NUTRIENT ASSESSMENT REPORT

CHALMERS HOPE

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Introduction

As part of the screening and scoping process, in relation to the redevelopment of an existing fish farm at Chalmers Hope in Orkney, Cooke Aquaculture Scotland were requested by Marine Scotland to carry out an assessment of the potential water column impacts. Details of the predicted nutrient enhancement likely to result from the discharge of the finfish site is to be provided, as well as taking into account any cumulative impacts from other sites in the surrounding area.

An Equilibrium Concentration Enhancement (ECE) assessment using the open water model described by Gillibrand (2006) will be used to assess nutrient enhancement at the Chalmers Hope site.

Cumulative impacts for the area will also be assessed due to multiple operational sites within the surrounding waters of Chalmers Hope. This will compare the wort case scenario to quantify the overall enrichment for the region any potential adverse effects from the proposed site modifications.

Background

Fish farms release nutrients as 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, with impacts from fish farms on productivity yet to be demonstrated, as dilution at marine sites is generally rapid. In the marine environment nitrogen is typically a limiting nutrient, its addition will dictate the amount of primary production (algal growth). Phosphorous is not considered a limiting nutrient for phytoplankton in marine waters, and therefore is of less importance than nitrogen (Environmental Assessment Office, 1997). The Scottish Executive Review of environmental impacts of aquaculture concluded that the present level of fish farming only has a small effect on the numbers and growth rate of phytoplankton and that this effect should not cause 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 well exceeds those from fish farming operations.

A number of steps have been taken by the industry in recent years to reduce nutrient release into the marine environment through improvements in husbandry practices, feed technology and feed quality. However, the continuing increase in total production means that the release of nutrients to the sea from aquaculture has also increased (Gubbins, 2003a). Therefore, monitoring nutrient levels around fish farms is important to ensure impacts on the water column and organisms present are reduced.

Site details

The Chalmers Hope development is located in the small embayment of Chalmers Hope off Hoy, Orkney. The proposed changes will relocate the farm 250m to the NNE, where the farm will be situated in deeper, faster flowing water. New site infrastructure will also be supplied, where 12 cages will remain in a 2x 6 layout. Cage depth will be increased to 12 m, cage circumference of 120 m and a grid spacing of 70m. The site centre of the proposed farm will be 58° 53′ 35.50″ N 003° 14′ 17.99″ W (328735 E 1001311 N). The proposed maximum biomass was modelled at 2500 t.

The closest site to Chalmers Hope is Bring Head, Hoy located 1.6 km to the NE. Other sites are located further into Scapa Flow with the following distances; Lyrawa Bay 2.5 km, Pegal Bay 3.8 km, South Cava 5.2 km, West Fara 6.6 km and Toy Ness 7.3 km.

The cumulative assessment of nutrient loading at the proposed Chalmers Hope site will be conducted. Only sites that have been active within the last 2 years are considered. Nutrient plume dimensions will be calculated for the sites using the open water model. Details and locations of all the fish farm sites including Chalmers Hope can be found in Table 1 and illustrated in Figure 1.

Table 1 Details of the fish farm sites.

CAR Licensee Number	Site Name	Biomass (t)	Location		Distance (km)
			Easting (m)	Northing (m)	
CAR/L/1015854	Bring Head, Hoy	968	327300	1002200	1.69
CAR/L/1003960	Lyrawa Bay	400	330020	998900	2.73
CAR/L/1003961	Pegal Bay	400	330400	997800	3.89
CAR/L/1082725	Cava South	2500	333300	998800	5.21
CAR/L/1004229	West Fara	800	331963	995227	6.89
CAR/L/1015855	Toy Ness	1343	335445	1003699	7.12

