Modelling of Sea Lice Dispersion from Salmon Farms and Post-Smolt Exposure in the South Skye–Torridon Region, West Coast Scotland

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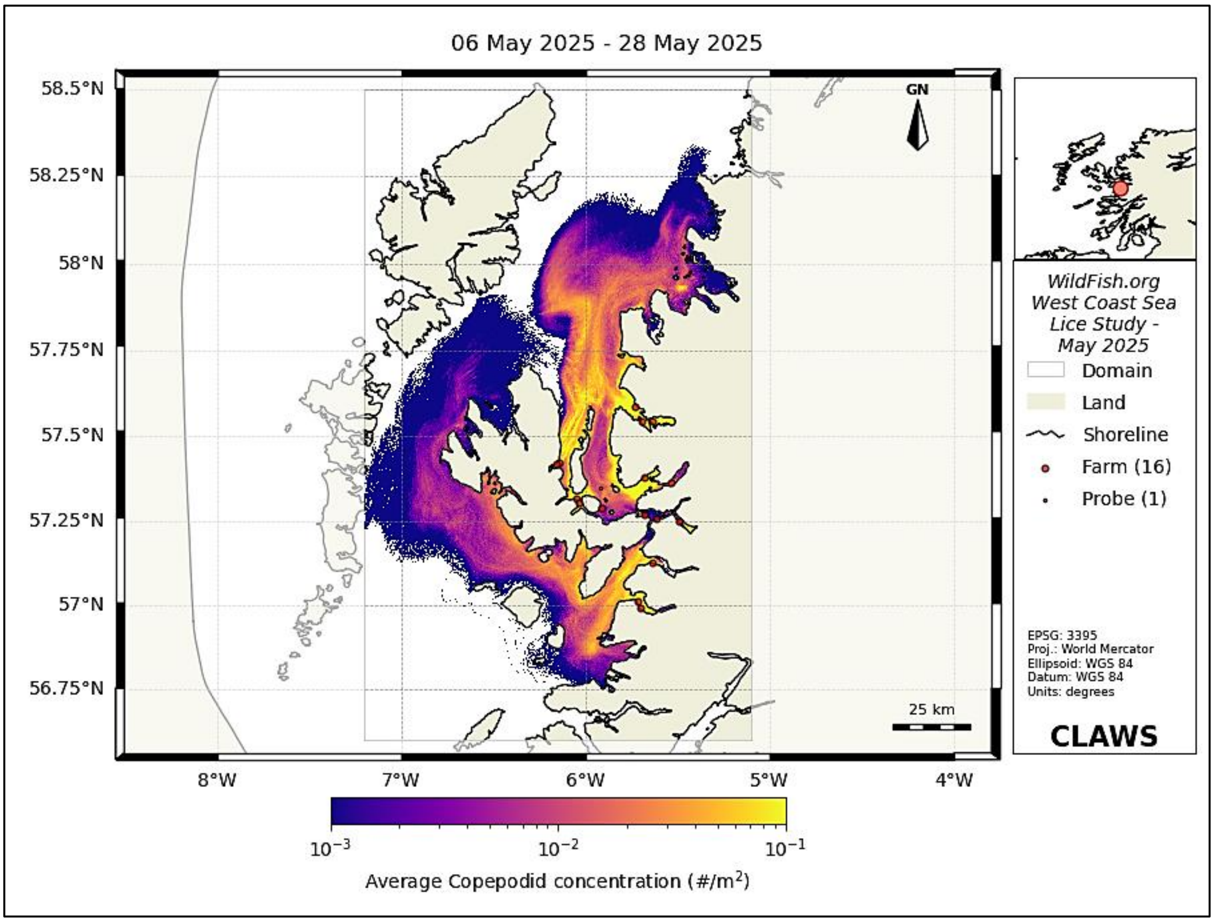

Key Findings

• Salmon lice released from farms in the South Skye–Torridon region can be transported tens of kilometres by tides and currents.

• The model shows that lice from multiple farms can accumulate along migration routes used by wild salmon smolts.

• Sea-lice risk is influenced by the combined effect of farms across a connected coastal region, rather than by individual farms in isolation.

• Under some conditions, modelled post-smolt exposure exceeds the screening threshold currently used within the Scottish regulatory framework.

• Exposure levels increase substantially under the SEPA precautionary biomass scaling scenario (1.75 × biomass).

• Sea trout may experience greater exposure than salmon because they remain in coastal waters for much longer periods.

• The modelling indicates that lice dispersal extends well beyond individual sea lochs, linking Loch Nevis, Loch Hourn, Loch Alsh, the Inner Sound and adjacent coastal waters.

• Results from five representative river routes showed that exposure can occur along multiple migration pathways and varies according to migration timing and location.

Executive Summary

This study presents an assessment of potential exposure of wild Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*) to salmon lice (*Lepeophtheirus salmonis*) within the South Skye–Torridon coastal system on the west coast of Scotland. The study area includes Loch Nevis, Loch Hourn, Loch Alsh, Kyle Rhea and the Inner Sound, representing a hydrodynamically complex fjordic environment that supports both aquaculture activity and migratory pathways for wild salmonids.

The assessment is based on a biophysical modelling framework combining a validated three-dimensional hydrodynamic model [MTS_CFD_2026] with a Lagrangian particle tracking model [CLAWS_2026] to simulate the dispersal and development of infective-stage salmon lice. The CLAWS modelling system acts as a higher-level workflow framework built around the OpenDrift [OpenDrift_2026] particle tracking model, where OpenDrift performs the core Lagrangian particle transport calculations while CLAWS manages simulation setup, biological parameterisation, environmental input processing, execution control and post-processing analysis.

The hydrodynamic model resolves tidal and density-driven circulation, providing a realistic representation of transport pathways across the region. Salmon lice are represented as particles released from farm locations and advected through the model domain, with biological processes applied in a manner consistent with established lice swimming and dispersal modelling approaches [LADIM_2020].

The modelling has been configured to align with the SEPA sea-lice screening framework, including adoption of the key assumptions set out in [SEPA_A_2026]. This includes representation of lice within the upper 10 m of the water column, application of diffusion coefficients equivalent to SEPA values, and use of screening-level biological parameterisation. Farm inputs and biomass assumptions are also consistent with SEPA practice, including application of a 1.75 biomass scaling factor. This ensures that results are directly comparable with regulatory screening outputs while incorporating a site-specific hydrodynamic representation.

To assess potential biological impact, a representative post-smolt migration route was defined extending from Loch Nevis through the Kyle Rhea–Loch Alsh system and northward through the Inner Sound into adjacent coastal waters. A virtual post-smolt modelling approach, consistent with SEPA methodology, was applied to quantify cumulative exposure to infective-stage lice along this route. To assess the sensitivity of the results to migration behaviour, additional virtual migration routes originating from the Rivers Shiel, Elchaig, Carron, Torridon and Sligachan were also evaluated. These route-specific results are presented in Appendix A. These routes represent plausible migration pathways through the wider South Skye–Torridon coastal system, recognising that actual migration behaviour may vary between river systems and individual fish.

The modelling results indicate that the South Skye–Torridon system functions as a hydrodynamically connected coastal network, enabling salmon lice to be transported between sea lochs and along the coastline over distances of tens of kilometres. Lice distributions are spatially structured and time-variable, reflecting tidal dynamics, bathymetric constraints and local retention processes. As a consequence, exposure is not uniform but is

concentrated along key transport pathways, including tidal constrictions, coastal channels and areas of enhanced exchange between adjacent water bodies.

The modelled migration routes intersect several of these hydrodynamically active zones, such that lice originating from multiple farm sites may be encountered sequentially along the migration pathways. Results from all assessed river systems indicate that exposure is influenced by the cumulative contribution of multiple farms operating within a hydrodynamically connected coastal network rather than by individual sites in isolation. Although exposure levels varied between routes, the overall pattern of cumulative exposure arising from regional-scale connectivity was consistent across the study area.

When assessed against the SEPA screening threshold of 0.7 copepodids $m^{-2} \cdot$days, the results indicate that threshold-relevant exposure is plausible under certain conditions, particularly where transport pathways from multiple sites converge. Exposure levels increased substantially under the precautionary 1.75 × biomass scenarios, with more frequent exceedance of the screening criterion observed across multiple migration routes.

The modelled post-smolt exposure represents a transient, screening-level estimate of exposure during migration through the study area. The virtual post-smolt model assumes continuous migration at a constant swimming speed along predefined routes and therefore represents a lower-bound estimate of potential exposure duration. Acoustic telemetry studies have demonstrated that post-smolt migration through estuarine and coastal environments may involve tidal transport, temporary residency and variable migration rates [Moore_1998; Thorstad_2012], potentially increasing exposure duration relative to that represented in simplified migration models. In contrast, sea trout do not migrate beyond coastal waters and may remain within nearshore environments for weeks or months, potentially resulting in substantially greater cumulative exposure to infective-stage lice.

Overall, the findings demonstrate that hydrographic connectivity is a primary control on lice dispersion and exposure within the South Skye–Torridon system, and that regional-scale interactions between multiple farm sites are an important factor in determining potential risk to wild salmonids. The modelling further demonstrates that salmon lice released within the study area may be transported well beyond individual sea lochs, linking Loch Nevis, Loch Hourn, Loch Alsh, Loch Carron, Loch Torridon, the Inner Sound and adjacent coastal waters. The results provide a SEPA-aligned, screening-level evidence base to inform cumulative impact assessment and regional management considerations.

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_2026, SEPA_B_2026]. In order to assess the risk that wild salmon and sea trout will be harmed by operational farms in the south Skye-Torridon system, WildFish has commissioned the development of a detailed hydrodynamic and biological model of the area. The model simulates water levels and flows (i.e., tides and currents), which govern the transport of salmon lice emanating from the fish farms - see [MTS_2026] for further details of the hydrographic model. All operational farms in the South Skye-Torridon area are included in the lice model using up-to-date biomass conditions (2024-25). In addition, a biomass scaling factor of 1.75 was applied in accordance with the SEPA sea lice screening framework [SEPA_A_2026], which uses this multiplier to account for operational variability in production, including factors such as stocking practices, early harvest and mortality during the production cycle, thereby providing a precautionary representation of potential lice output from each site. There were 16 farms in total 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_A_2026] 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_2026] has been adopted, where the biological effects of salmon lice production, maturity and mortality were included. Lice swimming behaviour was included in the model, following the established LaDIM approach [e.g. Myksvoll_A_2018, Myksvoll_B_2018, Sandvyk_2020] .The particles were restricted to exist in the top 10 m of the water column following the SEPA screening methodology [SEPA_A_2026].

The flow conditions (sea currents) driving the lice particles come from a validated hydrographic model that has been detailed elsewhere [MTS_2026] 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 [e.g. Johnsen_2020, ScotGov_2026, SEPA_A_2026]. 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 within the south Skye-Torridon system, so salmon lice densities averaged over two or more months do not best represent the risk they face. In this report the model outputs are presented in three ways, to demonstrate how the salmon lice density and therefore the apparent risk vary:

1. Infective lice (copepodid) densities averaged over a 24-day period in May, shown as a heat map.

2. 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.
3. A virtual post-smolt swimming model (VPSM) to predict the cumulative 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 beyond coastal waters and may remain within nearshore environments for weeks or months. They can return to freshwater to rid themselves of sea lice when heavily infested, but not without a physiological cost to the fish. Consequently, they are likely to be exposed to infective-stage salmon lice for substantially longer periods than migrating salmon post-smolts, potentially resulting in greater cumulative exposure.

2 Biomass Data and Farm Locations

Farm biomass data used in the modelling are presented in Table 1. Biomass values for May 2024 and May 2025 have been included in order to represent inter-annual variability in production levels during the salmon farming cycle. In addition to the reported biomass values, a precautionary biomass scaling factor of 1.75 was applied in accordance with the SEPA sea-lice screening framework. This scaling accounts for operational variability in production, including factors such as stocking practices, mortality and harvesting during the production cycle, and provides a precautionary representation of potential lice production. A total of 16 operational farm sites within the South Skye–Torridon system were incorporated into the model.

The geographical distribution of the farm sites is shown in Figure 1. The sites extend from Loch Nevis and Loch Hourn in the south through Loch Alsh, Loch Duich, Loch Carron and the Inner Sound to Torridon, Portree and adjacent waters to the north. This distribution spans a hydrodynamically connected coastal system in which tidal and residual circulation provide pathways for transport of salmon lice between individual sea lochs and coastal channels.

Table 1. Salmon Farm Sites and Biomass Inputs (2024–2025): *Biomass values (tonnes) represent site-specific inputs for May 2024 and May 2025. Scaled biomass (×1.75) follows SEPA screening guidance to account for operational variability in production, including stocking practices, mortality and harvesting during the production cycle.*

Farm	Owner	Location	Site no	Easting	Northing	Bio 5/24	Bio 5/25	Bio 5/24 ×1.75	Bio 5/25 ×1.75
NevisA Earnsaig	SSF	L Nevis	FS0430	174200	797000	1129	295	1976	516
NevisB Stoull	SSF	L Nevis	FS0616	174800	795200	806	865	1411	1513

Farm	Owner	Location	Site no	Easting	Northing	Bio 5/24	Bio 5/25	Bio 5/24 ×1.75	Bio 5/25 ×1.75
Creag an T'Sagairt	Mowi	L Hourn	FS0013	184000	810400	205	2356	359	4123
L Duich	Mowi	L Duich	FS0248	189300	823100	1581	127	2767	222
Ardintoul	Mowi	L Alsh	FS0245	182400	824400	2497	390	4370	682
L Alsh (Sron)	Mowi	L Alsh	FS0016	178500	825500	1984	824	3472	1442
W Strome	Bakkafrost	L Carron	FS1342	187300	836000	0	1107	0	1937
Kishorn West	SSF	L Kishorn	FS1274	176700	836100	0	782	0	1368
Aird	Bakkafrost	L Torridon	FS0594	178900	856000	562	847	984	1482
Torridon	Mowi	L Torridon	FS0234	182300	855900	1917	1689	3355	2955
Sgeir Dughall	Bakkafrost	L Torridon	FS1262	177000	861000	0	1440	0	2520
Sconser Quarry	Mowi	Sconser	FS1330	156200	832100	1498	839	2622	1468
Maol Ban	Mowi	Sconser	FS0519	156300	831100	483	585	845	1023
Scalpay	Mowi	Scalpay	FS1338	164100	828700	186	2468	326	4319
Portree Outer	Bakkafrost	Portree	FS1318	151100	844600	0	510	0	892
Portree	Bakkafrost	Portree	FS0708	150500	844100	0	714	0	1249
TOTAL						**12848**	**15838**	**22483**	**27716**

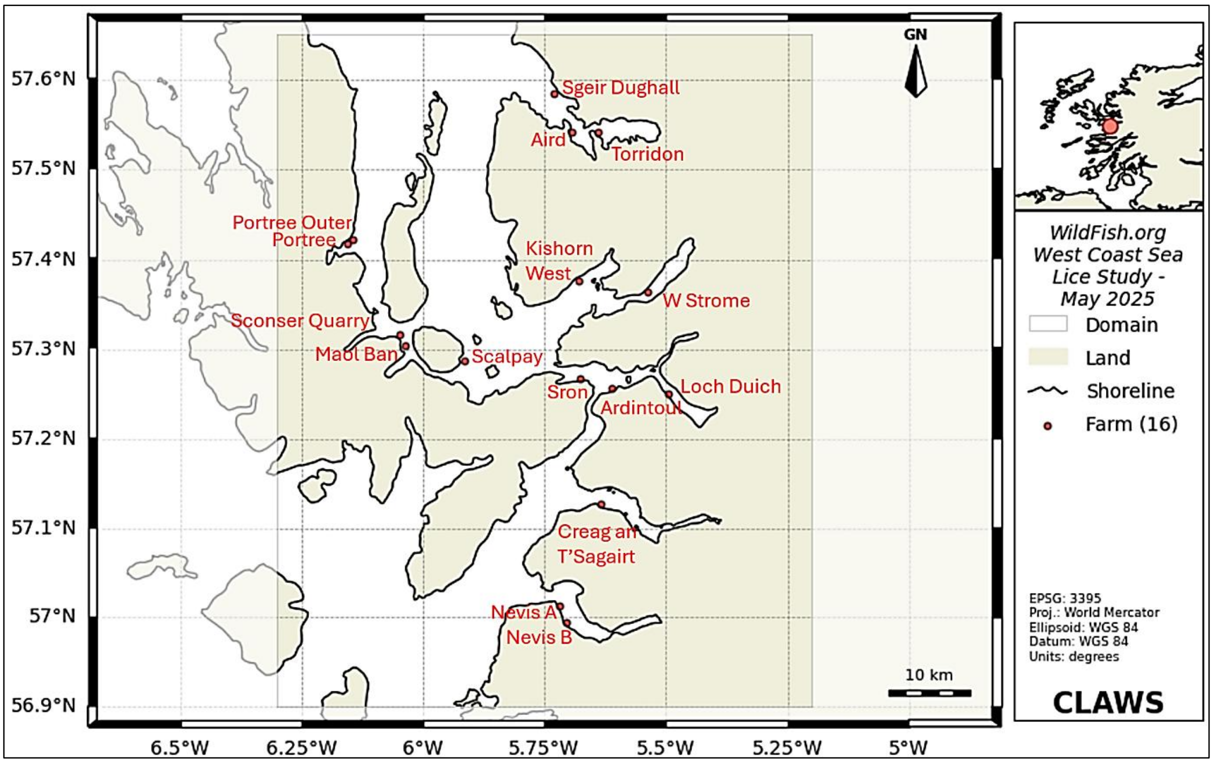

Figure 1 *Location of the 16 operational salmon farm sites included in the South Skye–Torridon sea-lice modelling study (red circles). Farm locations span Loch Nevis, Loch Hourn, Loch Alsh, Loch Duich, Loch Carron, the Inner Sound, Torridon, Portree and surrounding coastal waters.*

3. Lagrangian Advection and Diffusion Modelling (LADiM) Approach

3.1 Overview of the LADiM Framework

The dispersal of salmon lice within the study area has been simulated using a Lagrangian Advection and Diffusion Modelling (LADiM-type) approach, consistent with methodologies widely applied in operational lice modelling systems in Norway [e.g. Myksvoll_A_2018, Myksvoll_B_2018, Sandvyk_2020].

Within this framework, salmon lice are represented as discrete Lagrangian particles, each corresponding to a "*super-individual*" representing a cohort of larvae released from a given farm site. Particle trajectories are computed by combining:

- **Advection** by three-dimensional hydrodynamic currents
- **Turbulent diffusion** representing unresolved mixing processes
- **Behavioural responses**, primarily in the vertical dimension

The hydrodynamic forcing is provided by a validated TELEMAC-3D model, ensuring that transport pathways reflect the physical circulation of the south Skye–Torridon coastal system. This approach enables simulation of both local retention processes within fjordic environments and regional-scale transport between connected lochs and coastal corridors.

3.2 Consistency with SEPA Screening Methodology

The LADiM-type implementation adopted in this study has been configured to align with the SEPA sea lice screening framework, including the parameters outlined in Table C1 of the SEPA guidance [SEPA_A_2026]. In particular:

- Particles are transported using 3D velocity fields with random-walk diffusion
- Diffusivity coefficients are consistent with SEPA assumptions:
  - Horizontal: 0.1 m^2/s
  - Vertical: 0.001 m^2/s
- Particles are constrained to the upper water column (top ~10 m)
- Biological processes (development, mortality and infectivity) follow SEPA-defined timescales

This ensures that model outputs are directly comparable with SEPA screening assessments, while incorporating a site-specific hydrodynamic representation.

3.3 Particle Release and Transport Processes

In accordance with SEPA methodology, lice particles are released from each farm site into the hydrodynamic flow field at 5-minute intervals at random locations within a volume of radius 19 m and depth of 3 m. There were approximately 1.2 million particles in the system at steady-state conditions.

Particle motion is governed by:

Advection

Particles are transported by the resolved 3D velocity field, capturing tidal currents, density-driven circulation and wind-driven flow.

