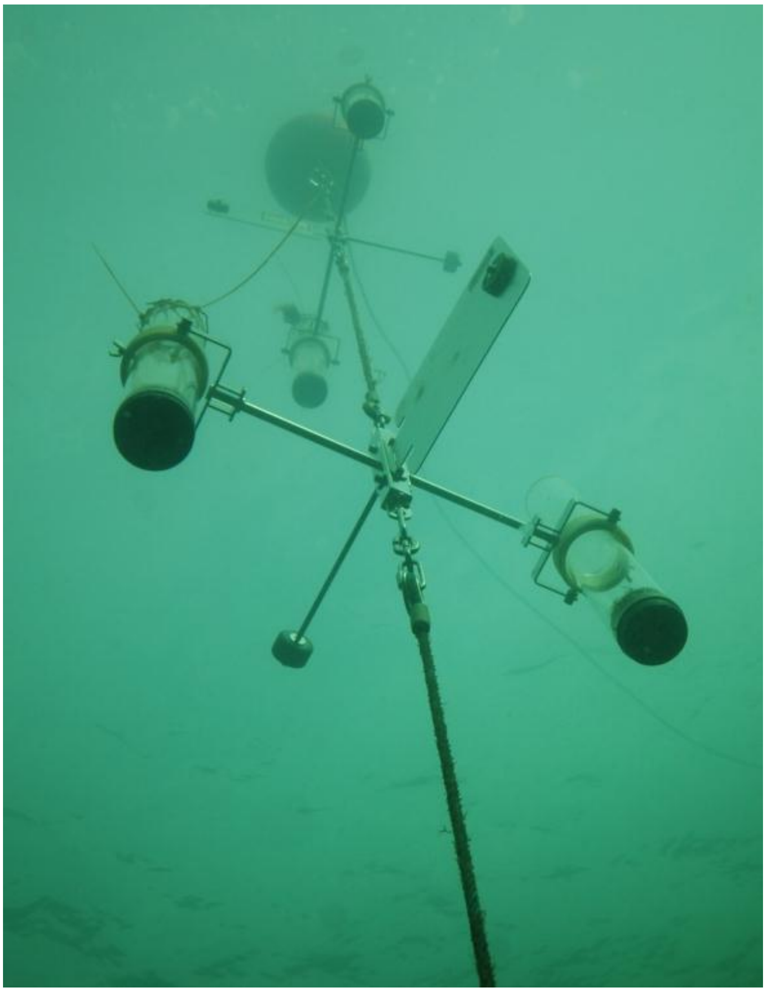
Final Report

Fehmarnbelt Fixed Link Hydrographic Services (FEHY)

Marine Water - Baseline

Suspended Sediment

E1TR0057 Volume III



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Note to the reader:
In this report the time for start of construction is artificially set to 1 October 2014 for the tunnel and 1 January 2015 for the bridge alternative. In the Danish EIA (VVM) and the German EIA (UVS/LBP) absolute year references are not used. Instead the time references are relative to start of construction works. In the VVM the same time reference is used for tunnel and bridge, i.e. year 0 corresponds to 2014/start of tunnel construction; year 1 corresponds to 2015/start of bridge construction etc. In the UVS/LBP individual time references are used for tunnel and bridge, i.e. for tunnel construction year 1 is equivalent to 2014 (construction starts 1 October in year 1) and for bridge construction year 1 is equivalent to 2015 (construction starts 1st January).

GLOSSARY/ABBREVIATIONS

NTU	Nephelometric Turbidity Units
SSC	Suspended Sediment Concentration [mg/l] (Total concentration including organic content)
MERIS	Medium Resolution Imaging Spectrometer
Exchange	Term used for the time period where a given instrument is located at a specific position
Count	Term used about the number of scatters counted by the NTU device during measuring
d_{50}	Median grain diameter
CTD	Instrument measuring Conductivity, Temperature, and Depth
WQM	Water Quality Monitor (Brand of instrument manufactured by WET Labs)
GSM	Global System for Mobile Communication
GPRS	Global Package Radio Service
SBE44	Underwater Inductive Modem
ADCP	Acoustic Doppler Current Profiler (Brand of Acoustic current profiler manufactured by RD Instruments)

1 EXTENDED SUMMARY

This report includes:

- Presentation of data collected with the purpose of quantifying the natural turbidity levels and thereby the levels of suspended sediment concentrations in the Fehmarnbelt

- An overview of related relevant data such as bed sediments and hydrographic conditions (waves and currents)

- Statistical analysis of the suspended sediment concentrations (SSC)

- Considerations regarding correlations between hydrographic conditions and suspended sediment concentrations

The report covers data collected from the initiation of the survey programme in February 2009 until the end of May 2011. Major parts of the programmes were suspended in February 2010 due to risks of ice. The survey programmes continued in March/April 2010 and most of the surveys ended in May 2011.

Turbidity measurements have been undertaken both as continuous time series in fixed stations, as profile measurements during monthly cruises and remotely from satellites. The fixed stations comprise three so-called main stations, MS01, MS02 and MS03 and 10 nearshore stations, NS01-NS10. At the main stations, the turbidity is measured at three levels, whereas the measurements are made at one level at each of the nearshore stations. Figure 1.1 and Figure 1.2 show the locations of the fixed stations and the stations visited during the cruises, respectively. The stations NS01–NS03 located in Danish waters were moved to more shallow locations in November 2010. German nearshore stations NS06–NS08 were moved in January 2011. The measurements made after this relocation are denoted with the letter "a" following the name (NS01a, etc.).

The turbidity measurements from the fixed stations and the profile measurements during the cruises have been converted into suspended sediment concentrations. The correlation between turbidity and suspended sediment concentrations is not trivial. It varies with a number of parameters including grain size distribution, sediment colour and organic content of the suspended matter. Comprehensive tests have been made in the laboratory to determine the relationship for the relevant types of material. Water samples have been collected at the fixed stations and analysed for suspended matter to calibrate the turbidity measurements in situ. The conclusion regarding the relation between measured turbidity in Nephelometric Turbidity Units (NTU) and Suspended Sediment Concentration (SSC) in mg/l shows a linear relation with factors of 1.9 and 3.4 for the main stations and the original positions of the nearshore stations, respectively (SSC = *factor* × NTU). The variation in the factor reflects the difference in material: the coarser the material the larger the factor. The uncertainty on the suspended sediment concentrations derived from the turbidity measurements is estimated at ±50%. At the relocated nearshore stations NS01a–NS03a and NS06a–NS08a, the relation between suspended sediment concentrations and measured NTU was found to be better described by a non-linear relation: $SSC = 2.0 \times NTU^{1.3}$, which captures large ranges of suspended sediment and grain size distributions. The applied relations between SSC and NTU for stations at different water depths are given in Table 1.1.

Table 1.1 Applied relations between SSC and NTU for stations at different water depths

Water depth	Relation between NTU and SSC	Stations
0m – 5m (except Rødsand)	SSC = 1.9849 x NTU$^{1.2575}$	NS01a, NS02a, NS03a, NS06a, NS07a, NS08a
5m – 10m (and Rødsand Lagoon)	SSC = 3.4 x NTU	NS01 – NS10
Above 10m	SSC = 1.9 x NTU	MS01 – MS03

