The effect of mussel farming on sediment dynamics in the Wadden Sea

Case studies evaluating the local effects of mussel seed fisheries and mussel harvest on turbidity and sedimentation

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Summary

The Wadden Sea is a dynamic system with high sediment dynamics. The turbidity of the water column is highly variable and it has been suggested that values have gradually increased over the past century. High turbidity may eventually lead to negative impacts on primary production, eel grass populations, or predatory fish. From literature it is evident that turbidity is important for the functioning of ecosystems. Anthropogenic activities like dredging, salt- and gas extraction, as well as fisheries and shellfish aquaculture all affect sediment dynamics in the Wadden Sea system. The current report describes the result of a study into the effect of mussel farming on sediment dynamics in the western Wadden Sea.

The role of mussel cultivation in sediment dynamics is two-fold: mussels filter suspended particulate matter from the water column thereby reducing turbidity, while sediment is resuspended during fisheries and harvest of mussels leading to (temporary) enhanced turbidity in the water column. The current study focussed on the latter processes, and specifically aimed to define the spatial scale of enhanced turbidity and sedimentation resulting from mussel culture (fisheries, harvest).

Sediment dynamics were evaluated in case studies during commercial mussel seed fisheries (in spring) and harvest on bottom plots (in autumn). Approaches differed slightly between sampling campaigns, but in essence focussed on two questions: (*i*) what is the size and magnitude of the sediment plume, and (*ii*) how long is the plume measurable:

- Fisheries campaigns were performed at Omdraai, Breesem, Dove Balg, Malzwin, ZuidWest:
  - Transects with towed turbidity sensors (Infinity, Hydrolab) were applied covering upstream, within and downstream locations with respect to the fishery zone. This provides an overview of spatial scale of the sediment plume based on turbidity in the water column caused by resuspended material.
- Harvest campaign at Scheer studied a single plot where regular harvest took place:
  - Transects with turbidity sensors followed a similar approach as for the fisheries studies.
  - Sediment traps were deployed in a gradient at both sides of the plot along the main current directions (at 0 m, 50 m, 100 m, 200 m), and sedimentation rates were quantified during the harvest. This provides an overview of spatial scale of the sediment plume based on sedimentation of resuspended material.
  - Sediment samples were collected (Van Veen Grab) before and after harvest on the mussel plot. Organic content of the samples was measured with the aim to define the reduction of organic material by harvest activities. Due to inconsistent results (methodological cause) these measurements were not continued at the other sites.
  - Fixed turbidity meters were deployed at the plot and a reference station over a period of 24 hours, including the period when harvest took place. This provided an overview of the short-term temporal scale of disturbance.
- Harvest campaign at Inschot studied a single plot where the activity consisted of ‘schoonvissen’ (the process where silt/sediment is removed from the plot after mussel harvest). Because of the type of activity and sediment characteristics of the site (relatively muddy), maximum disturbance was expected.
  - Turbidity transects followed a similar approach as for Scheer.
  - Sedimentation (traps) followed a similar approach as for Scheer.
  - Fixed turbidity meters followed a similar approach as for Scheer.
- Harvest campaign at Oosterom studied a cluster of mussel plots. Several plots were harvested during the sampling campaign.
  - Transects followed a similar approach as for Scheer and Inschot, but the transects/ gradients studied were much longer and covered multiple plots.
  - Sedimentation followed a similar approach as for Scheer and Inschot, but longer transects.
  - Fixed turbidity meters were deployed over a period of 4 weeks to monitor (natural) variability.

Results of the case studies showed that turbidity is enhanced within fishery and harvest zones, and the spatial scale of the sediment plume is limited to the direct vicinity of the mussel culture activities (within tens of meters). A ‘sediment plume’ that extended further than the seedbank or plot fished was hardly observed. The absence of a plume was confirmed by sedimentation rates, which were not enhanced above background variability in areas downstream of the mussel culture activities. Fixed turbidity meters indicated that turbidity dropped back to background values almost immediately after harvest stopped.

Magnitude of turbidity enhancement varies between areas and can be influenced by factors such as fishing intensity, type of activity (fisheries, harvest, ‘schoonvissen’), sediment characteristics of the bottom fished, depth and current dynamics. Turbidity enhancement during seed fisheries was higher than during harvest on culture plots (respectively up to a maximum of 40 and 8 times higher than background values). Turbidity within the fishery zones can be higher than observed for natural variability, but is restricted to the fished seed banks and a few days per year.

The current study is based on case studies presenting valuable information on local effects of mussel culture on sediment dynamics specifically for those areas. Although we include some spatial and temporal variation the results do not allow for extrapolation to the entire Wadden Sea.

1 Introduction

1.1 Background

Turbidity in the Wadden Sea is highly variable and it has been suggested that values have gradually increased over the past century. Increased turbidity might lead to negative impacts on the ecosystem. The Wadden Sea is a highly dynamic system in which large amounts of sediments are transported on both daily and annual basis. On top of natural processes, there are anthropogenic activities like dredging, salt- and gas extraction, as well as fisheries and shellfish aquaculture that affect sediment dynamics in the Wadden Sea system. Magnitude and scale of effects of sediment dynamics are largely unknown but are likely to vary between activities. The anthropogenic activities may affect local turbidity and sedimentation, rather than total sediment transports (Van Duren et al. 2015). The current study therefore evaluates the scale to which mussel cultivation (seed fisheries and harvest on bottom plots) contributes to local turbidity enhancement and sedimentation in the Wadden Sea.

1.2 Sediment dynamics in the Wadden Sea

1.2.1 Sediment transport

The Wadden Sea is a highly dynamic system with naturally high sediment transports, and contains relatively high amounts of silt compared to the North Sea. Sediment transport in the Wadden Sea has been evaluated by modelling studies (Van Duren et al. 2015, Kluiver et al. 2015, Kuijper & Brinkman 2015, Brinkman 2015). These studies showed that silt is imported through all tidal inlets, which eventually will settle in the Wadden Sea. It is estimated that there is a nett annual silt transport of 8 MT into the Wadden Sea.

At large time scale (order weeks to months) the horizontal transports (nett import) are important, as this defines the amount of silt locally available for resuspension. At smaller time scales (order hours to days) the amount of locally resuspended and settled silt is more important and defines the turbidity in the water column.

The afore mentioned studies also estimated the contribution of anthropogenic activities (dredging, sand nourishment, wetland construction and maintenance, mussel culture, shrimp fisheries, and shell extraction) on sediment transports. It should be noted though that these model simulations must be interpreted with care, as these were merely a rough first investigation (van Duren et al. 2015). Based on model simulations it was concluded that the sum of all anthropogenic activities is small (maximum 10%) compared to the silt transport from the North Sea into the Wadden Sea. They highlighted that although impact on silt transport was small, local turbidity values might be enhanced by each activity and consequently might have negative effects on the (direct) surrounding ecosystem. Effects of sediment disturbance by anthropogenic activities on local turbidity have not been evaluated in these studies, and are therefore the key focus in the current empiric study.

1.2.2 Changes in turbidity

The Wadden Sea has undergone many changes of which some are thought to have affected concentrations of suspended particulate matter (SPM) in these waters (Philippart et al. 2013). Turbidity in the Wadden Sea has indeed been increasing over the past century (Giesen et al. 1990). However, Philippart et al. (2013) concluded, based on methodologically corrected long-term data series (1974-2010), that turbidity shows strong seasonal and annual variability, but did not show any apparent long-term increase or decrease in time for one specific measurement location since the early ‘70s (NIOZ jetty, western Wadden Sea). These findings are in contrast to other studies that suggest an increase in turbidity during this period (Bot and Colijn 1996; De Jonge & de Jong 2002; Cadée & Hegeman 2002), but considering the consistent and robust data analysis by Philippart et al. (2013) this data series is considered as the best information on long-term changes in turbidity as presently available for the westernmost part of the Wadden Sea over the past four decades. Furthermore, Philippart et al. (2013) state that differences in long-term variations in turbidity trends may be a result of spatiotemporal variation within the study area.

1.3 Mussel culture in the Wadden Sea

The blue mussel represents the largest (in volume) aquaculture sector in the Netherlands. Production areas are located in the south (Delta) and the north (Wadden Sea) of the Netherlands. Approximately 48% of the mussels are produced in the Wadden Sea (Capelle, 2017). Mussel aquaculture in the Wadden Sea is characterised by bottom cultivation: mussel seed is either fished from natural banks or collected by suspended longlines, and subsequently relayed on bottom plots (Figure 1) for further growth to commercial size. During the growth phase mussels are two to three times (Jansen & Capelle, unpublished) transferred to other cultivation plots, either to reduce densities or to move them to better locations that then have become available as a result of harvest of a previous batch. Fisheries and harvest of mussels is done by bottom trawling with a specifically adapted dredge, the 'mussel dredge'.

Figure 1 General overview of mussel bottom plots (blue) in the western Wadden Sea. Source: Ministry of EZ.

The role of mussel cultivation in sediment dynamics is two-fold: on the one hand, mussels filter suspended particulate material from the water column. This may have a positive impact on the turbidity and visibility of the water column (Hawkins et al. 1996). On the other hand, organic rich sediment that has accumulated within mussel banks or culture plots is resuspended during fisheries and harvest of mussels and leads to enhanced turbidity in the water column. Temporal and spatial dynamics of both processes (filtration versus resuspension) are entirely different. Capture of silt and other (small) organic material is a continuous process. During fisheries, transfer and harvest, on the other hand, a significant amount of sediment is brought in suspension during a short time interval (hours to days). The current study specifically aims to quantify the latter process: the effect of fisheries, transfer, and harvest of mussels on turbidity enhancement.

1.3.1 Effects of trawling on the seafloor

Effects of mussel trawling has gained much attention, and questions have been raised about the environmental impact. Most research is focussed on quantifying the effects of mussel trawling activities on bottom fauna (Dolmer et al 1999, 2001, 2012, Frandsen et al 2015). A similar focus in research direction is observed for demersal fisheries with bottom trawls, which are to a certain extent comparable to mussel dredges. Effects on fauna (Van der Veer et al 1985) are most commonly described in literature. A few studies studied sediment resuspension in bottom trawl fisheries. Palanques et al. 2001 indicated that indirect effects (sediment destabilization) of trawling are larger than the direct impacts on turbidity disturbance, as highest turbidity concentrations were observed a few days after fisheries.

1.4 Nature values in the Wadden Sea

The Wadden Sea is an important coastal wetland and one of the largest intertidal ecosystems worldwide (Lotze, 2007). The tidal flats are densely populated with (mostly opportunistic) micro- and macrobenthic animals, which is a reliable food source to the shorebird population (Beukema et al. 1993) at low tide and for flatfish at high tide (Beukema, 1976). Shellfish, like blue mussels, are key species in the Wadden Sea food web. The blue mussel (*Mytilus edulis L.*) is an ecosystem engineer that has a broad effect on biodiversity by providing refuge and habitats for other species and being an important food source for birds, crabs and starfish (Capelle, 2017). Blue mussels create substrate for associated organisms and visitors, such as a variety of birds (Dankers & Zuidema, 1995). Furthermore, the Wadden Sea is a major nursery for juvenile fish and crustaceans of the North Sea (Baer et al 2017, Tulp et al 2017).

1.4.1 Effects of enhanced turbidity on nature values

Increased sediment concentrations in the water column may lead to effects of enhanced sedimentation and/or effects of enhanced turbidity. Enhanced sedimentation may lead to smothering of benthic life and changes in sediment characteristics that prevent settlement of new species (Thrush et al. 2004, McLeod et al. 2012). Sedimentation often has a more local nature compared to increases in turbidity (Thomas et al. 2001). Both processes are often addressed in studies describing degradation of marine habitats (Henley et al. 2000, Kaiser et al. 2006, Airoldi & Beck 2007, Österling et al. 2010).

Enhanced turbidity may lead to impacts on the aquatic organisms that rely on light. The consequences are first seen in the reduction of primary producers (plants and algae) due to lack of light availability and photosynthesis (Henley et al. 2000), followed by degradation of eel grass populations (Duarte 2002, Castorani et al. 2015), the unsuccessful adaptation of benthic life to resuspension or sedimentation (Castorani et al. 2015), the decrease of foraging success of piscivorous fish that rely on visibility to locate the prey (Figueiredo et al. 2016), clogging/damaging of feeding and breathing equipment of filter feeders, loss of important nursery habitats and reductions in prey abundances (Lowe et al. 2009). The increase in turbidity affects filter feeders because the elevated levels of suspended particulate matter (SPM, primary factor controlling turbidity in the water column) tend to clog feeding structures and reduce feeding efficiency, leading to reduction of growth rates, stress and death of these organisms (Newcombe & Macdonald, 2011). On the other hand, in young fish, a slight elevation of turbidity decreases the risk of predation, therefore increasing chances of survival of juvenile fish (Gregory & Levings, 1998). A long-term effect of enhanced turbidity included changes in feeding behaviour of fish from highly efficient visual feeding in clear conditions to an "encounter rate" feeding mode in turbid conditions and reductions on suitable habitats for spawning (Lowe et al. 2009). Effects of local sediment plumes on sea mammals suggested to have minimal impact as these animals are highly mobile (Todd et al. 2015).

1.5 Research questions & approach

The current study specifically aims to define the local impact of mussel culture activities on direct turbidity enhancement in the Wadden Sea, both for fisheries on wild banks as well as cultivation on bottom plots.

The overall research question is: Does mussel cultivation in the Wadden Sea contributes significantly to local enhancement of turbidity? We focus on determination of maximum levels of turbidity, the size and magnitude of the sediment plume and discuss what enhanced values mean for overall turbidity in the Wadden Sea.

In order to answer the main question, the following sub-questions are defined:

1) What is the turbidity enhancement during mussel seed fisheries in absolute values (maximum) and what is the spatial scale of impact (size of sediment plume)?
2) How are sediment dynamics affected during harvest on bottom plots?
    - What is the spatial and temporal magnitude of the sediment plume?
        - What is the size of the sediment plume around the bottom plots during harvest?
        - How long is the sediment plume still present after the harvest activities have stopped?
    - How does harvest affect sediment characteristics and how much sediment is removed from the plots?
3) How does turbidity enhancement by mussel culture activities relate to the natural variability in turbidity in the Wadden Sea.

To answer the research questions, several sampling campaigns were performed during commercial mussel seed fisheries (n=6 areas) and harvest (n=3 areas). These sampling campaigns are regarded as case studies providing an overall overview of potential scale of effect.

2 Materials and Methods

2.1 Study set up

Sampling campaigns were associated with commercial activities in order to investigate sediment dynamics connected to mussel cultivation, and thus followed the cycle of mussel culture activities: fisheries was investigated in spring, and harvest on bottom plots in autumn. The locations for these studies were selected by taking into account a geographical spread across the Wadden Sea, and the fisheries/harvest activity occurring during the selected sampling days/weeks. Fisheries campaigns focussed on the use of mobile turbidity meters (transects), while for the harvest additional measurements were taken with turbidity meters, sediment traps and Van Veen grabs. An overview of the different methods applied during the fisheries and harvest campaigns is provided in table 1.

Table 1 Overview of methods applied to measure sediment dynamics during mussel seed fisheries and during harvest on bottom plots.

	Research question	Turbidity in water column (Turbidity sensors)	Sedimentation (Sediment traps)	Sediment composition (Van Veen grab)
Seed fisheries	Magnitude and spatial scale sediment plume	X (transects)		
Bottom plots	Removal of organic material from bottom			X
	Spatial and temporal scale sediment plume	X (transects and fixed)	X	

2.2 Fisheries

2.2.1 Sampling locations

Mussel seed fisheries occurs on natural beds. The location of these beds were investigated prior the fishing season to define the fisheries (weekly) quota (Marinx 2017). Fisheries is only allowed during a time span of 4 weeks and because of the large amount of mussel seed available in 2017, most of the fishing effort was observed during the first fishing day of each week. This indicated that measurements had to take place in only a few days. In total, three field campaigns were performed:

1) During the first day of the 2nd week of fisheries at location Omdraai (morning and afternoon) and Dove Balg (9th of May)
2) During the second day of the 2nd week of fisheries at location Breesem (10th of May)
3) During the first day of the 3rd week of fisheries at location Malzwin and Zuidwest (22nd of May)

Sampling locations were selected by monitoring where the highest number of fishing vessels were aggregated the evening before the fisheries started. Sediment dynamics was determined by turbidity concentrations in the water column along a transect upstream, downstream and right in between the fisheries zones by using towed turbidity sensors. Turbidity was only measured when fisheries took place, situations without fisheries were not investigated.

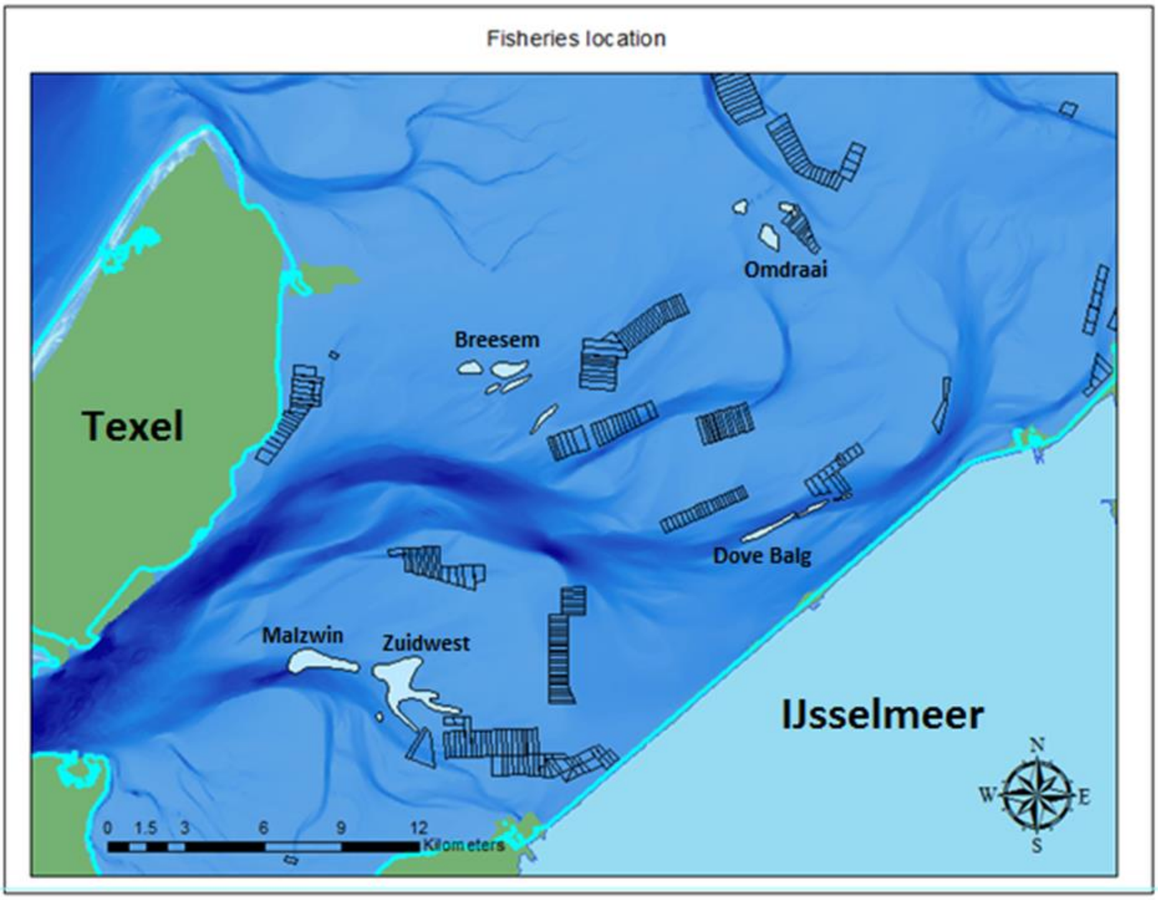

Figure 2 Map showing locations of the fisheries locations included in the current study. Wild mussel seed banks (as investigated during the mussel seed survey; Marinx 2017) are indicated in light blue.

Due to the highly dynamic character of the current patterns in the Wadden Sea it is difficult to define the exact current direction at each site during the investigations. It was not possible to place a current meter close to the fishing activity as the meter will be easily damaged. It is also difficult to predict where exactly fisheries will occur as fishing vessels will not only stick to the areas where mussel seed banks have been outlined, but they may also search around in the area. Current direction was therefore mostly defined by the tidal cycle and the topography of the site (and visual observations by, for example, the drag on buoys close by). Table 2 indicates the tidal cycle and associated current direction for each area during the day it was sampled.

Table 2 Overview of tidal cycle and derived current direction during sampling of the areas included in the fishery campaigns.

Area	Date	Time	Time	Time	Current direction
		Low tide (Harlingen)	High tide (Harlingen)	Sampling	
Omdraai	9 May	04:00 16:22	10:26 22:04	07:45-10:15	Incoming
Omdraai south	9 May	04:00 16:22	10:26 22:04	11:30-13:30	Outgoing
Dove Balg	9 may	03:30 15:52	10:00 21:34	17:05-17:35	Incoming
Breesem	10 May	04:00 16:10	10:00 22:00	08:15-11:00	Incoming
Malzwin	22 May	11:50	06:00 18:30	05:55-12:15	Outgoing
Zuidwest	22 May	11:50	06:00 18:30	13:00-15:00	Incoming

2.2.2 Turbidity concentrations along transects

The sediment plumes induced by mussel culture activities were measured by the turbidity of the water column. Turbidity is determined with high resolution turbidity sensors measuring scattered light, expressing the turbidity in the Formazin Turbidity Unit (FTU) or Nephelometric Turbidity Unit (NTU). As prior to the study it was unknown what maximum level of turbidity scould be expected, we used two sensors simultaneously to test the performance under high and variable sediment concentrations:

1) Hydrolab DS5. The advantage of this sensor is the high turbidity range (0-3000 NTU, 5% accuracy). The disadvantage is the relatively long measurement interval (5 or 10 seconds depending on the meter), which is particularly of importance when used as a towed device and a maximum number of samples should be collected to cover the spatial differences. http://www.ott.com/en-uk/products/water-quality-2/hydrolab-ds5-multiparameter-data-sonde-56/
2) Infinity-CLW (ACLW2) sensor. The advantage of this sensor is its robustness in use and the short measurement interval (1 second). Prior to the study it was unknown if the turbidity range (0-1500 FTU) was sufficient to measure maximum turbidity values. https://www.jfe-advantech.co.jp/eng/ocean/pdf/INFINITY-CLW(E)_201611.pdf

Sensors were mounted together to guarantee the same water body was sampled. The sensors were then submerged approximately one meter below the water surface. A pilot study indicated that highest turbidity was observed at this depth within the sediment plume (Jansen unpublished data). Once the sensors were submerged, the boat slowly (up to 4 knots h^{-1}) navigated in straight transects through the fisheries zones. Transects included both upstream, downstream and within fisheries sections. Sensors were placed at the side of the boat where no impact of the engines was expected. GPS coordinates and time of start and end of each location were noted, to calculate distance and to link to the turbidity data logged by the sensors.

Calibration

Both sensors provided reliable data for maximum concentrations, and the patterns observed were similar between the two sensors (see Annex 1 and 2). Because of the higher sampling frequency data from the Infinity sensor is used for mapping the results. To calibrate the high resolution turbidity data (FTU) to suspended particulate matter (SPM, mg l^{-1}), water samples were collected in triplicates at several (a minimum of n=4 per sampling day) high, medium and low turbidity sites and brought to the lab. In the lab samples were filtered according to standard protocols (Grasshoff et al 1999): water was filtered onto pre-burned and pre-weighed filters. After filtration, filters were rinsed with ammonium formate to remove salt particles. Filters were dried for 24 hours at 70°C and weighed to define dry weight (DW) and subsequently burned at 450°C and weighed to define ash-free dry weight (AFDW). FTU to SPM correlations were analyzed by linear regression using excel software.

