08th May 2024

Far-Field Benthic Modelling Report

Quanterness

Table of Contents

Summary

Cooke Aquaculture Scotland Ltd. (CAS) have developed a particle tracking model, driven by a decoupled hydrodynamic model, to simulate the dispersion of solid waste released from all marine fish farm sites within Wide Firth and Shapinsay Sound. This identifies possible areas of sediment accumulation and suspended sediment pathways that may pose adverse environmental risk to large areas of seabed or sensitive marine features.

A multi-point calibrated and validated hydrodynamic model and calibrated particle-tracking model with dye and drogue surveys, were used to predict faeces and waste food particle advection and dispersion from the proposed Quanterness site and 4 additional sites within the area. Operational conditions were simulated for 1 year assuming constant maximum stocking and no decay of organic particles.

Deposited and suspended sediment pathways are shown for the proposed Quanterness farm and the cumulative proposed site scenario. Deposition is shown to occur away from the site, where accumulation of the majority of the sediment occurs 3.5km southeast of the site centre. Cumulative effects show very small increases in the spatial deposition exceeding 250g/m^2. Suspension pathways indicate particle transportation routes, these are shown to avoid all sensitive marine features within Wide Firth and Shapinsay Sound. The result of this modelling indicates that the proposed development poses a very low far field and cumulative environmental risk from dispersion of solid waste material.

1. Introduction

This report details the results of the simulation of solid particulate waste from multiple aquaculture sites within a hydrodynamic and particle tracking model. The description of the hydrodynamic model, the calibration and validation, and the methods of simulating waste particles are presented in the Modelling Methods Statement. The measurement of the dispersion coefficient that is used within the particle tracking model is described in detail within the Dye and Drogue Release report. The results of the far-field benthic modelling are used to determine potential risk to sensitive marine features and cumulative impacts while maintaining compliance with the latest SEPA standards and guidance (SEPA, 2024)

1.1 Site description

Quanterness is considered a new potential site and would replace the existing West Shargun Shoal (Wide Firth) site (CAR/L/1001931) operated by Cooke Aquaculture Scotland. The site is located off the northeast coastline of the Orkney mainland, within the Bay of Kirkwall, in Wide Firth. The existing site consists of a single group of 8 circular, 90m circumference pens with a net depth of 8m. These are arranged in a 2 x 4 layout with a 50 m separation, housing a maximum consented biomass of 600T at a maximum stocking density of 14.54kg/m^3. The site is aligned with a bearing of ~8^o. The licensed site is centred on 343220.24E, 1013947.6N.

The proposed development relocates the site ~1.1km towards the northwest with a site centre location of 342733E, 1014921N. The infrastructure consists of 14 circular, 120m circumference pens in a 2 x 7 layout (see figure 1). The proposed site will house a maximum consented biomass of 1925T, providing a maximum stocking density of 14.99kg/m^3. Further information on the existing and proposed site infrastructure and pen layout is presented in Table 2.

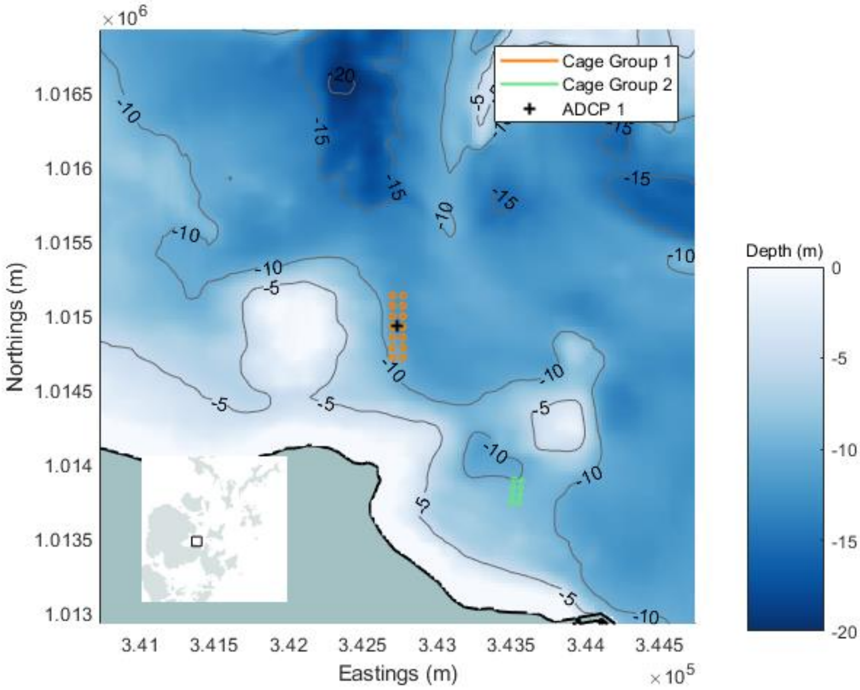

Figure 1. Existing (green) and proposed (orange) Quanterness site infrastructure, ADCP deployment location ('+') and bathymetry.

Table 2 – Existing and proposed site infrastructure and pen layout.

	West Shargun Shaol (Wide Firth)	Quanterness (Proposed)
Consent number	CAR/L/1001931	CAR/L/1001931
Company	Cooke Aquaculture Scotland	Cooke Aquaculture Scotland
Receiving water	Bay of Kirkwall	Wide Firth
Site centre (OSGB36)	343220.24E, 1013947.6N	342733E, 1014921N
Current meter location (OSGB36)/year of deployment		342733E, 1014921N /2021
Distance to shore (km)	0.56	0.9
Average water depth (m)	13.46	15.18
Maximum biomass (t)	600	1925
Total number of pens	8	14
Number of pen groups	1	1
Formation	2 x 4	2 x 7
Pen group orientation (°)	8	0
Pen shape	Circular	Circular
Pen circumference (m)	90	120
Mooring grid (m)	50	70

1.2 Surrounding Farms and Sensitive Marine Features

Wide Firth and Shapinsay Sound hosts 4 additional aquaculture sites and numerous sensitive marine features. Table 3 outlines the additional farms that are included within the cumulative assessment and the marine features that are assessed within this study. These sites were specified in the Screening and Risk Identification Report (SEPA 2022).

Table 3. Farm and sensitive marine features identified within Wide Firth and Shapinsay Sound.