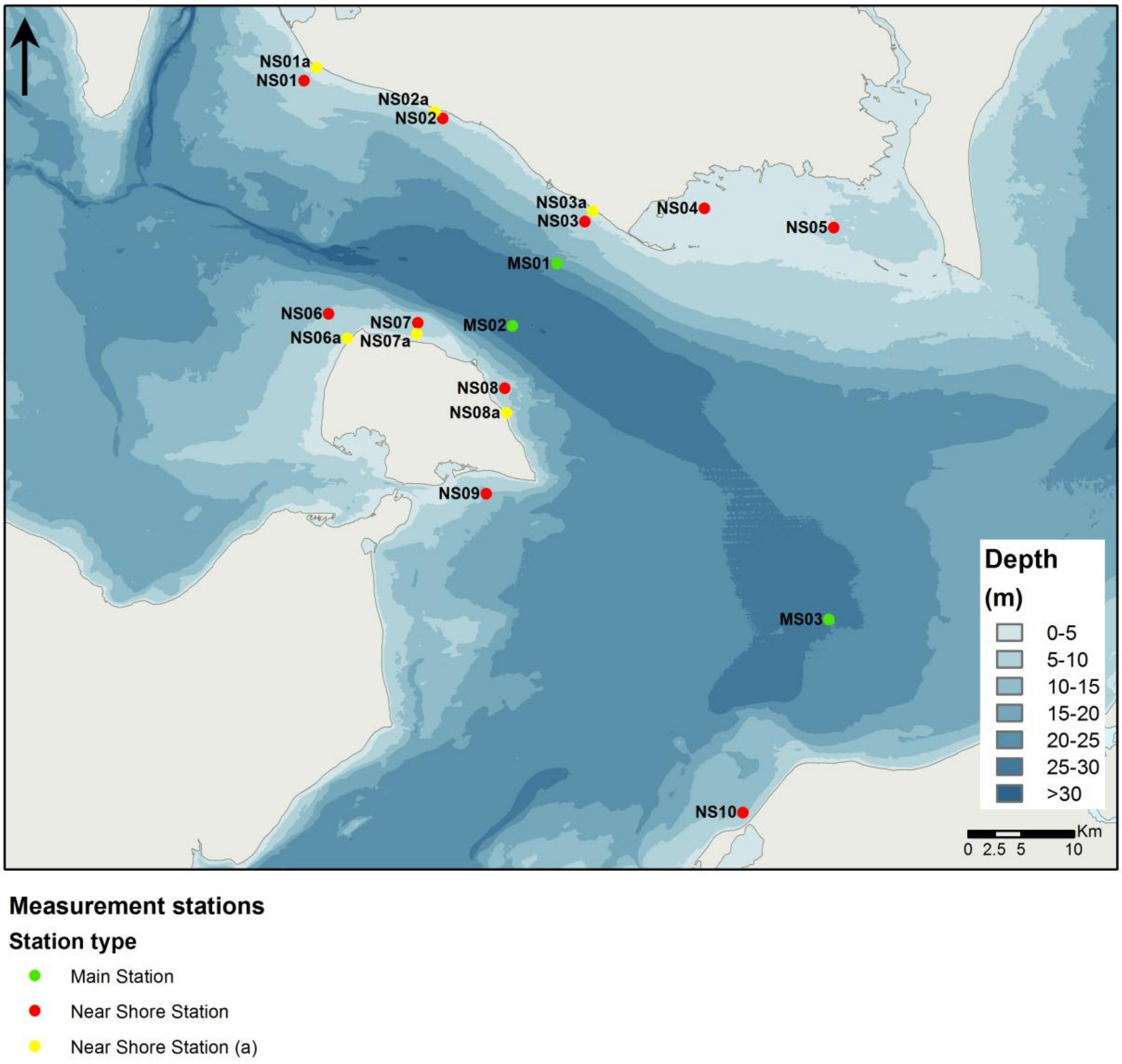


Figure 1.1 Fixed measurement stations from the Fehmarnbelt Fixed Link monitoring programme February 2009 to May 2011

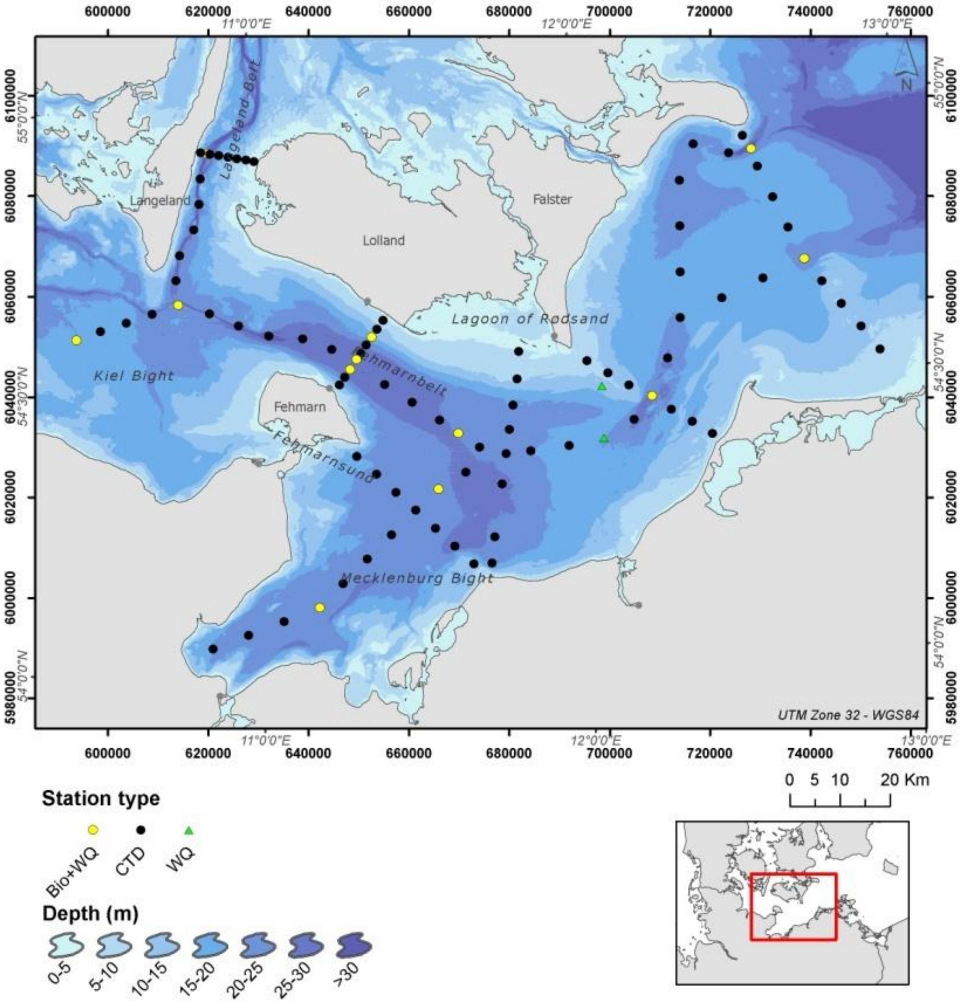


Figure 1.2 Stations visited during monthly cruises of the Fehmarnbelt Fixed Link monitoring programme February 2009-December 2010. Turbidity profiles are measured at all stations

The 50% and 95% percentiles of the suspended sediment concentrations (the concentrations exceeded 50% and 5% of the time, respectively) at the fixed stations are presented in Figure 1.3. It appears that the concentrations reach high levels with 95% percentiles larger than 30mg/l to 330mg/l for water depths smaller than 3-5m along the open coasts and decrease rapidly with increasing water depths.

