VEMENTRY DEVELOPMENT EQUILIBRIUM CONCENTRATION ENHANCEMENT MODELLING

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1. Introduction

As part of the screening and scoping process, in relation to a proposed new fish farm site, Vementry in Shetland, Cooke Aquaculture Scotland have assessed the potential water column impacts. The predicted nutrient enhancement likely to result from production at the proposed development has been evaluated. This will form a worst-case scenario to quantify any potential adverse effects from the proposed development.

1.1 Background

Fish farms release dissolved inorganic nutrients through excretion from the fish (ammonia and phosphate), particulate organic nutrients through defecation, and dissolved organic nutrients through resuspension from the particulate fractions. The majority of the nitrogen (N) wastes are released to open waters (68% of total) in the form of ammonia whereas the majority of the phosphorus (P) is accumulated in sediments (63%). Dissolved inorganic nutrients are rapidly assimilated by phytoplankton and bacteria and are then transferred to the higher trophic levels in the planktonic food web (Olsen and Olsen, 2008).

These nutrients can enhance the growth of marine plants and algae within the water column. High nutrient levels may lead to algal blooms and depletion of oxygen in the water column; however, it is not easy to identify the causal links of harmful algal blooms. In the marine environment, nitrogen is typically a limiting nutrient so its addition will dictate the amount of primary production (algal growth). Phosphorous is not considered a limiting nutrient for phytoplankton in marine waters and is therefore considered to be of lower importance than nitrogen (Environmental Assessment Office, 1997). A Scottish Executive Review of environmental impacts of aquaculture concluded that the present level of fish farming is having only a small effect on the numbers and growth rate of phytoplankton and that this effect should not be a cause of concern except in poorly flushed areas or areas of high farm density (Scottish Executive, 2002). It is also recognised in many areas, especially rural areas, that nutrient inputs from agricultural land runoff exceed those from fish farming operations. A number of steps have been taken by the sector in recent years to reduce nutrient release into the marine environment through improvements in husbandry practices, feed technology and feed quality.

1.2 Site description

The proposed Vementry development is located off the northern coast of Vementry, Shetland. This northern side of Vementry faces out into the navigational channel of the Swarbacks Minn, which is a waterbody (ID: 200268) classified under SEPA's River Basin Management Plan. The navigational channel is approximately 1.5km wide with depths ranging between 40m – 115m, and water depths ranging between 40m – 110m for the proposed development area, with greatest depths occurring to the north of the development area.

The proposed fish farm will consist of a single group of 10 x 120m circular pens with a net depth of 21m. These are arranged in a 2x5 layout moored within 85m grids, orientated on a bearing of 295.5 ^{o} (Figure 1). The maximum proposed consented biomass for the site is 1350T, with a stocking density of 5.61 kg m^{-3}. The site location will be 430285E, 1161466N.