2.3 Harvest on mussel bottom plots

2.3.1 Sampling locations

In autumn 2017 three field campaigns were performed to investigate sediment dynamics during harvest on bottom plots. Each of the field campaigns performed had slightly different aims:

1) Location Scheer (23-25 Oct) – sediment dynamics during regular harvest conditions on one mussel plot
2) Location Inschot (20-21 Nov) – sediment dynamics on a muddy location during 'schoonvissen'[1] on one mussel plot. This is expected to generate maximum impact
3) Location Oosterom (6-7 Nov) – sediment dynamics over an block of clustered mussel plots with multiple activities occurring (harvest and 'schoonvissen')

[1] Schoonvissen: the process where silt/sediment is removed from the plot after mussel harvest

For the campaigns 1 (Scheer) and 2 (Inschot) the ideal locations for monitoring were bottom plots where fishing activity was absent on the surrounding plots, to guarantee that neighboring bottom plots would not interfere with results from the monitored location. Similar to fisheries; current direction was defined by visual observations, topography of the area and the time of high and low tides (Table 1).

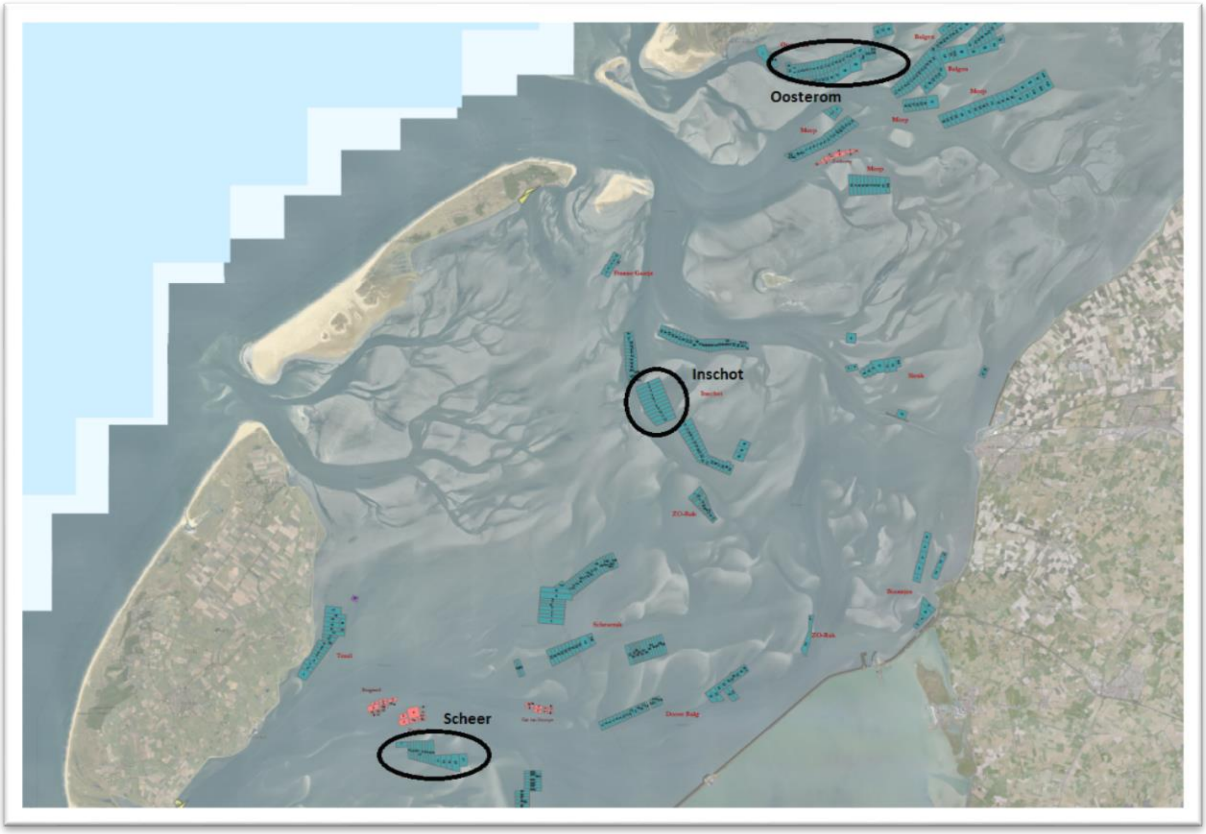

Figure 3 Map showing locations of the areas included in the harvest campaigns (circled in black).

Table 3 Overview of tidal cycle and derived current direction during sampling of the areas included in the harvest campaigns.

Area	Date	Time Low tide	Time High tide	Time Transects	Date & Time Sediment traps
Scheer (Den Oever)	7 Oct	6:15 18:20	12:16	09:00-17:30	6-7 Oct
Oosterom (Terschelling West)	7 Nov	5:18 17:39	11:26 23:40	10:00-18:00	7 Nov
Inschot (Den Oever)	21 Nov	6:25 18:26	11:55	06:45-11:20	20-21 Nov

2.3.2 Turbidity along transects

Sediment dynamics was defined by turbidity measurementsalong transects upstream- downstream and on the mussel plots, during harvest as well as prior and/or post-harvest activities to investigate natural gradients. The applied method using towed turbidity sensors (Inifinity and Hydrolab) was similar as described for fisheries (see section 2.2.2).

Because the plots are different in shape, and harvest did not take place over the entire plot, slightly different sampling strategies were chosen (Figure 4), but all aimed to provide a good spatial coverage of the sediment plume.

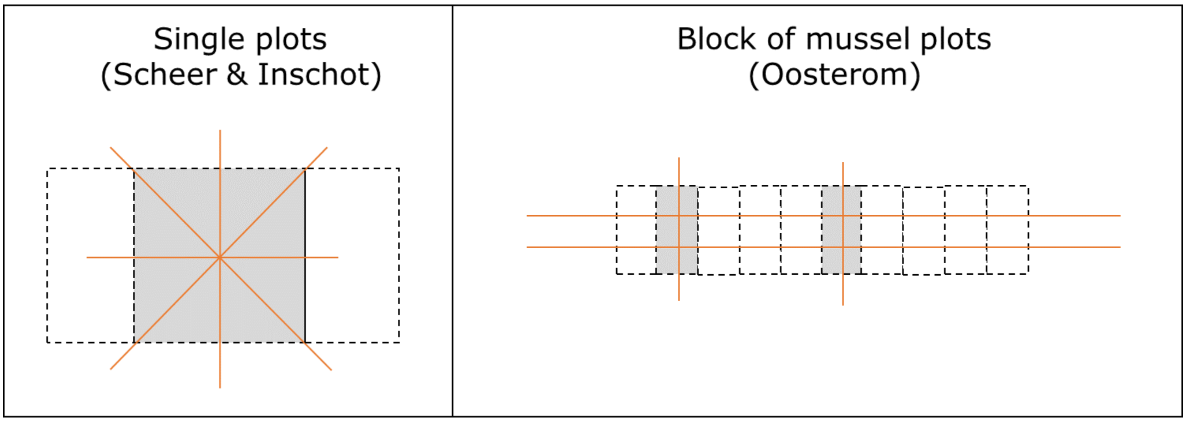

Figure 4 Schematic outline of transects measuring turbidity at the harvest locations (Scheer, Inschot, Oosterom). Mussel plots are presented by dotted squares (grey= with harvest activity, white=no harvest activity); Orange lines indicate transects with towed turbidity sensors (1-1.5m depth)

2.3.3 Sedimentation rates

At all locations, sediment traps were placed in a gradient upstream and downstream of the mussel plot(s). Sediment traps provide a time integrated picture of the sedimentation in the area, where transect data merely provide snapshots. It is expected that sediment traps close to the plots will collect more material, and that the material is higher in organic content, because of the fecal material being resuspended during harvest on the plots.

Sediment traps were constructed following principles described by Wassmann & Heiskanen (1988). Each sediment trap consists of three cores attached to an iron bar mounted on a concrete plate. The concrete plate (25 kg) is set on the sea floor. The cores consist of transparent Plexiglas PVC pipes 60 cm in height and a diameters of 6.7 cm (taking into account the aspect ratio of 5, Wassmann & Heiskanen 1988). The cores can be easily connected and removed from the frame.

The traps were placed before harvest started, in a gradient from the border of the plots until further away. At Scheer and Inschot traps were placed at approximately 0, 50, 100 and 200 m away from the mussel plot. Traps were placed at both sides of the plot to cover sedimentation in both directions of the tide. Two additional traps were placed at two remaining borders of the plot. The traps were removed after harvest finished.

At Oosterom a total of 6 traps were placed at the borders of fished mussel plots. A longer gradient was chosen at the east side of the last fished plot: traps were placed at 0 m (n=6), 140 m (n=3), 400 m (n=3), 1100 m (n=1) and 1400 m (n=1). At this location sediment traps were deployed during the field campaign when fisheries took place (6-7 Nov), and again during the weekend (18-19 Nov) to monitor sedimentation rates along the same gradient without any fisheries activities.

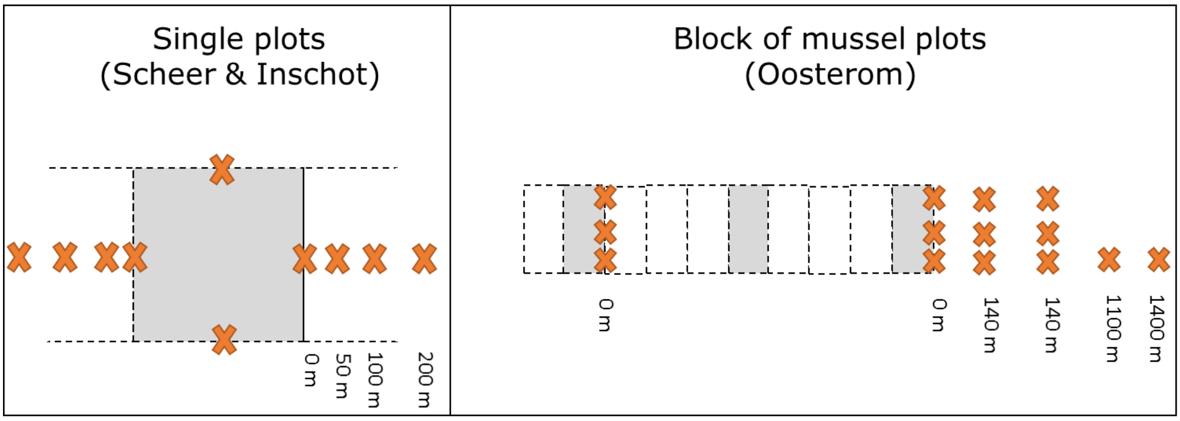

Figure 5 Schematic outline of sediment trap positions at the harvest locations (Scheer, Inschot, Oosterom). Mussel plots are presented by dotted squares (grey= with harvest activity, white=no harvest activity); Orange crosses indicate sediment trap positions (placed on the seafloor) where distance from plot border is indicated in meters.

The material accumulated inside the cores was transferred into a sample bottle and later analysed in the lab. Back in the lab, the sediment was washed twice with freshwater to remove salt particles. The entire sediment sample was then dried at 70°C and subsequently burned at 450°C to define dry weight (DW) and ash-free dry weight (AFDW) respectively.

2.3.4 Turbidity concentrations at fixed stations

Additional to the transects, at Scheer and Inschot, a Infinity turbidity sensor was deployed at fixed positions to follow turbidity at the same spot for a period of 24 hours. These 24 hours included periods when harvest took place and periods when no activity occurred on the plot. Sensors were deployed at one location where maximum impact was expected and at a reference station. At Scheer a wooden pole was present in the middle of the plot, onto which the meters could be attached without the risk of being damaged. At Inschot, sensors could only be placed on the edge of the mussel plot (downstream of fisheries). At both stations, two sensors were deployed; one at 50 cm above sediment and one approximately around the low water line. Fixed stations will provide insight in the temporal dynamics of the sediment plume: i.e. how long is the plume still visible after harvest has stopped.

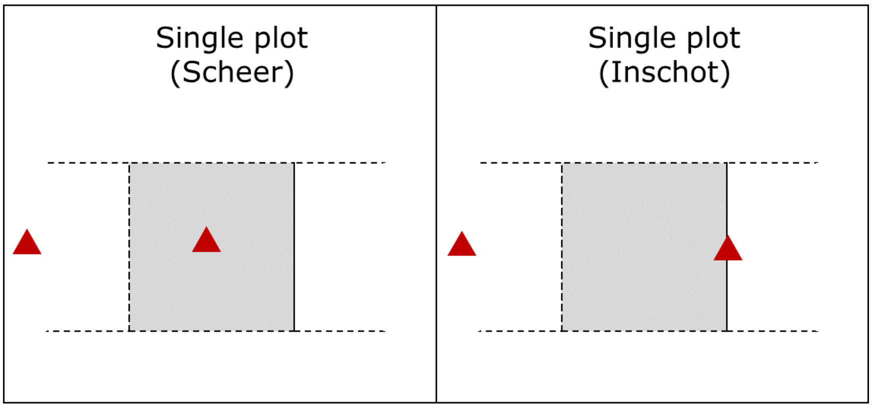

Figure 6 Schematic outline of the positions of the fixed turbidity meters at the harvest locations (Scheer, Inschot). Mussel plots are presented by dotted squares (grey= with harvest activity, white=no harvest activity); Red triangles indicate positions of the meters (50 cm above seafloor & low water line).

At Oosterom fixed meters were deployed over a period of 4 weeks. Meters were placed at locations also been used in KOMPRO-II to measure mussel growth. This long term deployment will provide information on the natural variability of turbidity, and will be linked to harvest information on the surrounding plots.

2.3.5 Sediment removal

Finally, during the first field campaign on bottom plots (Scheer), sediment samples were collected to define the amount of organic content in the sediment before and after harvest. Following the set-up by Van Bemmelen et al (2013), a total of nine (n=9) Van Veen grabs were taken covering the entire mussel plot. Two sub-samples were taken from each Van Veen Grab, using syringes removing the upper 3 cm of the sediment. This procedure was done for similar positions before and after harvest. The samples are then brought to the lab and dried (70ºC) and burned (450ºC) to define dry weight (DW), ash free dry weight (AFDW) and organic content (%OM).

The initial aim was that these samples would provide information on the amount of sediment removed from the plots during harvest. However, as the results were not providing solid results it was decided not to continue with these measurements (for results and discussion see section) at Inschot and Oosterom.

3 Results

3.1 Sediment plume dynamics during seed fisheries

The paragraphs below highlight trends in turbidity increases/decreases for the different case studies investigated (respectively Omdraai, Doove Balg, Breesem, Malzwin, ZuidWest). Each fisheries location covered transects that followed the plume as well as transects that were crossing the fisheries zones perpendicular to the current direction (see maps in Figures 7, 8, 9, 10, 11 and 12). The following section aggregates the information of the transects in figures showing similar types of transects for each location. The calibration of sensors (FTU) with water samples (SPM, mg/l) showed large variability (Annex 1), which indicates that the turbidity in the water column was very patchy, especially within the samples with high turbidity. Due to the large variability it was therefore decided to presented the turbidity gradients in FTU (which is a relative measure for turbidity measured by the sensor), and not to use the correlations to provide SPM (mg/l) values as the uncertainty is too high. Detailed information on turbidity for each transect separately are outlined in Annex 2. Both sensors (Hydrolab & INFINITY) provided similar responses (trends in time), and because they present relative values the trend is more important than the magnitude of the actual value. The correlation between the two sensors is good (see annex 1), and the INFINITY meter has proven to be suitable to measure the high concentrations observed in this study. The figures below present data from the INFINITY meter only.

3.1.1 Omdraai

Fisheries was aggregated around the mussel seed bed that was outlined in the survey executed previous to the fisheries season (Figure 7). Throughout the day the number of boats varied between 6 and 8. Transects from this site can roughly be divided into three categories that are similar to each other: (i) transects starting within the fisheries zones, where highest suspended sediment concentrations were expected, moving with the current direction towards the area downstream of the fisheries zone (Figure 7a), (ii) transects that crossed the fisheries zone perpendicular to the current direction (Figure 7b), and (iii) one transect crossed three fishing vessels that were each several hundred meters apart without other vessels interfering (Figure 7c).

Background turbidity values were relatively stable (transect 11, Figure 7a), and turbidity was strongly enhanced right in the middle of the fisheries zone (Figure 7ab). The maximum observed turbidity was nearly 300-400 FTU, while the background values vary between 5 and 10 FTU. Figure 7a demonstrates that although turbidity is high in close proximity of fishing vessels, the sediment plume is limited in spatial scale. All three figures (Figure 7abc) show that the turbidity along the transects is patchy, even within the sites where intensive fisheries took place for several hours.

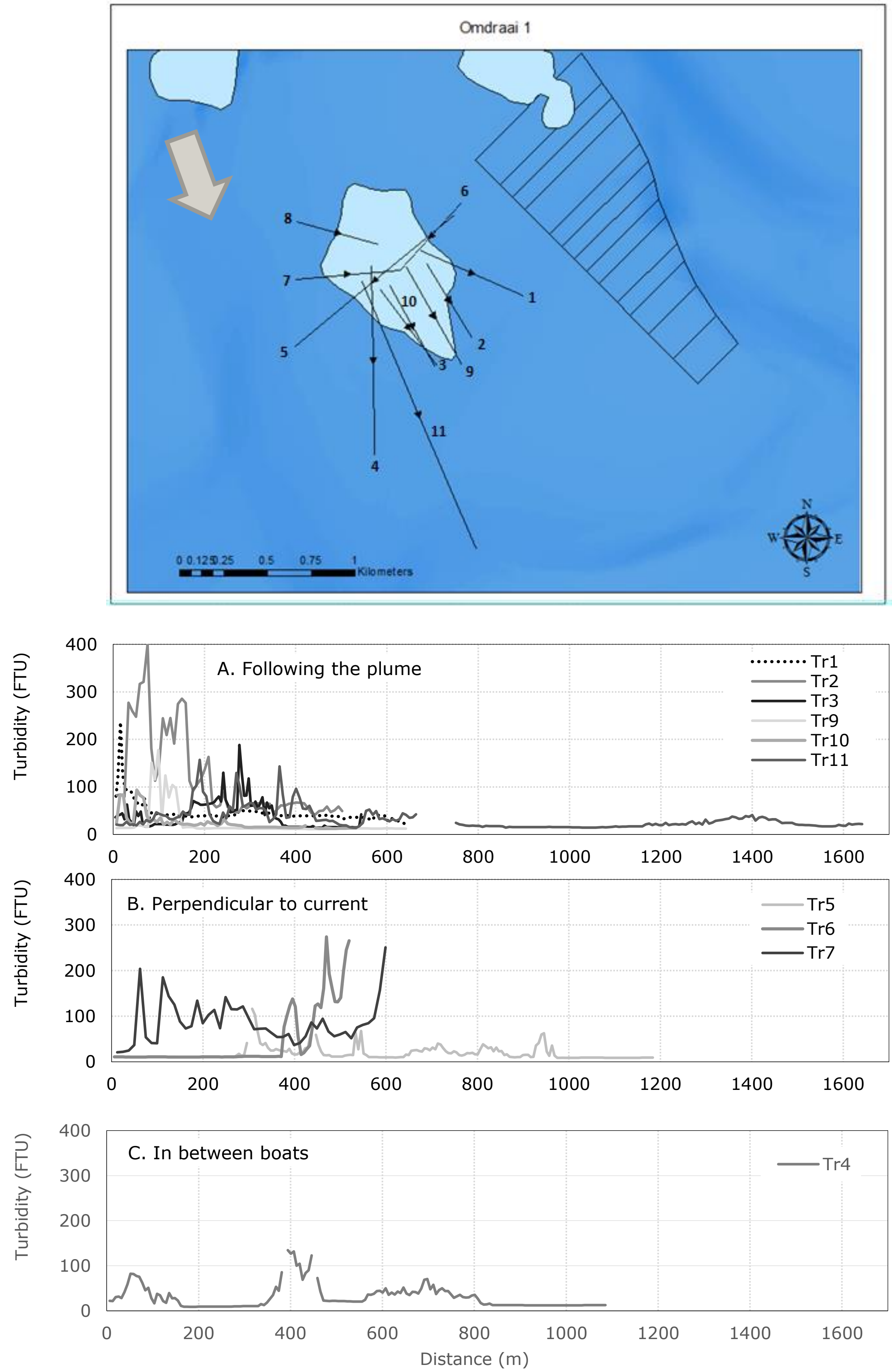

Figure 7 Map outlining the mussel seed bed (light blue), transects (black arrows), and current direction during sampling (grey arrow top corner) at location the Omdraai (morning). Graphs show the turbidity along the transects. Start of each transect is set to 0m Distance, and arrow indicate the direction of the transect. A: transects starting within the fisheries zone and moving to downstream areas, B: transects crossing the fisheries zone perpendicular to the current direction, C: transect crossing three individual fishing vessels over a section of one kilometre without other vessels interfering (visual observation during sampling).

Overview of mussel seed fisheries during the Sampling campaign at Omdraai in the morning (see section 3.1.1)© Niels Ultzen

3.1.2 Omdraai – south

Throughout the day, fishing vessels moved position and apparently more seed was found south of the seedbank contours. During the afternoon, when the tide had changed and water was retracting (see Table 2), most vessels moved south of the seed bed that was fished during the morning (see section 3.1.1). Approximately 4-5 boats were fishing at this site in the afternoon. Transects for this location include: (i) Two long transects were executed to get an idea about background variability (left side of the map, Figure 8), (ii) three transects following the current direction/plume and (iii) two transects perpendicular to the current direction (right side map).

Both reference transects showed some variability but values generally varied between 15-50 FTU (Figure 8a). The maximum observed turbidity was approx. 200-300 FTU (Figure 8b). Figure 8b demonstrates that turbidity increases when the fisheries zone is entered. For transect 19 the turbidity downstream of the fisheries drops down to background values, while for transect 16 and 19 it seems that the transect was too short (up to 500m in total) to have reached back to background concentrations. The turbidity gradient while crossing the plume resulted in maximum values of 100 FTU, and for transect 13 they did not go down to background. Considering the current direction this is likely a result of natural variation.

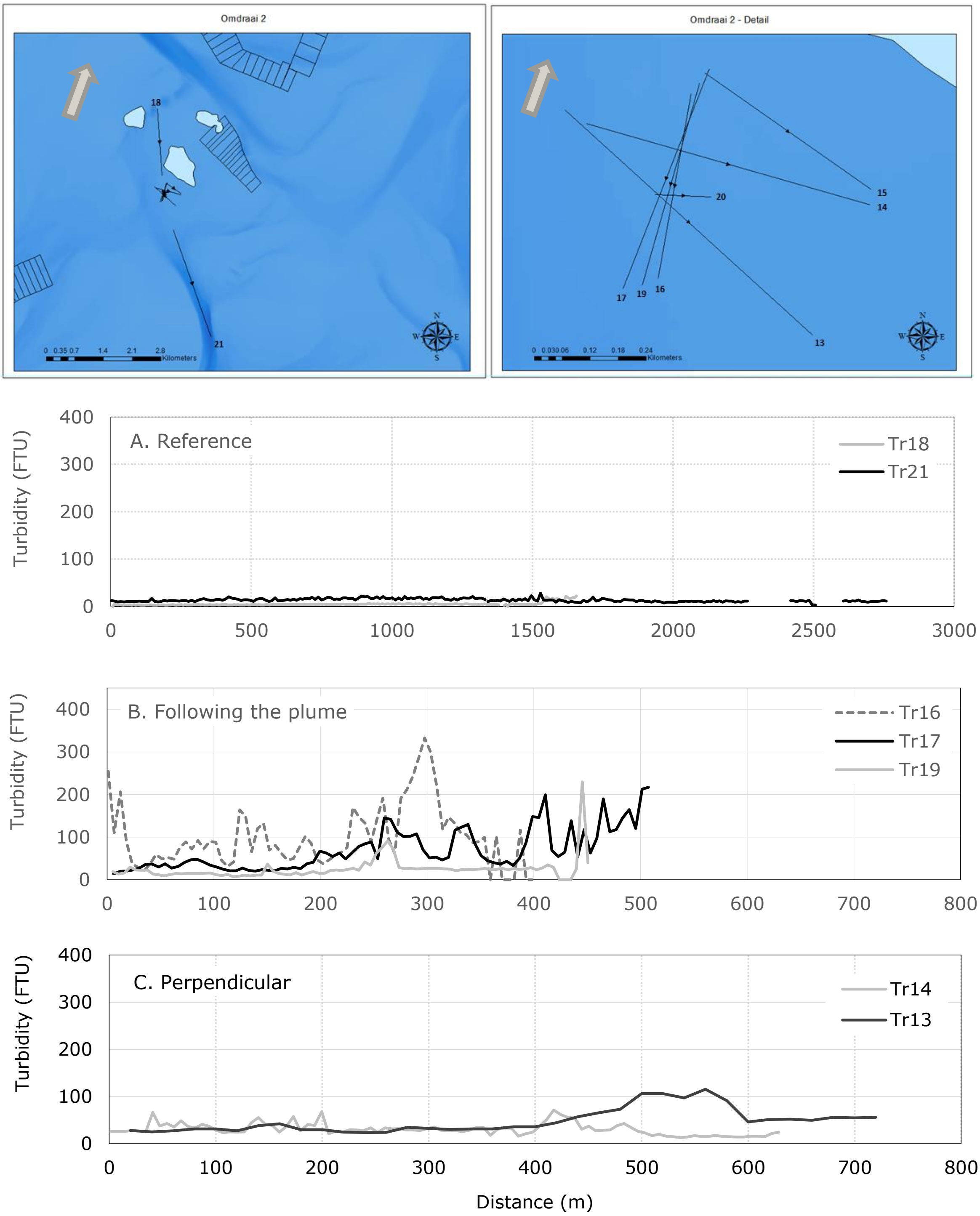

Figure 8 Map outlining the mussel seed bed (light blue), transects (black arrows), and current direction during sampling (grey arrow top corner) at location the Omdraai south. Graphs show the turbidity along the transects. Start of each transect is set to 0m Distance, and arrow indicate the direction of the transect. A: reference transects noth and south of the fisheries zone , B transects starting at reference station and moving to downstream areas, B: transects starting within the fisheries zones and moving to downstream areas, C: crossing the fisheries zone perpendicular to sediment plume direction.