Name	Feature type	Location (OSGB)		Mesh resolution (m^2)
		East (m)	North (m)	
Qaunterness (Proposed)	Fish farm	342733	1014921	1225 (35m)
Qaunterness (Existing)[#]	Fish farm	343220	1013947	1225 (35m)
Puldrite	Fish farm	342538	1018052	4000 (63m)
Carness	Fish farm	347095	1014085	1600 (40m)
Meil Bay (Proposed)	Fish farm	348440	1012644	1225 (35m)
Meil Bay (Existing)	Fish farm	348505	1012476	1225 (35m)
Berstane**	Fish farm	348300	1010800	3500 (59m)
Maerl beds	Marine habitat - Area	Shapefile		10000 (100m) - 2000 (45m)
Maerl beds	Marine habitat - Points	349210 349756 349865 350250 351113 346907 347526 342842 343750	1011840 1012489 1012987 1015610 1015166 1015999 1015671 1016019 1016110	2000 (45m) - 2500 (50m)
Horse mussel beds	Marine habitat - Area	Shapefile		2000 (45m)
Horse mussel beds	Marine habitat - Points	348810	1015440	2000 (45m) - 4000 (63m)
Seagrass beds	Marine habitat – Points	339455 339200 335800 336529	1013313 1018200 1014300 1013628	8000 (89m)
Bay of Firth (Pacific Oysters)	Shellfish water protected area - Area	Shapefile		8000 (89m)

Bay of Firth (Pacific Oysters)	Shellfish water protected area - Points	338966	1015259	8000 (89m)

[#] West Shargun Shoal (Wide Firth) has been colloquially named as Quanterness (Existing) as the proposed development will replace this site.
**Berstane has no historic record of being stocked and is considered a long-term inactive site.

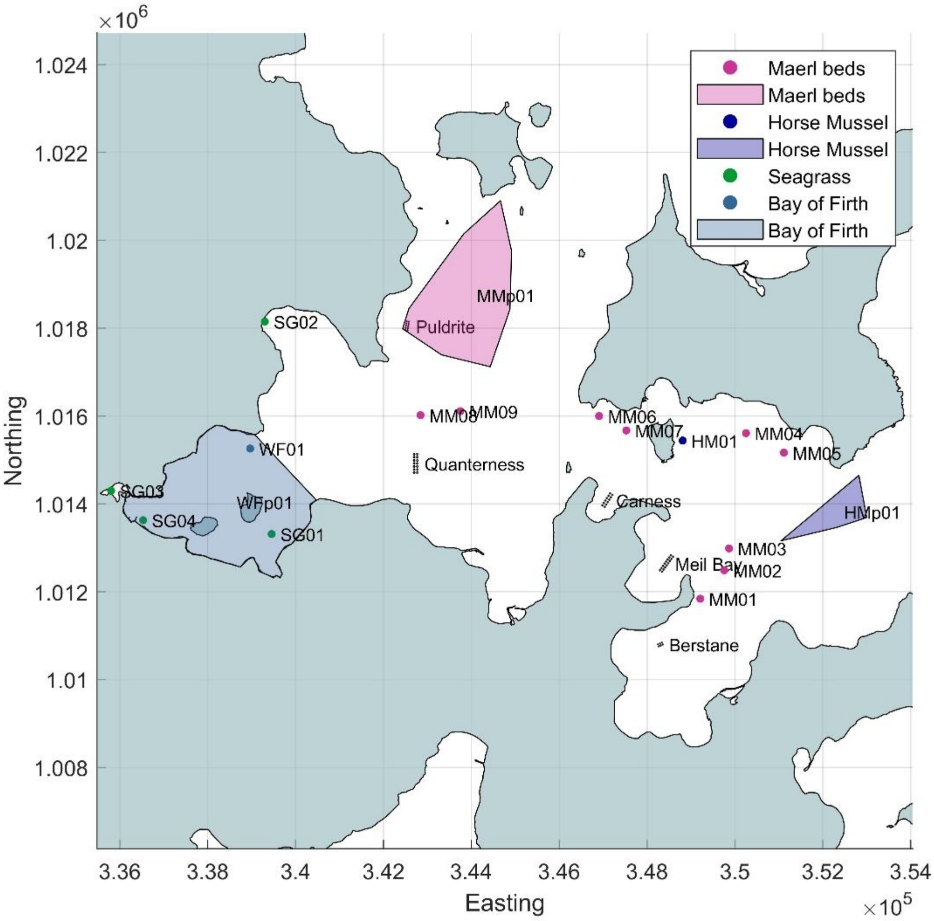

Figure 2. Farm locations and sensitive marine features identified within Wide Firth and Shapinsay Sound.

2. Model Description

This study uses DHI's MIKE3 flexible mesh model to simulate free-surface flow in a coastal environment. The model uses an unstructured mesh to replicate tidal hydrodynamics, wind and wave driven currents, and storm surges.

2.1 Hydrodynamic model

DHI's MIKE3 flexible mesh model solves the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, using the Boussinesq and hydrostatic pressure assumptions to simulate 3D hydrodynamics over the coastal domain of interest. Continuity of momentum, temperature, salinity and density are applied alongside the k-epsilon turbulent closure scheme. A cell centred finite volume approach is applied for the spatial discretion of the momentum equations over an unstructured triangular mesh.

2.1.1 Model domain

The model domain is created using the cartesian Ordnance Survey of Great Britain 1936 coordinate system (OSGB 1936). Coastline data is imported from Ordnance Survey (2020) and is used to define the land boundaries within the domain. Bathymetry data are taken from the UK Hydrographic Office (UKHO, 2021). The model mesh is unstructured, consisting of non-overlapping triangular elements covering a domain that extends from 229929E to 442733E, and 910599N to 1099869N (figure 3a). An unstructured mesh allows variation in element size, meaning near open boundaries the mesh resolution is relatively coarse (2km) to increase computational efficiency. In areas of specific interest, complex topography or complex bathymetry, the resolution is enhanced so that these features are adequately resolved (figure 3b). Horizontally the mesh comprises 73066 nodes and 139921 elements. In the vertical dimension, the model has 5 terrain following sigma layers, mostly concentrated within the upper part of the water column.

