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Influence of waves and current speed on resuspension of fish farm waste: Case study in Funningsfjørður, Faroe Islands

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Abstract

The Faroe Islands is an archipelago situated in the Northeast Atlantic Ocean. One of the major industries is farming of salmonids. The farms are mostly located in bays and fjords that are sheltered from strong currents. The small distance between the fjords and the open ocean implies that many Faroese fjords are periodically exposed to ocean swells, especially during winter. Ocean swells are generally long period waves with motion reaching deep into the water column. When the swells are large enough they can add to the cleaning of fish farming sites by resuspension of the bottom sediments. In the present study the influence of swells on the bottom sediment in Funningsfjørður is investigated. By means of wave- and current measurements, combined with turbidity and sedimentation trap measurements, we found that wave action induced major resuspension events. Events with significant wave height above 2 m and peak periods of around 13 sec caused sediment at bottom depths of 54 m to be in suspension at < 14 m depth in the watercolum. However, current speeds of 15-20 cm s^{-1} near the seabed did not induce noteworthy resuspension of fish farm wastes. Sediment inventory combined with mineralization measurements of organic carbon indicated, that the influence of waves contributed to the removal of fish farm wastes from the seabed below the fish farm.

Key words: waves, resuspension, fish farm wastes, Faroe Islands.

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Introduction

The most evident environmental impact of fish farming is the accumulation of particulate fish farm waste at the seabed below the net cages. This stimulates the metabolic activity in the sediment, resulting in decreased oxygen availability for the benthos beneath the fish cages and changed pathways for the mineralization of the organic material (Holmer & Kristensen 1992, Christensen et al. 2003, Hyland et al. 2005, Hargrave et al. 2008, Valdemarsen et al. 2012).

The local impact is determined by the amount of organic waste accumulating at the seabed. Thus the size of the farm, and the amount of waste produced affects the benthic impact. As fish food contains more than twice as much organic carbon as fish faeces (á Norði et al. 2011), and the fish food sinks trough the water column at a speed which is ~3 times higher than the sinking speed of fish faeces (Cromey et al. 2002a), the severity of the benthic impact is dependent on the husbandry method. However, site specific characteristics such as water depth and current speed, also play a highly significant role in the dispersion of fish farm wastes and thus the resulting benthic impact (Cromey et al. 2002a, á Norði et al. 2010). In recognition of this, modern farms are preferentially placed at moderately exposed sites rather than sheltered sites.

In addition to current speed and depth, resuspension of sediments impacted by fish farm wastes improves the benthic environment below the fish farms. Resuspension occurs when the water movement induces a shear stress on the bottom sediment above some critical value. This critical value is defined by several authors and varies as much as between 0.018 N m^{-2} (Cromey et al. 2002b, Yokoyama et al. 2006) and up to 0.814 N m^{-2} (Dudley et al. 2000) which corresponds to a steady current speed at a 1 m reference height of 9 cm s^{-1} and 60 cm s^{-1}, respectively. Resuspension can be due to different kinds of water motion, e.g. strong steady current or unsteady motion like the oscillating motion due to large surface waves. Due to the thinner bottom boundary layer for unsteady motion like wave motion, high bottom shear stress values can be achieved at much lower velocities at the 1 m reference height for wave motion than for steady currents (Niclasen & Simonsen 2009).

In the Faroe Islands many of the fish farming sites are located close to the open ocean, and even if the sites are partly sheltered from the wave action in the open ocean, many of the sites experience fairly large waves and also long period ocean swells. These long waves create movement at great depths that can reach the bottom sediment resulting in increased bottom stress. At sites with currents slower than the resuspension speed for the sediments this additional stress from the waves can be the triggering effect for resuspending sediments. At such sites the wave action can be a highly important cleaning mechanism.

In this study a fish farm which was periodically exposed to high current speed and/or wave action was investigated, in order to study the physical forces needed to induce resuspension and to examine the effect of resuspension on the local benthic impact of fish farming.

Materials and methods

Study site. The study was conducted in Funningsfjørður, Faroe Islands, a 9.6 km long fjord, with steep slopes along the shore and a relative flat base along the centre of the fjord. While the inner part of the fjord is narrow (400 – 800 m wide), the fjord is ~3 km wide at the outer 4 km of the fjord, where the fish farm is located at a bottom depth of 54 m (Fig. 1).