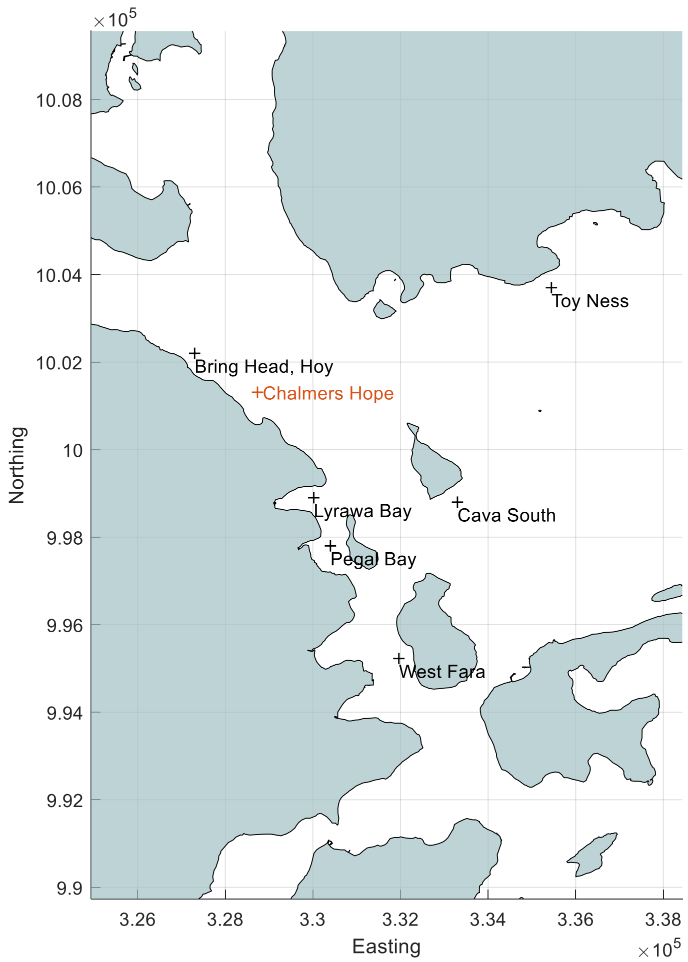

Figure 1. Neighbouring fish farm locations. Proposed site labelled in orange.

Nutrient Modelling

Nutrient enhancement of a water body can be estimated by using two types of model. The first is used for assessing semi enclosed water bodies, described in 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 to the extent that constant nutrient input achieves a steady state concentration with tidal export and replenishment.

The second model is used for assessing sites which are not located within semi enclosed water bodies described by Gillibrand (2006) and is an alternative approach to calculating the ECE for open water sites. 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 Gillbrand (2002) is designed for enclosed loch systems and is not suited to open water and large water bodies. As the proposed Chalmers Hope site is not located within a water body listed in Marine Scotland Science 'Locational Guidelines for Authorisation of Marine Fish Farms in Scottish Waters' and the site is located near the opening of Scapa Flow, where fast flowing waters export material away from the farm and tidal constituents dominate, the use of the open water model is more appropriate. The site is classed as largely re-suspensive and strongly flushed, with large dispersal of material in the north-easterly direction.

It is considered that the Chalmers Hope site should be classed as an open water location, where nutrient enhancement should be assessed using the model described by Gillibrand (2006) which has been specifically developed for open water sites.

Due to the presence of several sites within a nearby proximity (<10km) to the proposed site and the high material transport within Scapa flow, the surrounding sites cumulative nutrient loading will be considered. The dynamic nature of Scapa Flow provides strong tidal constituents for the majority of the sites named in table 1, this permits the use of the open water model for quantifying nutrient impact.

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, but also accounting for nitrogen emitted as particulate waste and re-dissolving into the water column from the seabed. This is equivalent to considering that seabed conditions at farms are generally not deteriorating with time. 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 cage 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 model is 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 (µmol l-1)	Nutrient enhancement index
>10	5
3-10	4
1-3	3
0.3-1	2
<0.3	1
0	0

ECE Calculations

The calculations to determine the ECE values for the proposed Chalmers Hope site and the cumulative assessment using the open water model are detailed in (Gillibrand, 2006). A summary of the calculations used to assess nutrient impact are detailed below.

Nitrogen output (S) in kg/s is calculated using the equation:

$$S = \frac{\text{Max harvested biomass} * 48.2}{31,536,000}$$

where 48.2kg is the value given to the combined source of nitrogen from dissolved and particulate wastes per tonne of salmon produced. 31,536,000 is the number of seconds in a year, this converts the nitrogen output from kg/yr to kg/s.

