CFD Results Summary for the Proposed Loch Long Salmon Site at Beinn Reithe Utilizing Semi-Closed Containment Enclosures.

March 2021

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1. Executive Summary

The Beinn Reithe site is being developed by Loch Long Salmon as the first site in Scotland to utilise semi-closed containment (SCC) technology to farm salmon in the marine environment. This technology has been demonstrated to eliminate the threat of sea lice to the farmed, and hence wild salmon, and allows the capture and removal of organic particulate material (salmon faeces and uneaten feed) from the farm, significantly reducing the solid deposition per kilogram of fish farmed.

SEPA have agreed that computational flow dynamic (CFD) modelling could be used to demonstrate the particulate capture rate of the SCC design accepting the modelling methodology presented to them by Loch Long Salmon on 30th April 2020. SEPA additionally require that the CFD modelling results should be provided to them and these are included in this paper. (They also requested the nutrient enhancement 2-D modelling results. These were submitted to and accepted by SEPA in December and January 2021 respectively. The 2-D nutrient modelling will not be covered in this report.)

The results from the comprehensive CFD modelling campaign demonstrate that 85% of organic particulate is captured by the semi-closed containment enclosure design which was modelled. This capture rate was then incorporated into to a *Newdepomod* run to determine a safe maximum biomass on site, the methodology of which was prepared in collaboration with the Scottish Association for Marine Sciences (SAMS) and considered prior requests made by SEPA regarding ADCP data use and preparation.

The *Newdepomod* report as prepared by SAMS has been provided with this document (NewDEPOMOD Modelling Report: Loch Long Phase 3). The CFD report, due to it containing sensitive commercial and technical information on enclosure design that Loch Long Salmon is unable to share due to a confidentiality agreement with the IP owner, will not be shared in its entirety. Instead, as agreed with SEPA, key results will be provided in this report and a technical presentation on the CFD report via *MS Teams* will be offered to SEPA staff.

2. Abbreviations

CAR	Controlled Activities Regulation	RAS	Recirculated Aquaculture System
CFD	Computational Flow Dynamics	SAMS	Scottish Association for Marine Sciences
FCR	Feed Conversion Ratio	SEPA	Scottish Environmental Protection Agency
LLS	Loch Long Salmon		
MAB	Maximum Allowable Biomass		

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3. CFD Modelling

3.1. Background

As presented to SEPA by Loch Long Salmon in December 2020, a comprehensive review was undertaken by Loch Long Salmon throughout 2020 to identify the best way to model the behavior of faceces and uneaten feed both inside and outside the semi-closed containment enclosures. Modelling guidance for aquaculture in Scotland has been written for traditional open-net enclosures but due to the differences in deposition is not suitable in its standard form for use when modelling deposition from a farm using semi-closed containment technology. On completion of a review, a proposal and subsequent methodology was agreed by SEPA to use CFD modelling to determine the capture performance of the technology. The results of that CFD model are presented below.

Particles (faeces and any uneaten feed) predicted to be released by the SCC enclosure and lost from the system, would then be modeled using *Newdepomod* to determine the deposition profile around the Beinn Reithe site as per the open pen SEPA aquaculture modelling guidelines. Changes to the *Newdepomod* baseline assumptions would need made to account for the faeces and feed captured and removed from the enclosures, and the geometry of the SCC enclosures themselves.

3.2. Describing Faeces for CFD Modelling

In order to predict the fate of faecal particles using the CFD model, a literature review was first conducted to identify a consensus or range of faecal pellet characteristics which would be used for further modelling. A brief description of particles as described in four key studies is provided in Sections 3.2.1 – 3.2.4.

From preliminary CFD model runs it was clear that the settling velocity was the key driver of faeces behaviour inside the enclosure which is consistent with *Newdepomod* which only considers particle settling velocity when predicting the behavior of particles (Newdepomod User Guide). The CFD model predicted that particle settling velocity was influenced by shape and mass.