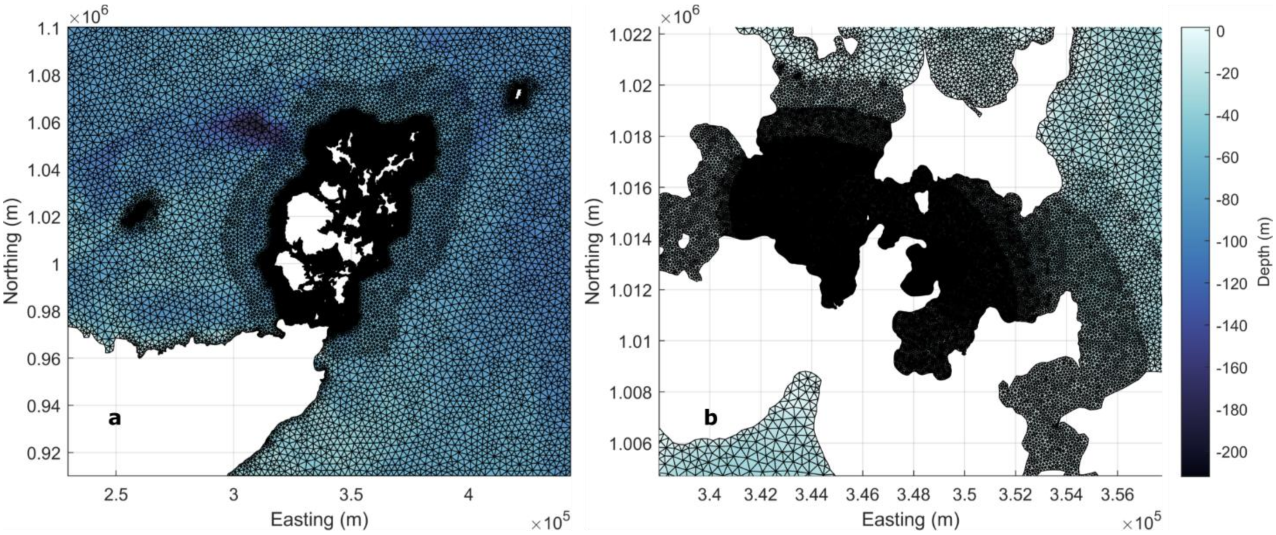

Figure 3. Hydrodynamic model mesh. a) wider computational mesh. b) Computational mesh around the proposed Quanterness site.

2.1.2 Configuration and boundary forcing

Boundary conditions are taken from DHI's global tidal model, where tidal elevations are calculated from 10 principal astronomical constituents (semidiurnal M2, S2, K2, N2, Diurnal S1, K1, O1, P1, Q1 and Shallow water M4). The global tidal model has a resolution of 0.125°x

0.125° and interpolates data to the nearest boundary element. Temporal resolution outputted elevations every 12 mins. Wind data was taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 model (ECMWF, 2023). This provides wind velocity in U and V components, as well as surface pressure with a resolution of 0.25°x. 0.25° at an hourly interval.

A minimum and maximum model time step of 0.01 and 60 seconds was applied, with a critical CFL number of 0.95 ensuring model stability. Point data outputs were produced at 10-minute intervals and area data outputs at 30-minute intervals. Flooding and drying were included, with a drying depth of 0.005m and a wetting depth of 0.1m. The horizontal eddy viscosity applies Smagorinsky's formulation with a constant value of 0.28. Bed roughness in the form of the roughness height is used as the main calibration term. This parameter is adjusted to calibrate the model. The best model performance was achieved using a spatially variable bed roughness. A local (3km radius) bed roughness of 0.025m was applied at Quanterness and 0.15m at Meil Bay. The background bed roughness across the remainder of the mesh was set to 0.05m.

2.2 Particle tracking model

Particle release is simulated using DHI's MIKE 3 particle tracking model. The particle tracking (PT) model is run in 3-dimension, with 10 sigma layers. The model is run offline from the hydrodynamic model to reduce computational time. The time step remains identical to that used within the hydrodynamic model. The PT model is run for 365 days, where the start date is located out with the hydrodynamic model warm-up period.

Wind forces were removed for the driving hydrodynamic model to prevent storms causing misrepresentation of dispersion during winter months. This provides a more conservative model with lower dispersion rates.

2.2.1 Particle Configuration

To simulate waste feed and faeces, two particle classes are specified for each farm. This allows separate particle parameters to be applied to each particle type that match their settling and resuspension characteristics. Peak biomass is used to calculate the feed waste and faecal matter using the following equations and values in table 3. The calculated quantities of waste and excreted solids for each farm are given in table 4. It should be noted Berstane is assumed to be stocked, however, this site hasn't been operational within current records, and it is most likely obsolete.

Table 3. Input feed parameters

Parameter	Symbol	Value
Feed requirement	f_r	7kg per tonne biomass per day
Feed water (%)	f_h	9%
Feed waste (%)	f_w	3%
Feed absorbed (%)	f_a	85%

Feed carbon (%)	f_c	49%
Faeces carbon (%)	f_f	30%

The amount of waste solids (w_s) per day is calculated as

$$w_s = (1 - f_h).f_w.f_r$$

Waste carbon (w_c) is calculated as

$$w_c = (1 - f_h).f_c.f_w.f_r$$

Excreted solids (e_s) are calculated as

$$e_s = (1 - f_h).(1 - f_w).(1 - f_a).f_r$$

Excreted carbon (e_c) is calculated as

$$e_c = (1 - f_h).(1 - f_w).(1 - f_a).f_f.f_r$$

Table 4. Particle mass per model timestep.

Site	Biomass (t)	Waste feed (kg)	Excreted Solids (kg)
Qaunterness (Proposed)	1950	15.5	75.3
Qaunterness (Existing)	600	4.8	23.2
Puldrite	980	7.8	37.8
Carness	1000	8.0	38.6
Meil Bay (Proposed)	1410	11.2	54.5
Meil Bay (Existing)	884	7.0	34.1
Berstane	500	4.0	19.3

Particle properties are defined in table 5. Waste feed and faeces particle settling rates are defined using the SEPA default values. The results of the drogue and dye release model calibration study were used to determine representative horizontal dispersion coefficients (K_h). This applies a horizontal dispersion coefficient of 0.105 m^2/s for Meil Bay and Quanterness while the remaining sites use the default value of 0.1m^2/s. Vertical dispersion coefficient uses the default value of 0.001 m^2/s for all sites.

Table 5. Benthic model particle parameters

Particle class	**Waste feed**	**Excreted solids**
Decay (s)	0	0
Settling velocity (m/s)	0.095	0.035
Horizontal dispersion (m^2/s)	0.105 (Quanterness and Meil Bay) 0.1 (remaining sites)	0.105 (Quanterness and Meil Bay) 0.1 (remaining sites)
Vertical dispersion (m^2/s)	0.001	0.001
Erosion threshold ($N/m^2/s$)	0.02	0.02
Density (kg/m^3)	1027	
Bed Roughness (m)	0.001	

Throughout the model run period, 10 particles per hour were released from each particle class (feed and faeces) into the domain from an area source. As it is not feasible to define each individual pen manually, a rectangular area for each cage group is defined using the central locations of the corner pens. Particles are randomly released across this rectangular source area in a vertical layer spanning from the sea surface to the depth of the cage bottom. This offers the most representative particle dispersion where concentration and area coverage are most similar to the individual pen simulation.