3.1.3 Dove Balg

Measurements at Dove Balg were performed during the end of the day when only one boat was still fishing. Transects from this fishery zone were divided into two categories: (i) following the plume, Figure 9a and (ii) perpendicular to the current direction, Figure 9b. As this is a deep site, two depths at which the turbidity sensor is towed were investigated (1 m below the water surface, as for other locations) and 6 m below water surface for transect 26 and 27.

Maximum values (60-80 FTU) were observed for the transects obtained at 6 m below the surface. This is different from the pilot studies where maximum concentration were observed close to the surface (Jansen et al unpublished). It is not straightforward to indicate the background values for this site because of the variability shown in Figure 9b. Based on Figure 9a background values can be estimated around 5-10 FTU.

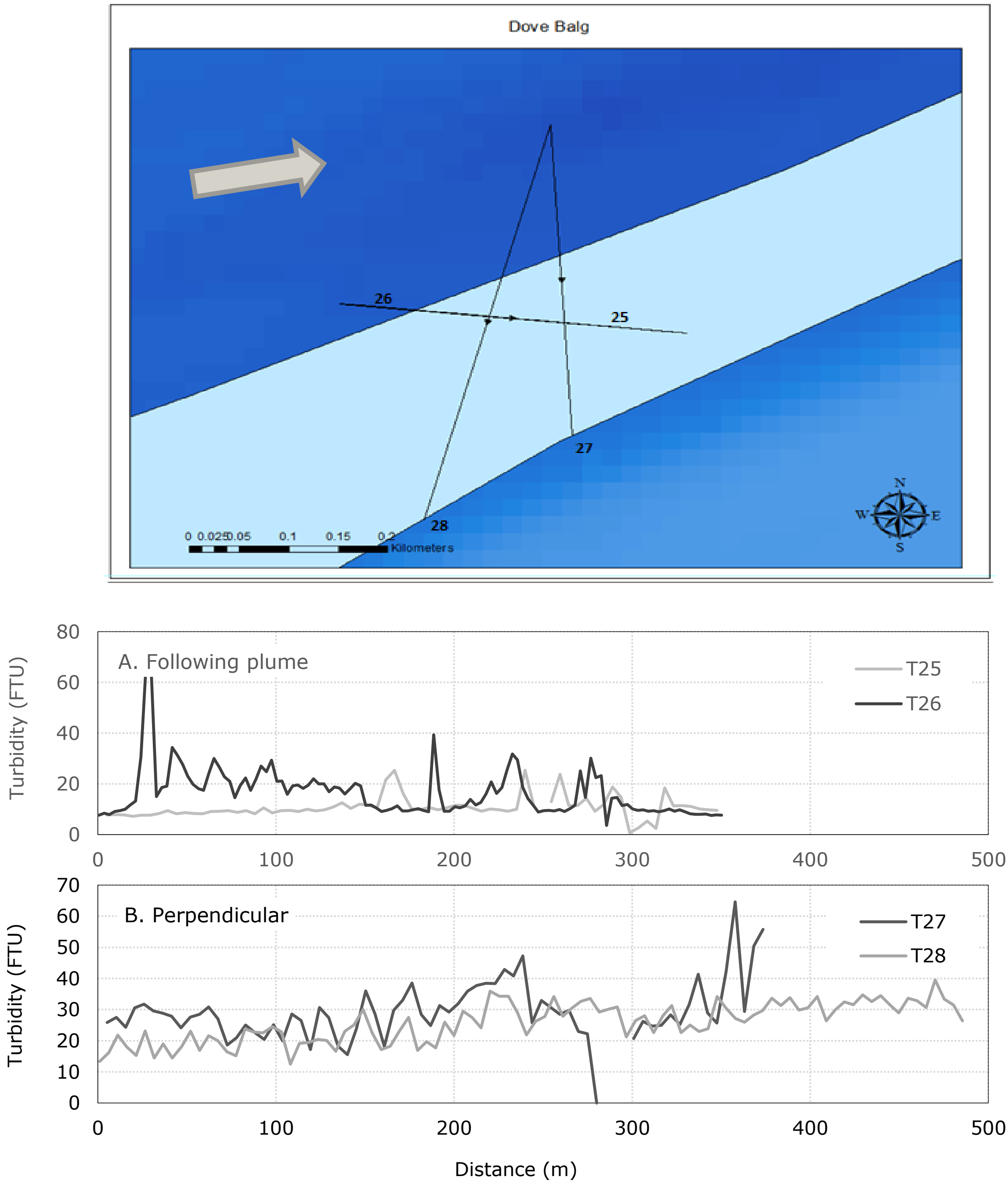

Figure 9 Map outlining the mussel seed bed (light blue), transects (black arrows), and current direction during sampling (large arrow top corner) at location the Dove Balg. Graphs show the turbidity along the transects. Start of each transect is set to 0m Distance, and arrow indicate the direction of the transect. A: transects following the plume, B: transects crossing the fisheries zone perpendicular to the current direction.

3.1.4 Breesem

At Breesem fisheries started just north from the identified seed bank (in the middle of the transects 29-34, see map in Figure 10). While following the plume (Figure 10a) surprisingly only transect 30 showed enhanced values while 32, 33 and 34 hardly provided a signal of enhanced values within the fisheries zone. Enhanced values faded out quickly after passing the fishing boats. Maximum values while following the plume (Figure 10a) and crossing the plume perpendicular (Figure 10b) reached values between 60-80 FTU. Background values for Breesem were low compared to other locations investigated (~5 FTU). Two transects were investigated among a site just east (transects 36,37). Two boats were fishing in this area, and a local increase up to 40 FTU was observed (Figure 10c).

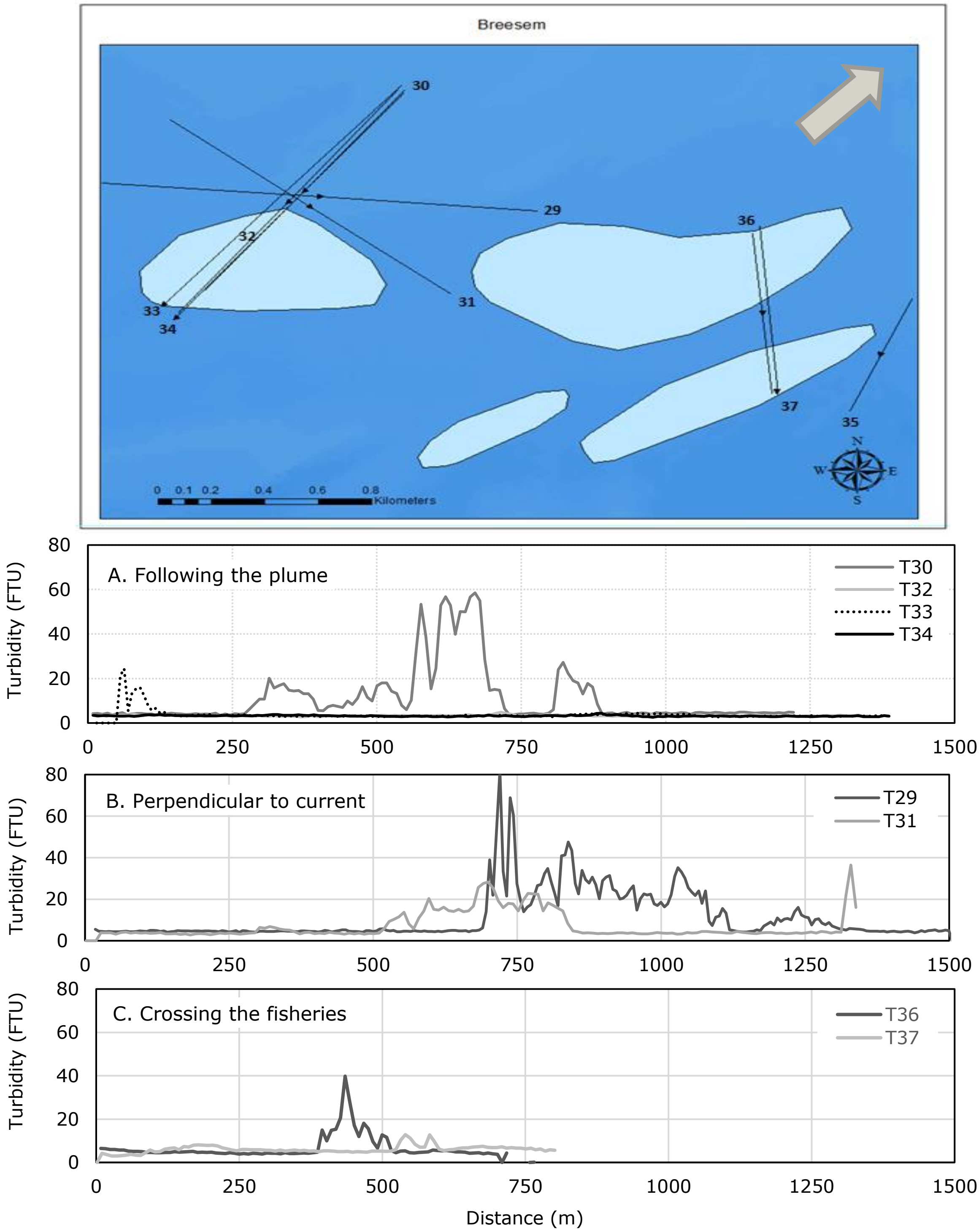

Figure 10 Map outlining the mussel seed bed (light blue), transects (black arrows), and current direction during sampling (large arrow top corner) at location the Breesem. Graphs show the turbidity along the transects. Start of each transect is set to 0m Distance, and arrow indicate the direction of the transect. A: transects starting downstream, moving into and then upstream of the fishery zone, B: transects crossing the fisheries zone, C: transect crossing a second fishery zones in this area.

3.1.5 Malzwin

The map of Malzin (map in Figure 11) shows that transects at this location did not follow a structured approach. Although transects did cover a large area and both 'following the plume' and 'perpendicular to plume' transects are included, graphs should be interpreted with care as some transects are long, others are short and not all start at the same place. For the sake of clarity we do not show all transects in Figure 11. Detailed information on each transect is available in Annex 2.

Background values at Malzwin were around 10 NTU. While following the plume, short peaks with enhanced values were observed, but these dropped down to background values rapidly. This could indicate that either the enhancement was very local, or that current direction was not evaluated correctly. Transects 43, 49 and 50 are oriented along a slightly tilted axis indicating that if current direction was estimated incorrect (for transects 39, 40, 46), these transects would be more representative for 'following the plume'. Data from these transects showed, however, a similar pattern with patchy and short enhanced values (Annex 2). Maximum values observed (Figure 11abc) were around 30 FTU.

All transects from the Malzwin sampling campaign indicate that turbidity is enhanced in the fisheries zone locally and the turbidity patterns are patchy and enhanced values quickly drop down back to background values.

Water samples collected for calibration of the turbidity sensors (for results see Annex 1): from left to right maximum (within fisheries zone), intermediate (in proximity of fisheries zone) and reference samples.

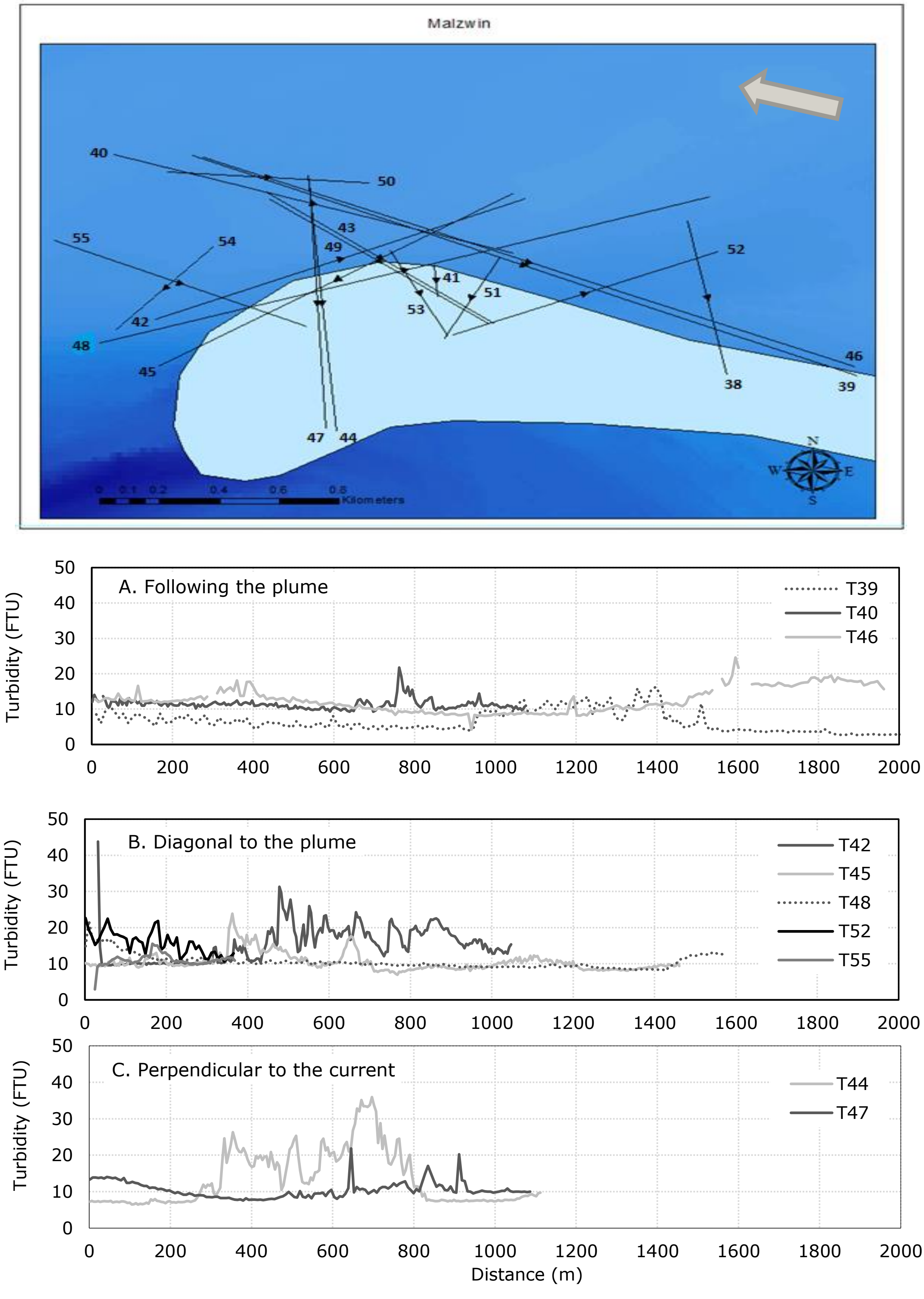

Figure 11 Map outlining the mussel seed bed (light blue), transects (black arrows), and current direction during sampling (grey arrow top corner) at location the Malzwin. Graphs show the turbidity along the transects. Start of each transect is set to 0m Distance, and arrow indicate the direction of the transect. A: transects starting outside the fisheries zone and moving to downstream areas following the sediment plume, B: transects crossing the fisheries zone and the plume, C: transect perpendicular to the plume

3.1.6 ZuidWest

When the tide on the 22th of May turned and the water level increased (low tide at 11:50, see Table 2), fishing vessels moved from Malzwin to the ZuidWest area. This is a shallow site and can only be fished when the water level is sufficient.

Two long transects (56 & 58, over 2 km in length) showed the gradient from upstream into the fisheries zone (following the water direction/plume; Figure 12a). From these transects the background value can be estimated at 5-10 FTU, and reached to 130 FTU right in the middle of the fisheries zone. Transects 60 and 61 started right in the fisheries zone (where 56 and 58 ended) and moved to downstream areas. These showed that values went down to background values within a few hundred meter.

With the incoming water, the water moved along the gully in the direction as indicated in the figure (dominant current direction), but also moved up to the shallow area east of the fisheries. Transect 59 followed this direction investigating if the sediment plume moved up onto the shallow bank. This transect clearly identifies when fisheries was passing (values up to 180 FTU), and then goes down to 50 FTU. Although the value goes down, it is not similar to background values as identified upstream of the fisheries. Because we lack detailed information on current speed and direction within the different zones of this site, it is difficult to say whether these enhanced values are the result of fisheries or because of water moving over the shallow bank and causing natural disturbance with the incoming tide.

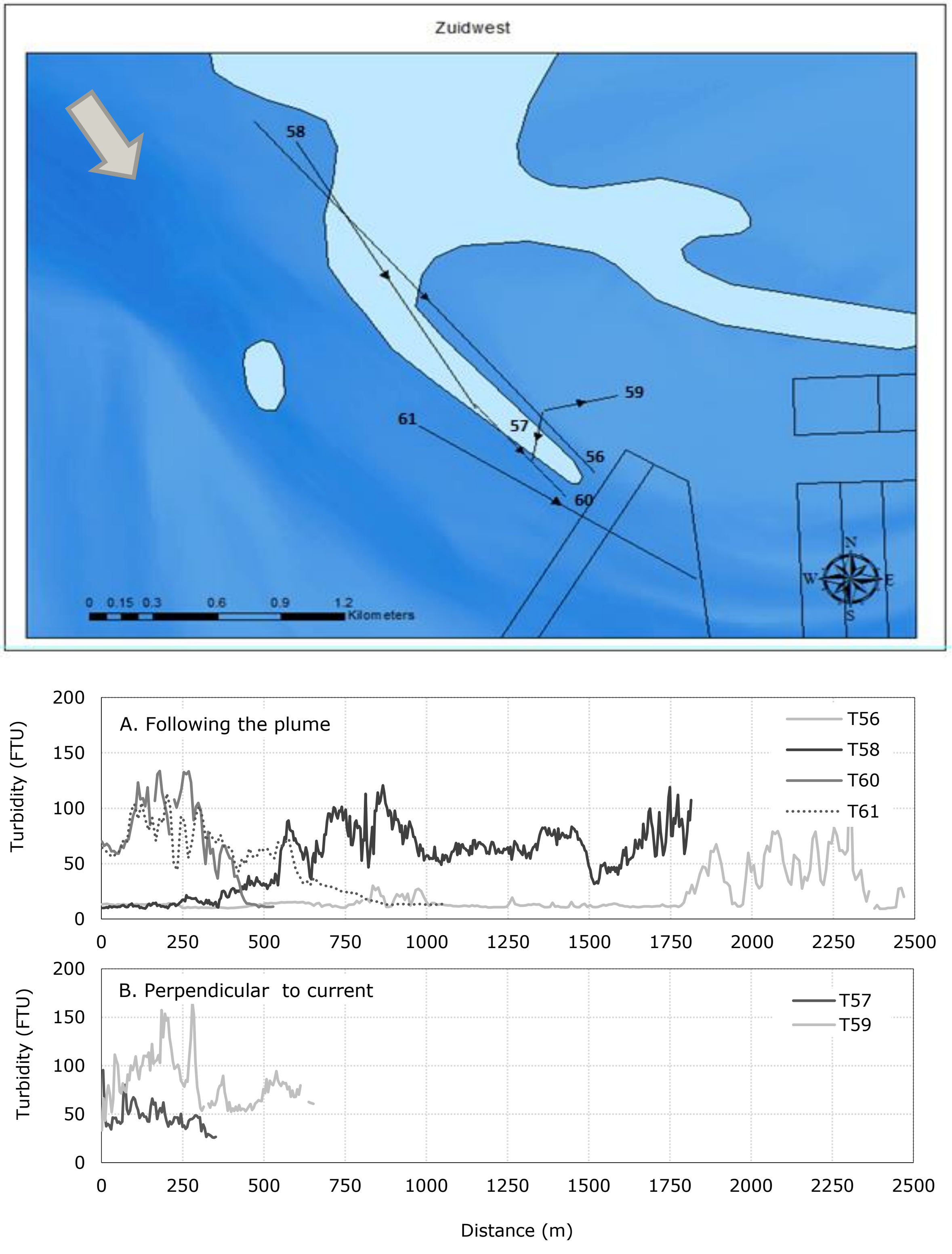

Figure 12 Map outlining the mussel seed bed (light blue), transects (black arrows), and current direction during sampling (large arrow top corner) at location the Zuidwest. Graphs show the turbidity along the transects. Start of each transect is set to 0m Distance, and arrow indicate the direction of the transect. A: transects starting upstream outside the fishery zone and moving downstream inside fishery, following the sediment plume, B: transects crossing the fisheries zone perpendicular to the current direction.

3.2 Sediment plume dynamics during harvest on mussel bottom plots

3.2.1 Turbidity along transects

Detailed information on turbidity is outlined for each transect separately in Annex 3. The Hydrolab sensor showed malfunctioning so only results from the INFINITY meters are available from the harvest locations. The paragraphs below highlight trends in turbidity increases/decreases for the different locations investigated (respectively Scheer, Inschot, Oosterom). At Scheer (regular harvest) and Inschot (schoonvissen) a single plot was investigated, while at Oosterom a block of plots was investigated. Like for fisheries (section 3.1), turbidity is presented in FTU and results of the calibration curves (FTU to SPM) are provided in Annex 1.

Scheer

At Scheer one mussel bottom plot was monitored during harvest (Figure 13). Only one vessel was harvesting on the entire block of plots, indicating that sediment dynamics was not disturbed by any nearby mussel culture activities. Transects were obtained prior to harvest, twice during harvest (incoming and outgoing tide) and once more two hours after harvest had stopped. The red lines in Figure 14 present the conditions without fisheries. As these were obtained before and after fisheries this indicated that they were also performed during a different moment of the tidal cycle. The Wadden Sea is a dynamic system and turbidity can vary over small temporal and spatial scales. It was indeed observed that the reference transects (without fisheries) varied and sometimes showed higher values than measured when harvest took place. To identify the impact of harvest on turbidity enhancement, it seems therefore most valid to look at upstream conditions as a reference (background) value, rather than the transects obtained before and after harvest. Maximum values were observed in the middle of the plot and reached approximately 40 FTU, against a background value of approximately 8 FTU. After passing the position where harvest had taken place, turbidity values rapidly decreased back to background values. This indicates that the spatial area of impact is limited.