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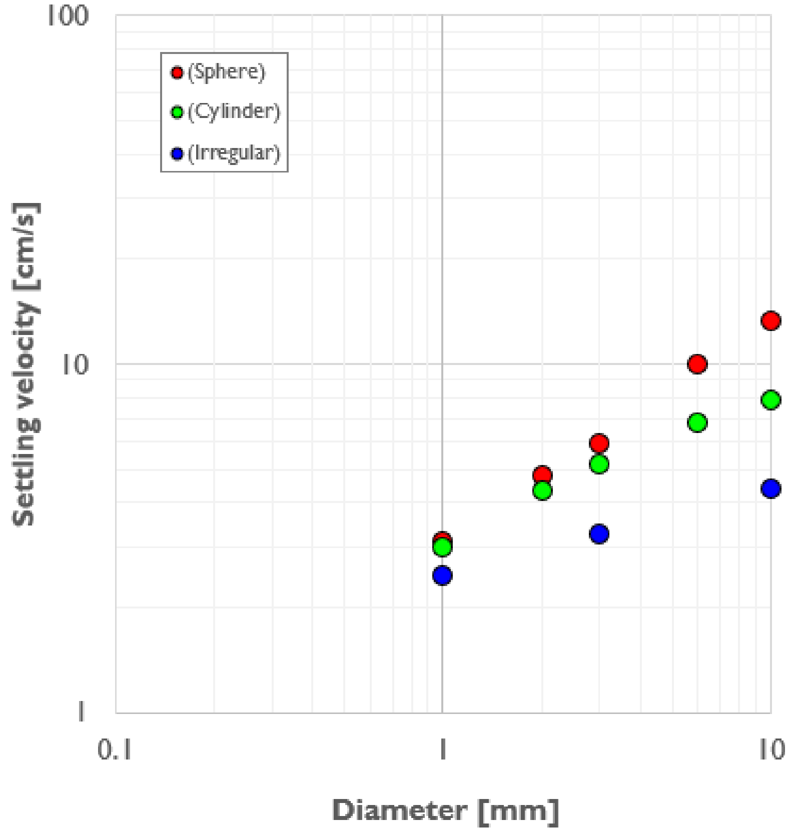

Figure 1.0 Relationship between particle diameter and settling velocity for three distinct shape factors as predicted by the CFD model. Particles with a greater settling velocity also have a greater particle diameter and mass.

3.2.1. Cromey

Many of the original assumptions that drive *Newdepomod* including faeces settling velocity are taken from a study by Cromey in 2002 which measured settling velocities of faecal particles to be from 1.5 - 6.1cm s^{-1} with a mean settling velocity of 3.3cm s^{-1} (Cromey et al, 2002). The paper itself does not provide any information on settling velocity by mass fraction, only the range and a mean.

The mean settling velocity of 3.3cm s^{-1} that Cromey reports is the mean by frequency of observed faecal pellet which ignores the mass of that pellet, i.e. a faecal pellet with a low mass which settles very slowly is weighted equally against a faecal pellet with a very large mass which has a greater settling velocity, and so the mean presented is artificially low. This was confirmed to be the case by

SAMS after they presented the distribution curve from the Cromey study to Loch Long Salmon, and is consistent with the relationship between particle diameter and settling velocity identified in the CFD model presented in *Figure 1*:

"There is not a mass-moment distribution. This means that if you only measure the settling velocity and use the mean it will be an artificially small value because of the potentially large numbers of small particles with low setting velocity but which do not contribute much to the mass flux. We do not have information on the joint distribution of settling velocity versus mass (density) of the particles. The same argument applies to eroded sediment." SRSL, email to SBA, 1st January 2020.

