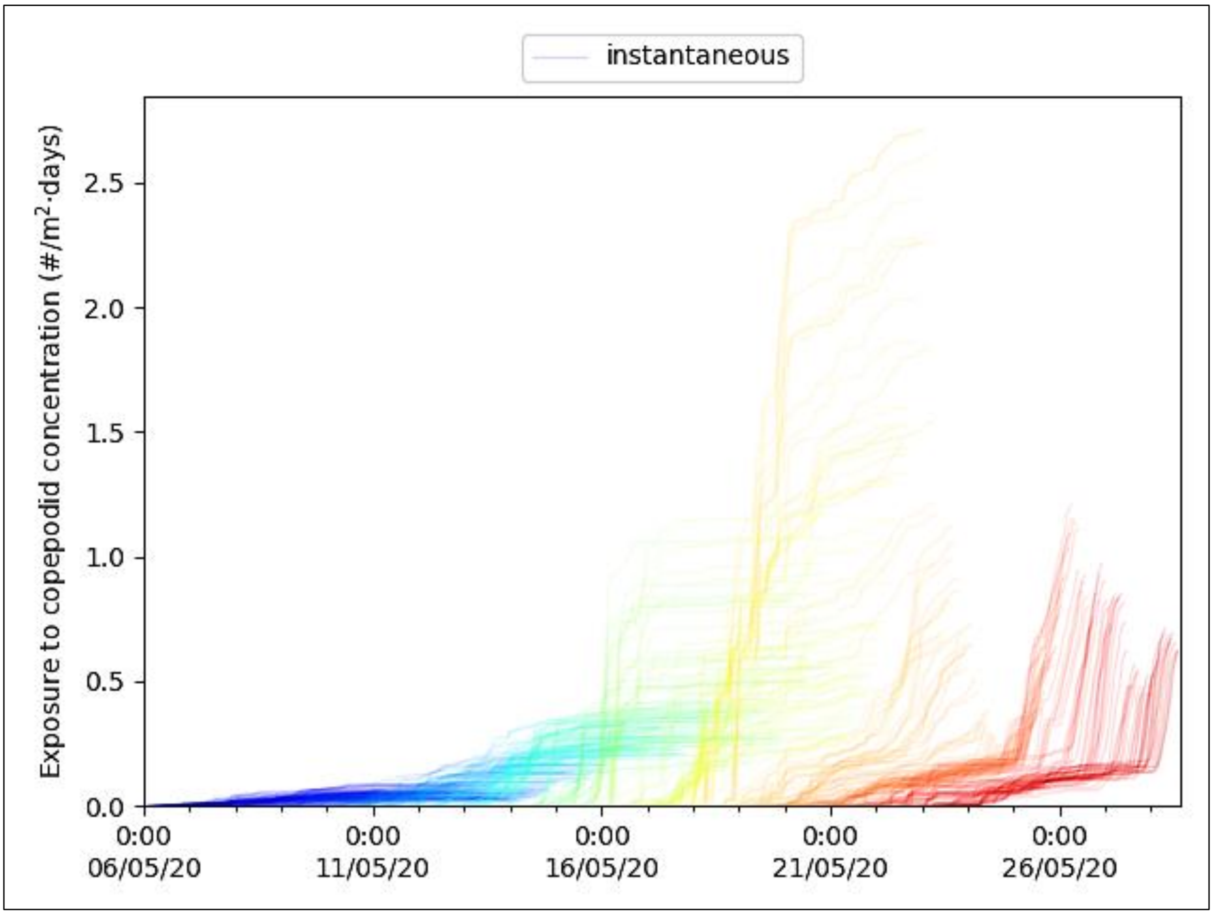

Figure 48 *Cumulative infective lice exposure (#/m^2-days) against time for all virtual post-smolt releases. May 2020 Orkney swim path shown in Figure 29. An average value of* ***0.78*** *adult female lice per farmed salmon was employed.*