Diffusion

Sub-grid scale mixing is represented using a random walk formulation, with diffusivity coefficients aligned with SEPA screening values. This ensures realistic lateral and vertical spreading of lice particles within the water column.

3.4 Behavioural Representation (LADiM-Type)

While screening-level approaches often simplify behaviour, the present model incorporates key processes consistent with LADiM-type formulations, particularly:

Light-Driven Behaviour (Phototaxis)

Salmon lice exhibit positive phototaxis, migrating towards light. This behaviour is represented in the model through:

- Activation of light sensing
- A characteristic wavelength of 500 nm (green-blue light penetration in seawater)

- Exponential attenuation of light with depth (decay constant ≈ 0.2 m^{-1})
- Threshold light levels for behavioural response:
    - Nauplii: very low threshold
    - Copepodids: higher threshold reflecting stronger behavioural response

This formulation results in near-surface aggregation during daylight conditions, increasing the likelihood of host encounter.

Salinity Avoidance Behaviour

Salmon lice are sensitive to reduced salinity and tend to avoid freshwater-influenced surface layers. This is represented through:

- A low salinity avoidance threshold (~31 PSU)
- A sinking threshold (~23 PSU) triggering downward movement

This behaviour is particularly relevant in fjordic systems such as Loch Nevis and Loch Hourn, where freshwater inputs may influence vertical distribution. The combined effect of salinity avoidance and phototaxis leads to dynamic vertical positioning within the upper water column.

Vertical Range Constraint

Particles are restricted to a natural swimming range of 10 m, consistent with SEPA screening assumptions. This ensures that lice remain within the biologically relevant surface layer while still allowing vertical redistribution due to environmental forcing.

3.5 Biological Development and Infectivity

The model incorporates a simplified but SEPA-consistent representation of lice life-cycle processes:

Maturation (Copepodid Development)

- Lice become infective after approximately 3.6 days post-release
- This corresponds to transition into the copepodid stage, during which host infection can occur
- Development rate is temperature-dependent, with values consistent with SEPA assumptions (≈10°C reference)

Infective Window

- Lice remain infective between approximately 3.6 and 17 days of age
- This defines the period during which particles contribute to exposure metrics

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Mortality

- A daily mortality rate of 17% is applied to particles
- This is implemented as an exponential decay in particle “mass” (or weighting)
- An upper limit based on degree-days (~200 degree-days) ensures consistency with temperature-dependent mortality formulations

This approach ensures that only biologically viable lice contribute to predicted exposure levels.

3.6 Lice Production and Farm Inputs

Lice production is parameterised following SEPA screening assumptions:

- A standardised value of 0.4 adult female lice per fish is applied
- Fish numbers were derived from the recorded biomass assuming an average harvest weight of 5 kg per fish. The use of a 5 kg harvest weight is consistent with the SEPA screening methodology. In practice, average fish weights present on farms during the production cycle are likely to be lower than harvest weight, implying a greater number of fish for a given biomass and potentially a higher abundance of adult female lice than estimated under this simplifying assumption.
- Each female produces 30 nauplii per day
- Fish numbers are derived from recorded biomass, scaled by a factor of 1.75, consistent with SEPA guidance [SEPA_A_2026] and [Moriarty_2023], to account for:
    - Overstocking practices
    - Mortality during production
    - Early harvesting

This results in a precautionary estimate of lice output from each farm site.

3.7 Exposure Modelling (Link to VPSM)

The output from the LADiM particle tracking model provides time-varying fields of infective copepodid concentration, which are subsequently used as input to the Virtual Post-Smolt Model (VPSM).

In this framework:

- Virtual fish move through the domain at a constant speed of 12.5 cm/s (~1 body length per second)
- Multiple release times and pathways may be considered
- Exposure is calculated as time-integrated, cumulative copepodid concentration (lice m^{-2}·days)
- Results are evaluated using the 95th percentile exposure, consistent with SEPA methodology
- An exposure threshold of 0.7 lice m^{-2}·days is applied to assess relative risk

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3.8 Summary

The LADiM-type modelling approach adopted in this study provides a physically and biologically consistent framework for simulating salmon lice dispersion within a complex coastal environment. By combining:

- Validated hydrodynamics
- SEPA-aligned diffusion and biological processes
- Behavioural responses to light and salinity

the model captures the key mechanisms governing transport, retention and exposure of lice within the south Skye–Torridon system.

The resulting outputs provide a robust basis for assessing connectivity, cumulative effects and exposure risk, consistent with current regulatory and scientific best practice.

4 Sea-Lice Exposure Assessment Along the Post-Smolt Migration Route

A series of sea-lice exposure simulations were undertaken using the validated hydrodynamic framework for the West Coast of Scotland study area for May 2024 and May 2025. The assessment considered both:

- the reported/actual farm biomass scenario; and
- a sensitivity scenario corresponding to 1.75 times the reported biomass, consistent with precautionary screening-type scaling approaches used within the SEPA sea-lice risk assessment framework.

May was selected as the principal assessment period because it coincides with the peak seaward migration of Atlantic salmon post-smolts across much of western Scotland. During this period, large numbers of recently migrated fish transition through coastal waters while salmon lice development rates are increasing with rising spring temperatures, making May a particularly important period for sea-lice risk assessment.

The exposure assessment was undertaken using virtual post-smolts travelling along an approximately 120 km migration corridor extending from the inner Loch Nevis region west coastward through the interconnected coastal channels of the Inner Sound and adjacent Hebridean waters before progressing northward offshore. The migration pathway is shown in Figure 2 and was designed to represent a plausible regional post-smolt migration route through the hydrodynamically connected coastal system. Additional virtual post-smolt migration routes originating from the Rivers Carron, Elchaig, Shiel, Sligachan and Torridon were also evaluated to assess the sensitivity of exposure predictions to migration pathway selection. Results for these route-specific assessments are presented in Appendix A.

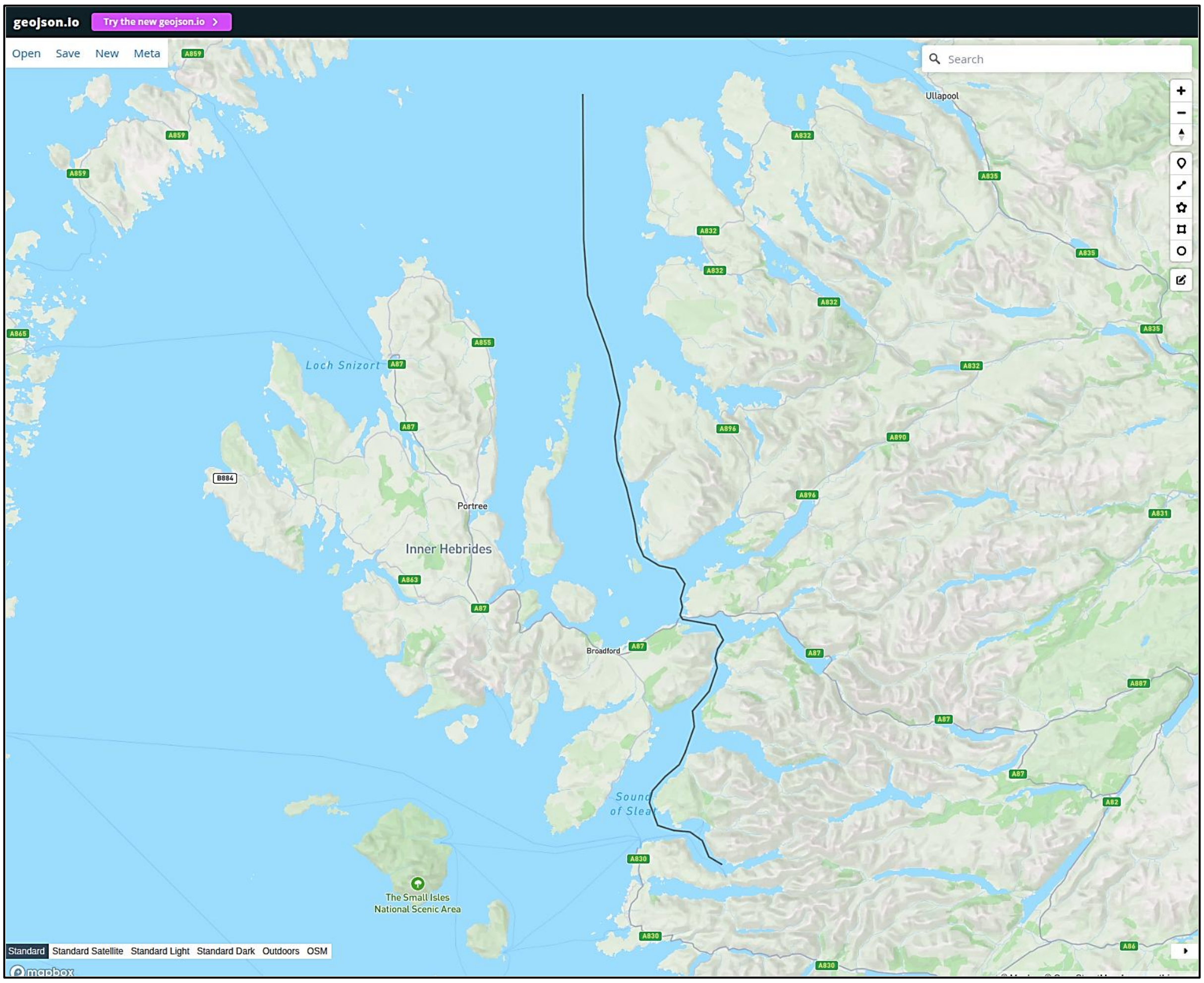

Figure 2 *Pathway for virtual post smolt migration shown as black line (120 km length).*

The route traverses multiple areas influenced by aquaculture-derived copepodid dispersal, including regions of enhanced tidal exchange and channelised flow between the mainland coast, Skye and the Inner Hebrides. Although a fixed migration pathway was adopted for modelling purposes, acoustic telemetry studies indicate that real post-smolts may exhibit variable migration rates, tidal transport and temporary residency within coastal waters [Moore_1998; Thorstad_2012]. The West Coast Tracking Project has similarly demonstrated substantial variability in migration pathways and marine movements of post-smolts originating from west coast river systems [Rodger_2024; WCTP_2024]. Consequently, the simulated route should be regarded as a representative migration pathway rather than a unique migration corridor, and the resulting exposure estimates as screening-level, lower-bound estimates of potential exposure duration.

Virtual post-smolts were assigned a swimming speed of 12.5 cm/s and cumulative exposure was calculated through interaction with the instantaneous copepodid concentration fields generated by the CLAWS sea-lice dispersion model.

To capture temporal variability in the copepodid field, virtual post-smolts were released at a frequency of one release per hour throughout the simulation period. For the May 2025 assessment, for example, releases commenced on 6 May 2025 following establishment of the copepodid field within the domain.

The coloured cumulative exposure curves shown in the exposure plots represent the individual virtual post-smolt trajectories and associated cumulative exposure histories. The colour progression from blue through to red corresponds to progressively later release times during the simulation period.

Exposure was evaluated against the proposed SEPA screening threshold of 0.7 copepodids·m^{-2}·days, which is shown as the dashed reference line on the figures.

For clarity of interpretation, the large number of individual virtual post-smolt simulations were grouped into 20 evenly populated release groups for presentation within the boxplot figures. Each group contains an equal number of virtual post-smolt particles that successfully completed the full 120 km migration route. The boxplots therefore represent the statistical distribution of cumulative exposure values within each grouped subset of successful migrations. This grouping approach was adopted to provide a clear and statistically meaningful summary of the large number of hourly release simulations whilst retaining the temporal variability associated with differing release times and evolving copepodid field conditions.

Within the boxplots:

- the blue line represents the median exposure;
- the green line represents the mean exposure;
- the box bounds represent the interquartile range;
- the whiskers represent the 5th and 95th percentiles; and
- the dashed red line represents the proposed SEPA screening threshold of 0.7 copepodids·m^{-2}·days.

In accordance with the SEPA screening methodology, exposure risk is interpreted primarily relative to the 95th percentile exposure level. Consequently, exceedance of the threshold by the upper whisker indicates that a proportion of the simulated virtual post-smolt population experienced exposure conditions above the proposed screening criterion during the simulation period.

4.1 May 2024 – Actual Biomass Scenario

The May 2024 actual biomass scenario indicates substantial spatial variability in copepodid concentrations across the study domain. Elevated average concentrations (Figure 3) were principally associated with Loch Nevis, Loch Hourn, the Kyle Rhea, Loch Alsh, the Inner Sound, Raasay/Skye channels, Loch Carron, Loch Torridon and near-field farm regions, with lower concentrations offshore and within more open coastal waters.

The cumulative exposure curves (Figure 4) indicate that exposure generally increased progressively along the migration route as virtual post-smolts traversed multiple interconnected lice plumes. Earlier releases (blue colours) generally experienced lower cumulative exposure than some of the later releases (yellow to red colours), reflecting temporal variability in copepodid production, transport and retention within the hydrodynamic system.

The grouped boxplot analysis (Figure 5) demonstrates that:

- median exposures for most groups remained below the 0.7 copepodids·m⁻²·days threshold;
- however, several groups approached or marginally exceeded the threshold at the upper percentile range; and
- the 95th percentile whiskers exceeded the SEPA threshold in a limited number of grouped cases.

Under the SEPA screening framework, exceedance of the 95th percentile relative to the proposed threshold is indicative of periods where elevated exposure risk may occur for a proportion of migrating post-smolts. The results therefore indicate that while typical exposures during May 2024 were generally below the screening criterion, intermittent higher-risk exposure conditions were identified during parts of the simulation period.

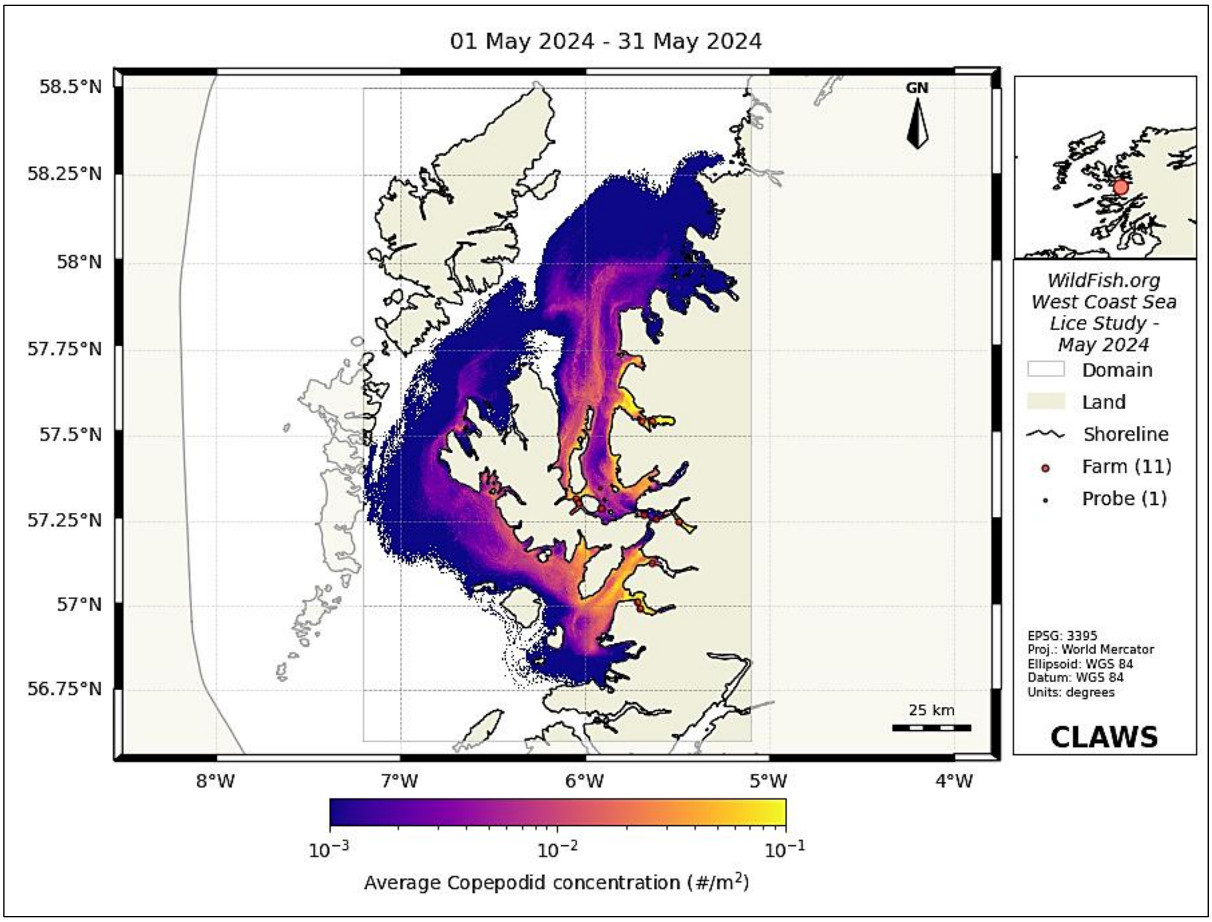

Figure 3 *Average copepodid concentration (#/m^2) across the south Skye-Torridon corridor based on actual biomass for May 2024.*

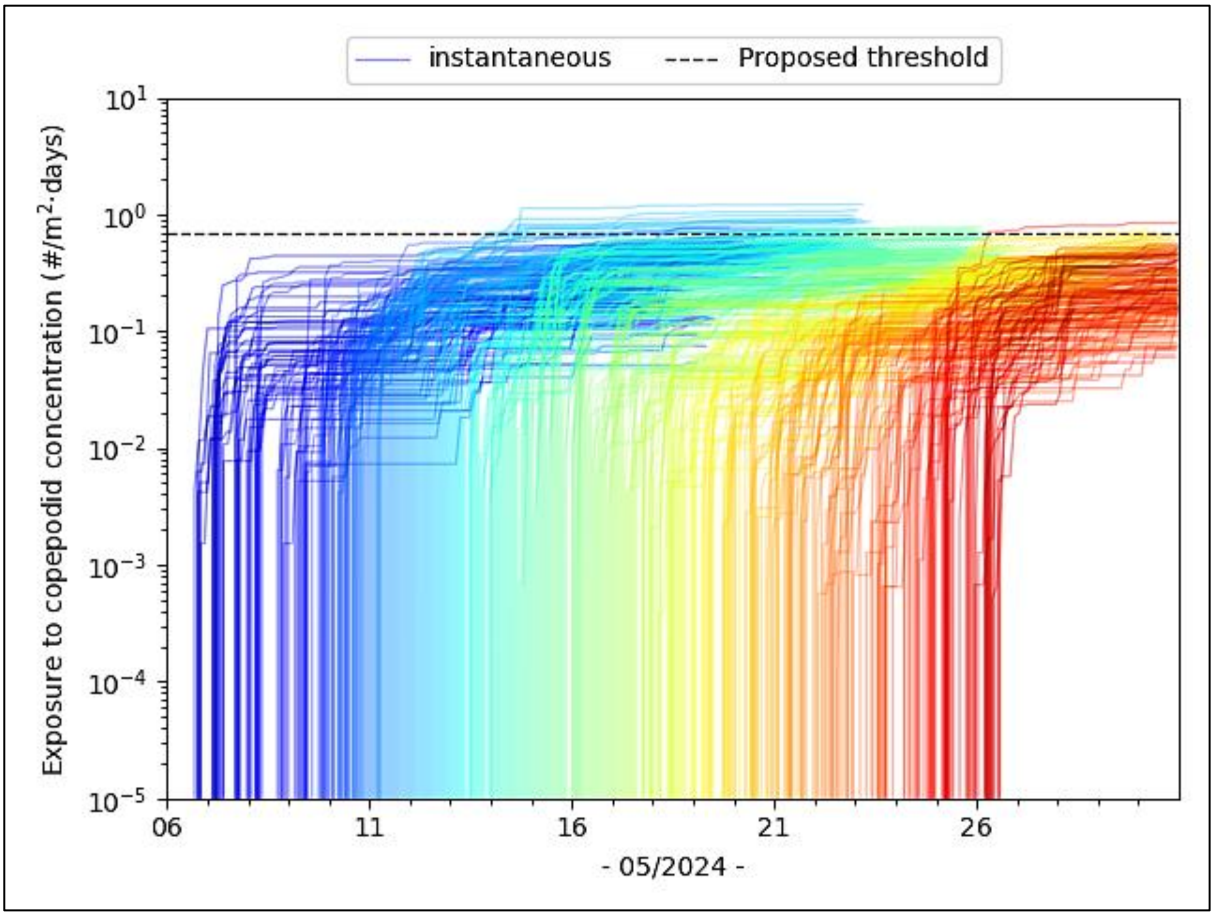

Figure 4 *Cumulative copepodid concentration exposure curves (#/m^2-days) along migration pathway for May 2024 based on actual biomass. Colour blue-to-red signifies early-to-late virtual smolt start time.*