The CFD model provides a relationship between the settling velocity, particle diameter and predicted particle mass. The Cromey data can be replotted for mass (rather than frequency) by assigning an assumed mass to each particle based on that particles settling velocity. By doing this the mean settling velocity shifts from Cromey's 3.3 cm s^{-1} to a corrected 5.6 cm s^{-1} aligning well with the Chen and Bannister data sets (both the mean and the cumulative frequency).

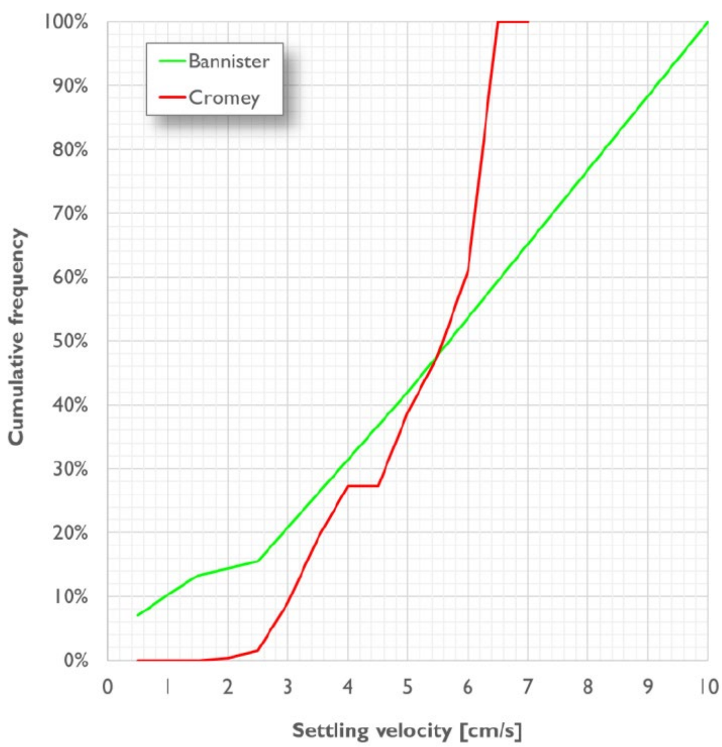

Figure 2.0 Comparison of cumulative frequency (mass) against settling velocity for Bannsiter and re-plotted Cromey data sets.

On comparison with other data sets, it is reasonable to assume that Cromey's method of reporting mean settling velocity by observed particle without considering particle mass has lead to a significantly underestimation of salmon faeces settling velocity.

[redacted]

3.2.2. Newdepomod

Newdepomod describes 100% of the mass of faeces as having a settling velocity of 3.5 cm s^{-1} (with a small, uniform distribution). This is only 6% higher than Cromey reported and may partially offset Cromey's reported mean being by particle frequency without considering mass. However, when compared against other data sets the 3.5 cm s^{-1} used by *Newdepomod* is still considerably lower (Newdepomod User Guide).

3.2.3. Chen

Chen observed salmon faeces as having a range of settling velocity between 3.7 – 9.2cm s^{-1} with a mean velocity range of 5.1 – 6.4cm s^{-1} across multiple groups (Chen et al, 2003).

3.2.4. Bannister

Bannister provides settling velocity by mass fraction from a much more recent study that recorded data under *in situ* conditions (Bannister et al, 2016). The mean settling velocity recorded by Bannister, is approximately 5-6 cm s^{-1}, overlapping well with the mean reported by Chen. Bannister records a much greater range of faeces settling velocity. Bannister records approximately 14% of all faeces to have a settling velocity below 1.5 cm s^{-1} compared to Cromey who records no faeces with a settling velocity lower than 1.5cm s^{-1} and Chen who reports no faeces to have a settling velocity less than 3.3 cm s^{-1}.