For the open water model impacts resulting from nutrient discharges are considered over three spatial scales: Zone A is a region very close to the nutrient source; Zone B is the near field region, with residency times in the order of a few days and typically of the same spatial scale as a tidal excursion; Zone C is the far field region where residence time is the order of weeks to months. In Zone B phytoplankton may grow if conditions are favourable, therefore the model considers the exchange of water in the Zone B scale region surrounding coastal aquaculture sites. The model aims to predict the concentration of nutrients within Zone B which represents the volume of water into which nutrients are released from the source and are rapidly mixed within a tidal cycle. The concentration in the body of water depends on the rate at which it is replaced or exchanged by uncontaminated water.

We must assume the flow at the site contains a tidal component and that the dominant tide is the semi-diurnal lunar constituent. We also must assume that the vertical extent of the nutrient plume is bounded either by seabed or by a pycnocline and that the contaminant mixes evenly vertically through this surface layer.

The model uses site specific data from hydrographic surveys to calculate the rate of change of water within Zone B. The basic method of calculating the rate of change of water within Zone B is a simple calculation based on the current velocities of an average tide.

Zone B is determined by its length (L) and width (W) in metres which are based on tidal excursion and calculated using the equations –

$$L = \frac{(\sqrt{2})\sigma_u T}{\pi} \qquad W = \frac{(\sqrt{2})\sigma_v T}{\pi}$$

Where:

σ_u is the standard deviation of “along shore” flow (m/s)

σ_v is the standard deviation of “across shore” flow (m/s)

T is the semi diurnal tidal period (s)

π=3.1415

We assume for simplicity that Zone B is rectangular with area (m^2) and volume (m^3) calculated using the equations –

$$A=LW \qquad V=AH$$

Where:

H is the water depth or pycnocline depth (m)

The concentration of effluent within the box (Zone B) is determined by the exchange rate (E) which is the inverse of the flushing time (Tf). The flushing time is defined as the time after which the mean concentration (C) in the box would have fallen to a value which is 37% of the initial concentration due to the action of physical exchange processes only.

In the model we define the exchange rate in seconds as:

$$E = E_A + E_x + E_y$$

Where:

E_A is the exchange rate due to advection (residual flow - U_R) and Ex and Ey are due to along shore and across shore diffusion respectively.

The exchange rate due to advection (E_A) is calculated by –

$$E_A = \frac{U_R}{L}$$

Where:

U_R is the residual flow (m/s)

Exchange rates due to diffusion are calculated by –

$$E_x = \frac{K_x}{2L^2} \qquad E_y = \frac{K_y}{2W^2}$$

Where:

Kx is the along shore diffusion coefficient

Ky is the across shore diffusion coefficient

Results

Chalmers Hope ECE

Model inputs

To derive the three current velocity inputs, data from the joined 90-day hydrographic survey was used. The reported hydrographic data for the near surface (NS), cage bottom (CB) and near bed (NB) layers for the Chalmers Hope site are shown in Table 3, with the averaged hydrographic data required for the model shown in Table 4 below.

Table 3 Hydrographic data at the three reported water depths

Residual Current (U_R)			"along shore" flow (σ_u)			"across shore" flow (σ_v)		
NS	**CB**	**NB**	**NS**	**CB**	**NB**	**NS**	**CB**	**NB**
0.0130	0.0162	0.0219	0.183	0.216	0.188	0.091	0.069	0.0629

Table 4 Averaged hydrographic data for input into the model

Residual Current (U_R)	"along shore" flow (σ_u)	"across shore" flow (σ_v)	Vector Average Residual Direction (Degrees)
0.017	0.1956	0.0736	260

The production cycle for the Chalmers Hope site 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 5 below shows the nitrogen data used to calculate the nitrogen output value for the Chalmers Hope site which is subsequently used in the ECE model.

Table 5 Nitrogen data

Nitrogen (kg per tonne salmon)	48.2
Proposed maximum biomass on site (t)	2500
Nitrogen output (kg/yr)	120,500
Nitrogen output (kg/s)	**3.8×10^{-3}**

Table 6 outlines the data inputs required to run the open water ECE model for the Chalmers Hope site.