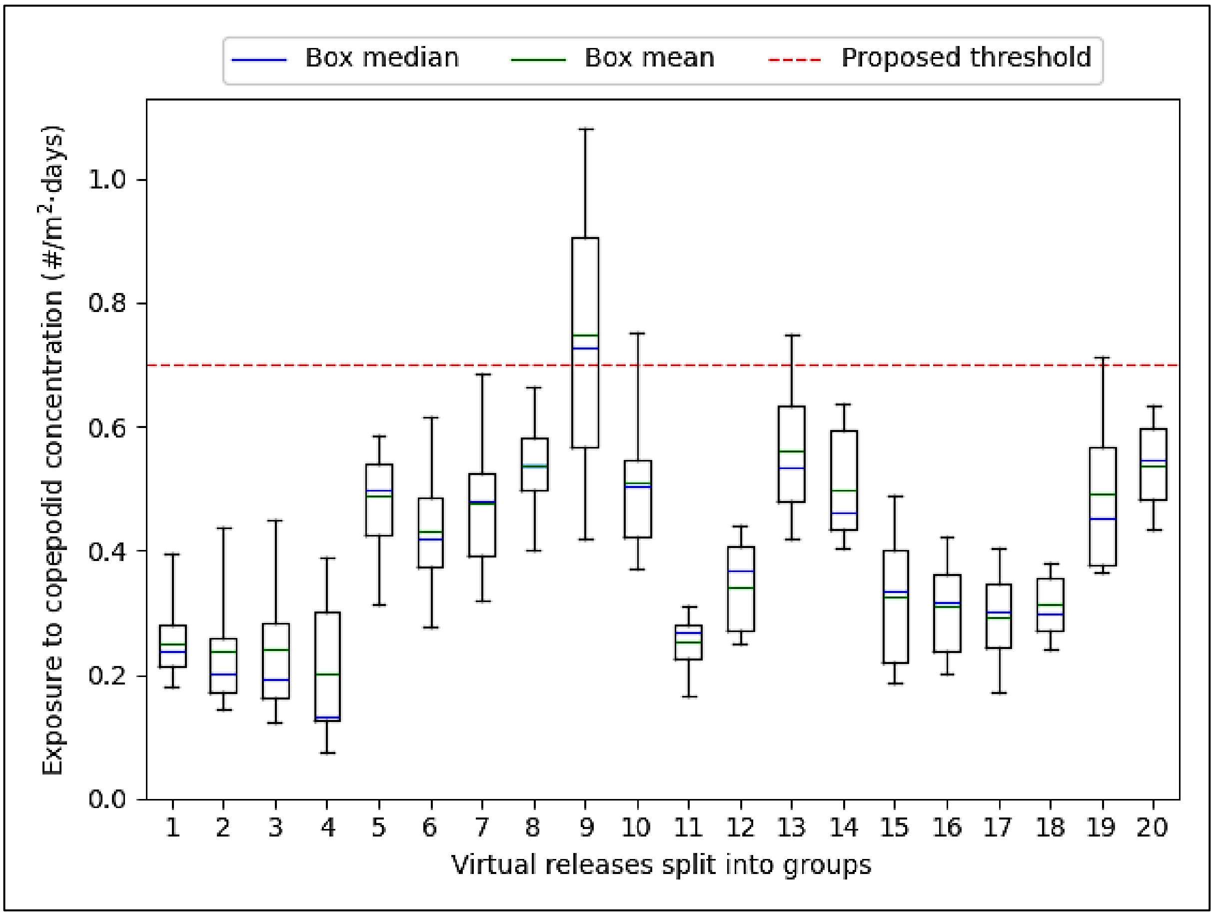

Figure 5 *Grouped boxplot copepodid exposure (#/m^2-days)) in May 2024 based on actual biomass for virtual smolts along the migration pathway.*

4.2 May 2024 – 1.75 × Biomass Scenario

The 1.75 × biomass sensitivity scenario produced a clear increase in both spatial copepodid concentrations (Figure 6) and cumulative exposure along the migration route.

The exposure curves (Figure 7) show that a substantially larger proportion of individual virtual post-smolt trajectories exceeded the 0.7 copepodids·m^{-2}·days threshold compared with the actual biomass case. The increase in exposure is evident both in the magnitude of cumulative exposure and in the duration over which elevated exposure conditions persisted.

The grouped boxplot analysis (Figure 8) indicates:

- median exposures for several groups were at or above the SEPA threshold;
- mean values similarly increased across most groups; and
- the 95th percentile values exceeded the threshold across a greater number of grouped releases.

These results indicate that scaling biomass upward by a factor of 1.75 produces a marked increase in predicted exposure risk along the migration corridor. The analysis therefore demonstrates sensitivity of post-smolt exposure to increased regional lice loading within the hydrodynamically connected system.

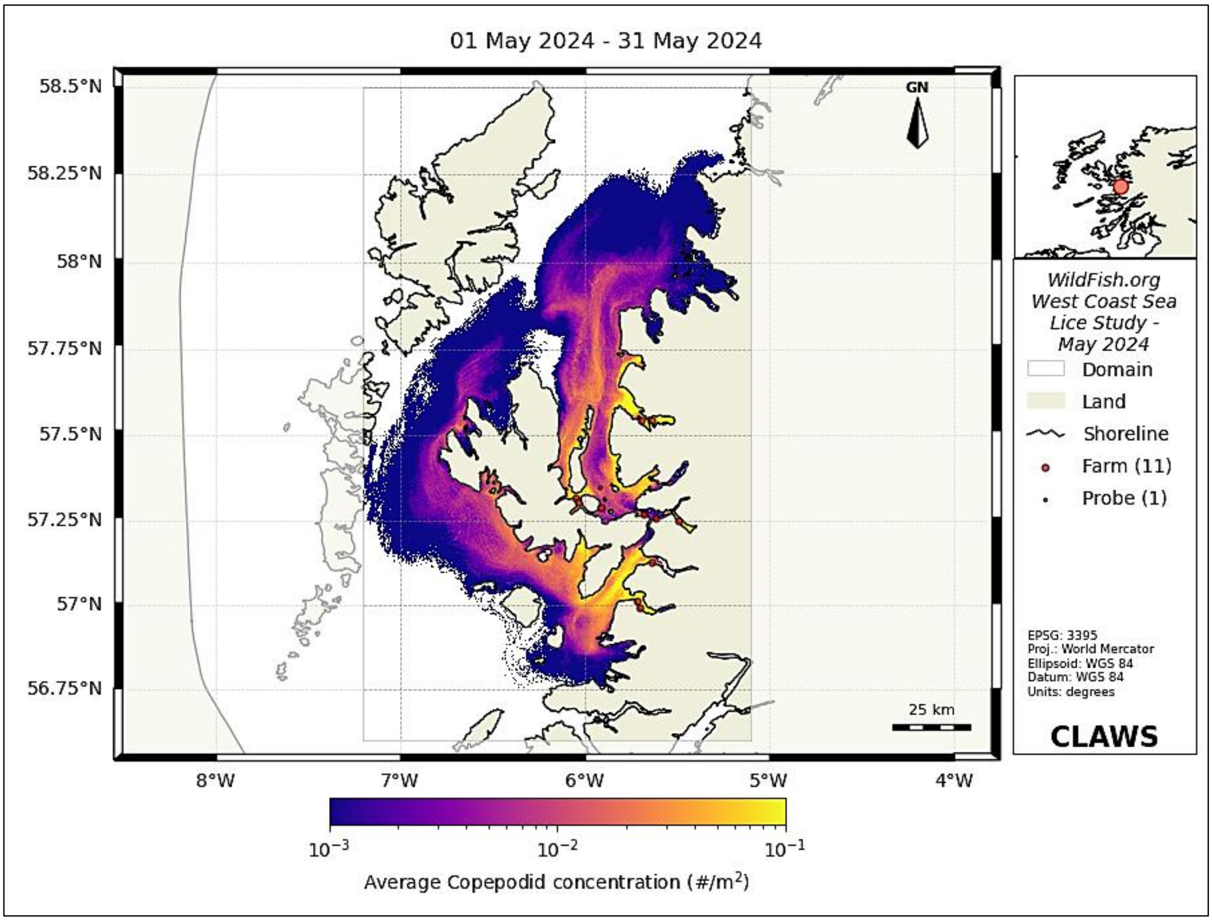

Figure 6 *Average copepodid concentration (#/m^2) across the south Skye-Torridon corridor based on 1.75 × biomass for May 2024.*

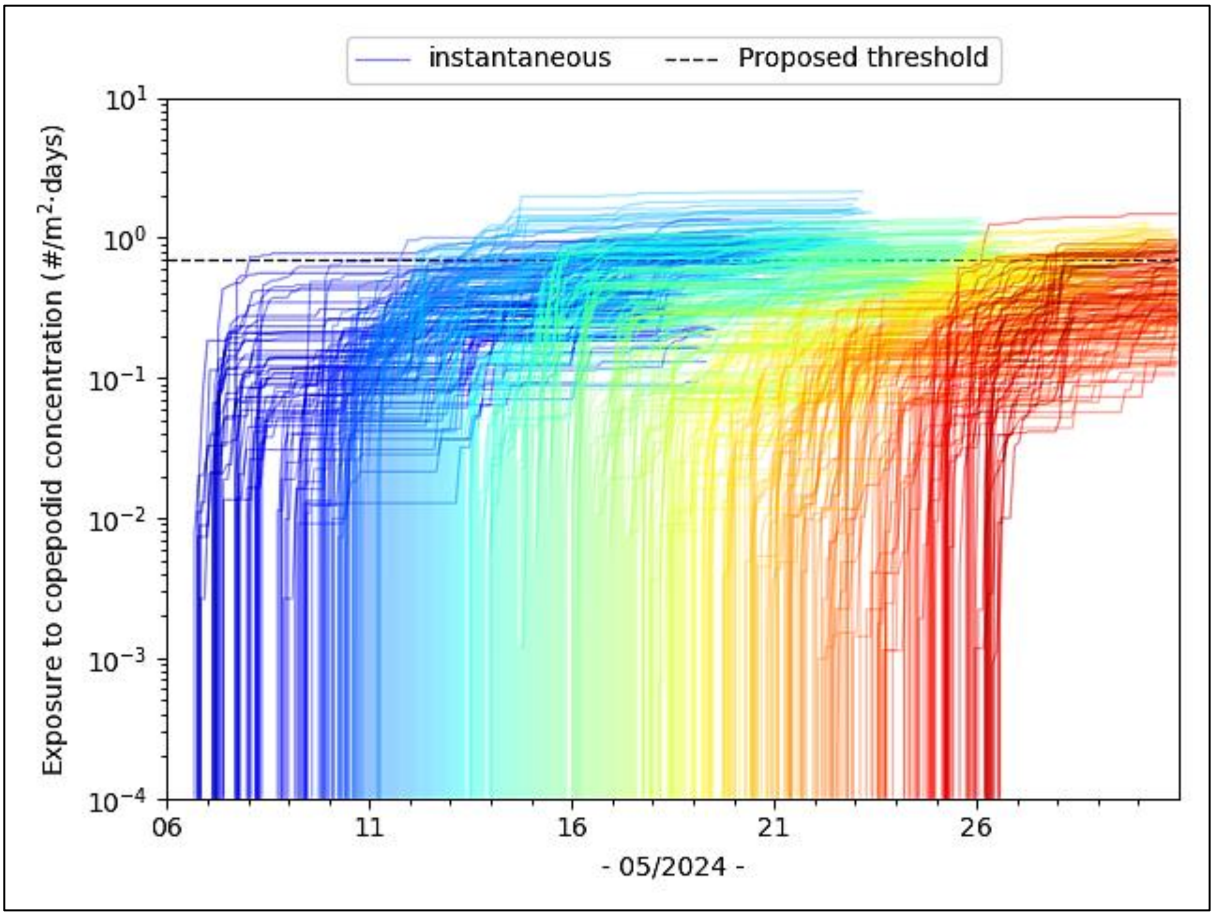

Figure 7 *Cumulative copepodid concentration exposure curves (#/m^2-days) along migration pathway for May 2024 based on 1.75 × biomass. Colour blue-to-red signifies early-to-late virtual smolt start time.*

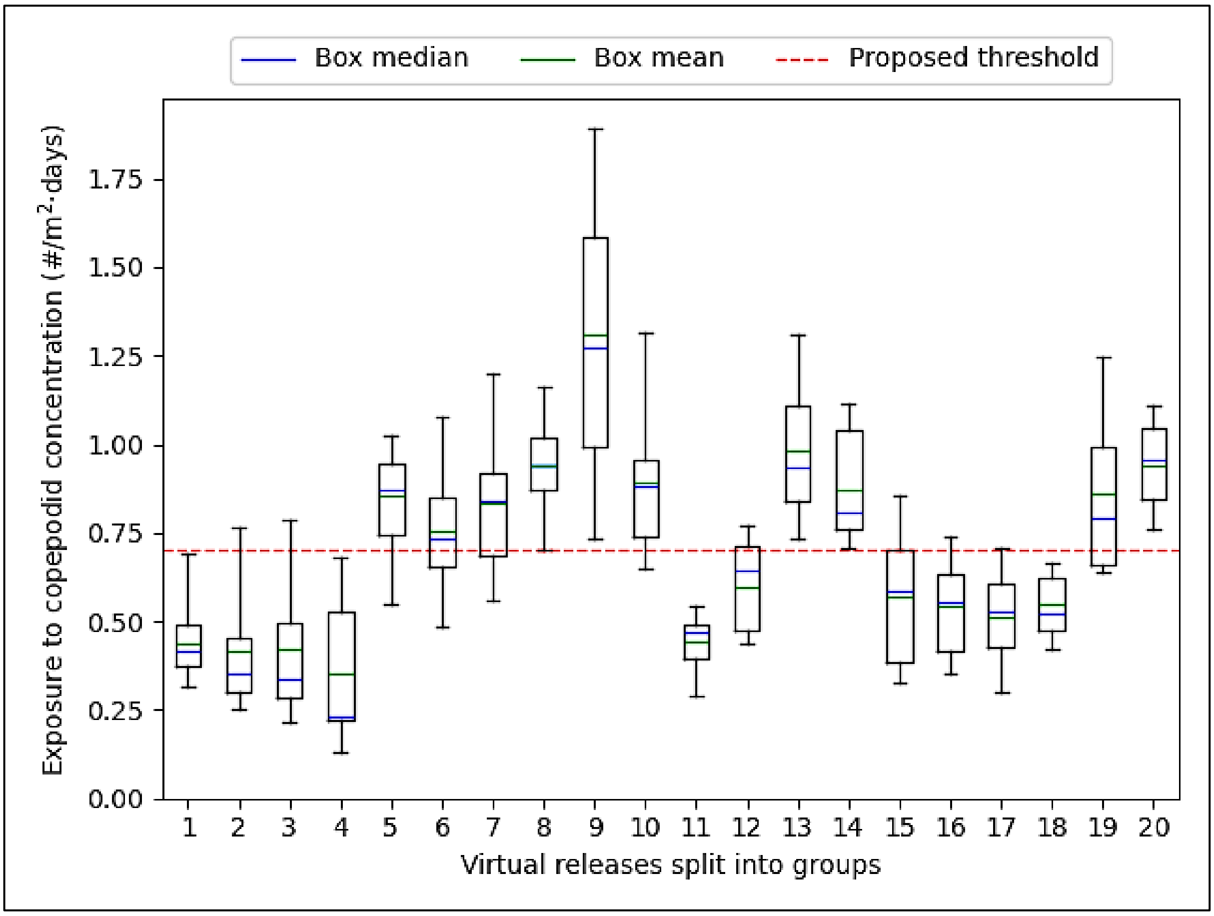

Figure 8 *Grouped boxplot copepodid exposure (#/m^2-days)) in May 2024 based on 1.75 × biomass for virtual smolts along the migration pathway.*

4.3 May 2025 – Actual Biomass Scenario

The May 2025 actual biomass simulations indicate broader regional dispersal of copepodids (Figure 9) relative to the May 2024 actual biomass scenario, with enhanced connectivity evident through the Inner Sound and adjacent coastal channels.

The cumulative exposure plots (Figure 10) show a progressive increase in exposure through time and along-route distance, with later-release virtual post-smolts again generally experiencing higher cumulative exposure. A significant proportion of trajectories approached the SEPA threshold, with some individual trajectories exceeding it.

The grouped boxplot results (Figure 11) indicate that:

- median exposures for many groups remained below the threshold;
- several grouped releases exhibited 95th percentile exceedances; and
- some groups displayed relatively broad interquartile and percentile ranges, indicating notable temporal variability in exposure conditions.

From a screening perspective, these results suggest that while average conditions may remain below the proposed threshold for much of the period, episodic exceedances occur for a proportion of virtual post-smolts under particular release timings and hydrodynamic conditions.