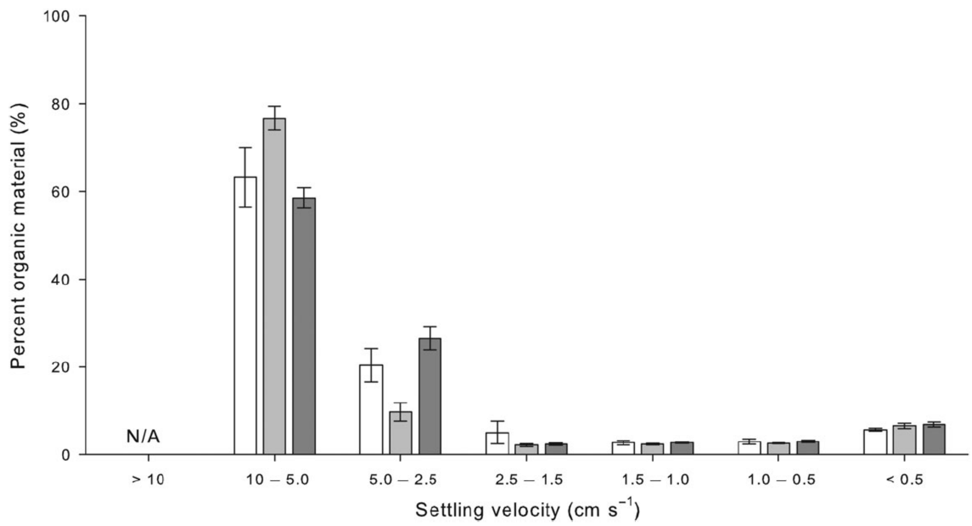

Figure 3.0 settling velocity of salmon faeces by mass fraction as described by Bannister et al 2016. The darkest band describes the observed faecal settling velocity from the largest sized class of fish, 3,500g. The large range of settling velocity covered by the first band makes it difficult to calculate an exact mean settling velocity.

3.2.5. Consensus

SEPA have informed Loch Long Salmon that through comparison of deposition predicted by *Newdepomod* (and its predecessors) against real world data from benthic surveys, they have some confidence in the 3.5 cm s^{-1} settling velocity to describe faeces behaviour released from open net salmon pens for modelling the predicted environmental effects/particle fates.

Therefore, though having the lowest mean settling velocity of all the data sets reviewed (once adjusting the Cromey results) Loch Long Salmon believe that, while likely very conservative, 3.5 cm s^{-1} is the most suitable description of faecal particles to use for CFD modelling and subsequent deposition modelling.

To increase confidence in the capture rate results when using this dataset, Loch Long Salmon modelled the enclosure capture efficiency for a range of particle settling velocities in order to assess whether the capture result for faeces as described by *Newdepomod* sits within a reasonable range of results from modelling other datasets.

3.3. Results

The CFD model predicted that capture efficiency is somewhat dictated by enclosure volume turnover time for a given geometry. A decreasing turnover time facilitates an increase in particle capture across the range of turnover times modelled in this study. A decreased turnover time, optimized for fish welfare, provides the farmer many other advantages additional to increased capture rate such as a significantly reduced power demand and a longer working life of pumps and other equipment and should be favored.

All results discussed further in this document will assume a turnover time of 100 minutes unless specifically detailed otherwise, i.e., over 100 minutes the volume of the enclosure is pumped through the enclosure. This rate has been recommended by technology providers and is based on the experience of salmon farmers in Norway.

The model predicted the fate (capture rate) of particles over a range of settling velocities. The settling velocity range for feed pellets was available directly from the feed manufacturers and corresponded well with the *Newdepomod* baseline assumptions for feed pellets. The faecal particle settling velocity range was determined by the combined ranges of the studies listed above in 3.2.

[redacted]

Table 1. Results of feed and faecal particle capture for a range of settling velocities as predicted by the CFD model. The capture rate for the lightest two bands has been given as zero due to a numerical issue leading to a failure to predict the fate of these particles in the model.