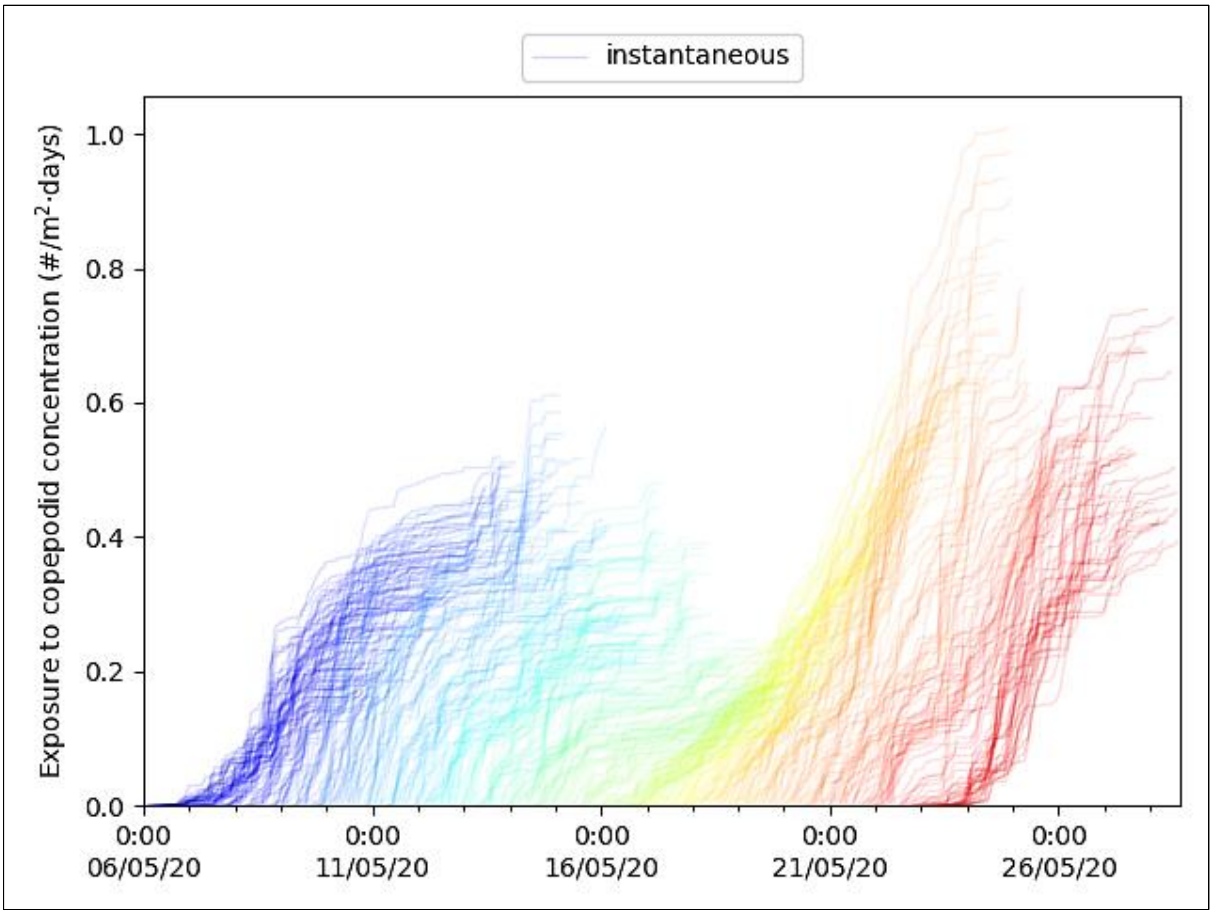

Figure 49 *Cumulative infective lice exposure (#/m^2-days) against time for all virtual post-smolt releases. May 2020 Shetland swim path shown in Figure 30. An average value of* ***0.78*** *adult female lice per farmed salmon was employed.*

4. Conclusions

A biological model of salmon lice (*Lepeophtheirus salmonis*) has been developed in order to assess the risk that wild salmon and sea trout will be harmed by lice emanating from salmon farms in the Northern Isles (26 farms on Orkney and 42 farms on Shetland). For the hydrodynamics, the years 2019 and 2020 were considered. In order to account for annual variations in the farmed salmon production cycle, up-to-date biomass conditions for the years 2023 and 2024 were employed.

Results for the lice model show that the main salmon lice concentrations on Shetland tend to remain localised close the coastal fringes while for Orkney there is evidence of enhanced dispersion over a wider area. Virtual probe results show that the highest instantaneous lice densities are predicted to occur in Shetland in the hydrodynamic period of May 2019 using biomass data from 2023 where levels of 2 cop/m^2 can persist over several days.

Snapshots of the instantaneous lice densities show how the salmon lice fields evolve with time and provide evidence of large-scale organised behaviour, often manifesting as long filaments of lice extending over many kilometres. For the extent of the southward copepodid distribution from the Orkney farms it is observed that the lice are channelled southwards from the Pentland Firth to occupy a large portion of the North Sea towards the Moray Firth.