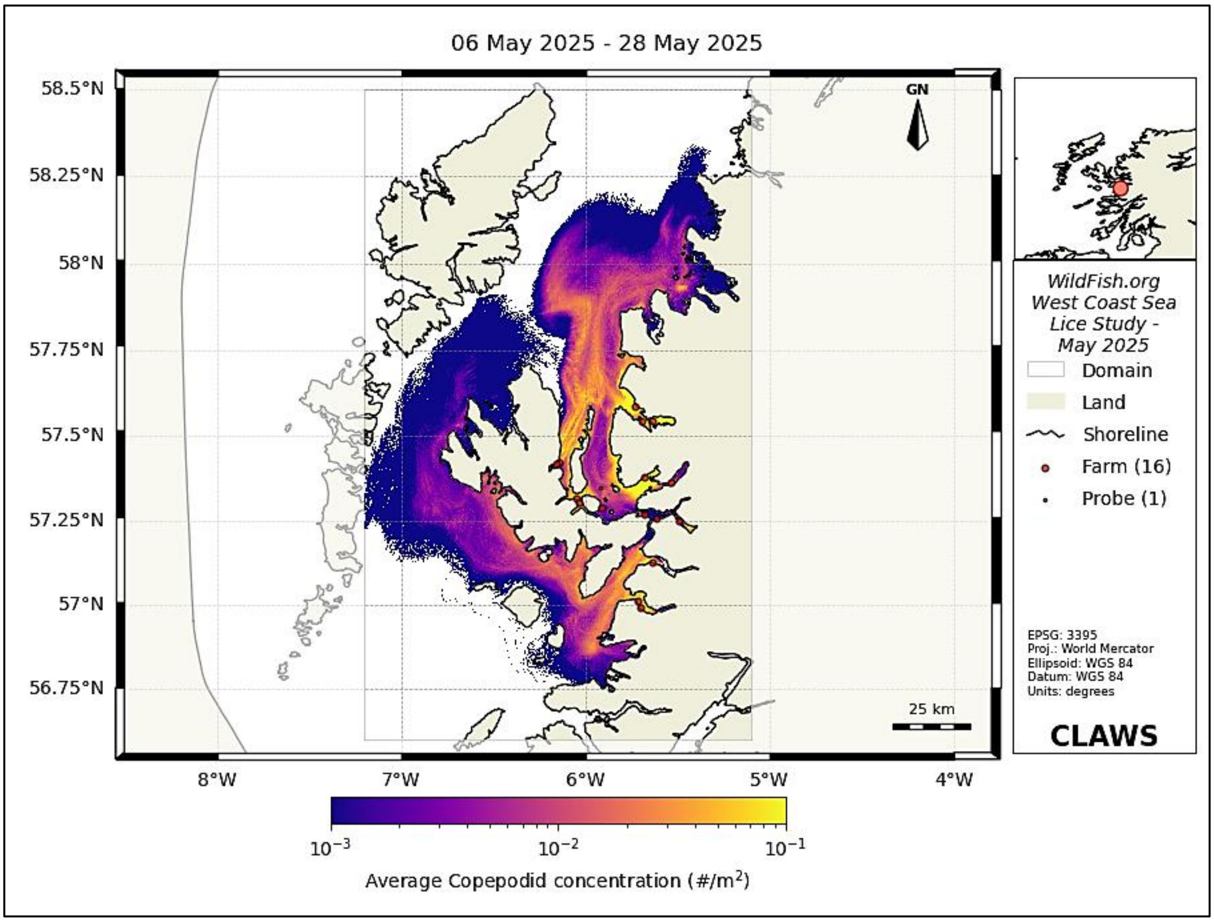

Figure 9 *Average copepodid concentration (#/m^2) across the south Skye-Torridon corridor based on actual biomass for May 2025.*

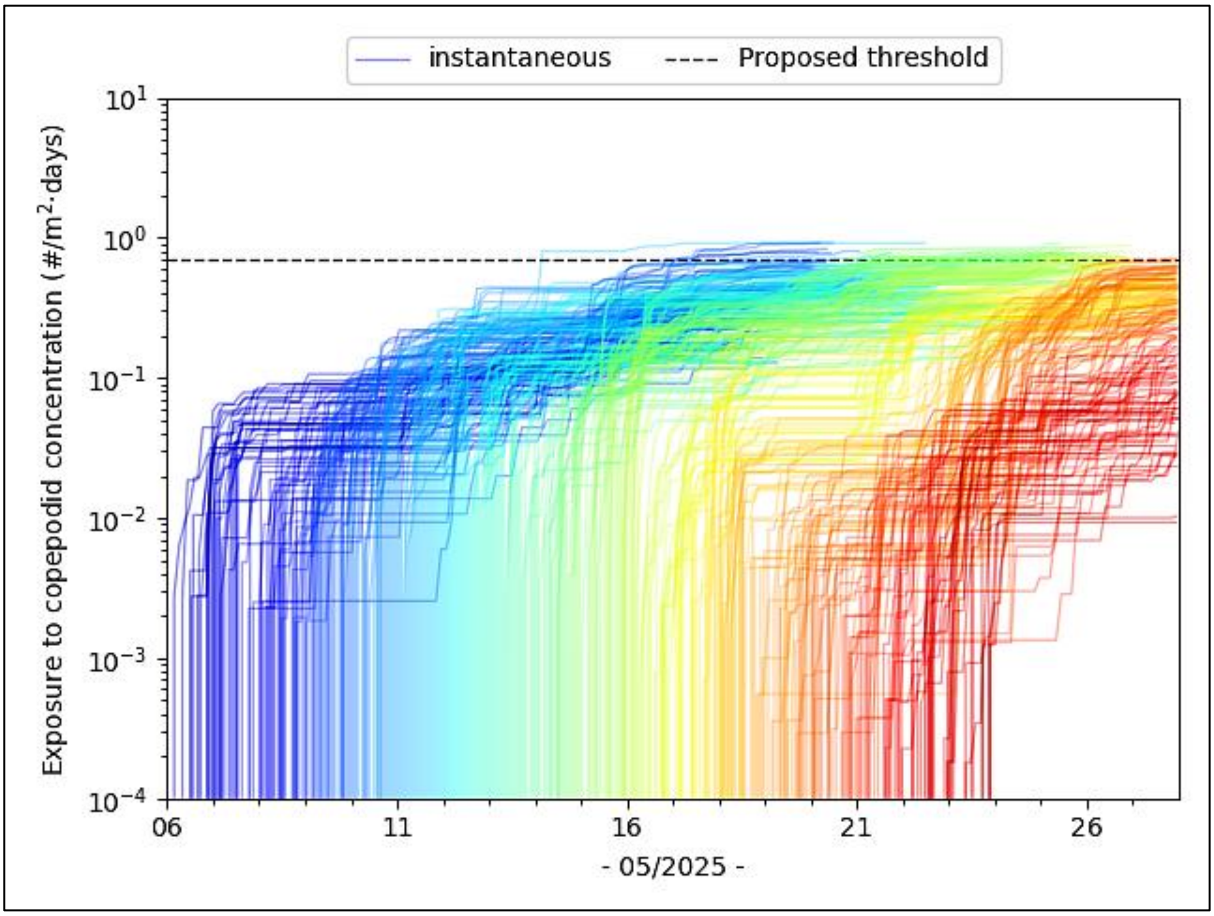

Figure 10 *Cumulative copepodid concentration exposure curves (#/m^2-days) along migration pathway for May 2025 based on actual biomass. Colour blue-to-red signifies early-to-late virtual smolt start time.*

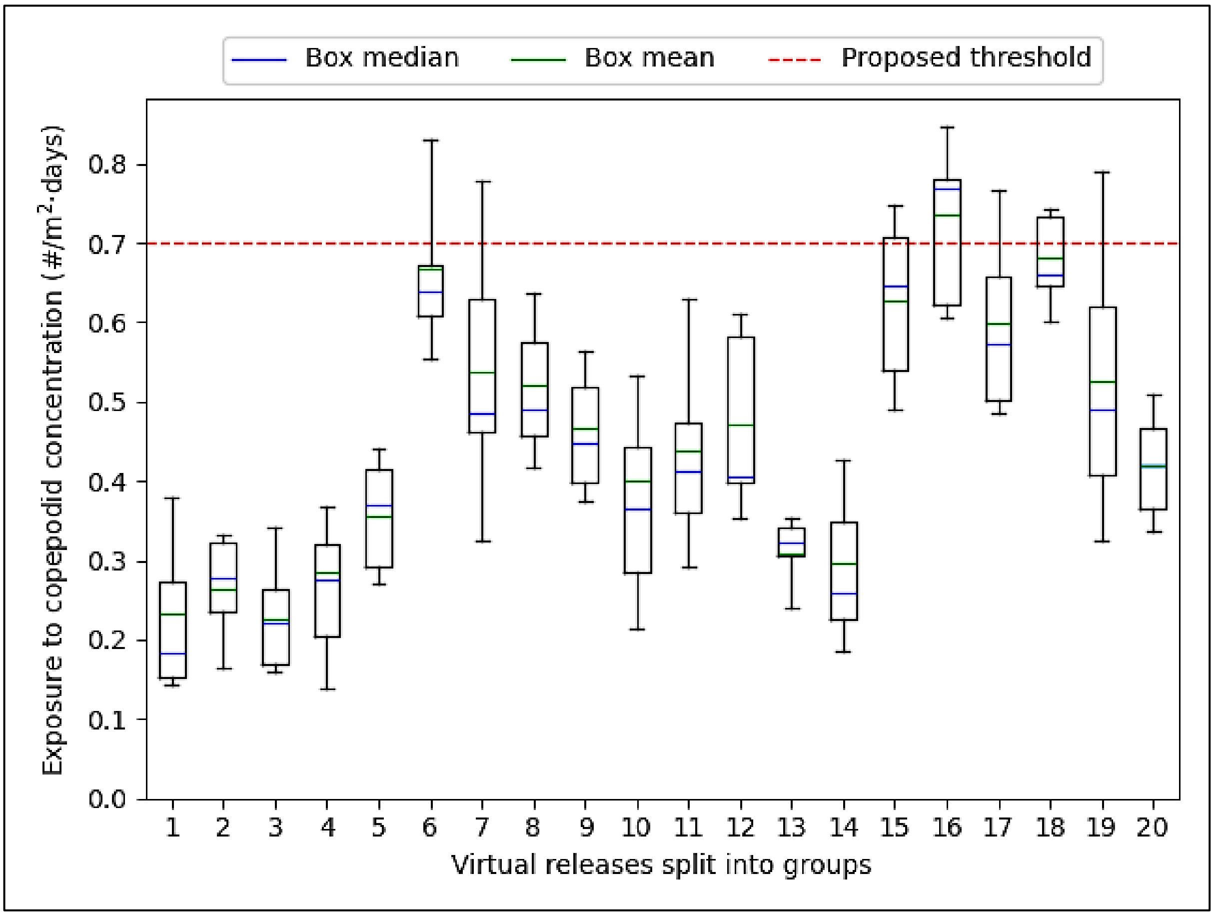

Figure 11 *Grouped boxplot copepodid exposure (#/m^2-days)) in May 2025 based on actual biomass for virtual smolts along the migration pathway.*

4.4 May 2025 – 1.75 × Biomass Scenario

The May 2025 1.75 × biomass scenario produced the highest predicted exposure levels of all scenarios assessed (Figure 12).

The cumulative exposure trajectories (Figure 13) demonstrate widespread exceedance of the 0.7 copepodids·m^{-2}·days threshold, particularly for mid- to late-period releases. Elevated exposure conditions persisted over extended sections of the migration corridor, indicating strong regional hydrodynamic connectivity between farm locations and the post-smolt migration route.

The grouped boxplot analysis (Figure 14) demonstrates that:

- median exposures exceeded the SEPA threshold for multiple grouped releases;
- mean exposures were consistently elevated; and
- 95th percentile values exceeded the threshold across a substantial proportion of the grouped release sets.

In accordance with the SEPA screening interpretation approach, these results indicate that a proportion of virtual post-smolts would experience exposures above the proposed screening criterion under this higher biomass sensitivity case.

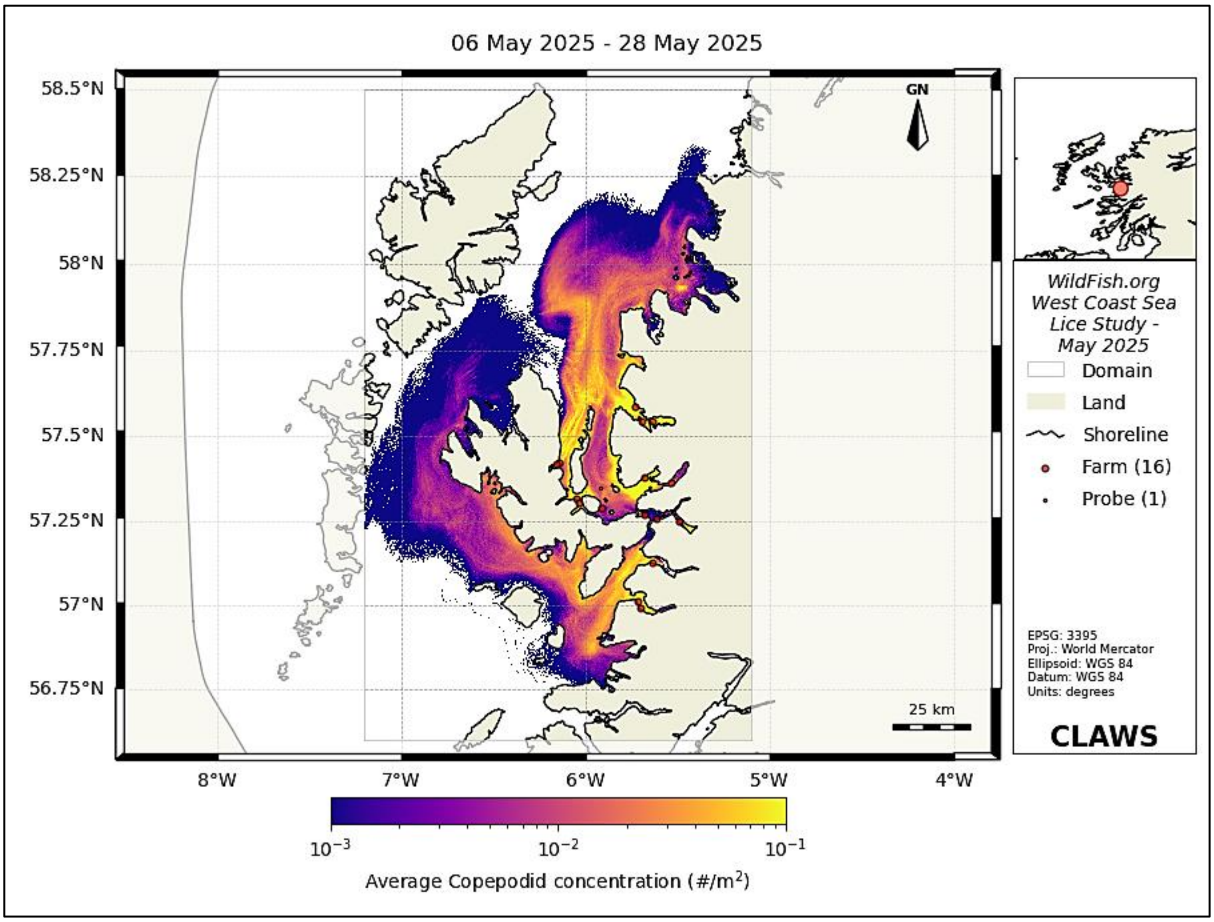

Figure 12 *Average copepodid concentration (#/m^2) across the south Skye-Torridon corridor based on 1.75 × biomass for May 2025.*

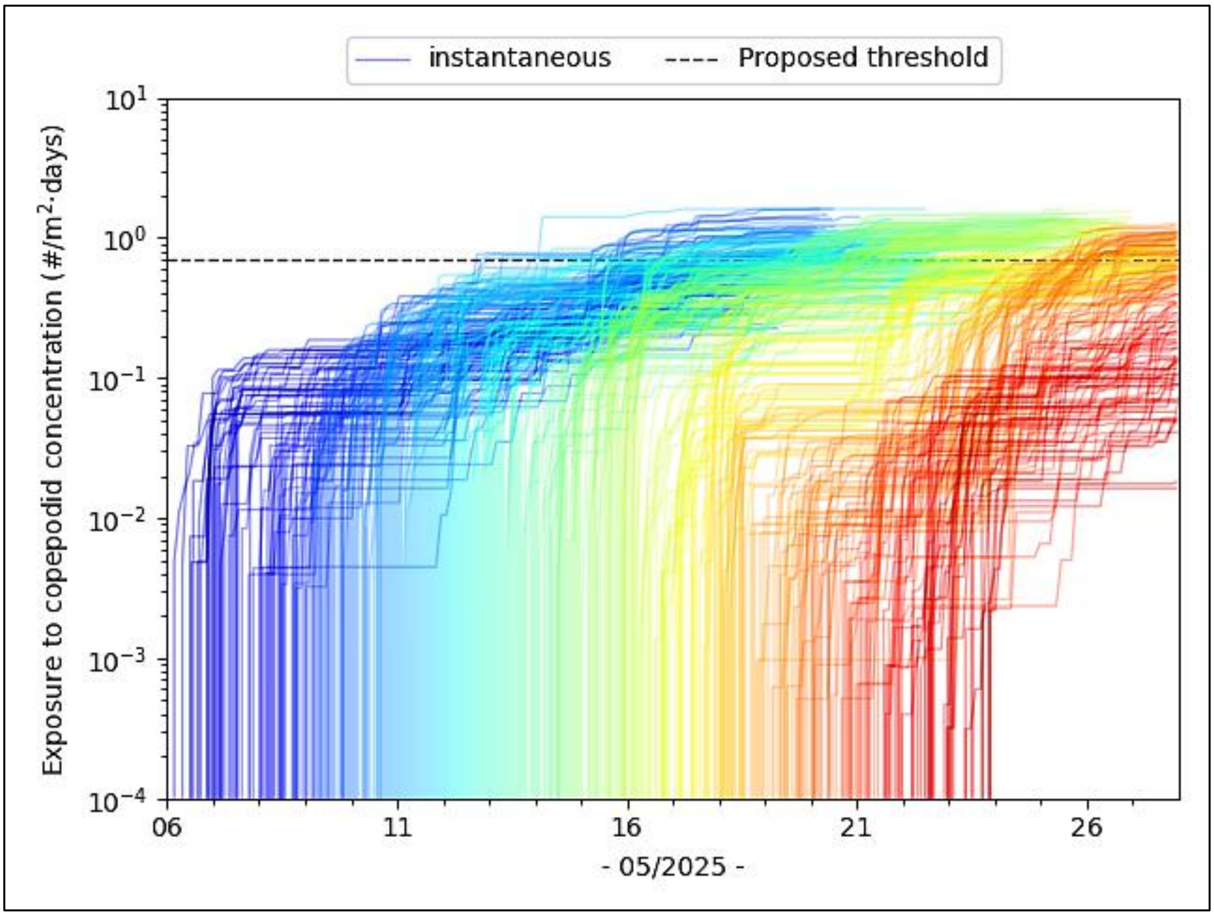

Figure 13 *Cumulative copepodid concentration exposure curves (#/m^2-days) along migration pathway for May 2025 based on 1.75 × biomass. Colour blue-to-red signifies early-to-late virtual smolt start time.*

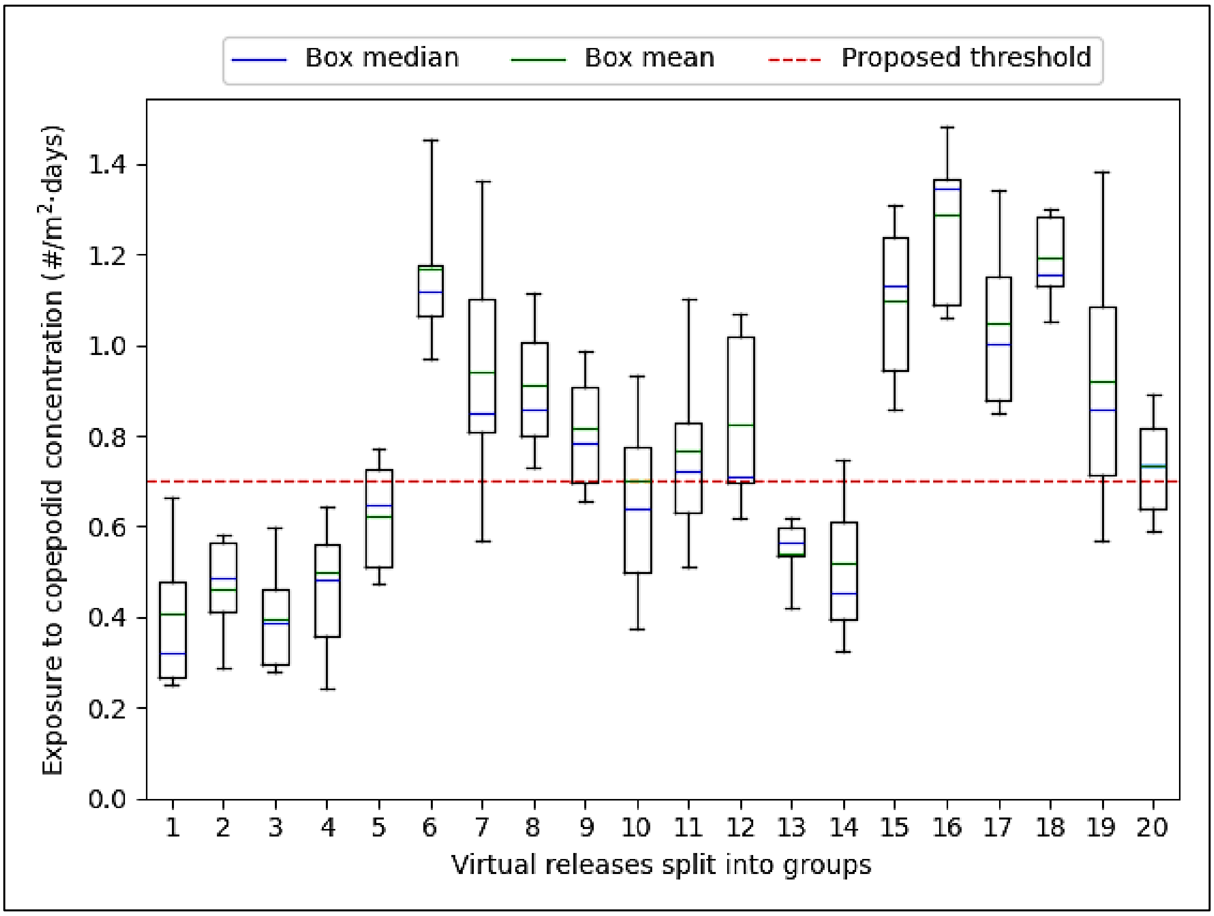

Figure 14 *Grouped boxplot copepodid exposure (#/m^2-days)) in May 2025 based on 1.75 × biomass for virtual smolts along the migration pathway.*

4.5 Overall Interpretation

Across both study years, the modelling demonstrates that cumulative exposure along the migration corridor is strongly influenced by:

- regional hydrodynamic connectivity;
- temporal variability in copepodid production and transport;
- release timing of migrating post-smolts; and
- total regional biomass loading.