Representative settling velocity value for bin (cm/s)	Capture rate (per bin)
(Feed)	100%
0.5	0%
1.5	0%
2.5	36%
3.5	85%
4.5	98%
5.5	99%
6.5	100%
7.5	100%
8.5	100%
9.5	100%

The model predicted a 100% capture rate for any particle with a settling velocity greater than 6.5 cm s^{-1}. From a review of feed pellet settling velocities, all pellets were described as having a settling velocity of 9 cm s^{-1} and above, and so it can be assumed that all uneaten feed pellets regardless of formula will be captured, including a pellet as described by the *Newdepomod* user guide.

The model predicted a very high rate of particle capture for most settling velocities above 3 cm s^{-1} (69% or higher for faster settling rates).

For settling velocities lower than 2cm s^{-1}, 0% capture is reported. This is due to an issue with the modelling and not a true reflection of modelled enclosure capture performance of faecal particles at these lower bands. The below explanation is taken from the CFD report as provided by Partrac;

Despite best efforts to do so, CFD predictions are not achieved for settling velocities lower than 2 cm/s due to numerical difficulties when attempting to simulate these cases. As a consequence, the predictions for waste capture for the smallest faeces particles (presented later in Figure 6) may be conservative – waste capture for particles <2 cm/s is presented as zero in Figure 6, but a low proportion of the smallest particles might be captured in the real pen.

In order to understand the overall capture rate of faeces, the capture rates presented in *Table 1* were applied to the observed distributions of faeces settling velocities described in the studies in Section 3.1. The faeces settling velocity as reported by Newdepomod, due to its simplicity, was the only description of faeces that provided a concise settling velocity that the results could be applied

[redacted]

to neatly. The other data sets did not provide the mass fractions in sufficiently narrow settling velocity bands to draw an exact overall capture percentage and so performance capture has been applied in some cases to multiple interpretations of the same data set in order to build confidence around the overall capture rate.

Table 2. Summary of CFD particle capture results as described in *Table 1* applied to various data sets describing the distribution of faeces settling velocity. For full results, including adjusted results for Banister data sets see Appendix 1. The mass balance of expected discharge between faeces and feed was taken directly from the *Newdepomod* User Guide. The Bannister results assume faeces from the largest class of salmon observed.

Data Set Interpretation	Capture Efficiency Faeces (%)	Capture Efficiency Total- faeces + feed (%)
Cromey, when assigning mass to observed particles*	91	92
Chen, crude interpretation using mean and range	96	97
Newdepomod User Guide (Baseline)	85	88
Bannister S-Curve, Coarse**	83	86
Bannister Linear, Coarse**	82	85
Bannister Linear, Refined* **	80	84

* Data sets used to demonstrate capture efficiency in CFD report at various circulation rates

**Bannister results are not adjusted to account for failure to model particles lower than 2 cm s^{-1}.

The capture performance when applied to the Bannister datasets, who recorded a higher percentage of faeces mass with a settling velocity < 2cm s^{-1}, is artificially low due to zero percent capture rate being assigned to these lightest fractions. If allowance is made for only 10% capture of the lightest bands of faeces, capture performance of faeces increases by 2% and total capture by 1% in all three Bannister examples.

If the results are adjusted to account for 10% capture of the lightest bands of faeces then the range of faeces capture efficiency across all data sets and interpretations is 82% - 91%. Including wasted feed, the capture rate range is 86% to 92% of all solid material.

Diet Manipulation to Improve Faeces Capture:

It is presumed that Bannister observed faeces from salmon on a conventional diet. Loch Long Salmon will use a RAS style diet that has been engineered to reduce fine particles of faeces being produced once digested by the fish. As presented in *Figure 1*, the CFD study linked particle diameter, or mass, to lower settling velocities. Particles with a diameter of less than 100 µm modelled as having a settling velocity of less than 1cm s^{-1}, these relatively small particles are reduced by approximately 75% when using a RAS diet.

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If the effect of changing diet is applied to the Bannister data set, the faeces capture performance increases further to 88%.