Box-plots from a virtual post-smolt swimming model demonstrate that the harmful exposure threshold of 0.75 copepodid per m^2-days [SEPA_2024] is likely to be exceeded for certain swim groups. This suggests that there is a likely risk of harmful lice infestation to the virtual post-smolts on these swim routes. Sea trout do not migrate, spending months rather than days in the coastal waters around Shetland and Orkney, so they would be at much higher risk than indicated for migrating salmon, due to their longer exposure time.

Other results show that instantaneous peak copepodid values of 9 cop/m^2 are possible and peak lice densities of at least 6 cop/m^2 may persist over a distance on the virtual swim path of approximately 1 km. Finally, a peak cumulative exposure concentration of approximately 1.9 cop/m^2-days was observed for a virtual post-smolt swim route near Shetland.

Comparisons were made between results using the industry-standard value of 0.5 adult female lice per fish compared with the actual value of 0.78 lice per fish, measured across salmon farms on Orkney and Shetland for Q1/2 2024. The higher lice density per fish gives predictions that show a likely increase in the risk of infestation harm.

References

[Asplin_2020], Asplin, L. *et al.*, *The hydrodynamic foundation for salmon lice dispersion modelling along the Norwegian coast*, Ocean Dynamics, 2020 https://doi.org/10.1007/s10236-020-01378-0.

[G2G_2018], Bell *et al*., The MaRIUS-G2G datasets: Grid-to-Grid model estimates of flow and soil moisture for Great Britain using observed and climate model driving data. https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/gdj3.55.

[Johnsen_2020], Johnsen, I. A., Harvey, A., Sævik, P. N., Sandvik, A. D., Ugedal, O.,A˚ dlandsvik, B., Wennevik, V., Glover, K. A., and Karlsen, Ø. *Salmon lice induced mortality of Atlantic salmon during post-smolt migration in Norway.* – ICES Journal of Marine Science, 2020, doi:10.1093/icesjms/fsaa202.

[MTS_2024], *Orkney and Shetland Hydrodynamics Model Validation* – report produced for WildFish.org, March 2024.

[Myksvoll_A_2018], Mari S. Myksvoll, Lars Asplin, Anne D. Sandvik, Ingrid A. Johnsen, Bjørn Ådlandsvik, Jon Albretsen and Jofrid Skarđhamar, *Modelling salmon lice copepodids along the Norwegian coast – comparing old and new particle tracking models*, https://www.hi.no/resources/publikasjoner/rapport-fra-havforskningen/2018/39-2018_ladim.pdf - accessed 25th March 2024.

[Myskvoll_B_2018], Myksvoll MS, Sandvik AD, Albretsen J, Asplin L, Johnsen IA, Karlsen Ø, et al. (2018) *Evaluation of a national operational salmon lice monitoring system—From physics to fish.* PLoS ONE 13(7): e0201338. https://doi.org/10.1371/ journal.pone.0201338.

[Sandvik_2020], Sandvik, A. D. *et al.*, *Prediction of the salmon lice infestation pressure in a Norwegian fjord*, ICES Journal of Marine Science, Volume 77, Issue 2, March 2020, Pages 746–756, https://doi.org/10.1093/icesjms/fsz256

[ScotGov_2024], https://www.gov.scot/publications/summary-of-information-relating-to-impacts-of-salmon-lice-from-fish-farms-on-wild-scottish-sea-trout-and-salmon/ - accessed 25th March 2024.

[SEPA_2024] https://consultation.sepa.org.uk/regulatory-services/detailed-proposals-for-protecting-wild-salmon/ - accessed 25th March 2024.

[Skardhamar_2018], Jofrid Skarðhamar*, Jon Albretsen, Anne D. Sandvik, Vidar S. Lien, Mari S. Myksvoll, Ingrid A. Johnsen, Lars Asplin, Bjørn A˚dlandsvik, Elina Halttunen, and Pa˚l Arne Bjørn, *Modelled salmon lice dispersion and infestation patterns in a sub-arctic fjord*, ICES Journal of Marine Science (2018), 75(5), 1733–1747. doi:10.1093/icesjms/fsy035.

[SPILLS_2022], https://marine.gov.scot/information/salmon-parasite-interactions-linnhe-lorn-and-shuna-spills - accessed 25th March 2024.

[Stein_2005], Stein, A., Bjorn, P. A., Heuch, P. A. and Elston, D. A., *Population dynamics of salmon lice Lepeophtheirus salmonis on Atlantic salmon and sea trout*, April 2005, Marine Ecology Progress Series 290:263-275, doi:10.3354/meps290263.

[WildFish_2024], https://wildfish.org/ - private communication.