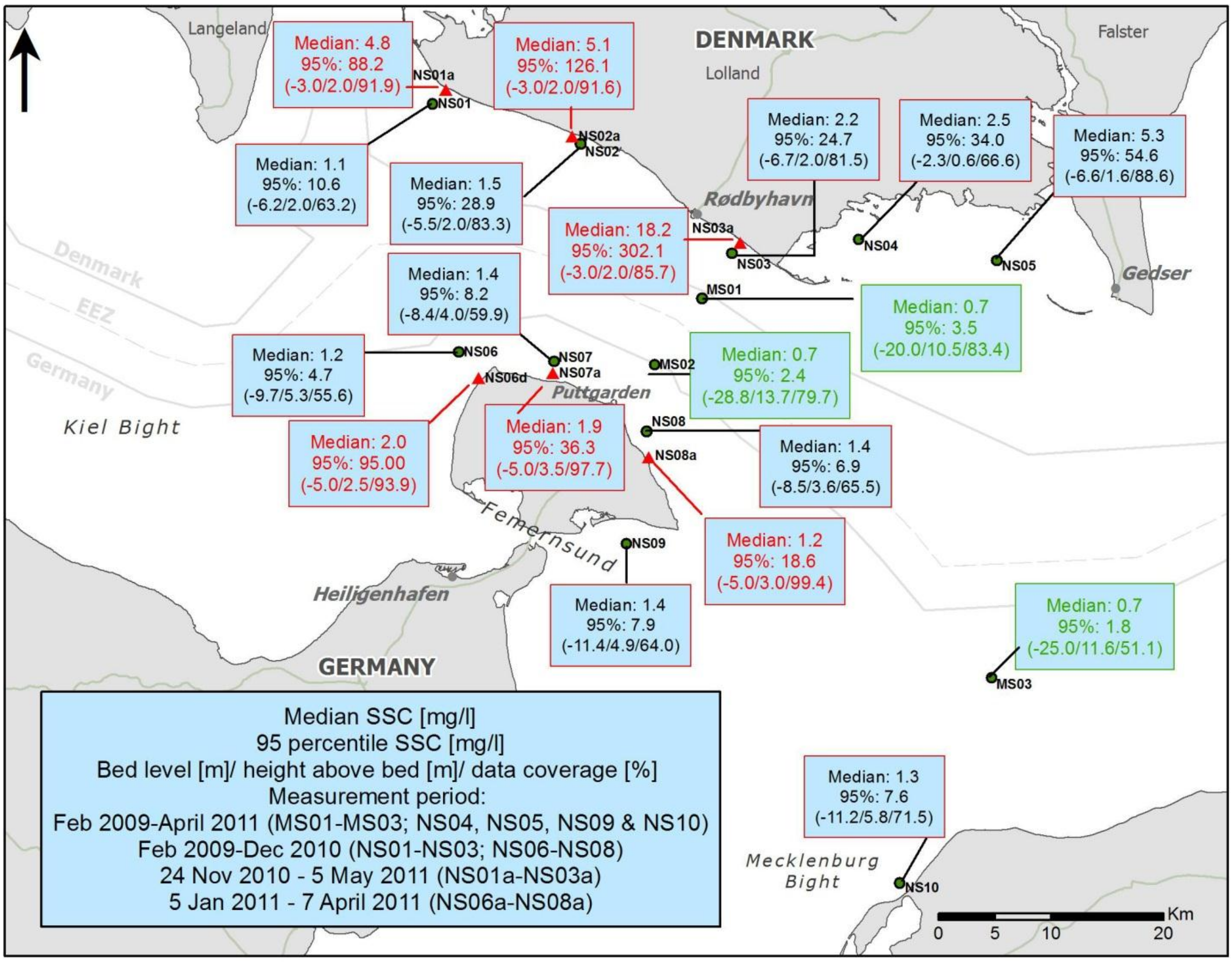


Figure 1.3 *Overall statistics for the suspended sediment concentration at the nearshore stations and the main stations. 'Median' is the value which is exceeded in 50% of the observations. The values presented at the main stations are from the mid water measurements*

The seasonal variation of the suspended sediment concentrations is shown for the nearshore stations in Table 1.2 and Table 1.3. The suspended concentrations are seen to be higher in autumn and winter than in spring and summer at all stations. For the shallow water stations, spring and winter periods reach the highest levels.

Table 1.2 *Seasonal statistics of suspended sediment concentration for the nearshore stations*

	NS01	NS02	NS03	NS04	NS05	NS06	NS07	NS08	NS09	NS10
	Spring 2009/2010/2011: March, April and May									
Median SSC [mg/l]	**0.8**	**1.1**	**1.8**	**2.6**	**3.9**	**1**	**1.1**	**1**	**1.2**	**1.2**
95% SSC [mg/l]	**2.3**	**4.5**	**13.2**	**24.2**	**28.8**	**2.7**	**3.8**	**4.1**	**3.8**	**3.8**
	Summer 2009/2010: June, July and August									
Median SSC [mg/l]	**1.2**	**1.5**	**1.7**	**1.8**	**3.1**	**1**	**1.3**	**1.4**	**1.1**	**1.1**
95% SSC [mg/l]	**7.2**	**11.7**	**10**	**6.5**	**28.7**	**3.3**	**3.9**	**2.9**	**2.4**	**2.9**
	Autumn 2009/2010: September, October and November									
Median SSC [mg/l]	**2.8**	**2.3**	**2.9**	**4**	**8.4**	**1.5**	**1.7**	**1.8**	**1.5**	**1.4**
95% SSC [mg/l]	**28.4**	**46.4**	**22.8**	**58.4**	**67.3**	**5.9**	**10.7**	**14**	**6.6**	**7**
	Winter 2009/2010: December and 2010/2011: January and February									
Median SSC [mg/l]	**1.5**	**4**	**6.8**	**6.1**	**14.1**	**1.8**	**2.5**	**2.2**	**2.6**	**2.1**
95% SSC [mg/l]	**13.1**	**46.8**	**76.1**	**40.8**	**85.4**	**7.4**	**17.4**	**11.9**	**18.3**	**13**

Table 1.3 *Seasonal statistics of suspended sediment concentration for the nearshore stations in shallow waters. Note that measurements at these locations are available from the period November 2010 to April 2011*

	NS01a	NS02a	NS03a	NS06d	NS07a	NS08a
	Spring 2011: March and April					
Median SSC [mg/l]	**3**	**2.6**	**7.9**	**3.1**	**2.6**	**1.4**
95% SSC [mg/l]	**36.8**	**39.3**	**171.3**	**63.6**	**30.5**	**6.2**
	Autumn 2010: November					
Median SSC [mg/l]	**2.7**	**1.0**	**11.6**	**-**	**-**	**-**
95% SSC [mg/l]	**103.1**	**13.7**	**158.9**	**-**	**-**	**-**
	Winter: December 2010 and January and February 2011					
Median SSC [mg/l]	**8**	**15.2**	**36.1**	**2.4**	**1.9**	**1.5**
95% SSC [mg/l]	**99**	**208.9**	**432.1**	**68.5**	**43**	**40.4**

The concentration levels found from the measurements at the fixed stations are confirmed both by the measurements made during the monthly vessel-based surveys, water samples collected at NS03a and the analysis of satellite images.

One of the highest turbidity levels and thereby level of suspended sediment concentrations observed outside the nearshore zone during cruises as well as fixed stations appeared in January 2010. Figure 1.4 and Figure 1.5 show an overview of the average suspended sediment concentrations in the upper 5m and the lower 5m of the profiles measured during the January 2010 cruise. The upper 5m was chosen in order to evaluate the visible part of the water column and to compare with satellite images. As a general observation, the turbidity profiles showed only small variations over the water column. Only few observations showed a significant increase towards the bed. A north-easterly storm with wind speeds up to 14m/s occurred during the three days prior to the cruise. During the cruise, the wind turned to east south-easterly directions and exceeded 10m/s. The current speeds are generally low below 0.3m/s at MS01 during the cruise. The increased turbidity level is caused by the waves generated by the strong wind prior to and during the cruise, which re-suspends sediment from the nearshore zones.