3.2.3 Environmental Standards (EQS)

Benthic impact area is determined using the Infaunal Quality Index (IQI), where a relationship between sediment flux and IQI is defined as a proxy for environmental impact. SEPA (2024) states that an average solid flux calculated from the last 90 days of a simulation should be used as the representative flux. For NewDepomod modelling this suggests that a flux value of 250g/m^2 is equivalent to an IQI of 0.64 and acts as the far field EQS. Therefore, any deposition above the 250g/m^2 is defined as having a significant impact on the seabed. This EQS and the intensity parameter used within NewDepomod are outlined in table 6. While these EQS parameters were calibrated and validated within NewDepomod, there has been no assessment in the applicability of this method and optimal particle parameters within a larger scale hydrodynamic and particle tracking model. This suggests that the application of the 250g/m^2 within a marine model offers a more appropriate tool in determining geographical distribution of sediment rather than attempting to accurately forecast the magnitude of deposition.

Table 6. Benthic EQS parameters

Benthic		
Pen-edge	Intensity	Mean deposited mass within the 250 g/m^2 impact area should not exceed 2000 g/m^2 where wave exposure is less than 2.8, and 4000 g/m^2 where wave exposure is more than 2.8.
Mixing zone	Area	Total area (m^2) with a mean deposited mass in excess of 250 g/m^2 should not exceed the 100 m composite mixing zone area (m^2). If wave exposure is 2.8 or above, the mixing area may occupy 120% of the 100m mixing zone.

3. Results

3.1 Far-field Sediment and Suspension

The average deposition from the proposed Quanterness farm within Wide Firth is shown in figure 4. The concentrations displayed represent the mean of the final 90 days of the particle tracking model run. Concentration values of less than 1g/m^2 have been excluded from the map and all subsequent figures. Such low concentrations are not considered to be representative of the main influence of a discharge. Highlighted predicted impact areas are defined as those with deposited concentrations of 250g/m^2 or higher. This shows the majority of the deposition is dissociated from the site and located around 3.5km towards the southeast. Other patches of deposited sediment are shown to occur within the domain at much smaller concentrations and spatial coverage.

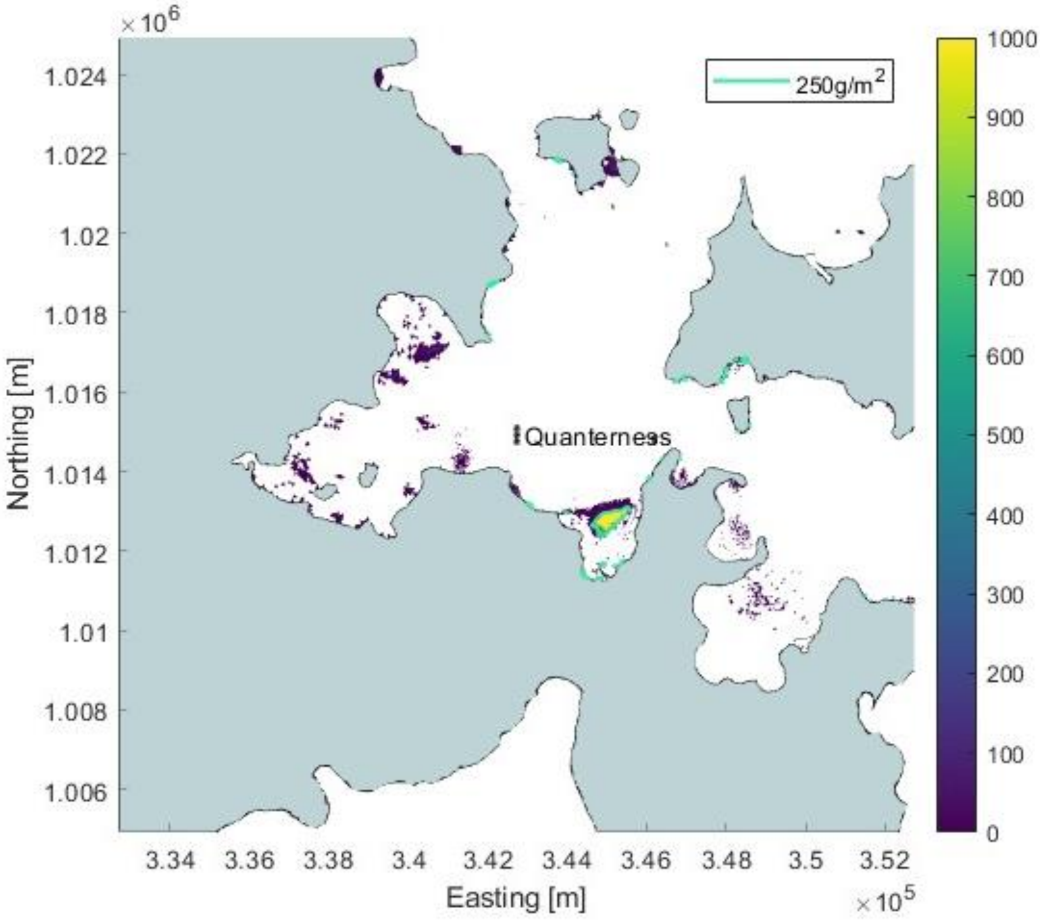

Figure 4. Average far field deposition (g/m^2) from the last 90 days of the simulation for the proposed Quanterness development.

The average deposition from all proposed sites including the Proposed Quanterness and Meil Bay farms are shown in figure 5. The cumulative assessment of deposition shows sediment accumulations around Carness, Meil Bay and Berstane. The joint deposition shows small increases towards the west of the Quanterness farm where a subtle increase in deposition occurs at low intensities.