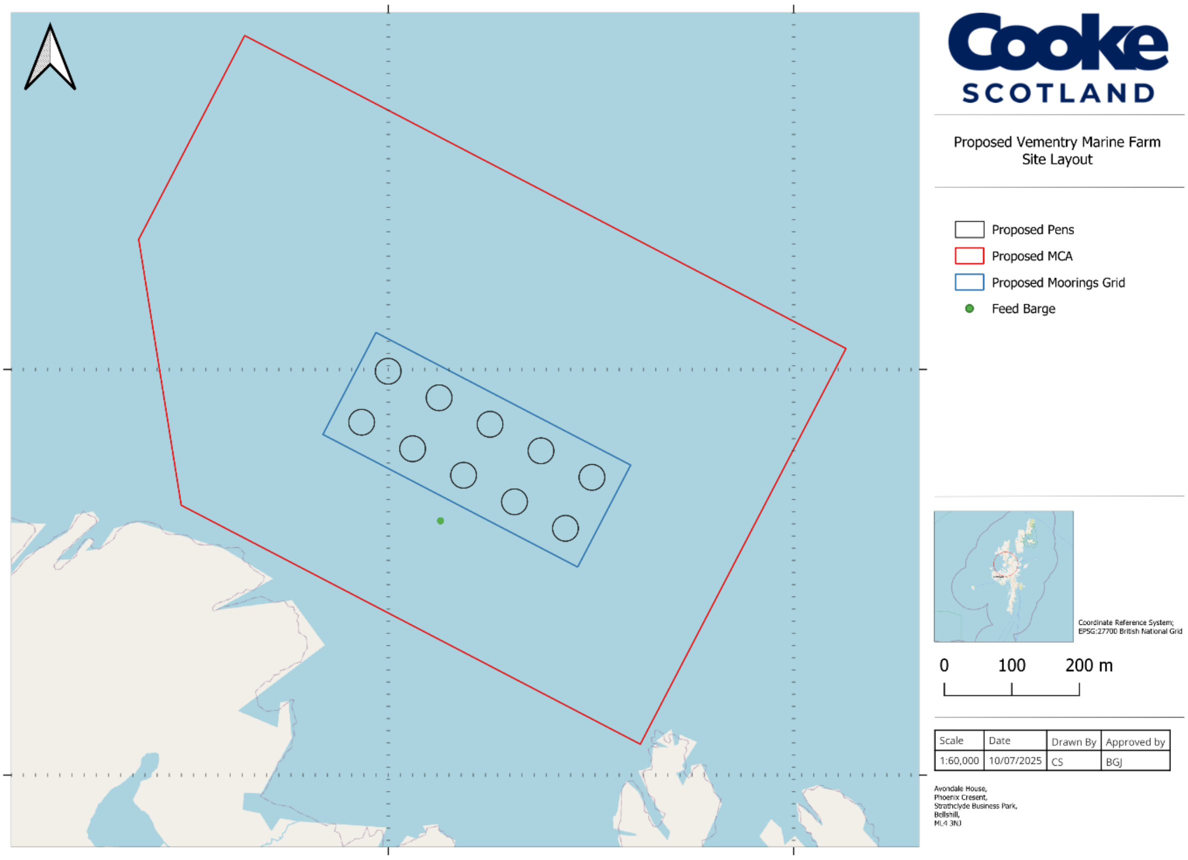


Figure 1. Proposed setup for the Vementry site.

Details of the Vementry fish farm and the other fish farm sites in the surrounding area (<10km) can be found in Table 1, with their locations illustrated in Figure 2.

Table 1 Details of all existing and proposed fish farms within the extended vicinity of Vementry.

CAR licence number	Site name	Operator	Maximum biomass (tonnes)	Site centre position		Distance from Vementry (km)
				WGS 84	NGR	
CAR/L/5006546	Vementry	CAS	1350[1]	60.336121, -1.4532962	430285 1161466[2]	0
CAR/L/1025370	Lee of Burrafirth	CAS	962	60.317967, -1.3728000	434749, 1159484	4.86
CAR/L/1004195	Stead of Aithness	CAS	2442.5	60.322533, -1.4190833	432187, 1159967	2.42
CAR/L/1003004	Cole Deep	SSF	2178	60.350973, -1.3534372	435782.1 1163170	5.76
CAR/L/1108670	East of Papa Little	SSF	1750	60.344669, -1.3814279	434244.1, 1162453	4.06
CAR/L/1004042	Olnafirth South (Site 1)	SSF	1000	60.360612, -1.3236666	437414.1, 1164260	7.66