Due to the open shape of the fjord it is subjected to quite strong wave action. Ocean waves from northerly directions enter the sound north of Funningsfjørður and the long waves are diffracted along the coast and enter the fjord. Due to the diffraction the waves are reduced in height while the period stays approximately constant. The expected wave height during winter storms is 2 – 5m.

In Funningsfjørður there is one fish farm, and it represents the major source of anthropogenic organic carbon and nutrients to the fjord, since most of the catchment area is uncultivated and uninhabited (Mortensen 1990). The fish farm consisted of circular net cages (diameter 40 m) arranged in 2 rows. At the study site fish farming had been active since 2006 with ~18 moths farming periods followed by a fallow period of at least 2 moths.

Throughout the farming cycle prior to this investigation, the production of Atlantic Salmon was ~7000 tonnes of which ~290 tonnes were located in the investigated net cage. The investigation started immediately as the fish were removed from the farming site.

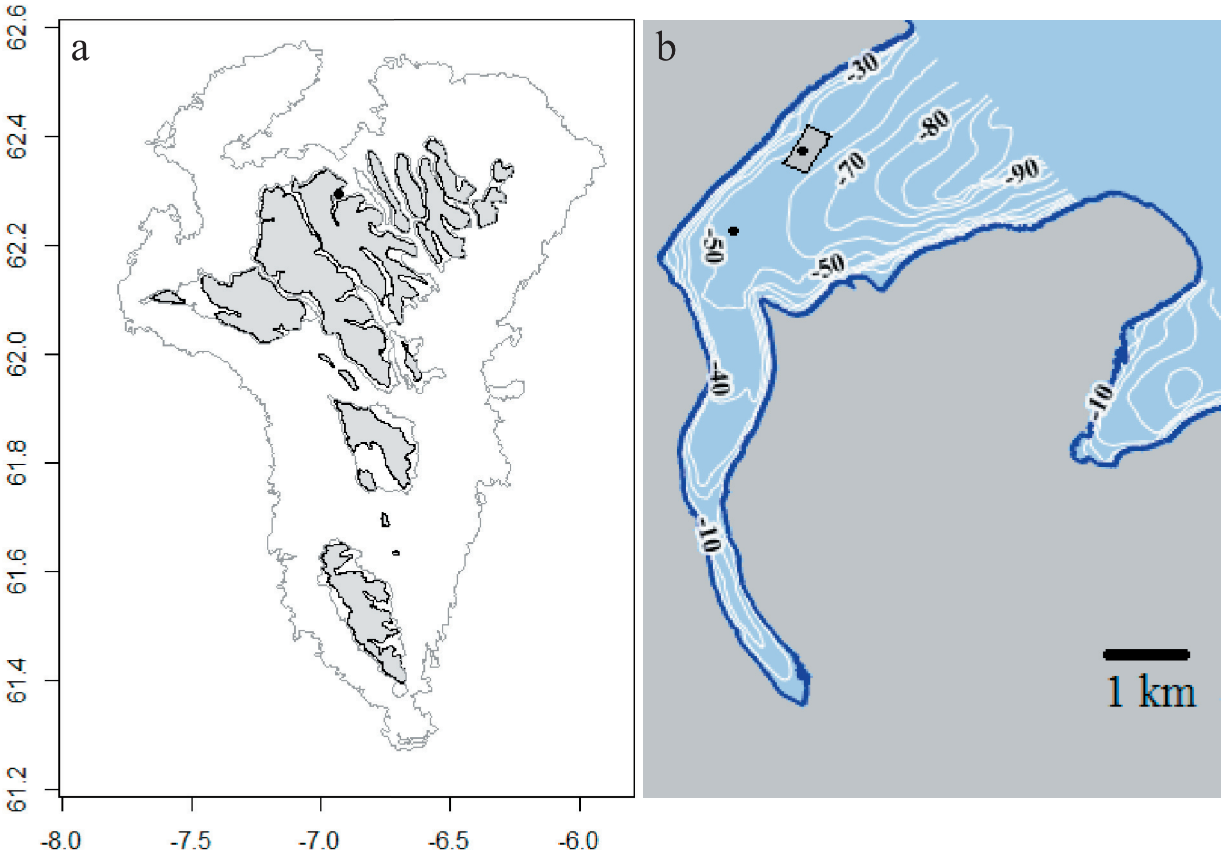

Figure 1. Map of the Faroe Islands showing the 50 and 100 m bottom depth contours (a) and Funningsfjørður (b). The farming site is marked grey, while black dots represent the sampling stations at the farming site and the reference station.