Table 6 ECE model inputs

Semi-diurnal tidal period (s)	T	45,000
Water depth (m)	H	34
Residual flow (m/s)	U_R	0.017
Standard deviation "along-shore" flow (m/s)	σ_u	0.1956
Standard deviation "across-shore" flow (m/s)	σ_v	0.0736
Nutrient decay rate (s-1)	k	0
Nitrogen output (kg/s)	S	3.8×10^{-3}

Model outputs

Area of impact (Zone B) is calculated using the hydrographic data. Table 7 details the area of impact for the Chalmers Hope site.

Table 7 Zone B dimensions

Length (m)	3961
Width (m)	1490
Area (m^2)	5902899
Volume (m^3)	202311956

Exchange rates and flushing times for the Chalmers Hope site are detailed in Table 8. The model determines a flushing time by calculating a refreshment rate. This is based on the size of Zone B and the residual currents in the area.

Table 8 Exchange rates and Flushing times

Minimum exchange rate (s-1)	E_{MIN}	4.329e-06
Median exchange rate (s-1)	E_{MEDIAN}	4.358e-06
Maximum exchange rate (s-1)	E_{MAX}	4.847e-06
Minimum flushing time (hrs)	Tf_{MIN}	57.30
Median flushing time (hrs)	Tf_{MEDIAN}	63.74
Maximum flushing time (hrs)	Tf_{MAX}	57.30

The resultant open water ECE model outputs are detailed in Table 9 below for the Chalmers Hope site.

Table 9 Equilibrium Concentration Enhancement

		(kg/m³)	**(µmol l-1)**
Minimum ECE	C_{MIN}	3.896e-06	0.28
Median ECE	C_{MEDIAN}	4.235e-06	0.30
Maximum ECE	C_{MAX}	4.362e-06	**0.31**

The predicted maximum nutrient enhancement value for the Chalmers Hope site is 0.31 µmol l-1, equivalent to nutrient enhancement index category 2. This at the very lower end of category 2. The nutrient loading was calculated for the existing site using the same current data and adjusting the biomass to 1000T and a net depth 10m. As the flow data remains identical the exchange rates and flushing time remain the same. However, the plume concentration is reduced to a maximum value of 0.126, equivalent to nutrient enhancement index category 1.

Cumulative Effects

An assessment of the cumulative effects of nutrients released from the sites in the waters surrounding Chalmers Hope was undertaken.

The cumulative assessment will be carried out on all the sites surrounding the Chalmers Hope site using the open water model (Gillibrand 2006). The sites current regimes and topography mean the open water model is applicable. Using the most recent hydrographic data for the sites, plume dimensions were calculated. The plumes were mapped using the vector averaged residual current direction to assess whether they had potential to influence nutrient loading at the Chalmers Hope site.

Model inputs – Plume calculations

Three current velocity inputs are required to calculate the nutrient plume dimensions, with data obtained from hydrographic surveys at the 7 sites (including Chalmers Hope). Data from three reported water depths (NS-near surface, CB-cage bottom & NB-near bed layers) are shown in Table 10.

Table 10 Hydrographic data at the two or three reported water depths.

	Residual Current (U_R)			"along shore" flow (σ_u)			"across shore" flow (σ_v)		
	NS	CB	NB	NS	CB	NB	NS	CB	NB
Chalmers Hope	0.013	0.016	0.021	0.183	0.216	0.187	0.091	0.066	0.062
Bring Head, Hoy	0.033	0.034	0.027	0.282	0.276	0.222	0.043	0.042	0.052
Lyrawa Bay	0.039	0.04	0.039	0.048	0.051	0.051	0.032	0.031	0.035
Pegal Bay	0.045	0.046	0.059	0.076	0.074	0.072	0.047	0.044	0.049
Cava South	0.025	0.052	0.054	0.051	0.057	0.066	0.03	0.31	0.035
West Fara	0.092	0.108	0.117	0.171	0.171	0.171	0.032	0.032	0.032
Toy Ness	0.027	0.023	0.02	0.093	0.106	0.11	0.047	0.04	0.046

Table 11 outlines the data inputs required to calculate the nutrient plume dimensions including the averaged hydrographic data, depth and residual direction. Additional data inputs required to calculate the plume dimensions include the semi-diurnal tidal period of 45,000 seconds which remains the same for all sites.