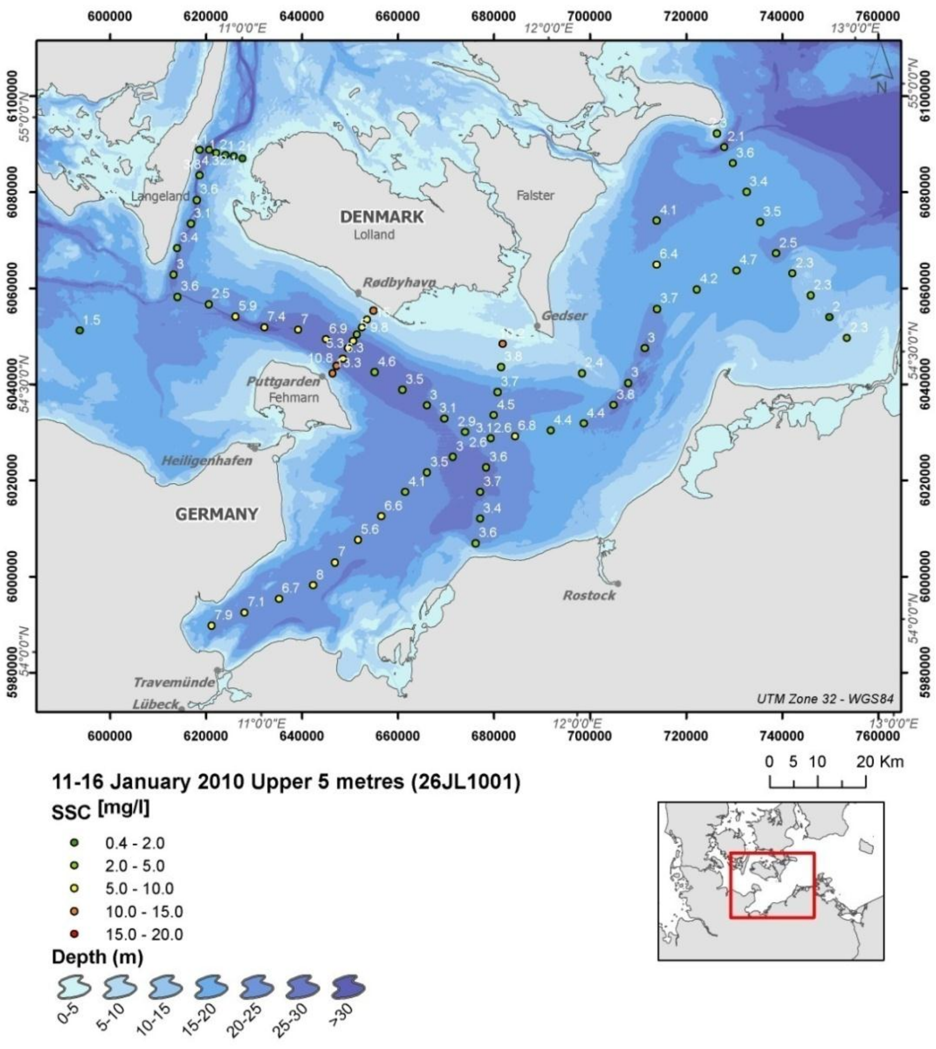


Figure 1.4 *Example of spatial distribution of suspended sediment concentrations derived from turbidity profile measurements during the cruise 11-16 January 2010. Concentrations averaged over the upper five metres of each profile*

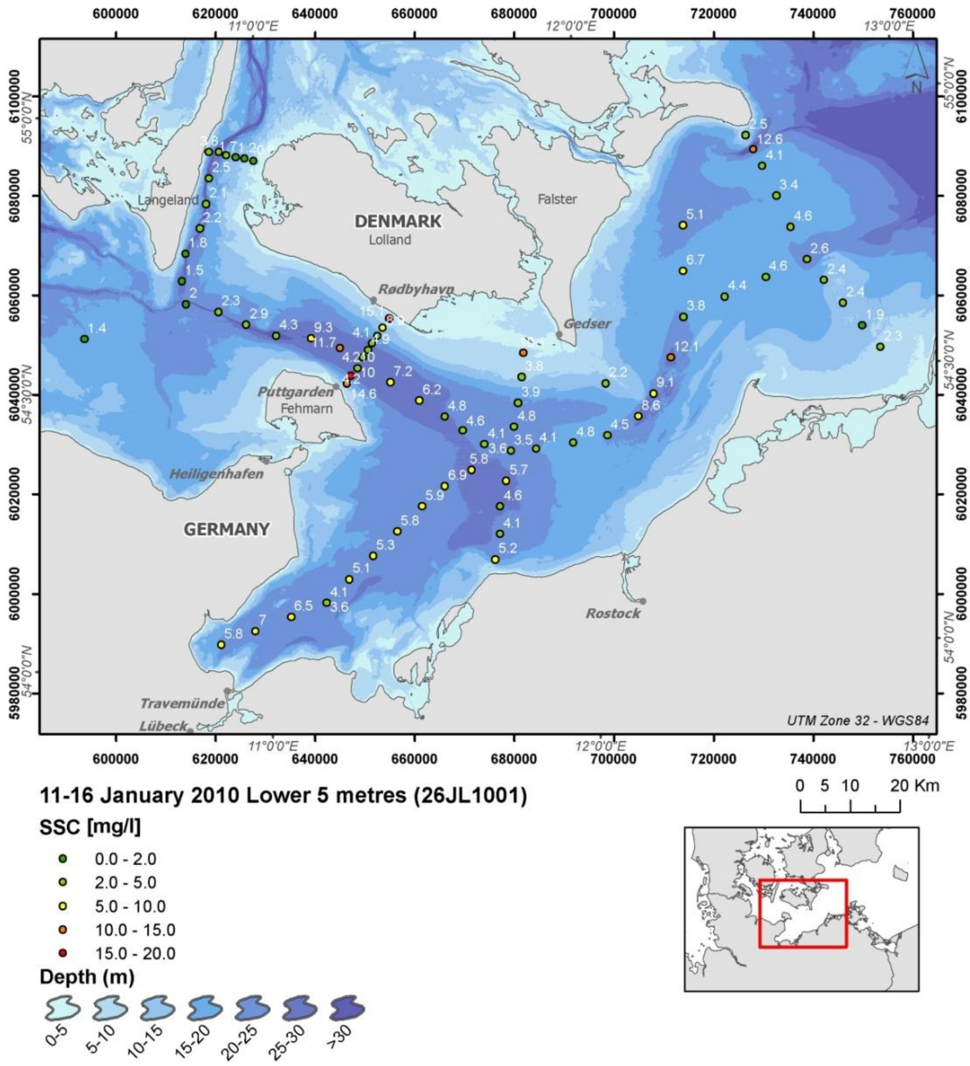


Figure 1.5 *Example of spatial distribution of suspended sediment concentrations derived from turbidity profile measurements during the cruise 11-16 January 2010. Concentrations averaged over the lower five metres of each profile*

Analysis of hydrographic conditions and suspended sediment concentrations has revealed that a fixed correlation between various hydrographic parameters and the level of suspended sediment concentrations does not exist. The level of suspended concentrations along the Danish coast and inside the Lagoon of Rødsand can be correlated to the wind speed and direction, i.e. the waves. However, situations with identical wind conditions have been identified where the level of concentrations is not the same at the same position. This is probably due to limited availability of fine sediments. The measurements indicate an approximate threshold wind speed of 8m/s before significant increase in concentrations takes place at the Danish nearshore stations at water depths around 6m. The threshold is derived based on visual inspections of wind and concentration measurements.

The dependency of suspended concentrations on the wind (or wave conditions) is illustrated by statistical analysis of wind and concentrations at the nearshore station NS03. Table 1.4 and Table 1.5 show the wind statistics and the frequency of exceedance of 10mg/l for NS03 at specific wind speed and directions. It appears that for higher wind speeds and wind from offshore directions, the frequency of occurrence of high concentrations comes closer to the frequency of occurrence of the specific wind condition.

Table 1.4 Wind statistics for the period 1/2-2009 – 24/11-2010. Wind speed is in m/s, wind direction in degrees

Wind stat					
Wind dir/Wind speed	**0-5**	**5-10**	**10-15**	**15-20**	**Sum**
0-30	2.2%	3.7%	0.4%	0.0%	6.2%
30-60	2.0%	2.4%	0.7%	0.0%	5.1%
60-90	1.9%	3.7%	1.2%	0.1%	6.9%
90-120	2.9%	5.7%	1.1%	0.0%	9.7%
120-150	3.0%	5.2%	0.9%	0.0%	9.2%
150-180	2.4%	3.6%	0.2%	0.0%	6.2%
180-210	2.1%	4.3%	0.7%	0.0%	7.2%
210-240	2.2%	5.3%	2.1%	0.1%	9.7%
240-270	2.7%	7.0%	2.0%	0.1%	11.8%
270-300	4.0%	8.4%	2.8%	0.1%	15.4%
300-330	3.0%	3.9%	0.8%	0.0%	7.6%
330-360	2.3%	2.5%	0.1%	0.0%	4.9%
Sum	30.7%	55.8%	13.0%	0.5%	100.0%

Table 1.5 Wind statistics 1/2-2009 – 24/11-2010 and exceedance of 10mg/l at nearshore station NS03. Example: the SSC exceeds 10mg/l 23.0% of the time. Under conditions where the wind speed is between 10-15m/s and the wind direction is between 270-300 degrees, concentrations exceed 10mg/l 1.1% of the time

SSC >10mg/l					
Wind dir/Wind speed	**0-5**	**5-10**	**10-15**	**15-20**	**% > 10 mg/l**
0-30	0.3%	0.6%	0.3%	0.0%	1.2%
30-60	0.3%	0.6%	0.6%	0.0%	1.5%
60-90	0.2%	0.8%	1.0%	0.1%	2.1%
90-120	0.2%	1.4%	1.0%	0.0%	2.6%
120-150	0.4%	0.7%	0.7%	0.0%	1.8%
150-180	0.2%	0.5%	0.1%	0.0%	0.8%
180-210	0.3%	1.0%	0.3%	0.0%	1.5%
210-240	0.2%	1.9%	1.6%	0.2%	4.0%
240-270	0.2%	1.5%	1.1%	0.1%	2.9%
270-300	0.3%	0.8%	1.1%	0.1%	2.3%
300-330	0.3%	0.7%	0.3%	0.0%	1.3%
330-360	0.2%	0.5%	0.2%	0.0%	0.9%
% > 10 mg/l	3.2%	11.1%	8.2%	0.5%	23.0%

The suspended sediment concentrations in deeper water, at the main stations, and at the nearshore stations along the German coast seem determined by the current conditions. The flow patterns can be very complex with upwelling and downwelling. Sediment can thus be re-suspended at one location and transported to other locations. Therefore, it is also difficult to relate the monitored sediment concentration to any hydrodynamic or meteorological situation. Mapping of the bed sediments in the Fehmarnbelt has revealed that there is a large variation in the bed composition. In large areas, the seabed is hard and there is a scarcity of loose fine sediments. The variations in the suspended sediment concentrations are therefore determined by the hydrographic conditions as well as the availability of easily erodible fines.