[1]Proposed biomass
[2]Proposed location

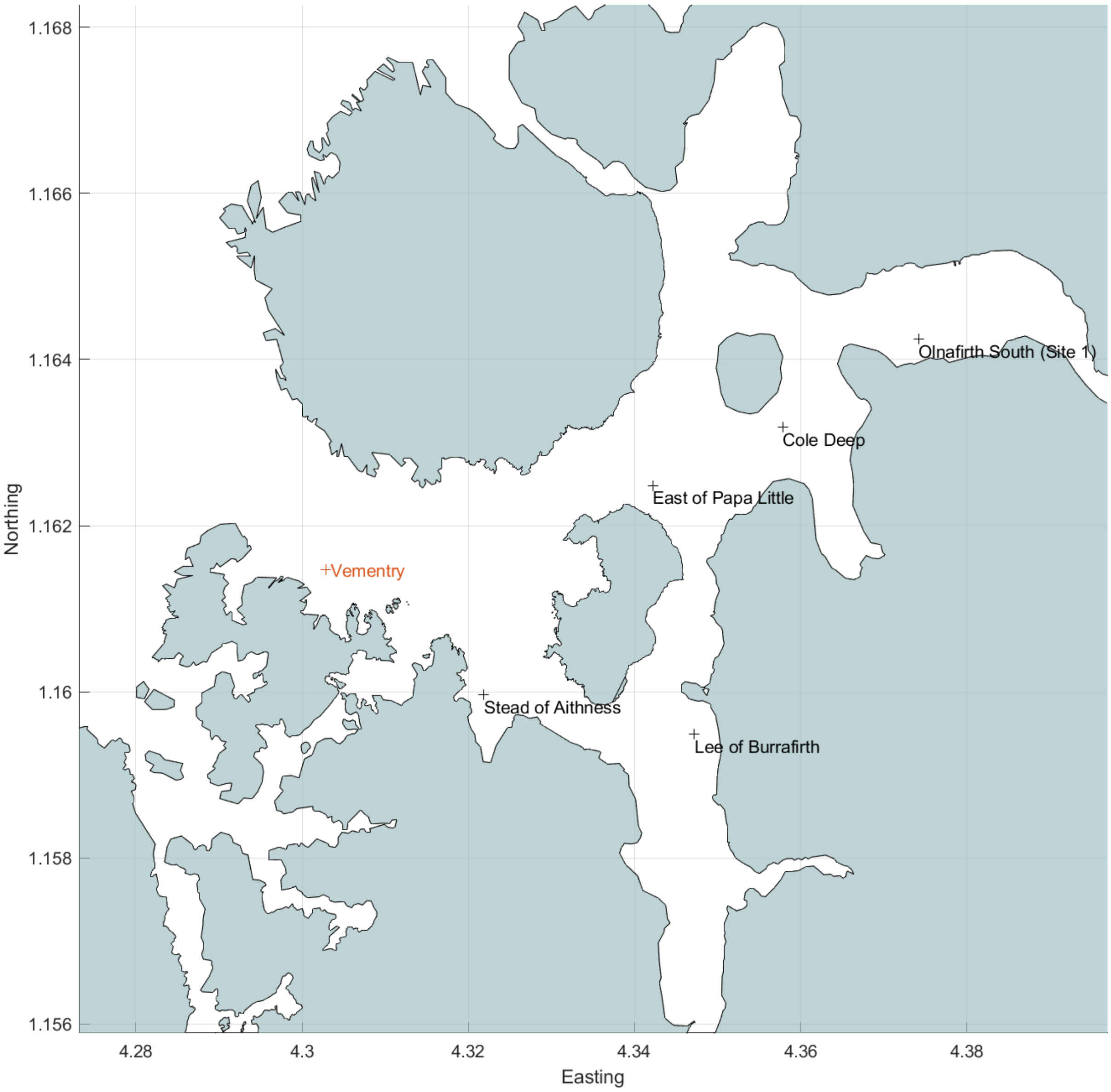


Figure 2. Locations of the fish farms within 10km of Vementry

2. Nutrient modelling

Nutrient enhancement of a water body can be estimated by using two types of models. The first is used for assessing semi-enclosed water bodies, described by Gillibrand (2002). This model is a technique used by Marine Scotland in the 'Locational Guidelines for Authorisation of Marine Fish Farms in Scottish Waters' issued to aid marine fish farm planning. This model is based on a semi-enclosed loch scenario, with exchange of the water body achieved through the ebbing and flooding tide. This flushing allows a constant nutrient input while maintaining a steady state concentration. The second model is used to assess sites which are located in open water (Gillibrand 2006). Length and width of nutrient plumes are defined by parameters extracted from hydrographic survey data, where current velocities have been resolved to along-shore and across shore components. The standard ECE model described by Gillibrand (2002) and designed for enclosed loch systems is used to model the additional nutrient loading caused by the proposed Vementry development.