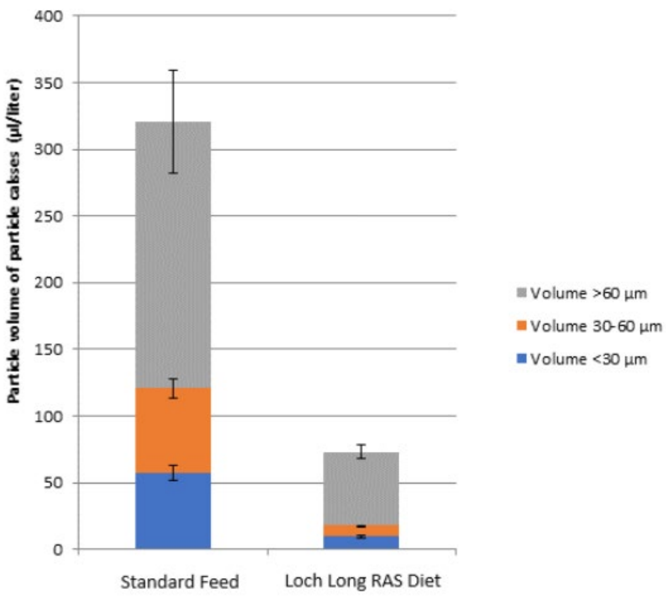

Figure 3.0 Data provided by Biomar of comparison of salmon faeces from salmon on different diets. The RAS style diet reduces the fraction of faecal particles that have been modelled to have a settling velocity of <1 cm s^{-1} by approximately 75%. See Appendix 2 for more information on RAS style feed.

3.4. Conclusion and Recommendations for Further Modelling

From the modelling results, Loch Long Salmon have concluded that:

1. For a given geometry and within the rates modelled, overall particle capture rate increases when decreasing circulation rate;
2. Capture performance improves as settling velocity of particles increases, which can be controlled by diet, and;
3. As the range of total capture percentage across the various data sets is very narrow, the overall capture results are robust.

A Conservative Approach:

From the understanding of faeces and feed behaviour within the pen gained from the modelling process, Loch Long Salmon have confidence that using the particle capture rate of faeces as described by *Newdepomod* as the assumed faeces capture rate for the modelled pen is a conservative approach, as the default settling velocity used in *NewDepomod* is lower than is likely to be the case in reality. Additionally, farm management practices (including use of RAS feed formulations, feeding regime and the enclosure turnover rate) can be adapted in order to improve the waste capture beyond what has been modelled and presented in this report.

Baseline *Newdepomod* Model Recommendations/Proposals:

As the total capture rate of faeces particles as described by *Newdepomod* (the only description of faeces particles that has been field tested against other particle tracking models) sits within the total capture range of all data sets modelled, Loch Long Salmon recommend that the 85% faeces capture rate is suitable, conservative and the most appropriate rate to use for subsequent deposition modelling. It is proposed that LLS apply an 85% reduction to the mass of faeces produced per salmon and a 100% reduction in uneaten feed in the *Newdepomod* run which will support the Beinn Reithe CAR application. The daily feed rate will require adjusting down to account for uneaten feed being captured rather than being eaten (which would wrongly increase the mass balance of faeces produced).

No other changes to the profile of faeces will be made as it has been determined that results from *Newdepomod* are sensitive to changes in faeces settling velocity (modelled in phase 1 by SAMS for Loch Long Salmon), do not benefit from being previously field validated, and therefore results adopting these changes are unlikely to predict an accurate deposition profile from a marine farm.