Table 11 Plume calculations - model inputs

Site Name	Residual Current (UR)	"along shore" flow (σu)	"across shore" flow (σv)	Water depth (m)	Vector Average Residual Direction (Degrees)
Chalmers Hope	0.02	0.196	0.074	34.000	260.8
Bring Head	0.03	0.194	0.179	20.500	296.7

Lyrawa Bay	0.04	0.050	0.033	18.700	3.3
Pegal Bay	0.05	0.074	0.047	17.730	200.0
Cava South	0.04	0.058	0.032	29.480	232.9
West Fara	0.11	0.171	0.032	15.000	104.0
Toy Ness	0.02	0.104	0.044	27.000	234.3

Model outputs – Plume dimensions

Table 12 details the plume dimensions of the area of impact (Zone B) for the sites around the Chalmers Hope site with Figure 2 illustrating the nutrient plumes for all the sites including the proposed Chalmers Hope site.

Table 12 Zone B plume dimensions

Site Name	Easting	Northing	Length (m)	Width (m)	Area (m^2)	Volume (m^3)	Nutrient enhancement index
Chalmers Hope	328735	1001311	3961.5	1490.1	5902951	202471208	2
Bring Head	327300	1002200	3929.9	3632.8	14276378	299803931	1
Lyrawa Bay	330020	998900	1012.9	661.7	670240	12533481	1
Pegal Bay	330400	997800	1499.0	945.3	1417078	25124794	1
Cava South	333300	998800	1174.9	648.2	761611	22452294	2
West Fara	331963	995227	3464.0	648.2	2245440	33681593	1
Toy Ness	335445	1003699	2106.7	898.1	1891991	51083750	1