During the fallow period from 17 September 2011 to 9 January 2012, currents, turbidity and waves were measured continuously within a 100 m distance from the fish farm. Sediment time series samples were collected at the edge of the investigated net cage, which was positioned near the centre of the fish farm (Fig. 1b). In addition, sediment was collected at a reference station located 1.2 km from the fish farm (depth 52 m). During the first 8 weeks samples were collected on a weekly basis, while the sampling intensity decreased towards the end of the fallow period. Sediment traps were deployed on 5 occasions.

Current, turbidity and wave measurements. The current and turbidity measurements were performed using a Seaguard instrument from Aanderaa placed 0.8 m above the seabed, using a bottom mounted frame. The wave measurements were performed using a 600 kHz AWAC instrument from Nortek in a moored deployment ~30 m above the bottom.

In the first 8 weeks currents and turbidity were measured every 10 minutes while for the rest of the deployment 20 minute intervals were used. Each 10 minute interval data point was an average of 650 samples of current speed and 13 samples of turbidity measured over 2 minutes while the 20 minute interval data points were averages of 1250 samples of current speed and 25 samples of turbidity measured over 4 minutes. The wave measurements consisted of 1024 samples at 1 Hz every 20 minutes. The AWAC measures the full wave spectrum, but for this presentation, only the wave height (Hm0) is used.

Sedimentation traps. Duplicate sedimentation traps were deployed on 5 occasions, for 1 to 2 days. The timing of the deployments was based on weather and wave forecasts from www.yr.no, attempting to catch events with high current speeds and or high wave actions, and also events with calm weather. The sediment traps were moored within 20 m to the net cage, at a distance of 0.8, 2, 5, 10, 20 and 40 m to the seabed.

The trap content was filtered on pre-combusted (500° C) and pre-weighed Whatman GF/F filters, and the amount of total particulate material (TPM) was determined as the weight gain of the filters after drying at 55 °C. Particulate organic carbon (POC) and particulate nitrogen (PN) content was determined on a CE 440 Elemental analyzer on sub-samples of the dried filters, after fuming with HCl.

Sediment characteristics. Sediment was retrieved with a HAPS bottom corer (KC-Denmark). Sub-cores were collected in Plexiglas tubes (i.d. 5.6 cm) for further analysis. Cores were kept dark and at bottom water temperature during transport to the laboratory, which was reached within 4 hours of sampling. For determination of porosity, total organic carbon (TOC) and total nitrogen (TN) two cores from each station were sectioned into 1 cm intervals down to 4 cm depth, and 2 cm intervals down to 12 cm depth. Sediment water content was determined as weight loss after drying for >48 hours at 55 °C until constant weight, and the density of the sediment was determined as the weight of a known volume sampled with cut-off syringes. TOC and TN were measured on a CE 440 Elemental analyzer after the sediment had been homogenized, acidified (4-5% H_2SO_4), and dried.

The grain size of the top 4 cm of the sediment was determined by sieving dried sediment through a sequence of sieves with mesh sizes of 63, 250, 500, 710, 1000 and 2000 µm.

Results

Sediment description. At the onset of the fallow period the sediment below the fish farm was visually impacted from the farming activity, as the top ~6 cm were black and the surface was covered by *Beggiatoa*. However the sediment was not devoid of macrofauna.

During the fallow period, the sediment recovered to some degree. After one month the *Beggiatoa* was gone, and the sediment surface at the farming station resembled the reference station, which was light brown. However, impact from the farming activity was still evident deeper in the sediment at the end of the fallow period which lasted almost 4 months.

In consistency with the visual observations, the top 6 cm of the sediment below the fish farm were enriched in organic carbon and nitrogen relative to the reference station (Fig. 2a and b). Although the organic carbon and nitrogen content decreased over time, it did not reach reference level. The density of the sediment below the fish farm and the reference station was similar at the top of the sediment, but the density of the sediment below the fish farm increased 14% from the sediment surface to 6 cm depth, while it only increased 7% at the reference station (Fig. 2c). The water content at the reference