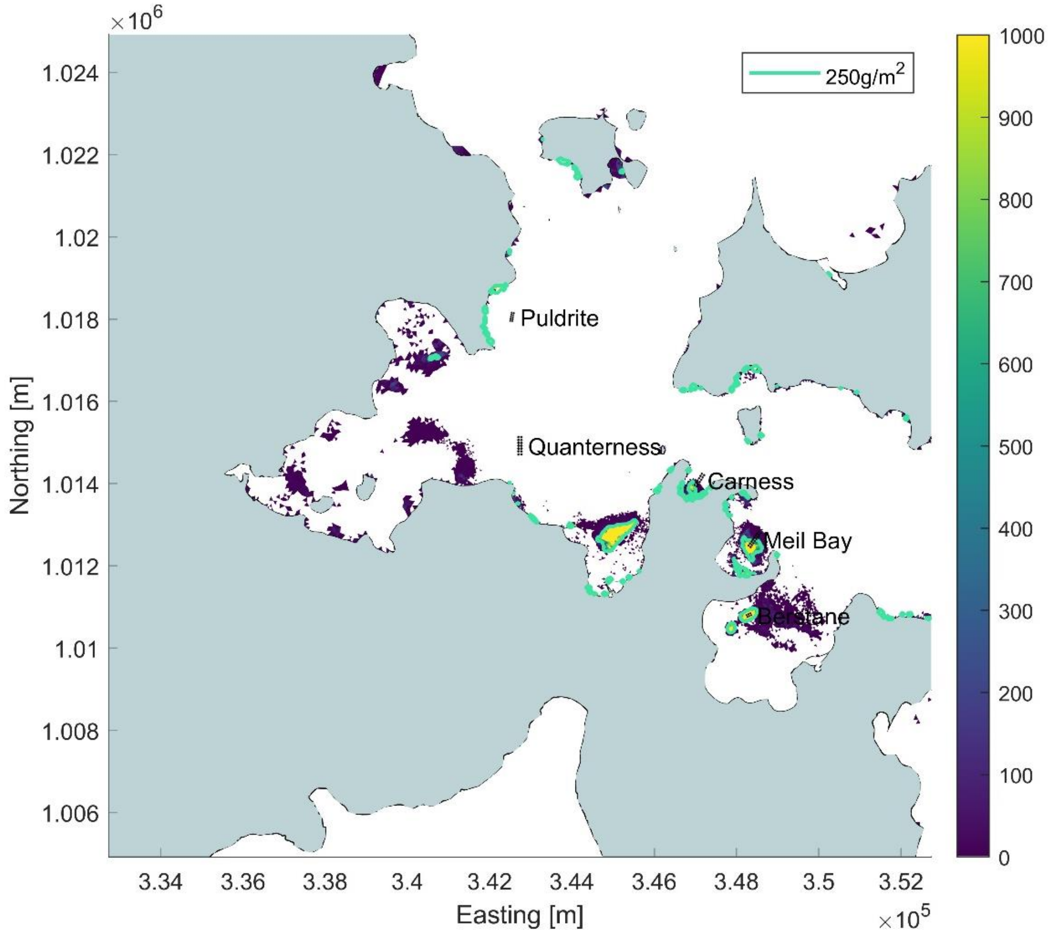

Figure 5. Average far field deposition (g/m^2) from the last 90 days of the simulation for all sites including the proposed Quanterness and Meil Bay developments.

The suspended sediment pathway for all proposed developments is shown in figure 6. Suspension around the proposed Quanterness development occurs towards the west and towards the southeast. This sediment is a combination of outputs from Pudrite and Quanterness. When compared to the sediment flux map it can be seen that very little of the suspended sediment settles towards the west and there is a clear suspension pathway heading southeast, where sediment curves round the south coastline of Wide Firth and exits the waterbody through the eastern tidal straight. During this journey, some suspended sediment is deposited towards the south of Wide Firth.

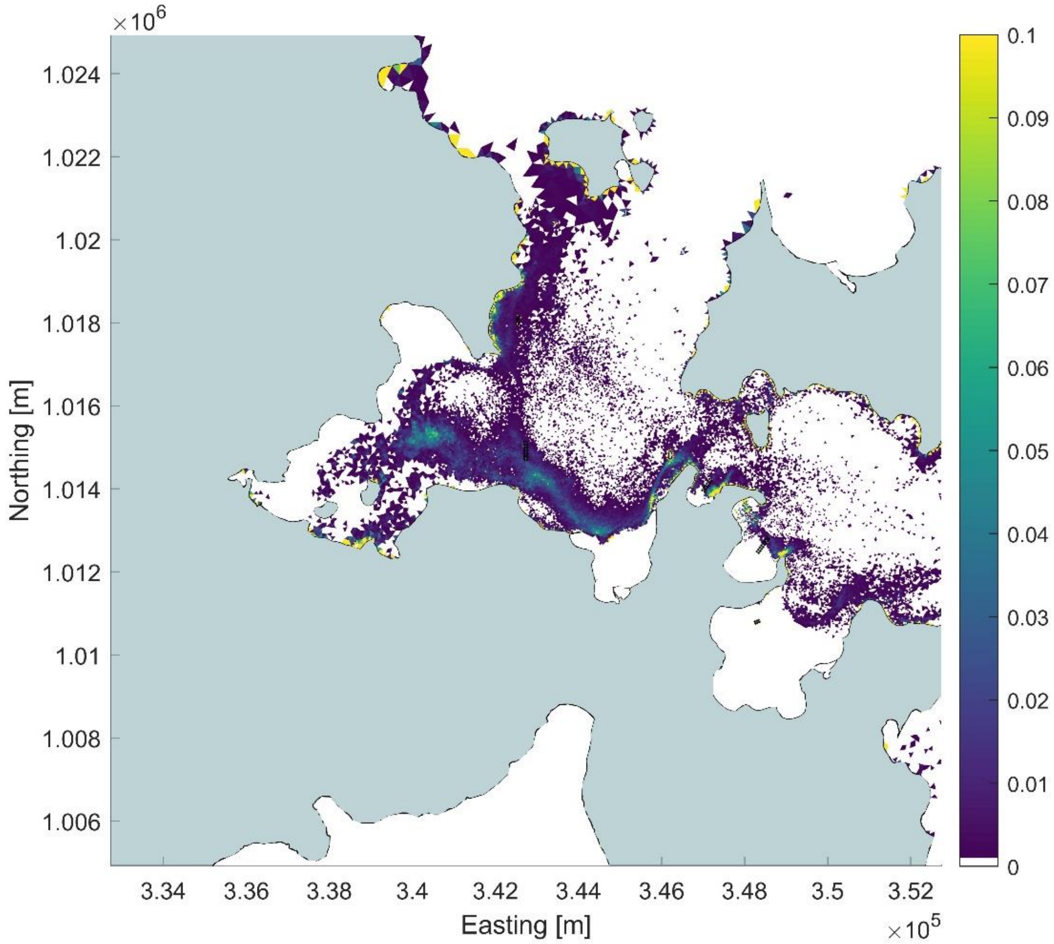

Figure 6. Average far field suspension pathway (g/m^3) of the last 90 days of the simulation for all sites including the proposed Quanterness and Meil Bay developments.

A time series of the area exceeding 250 g/m^2 and the intensity for the sedimented material originating for each farm is shown for the last 90 days of the simulation in Figures 7 and 8. All sites show a gradual increase in sediment accumulation in both area extent and intensity. This is due to sustained maximum biomass and non-decaying particles used within the simulation. Fluctuations within the area assessment show larger variation within spring tides where resuspension events are more common.