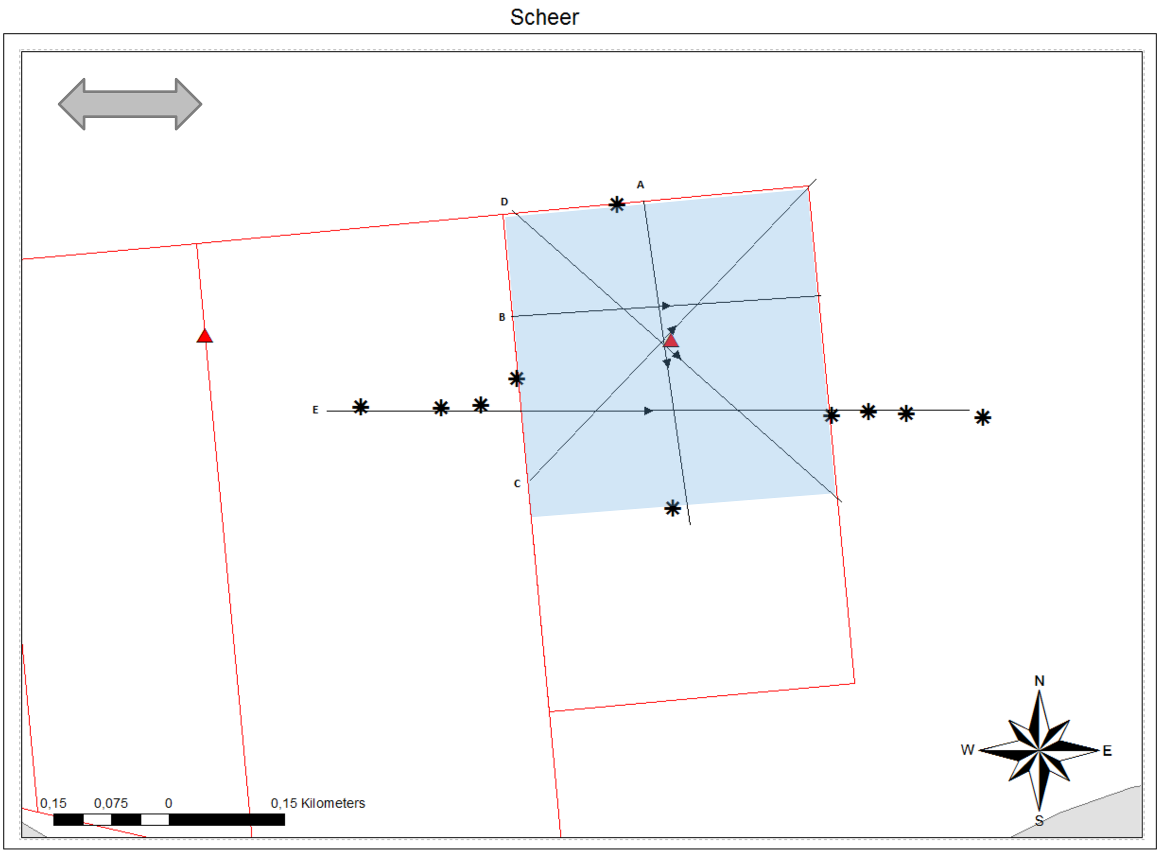

Figure 13 Map from location Scheer indicating transects (black lines), positions of sediment traps (stars) and fixed turbidity meters (red triangles) and fisheries activity (blue)

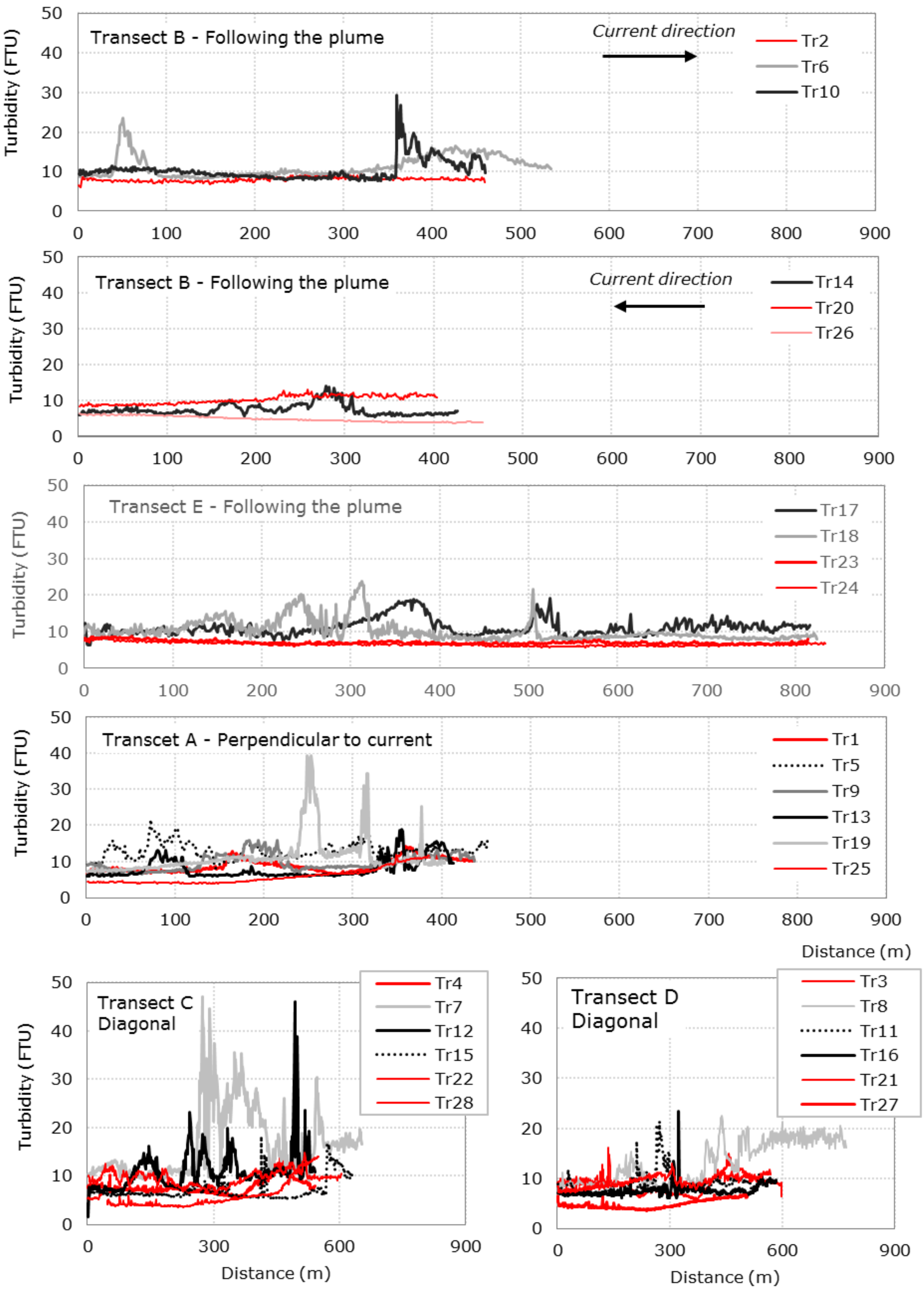

Figure 14 Turbidity along the transects at Scheer. Red lines indicate the situation without fisheries and black/grey lines present the situation during harvest. Transect letters are indicated in the map (Figure 13).

Inschot

The location Inschot was chosen as a site where maximum impact could be expected: it is a muddy site, not too deep and the plot was prepared for the next growing season (In Dutch this is referred to as schoonvissen which means as much as 'cleaning fisheries', and it is the process where silt/sediment is removed from the plot after mussel harvest). The cleaning is a technique that consists of the removal of sediment from the bottom plot, which is expected to show maximum impact in sediment enhancement. A similar sampling strategy to Scheer was applied (transect cross) and two additional transects were added: transects perpendicular to the current, downstream of the expected sediment plume (transect D and E in Figure 15). If due to patchiness of the plume it is difficult to follow the spatial scale by the transects "following the plume" (transect A, B and H in Figure 15), transect D and E might give a better indication of the spatial magnitude.

Fisheries took only place in the morning as due to bad weather other activities were prioritized during the afternoon. This means that current direction has been the same way during the entire sampling (north to south). There was one other vessel active on the same mussel plot, but judging the distance between the sites as well as the current direction, it was assumed that this would not have influenced our results.

A situation without fisheries was only monitored before fisheries, as when fishing stopped the tide also turned. Similar to Scheer, it was also observed that the reference transects obtained before fisheries sometimes showed higher values than the situation with fisheries. For this site it is therefore also better to analyse the upstream and downstream values from the transects obtained during harvest (each set of transects A-G took approximately 1 hour to collect). Transect A and B (following the plume) indicated that the height of the plume quickly decreased, but that the plume was still visible outside the border of the plot. This was however not confirmed by transect D and E, indicating that turbidity was similar to background values at respectively 100 m and 200 m from the plot.

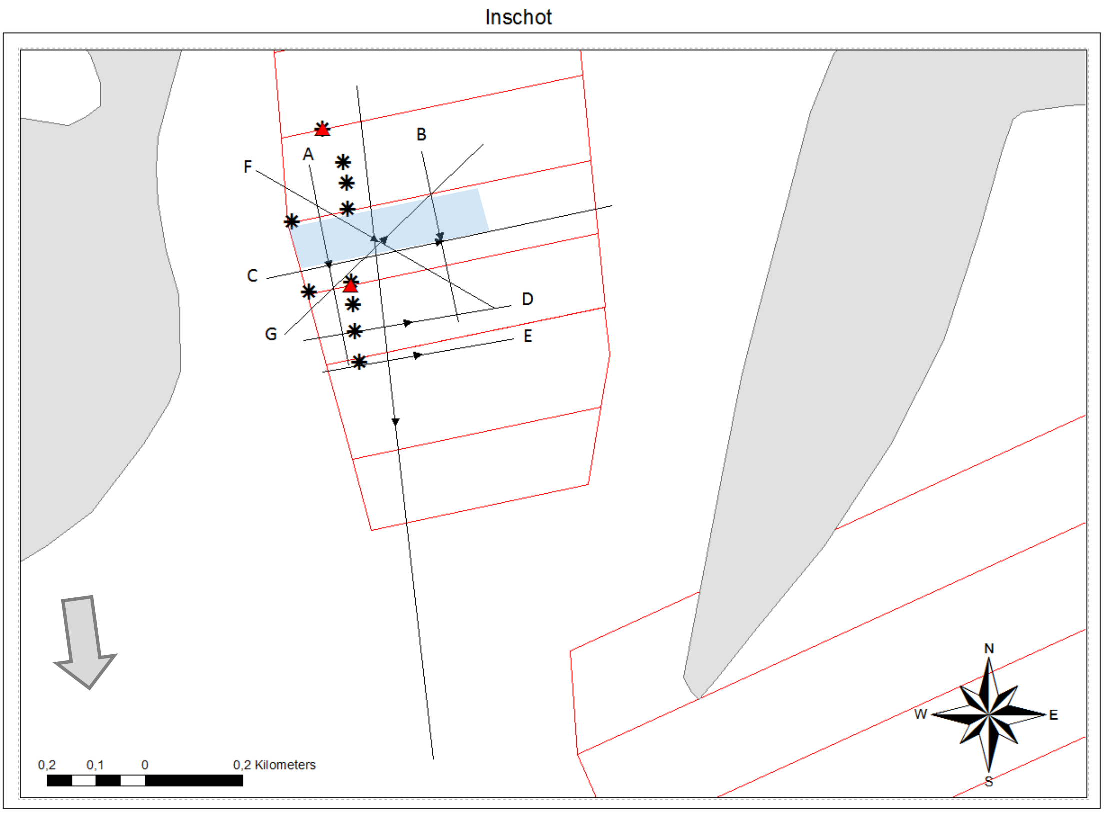

Figure 15 Map from location Inschot indicating transects (black lines), positions of sediment traps (stars) and fixed turbidity meters (red triangles) and fisheries activity (blue).

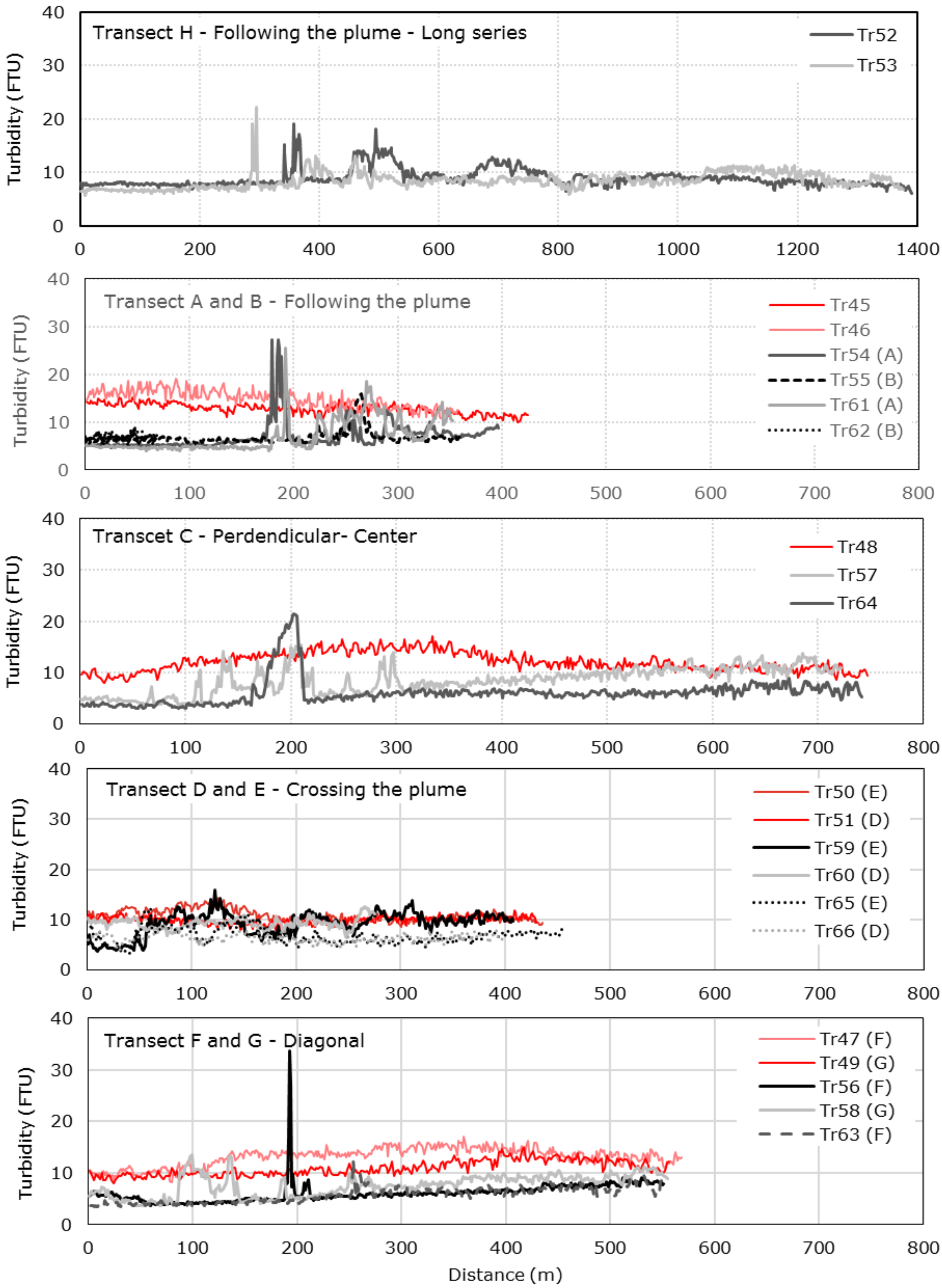

Figure 16 Turbidity along the transects at Inchot. Red lines indicate the situation without fisheries and black/grey lines present the situation during harvest. Transect letters are indicated in the map (Figure 15).

Oosterom

At Oosterom a cluster of culture plots was investigated simultaneously. During the sampling campaign harvest activities took place at 8 mussel plots, and interference might be expected. Transects were long in comparison to Inschot and Scheer (zie maps in Figure 17).

The reference situation (without mussel culture activities) was investigated the evening before (6 Nov) the transects with harvest activities were investigated (7 Nov). Despite the length of the transect, reference values were relatively stable.

Highest values were observed for the transects crossing the plots perpendicular to the current direction (up to 40 FTU, against a background value of 5). The long transects showed a similar pattern as observed voor Scheer and Inschot: turbidity is enhanced at the plots, but values decrease to background quickly (e.g. transect 41). Transect 31, crossing harvested plots at 1/3rd and at the end of the transect seems to indicate that turbidity values might remain slightly above background after passing a harvested plot. Values reach very high values (>500 FTU) during transect 37, however, considering the overall enhancement to maximum values of 50 FTU at harvested plots (Scheer, Inschot, Oosterom) this suggests that this is a measurement artefact (e.g. something blocking the sensor reading) rather than actual turbidity enhancement.

Turbidity meter deployed alongside the boat

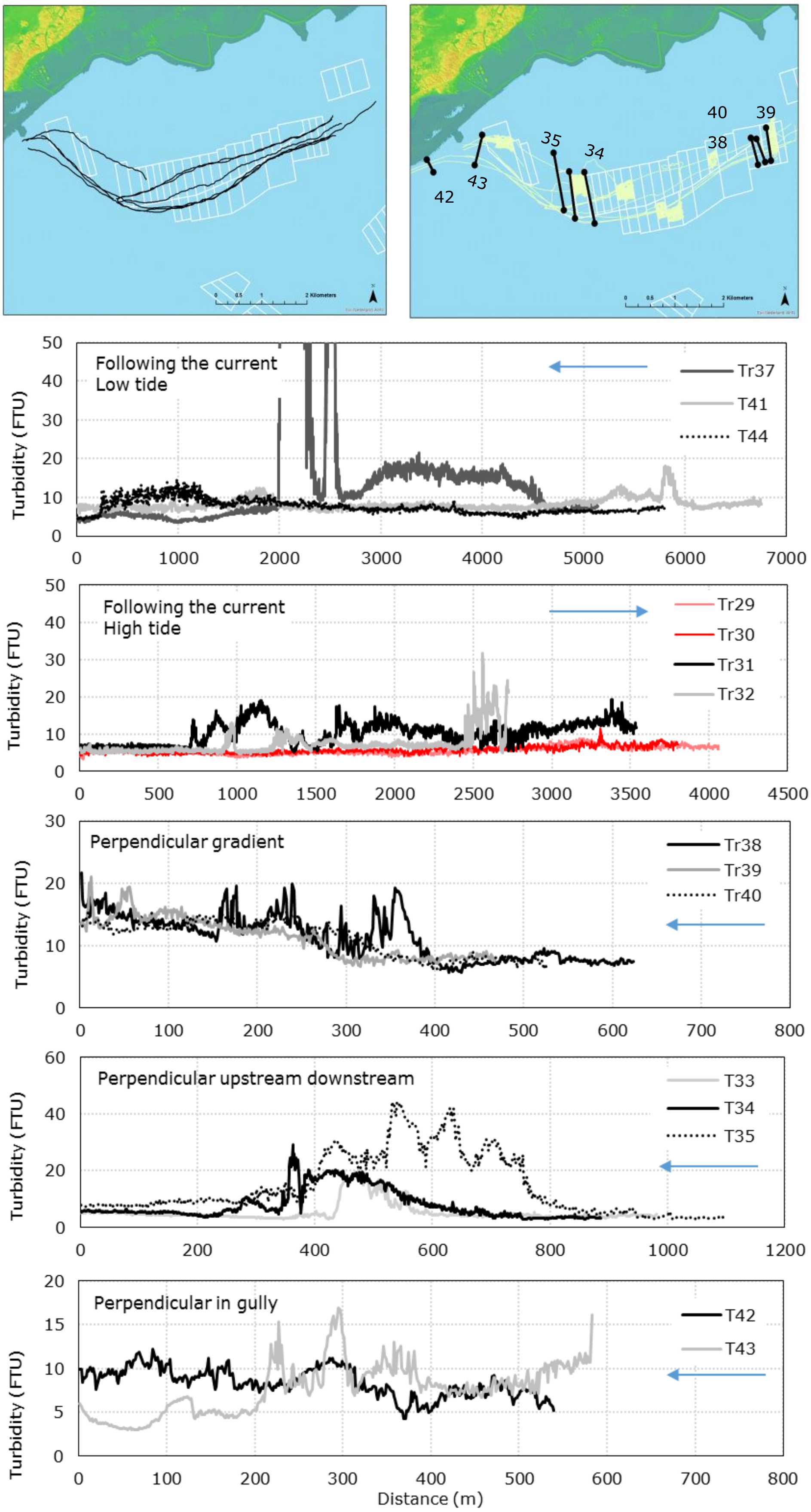

Figure 17 Map from location Oosterom indicating transects (black lines) and fisheries activity (green lines). Left: transects following the current direction, Right: transects perpendicular to current direction. Turbidity along the transects at Oosterom. Red lines indicate the situation without fisheries and black/grey lines present the situation during harvest.

3.2.2 Sedimentation

Locations of the sediment traps at Scheer and Inschot are presented in Figure 13 and Figure 15 respectively: generally they are placed in a gradient upstream and downstream from the edge of the mussel plot (0 m) to approximately 200 m away from the plot. At Scheer fisheries took place during the entire day, indicating that sediment has been dispersed with both the incoming and outgoing tide. For both the total sedimentation (DW) and %OM gradients would therefore be expected on both sides of the plot at Scheer; with high values close to the plot and decreasing values further away. For Inschot, *schoonvissen* took only place during the morning (incoming tide) and therefore only a gradient was expected on the South side of the plot. However, sedimentation was high in all sediment traps: between 1350-2600 g DW m^{-2} d^{-1} and 1700-4050 g DW m^{-2} d^{-1} and 1700 at Inschot. No gradient was observed for total sedimentation, and neither for the percentage Organic Material, at either location.

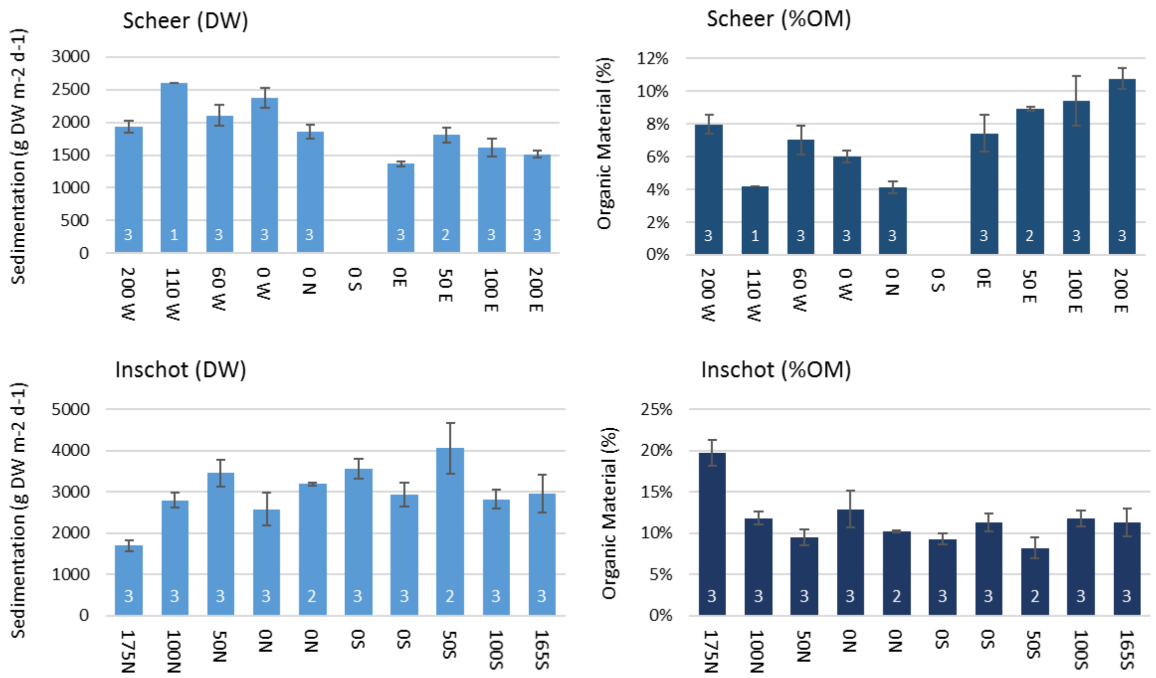

Figure 18 Average (± sd) sedimentation rates at Scheer and Inschot base on sediment trap data. Left graphs: total sedimentation in DW (g m^{-2} d^{-1}), right graphs: organic fraction in the collected material (%Organic Material). Each bar represents one sediment trap, and the numbers in each bar indicate the number of cores included in analysis (some cores were lost during sampling)

At Oosterom the sediment traps have been deployed stretching over a longer transect (up to 1400 m). The traps have been deployed during harvest (7 Nov) and in a situation without any harvest (weekend 18-19 Nov). The positions during both campaigns were exactly similar (Figure 19). Total sedimentation is high, and rates were higher during the weekend without fisheries (5771±2617) compared to the harvest measurements (3458±2902) (Figure 22 left panels). All rates have been standardised to sedimentation per square meter per day, meaning that deployment time has been corrected for. Weather conditions during the weekend (18-19 Nov) were quite stormy (see upper graph with wind conditions in Figure 22). This might have resulted in sediment disturbance and thus higher sedimentation rates. The fraction organic material was, however, much lower (2.0±0.8%) for the situation without fisheries compared to the situation with fisheries (5.2±3.0%) (Figure 20 right panels).