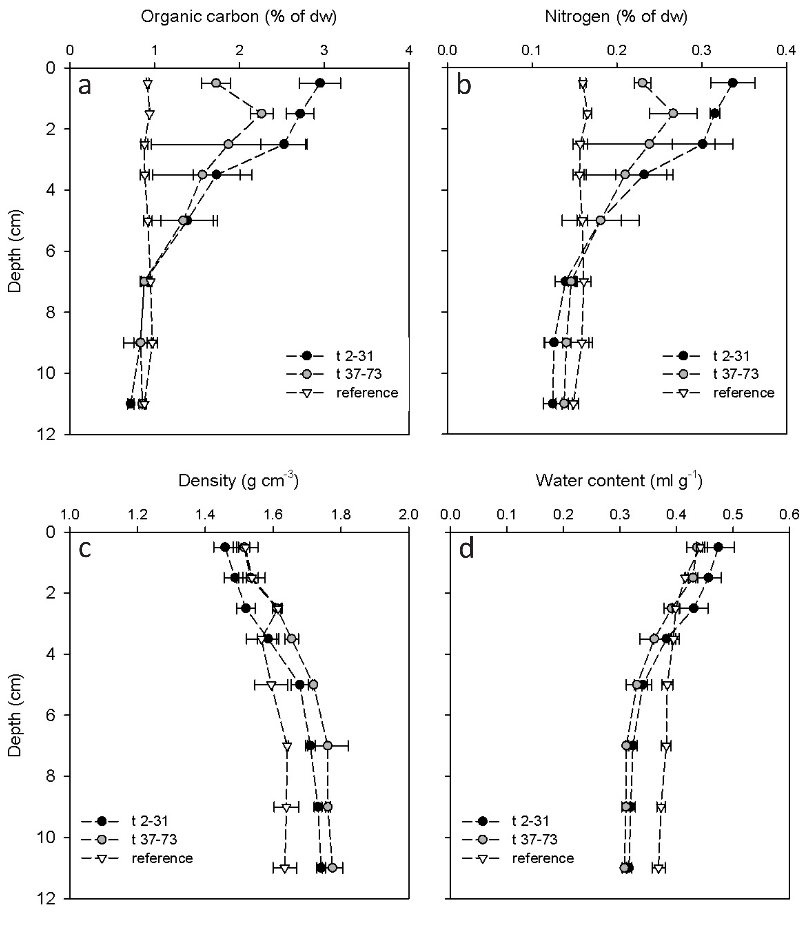

Figure 2. Depth distribution of (a) organic carbon (b) nitrogen (c) density and (d)water content in the sediment below the fish farm (dots) and at the reference station (triangles). Black dots represent the mean (±SE) of 4 samplings taken on day 2, 10, 18, and 31 after the fish were removed, while grey dots represent the mean of 2 samplings taken on day 37 and 73. Triangles show the mean of 3 samplings at the reference station.

station was fairly constant with depth while it decreased 28% from the surface to 6 cm depth at the farming station (Fig. 2d).

At depths greater than 6 cm, the sediment was seemingly unaffected by the farming activity (Fig. 2). The organic carbon and nitrogen content was somewhat lower at the fish farm than at the reference station, which also was the case with the water content (Fig. 2c), while the density of the sediment below the fish was higher (Fig. 2d).

At the reference station 78% of the sediment was mud (defined as grainsize < 63µm) while the sediment at the farming station only contained 30% mud, with the majority being fine sand