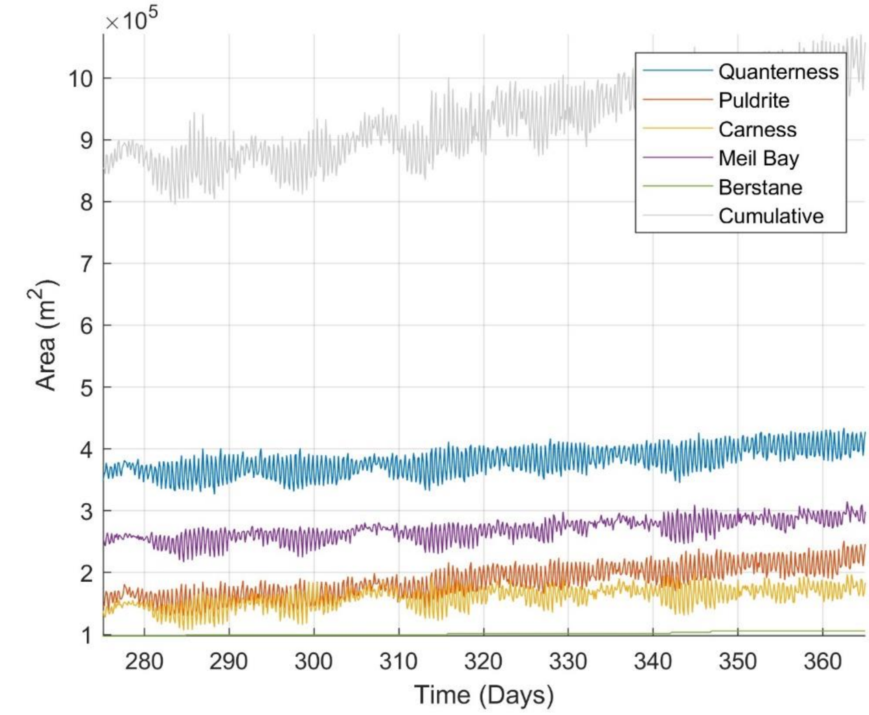

Figure 7. Average area exceeding 250g/m^2 for the cumulative and independent sites over the last 90 days of the simulation.

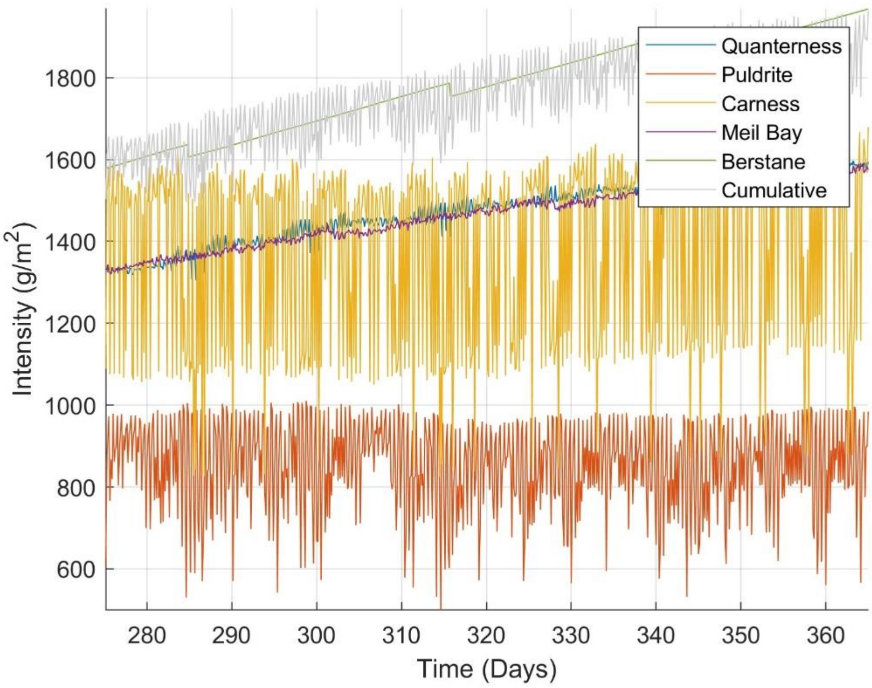

Figure 8. Average deposition intensity for areas exceeding 250g/m^2 for the cumulative and independent sites for the last 90 days of the simulation.

The average individual and cumulative area exceeding 250 g/m^2 for the last 90 days of the simulation is shown in table 7.

Table 7. Average concentration at 250g/m^2 contour, averaged over the last 90 days of simulation.

	Area (m^2)
Qaunterness (Proposed)	380,753
Puldrite	186,525
Carness	160,228
Meil Bay (Proposed)	269,665
Berstane	101,075
Cumulative	**926,543**

3.2 Sensitive Marine Features

Waste particulates released from all aquaculture farms in the form of deposition and suspended flux are calculated at previously identified sensitive marine feature locations. Figure 9 shows the average cumulative deposition flux, where all point sensitive features experience very low or no deposition. For area-based features, only the Wide Firth SWPA experiences any deposited material within the boundary, where the coverage and concentration remains low with a patchy distribution.