2 INTRODUCTION

This report includes presentation and analysis of data collected to determine the baseline conditions for suspended sediment in the Fehmarnbelt. The report includes data measured in the Fehmarnbelt since the commencement of the survey programme from February 2009 to May 2011.

In the present context, suspended sediment concentration (SSC) is defined as the ratio of the mass of dry sediment in a water-sediment mixture to the mass of the water-sediment mixture. SSC is typically expressed in milligrams of dry sediment per litre of water-sediment mixture.

The objectives of the baseline investigations are as follows:

- Gather general information on seasonal-varying background SSC
- Gather information on local variations in SSC levels both nearshore and offshore
- Attempt to establish correlations between local variations in SSC and known local physical or biological phenomena
- Provide enough information on background concentration levels to allow for comparisons between background SSC and SSC originating from dredging operations

Section 3 presents the relevant data collected in the Fehmarnbelt. Section 5 describes how the measured turbidity data are translated into suspended sediment concentrations. In Section 6, the correlations between hydrographic conditions and suspended sediment concentrations are discussed. Finally, Section 7 gives an overview of the statistical variation of suspended concentrations. Section 1 includes a summary of the most important findings.

3 DATA BASIS AND METHODS

The data used for the quantification of suspended sediment concentrations are collected under a number of sub-projects under the Fehmarnbelt environmental programme:

- Fixed offshore and nearshore stations
- Monthly hydrographic vessel-based surveys
- Nearshore surveys
- Marine fauna. 1st year baseline

Sections 3.1 to 3.7 present the survey programmes from which data have been further analysed in this project.

3.1 Survey Programme, Fixed Stations

3.1.1 Measurement Set-up, Period of Data

An intensive monitoring programme based on fixed stations has been established in the Fehmarnbelt. The system consists of three main stations monitoring a range of parameters and ten nearshore stations monitoring turbidity. Six of the ten nearshore stations have been deployed at two different positions. The locations of the fixed stations are shown in Figure 3.1.

Main Stations

Main stations MS01 and MS02 are located in the anticipated link corridor about 6km from the coasts on both sides. MS03 is located in the Mecklenburger Bight 14km from the German coast. All main stations are equipped in the same way with only a slight difference in number of sensors due to different water depths. The stations provide online data, utilising a processor that collects data from all sensors every 10 minutes (waves every hour). Every hour, six data sets are transmitted to an ftp-server on land. Data are immediately run through an automatic QA filter and transmitted to a central database for download to end-users.

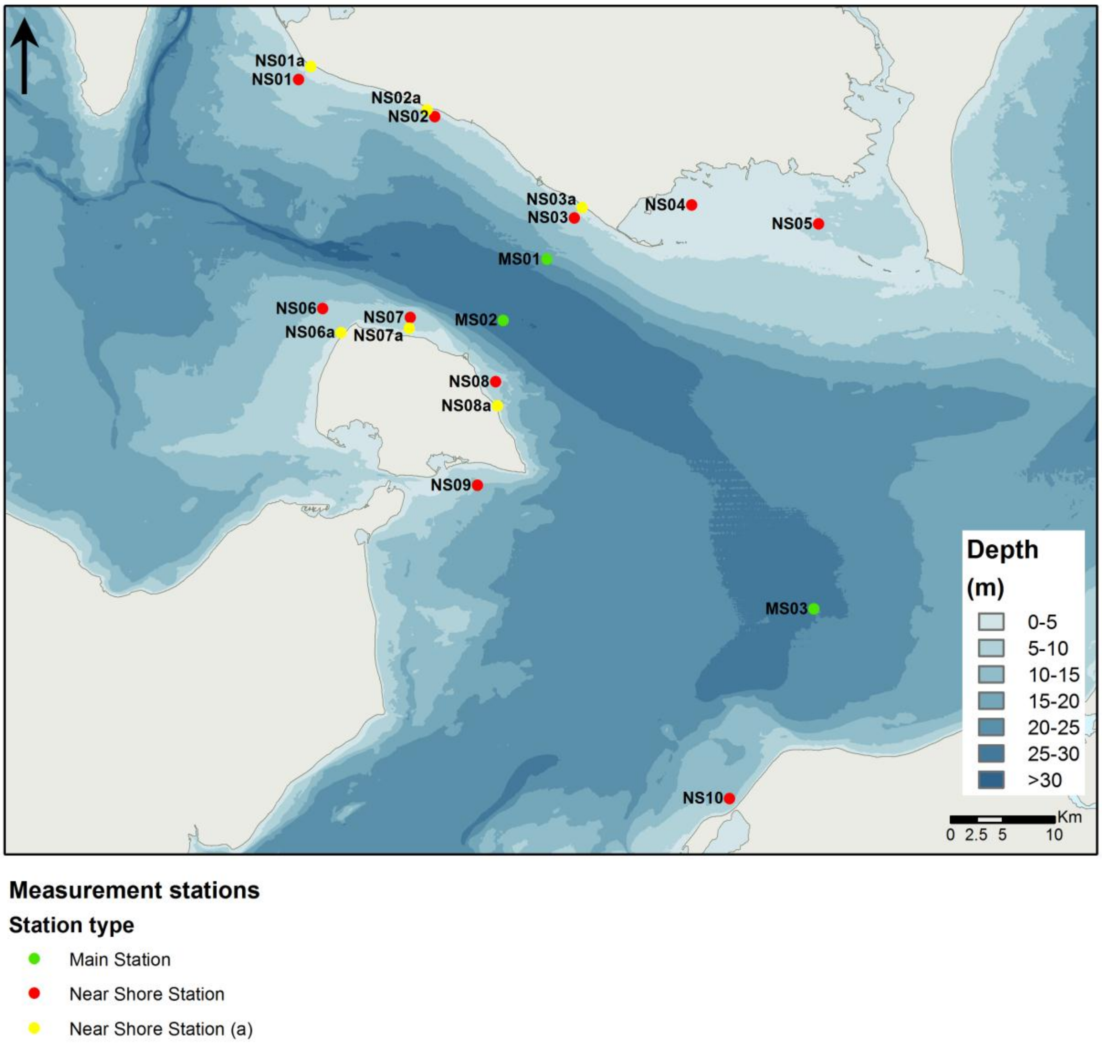


Figure 3.1 Overview of fixed stations in the Fehmarnbelt monitoring programme

The stations monitor the following parameters:

- Current profile with data every 75cm
- Wave parameters
- Salinity and temperature every 2m
- Environmental parameters: dissolved oxygen, fluorescence and turbidity. Measured near the bed, at mid water, and near the surface

Turbidity is monitored with the WQM instruments manufactured by WET Labs (WET Labs ECO-FLNTU(RT)). The instruments have a chemical and mechanical anti biofouling system. The turbidity sensor is a traditional optical backscatter sensor (OBS) which measures the light backscatter. The raw data are converted to NTU and are later calibrated to SSC by use of water samples (see Section 5.2). The set-up of the main stations is presented in Figure 3.2.

The precise locations of the main stations are presented in Table 3.1.