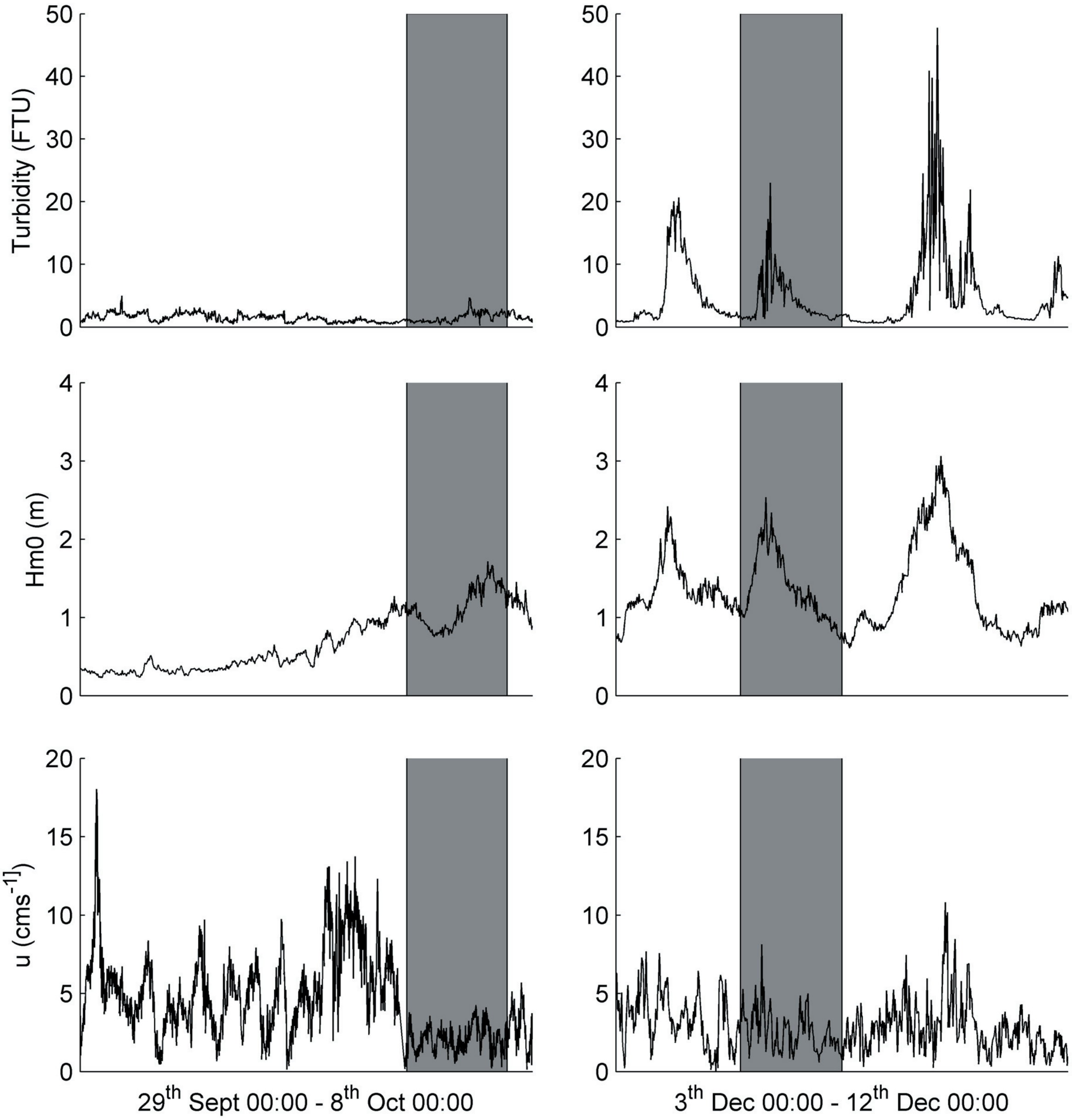

Figure 3. Turbidity 0.8 m above the seabed, wave height (Hm0) and current speed (u) for the periods 29th September to 8th October and 3th December to 12th December. The highlighted grey areas indicate the timing of the sediment trap deployments.

(grainsize 63-250µm). This difference is most probably the origin to the dissimilarity in density and water content between the farming and the reference station at depth >6 cm (Fig. 2c and d).

Waves, currents and resuspension. The average current speed over the entire measurement sequence was 4.1 cm s^{-1}, and the maximum 10% were from 7.1 to 24.1 cm s^{-1}. The average wave height (Hm0) was 0.72 m and the maximum 10% were from 1.28 to 3.06 m. The site can thus be classified as sheltered from strong currents, but fairly exposed to waves. The largest waves at the site are long period ocean swells, hence the motion in the water due to the waves reaches deep into the water column.

The influence of wave action and current speed on the seabed was highly different, as exemplified in figure 3. With the absence of high waves (average = 0.7, maximum 1.7 m), strong currents with several episodes with current speed above 10 cm s^{-1} (maximum ~18 cm s^{-1}), did not influence the turbidity, which was steadily low (average = 1.5 FTU) (Fig. 3 left panels). However, during episodes of high waves (average Hm0 = 1.3 m and three maxima with Hm0 between 2.4 and 3.1 m) the turbidity reached much higher levels (maxima between 20 and 48 FTU) with peaks that followed the peaks in wave height. The average turbidity for this episode was 4.9 FTU. During this episode the current speed was slower with only one single peak (11 cm s^{-1}) above 10 cm s^{-1} (Fig. 3 right panels).

The interaction between turbidity, current speed and wave height is further investigated in figure 4. The scatterplot of turbidity and current speed (Fig. 4a) shows no indication of a correlation between the turbidity and the current speed, as the turbidity does not increase with increasing current speed even with current speed above 20 cm s^{-1}.