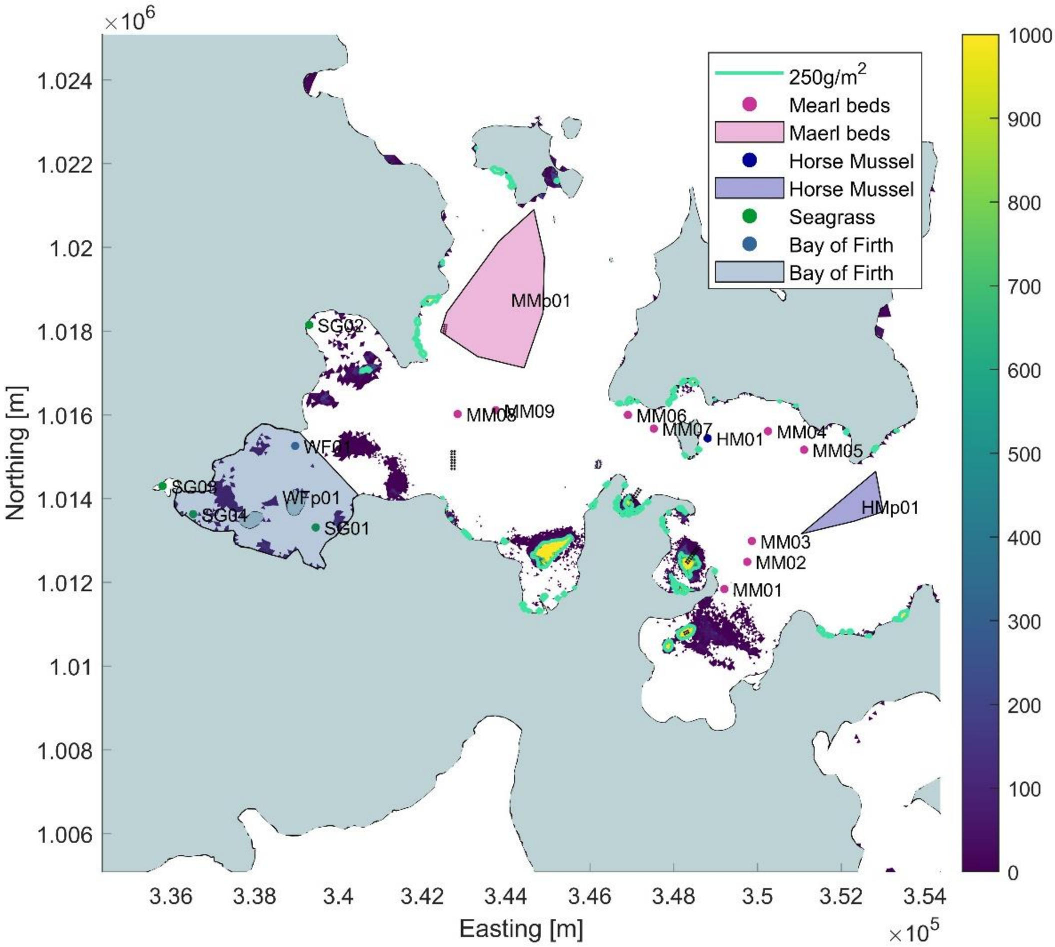

Figure 9. Average far field deposition (g/m²) of the last 90 days of the simulation for all sites including the proposed Quanterness and Meil Bay developments. All sensitive marine features identified in the screening report are shown.

Suspended sediment from the cumulative assessment is shown relative to the sensitive marine features within figure 10. This indicates no sensitive features are located within the main sediment pathway for any of the farms included within the assessment. For some locations, MM06, MM07 and SG01, suspended sediment is shown to be in the surrounding area. However, the low concentrations and granular nature of the spatial average suggest a very low potential risk to sensitive features, even with enhanced sediment traps caused by complex seabed structures from marine features.

Table 8 shows the average deposited and sedimented values for each sensitive feature, for area features, the centre of the polygon shape is used in addition to the area exceeding 250g/m^2. For the majority of sensitive features, the suspension and deposition values are zero or negligible. SG02 and WFp01 show very small values for deposition and suspension, where SG02 has an average deposition of 5.26 g/m^2 and a suspension of 0.12 g/m^3. Within the area polygons, no deposition exceeds the 250g/m^2 for any sensitive feature.

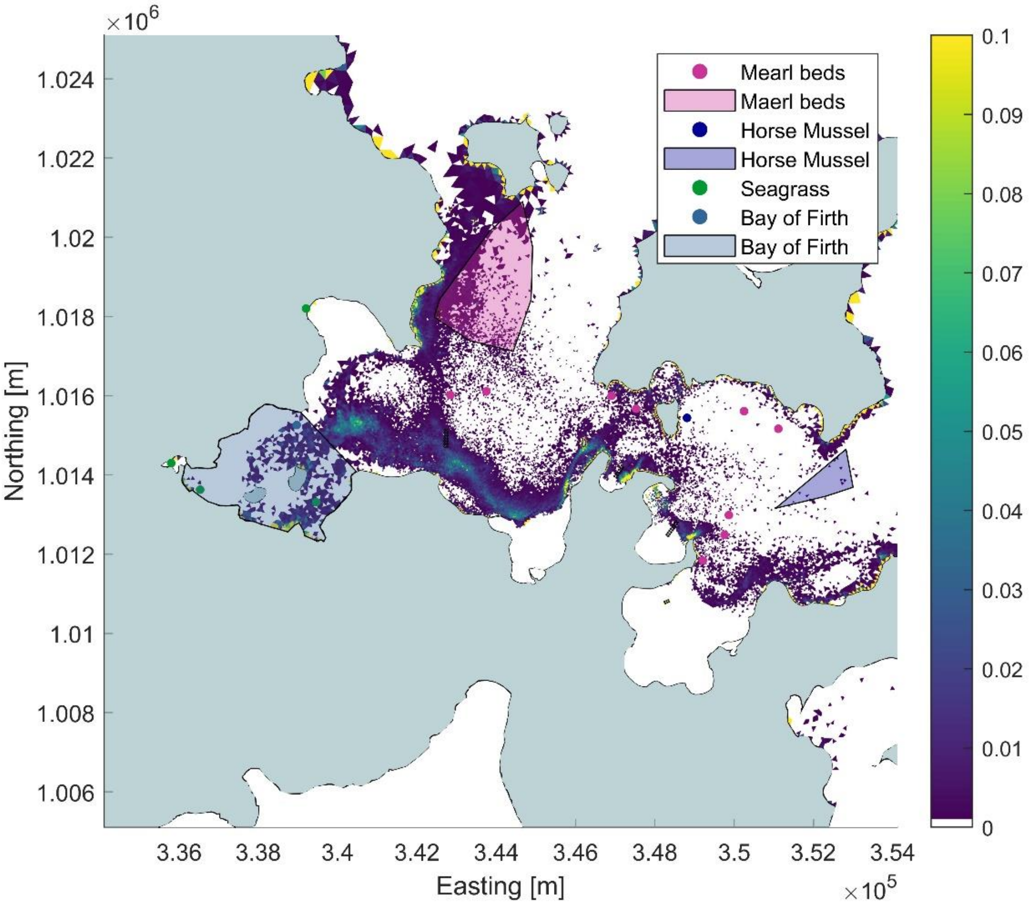

Figure 10. Average far field suspension (g/m^3) of the last 90 days of the simulation for all sites including the proposed Quanterness and Meil Bay developments. All sensitive marine features identified in the screening report are shown.

Table 8. Average deposition and suspension at the location of each sensitive marine feature.

	Name	Easting (m)	Northing (m)	Sediment Flux (g/m^2)	Suspended Flux (g/m^3)
Mearl - points	MM01	349210	1011840	0.00	0.000
	MM02	349756	1012489	0.00	0.000
	MM03	349865	1012987	0.00	0.000
	MM04	350250	1015610	0.00	0.000
	MM05	351113	1015166	0.00	0.000
	MM06	346907	1015999	0.00	0.000

	MM07	347526	1015671	0.00	0.000
	MM08	342842	1016019	0.00	0.000
	MM09	343750	1016110	0.00	0.000
Mearl – polygon centre	MMp01	343921	1018754	0.00	0.000
Horse Mussel - point	HM01	348810	348810	0.00	0.000
Horse Mussel – polygon centre	HMp01	352282	1013818	0.00	0.000
Sea grass bed - point	SG01	339455	1013313	0.00	0.000
	SG02	339200	1018200	5.26	0.120
	SG03	335800	1014300	0.00	0.000
	SG04	336529	1013628	0.00	0.000
Bay of Firth - point	WF01	338966	1015259	0.00	0.000
Bay of Firth – polygon centre	WFp01	338458	1014042	0.05	0.000

	Polygon Area (m^2)	**Area exceeding 250g/m^2 (m^2)**	**Percentage Area of Polygon (%)**	**Area exceeding 1g/m^2 (m^2)**	**Percentage Area of Polygon (%)**
Mearl Bed	5,502,842	0	0	0	0

Horsel Mussel	1,023,467.5	0	0	0	0
Wide Firth	8,594,543.3	0	0	22,722	0.26

A time series of deposition and suspension for each point based sensitive feature is shown in figure 11. For the majority of features, particle occurrence is shown to be an infrequent event, that are transient in nature. For sediment particles these do not persist and accumulate and are quickly eroded. Features SG02 and WFp01 show the only sustained deposition, where SG02 begins the time series with 5.26g/m^2 and experiences no resuspension, deposition, or particle decay within this period, WFp01 has a more active bed process, where several deposition and erosion events occur within the time series, with no continual accumulation occurring. The suspension process shows a more variable mechanism where particles often pass by a location without depositing any material. Most feature locations show numerous time steps where suspended material occurs at the location. These plumes of suspended sediment are not shown to be persistent for any sensitive feature location which results in low average suspension rates.