2.1 ECE model

The proposed Vementry farm is located in Swarbacks Minn, Shetland, classified as a coastal water body (ID: 200268) in the Scottish Water Framework Directive (WFD). The waterbody is 20.33 square kilometres in area, and is a category 2 waterbody as per MSS Locational Guidelines (April 2024).

For the Vementry farm, the semi-enclosed water model is more appropriate to use to assess nutrient enhancement, as it is located at the entrance of Swarbacks Minn. The site is classed as moderately quiescent and weakly flushed, with a partial resuspension of the material released from the site being exported in a predominantly south-eastern direction. Due to the presence of other fish farms located near the proposed farm and the dynamic nature of the surrounding waters, active fish farms located within 10km of the proposed location will be incorporated in the assessment.

2.1.1 ECE modelling methodology

The ECE model is a simple box model used to predict the level of enhancement of soluble nutrient nitrogen from fish farming sources, treating nitrogen as a conservative substance. The model is a function of the flushing rate of a sea loch or voe, nitrogen source rate and total consented biomass within a defined area.

The nutrient considered by the model is nitrogen, mainly in the form of dissolved ammonia, however, nitrogen emitted as particulate waste is also considered, as it is re-dissolving into the water column from the seabed. The combined source of nitrogen from dissolved and particulate wastes is 48.2kg N per tonne of salmon produced. This value is derived from a mass balance model used to estimate the release of dissolved and particulate nitrogenous waste from cultivated salmon (Davies, 2000). Such an estimate is dependent on details such as stocking, feeding and harvesting strategies employed during cultivation. This information was derived from the records of a major salmon producer in Scotland averaged over a large number of their on-growing sea pen sites. Total nitrogen discharge rate is therefore the sum of the dissolved and particulate rates.

The ECE models predict the relative levels of nutrient enhancement. The results of the models are scaled 0-5 to give a nutrient enhancement index (Table 2). Areas with higher ECE values are considered to be the most environmentally sensitive to further fish farming development due to high predicted levels of nutrient enhancement.

Table 2 Index of nutrient enhancement, derived from predicted levels of equilibrium concentration enhancement (ECE) for nitrogen.

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

2.1.2 ECE calculations

The calculations to determine the ECE index for the proposed Vementry are described by Gillibrand (2002). The calculations used to assess nutrient impact are detailed below.

The flushing time of the loch is calculated with

$$T_f = \frac{0.52V}{0.7AR}$$

where V is the volume of the loch in $m^3\ s^{-1}$, A the area in m^2 and R the tidal range at springs in m. The flushing time is used to calculate the flushing rate (Q) in $m^3\ yr^{-1}$.

$$Q = \frac{365V}{T_f}$$

The equilibrium concentration enhancement (ECE) is calculated with

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

where S is the nitrogen output with a value pf 48.2 kgN. SM and Q are converted from $kgN\ yr^{-1}$ and $m^3\ yr^{-1}$ to $kgN\ s^{-1}$ and $m^3\ s^{-1}$, respectively, to get an ECE in $kg\ m^{-3}$, which is then converted to $\mu mol\ l^{-1}$.

2.2.3 Model inputs

The model inputs to calculate the ECE index are shown in Table 3. The volume, surface area, tidal range and current biomass of Swarbacks Minn are taken from the Locational Guidelines, Marine Directorate (2025).

Table 3 Input variables for the ECE index calculation

Variable	Value
Volume of Swarbacks Minn	995.1 Mm^3
Surface area of Swarbacks Minn	30.9 km^2
Tidal range at springs	1.7m
Current biomass of Swarbacks Minn	20342 tonnes
Proposed biomass of Vementry	1350 tonnes
Proposed biomass of Swarbacks Minn	20342 + 1350 = 21692 tonnes

2.2 Benthic impact model

2.1.2 Benthic modelling methodology

A modified ‘Gowden’ model is used to estimate the benthic impact of the deposition of organic matter in the form of solid waste from fish farming sources. The area of the farm, as well as the along- and across loch dispersion of the solid waste, is calculated for each farm in a loch, which can then be used to predict an elliptical area of seabed around the farms, which are impacted by organic carbon deposition. An area is defined as impacted when the cumulative carbon loading ($C_L(A_I)$) is bigger than 0.0 kgC $m^{-2}yr^{-1}$ and as degraded when $C_L(A_I) > 0.7$ kgC $m^{-2}yr^{-1}$. The calculation of $C_L(A_I)$ is detailed in the next section.