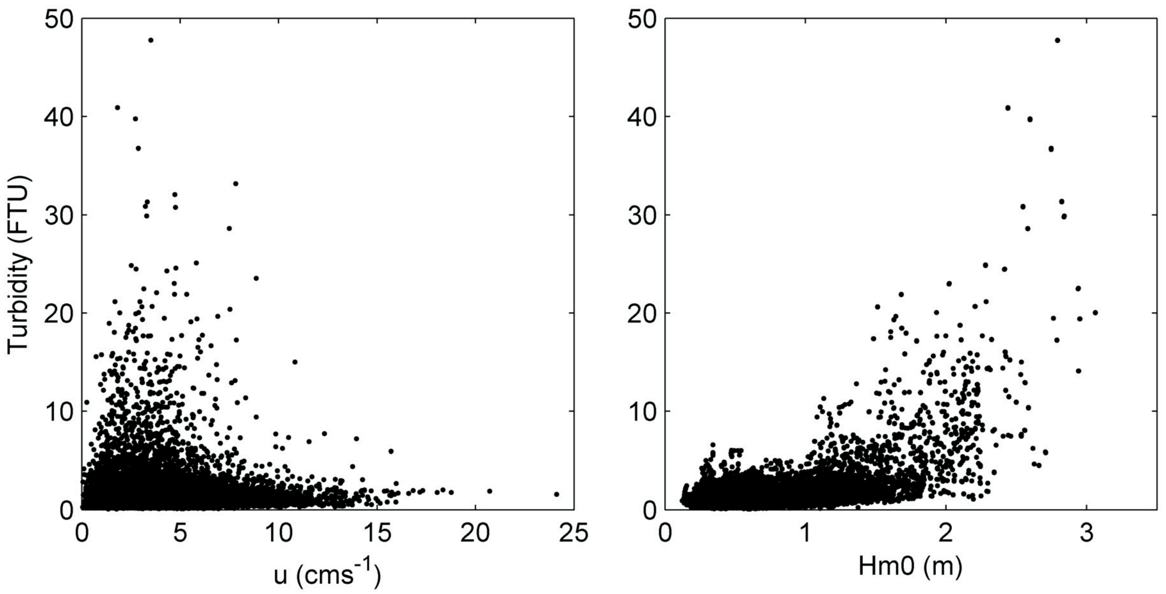

Figure 4. Scatterplots of (a) turbidity and current speed(u) and (b) turbidity and wave height (Hm0).

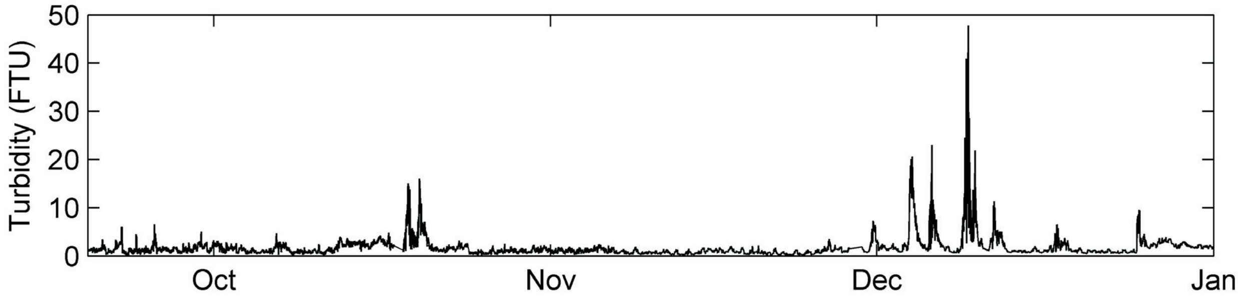

Figure 5. Turbidity 0.8 m above the seabed during the fallow period at the fish farm.

On the other hand there seems to be a correlation between the turbidity and the wave height (Fig. 4b) as the turbidity increases with increasing wave height. This correlation seems to be somewhat split into two parts, with one relationship when the wave height is below 1.5-2 m and another at the higher waves. This indicates that the critical shear stress for the bottom sediments at the present site is reached with wave heights around 1.5-2 m.

Resuspended material. Throughout the first month of the fallow period (17 september to 17 oktober 2011) the turbidity 0.8 m above the seabed was constantly low (average = 1.1 ± 0.55 (SD)), with occasional spikes lasting for around 3 hours reaching up to a maximum of around 6.6 FTU (Fig. 5). Two deployments of sedimentation traps (5-7 and 10-11 October) showed small amounts of particles in the water column (Fig. 6). The amount of TPM in suspension was 8-11 g m^{-2} d^{-1} at 14 m depth (40 m above the seabed), and increased somewhat towards the seabed.