No clear gradient in sedimentation rates could be observed during harvest, indicating that sedimentation was variable but not higher close to the harvested plots (0 m). There seems a tendency that the organic fraction is higher further away from the plots (140, 400 m) potentially indicating that the small organic particles resuspended during harvest are transported further away from the plots before they settle. At Scheer a similar trend was observed on the east side of the plot (Figure 18 upper right panel).

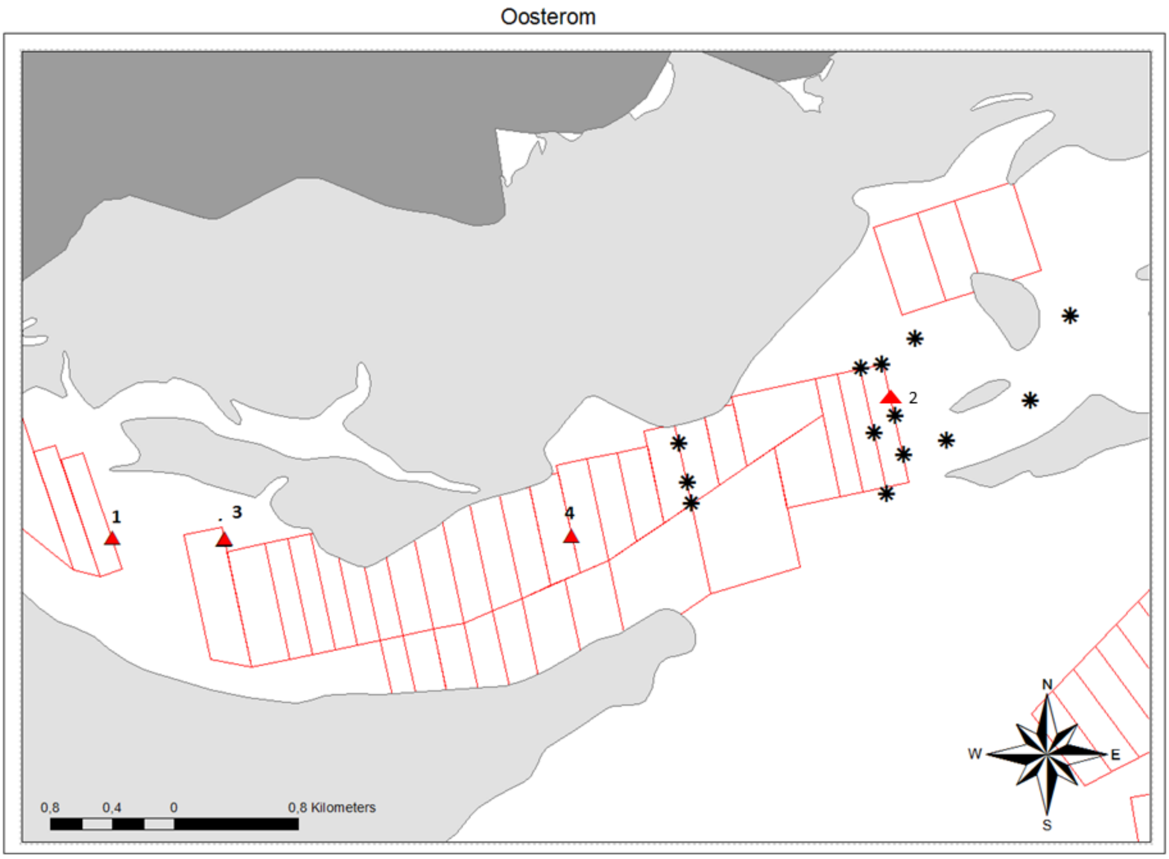

Figure 19 Map with locations of sediment traps (stars) and fixed turbidity meters (red triangles) at location Oosterom.

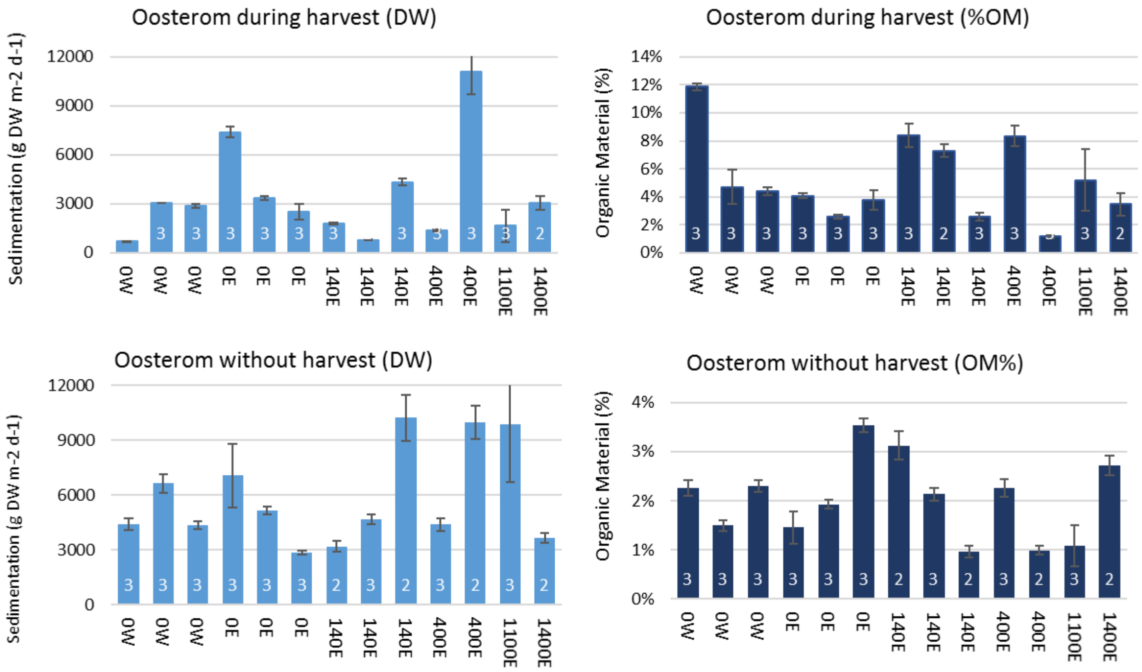

Figure 20 Average (± sd) sedimentation rates at Oosterom during harvest (upper graphs) and without harvest (lower graphs). Left graphs: total sedimentation in DW (g m^{-2} d^{-1}), right graphs: organic fraction in the collected material (%Organic Material). Each bar represents one sediment trap, and the numbers in each bar indicate the number of cores included in analysis (some cores were lost during sampling)

3.2.3 Fixed turbidity sensors

Inschot & Scheer

At Scheer and Inschot fixed turbidity sensors were placed at maximum impact (on mussel plot) and reference stations to monitor the temporal dynamics of the turbidity at the bottom (50 cm above the seabed) and at low water level (near the surface). The time before, during and after harvest was monitored (Figure 21).

Both sensors at reference and on the plot show changes over time, which demonstrates the temporal variability at the sites. At Inschot an increase in turbidity is observed when the tides are turning. The same seems the case at Scheer, but the pattern is not as clear. The bottom sensor at the reference station (scheer) showed extremely high and variable results and this was judged to be a measuring artefact. Data is therefore not shown.

When harvest starts (around 7:30 in the morning) turbidity values increase for the sensors placed at the bottom plot and show highly variable values. This is observed both for Inschot and Scheer. During the same time the reference stations show low and stable turbidity values. At Inschot background values during the harvest period are around 8 FTU for both the bottom and the surface sensor, and at the mussel plot vary between 8 and 30 NTU. The bottom sensor at the plot shows somewhat higher values, both during harvest as well as in the periods before and after harvest. At Scheer background values are also around 8 FTU (surface sensor) and increase to maximum 20 NTU at the mussel plot. After harvest is finished turbidity almost directly decreases on the plots, and the reference and plot show similar temporal patterns and magnitude of turbidity.

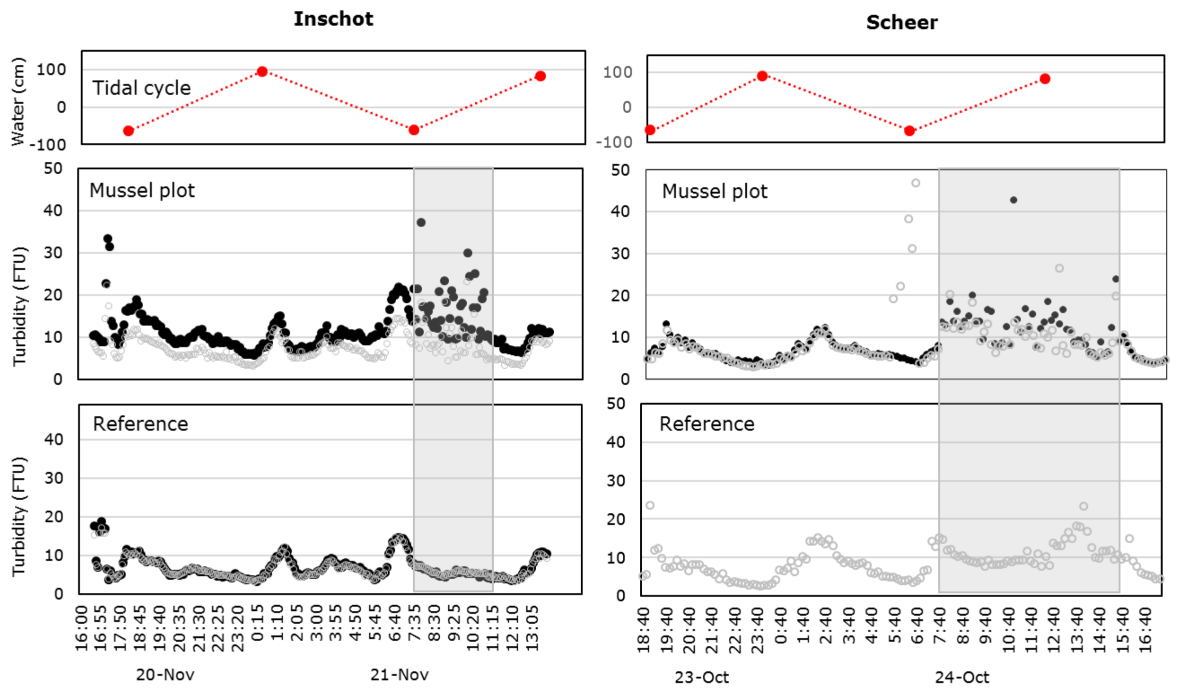

Figure 21 Turbidity measured at fixed stations on the bottom plot and at reference locations over a period of approximately 24 hours. Grey inset highlights the time when harvest took place on the bottom plot. Black dots (•) represent turbidity meters deployed close the bottom, Grey circles (◦) represent meters placed just below the low water line and present surface water concentrations. Upper graphs indicate the tidal cycle.

Oosterom

At location Oosterom the fixed turbidity sensors were deployed over a period of 4 weeks to measure natural variability and to link it to fisheries activities. As on forehand it is unknown where harvest will take place, the sensors were deployed at locations used for mussel growth studies in other projects (Capelle, unpublished). One additional sensor was deployed at Gat van Aartsen which is an exposed site, and thought to show high turbidity.

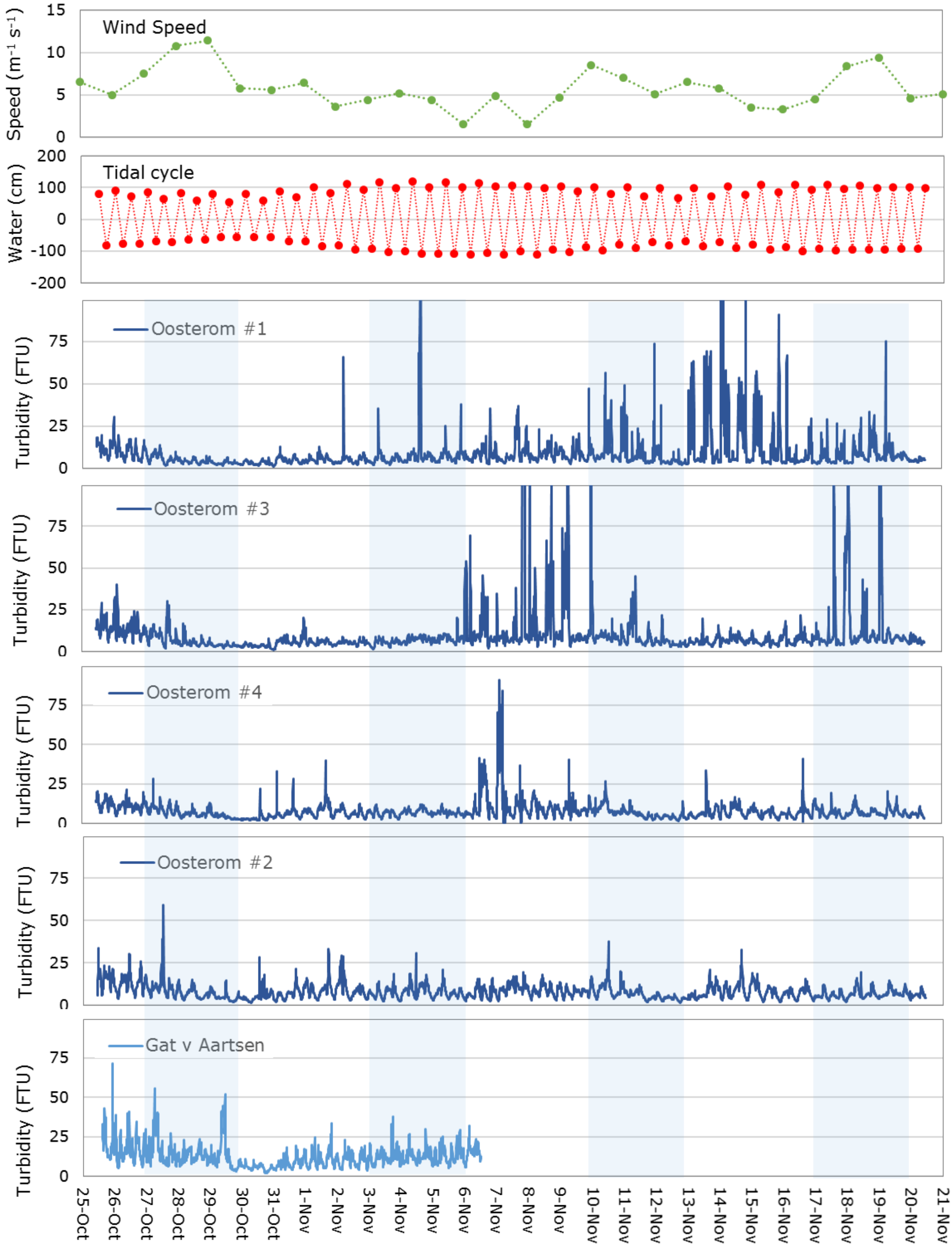

Figure 22 Turbidity (50 cm above bottom) over the course of one month (25 Oct- 21 Nov) at four locations in Oosterom (see Figure 19 for deployment positions), and for 2 weeks (25 Oct-6 Nov) at Gat van Aartsen. Upper graphs provide wind speed (KNMI, Terschelling) and tidal cycle. Blue bars indicate weekends (fri-sun), which are periods when it was known no fisheries took place

All meters showed relatively low values and low variability until the 6th of November, after that the turbidity became more variable. This did not coincide with increased wind speeds, nor with changes in the wind direction (data not presented). Minimum values for all four locations at Oosterom varied between 4-7 FTU.

The meters deployed at Oosterom #1 and #3 showed highest variation in turbidity. In Oosterom #1 the values frequently reached values above 50 FTU. Highest turbidity was observed during week days, but also during hours of the day when harvest was not taking place (at night).

Concentrations measured at Gat v Aartsen (average of 12.4 FTU) were indeed somewhat higher compared to concentrations at Oosterom for the same period of time (averages ranging between 6.4 and 8.4 FTU), indicating that that location is generally more turbid.

3.2.4 Sediment removal

Grab samples were collected in order to evaluate how much (organic) material will be removed during the harvest activities. It is expected that the organic fraction will be higher before harvest because of the mussel feces captured within the mussel matrix and sediments.

The average organic content was 2.2±1.6% before harvest, which did not statistically differ from the organic content after harvest 2.4±1.6% (paired ttest, p=0.8516). Those results were not according to the expectation, and since the number of samples was limited it was assumed that heterogeneity of the mussel plot was too large to pick-up on these signals. The total number of 9-12 samples was based on Van Bemmelen et al (2012). However, Capelle et al (2017) indicates that sample size should be higher for defining mussel biomass/coverage on mussel plots. The latter study applies 70 grab samples per mussel plot. It is likely that a higher number of samples is required to be able to measure changes in organic content. The time frame of the sampling campaigns was restricted and a larger number of grabs was not feasible. It was therefore decided to discard these measurements for the Inschot and Oosterom sampling campaigns.

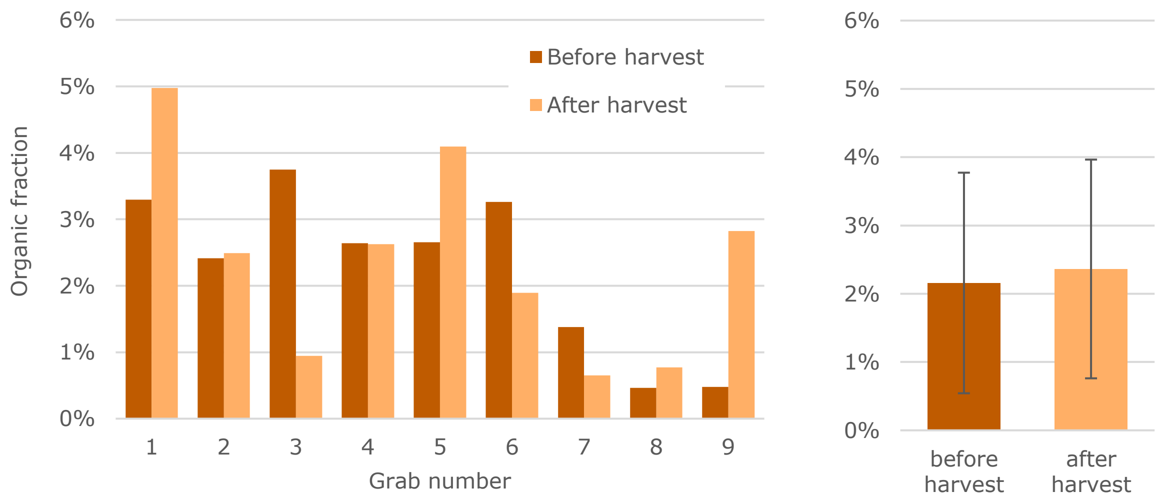

Figure 23 Fraction Organic Material in sediment collected before and after harvest at Scheer. A total of 9 positions were evenly distributed over the mussel plot and samples collected with a Van Veen Grab.

3.3 Natural variability in turbidity

The time series presented for location Oosterom (Figure 23) present high frequency data (sampling interval every 10 minutes), but only covered one month during autumn 2017. The water quality monitoring program by Rijkswaterstaat monitors several stations throughout the Wadden Sea on a regular basis (every month) since the ‘90s. Water samples are obtained at 1 m below the surface and analysed in the lab to determine the Suspended Particulate Matter (SPM) concentration. Figure 24 presents the data from this long-term time series, and indicates that SPM concentrations are generally lower in summer, and variability increases in autumn and winter. Highest concentrations are observed in Blauwe Slenk. It should be noted though that maximum values in this program are underestimated as no samples are collected during stormy weather conditions.

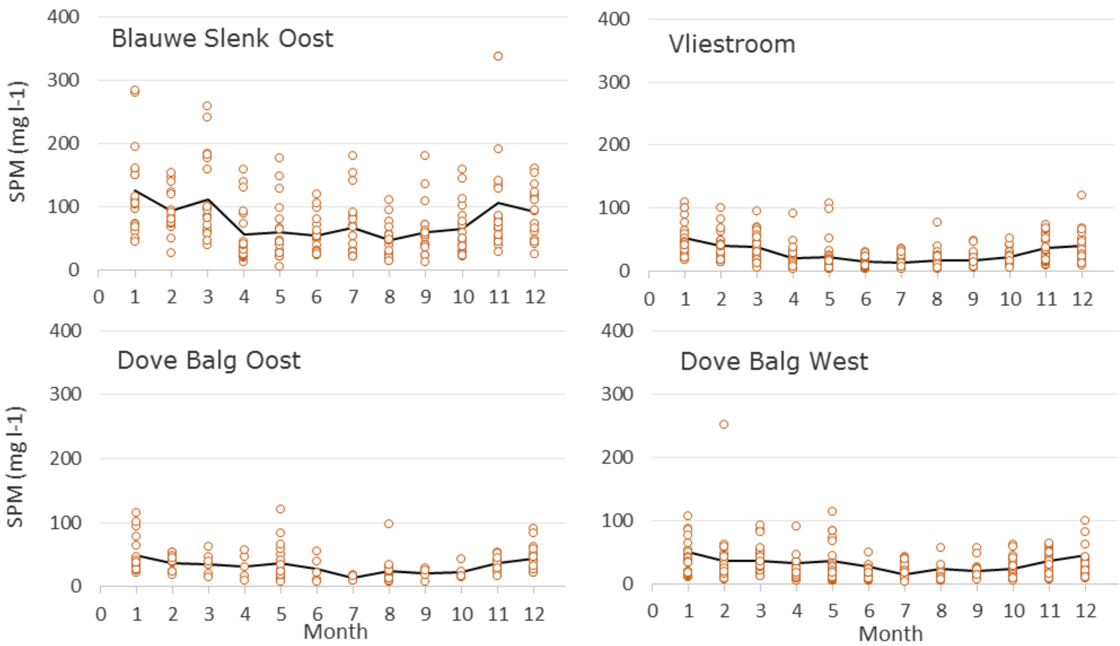

Figure 24 Monthly variability in Suspended Particulate Matter (SPM) at 4 locations in the Wadden Sea (Data source: Waterbase.nl). Data included from 1991-2015, where each dot represent one year and the black line presents the average value for each month.

4 Discussion and Conclusions

4.1 Sediment dynamics during seed fisheries

What is the turbidity enhancement during mussel seed fisheries in absolute values (maximum) and what is the spatial scale of impact?

This study indicates that mussel seed fisheries does enhance local turbidity significantly (Table 4). The highest turbidity values were observed for Omdraai. This was also the site with highest fishing activity. Table 4 indicates that fisheries intensity does not always define the level of enhancement, as high fisheries intensity at Malzwin did not result in high turbidity enhancement. Visual observations during the seed survey (Marinx, pers comm) showed that the seed bank at Omdraai consisted of loose material ('raal zaad' in Dutch) and much accumulated organic material. Type of sediment is therefore another factor defining the amount of material getting into suspension during fisheries (Pejrup and Mikkelsen 2010). Finally, the characteristics of the site such as current speed or water level (depth) are of importance, as they might affect dilution of resuspended sediments throughout the water column.

Pilot studies indicated that highest sediment concentrations were observed in the upper water body, as a result of the water discharged from the boats (water used for washing the mussel on board of the ship). Taking this into account, and to standardise between sites, the towed sensors were submerged at a depth of 1-1.5 m below the surface. Potentially this could have underestimated maximum enhancement as at Dove Balg it was shown that slightly higher values were observed at 6 m below te surface (at mid water depth) compared to 1.5 m. Results from harvest on mussel plots however showed only small differences between depths.

Table 4 Overview of background and maximum turbidity, and fisheries intensity and depth for each location included in the fisheries campaigns. Turbidity is presented in FTU (as in all previous transect figures) and approximate corresponding SPM values are provided based on the correlations described in Annex 1.