The only other change to the baseline assumptions that will be made when running *Newdepomod* will be to the particle discharge locations to reflect the geometry of the bag and outlets as previously presented to SEPA and detailed in the *Newdepomod* report provided by SAMS. The jetting effect will not be simulated by using a stretched particle release area at each port as this was found to be too difficult to size accurately (the CFD model tracked particles inside the enclosures but not once released). When experimenting with the sensitivity of using stretched particle release areas to simulate the jetting effect from the SCC ports, it was found that by releasing particles over a rectangular area 2.5m long and 0.5m wide perpendicular to the angle of the enclosure wall at each side port, the mean intensity across the 250g contour decreased by 20% with no significant increase in the area of the 250g contour itself (+~1%). Not modelling the jetting effect is therefore likely to add some additional conservatism to the predicted maximum allowable biomass predicted. See Appendix 3 for results of sensitivity run.

Newdepomod Additional Comparative Runs:

To support the CAR application by providing a comparison of deposition and/or biomass when further changes are made to the model, Loch Long Salmon will carry out two further biomass runs using *Newdepomod*.

The first, as requested by SEPA, will rerun the previously predicted maximum allowable biomass but reset all the baseline model assumptions. This will allow a comparison of benthic impacts when using an open net farm compared to SCC enclosures at this location. The benefits will be very significant due to an 88% reduction in particles released.

The second supporting run will be another biomass optimization run applying the particle capture rate demonstrated in the CFD model but with a reduced daily feed rate. The default *Newdepomod* setting calculates the daily feed rate by applying 0.7% to the MAB which is assumed to be the standing biomass for 365 days. The maximum average daily feed rate over any 365-day period within a farming cycle planned for the Beinn Reithe site is only 0.53% of the MAB. The average daily feed rate as a percentage of MAB over the recurring two-year cycle is planned to be as low as 0.4% of MAB. Loch Long Salmon will submit the results from this run to provide a comparison of the safe biomass expected against the biomass predicted using the *Newdepomod* assumed feed rate for a given deposition profile.

4. Dewatering plant outfall

85% of faeces, and 100% of feed pellets have been modelled to be captured. Once captured this material will be pumped ashore for dewatering. This material will be carried from each enclosure in water pumped at approximately $1m^3 min^{-1}$. The treatment facility on the shore will dewater the waste stream so that it is suitable to be removed from site and used as a useful biproduct (fertilizer ingredient and waste to energy). A methodology statement will be provided to SEPA on how the impact from the outfall, which releases seawater that has been removed from this waste stream back into the loch, will be assessed. This will be treated as a separate licensing activity as agreed by SEPA.

5. References

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Cromey, C. J., Nickell, T. D., and Black, K. D. 2002a. Depomod – modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture, 214: 211–239.

Newdepomod User Guide, 2018.

Partrac, 2021. CFD Modelling of Hydro-Sedimentary Dynamics within a Semi-Enclosed Fish Pen for Loch Long Salmon.

SAMS, 2020. Email to Loch Long Salmon on the mass-moment distribution built into Newdepomod from Cromey data.

SRSL, NewDEPOMOD Sensitivity runs for pen geometry and jetting effect 2020.

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6. Appendices

Appendix 1 – Full table of capture results. Bannister data has been updated to reflect numerical issues in the CFD model and the change in faeces particle size distribution brought on by a switch to RAS-style diet.

Data Set Interprotation	Capture Efficiency Faeces (%)	Capture Efficiency Total (%)
Cromey, assigned mass to observed particles	91	92
Chen, crude interpretation using mean and range	96	97
Faeces as described by *Newdepomod* *	85	88
Bannister S-Curve, Coarse (unadjusted)	83	86
Bannister Linear, Coarse (unadjusted)	82	85
Bannister Linear, Refined (unadjusted)	80	84
Bannister S-Curve, Coarse (10% capture lightest bands)	85	87
Bannister Linear, Coarse (10% capture lightest bands)	84	86
Bannister Linear, Refined (10% capture lightest bands)	82	85
Bannister S-Curve, Coarse (RAS style feed)**	89	91
Bannister Linear, Coarse (RAS style feed)**	88	90
Bannister Linear, Refined (RAS style feed)**	89	91

* Chosen for further deposition modelling.