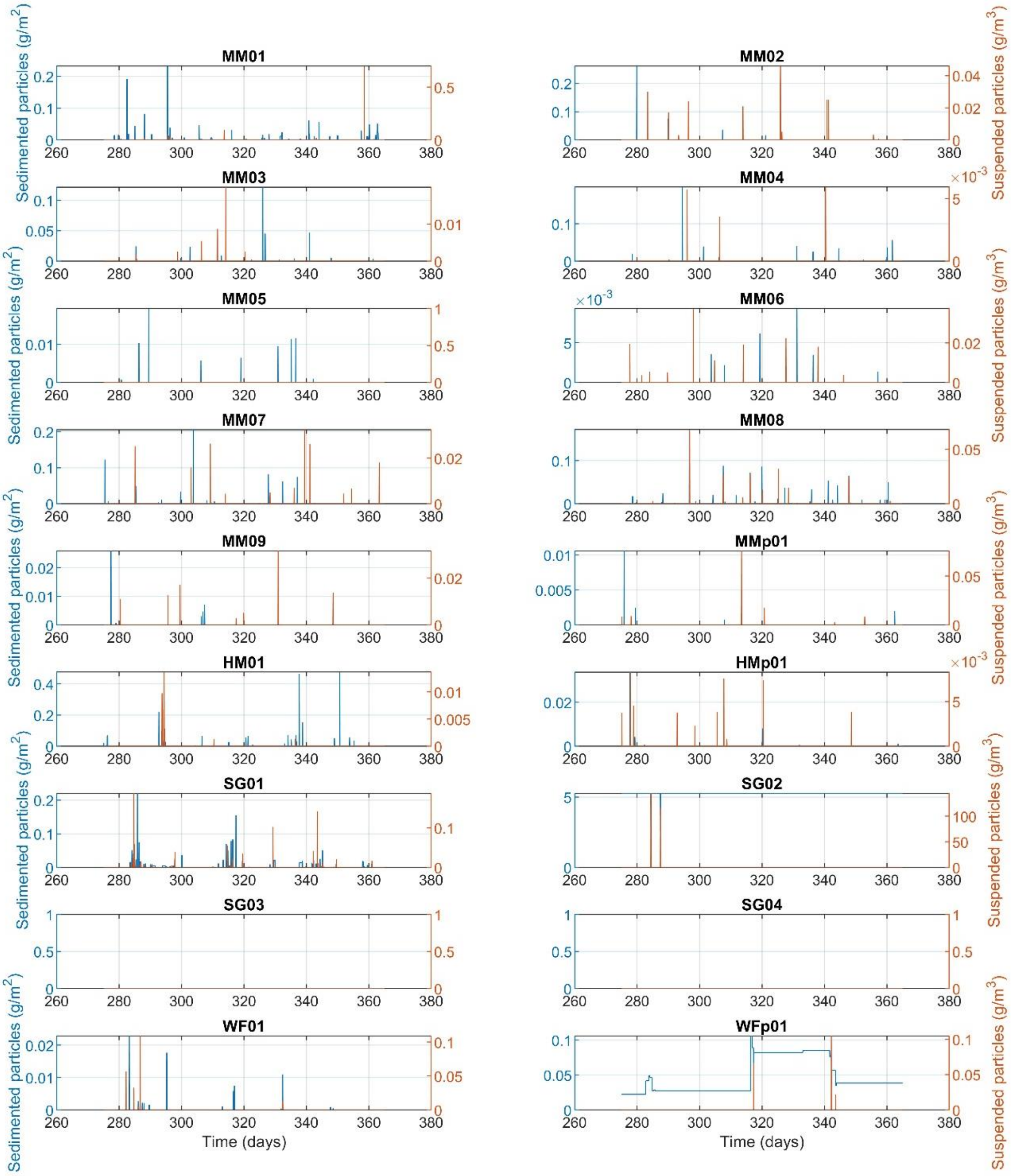

Figure 11. Timeseries of sedimented (left axis) and suspended (right axis) particles over the last 90 days for all identified point sensitive features.

4. Conclusions

This report outlines the hydrodynamic and particle tracking model for the distribution of solid waste particles from all surrounding aquaculture farms. This is used to help regulate development when considering cumulative deposition and potential risk towards sensitive marine features.

The proposed Quanterness development shows no impacted seabed beneath the farm with the main area of deposition occurring 3.5km to the southeast of the farm. An additional small patch of sediment is distributed to the west. The cumulative effects from the nearby Puldrite site causes a subtle increase in deposition but this remains at low levels. Average suspension pathways indicate a clear route of suspended material that curves round the southern edge of Wide Firth and exits through the eastern tidal straight.

Deposition and suspension values were output for 18 sensitive feature locations within the waterbody. Deposition and suspension were only shown to occur at 2 locations at very low levels. The remaining locations reported no or negligible values. A time series of deposition and suspension shows activity in most locations, however these suspension events were scarce, consisting of small plumes of sediment that were transient and did not result in accumulation of deposited material.

The result of this study provides a very cautious approach at predicting the dispersal of solid waste from all fish farm developments within the area. The results show that the proposed Quanterness site lies within a very dispersive environment where any sediment released from the site is quickly dispersed and assimilated. Both Suspended and deposited sediment pathways do not interact with marine sensitive features and therefore pose no additional environmental risk.

5. References

Ordnance Survey (2020) “Data Downloads” (Accessed September 2020) Available at: https://osdatahub.os.uk/downloads/open

SEPA (2018) “Supporting Guidance (WAT-SG-53): Environmental quality standards and standards for discharges to surface waters”.

SEPA (2022) “Aquaculture Modelling Screening &Risk Identification Report: Quanterness (QUAN1)” May, 2022

SEPA (2024) “Marine Modelling Guidance for Aquaculture Applications” January, 2024.

UK Hydrographic Office (2021) Marine Data Portal (Accessed May 2021) Available at: https://datahub.admiralty.co.uk/portal/apps/sites/#/marine-data-portal