Area	Background conc		Max conc in fisheries zone		Fisheries intensity	Depth (cm +NAP)
	FTU	SPM (mg l^{-1})	FTU	SPM (mg l^{-1})	# boats	
Omdraai	10-15	~20-30	300-400	~575-775	6-10	-172/-74
Omdraai-south	10-15	~20-30	200-300	~380-575	4-6	-302/-173
Dove Balg	10	~20	60	~115	1	-1488/-1279
Breesem	5	~10	60-80	~115-150	4-6	-302/-173
Malzwin	10	~20	30-35	~55-65	5-8	-469/-303
ZuidWest	10	~20	130-150	~250-290	3-6	-469/-173

Despite the significant enhancement within fishery zones, the spatial patterns (turbidity transects) indicate that fishery impacts are local and that suspended sediment settles quickly. It was observed at all sites that sediment plumes have its maximum value in the middle of the fishery zones, but turbidity values go back to background values within a few tens to hundreds of meters of the fishery zone. This is confirmed by results found for the Danish fisheries (Saurel et al unpublished): drone images of mussel fisheries demonstrate that the plume is visible up to 50-75 m. Another indication of local turbidity enhancement is the patchiness of the sediment plume. Within fisheries zones the water column does not consist of a murky mixed water body, but enhanced values are clearly observed at spots where fishing boats have passed.

Sediment transport, and thus plume dynamics, is dependent on grain size and composition of the disturbed sediment; the smaller the sediment the further it will be transported. Results from this study indicate that most of the sediment brought into suspension during fisheries is apparently that heavy that it settles quickly. This is somewhat contradictory to our expectation since much of the disturbed sediment consist of light faecal material, and might thus be transported further away. Our expectation might, however, not be fully correct as water samples collected to calibrate the sensors (FTU to SPM) demonstrated that areas with high concentrations of particulate material (SPM) contain low fractions of organic material (>30%OM at reference sites; <20%OM within fishery zones).

Mussel seed fisheries thus results in enhanced turbidity, within the near vicinity of the fished mussel beds. Mussel fisheries is an activity that is restricted in time and space: every spring and autumn defined areas are appointed where fisheries is allowed. The total biomass (quota) varies between years and is depended on the total stock of mussel seed present. Figure 25 presents the biomass and the maximum allowed fishing days per year. Since 2008, mussel seed fisheries is in transition, and the quotas are being reduced. Maximum number of fishing days varied between zero in 2011 and 30 in 1999. This indicates that the temporal resolution of disturbance by seed fisheries is limited to an average of 17±6 days per year divided over two seasons. This number is likely an overestimation as many boats do not use all allowed days to obtain their quota. These data sources do not provide insight in the actual number of days fished, number of boats, nor the total area fished each day but shows that the fishing effort, and thus potential disturbance, varies between years.

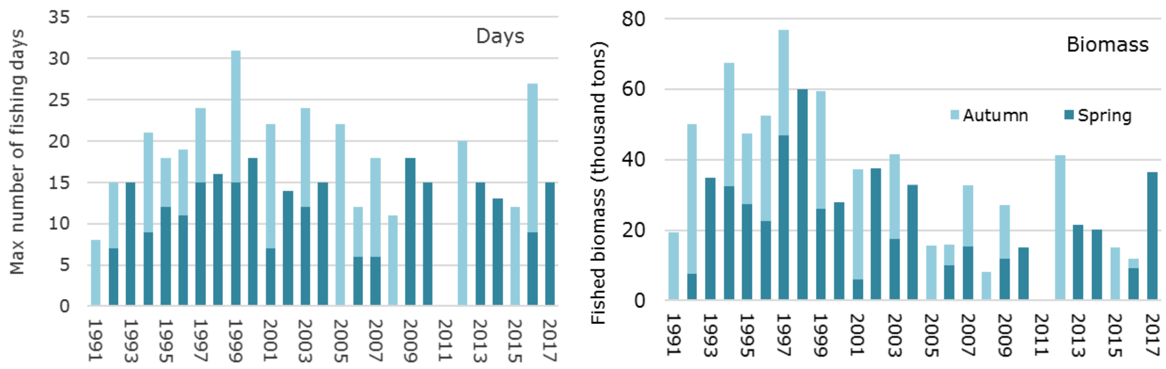

Figure 25 Overview of mussel seed fisheries in the Wadden Sea 1991-2011. Left: Maximum number of fishing days as allowed by the licence (visplan), not all days will be used as quotas are given by each week and many boats fish their quota on the first day of that week, Right: total fished biomass (actual quantity, not quota)

4.2 Sediment dynamics during harvest on bottom plots

4.2.1 Spatial and temporal magnitude of the sediment plume

What is the size of the sediment plume around the bottom plots during harvest activities?

Turbidity naturally varies between areas and within time. During harvest on bottom plots the turbidity increases and shows higher variability. The resuspension of sediment from the mussel bottom plots is visible during harvest. Maximum turbidity values were observed within the borders of the mussel plot. Background values were relatively similar between the three studied sites (5-10 FTU), and maximum enhancement was up to 40 FTU, which is 4-8 times the background values. Areas differ in sediment type, varying from hard bottoms to muddy sediments (see also sediment atlas of the Wadden Sea which provides a general description of sediment types for most areas in the Wadden Sea but exclude bottom plots; Dankers et al. 2007). Muddy sediments are expected to cause higher turbidity enhancement when disturbed by mussel dredges. Based on expert judgement, Inschot was chosen as a site with muddy sediments and on top of that the activity performed included 'schoonvissen'. Based on the combination of these two factors, we assumed maximum impact on turbidity concentrations at this site. Surprisingly, schoonvissen at Inschot showed similar, or even slightly lower, enhancement of turbidity concentrations compared to regular harvest at Scheer and Oosterom.

Based on the results from the transects (turbidity) it can be concluded that the spatial scale of the sediment plume is limited: turbidity values increase within the border of the harvested plot, but decrease rapidly, within tens of meters, to background values.

Table 5 Overview of background and maximum turbidity, and fisheries description and depth for each location included in the harvest campaigns. Turbidity is presented in FTU (as in all previous transect figures) and approximate corresponding SPM values are provided based on the correlations described in Annex 1.

Area	Mussel culture activity	Depth (cm + NAP)	Background concentration		Maximum concentration during harvest	
			FTU	SPM (mg/l)	FTU	SPM (mg/l)
Scheer	Single plot, harvest	-469/-173	5-10	~10-18	40	~75
Inschot	Single plot, schoonvissen	-1074/-665	5-8	~10-15	20-25	~35-45
Oosterom	Cluster of plots	-1488/-173	5-10	~10-18	30-40	~55-75

Sediment trap data confirmed that resuspended sediments do not settle along a gradient away from the mussel plot. Both the gradients in the turbidity transects as the sedimentation suggest that most resuspended sediments settle quickly (within the plot), which is similar to results found during the fisheries campaigns (4.1). Sedimentation rates at the border of the plot were not higher than reference values and sedimentation with and without fisheries (Oosterom) was similar. This suggests that resuspension by mussel culture activities is not higher than natural variability. Sediment trap (1-10% OM) and grab samples (2% OM) further indicate that much of the resuspended material consists of heavy inorganic material. Water samples collected for calibration of the sensors showed large variability (5-40%OM) without any clear correlation to total SPM value, which indicates that the fraction of organic material is similar between reference and fishery zones (this is different from seed fisheries, see 4.1).

In highly dynamic systems it is difficult to obtain representative reference values (Jansen et al 2016), especially if these are taken during different time intervals, as was done during the transect study: reference situation without fisheries was investigated before and after fisheries, which also meant they were obtained during different moments of the tidal cycle. Fixed turbidity meters indicated that natural variability is high, and related to the tidal cycle and thus differences in transect background values might be expected throughout the day. To evaluate disturbance by fisheries/harvest activities it seems therefore better to use upstream values as a reference. This is in accordance with Jansen et al (2016) who conclude that in dynamic areas, gradient studies provide more insight in disturbance by (fish) aquaculture than comparing farm and reference locations.

How long is the sediment plume still present after the harvest activities have stopped?

Fixed turbidity meters were deployed to measure how long the sediment plume was still visible after harvest had stopped. During harvest the turbidity was clearly higher and variable, but almost as soon as harvest activities stopped, the turbidity concentrations dropped to reference values. This indicates that the temporal scale of the plume is also limited. Theoretically this might be caused by either quick transport away from the plot (high current velocity) or by quick settlement of resuspended material. Results on the size of the sediment plume (previous section) suggest that the latter is more likely. Quick settlement (or dilution) of the sediment plume is confirmed by Saurel et al (unpublished, Denmark), who showed that the sediment plume is significantly reduced 10 minutes after mussel fisheries stopped based on drone images.

The current case studies focussed on direct turbidity enhancement during fisheries and harvest. Direct effects include disturbance by the dredges (bottom) and release of muddy water from the washing of mussel on deck (surface). However, dredging and removal of mussels might also have indirect, long term effects. Dredges might demobilize sediments which thereby might become more susceptible for resuspension by currents. This is for example shown by Palanques et al. (2001) for bottom trawling (using the trawl gear, composed of net, sweep lines, doors, and warps) in the north-western Mediterranean. They showed that sediment concentrations were up to 3 times higher compared to pre-fisheries conditions and disturbance caused by trawling was still seen five days after the event due to demobilizing of the sediment. Shellfish beds can stabile sediments (Borsje et al 2011; Zimmerman et al 2007), and the actual removal by fisheries or harvest might result in lower sediment cohesion and thereby increased risk for resuspension. Based on the current information we have no insight whether or not long term destabilization occurs due to mussel harvest and how this might affect sediment resuspension and thus turbidity in the Wadden Sea.

4.2.2 Sediment removal

How much sediment is removed during harvest on mussel plots?
This question could not be answered by the current set-up. After the first sampling campaign (Scheer), it was concluded that the number of samples that realistically could be taken during each sampling campaign was too small to detect changes in sediment organic content. Nevertheless, sediment trap data (see above) suggests that much of the resuspended sediments settles within the plot area.

Data from sediment traps, grab samples and water samples indicate that the amount of organic material in the resuspended material is lower than initially assumed. The sediment in the mussel matrices (beds and plots) defines the eventual amount and type being resuspended, and a good quality description of the sediment seems therefore of great importance.

4.3 Natural variability

How does disturbance by mussel culture activities relate to natural variability?
The sediment dynamics in the Wadden Sea is naturally high due to the shallow characteristics of the area and the tidal movement. Suspended Particulate Matter (SPM) concentrations increase during fisheries and harvest, and might peak to values that are on the higher range reported for natural variability in the Wadden Sea. Those maximum values are only reported on a small spatial scale and drop quickly back to background values. It should be noted though that maximum values measured by the long-term monitoring program of Rijkswaterstaat are generally underestimated as no samples are collected during extreme weather conditions, when high values might be expected.

4.4 Recommendations

4.4.1 Sampling strategy

The paragraphs above have identified improvements for the sampling strategies. To summarize:

- Better calibration and validation of turbidity sensors with mussel bed/plot resuspended material
- Focus on transects and gradients rather than comparison with reference stations (or transects without mussel culture activities) for spatial scale
- At deep sites include transects at multiple depths
- Include drone surveys to correlate turbidity and visual observations
- Deploy sediment traps on the plot that is being harvested to confirm that resuspended material settles quickly (within the borders of the plot)
- Deploy fixed sensors over a longer time span to monitor long term (indirect) effects harvest/fisheries on turbidity
- Increase sampling size to be able to quantify changes in sediment characteristics

4.4.2 Sediment grain size

The current research focussed on the measurement of turbidity concentrations and sedimentation of suspended material. Both parameters are affected by sediment grain size on the mussel plots investigated. To better understand the spatio-temporal scale of the sediment plume, more insight in the sediment grain size of the resuspended material is of interest and could be coupled to predictive models.

4.4.3 Comparison to other anthropogenic activities

Van Duren et al (2015) suggests that the estimated sediment transport by dredging and shrimp fisheries can be higher than for mussel culture activities. Estimating the spatiotemporal scale of turbidity and sedimentation for these activities following a similar approach as outlined in this report provides insight on the potential local impact of these activities. This provides input for the discussion of the effects for all anthropogenic activities in the Wadden Sea ecosystem.

4.4.4 System wide effects

The current study identified spatial and short-term temporal variability in turbidity and sedimentation for a number of case studies, both for mussel fisheries and mussel harvest activities. The results provide an overview of the expected spatial scale of effect (local), but cannot be used to extrapolate to the scale of impact at ecosystem scale, as spatial differences in sediment characteristics, water quality and current dynamics in the Wadden Sea are large. As this study did not aim to describe cause-effect relations between environmental conditions and turbidity/sedimentation, results cannot be used in a predictive manner.

To extrapolate to system scale requires insight in the combination of:

- System variability in time and space. The use of satellite data for turbidity should be investigated. This can be part of the Coast Obs H2020 project, and requires validation with continuous measurements of turbidity sensors, at a number of locations.
- Experimental studies defining the relations between:
    - substrate type and sediment dynamics,
    - fisheries (harvest) intensity and sediment dynamics
    - gear type and sediment dynamics
    - combination of gear type and sediment type against sediment dynamics
- Spatiotemporal overview of mussel culture activities

The current study focussed on quantifying turbidity enhancement and sedimentation by mussel culture activities. It shouldn’t be forgotten that the role of mussels in sediment dynamics is two-fold, as mussels also filter suspended particulate material from the water column resulting in lower turbidity. De Groot et al (2013) estimates that 1200-2400 thousand tons of silt is being captured by mussels in the Wadden Sea. When evaluating system wide effects both processes should be considered by creating a sediment balance that defines the fluxes of sediment capture (filtration) and sediment resuspension (disturbance by fisheries and harvest).

4.5 Concluding remarks

Based on the current study the following conclusions can be drawn with regard to the question to what extent mussel cultivation contributes to local enhancement of turbidity and sedimentation in the western Wadden Sea:

- The case studies showed that turbidity is enhanced within fishery and harvest zones, but the spatial scale of the sediment plume is limited to the direct vicinity of the mussel activity. It was difficult to observe a 'sediment plume' that extended further than the seedbank or plot fished. The absence of a plume was confirmed by sedimentation rates, which were not enhanced above background variability in areas downstream of the mussel culture activities.
- Turbidity enhancement during fisheries was higher than during harvest (respectively up to 40 and 8 times higher than background values).
- Magnitude of turbidity enhancement varies between areas and seems dependent on fishing intensity, type of activity (fisheries, harvest, schoonvissen), sediment characteristics of the bottom fished, depth and current dynamics.
- Case studies in this report show the spatial and temporal effects of mussel culture activities on sediment dynamics (turbidity and sedimentation). This is new and valuable information. Given the variation in sites studied it is not expected that studying more/other sites will lead to different conclusions on the relatively small spatial and temporal scale of the sediment plume created by seed fisheries or harvest on bottom plots. The current study set-up, however, does not allow for extrapolation to ecosystem scale estimates in terms of absolute disturbance, comparison with other human activities, or effects on water clarification by filtration of mussels in the Wadden Sea.
- Bottom disturbance and resuspension of sediments during seed fisheries and harvest on bottom plots is temporary (limited to a few days/weeks per year), in contrast to filtration by the mussels which is a continuous process that generally leads to higher visibility of the Wadden Sea.

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6 References

Airoldi L, Beck MW (2007) Loss, Status and Trends for Coastal Marine Habitats of Europe. *Oceanography and Marine Biology: An Annual Review* 45: 345-405

Baer J., Smaal A., van der Reijden K. & Nehls G. (2017) Fisheries. In: Wadden Sea Quality Status Report 2017. Eds.: Kloepper S. et al., Common Wadden Sea Secretariat, Wilhelmshaven, Germany

Beukema JJ (1976). Biomass and species richness of the macro-benthic animals living on the tidal flats of the Dutch Wadden Sea. *Netherlands Journal of Sea Research* 10(2): 236-261.

Beukema JJ, Essink K, Michaelis H, & Zwarts L (1993). Year-to-year variability in the biomass of macrobenthic animals on tidal flats of the Wadden Sea: How predictable is this food source for birds? *Netherlands Journal of Sea Research* 31(4): 319-330.

Borsje BW, van Wesenbeeck BK, Dekker F, Paalvast P, Bouma TJ, van Katwijk MM, de Vries MB (2011) How ecological engineering can serve in coastal protection. Ecological Engineering, Volume 37, Issue 2, February 2011, Pages 113-122

Bot PVM, Colijn F (1996) A method for estimating primary production from chlorophyll concentrations with results showing trends in the Irish Sea and the Dutch coastal zone. *ICES Journal of Marine Science* 53: 945–950

Brinkman AG (2015) Ecosysteemeffecten van lokaal veranderende slibgehaltes in de westelijke Waddenzee. IMARES rapport C157/15

Cadée GC, Hegeman J (1974). Primary production of phytoplankton in the Dutch Wadden. *Netherlands Journal of Sea Research* 8: 240–259

Capelle JJ (2017) *Production Efficiency of Mussel Bottom Culture.* PhD thesis Wageningen University, The netherlands.

Castorani MC, Glud RN, Hasler-Sheetal H & Holmer M (2015). Light indirectly mediates bivalve habitat modification and impacts on seagrass. *Journal of Experimental Marine Biology and Ecology*, 41-53

Dankers N. & Zuidema DR (1995). The Role of the Mussel (Mytilus edulis L.) and Mussel Culture in the Ducth Wadden Sea. *Estuaries* 18(1): 71-8.

Dankers NMJA, Cremer JSM, Dijkman EM, Brasseur SMJM, Dijkema KS, Fey-Hofstede FE, Jong ML de; Smit CJ (2007) Ecologische atlas Waddenzee. IMARES http://edepot.wur.nl/44722

De Groot A, Brinkman B, Fey F, van Sluis C, Oost A, Schelfhout H, Smale A, Dijkman E, Scholl M (2013) Biobouwers als onderdeel van een kansrijke waterveiligheidsstrategie voor Deltaprogramma Waddengebied. IMARES-rapport C163/13A

De Jonge VN, De Jong DJ (2002) Ecological restoration in coastal areas in the Netherlands: concepts, dilemmas and some examples. *Hydrobiologia* 478, 7–28

De Robertis A, Ryer CH, Veloza A, Brodeur RD (2003) Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Canadian Journal of Fisheries and Aquatic Sciences* 60:1517-1526

Dolmer P , HT Christensen, BW Hansen, B Vismann, (2012) Area-intensive bottom culture of blue mussels Mytilus edulis in a micro-tidal estuary. *Aquaculture environment interactions* 3 (1); 81-91

Dolmer P, Kristensen T, Christiansen ML, MF Petersen, PS Kristensen, E Hoffmann (2001) Short-term impact of blue mussel dredging (Mytilus edulis L.) on a benthic community. *Hydrobiologia* 465 (1-3): 115-127

Dolmer P, PS Kristensen, E Hoffmann, (1999) Dredging of blue mussels (Mytilus Edulis L.) in a Danish sound: stock sizes and fishery-effects on mussel population dynamic. *Fisheries research* 40 (1): 73-80

Duarte CM (2002) The future of seagrass meadows. *Environmental conservation* 29:192-206

Frandsen RP, OR Eigaard, LK Poulsen, D Torring, B Stage, D Lisbjerg, P Dolmer (2015) Reducing the impact of blue mussel (Mytilus edulis) dredging on the ecosystem in shallow water soft bottom areas. *Aquatic conservation-marine and freshwater ecosystems* 25(2):162-173

Figueiredo, Mormul, Chapman, Lolis, Fiori, & Benedito. (2016). Turbidity amplifies the non-lethal effects of predation and affects the foraging success of characid fish shoals. *Freshwater Biology*, 293-300

Giesen WBJT, van Katwijk MM, & den Hartog C (1990) Eelgrass condition and turbidity in the Dutch Wadden Sea. *Aquatic Botany*, 71-85

Giles H, Pilditch CA, & Bell DG (2006) Sedimentation from mussel (*Perna canaliculus*) culture in the Firth of Thames, New Zealand: Impacts on sediment oxygen and nutrient fluxes. *Aquaculture*, 125-140

Grasshoff K, Kremling K and Ehrhardt MG (1999) Methods of Seawater Analysis (3rd Edition). VCH Publishers. 632 p.

Gregory RS & Levings CD (1998) Turbidity Reduces Predation on Migrating Juvenile Pacific Salmon. *Transactions of the American Fisheries Society* 127(2): 275-285

Groot SJ de (1984). The Impact of Bottom Trawling on Benthic Fauna of the North Sea. *Ocean Management* 9(3-4): 177-190.

Hawkins AJS, Smith RFM, Bayne BL, Heral M (1996) Novel observations underlying fast growth of suspension feeding shellfish in turbid environments: *Mytilus edulis*. *Marine Ecology Progress Series* 131 179-190

Henley W, Patterson M, Neves R, Lemly AD (2000) Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. reviews in Fisheries Science 8:125-139Jones. (1992). Environmental impact of trawling on the seabed: A review. *New Zealand Journal of Marine and Freshwater Research*, 59-67

Jansen HM , GK Reid, RJ Bannister, V Husa, SMC Robinson, JA Cooper, C Quinton, Ø Strand (2016) Discrete water quality sampling at open-water aquaculture sites: limitations and strategies. *Aquaculture environment interactions* 8: 463–480

Kaiser M, Clarke K, Hinz H, Austen M, Somerfield P, Karakassis I (2006) Global analysis of response and recovery of benthic biota to fishing. *Marine Ecology Progress Series* 311:1-14

Kluiver K, Brinkman B, van Duren L. Fey F (2015) Effecten van slib op de ecologische doelen van de KRW. Deltares 1220102-000-ZKS-0009

Kuiper K & Brinkman B (2015) Antropogene bodemberoering Verkenning Slibhuishouding Waddenzee. Delatres 1220102-000-ZKS-0002

Lotze HK (2007) Rise and fall of fishing and marine resource use in the Wadden Sea, southern North Sea. *Fisheries Research* 87: 208-218

Marine U (n.d.). *UK Marine Special Areas of Conservation*. Retrieved from UK Marine SACs Project: http://www.ukmarinesac.org.uk/activities/ports/ph5_2_3.htm

Marinx (2017) Inventarisatie van het sublitorale wilde mosselbestand in de westelijke Waddenzee in het voorjaar van 2017. RAPPORT 2017.175

McLeod IM, Parsons DM, Morrison MA, Le Port A, Taylor RB (2012) Factors affecting the recovery of soft-sediment mussel reefs in the Firth of Thames, New Zealand. *Marine and Freshwater Research* 63,78-83

Lowe M, McLeod I, Morrison M, Parsons D, Usmar M (2009). *A review of land-based effects on coastal fisheries and supporting biodiversity in New Zealand.* Wellington: Ministry of Fisheries.

Newcombe CP & Macdonald DD (2011) Effects of Suspended Sediments on Aquatic Ecosystems. *North American Journal of Fisheries Management*, 72-82

Österling ME, Arvidsson BL, Greenberg LA (2010) Habitat degradation and the decline of the threatened mussel Margaritifera margaritifera: influence of turbidity and sedimentation on the mussel and its host. *Journal of Applied Ecology* 47:759-768

Palanques A, Guillén J & Puig P (2001). Impact of bottom trawling on water turbidity and muddy sediment of an unfished continental shelf*. American Society of Limnology and Oceanography* 46(5), 1100-1110

Pejrup M and Mikkelsen OA, 2010. Factors controlling the field settling velocity of cohesive sediment in estuaries. *Estuarine, Coastal and Shelf Science* 87(2): 177-185

Philippart CJM, Salama MS, Kromkamp JC, van der Woerd H, Zuur AF, & Cadée GC (2013). Four decades of variability in turbidity in the western Wadden Sea as derived from corrected Secchi disk readings. *Journal of Sea Research*, 67-79.

Reise K (2005) Coast of change: habitat loss and transformations in the Wadden Sea. *Helgoland Marine Research*, 9-21.