**The RAS style feed variations of the Bannister results do not also assume a 10% capture rate of the lightest fractions.

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Appendix 2 – Email from Biomar to LLS detailing change in faeces particle size distribution when using RAS style diet.

15 March 2021

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<u>Loch Long Salmon Farm</u>

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As discussed, our diets for recirculation systems (RAS) are designed not only to meet the nutritional requirements of the fish, but to reduce the nutrient discharges and improve faecal stability. Through the selection of highly digestible raw materials it is possible to reduce the organic and nitrogenous waste from faeces, and when combined with faecal binders it is also possible to improve faecal stability and reduce the volume of small or low mass faecal material.

The use of BioMar diets containing faecal binders at your proposed Loch Long site would mean that the semi closed containment system planned to be used would be able to remove more of the faecal material than if you were using a non-RAS optimised diet.

This is an exciting and innovative project, and it's good to see companies bringing new technology to Scotland which will help with the sustainable growth of the aquaculture industry in Scotland. With over 25 years involvement in Scottish Aquaculture, BioMar support the continued development of an industry we are product to be part of.

Kind regards,

[redacted]

Powered by Partnership. Driven by Innovation. 1 / 1

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Appendix 3 – Jetting Effect Sensitivity Run carried out by SAMS for Loch Long Salmon

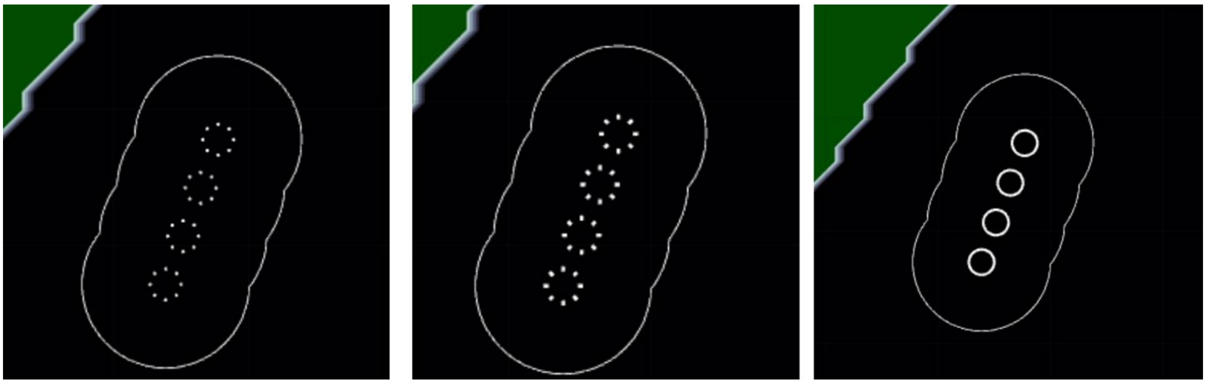

Diagram of cage shapes/particle release zones for *Point* configuration (8 spherical cages, 0.5m diameter, placed at edge of where normal cage would be) and *JetSmall* configuration (8 rectangular cages, 0.5m width and height, length 2.5m, placed with 'inside' edge at edge of normal cage) and *Normal* configuration (standard cage shape typical of *Newdepomod* modelling). Note calculated allowable mixing zone is the same in each case.

	Sensitivity Run – Jetting Effect	
	250g contour - % of allowed area	mean across 250g contour
'jetSmall'	77.63	11264
'normal'	78.31	13894
'point'	76.73	13999

Results from modelling the deposition of an arbitrary biomass with no capture rate applied using three cage shapes as described above. Loch Long Salmon will use a variation of the *Point* approach for the CAR application *Newdepomod* run which appears to be the most conservative across all results. When operational, any jetting effect may provide some benefit and reduce benthic impact as presented in the table above.