The analysis indicates that the actual biomass scenarios generally produced exposures that were frequently below, but periodically approaching or exceeding, the proposed SEPA screening threshold at the upper percentile ranges. In contrast, the 1.75× biomass sensitivity scenarios produced more frequent and spatially extensive exceedances of the threshold, particularly when assessed using the SEPA 95th percentile screening criterion.

The results therefore demonstrate that while exposure conditions vary substantially in time and space, elevated cumulative exposure conditions can occur within the modelled migration corridor under certain hydrodynamic and biomass loading scenarios.

5 Conclusions

This study has presented a regional-scale assessment of salmon lice dispersion and post-smolt exposure within the South Skye–Torridon coastal system using a coupled hydrodynamic and biological modelling framework. The work combined a validated three-dimensional TELEMAC hydrodynamic model with a CLAWS/LADiM-type Lagrangian particle tracking model configured in accordance with the SEPA sea-lice screening methodology.

The modelling demonstrates that the west coast fjordic system comprising Loch Nevis, Loch Hourn, Loch Alsh, Kyle Rhea, the Inner Sound and adjacent coastal waters functions as a strongly hydrodynamically connected environment. Tidal exchange, channelised flow pathways and coastal circulation processes allow infective-stage copepodids to disperse over distances of tens of kilometres, linking multiple aquaculture production areas within the wider regional system.

Although copepodid concentrations decrease with distance from source farms, the model demonstrates regional-scale connectivity extending beyond the principal farming areas. Transport pathways link the South Skye–Torridon system with adjacent coastal waters, including the Minch and waters extending towards the Summer Isles, illustrating the large spatial scale over which biological interactions may occur.

The simulated copepodid distributions were spatially heterogeneous and strongly time-dependent, with enhanced concentrations occurring within tidal constrictions, coastal channels and areas of partial hydrodynamic retention. The results demonstrate that lice exposure to migrating salmonids is therefore cumulative and regionally integrated rather than attributable solely to individual farm locations in isolation.

Virtual Post-Smolt Model (VPSM) simulations were undertaken for a representative migration route originating in Loch Nevis together with additional migration routes associated with the Rivers Shiel, Elchaig, Carron, Torridon and Sligachan. Detailed route-specific exposure assessments for these rivers are provided in Appendix A. Although cumulative exposure levels varied between individual routes and release periods, all routes intersected hydrodynamically connected regions influenced by lice dispersal from multiple farms. The results therefore demonstrate that cumulative exposure is not restricted to a single migration corridor but is a characteristic of the wider South Skye–Torridon coastal system.

Across all assessed routes, exposure experienced by individual virtual post-smolts varied according to release timing, reflecting temporal variability in lice production, transport processes and hydrodynamic connectivity across the domain. Routes passing through regions of enhanced connectivity between Loch Alsh, the Inner Sound, Loch Carron and Loch Torridon generally experienced the greatest cumulative exposure owing to interaction with overlapping copepodid plumes originating from multiple farm locations.

Under the actual biomass scenarios for May 2024 and May 2025, predicted cumulative exposures were frequently below the proposed SEPA screening threshold of 0.7 copepodids$\cdot m^{-2}\cdot$days for median conditions, although exceedances of the 95th percentile threshold criterion were identified for certain routes, release groupings and time periods. These exceedances indicate that a proportion of simulated post-smolts may experience exposure conditions above the proposed SEPA screening level under particular hydrodynamic and biological conditions.

The 1.75 × biomass sensitivity simulations, undertaken in accordance with the SEPA precautionary scaling methodology, produced substantially increased copepodid concentrations and cumulative exposure levels throughout the migration corridors. In these simulations, exceedance of the proposed screening threshold became more widespread, with multiple routes and grouped releases exceeding the threshold at both median and 95th percentile levels. The results therefore indicate a strong sensitivity of regional exposure risk to increased biomass loading and associated lice production.

The modelling further demonstrates the importance of considering cumulative regional interactions between farms within interconnected hydrographic systems. Predicted exposure patterns were controlled not only by local farm biomass but also by wider-scale circulation pathways capable of transporting copepodids between adjacent sea lochs and coastal corridors over extended distances. The results indicate that biological connectivity extends beyond individual sea-loch boundaries, linking Loch Nevis, Loch Hourn, Loch Alsh, Loch Carron, Loch Torridon, the Inner Sound and adjacent coastal waters within a broader regional network.

The study represents a screening-level assessment consistent with current SEPA methodology and assumptions, including upper-water-column particle restriction, SEPA-aligned diffusion coefficients, standardised biological development rates and application of the SEPA biomass scaling factor. As such, the outputs provide a directly comparable regional evidence base for cumulative impact assessment and regulatory screening purposes.

The modelled post-smolt exposures should be regarded as screening-level estimates of exposure during migration through the study area. The virtual post-smolt model assumes continuous migration at a constant swimming speed along predefined routes and therefore represents a lower-bound estimate of potential exposure duration. Telemetry studies have shown that post-smolt migration through estuarine and coastal waters may involve tidal transport, temporary residency and variable migration rates [Moore_1998; Thorstad_2012], potentially increasing exposure duration relative to that represented in simplified migration models.

The assessment focuses on exposure experienced by fish migrating through the South Skye–Torridon system itself. However, Atlantic salmon originating from more southerly regions of the west coast, including from rivers in Lochaber, Argyll and the Firth of Clyde, may also pass through parts of the wider Inner Hebrides and Sound of Sleat region during their marine migration. Such fish may already have accumulated lice burdens before entering the study area. Consequently, the modelled exposures presented here should be interpreted as potential additional exposure occurring within the South Skye–Torridon system rather than necessarily representing total lifetime marine exposure.

Finally, the results suggest that sea trout may experience proportionally greater exposure risk than migrating Atlantic salmon post-smolts, owing to their longer residence times within nearshore coastal waters. Because sea trout remain within coastal environments rather than migrating rapidly offshore, cumulative exposure to infective-stage lice may persist over substantially longer timescales than those represented by the post-smolt migration simulations.

Overall, the study demonstrates that hydrographic connectivity is a primary governing factor controlling lice dispersion and post-smolt exposure within the South Skye–Torridon system and that cumulative regional interactions between multiple farm sites are likely to be important in determining potential exposure risk to wild salmonids. The consistency of the findings across multiple plausible migration routes indicates that regional-scale connectivity, rather than any individual migration pathway, is the dominant factor governing exposure patterns within the study area.

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Appendix A. Individual River Post-Smolt Migration Routes and Route-Specific Exposure Assessment

This appendix presents route-specific virtual post-smolt migration pathways and associated exposure assessments for five representative rivers within the study area: the River Carron, River Elchaig, River Shiel, River Sligachan and River Torridon. For each river, results are presented for both the normal biomass scenario and the 1.75 × biomass sensitivity scenario. Interpretation follows the SEPA screening approach adopted in the main report, with emphasis placed on median exposure, upper-percentile exposure, threshold exceedance and temporal variability between release groups.

The purpose of this appendix is not to identify a single representative exposure value for each river, but rather to illustrate the temporal variability in predicted exposure arising from differences in migration timing and the evolving regional copepodid field.

A.1 Overall Interpretation

Across all routes, cumulative exposure was strongly influenced by temporal variability in copepodid transport, release timing and regional hydrodynamic connectivity. Application of the 1.75 × biomass scaling factor increased both the magnitude and frequency of threshold-relevant exposures in all cases. Consistent with the findings presented in the main report, exceedances were generally associated with upper-percentile exposure conditions rather than median conditions, indicating that exposure risk is episodic and dependent upon the interaction between migration timing and the evolving copepodid field.

A.2 River Carron (139 km)

Figure A1 *Virtual post-smolt migration route for the River Carron*.

A.2.1 Normal biomass Scenario

The Carron route exhibited moderate-to-high cumulative exposure relative to the other routes assessed. Under the Normal biomass scenario, median exposure values remained below the proposed screening threshold of 0.7 copepodids·m^{-2}·days for all release groups. However, several upper-percentile values approached or exceeded the threshold, indicating threshold-relevant exposures for a proportion of virtual post-smolts. Upper-percentile exceedances occurred intermittently rather than persistently and reflect temporal variability in copepodid transport and retention.

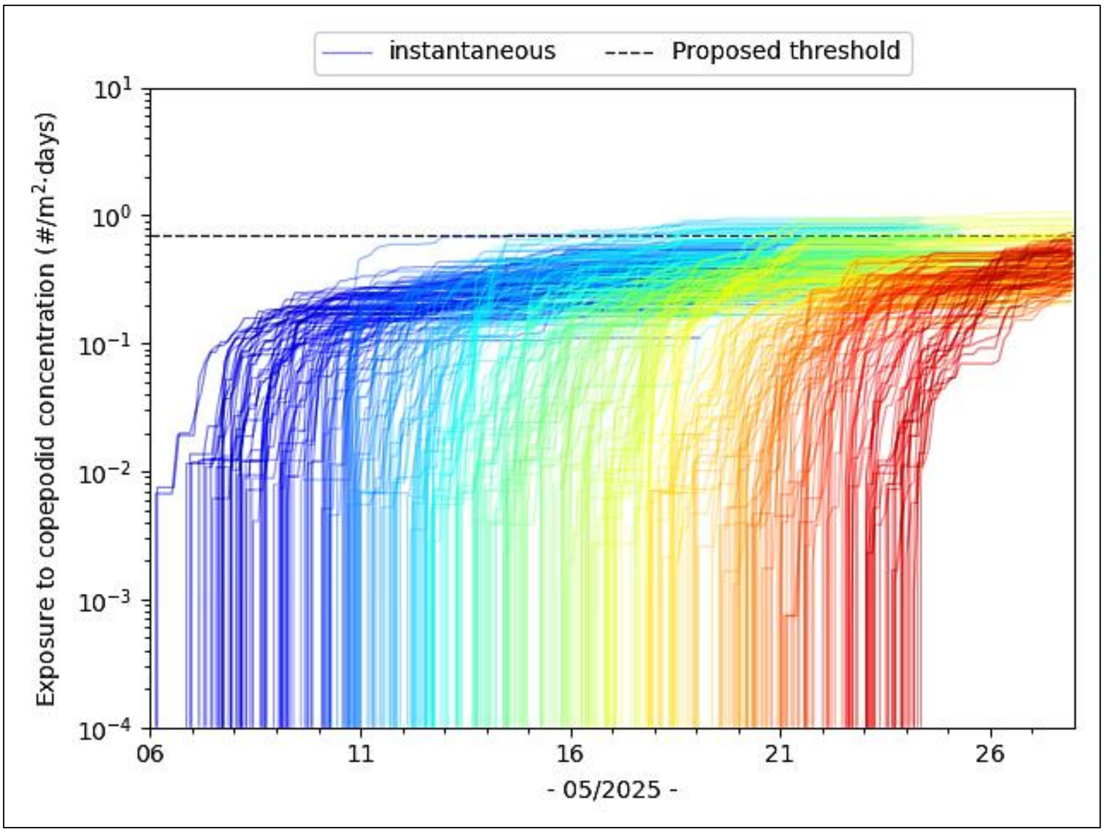

Figure A2 *Cumulative copepodid exposure curves for the River Carron under the normal biomass scenario.*

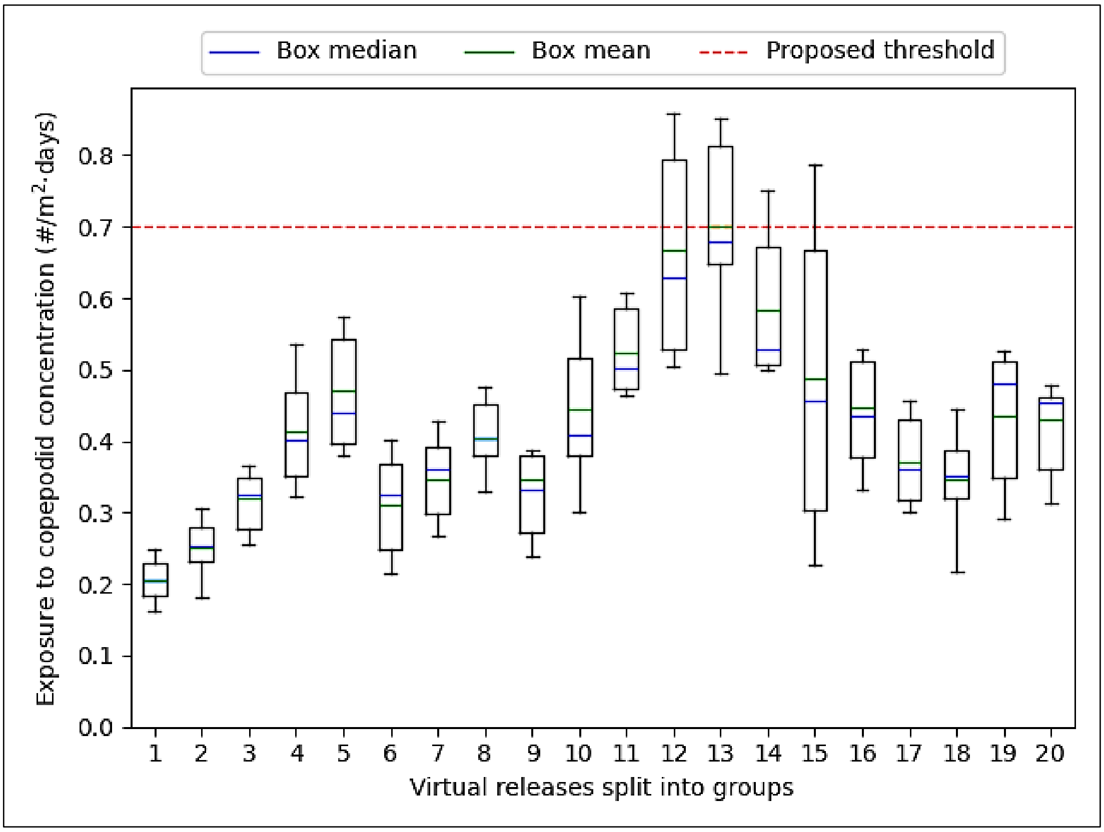

Figure A3 *Grouped boxplot copepodid exposure results for the River Carron under the normal biomass scenario.*

A.2.2 1.75 × Biomass Scenario

Application of the 1.75 × biomass scaling factor resulted in a clear increase in cumulative exposure. Several release groups exhibited upper-percentile exposures exceeding the proposed screening threshold and a greater proportion of trajectories approached threshold-relevant conditions.

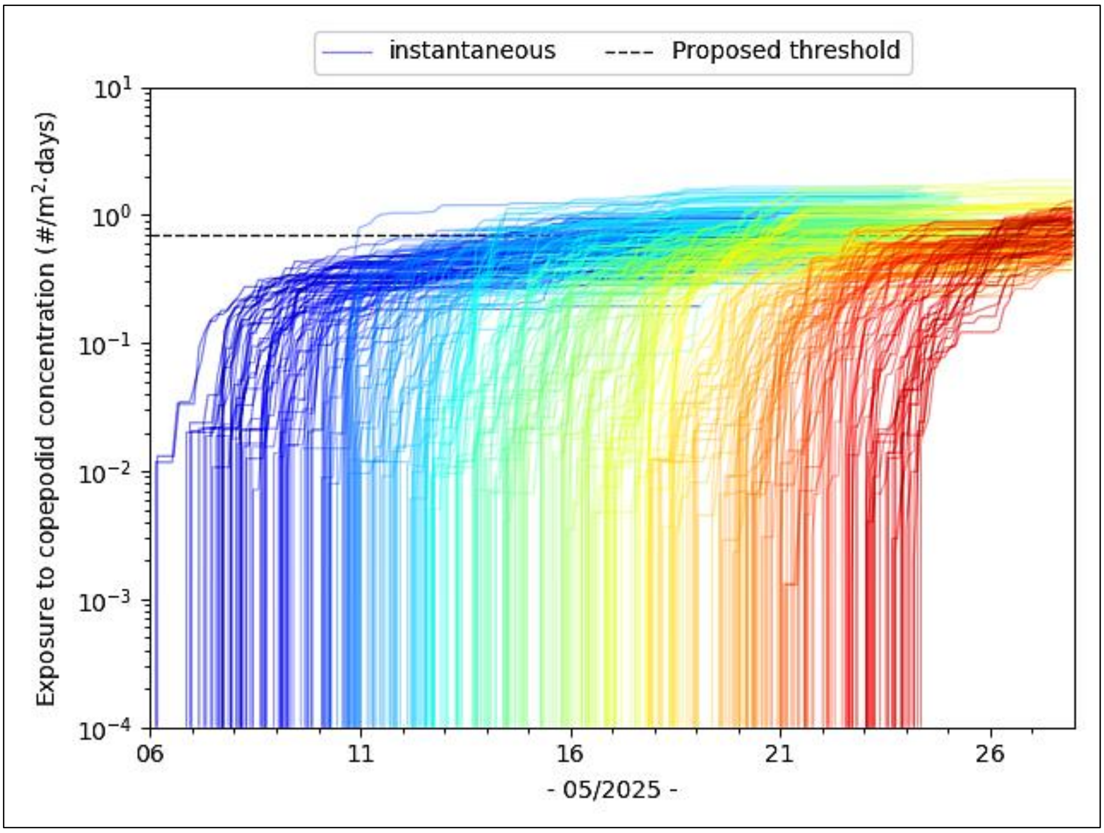

Figure A4 *Cumulative copepodid exposure curves for the River Carron under the 1.75 × biomass scenario.*

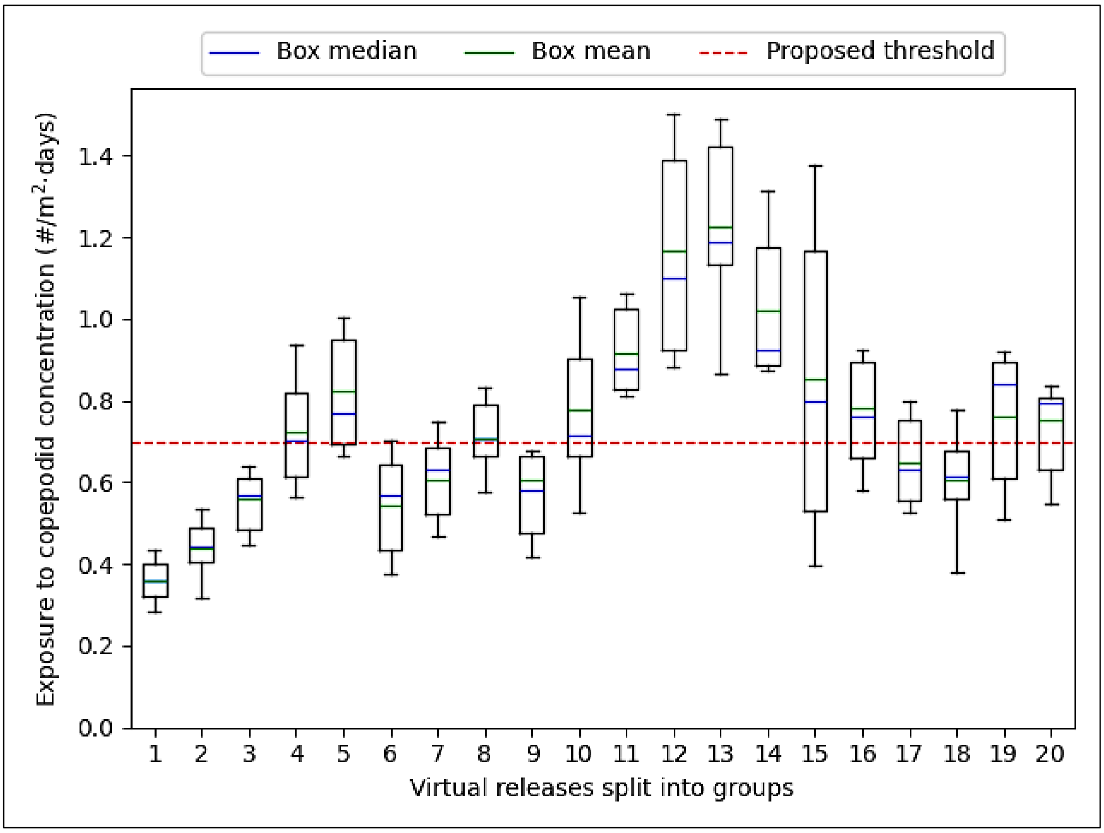

Figure A5 *Grouped boxplot copepodid exposure results for the River Carron under the 1.75 × biomass scenario.*