Table 3.1 Locations of the main stations (UTM-32)

ID	UTM Easting (m)	UTM Northing (m)	Seabed (m) DRV90	**Surface** OBS instrument above seabed (m)	**Mid water** OBS instrument above seabed (m)	**Seabed** OBS instrument above seabed (m)
MS01	652231	6051219	-20.0	18.9	10.5	2.9
MS02	648039	6045345	-28.8	26.6	13.7	2.3
MS03	677943	6017566	-25.0	23.7	11.6	2.3

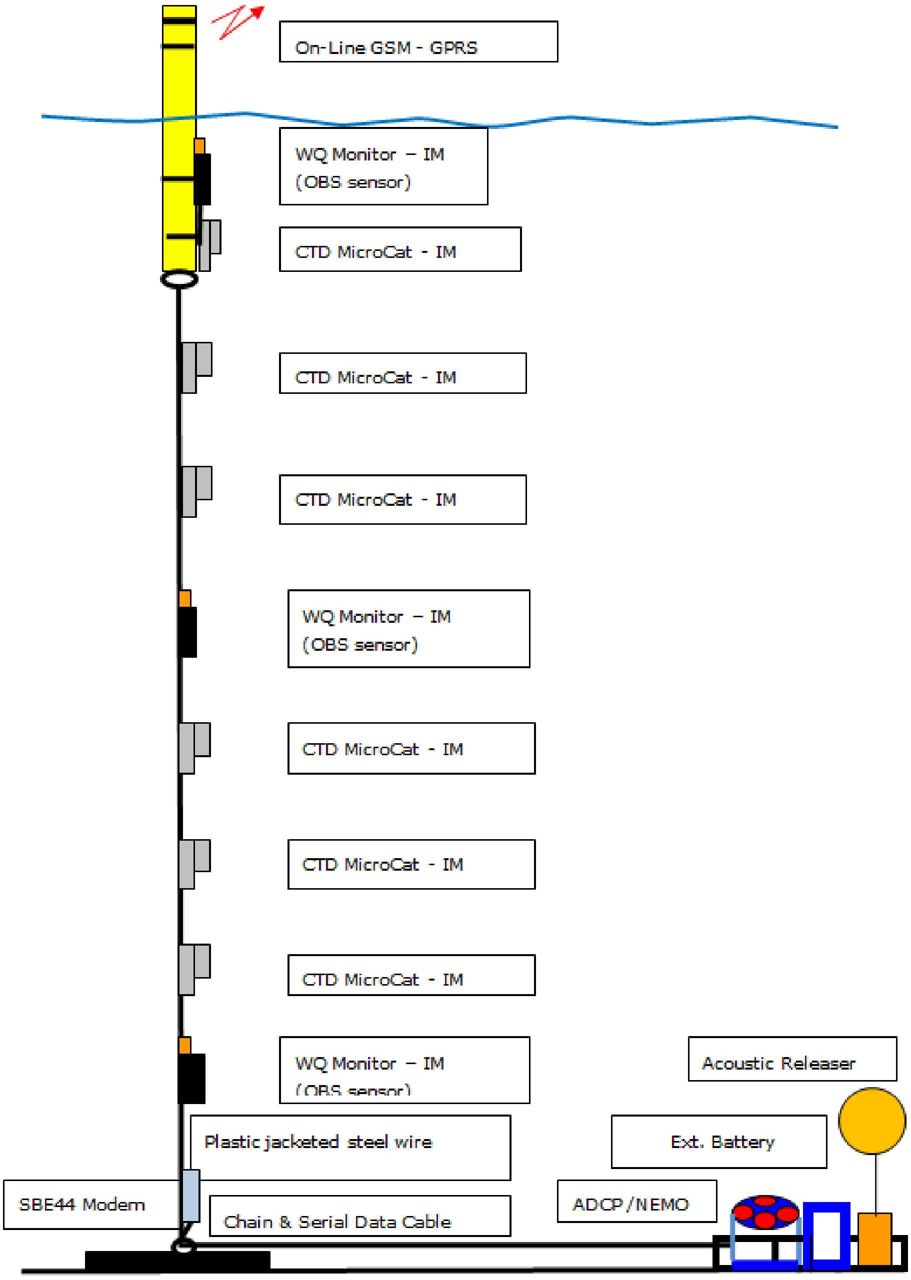


Figure 3.2 Sketch of the set-up at the main stations

Nearshore Stations

The nearshore stations are equipped with the OBSs manufactured by Wetlabs, in the following denoted NTUsb, "sb" for integrated anti-fouling bio-wiper and internal batteries for autonomous operation. The stations are located along the shores on both sides of the Belt and in the Lagoon of Rødsand at water depths between 3m and 12m. The technical set-up of the nearshore stations is presented in Figure 3.3. The stations are self-recording and are serviced every 30 days. Data from the sensors are subsequently transferred to the Data Handling Centre at DHI, where automatic and manual QA filtering and uploading to the central database are carried out. On Figure 3.4, a photo of an NTUsb sensor just before deployment is presented. The instruments are programmed to measure the NTU level every 10 minutes. This is done by measuring 8 times during a 16-second period every 10 minutes. The sensors are designed in order to minimise growth problems which are known to disturb turbidity measurements. The cylindrical instrument is measuring from a small window on the bottom of the cylinder. The area around this window is made entirely of copper on which no algae will grow. Further, the measurement window is covered by a so-called bio wiper which is only open during the 16 seconds of measurements. Thereby, the measurement window is kept clean. During the two-year period of measurements, the window has not appeared disturbed by microalgae. On a few instances, a leaf of macroalgae has been caught on the bio wiper itself.