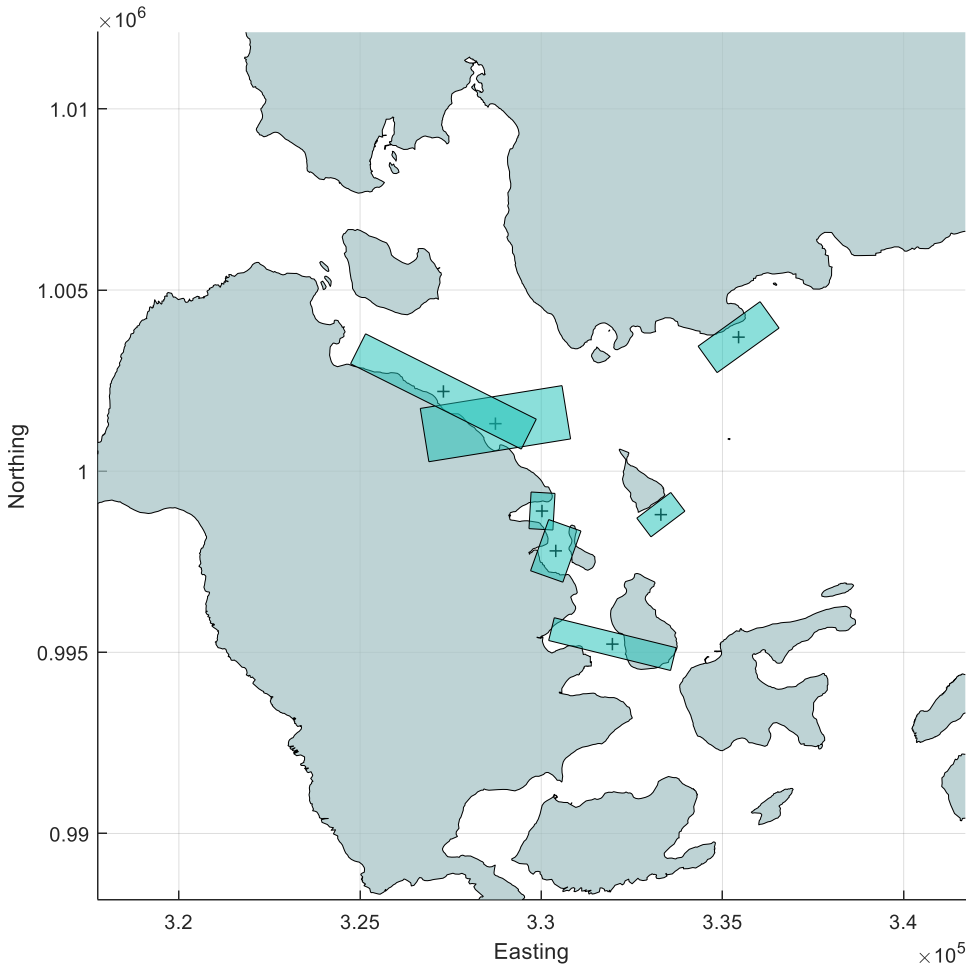

Figure 2. Cumulative Zone B areas.

Nutrient plumes are shown to overlap between the Bring Head and the proposed Chalmers Hope site.

Total Enrichment

The total enrichment of west Scapa flow is considered, this uses the open water model combined with the cumulative effects from surrounding farms to quantify the total ECE concentration. The area is calculated from the unified cumulative areas modelled previously. The volume is calculated using an average depth of 20m. The plume length and width are extracted from the largest continual impact area as shown in Figure 3. The model input parameters are shown in Table 13 and 14. The combined consented biomass of the active sites within the region is multiplied by a scaling factor of 2. This provides a precautionary estimate of the maximum theoretical harvestable biomass.

Table 13 Nitrogen data

Nitrogen (kg per tonne salmon)	48.2
Combined maximum biomass on site (t)	8911
Maximum theoretical biomass (t)	17,822
Nitrogen output (kg/yr)	859,020
Nitrogen output (kg/s)	**0.0272**

Table 14 ECE model inputs

Semi-diurnal tidal period (s)	45000
Water depth (m)	20
Length (m)	6,415
Width (m)	2,394
Area (m^2)	15,854,856
Volume (m^3)	317,097,119
Average residual flow (m/s)	0.0432
Nutrient decay rate (s-1)	0
Nitrogen output (kg/s)	0.0272

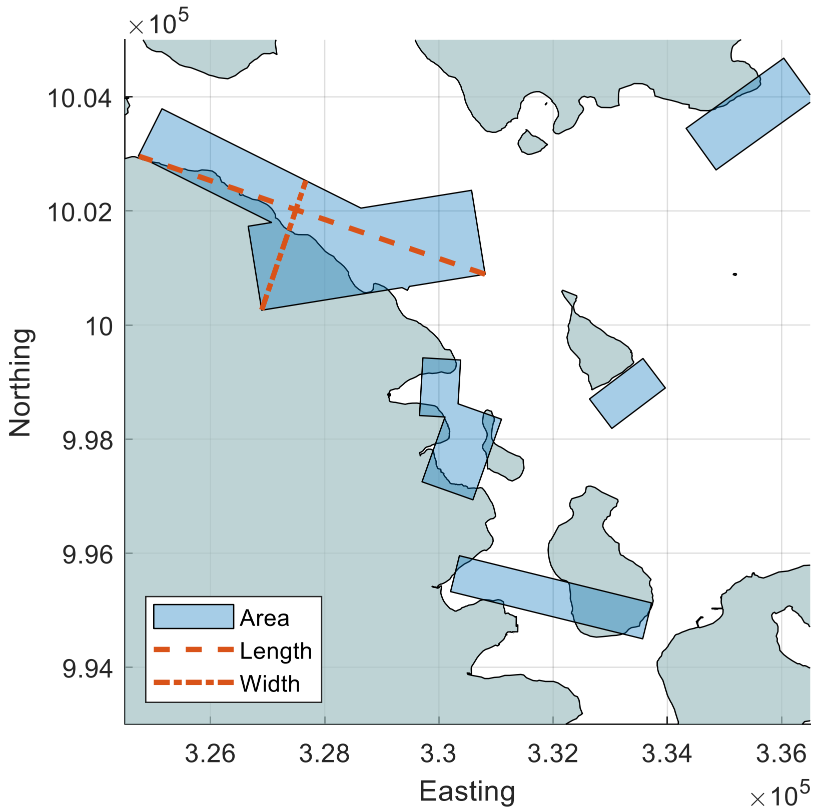

Figure 3. Total enrichment area with plume length and width.