Table 4 Benthic impact index

Percentage area of seabed predicted to be ‘degraded’ by organic deposition (%)	Benthic impact index
>10	5
3-10	4
1-3	3
0.3-1	2

<0.3	1
0	0

2.2.1 Carbon deposition model calculations

For each fish farm site in Swarbacks Minn, the two horizontal dispersion distances are calculated using

$$D_X = \frac{U_S H_S}{w_i}; D_y = \frac{V_S H_S}{w_i}$$

where U_S is the along-channel current amplitude at the site in m s^{-1}, V_S is the across-channel current amplitude at the site in m s^{-1}, H_S is the water depth at the site in m and w_i is the faecal settling velocity in m s^{-1}. As U_S and V_S are known for all locations, those values are used instead of the estimations described in Glillibrand (2002). Nine linearly increasing particle settling velocities are used, ranging from 0.015 to 0.063 m s^{-1}, as outlined in Gillibrand (2002).

Then, D_X and D_Y are modified to allow for horizontal diffusion using

$$D_X = D_X + \sqrt{2K_H H_S / w_i}$$

$$D_Y = D_Y + \sqrt{2K_H H_S / w_i}$$

with K_H being 0.1 m^2 s^{-1}.

2.2.2 Calculation of the Impacted Seabed Area

The cage area of the farm A_C is estimated using

$$A_c = \frac{M}{S_D C_D}$$

where S_D is the stocking density in kg m^{-3} and C_D is the net depth in m. For all the Cooke Aquaculture Scotland farms, the actual S_D and C_D were used, while for the other three farms a S_D of 20 kg m^{-3} and C_D of 10 m were assumed following Gillibrand (2002) methods.

The farm area (A_F) was increased by a factor of 30% using

$$A_F = 1.3A_C$$

Then, the dimension of the farm (L_F) is calculated using

$$L_F = 0.5\sqrt{A_F}$$

For each settling velocity, the impacted seabed area ($A_I(w_i)$) is calculated using

$$A_I(w_i) = \pi(L_F + D_X)(L_F + D_Y)$$

This gives an impacted seabed area for each settling velocity. The mass of carbon (M_C) is calculated using

$$M_C = M\, FCR\, (1 - F_W)\, C_C\, C_E$$

with those variables:

- Feed Conversion Ratio (FCR) = 1.17
- Quantity of feed wasted (F_W) = 0.05
- Carbon content of feed (C_C) = 0.44
- Particulate waste excreted by the fish (C_E) = 0.30
- M is the biomass in kg.

Then the carbon mass for each settling velocity is calculated using

$$M_C(w_i) = \frac{\Delta w\, M_C}{\sqrt{2\pi}\sigma} e^{-(w_i - \overline{w_i})^2 / 2\sigma^2}$$

With $\overline{w_i}$ being the mean settling velocity (0.011 m s^{-1}) and σ the standard deviation with 0.006 m s^{-1}.

The carbon loading is then calculated with

$$C_L(w_i) = \frac{M_C(w_i)}{A_I(w_i)}$$

and finally, the cumulative loading over the impacted area is calculated using

$$C_L(A_I) = \sum_{j=1}^{i} C_L(w_j)$$

2.2.2 Model inputs

Current meter data

For Vementry, an acoustic profiling current meter was deployed near the proposed site centre location for ~97 days, from the 31st October 2023 and the 6th February 2024 at 430285.5E, 1161466.97N. From this, a 90-day subset was selected, spanning from 31/10/2023 11:44 to 29/01/2024 12:24 (GMT). The reported hydrographic data for the near surface (NS), cage bottom (CB) and near bed (NB) layers for the proposed Vementry farm are shown in Table 5.