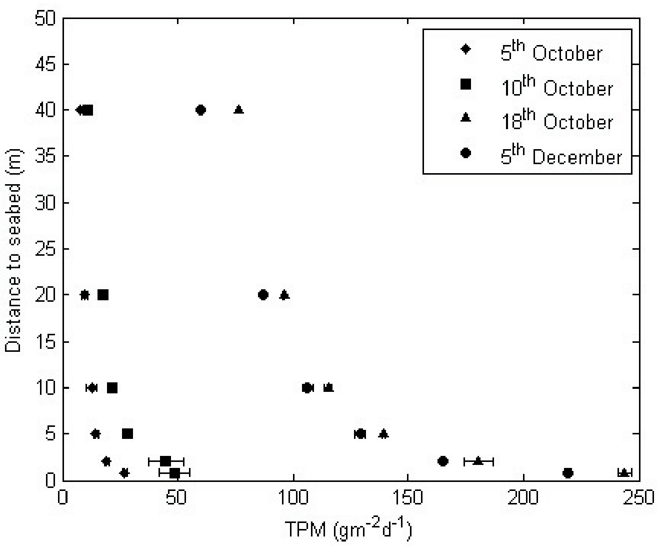

Figure 6. Sedimentation of total particulate matter (TPM) at the fish farm. Two deployments with small waves (max 1.68 and 1.72 m) at 5th and 10th oktober, and two deployments with maximum wave heights of 2.34 and 2.54 m at 18th October and 5th December. The traps were deployed for 2 days, with exception of 18th October when the traps were deployed for 28 hours.

The first major resuspension event occurred on 18-19 October (Fig. 5), at which time sedimentation traps were deployed (Fig. 6). This event was followed by a second resuspension event from the 19-21 October. In November no resuspension events were observed, but in December six resuspension events occurred where the turbidity was above 5 FTU for periods lasting 1 to 31 hours (Fig. 5).

During the resuspension events, the amount of TPM in suspension 0.8 m above the seabed was 219 – 244 g m^{-2} d^{-1}, which is 5-9 times higher than the amount measured during the first month of the fallow period

Table 1. Organic carbon and nitrogen content (± SE) in the particulate matter in the sedimentation traps during wave induced resuspension events, and at deployments without major resuspension. The organic carbon and nitrogen content of the sediment at the fish farm and reference station is likewise shown. P-values represent independent two way t-tests of the sedimentation traps during resuspension (top row) and the corresponding row.

	OC (% of DW)	n	P	N (% of DW)	n	P
Sedimentation traps during resuspension	2.2 ± 0.16	11		0.31 ± 0.015	11	
Sedimentation traps at no resuspension	1.6 ± 0.14	11	0.0132	0.28 ± 0.026	11	0.0238
Top cm of sediment at fish farm	2.3 ± 0.19	5	0.5207	0.26 ± 0.019	5	0.0248
Top cm of sediment at reference	0.92 ± 0.02	3	<0.0001	0.31 ± 0.015	3	<0.0001
8-10 m depth in sediment at fish farm	0.81 ± 0.06	5	<0.0001	0.31 ± 0.015	5	<0.0001

(Fig. 6). TPM decreased exponentially ($r^2 > 0.96$) with height above the seabed. However, the amount of TPM was high even at a water depth of 14 m (40 m from the seabed) where the amount of material in suspension amounted to ~30 % of TPM at 0.8 m above the seabed.

The organic carbon content of the particulate matter in suspension was somewhat higher during resuspension events than in the deployments without major resuspension, while the nitrogen content was more similar (Table 1). The material in the water column during resuspension events had no resemblance to the material at the reference station, neither to the material deeper in the sediment at the fish farming station, while the organic carbon content in the top cm of the fish farm sediment and the sedimentation traps during resuspension was highly similar (Table 1), indicating that the resuspended material was sediment from the fish farm enriched with organic carbon.