A.3 River Elchaig (133 km)

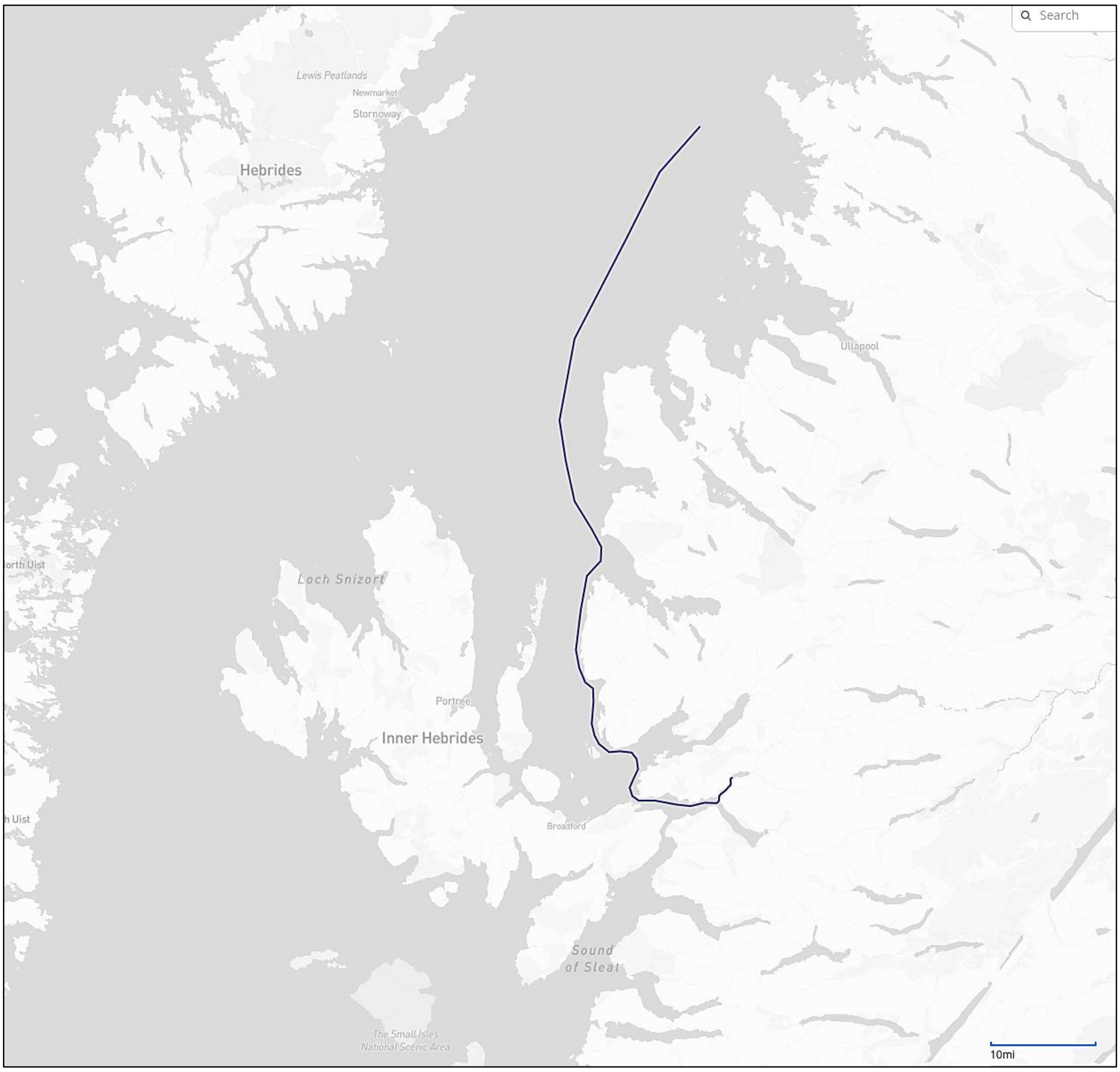

Figure A6 *Virtual post-smolt migration route for the River Elchaig.*

A.3.1 Normal biomass Scenario

The Elchaig route generally exhibited lower cumulative exposures than the Carron route. Median and mean exposures remained below the proposed screening threshold and only limited upper-percentile exceedances were observed, indicating episodic exposure events associated with particular release timings and hydrodynamic conditions.

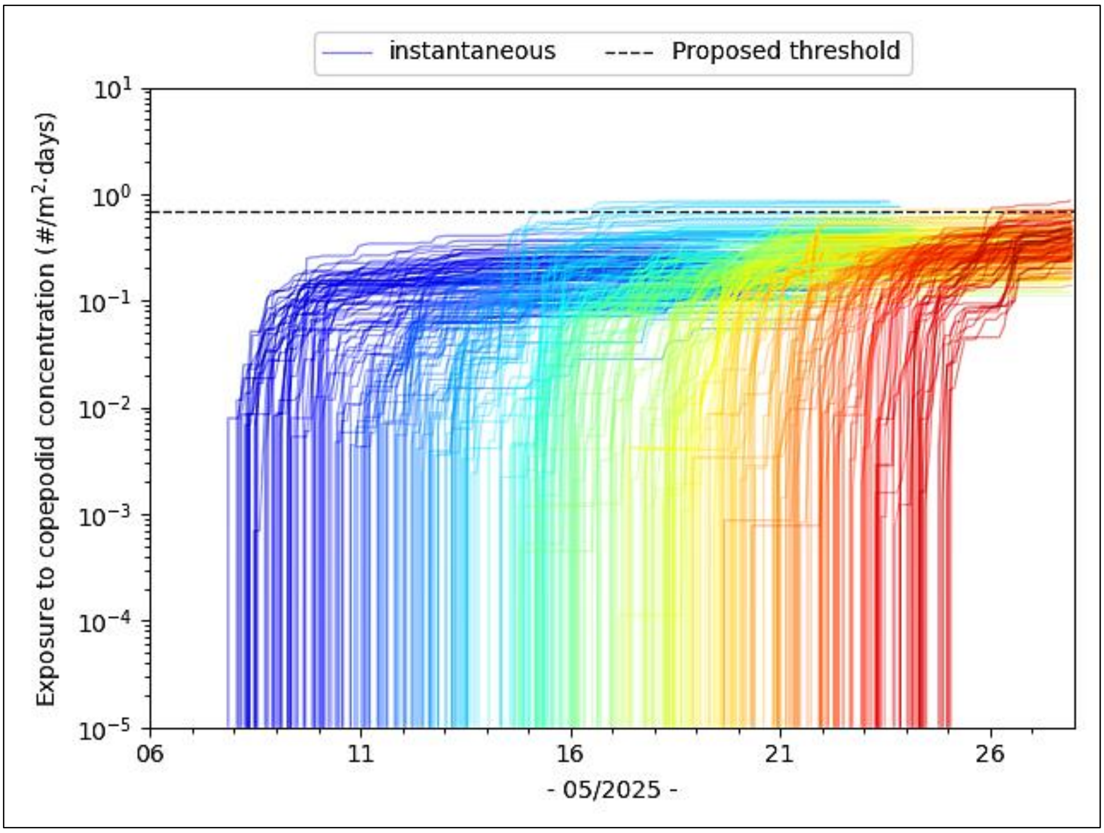

Figure A7 *Cumulative copepodid exposure curves for the River Elchaig under the normal biomass scenario.*

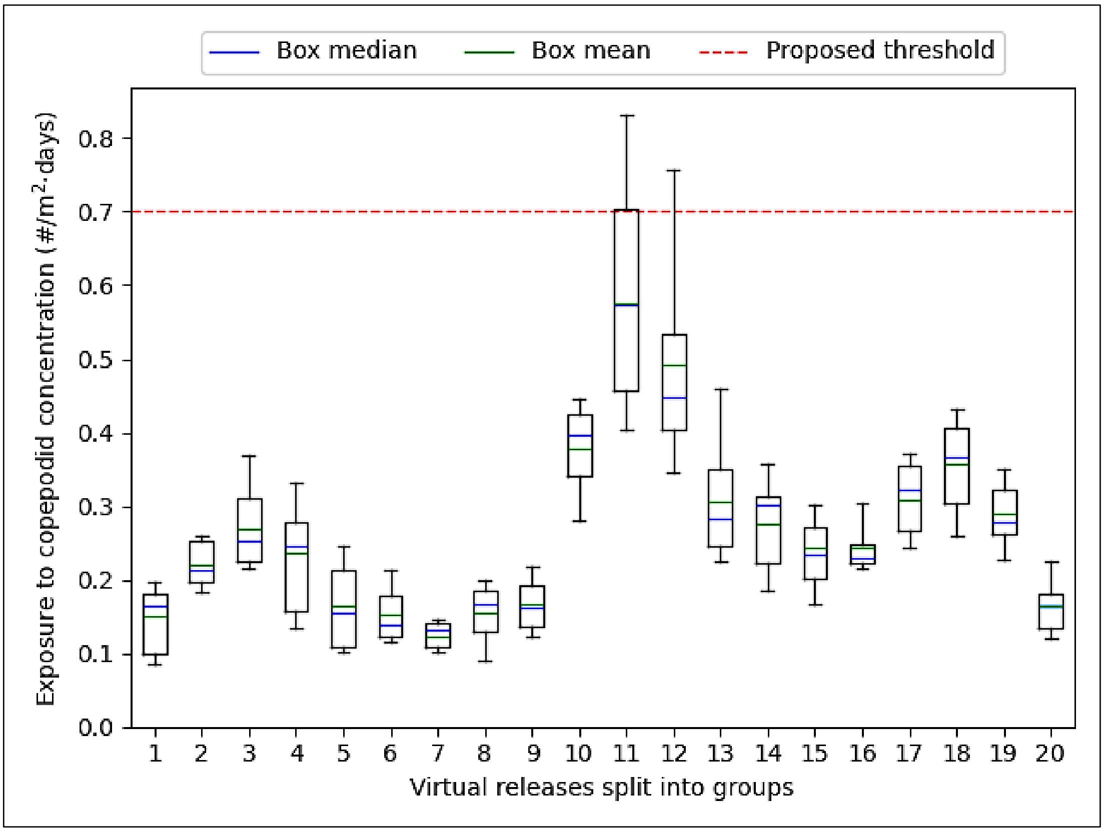

Figure A8 *Grouped boxplot copepodid exposure results for the River Elchaig under the normal biomass scenario.*

A.3.2 1.75 × Biomass Scenario

The scaled biomass scenario produced a noticeable increase in cumulative exposure. While median exposures remained below the threshold, upper-percentile values exceeded the threshold for a greater number of release groups.

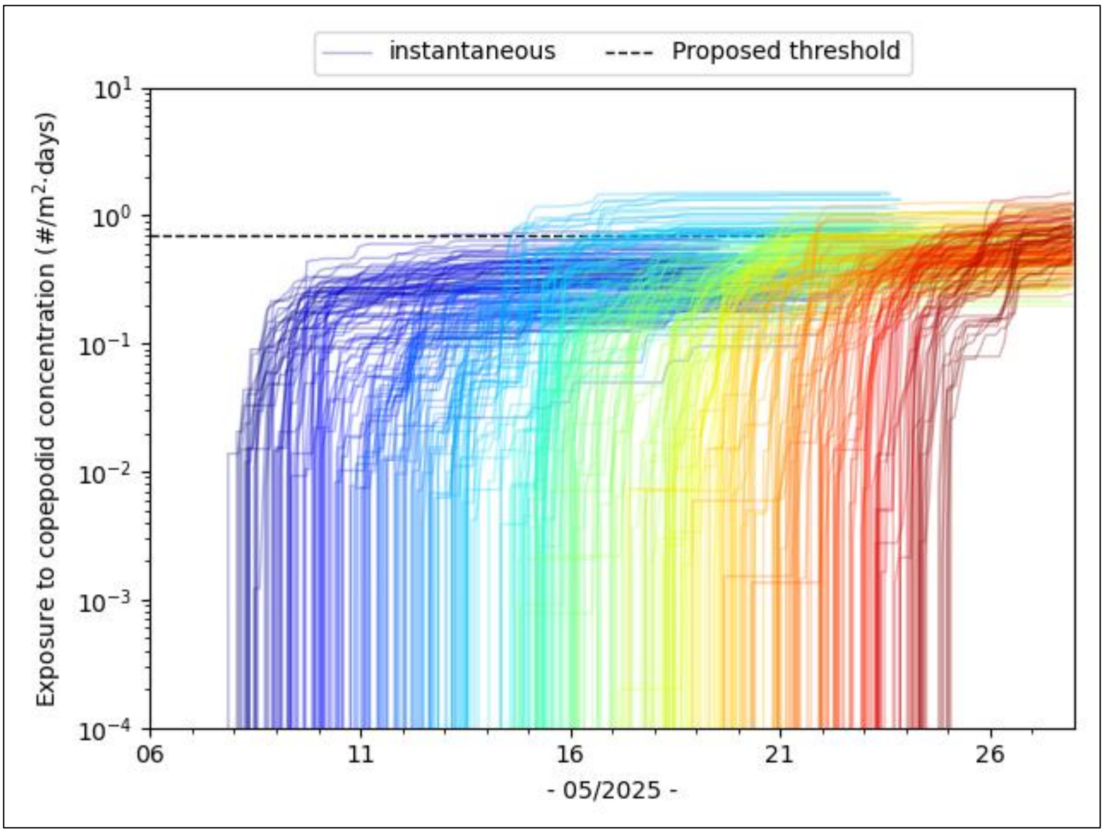

Figure A9 *Cumulative copepodid exposure curves for the River Elchaig under the 1.75 × biomass scenario.*

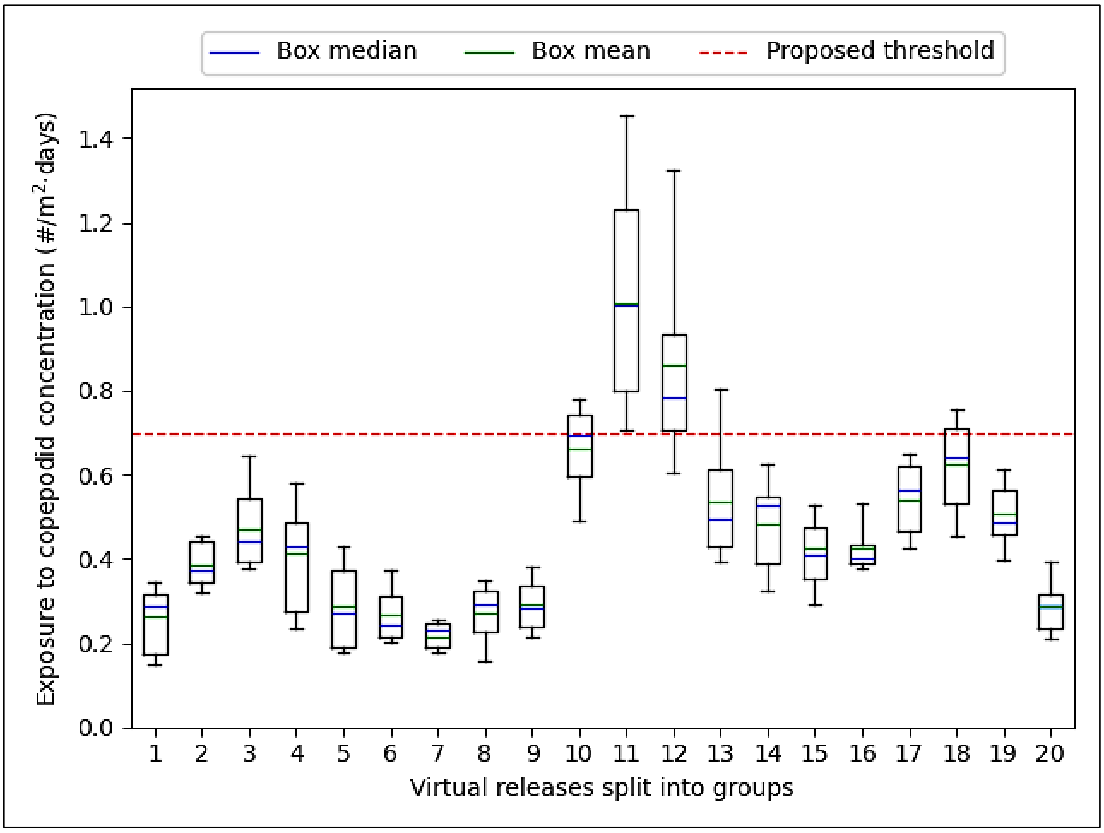

Figure A10 *Grouped boxplot copepodid exposure results for the River Elchaig under the 1.75 × biomass scenario.*

A.4 River Shiel (184 km)

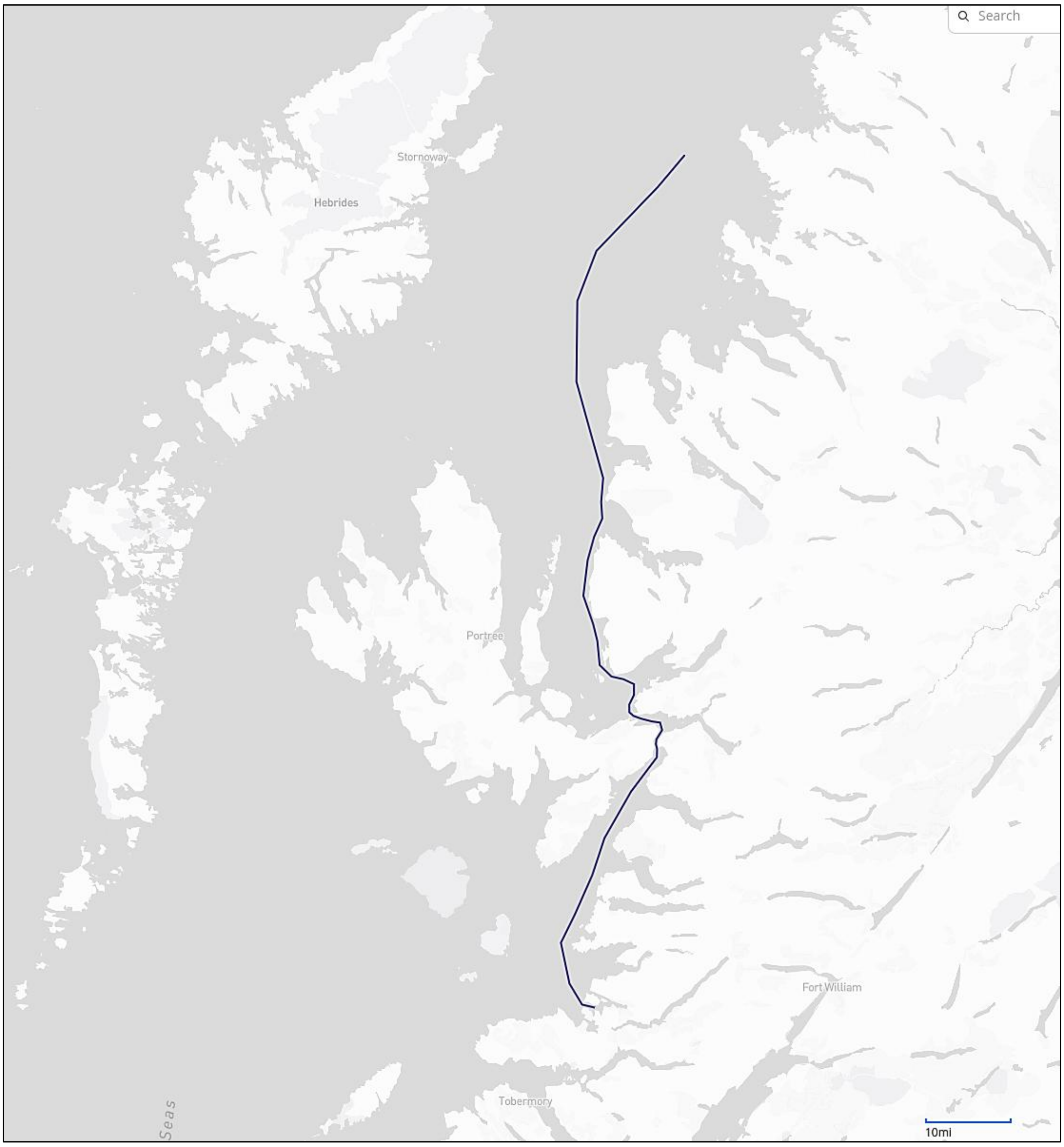

Figure A11 *Virtual post-smolt migration route for the River Shiel in Lochaber*.