Table 5 Hydrographic data at the three reported water depths

"along shore" flow (U_S)			"across shore" flow (V_S)		
NS	**CB**	**NB**	**NS**	**CB**	**NB**
0.055	0.054	0.057	**0.038**	0.037	0.043

Current velocity inputs are required to calculate the nutrient plume dimensions, with data obtained from hydrographic surveys at all nearby farms. Data from all reported water depths (NS-near surface, CB-cage bottom & NB-near bed layers) are shown in Table 6.

Table 6 Hydrographic data at the three reported water depths.

	"along shore" flow (U_S)			"across shore" flow (V_S)		
	NS	**CB**	**NB**	**NS**	**CB**	**NB**
Stead of Aithness	**0.099**	0.090	0.064	**0.094**	0.080	0.027
Lee of Burrafirth	**0.058**	0.045	0.034	**0.046**	0.036	0.035
East Papa Little	**0.058**	0.062	0.001	**0.053**	0.049	0.019
Cole Deep	**0.047**	0.053	0.069	**0.049**	0.037	0.036
Olnafirth South	**0.054**	0.049	0.060	**0.054**	0.049	0.052

Instead of estimating the along - and across-channel current amplitude (U_S and V_S), the near surface (NS) current meter data from each site in Swarbacks Minn were used.

Nitrogen input

The production cycle for the Vementry farm is 22 months with 2 months fallowing. To adopt a precautionary approach and to follow the methods detailed in Gillibrand (2002), the source of nitrogen from dissolved and particulate wastes was set at 48.2kg Nitrogen per tonne of salmon produced.

Table 7 below shows the nitrogen data used to calculate the additional nitrogen output value for the Vementry farm, which is subsequently used in the ECE model.

Table 7 Nitrogen data

	Current Swarbacks Minn	**Proposed Swarbacks Minn**
Nitrogen (kg per tonne salmon)	48.2	
Proposed maximum biomass on site (t)	20342	21692
Nitrogen output (kg yr^{-1})	980,484.4	1,045,554.4
Nitrogen output (kg s^{-1})	**0.0311**	**0.0331**

Farm details

The depth of each farm, biomass, stocking density and the net depth are also needed for the benthic impact model calculation. For the Cooke Aquaculture Scotland sites, the details are in Table 8.

Table 8 Farm details

	Net depth [m]	Stocking density [kg m^{-3}]
Proposed Vementry site	21	5.61
Lee of Burrafirth	10	4.32
Stead of Aithness	12	6.45

3. Results

3.1 ECE model output

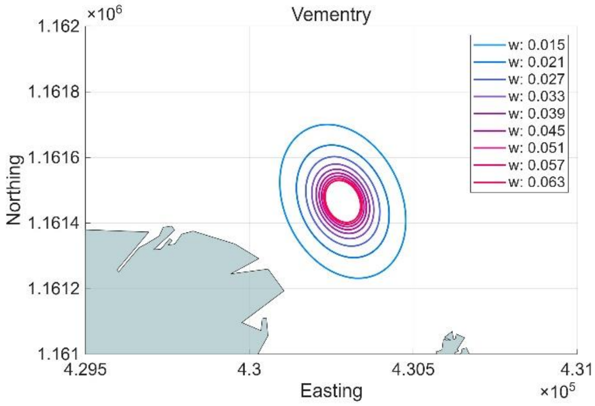
With the current total biomass in Swarbacks Minn the maximum nutrient enhancement value is 2.71 µmol l^{-1}, which is equivalent to a nutrient enhancement index of 3. Adding the biomass of the proposed Vementry site gives a maximum nutrient enhancement value of 2.89 µmol l^{-1}, which is also a nutrient enhancement index of 3.