Reichert JM, Fryer BJ, Pangle KL, Johnson TB, Tyson JT, Drelich AB, Ludsin SA (2010) River-plume use during the pelagic larval stage benefits recruitment of a lentic fish. *Canadian Journal of Fisheries and Aquatic Sciences* 67:987-1004

Thomas SA, Newbold JD, Monaghan MT, Minshall GW, Georgian T, Cushing CE (2001) The influence of particle size on seston deposition in streams. *Limnology and Oceanography* 46:1415-1424

Thrush S, Hewitt J, Cummings V, Ellis J, Hatton C, Lohrer A, Norkko A (2004) Muddy waters: elevating sediment input to coastal and estuarine habitats. *Frontiers in Ecology and the Environment* 2,299-306

Todd VLG, Todd IB, Gardiner JC, Morrin ECN, MacPherson NA, DiMarzio NA, Thomsen F (2015) A review of impacts of marine dredging activities on marine mammals. *ICES Journal of Marine Science* 72:328-340

Tulp I., Bolle L.J., Dänhardt A., de Vries P., Haslob H., Jepsen N., Scholle J. & van der Veer H.W. (2017) Fish. In: Wadden Sea Quality Status Report 2017. Eds.: Kloepper S. et al., Common Wadden Sea Secretariat, Wilhelmshaven, Germany.

UNESCO. (2014). *Wadden Sea.* Retrieved from United Nations Educational, Scientific and Cultural Organization - World Heritage Convention: http://whc.unesco.org/en/list/1314

van Bemmelen R, Brinkman B, Holthuijsen S, Jansen J (2013) The effects of subtidal mussel seed fisheries in the Dutch Wadden Sea on Sediment composition. IMARES Report number C163/12

Van Duren LA, van Kessel T, Brinkman AG, de Kluijver A, Fey F en Schmidt CA (2015). Verkenning Slibhuishouding Waddenzee. http://publications.deltares.nl/WeL1818.pdf

Van Der Veer HW, MJN Bergman, JJ Beukema (1985) Dredging activities in the Dutch Wadden Sea: effects on macrobenthic infauna. *Netherlands Journal of Sea Research* 19(2): 183-190

Wassmann P & Heiskanen AS (1988). Sediment trap studies in the nordic countries. *Tvarminne Zoological Station*, 24-28.

Zimmerman G F & de Szalay FA (2007) Influence of unionid mussels (Mollusca: Unionidae) on sediment stability: an artificial stream study. Fundamental and Applied Limnology Volume 168 (4): 299 – 306

Justification

Report C046/18
Project Number: 4313200007-08 KOMPRO 3

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. ir. M.J. Baptist
Senoir scientist

Signature:

Date: 9 July 2018

Approved: Dr. ir. T.P. Bult
Director

Signature:

Date: 9 July 2018

Annex 1 Calibration turbidity sensors

Fisheries and harvest campaign

High resolution sampling with the turbidity sensors (in NTU/FTU) were correlated to actual concentrations of suspended particulate matter (SPM) in the water column (Figure A1 and A2). High standard deviations, especially in the higher end of the calibration curves, indicate that the water column sampled was patchy and could vary within a small spatial scale. Variation was both observed in the water sampling as well as with the turbidity sensors. This indicates that care should be taken with interpretation of the absolute turbidity, and information from the turbidity sensors can best be used to compare relative increases/decreases throughout transects.

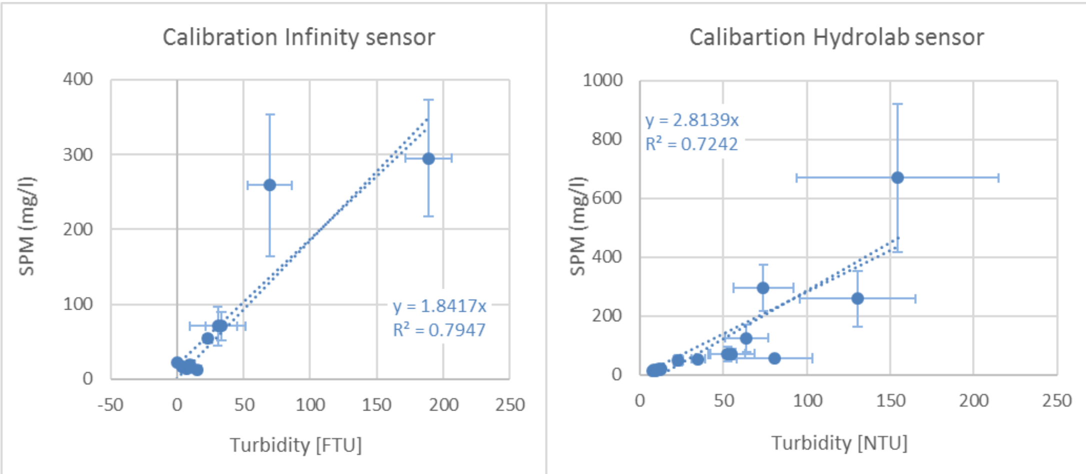


Figure A1 *Calibration curves of the turbidity sensors against measured turbidity in water samples during the fisheries campaign in Spring 2017. A: Correlation between INFINITY sensor (in FTU) and Total Suspended Matter (in mg DW l^{-1}), B: Correlation between Hydrolab sensor (in NTU) and Total Suspended Material (in mg DW l^{-1}). Note: fewer sampling points are available for the INFINITY calibration due to malfunctioning of the sensor during the first sampling occasions (high turbidity locations), therefore calibration in the higher end was not possible for this sensor. Numbers are given as mean±sd.*

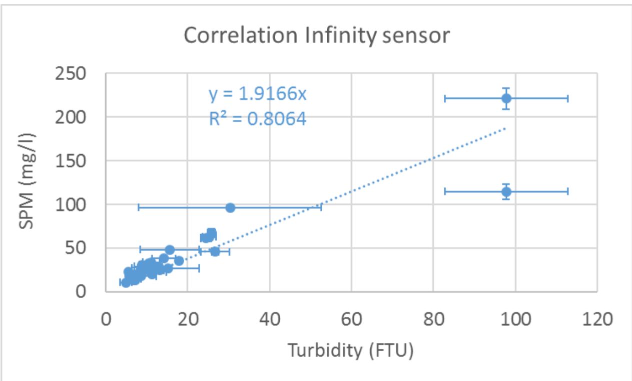


Figure A2 *Calibration curves of the Infinity turbidity sensor against measured SPM concentrations in water samples during the harvest campaign in Autumn 2017*

Validation with different sediment types

Before use, the turbidity sensors were calibrated using standard solutions to test the response of the sensor. During the sampling campaigns water samples have been collected to convert FTU/NTU units to the concentration of suspended particulate matter (SPM) in the water column (section 6.1.1). This has to be done for each area/season as type of organic material might give a different response. To gain more insight in the linearity of the response to different sediment types, lab measurements have been performed with the Hydrolab sensor. The infinity sensor was not available because of other fieldwork activities, but considering the good relation between the two sensors (see graphs annex 2) it is expected that both will respond in a similar way.

Two types of sediment were brought in solution and turbidity was measured by the Hydrolab sensor, and subsequently the SPM concentrations determined by filtrations (see section 2.2). One type consisted of coarse sand including large particles (in dutch 'ophoogzand'), the other type consisted of very fine porcelain sand. Both types were dissolved in filtered seawater so there was no background response (e.g. from phytoplankton). Correlation curves presented in figure A3 indicate that the sensors are less sensitive to smaller concentrations of the coarse particles. Figure A4bcd demonstrates that suspensions of similar concentrations SPM (~200 mg l^{-1}) look different in terms of water transparency, which is also represented by turbidity readings. Resuspended material from bottom plots and seedbeds investigated in the current study likely consist of much organic material (mussel feces and settled flocculent matter, e.g. phytoplankton). We therefore tested the response of the hydrolab sensor for mussel faeces and settled organic material collected in outdoor tanks. This showed a linear response, also for lower concentrations (<200 mg l^{-1}), although it did not include the base (0,0) as lowest SPM concentration (27 mg l^{-1}) resulted in a baseline (zero) response in terms of turbidity readings.

In nature the turbidity is based on a number of different types of particles in the water, varying from small phytoplankton to larger resuspended material, and NTU/FTU values measured where therefore never down to zero (annex 2). For this study we were interested in the increase in turbidity by mussel activities. If the sediment plume only consisted of large particles (like coarse sand) the turbidity readings might have given an underestimation in terms of the spatial scale. However, sediment trap results did not indicate that large larger particles were transported away from the bottom plots. The linear correlation between SPM and Turbidity for the mussel faeces/flocculent material suggests that turbidity readings during the field campaigns are valid, but a small underestimation cannot be ruled out based on these results (0 NTU by 27 mg l-1).

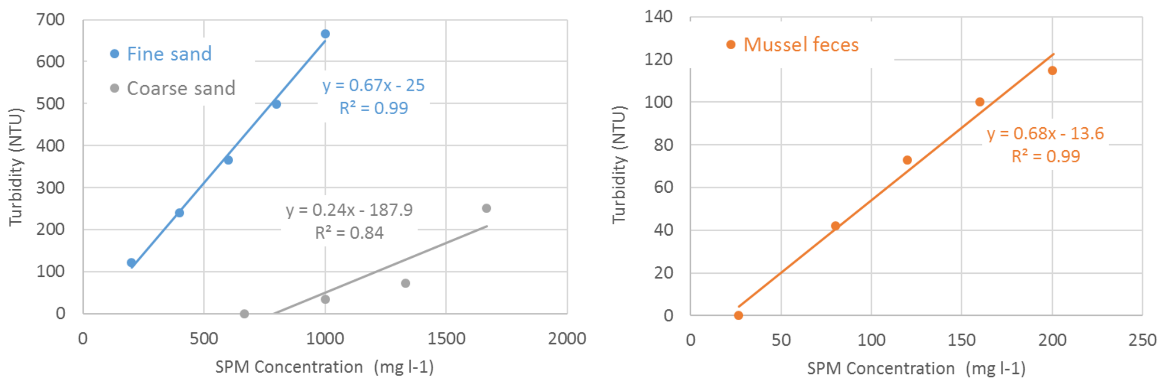


Figure A3 *Correlation between the hydrolab turbidity sensor (NTU) and SPM concentration (mg l^{-1}). Left: for fine and coarse sand, Right: for suspended mussel feces. Measurements performed in the lab.*

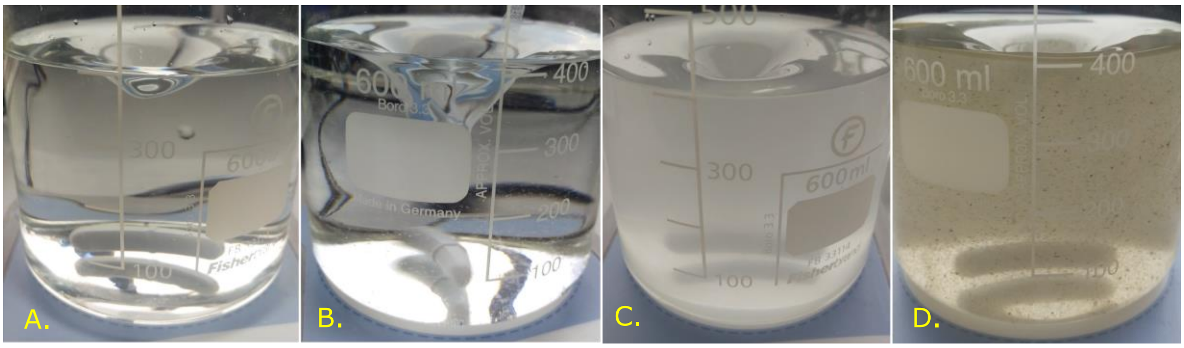
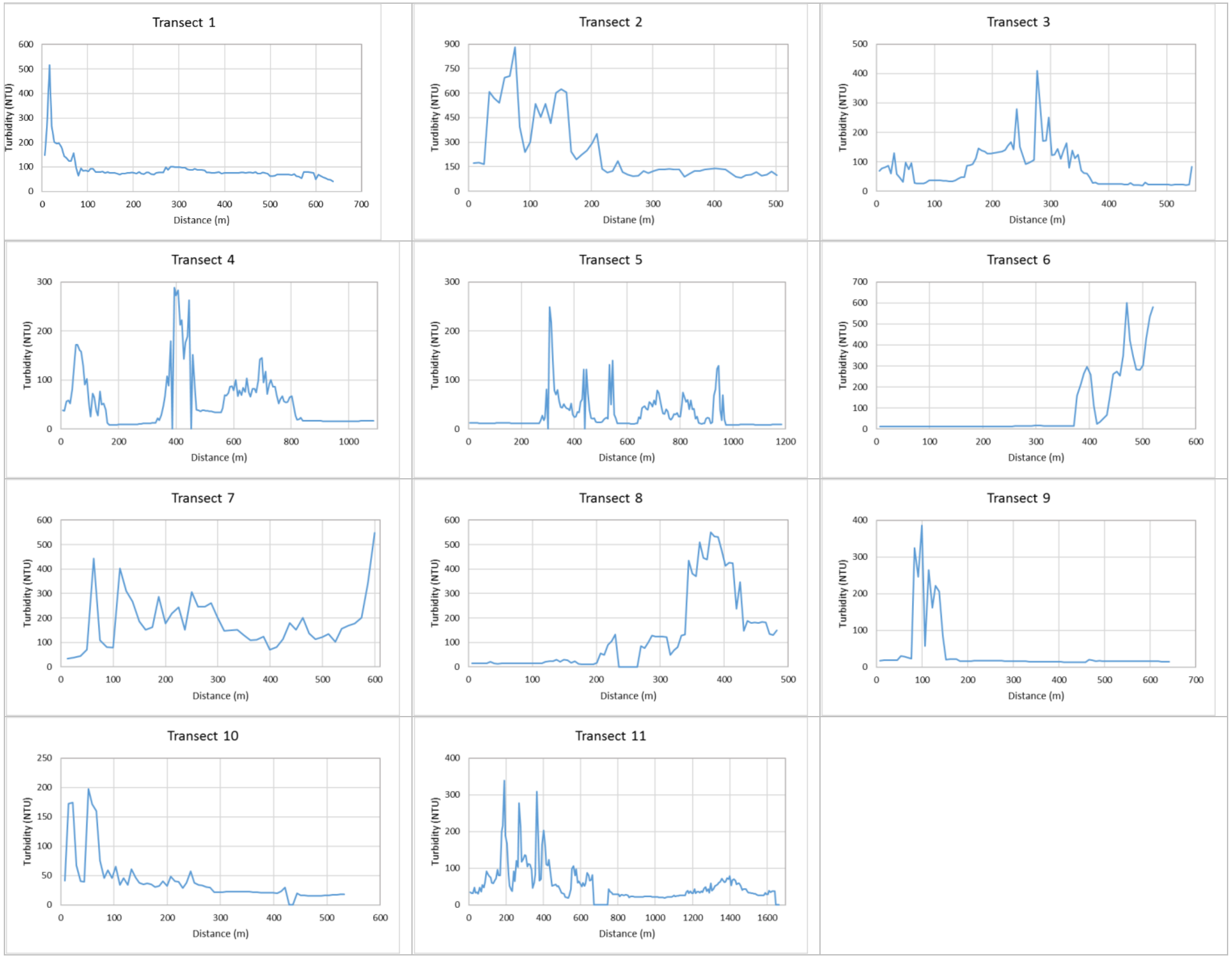


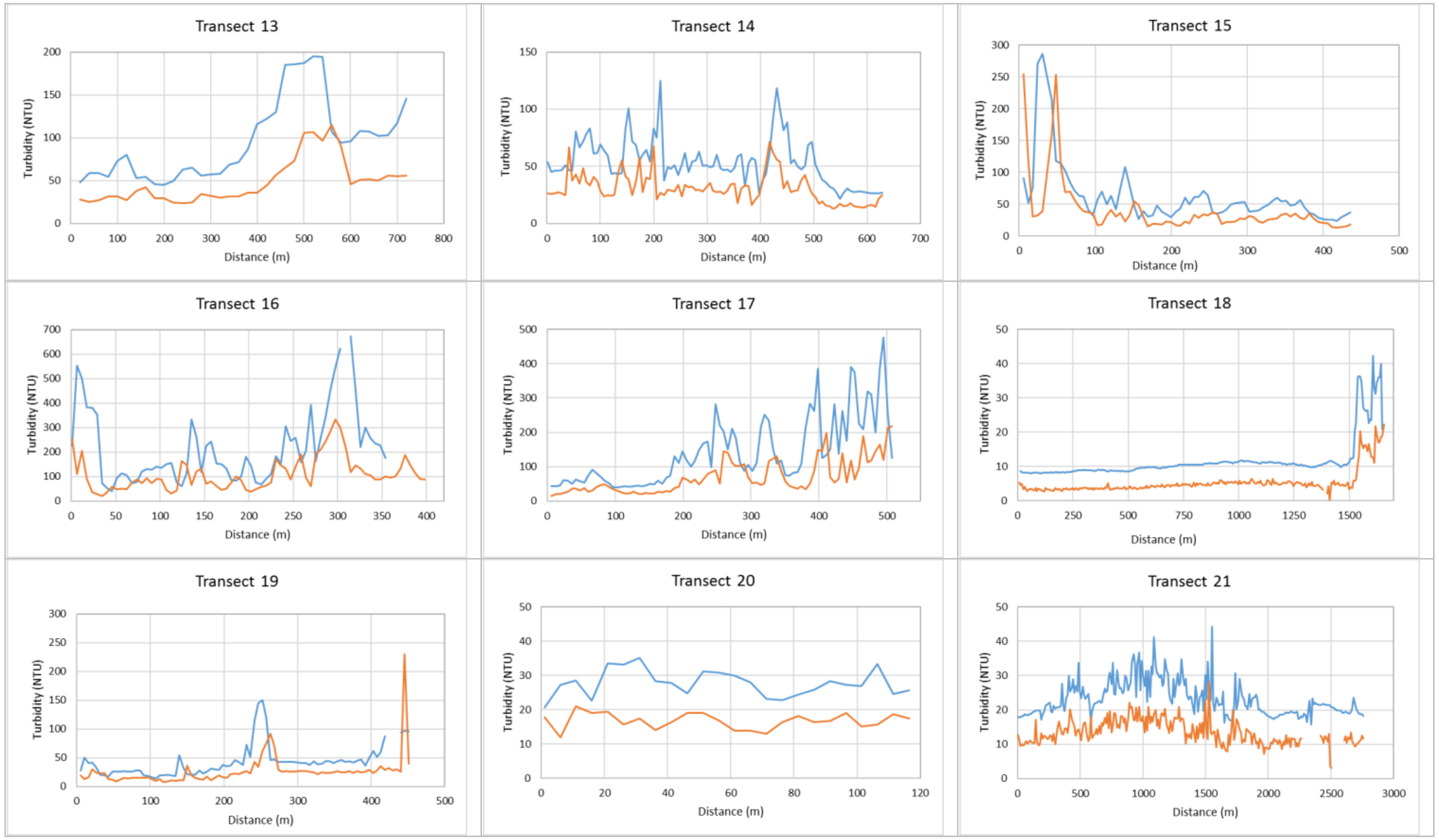
Figure A4 Photos of (A) clean filtered seawater (~0 mg $l^{-1,}$ NTU=0), (B) suspended coarse sand (~200 mg l^{-1}, NTU=0), (C) suspended porcelain sand (~200 mg l^{-1}, NTU=120), (D) suspended mussel faeces (~200 mg l^{-1}, NTU=115)

Annex 2 Transects fisheries

Omdraai 1



Omdraai 2

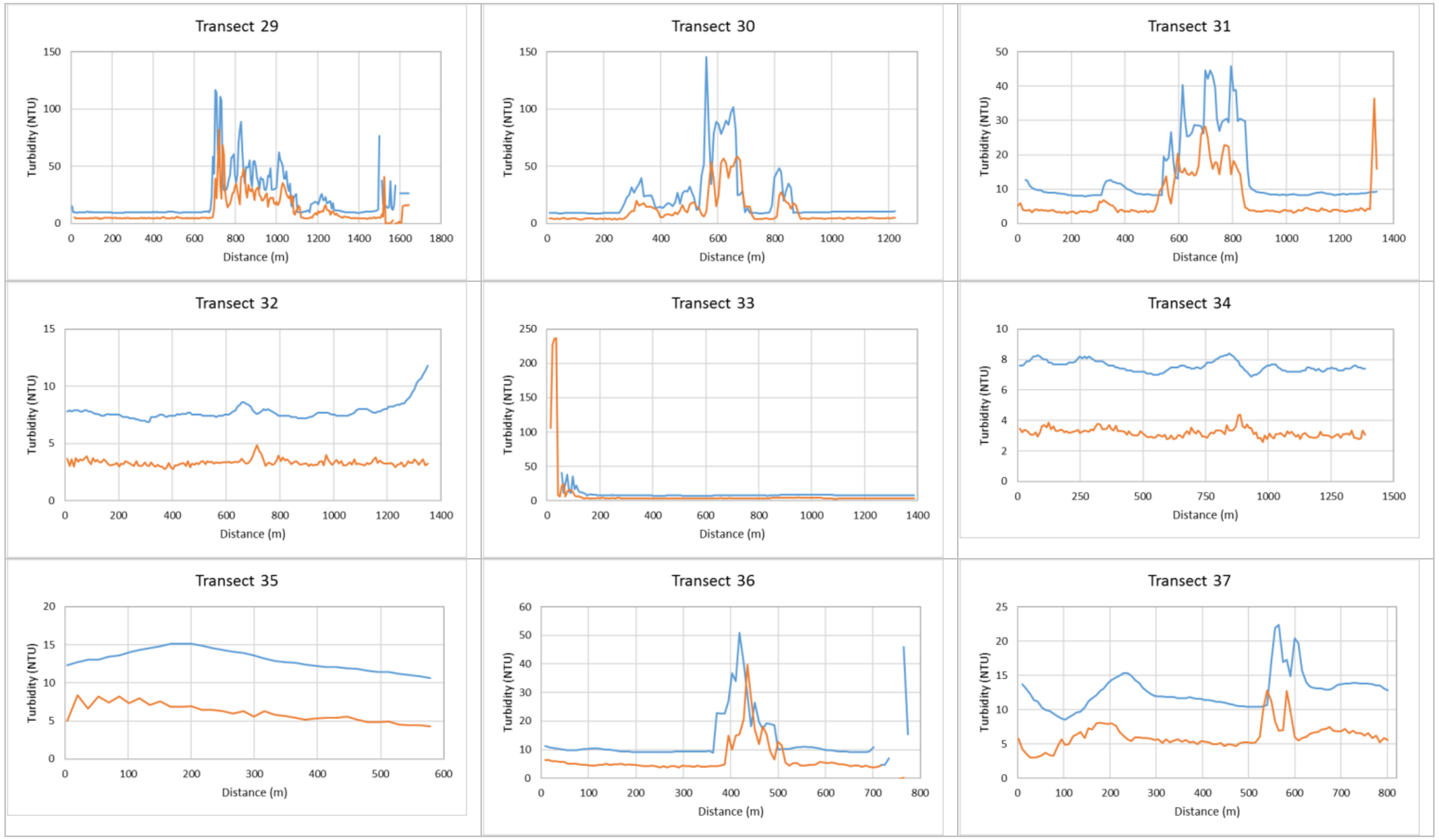


Transect 13
Turbidity (NTU)
Distance (m)
Transect 14
Turbidity (NTU)
Distance (m)
Transect 15
Turbidity (NTU)
Distance (m)
Transect 16
Turbidity (NTU)
Distance (m)
Transect 17
Turbidity (NTU)
Distance (m)
Transect 18
Turbidity (NTU)
Distance (m)
Transect 19
Turbidity (NTU)
Distance (m)
Transect 20
Turbidity (NTU)
Distance (m)
Transect 21
Turbidity (NTU)
Distance (m)

Dove Balg


Transect 25
Turbidity (NTU)
0 10 20 30 40 50
0 50 100 150 200 250 300 350
Distance (m)
Transect 26
Turbidity (NTU)
0 20 40 60 80 100
0 50 100 150 200 250 300 350 400
Distance (m)
Transect 27
Turbidity (NTU)
0 20 40 60 80 100
0 50 100 150 200 250 300 350 400
Distance (m)
Transect 28
Turbidity (NTU)
0 10 20 30 40 50 60 70
0 100 200 300 400 500
Distance (m)