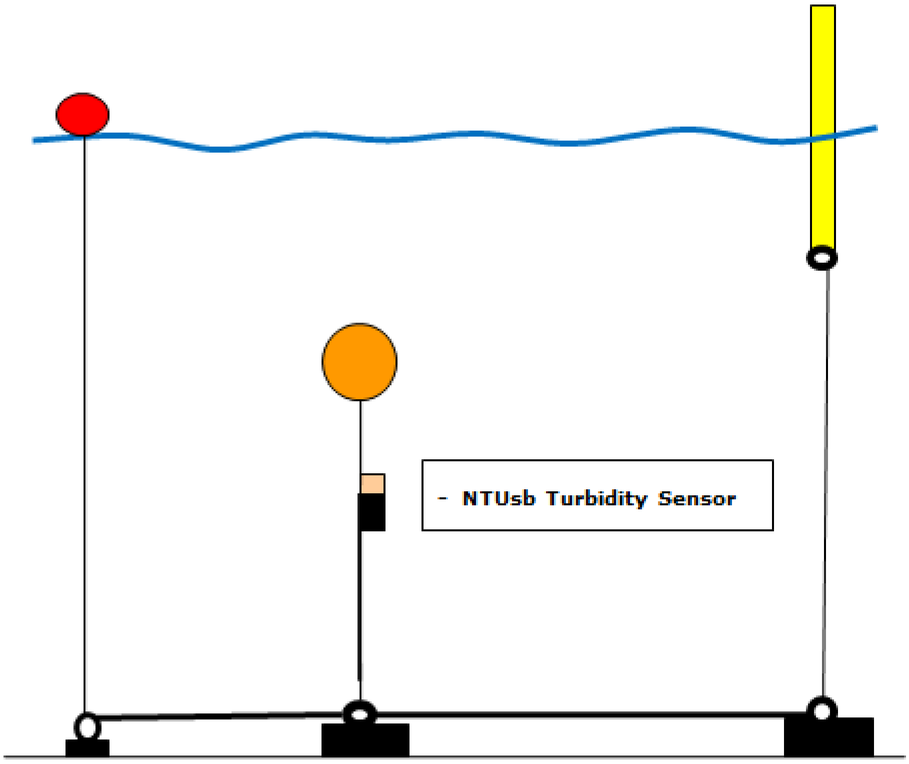


Figure 3.3 Sketch of the technical set-up of the nearshore stations

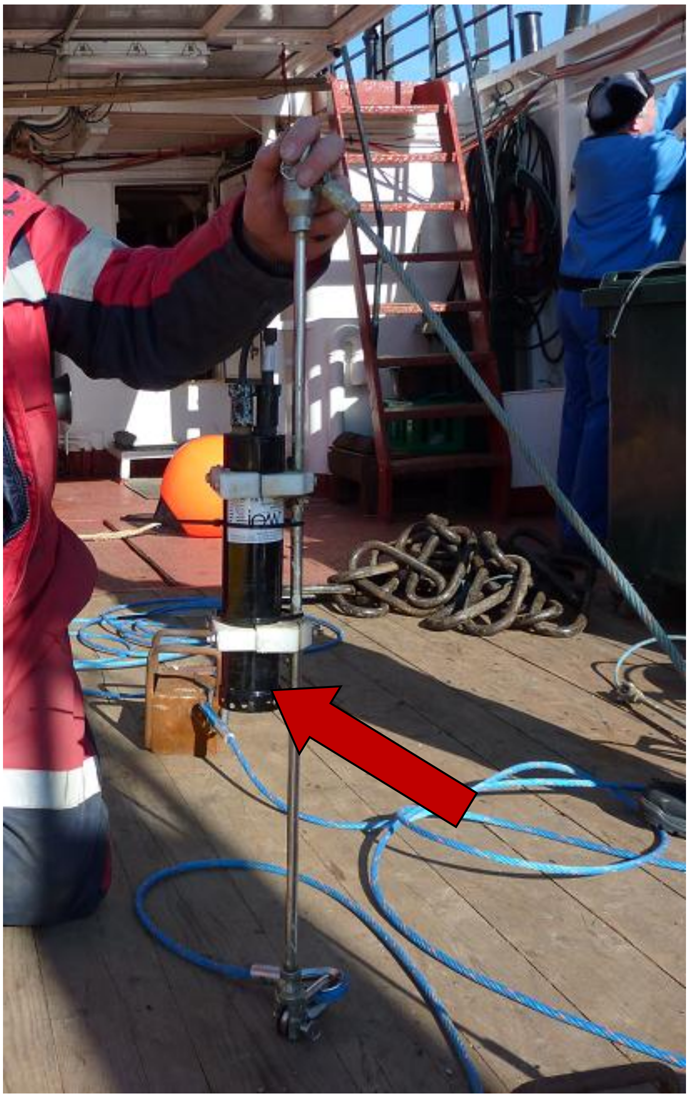


Figure 3.4 NTUsb instrument placed on its wire just before deployment of the instrument

The precise location of the nearshore stations is presented in Table 3.2. Six of the nearshore stations were re-deployed at lower water depths for the last 4 to 6 months of the 2-year measurement period. NS01-NS03 have been renamed as NS01a-NS03a and were moved on 24 November 2010. NS06-NS08 have been renamed as NS06a-NS08a and were moved on 12 January 2011.

Table 3.2 Locations, seabed level and height of instruments for the nearshore stations

ID	UTM Easting [m]	UTM Northing [m]	Seabed (m) DRV90	Instrument height above seabed (m)
NS01	628348	6068507	-6.2	2.0
NS01a	629533	6069758	-3.0	1.0
NS02	641454	6064951	-5.5	2.0
NS02a	640718	6065583	-3.0	1.0
NS03	654886	6055205	-6.7	2.0
NS03a	655643	6056183	-3.0	1.0
NS04	666176	6056440	-2.3	0.6
NS05	678415	6054612	-6.6	1.6
NS06	630653	6046483	-9.7	5.3
NS06a	632429	6044165	-5	2.5
NS07	639094	6045620	-8.4	4.0
NS07a	638996	6044587	-5	3.5
NS08	647324	6039420	-8.5	3.6
NS08a	647490	6037113	-5	3.0
NS09	645566	6029453	-11.4	4.9
NS10	669814	5999326	-11.2	5.8

a) Indicates the change of locations of the nearshore stations by end of the monitoring period.

3.1.2 *Data from Nearshore and Main Stations*

The dataset covers the period from 1 February 2009 to May 2011; however, from 19 January 2010 onwards until the month of February 2010, most of the field equipment for all nearshore stations was recovered due to risk of ice. The exchange dates, i.e. dates for service of instruments and retrieval of offline data for all the nearshore instruments, are presented in Appendix A.

The main stations have been serviced up to 7 times during the period; see the dates in Table 3.3.

Table 3.3 Service dates of the main stations

	MS01	MS02	MS03
Deployed at	7/3-2009	29/3-2009	30/3-2009
1. service	22-6-2009	9/7-2009	9/6-2009
2. service	9/12-2009	14/7-2009	15/12-2009
3. service	29/1-2010	24/10-2009	6/7-2010
4. service	28/4-2010	30/9-2010	23/11-2010
5. service	10/11-2010	19/1-2011	4/4-2011 (demobilised)
6. service	28/12-2010	30/05-2011	
7. service	14/6 2011		

An overview of the raw NTU data (average of 8 samples every 10 minutes) for the nearshore stations and the main stations is presented in Appendix B.

3.2 Data from the Cruise Programme

3.2.1 Measurement Set-up, Period of Data

Data collection cruises are performed to obtain a wider spatial coverage of hydrographic and biological data. The cruises are carried out on a monthly basis, and the sampling programme is planned for seven full days (24 hours) of cruising. After a successful first year, it was decided to reduce the programme to five days. The cruise coverage and location of the project stations are presented on Figure 3.5.

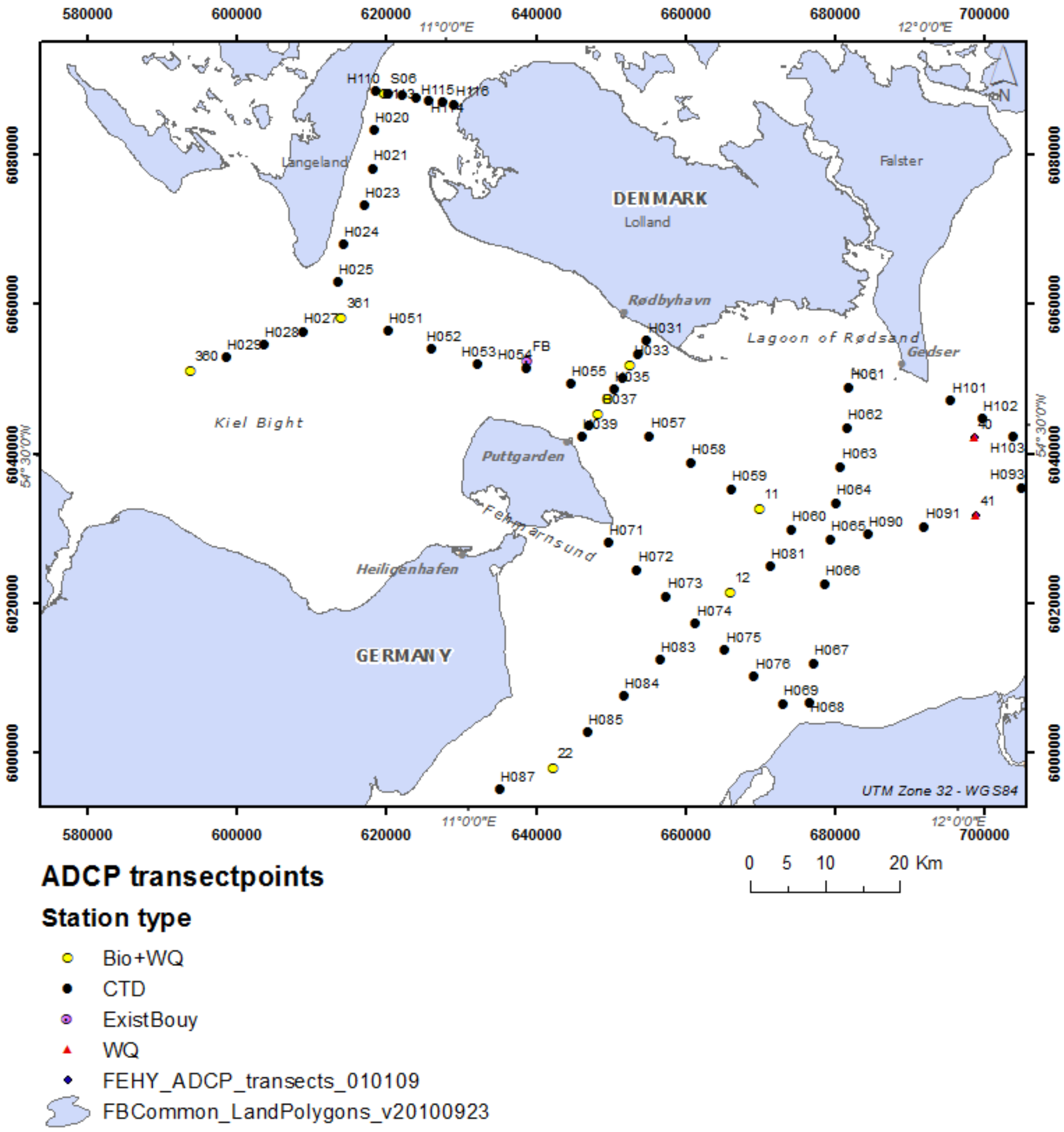


Figure 3.5 Cruise coverage and profile stations map

During each cruise, the measurements and samplings listed in Table 3.4 have been performed. An overview of the cruises is presented in Table 3.5.