Table 9 Equilibrium Concentration Enhancement

	Current Swarbacks Minn	Proposed Swarbacks Minn
ECE [kg m^{-3}]	3.80×10^{-5}	4.05×10^{-5}
ECE [µmol l^{-1}]	2.71	2.89
ECE [index]	3	3

3.2 Benthic impact model output

Overall, the current impacted seabed in Swarbacks Minn without the proposed Vementry farm is 2.19 %, which results in a benthic impact index of 3. Including the biomass of the proposed Vementry site results in an impacted seabed of 2.52 %, which is still a benthic impact index of 3. The spatial distribution of the calculated benthic impact is presented in Figure 3, which shows site-specific and waterbody distribution of the potentially impacted area. This shows no area of overlapping from any site or any increased impact on the water body as defined in the locational guidelines (Gillibrand, 2002)



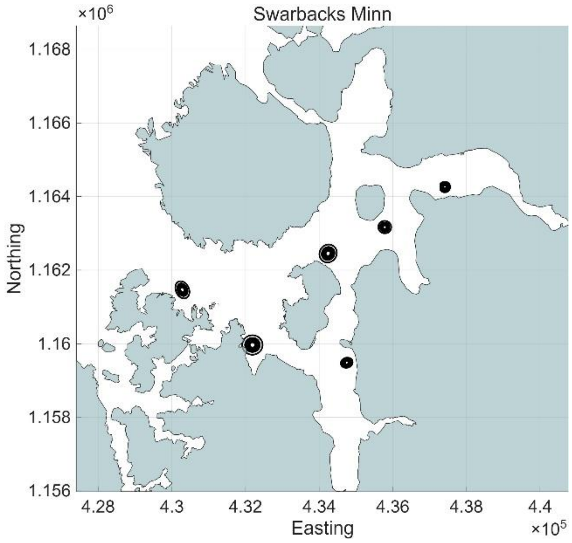


Figure 3. Benthic footprint of the different settling velocities for the proposed Vementry site on the left and all farms within Swarbacks Minn on the right.

4. Discussion

4.1 Vementry ECE

The ECE calculation for semi-enclosed waterbodies has been used to calculate nutrient enhancement at the proposed Vementry farm following the methods from Gillibrand (2002). With the current biomass in Swarbacks Minn, the ECE is 2.71 µmol l^{-1}, which is a nutrient enhancement index of 3. Adding the biomass of the proposed Vementry site (1350 tonnes) increases the maximum nutrient enhancement value to 2.89, which is still a nutrient enhancement index of 3.

There will be some nutrient enrichment in the vicinity of the development due to nutrient release from the fish farm. The nutrient enhancement of the area from the Vementry site is not considered to be significant in terms of the current regime of the Swarbacks Minn waterbody. The proposed site is unlikely to lead to any environmental impacts, with the majority of nutrients from the site dispersed in the active waters around the site.

The neighbouring Northa Voe waterbody is classified as category 1 under Marine Directorates' locational guidelines for aquaculture, which prevents any additional nutrient loading from taking place in the waterbody. The nutrient plume from Vementry is shown to be small, and oriented so the plume does not overlap with the Northa Voe waterbody. This complies with the category 1 requirement and suggests that the Vementry development will have no interaction with the Northa Voe waterbody.

4.2 Benthic impact

The benthic impact of Swarbacks Minn has been calculated following the Gillibrand (2002) methods. The current impacted seabed in Swarbacks Minn without the proposed Vementry farm is 2.19 %, which is a benthic impact index of 3. Including the biomass of the proposed Vementry site results in an impacted seabed of 2.52 %, which is also a benthic impact index of 3.

Additionally, the modelling assumptions have considered a worst-case scenario. It assumes that all farms are at maximum biomass. However, the actual biomass of salmon in the area at any one time will be significantly lower than that of the modelled assumptions and therefore nitrogen enrichment in the area is expected to be much lower than predicted.

Additional benthic modelling will be undertaken using NewDepomod as well as far-field modelling using a hydrodynamic and particle tracking model to further determine the benthic impact Vementry will have on Swarbacks Minn.

5. Mitigation

In order to minimise nutrient input from the Vementry site, measures are in place to reduce the amount of waste feed entering the water column and settling on the seabed. Improvements in feeding efficiency and feed quality reduce waste entering the water column, lowering the environmental impact.

Monitoring will be carried out in accordance with SEPA water quality monitoring procedures throughout the production cycle to detect nutrients entering the water column and to act as an early warning of a potentially harmful algal bloom.

6. References

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