A.4.1 Normal biomass Scenario

The Shiel route from south of the study area displayed moderate cumulative exposure together with substantial temporal variability. Median exposures remained below the proposed screening threshold throughout the assessment period. Several upper-percentile values approached the threshold, indicating intermittent periods of elevated exposure.

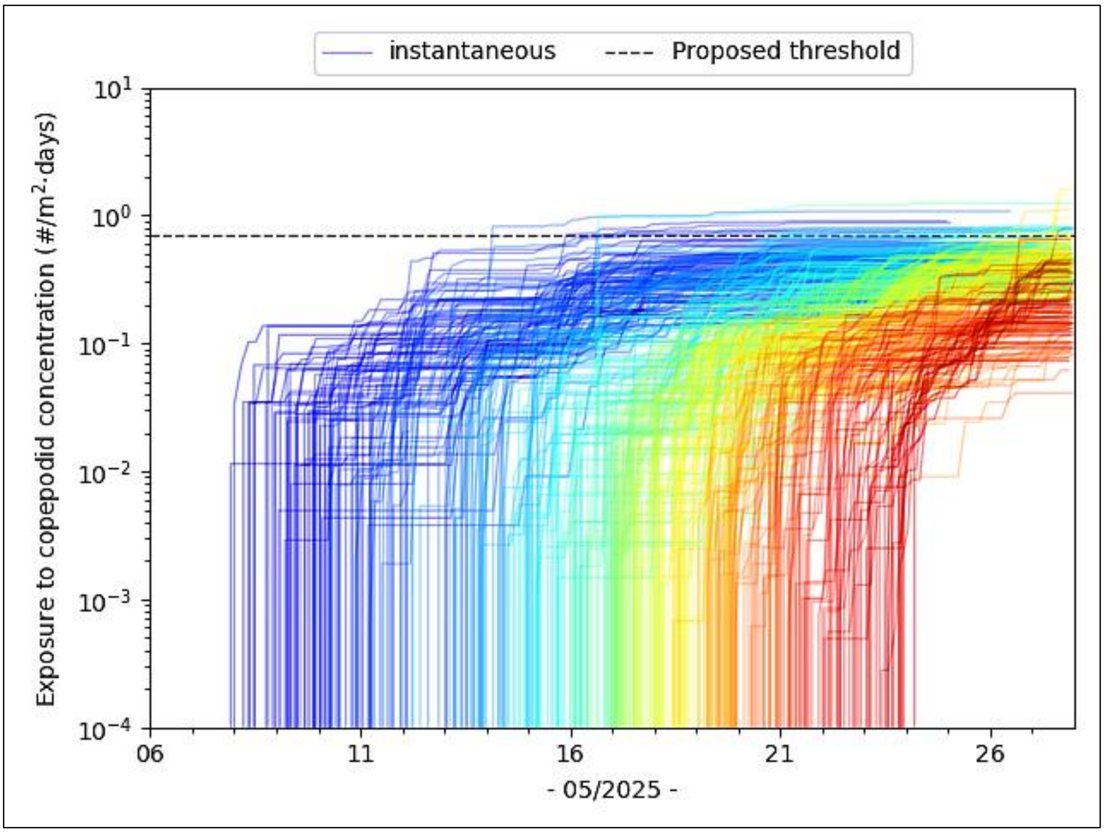

Figure A12 *Cumulative copepodid exposure curves for the River Shiel under the normal biomass scenario.*

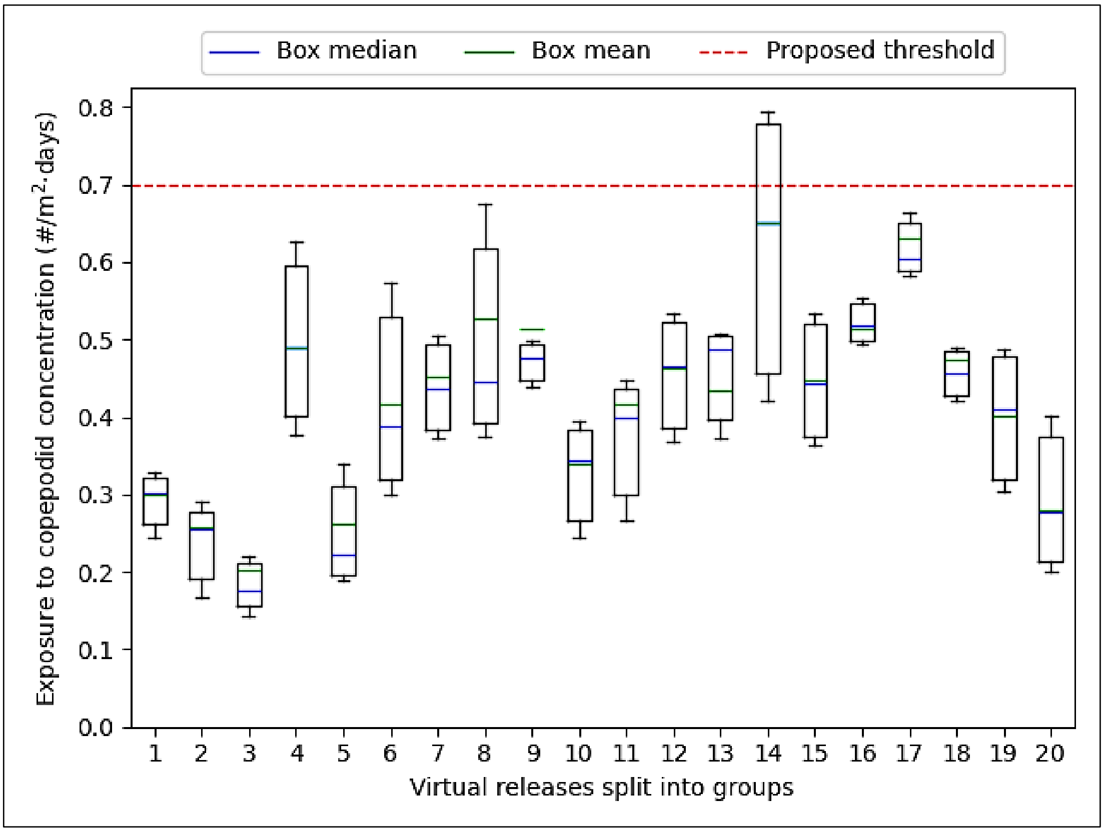

Figure A13 *Grouped boxplot copepodid exposure results for the River Shiel under the normal biomass scenario.*

A.4.2 1.75 × Biomass Scenario

Under the 1.75 × biomass scenario, cumulative exposures increased across much of the assessment period. Several release groups exhibited upper-percentile threshold exceedance and exposure conditions became more persistent.

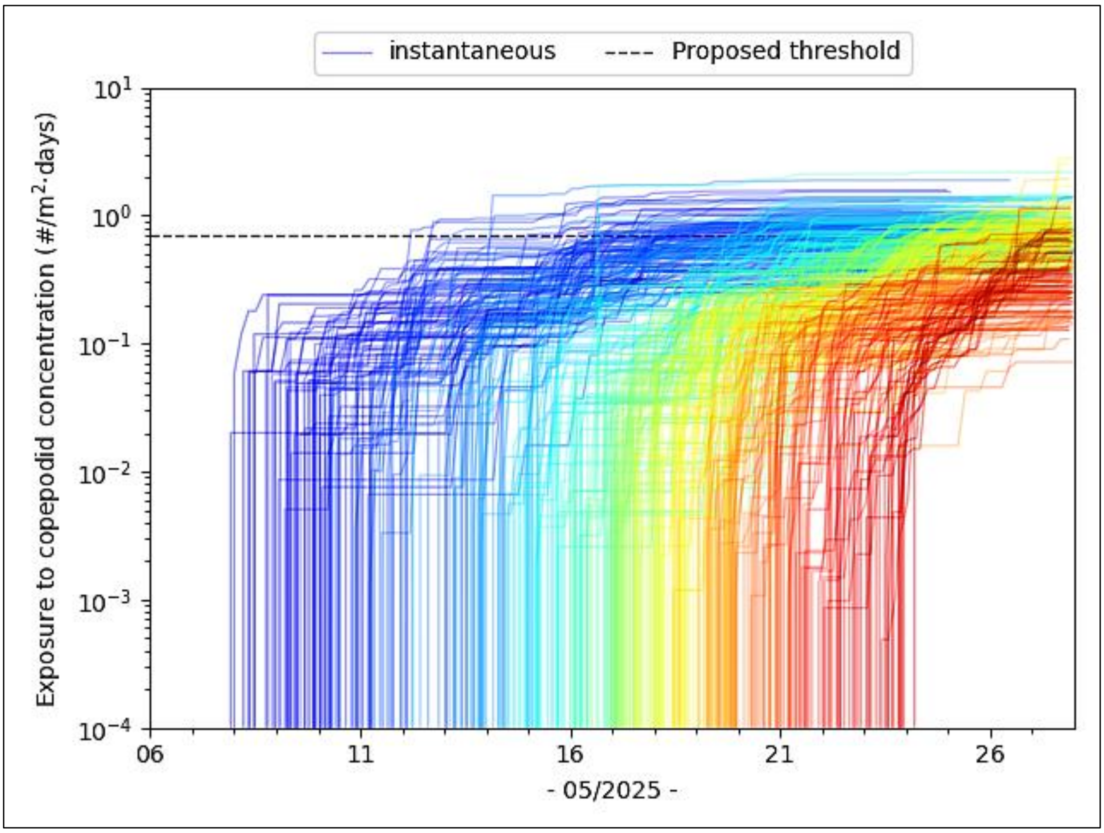

Figure A14 *Cumulative copepodid exposure curves for the River Shiel under the 1.75 × biomass scenario.*

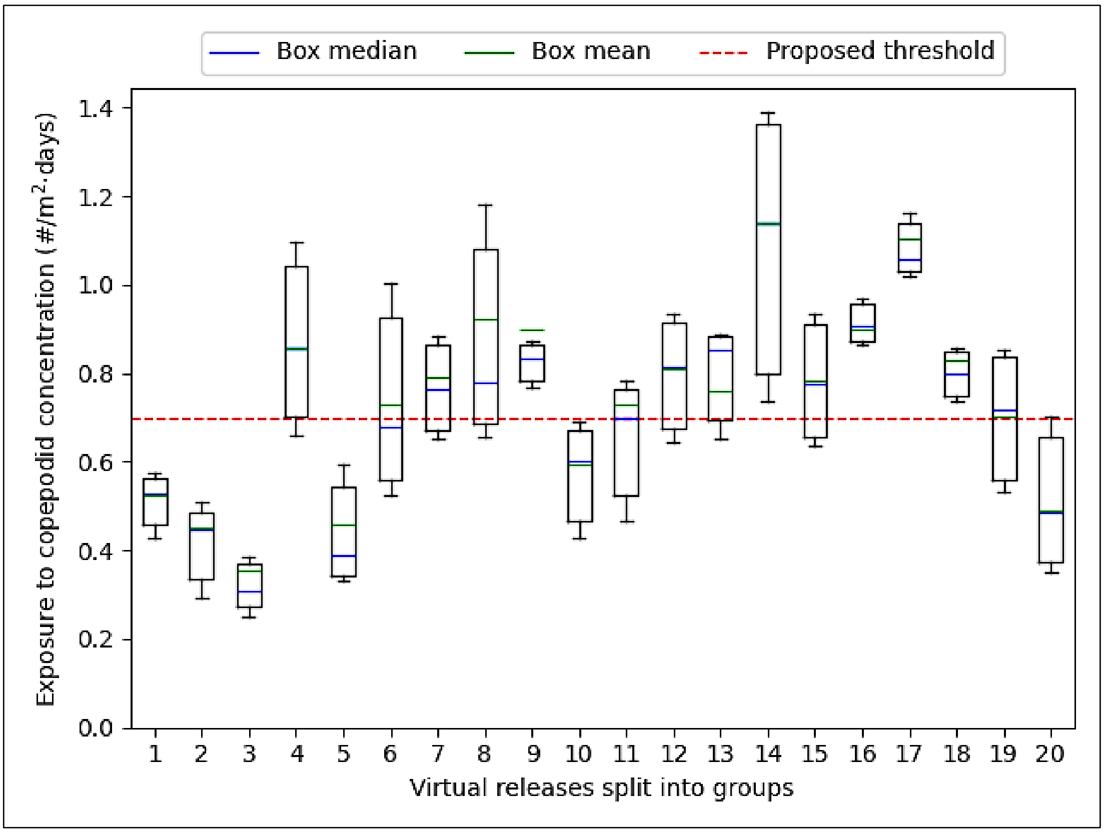

Figure A15 *Grouped boxplot copepodid exposure results for the River Shiel under the 1.75 × biomass scenario.*

A.5 River Sligachan (116 km)

Figure A16 *Virtual post-smolt migration route for the River Sligachan.*

A.5.1 Normal biomass Scenario

The Sligachan route exhibited the lowest cumulative exposure levels among the routes assessed. Median, mean and upper-percentile exposures remained below the proposed screening threshold for almost all release groups. Exposure variability was comparatively limited.

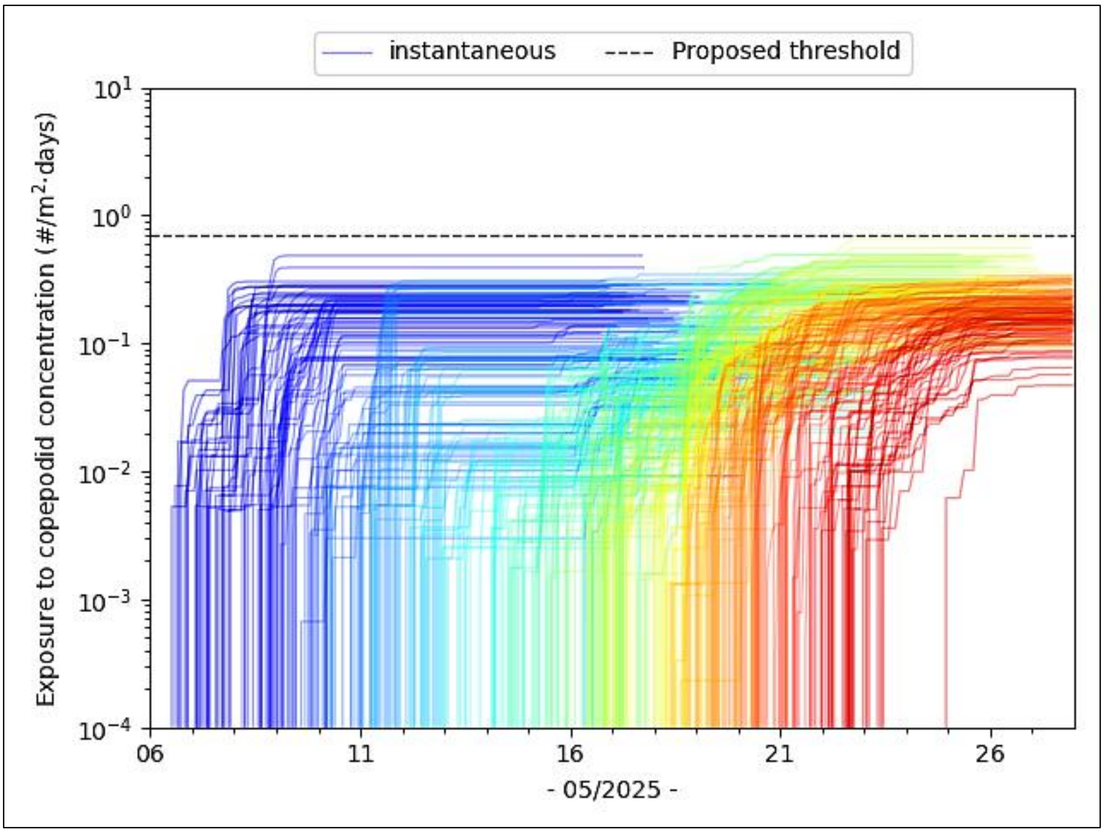

Figure A17 *Cumulative copepodid exposure curves for the River Sligachan under the normal biomass scenario.*

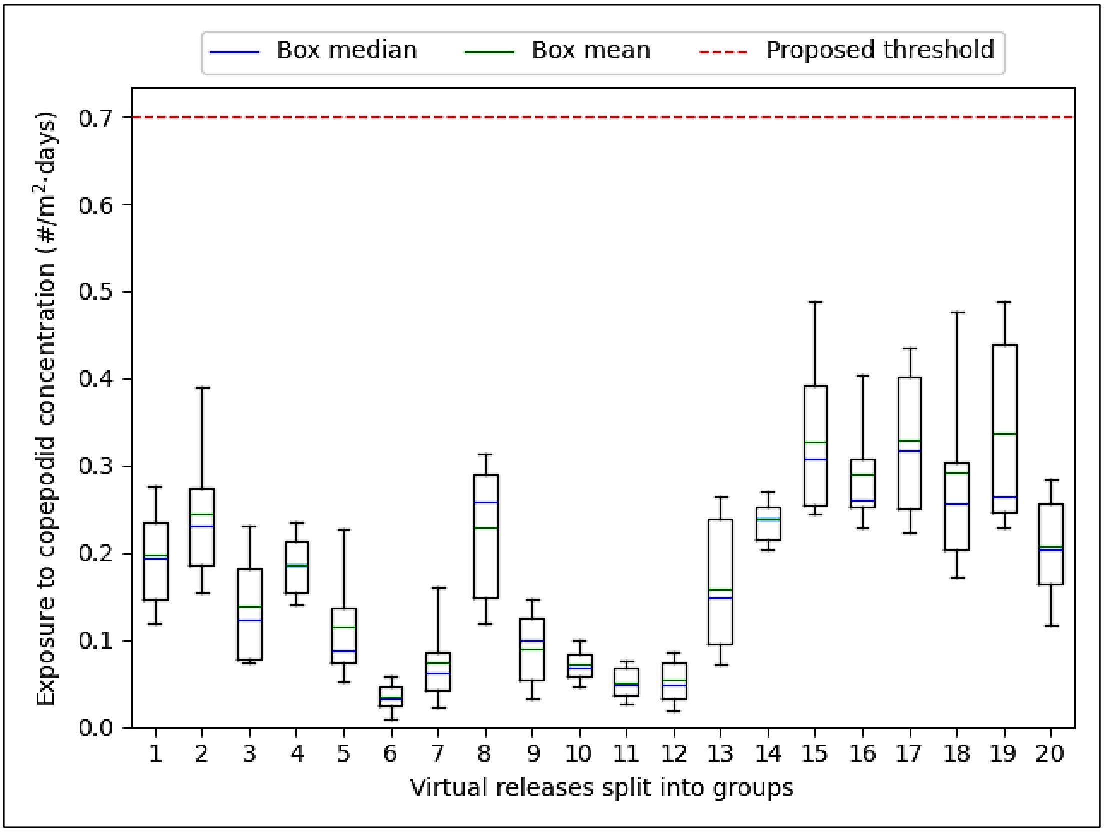

Figure A18 *Grouped boxplot copepodid exposure results for the River Sligachan under the normal biomass scenario.*

A.5.2 1.75 × Biomass Scenario

The 1.75 × biomass scenario resulted in increased exposure relative to the normal biomass case; however, cumulative exposures remained substantially below the proposed screening threshold for most release groups.