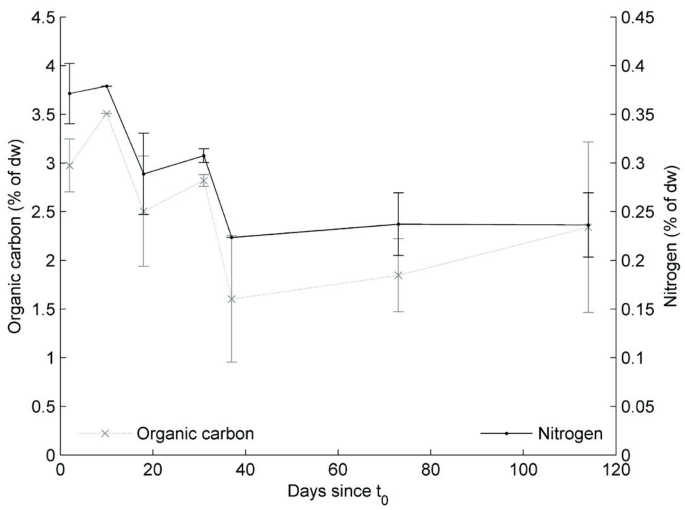

Figure 7. Time series of the organic carbon and nitrogen content in the top cm of the sediment below the fish farm during the fallow period. t_0 is when the fish was removed. Error bars represent the standard deviation of two sample replicates.

The total amount of TPM in the water column during the resuspension events on 18-19 Oktober, which lasted for ~12 hours, corresponded to the erosion of 0.8 cm of the seabed, while the TPM amount at the resuspension event the 5 -6 December, which lasted for ~24 hours, corresponded to the erosion of 1.1 cm of the seabed.

The organic carbon and nitrogen content in the top cm of the sediment also decreased markedly during the week between the sampling prior to and after the two resuspension events in October, with the OC content decreasing from 2.8 ± 0.06 to 1.6 % of dw, and the nitrogen content decreasing from 0.31 ± 0.07 to 0.22 % of dw (Fig. 7). In fact the fallow period can be divided into prior- and after the onset of resuspension when regarding OC and nitrogen in the top cm of the sediment, with the 4 samplings before consisting of 2.95 ± 0.24 % OC and 0.34 ± 0.03 % nitrogen, while the three samplings after the onset of resuspension contain 1.9 ± 0.27% OC and 0.23 ± 0.01 % nitrogen. Thus the top cm of the sediment has changed significantly with the onset of resupension. P values of 0.001453 and 0.0001103 for OC and nitrogen, respectively in two tailed t-test.

Discussion

The accumulation of fish farm waste at the seabed was limited compared to other studies, despite the fact that the samples were taken at the edge of the net cage, just after 290 t of fish were taken for slaughter. At the first sampling the OC content at the top of the sediment was 2.97 ± 0.27 % of dw (Fig. 7), which is considerably lower than in similar recent studies of modern farms, with OC content in the range of 7-12 % of dw (á Norði et al. 2011, Sanz-Lázaro et al. 2011, Valdemarsen et al. 2012). Considering the depth and the current regimes of the mentioned studies, one might expect that the distribution of fish waste at the seabed in our study would be more similar to the other studies.

The study by á Norði et al. (2011) is performed at a site with similar depth (48 m) and current speed (average current speed 4 cm s^{-1}), which is run by the same company. It is therefore expected that the husbandry methods were similar and the difference in OC content was caused by some mechanism that significantly improved the dispersion of the fish farm waste. The most evident cause would be resuspension of the sediment.

At the present site our study showed that it was not the peaks in current speed that forced resuspension, since no significant increase in turbidity was measured near the bottom during the high current speed events (Fig. 4a). On the other hand events with large waves (Hm0 > 1.5-2 m) resulted in a significant increase in turbidity near the bottom and sedimentation trap measurements showed that significant resuspension occurred (Fig. 4b and 6).

These events eroded ~ 1 cm of the sediment surface, physically redistributing some of the fish farm waste to a larger area. Resuspension also facilitates a faster mineralization of the fish farm waste, as e.g. high respiration rates, and rapid oxygenation of sediment iron sulfides occur when the particles are in suspension, and a high release of porewater occurs during resuspension events, significantly altering the conditions in the sediment (Sloth et al. 1996, Porter et al. 2010).

The effects of resuspension were also evident in this study, as the OC content in the top cm of the sediment below the fish farm reduced markedly (Fig. 7). It was also evident when comparing the mineralizaton rates to the OC inventory of the sediment below the farm (data not shown). During the first month of the fallow period, the total removal of organic carbon was ~140 g m^{-2}, with the efflux of CO_2 and DOC accounting for more than half of the carbon removal. During the following week with two resuspension events, the removal of organic carbon was almost as high (~135 g m^{-2}), with the CO_2 and DOC efflux accounting for less than 5% of the organic carbon removal.

The conclusion from the present study is that wave action is an important factor when estimating the carrying capacity for exposed fish farming sites. This is especially important for sites with moderate water depth and are exposed to long period ocean swells even if the waveheight is fairly small.

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