Exchange rates and flushing times for the combined sites are detailed in Table 14. The model determines a flushing time by calculating a refreshment rate based on the area defined in Figure 3 and the average residual flow speed from all sites.

Table 14 Exchange rates and Flushing times

Minimum exchange rate (s-1)	E_{MIN}	6.74e-06
Median exchange rate (s-1)	E_{MEDIAN}	6.75e-06
Maximum exchange rate (s-1)	E_{MAX}	6.94e-06
Minimum flushing time (hrs)	Tf_{MIN}	40.01
Median flushing time (hrs)	Tf_{MEDIAN}	41.12
Maximum flushing time (hrs)	Tf_{MAX}	41.19

The resultant open water ECE model outputs are detailed in Table 15 below for the total enrichment within Scapa Flow.

Table 15 Equilibrium Concentration Enhancement

		(kg/m^3)	**(µmol l-1)**
Minimum ECE	C_{MIN}	1.24e-05	0.88
Median ECE	C_{MEDIAN}	1.26e-05	0.90
Maximum ECE	C_{MAX}	1.27e-05	**0.91**

The predicted maximum nutrient enhancement value for the west Scapa Flow region is 0.91 µmol l-1, equivalent to nutrient enhancement index category 2.

The cumulative nutrient enrichment for the existing farm was also calculated to act as the existing benchmark. This adjusted the biomass and farm location to the existing values. The results provide marginal change to the plume length and width where the values are 6,366m and 2,591m respectively. The combined plume concentration provides a maximum value of 0.74 µmol l-1 for the region. This is equivalent to nutrient enhancement index category 2.

Discussion

Chalmers Hope ECE

For the ECE calculations the open water model was used to assess the Chalmers Hope site. Due to the location of the site being in relatively exposed and open waters near large tidal currents, the majority of the exported material is well dispersed. Combined with Scapa Flow not being listed as a sea loch in Marine Scotland guidelines the open water model was deemed to be the most appropriate model to calculate nutrient enhancement at the Chalmers Hope site.

Using the open water ECE model, the Chalmers Hope site has a maximum nutrient enhancement value of 0.31 µmol l-1 when stocked to the proposed maximum biomass, giving a nutrient enhancement index value of 2. This remains at the very lower end of the level 2 index as it ranges from 0.3 to 1 µmol l-1. When compared with the existing layout, the proposed site shows an increase in the maximum concentration from 0.126 (index level 1) to 0.31 (index level 2). However, the local nutrient enrichment from the site is still considered very low.

There will be some nutrient enrichment in the vicinity of the development due to nutrient release from the fish farm, however it is not considered to be significant in terms of the current regime out with the immediate Chalmers Hope area. It is unlikely to lead to any environmental impacts with the majority of the effluent from the site dispersed in the energetic waters that pass the site.

Cumulative assessment

Due to the number of sites and the energetic nature of the waters surrounding Chalmers Hope, there was potential for nutrient plumes to interact, leading to increased nutrient loading. Therefore, the cumulative effects of the sites in this area were investigated.

Seven active sites in west Scapa Flow were modelled at maximum biomass. The results concluded a maximum nutrient enhancement value of 0.91. This value is ranked within the nutrient enhancement index as 2. When compared with the existing cumulative enrichment the proposed site increased the region nutrient enrichment from 0.74 to 0.91. This value maintains a nutrient enhancement index of 2. The proposed enrichment indicates a low value for nutrient loading, and it is unlikely that localised nutrient build-up will occur within this region.

The modelling assumptions have considered a worst-case scenario. This assumes all sites operate at maximum biomass continuously. It is very unrealistic and impractical to have all sites running at maximum biomass. Because of this, it is unlikely that nutrient loading from the surrounding farms would result in an algal bloom.

Nutrient discharge is expected from the proposed Chalmers Hope site. However, the development should be considered as low risk as the cumulative results indicate the region remains within the nutrient enhancement index of 2. This is aided by the dispersive qualities of waters in Scapa Flow, providing rapid water exchange that facilitates the dilution of nutrients.

Mitigation

In order to minimise nutrient input from the Chalmers Hope 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 could 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 monitor nutrients entering the water column and to act as early warning of a potentially harmful bloom.

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