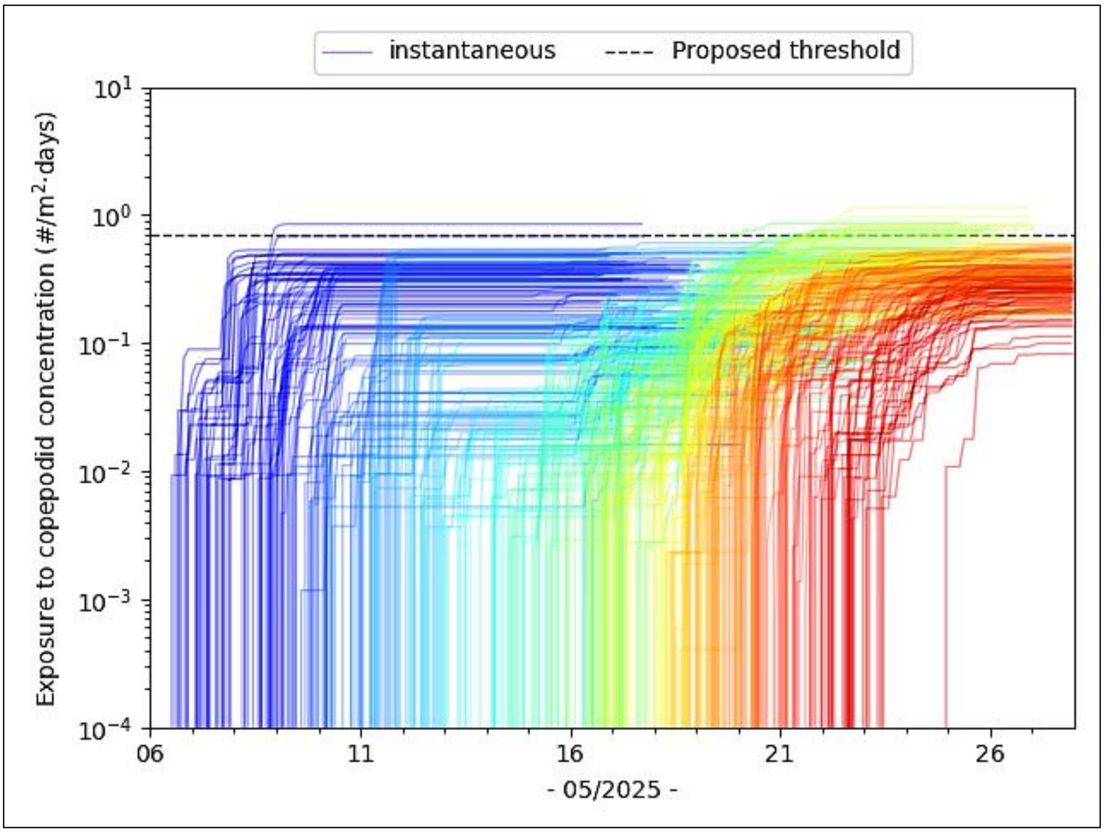

Figure A19 *Cumulative copepodid exposure curves for the River Sligachan under the 1.75 × biomass scenario.*

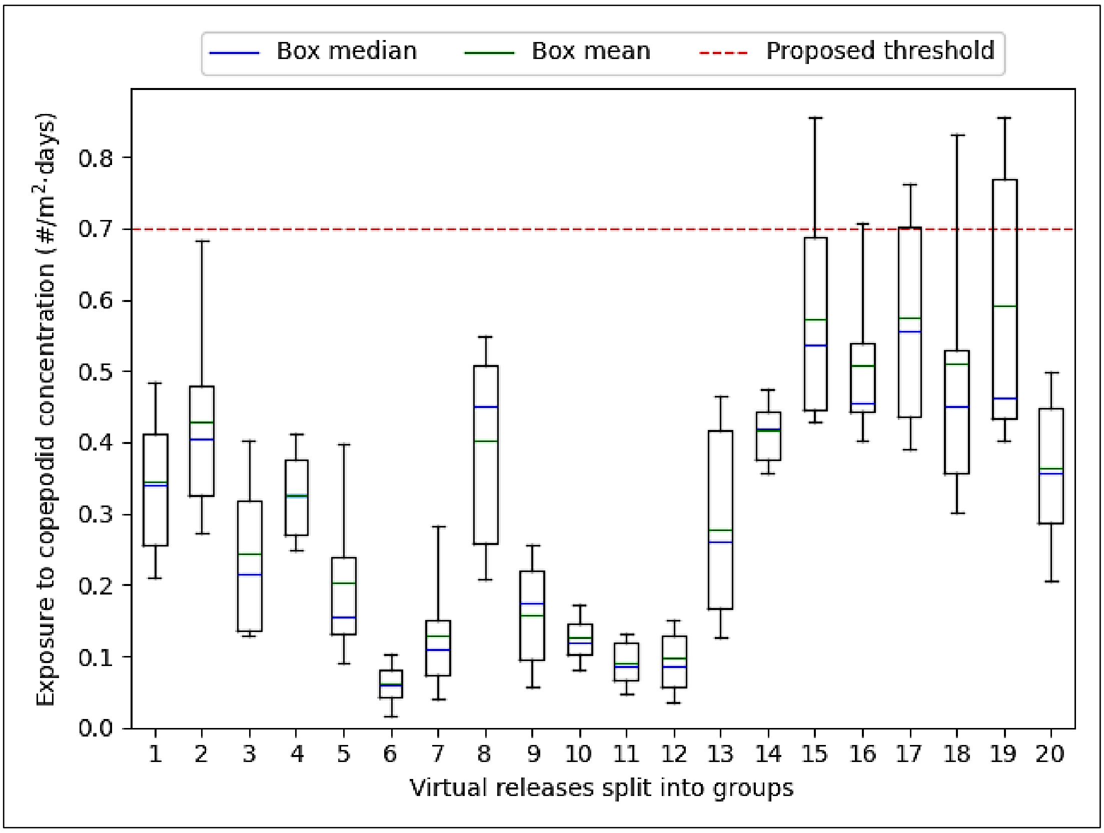

Figure A20 *Grouped boxplot copepodid exposure results for the River Sligachan under the 1.75 × biomass scenario.*

A.6 River Torridon (105 km)

Figure A21 *Virtual post-smolt migration route for the River Torridon.*

A.6.1 Normal biomass Scenario

The Torridon route exhibited some of the highest cumulative exposure levels observed among the individual river routes. While median exposures generally remained below the screening criterion, multiple release groups exhibited upper-percentile values approaching or exceeding the threshold.

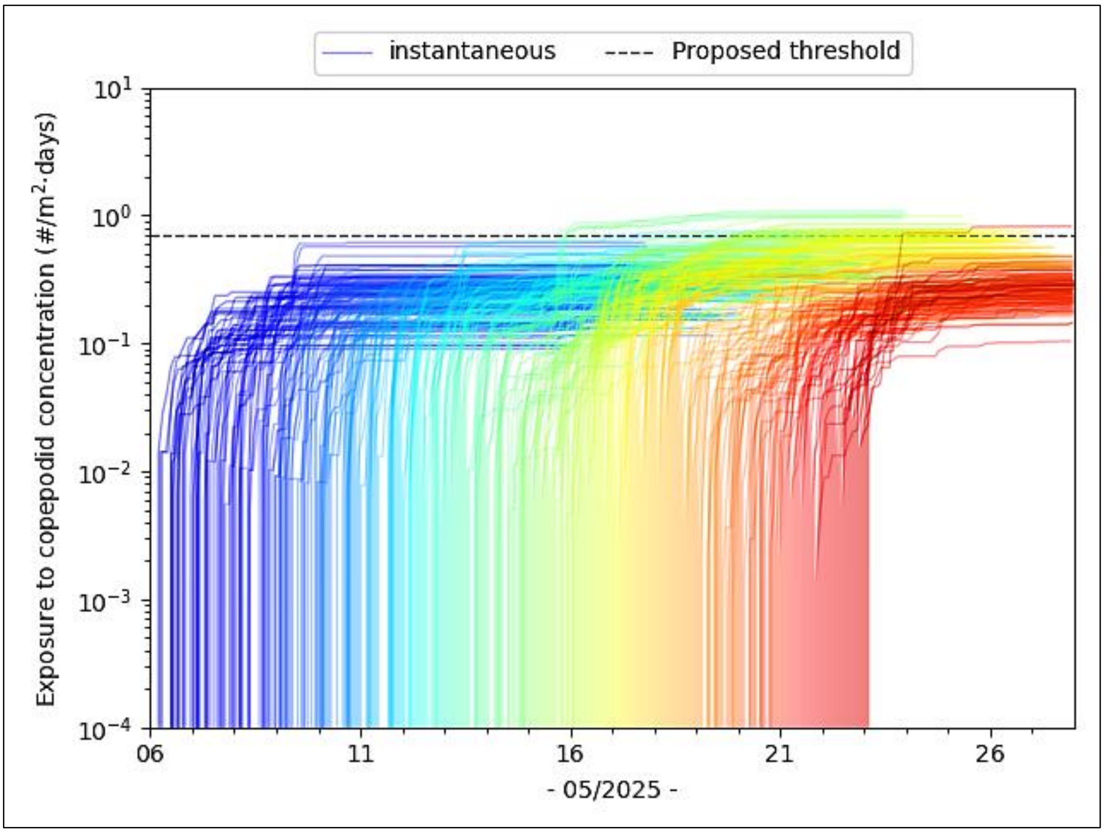

Figure A22 *Cumulative copepodid exposure curves for the River Torridon under the normal biomass scenario.*

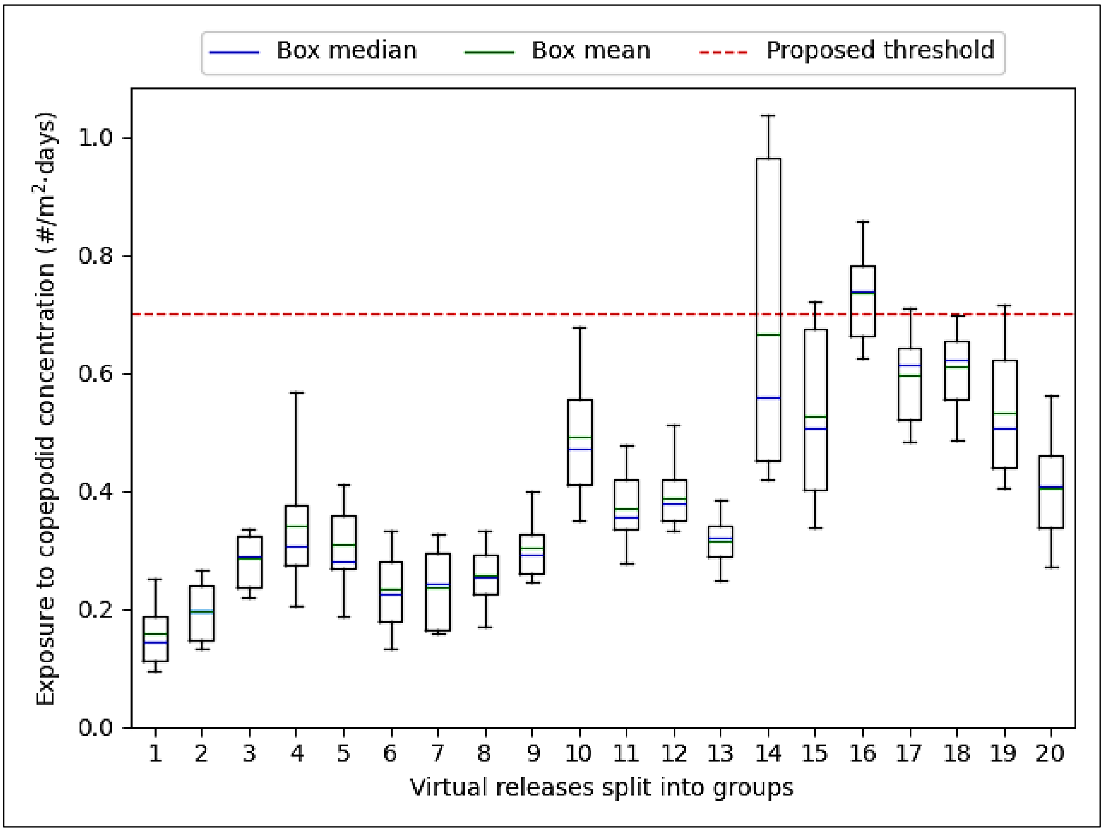

Figure A23 *Grouped boxplot copepodid exposure results for the River Torridon under the normal biomass scenario.*

A.6.2 1.75 × Biomass Scenario

The 1.75 × biomass sensitivity scenario produced a marked increase in cumulative exposure. Multiple release groups exhibited upper-percentile exceedance of the proposed screening threshold and threshold-relevant conditions persisted over a larger proportion of the assessment period.

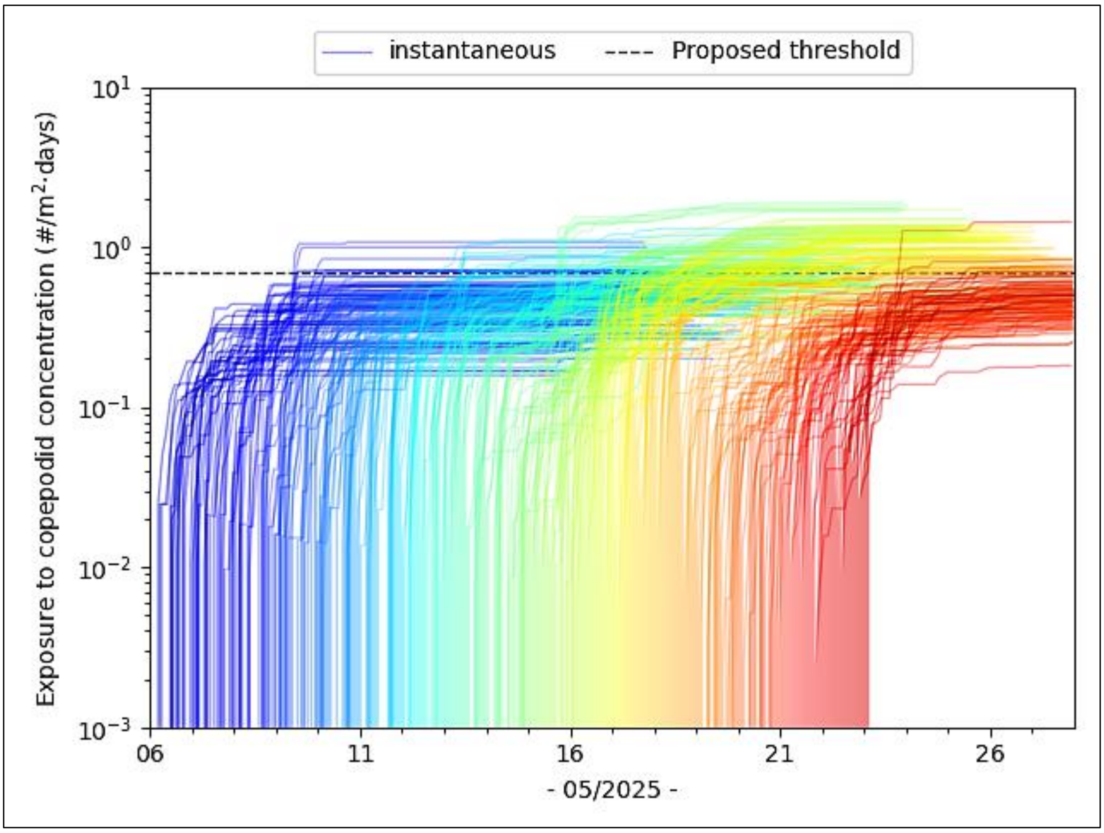

Figure A24 *Cumulative copepodid exposure curves for the River Torridon under the 1.75 × biomass scenario.*

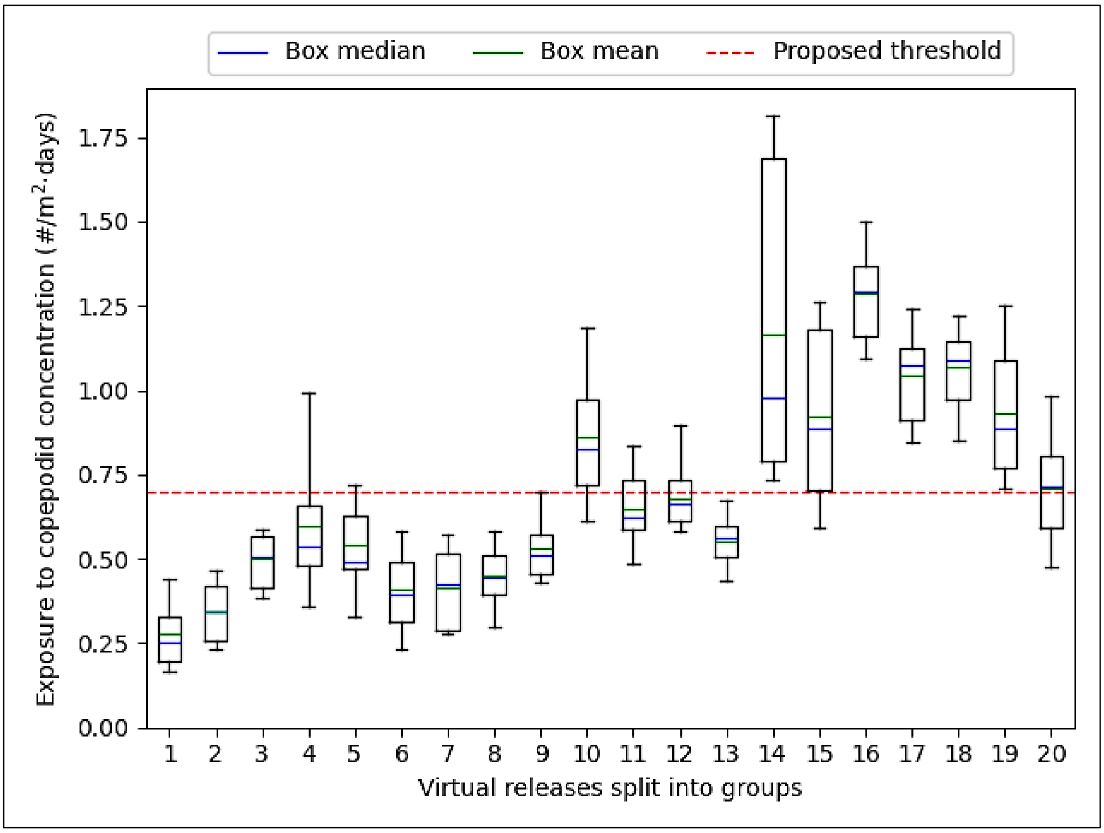

Figure A25 *Grouped boxplot copepodid exposure results for the River Torridon under the 1.75 × biomass scenario.*

A.7 Appendix Conclusions

The route-specific assessments presented in this appendix support the regional-scale findings presented in the main report. For all routes, the 1.75 × biomass sensitivity scenario increased both the magnitude and frequency of threshold-relevant exposure conditions. Exceedances were generally associated with upper-percentile exposure conditions rather than median conditions, indicating that exposure risk is strongly dependent upon migration timing and the evolving copepodid field. The results therefore demonstrate that increased regional lice loading increases the likelihood of threshold-relevant exposure for migrating post-smolts within the south Skye–Torridon system.