Breesem



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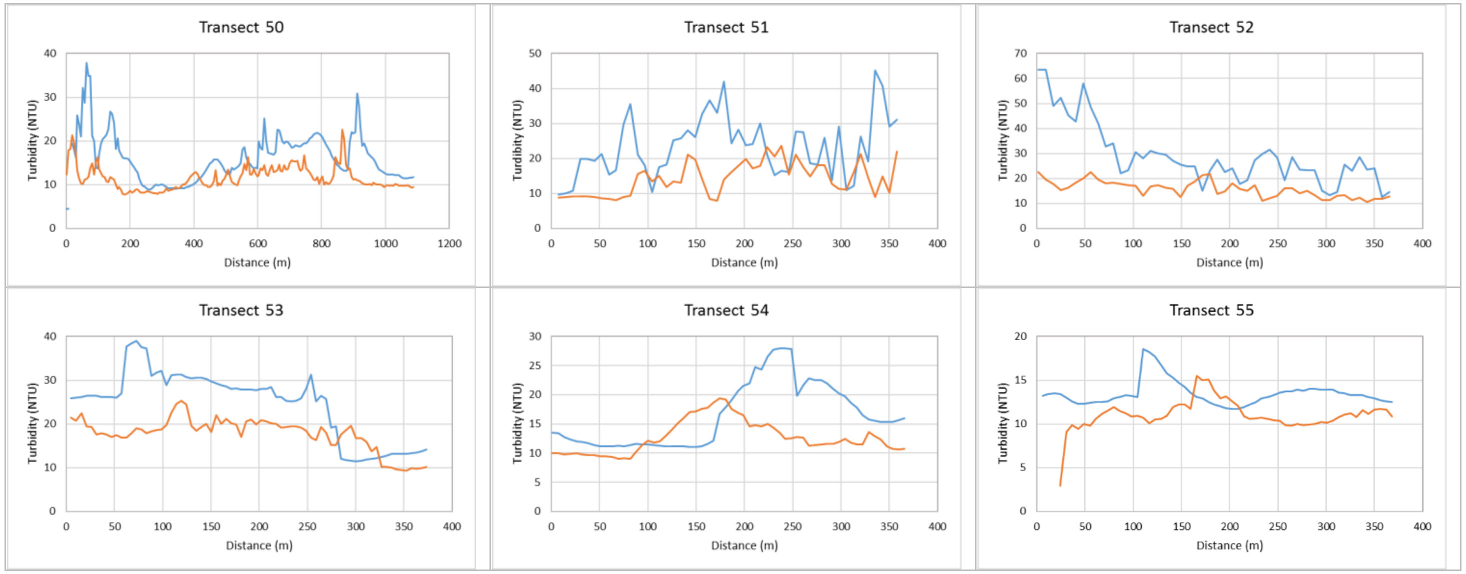
Turbidity (NTU)
Distance (m)
Transect 30
Turbidity (NTU)
Distance (m)
Transect 31
Turbidity (NTU)
Distance (m)
Transect 32
Turbidity (NTU)
Distance (m)
Transect 33
Turbidity (NTU)
Distance (m)
Transect 34
Turbidity (NTU)
Distance (m)
Transect 35
Turbidity (NTU)
Distance (m)
Transect 36
Turbidity (NTU)
Distance (m)
Transect 37
Turbidity (NTU)
Distance (m)

Malzwin


Transect 38
Transect 39
Transect 40
Transect 41
Transect 42
Transect 43
Transect 44
Transect 45
Transect 46
Transect 47
Transect 48
Transect 49
Turbidity (NTU)
Distance (m)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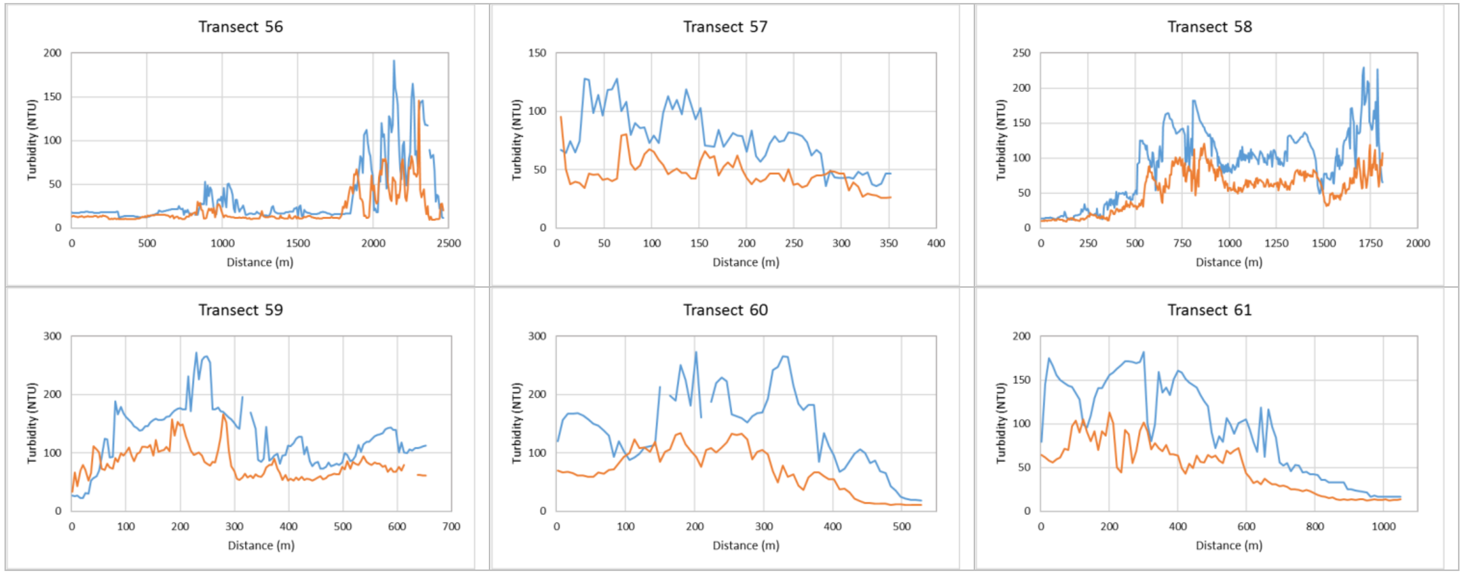
Turbidity (NTU)
Distance (m)
Transect 51
Turbidity (NTU)
Distance (m)
Transect 52
Turbidity (NTU)
Distance (m)
Transect 53
Turbidity (NTU)
Distance (m)
Transect 54
Turbidity (NTU)
Distance (m)
Transect 55
Turbidity (NTU)
Distance (m)

Zuidwest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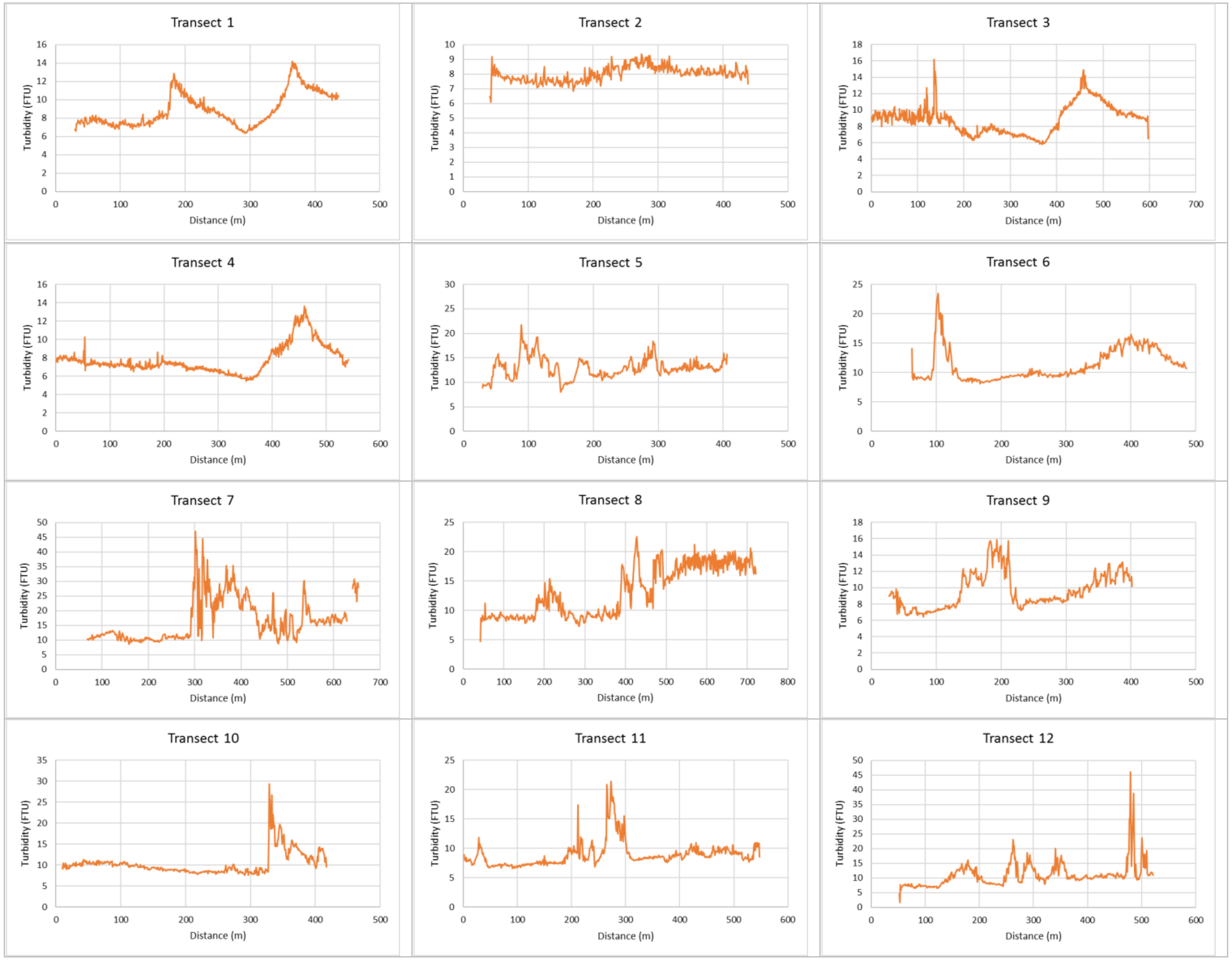
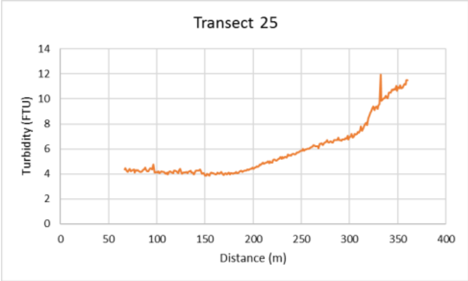
Turbidity (NTU)
Distance (m)
Transect 57
Turbidity (NTU)
Distance (m)
Transect 58
Turbidity (NTU)
Distance (m)
Transect 59
Turbidity (NTU)
Distance (m)
Transect 60
Turbidity (NTU)
Distance (m)
Transect 61
Turbidity (NTU)
Distance (m)

Annex 3 Transects bottom plots

Sheer




Transect 13
Transect 14
Transect 15
Transect 16
Transect 17
Transect 18
Transect 19
Transect 20
Transect 21
Transect 22
Transect 23
Transect 24
Turbidity (FTU)
Distance (m)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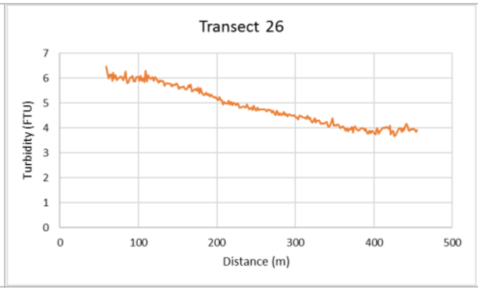
Distance (m)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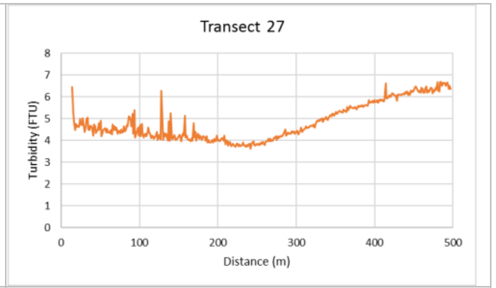
Distance (m)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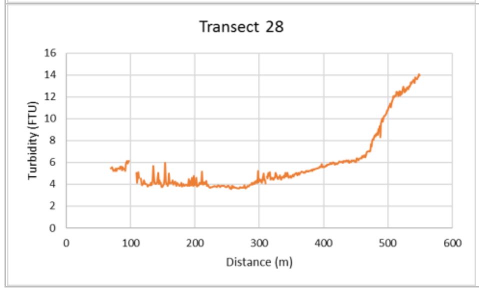
Distance (m)


Transect 28
Turbidity (FTU)
0 2 4 6 8 10 12 14 16
0 100 200 300 400 500 600
Distance (m)

Oosterom

Transect 29
Transect 30
Transect 31
Transect 32
Transect 33
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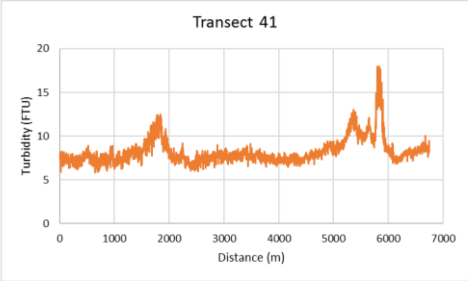
Transect 36
Transect 37
Transect 38
Transect 39
Transect 40
Turbidity (FTU)
Distance (m)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Turbidity (FTU)
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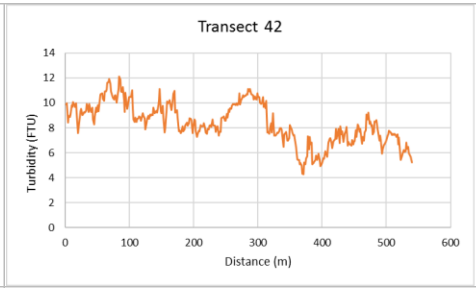
5
10
15
20
0 1000 2000 3000 4000 5000 6000 7000
Distance (m)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4
6
8
10
12
14
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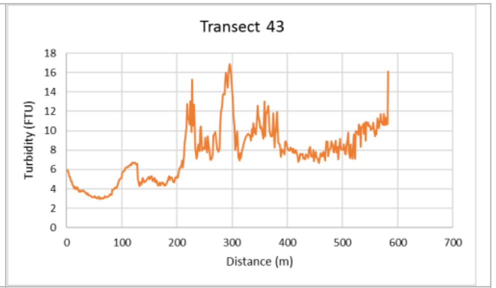
Distance (m)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2
4
6
8
10
12
14
16
18
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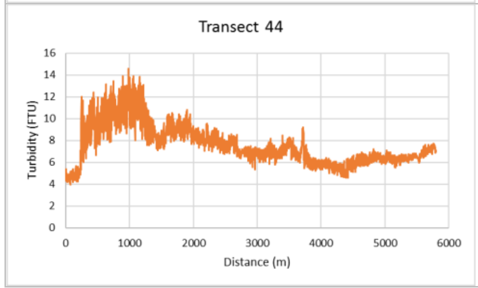
Distance (m)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Turbidity (FTU)
0
2
4
6
8
10
12
14
16
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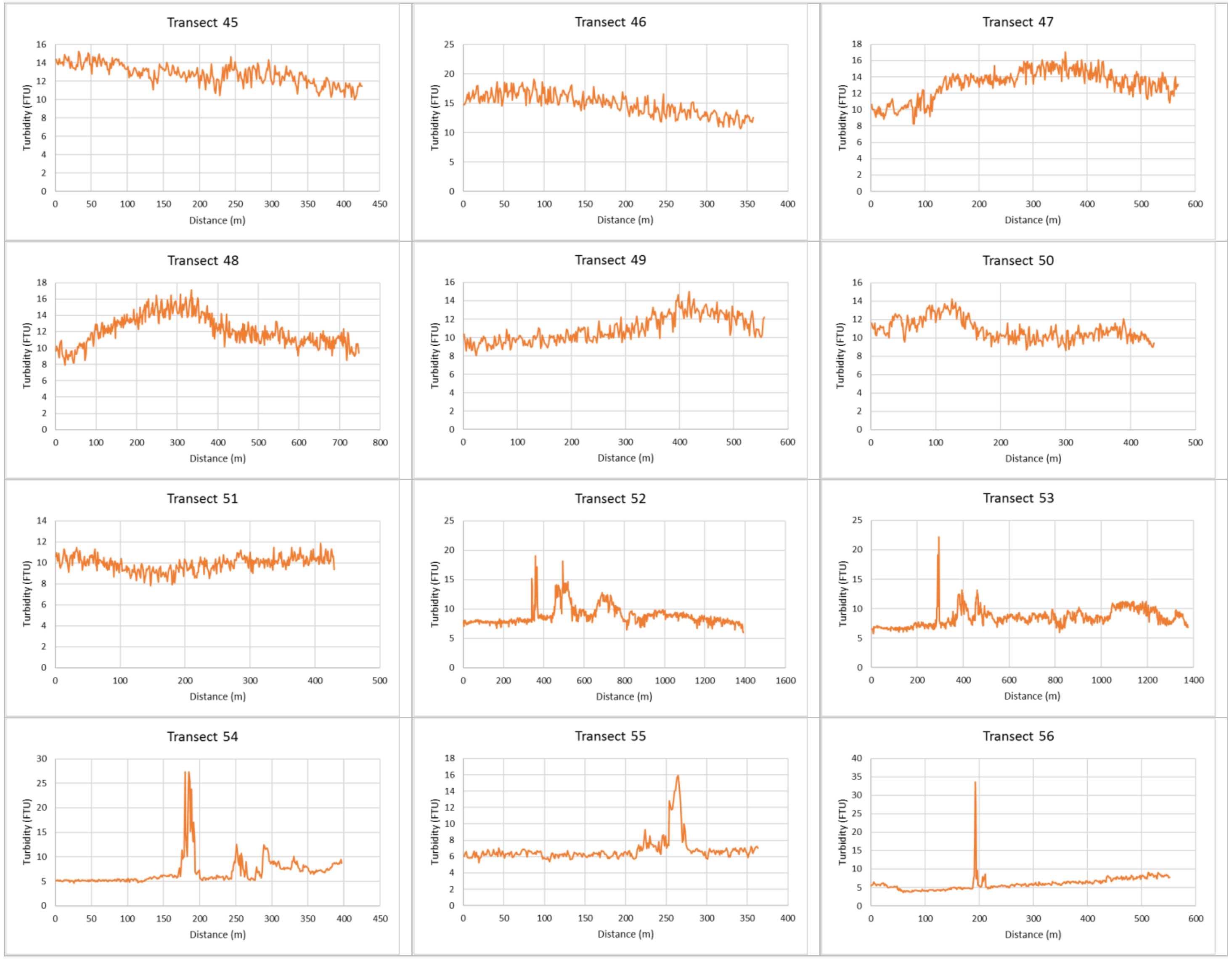
Distance (m)

Inschot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Transect 46
Transect 47
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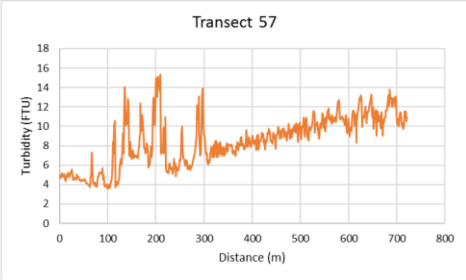
Transect 51
Transect 52
Transect 53
Transect 54
Transect 55
Transect 56
Turbidity (FTU)
Distance (m)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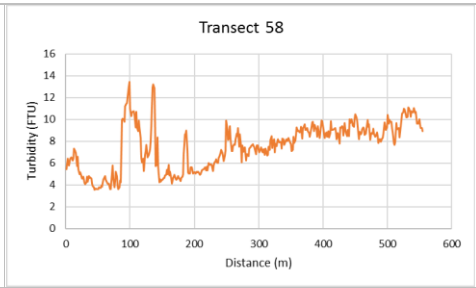
Distance (m)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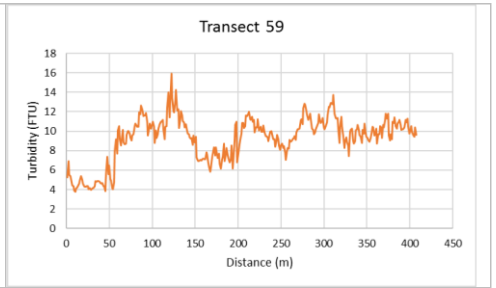
Distance (m)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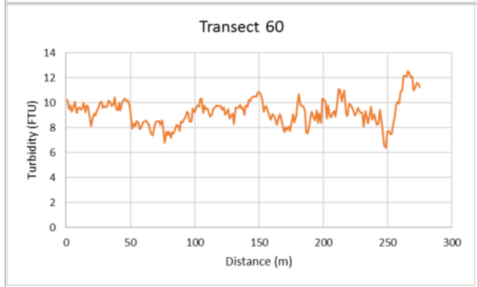
Turbidity (FTU)
Distance (m)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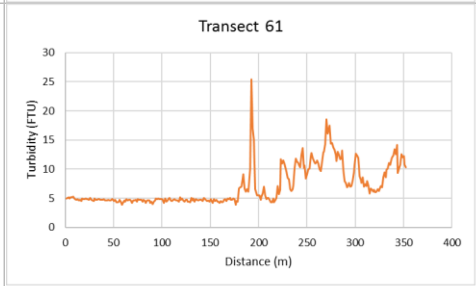
Turbidity (FTU)
Distance (m)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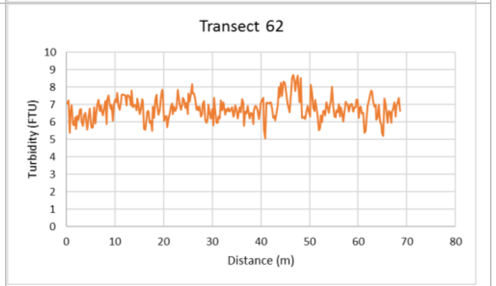
Turbidity (FTU)
Distance (m)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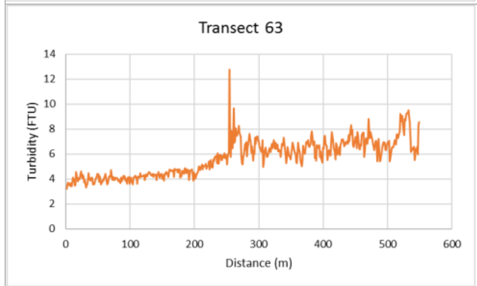
Turbidity (FTU)
Distance (m)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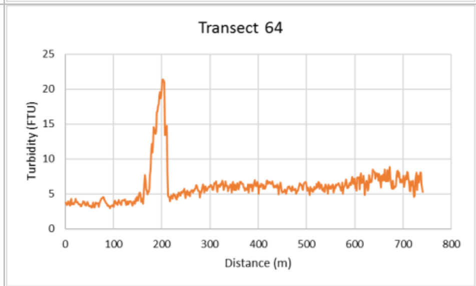
Turbidity (FTU)
Distance (m)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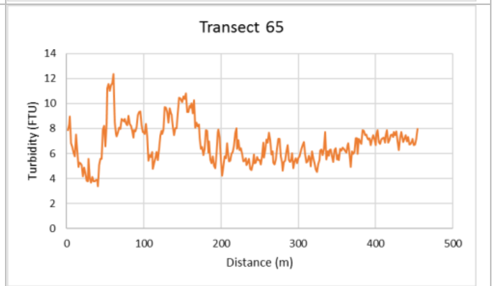
Distance (m)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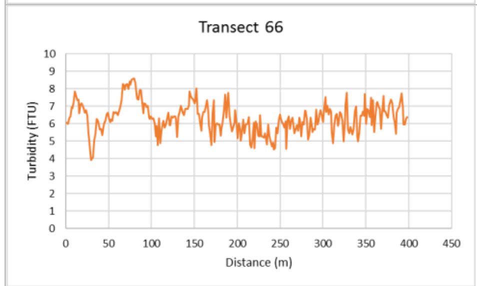
Turbidity (FTU)
Distance (m)


Transect 66
Turbidity (FTU)
Distance (m)

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The Wageningen Marine Research vision
'To explore the potential of marine nature to improve the quality of life'

The Wageningen Marine Research mission

- To conduct research with the aim of acquiring knowledge and offering advice on the sustainable management and use of marine and coastal areas.
- Wageningen Marine Research is an independent, leading scientific research institute

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