Table 3.4 Overview of cruise measurements and samples

Measurement type	Comment
Continuous measurements of current velocity profile, depth and meteorological parameters	
Approximately 96 CTD stations	In situ profile measurements of temperature, salinity, dissolved oxygen, fluorescence, optical backscatter, photosynthetic active radiation (PAR)
14 "CTD-WQ" stations	In situ measurements of temperature, salinity, oxygen concentration, chlorophyll-*a* fluorescence, optical backscatter, and water sampling at 5-7m depths for nutrient analyses
12 Biological Stations (identical with 12 of the CTD-WQ stations)	Additional biological water analysis including primary production. Net sampling using WP2 net, phytoplankton net and towed multinet for jellyfish sampling

Table 3.5 Overview of cruises

Cruise ID	Start date	End date
26JL0901	26/02/2009	28/02/2009
26JL0902	23/03/2009	27/03/2009
26JL0903	27/04/2009	01/05/2009
26JL0904	28/06/2009	04/07/2009
26JL0905	27/07/2009	02/08/2009
26JL0906	24/08/2009	29/08/2009
26JL0907	28/09/2009	05/10/2009
26JL0908	27/10/2009	03/11/2009
26JL0909	30/11/2009	06/12/2009
26JL1001	11/01/2010	16/01/2010
26JL1002	16/02/2010	20/02/2010
26JL1003	08/03/2010	12/03/2010
26JL1004	12/04/2010	16/04/2010
26JL1005	17/05/2010	21/05/2010
26JL1006	14/06/2010	18/06/2010
26JL1007	19/07/2010	21/07/2010
26JL1008	16/08/2010	20/08/2010
26JL1009	13/09/2010	23/09/2010
26JL1010	11/10/2010	14/10/2010
26JL1011	15/11/2010	19/11/2010
26JL1012	13/12/2010	17/12/2010

Cruise ID: xxxxyyno: xxxx: Vessel ID, yy: year, no: cruise number

Results from selected OBS profile measurements are presented in this report.

In addition to the measurements from the above listed stations, water samples are collected for calibration of oxygen, salinity and turbidity sensors. The latter is made at MS01, MS02, and MS03 (see Section 3.1 for reference). Samplings are performed at three depths where the turbidity sensors are placed.

Water samples have also been taken at all nearshore stations during services. At the nearshore stations, the water samples are taken at the same depths as the turbidity sensors.

After sampling in 2L water bottles, the water samples are kept dark and cool and analysed at DHI laboratory facilities. The water samples are filtered, and the final concentration calculated. The sediment measurements from the three main stations and the ten nearshore stations are presented in the following.

3.2.2 Water Sample Data from the Fixed Measurement Stations

An overview of the samples taken at nearshore stations and main stations is given in Table 3.6. Due to safety issues, the majority of the nearshore surveys have been performed in conditions with wind speed below 8m/s. Therefore, only few water samples with high concentrations have been collected.

The sampling results are presented in Appendix E and F together with time series of SSC derived from the measured time series of NTU. Due to the very low sediment concentrations, it has not been possible to perform loss on ignition tests on the suspended material. A large number of bed samples are collected in connection with other Fehmarnbelt activities. Nearly all bed samples have revealed an organic content of 1-2%. Very few bed samples have higher organic content up to about 20%. No analysis of yellow substances or humic acids has been performed.

Table 3.6 Overview of water samples taken at nearshore stations and main stations during service visits

Station	Number of samples	Average concentration [mg/l]	Minimum concentration [mg/l]	Maximum concentration [mg/l]
NS01	22	5.34	0.61	37.8
NS01a	9	22.96	2.20	39.70
NS02	20	5.39	0.62	35.00
NS02a	9	27.14	1.20	57.80
NS03	20	5.39	0.77	36.90
NS03a	9	25.51	1.70	53.40
NS04	19	5.63	0.31	49.4
NS05	21	8.01	0.71	40.2
NS06	14	1.21	0.7	2.5
NS07	14	1.44	0.65	3.8
NS08	15	1.45	0.6	2.9
NS09	16	1.27	0.64	2.8
NS10	10	1.16	0.41	3.04
MS01 surface	8	1.08	0.53	2.18
MS01 mid water	9	1.34	0.53	2.82
MS01 seabed	8	1.94	0.64	5.48
MS02 surface	11	1.42	0.52	3.77
MS02 mid water	11	1.2	0.44	3.56
MS02 seabed	10	1.54	0.57	2.84
MS03 surface	2	2.26	0.95	3.57
MS03 mid water	8	1.33	0.51	4.03
MS03 seabed	2	1.17	1.01	1.33

3.3 Automatic Water Sampling at NS03a

After a period of 18 months at water depths of 6-10m, some of the Fehmarn nearshore stations (NS01-NS03 and NS06-NS08) were redeployed at more nearshore positions in order to capture anticipated higher suspended sediment concentrations during rough weather. The new deployment locations were labelled NS01a, NS02a, etc.

The relocated set-up included establishment of an automatic water sampler at NS03a, which could be operated remotely using SMS triggering. In this way, it was possible to extract water samples at any requested time also during rough weather where waves prevented water sampling from vessels.

Figure 3.6 View of the automatic water sampling station at NS03a

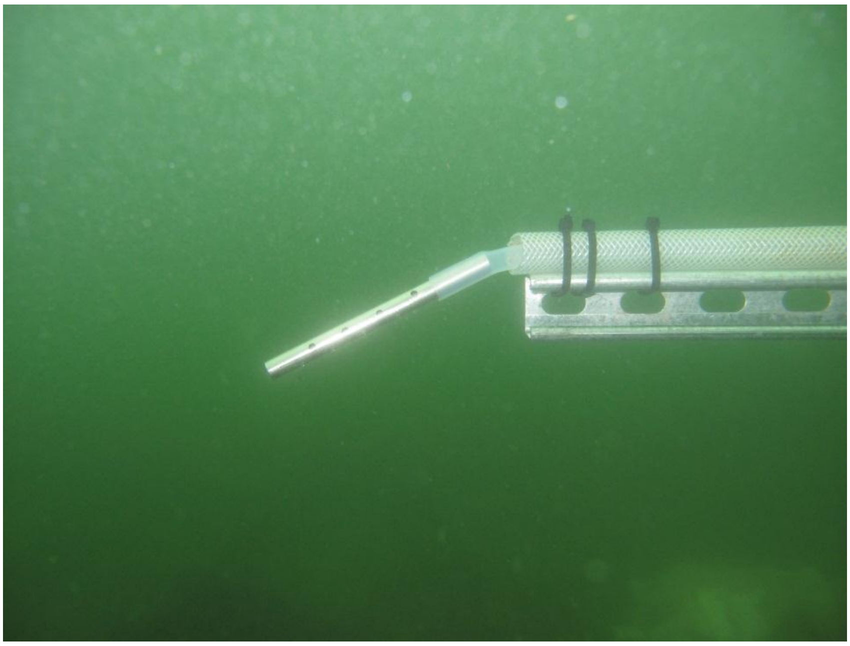


Figure 3.7 View of water intake for automatic water sampling. The intake is placed approximately 10m from the NTU instrument. Both NTU and water sampling intake is placed about 1m above the bed

The automatic water sampler was an ISCO type and included up to 24 1L water bottles. The water intake was located 1m above the seabed about 10m from the NTU (also located 1m above the seabed). The sampler was in action during three events with high wind speeds during the spring of 2011. After sampling, the ISCO was serviced at the earliest opportunity, and samples were analysed. The filtration was done so every other sample could subsequently be analysed for grain size distribution by laser diffraction, and the other samples could be analysed for organic content (loss on ignition).

The bed at the site is described as a coarse sandy bed widely covered with pebbles and shells as well as scattered beds of seaweed (Figure 3.8 and Figure 3.9).

Figure 3.8 Camera shot of the seabed at NS03a

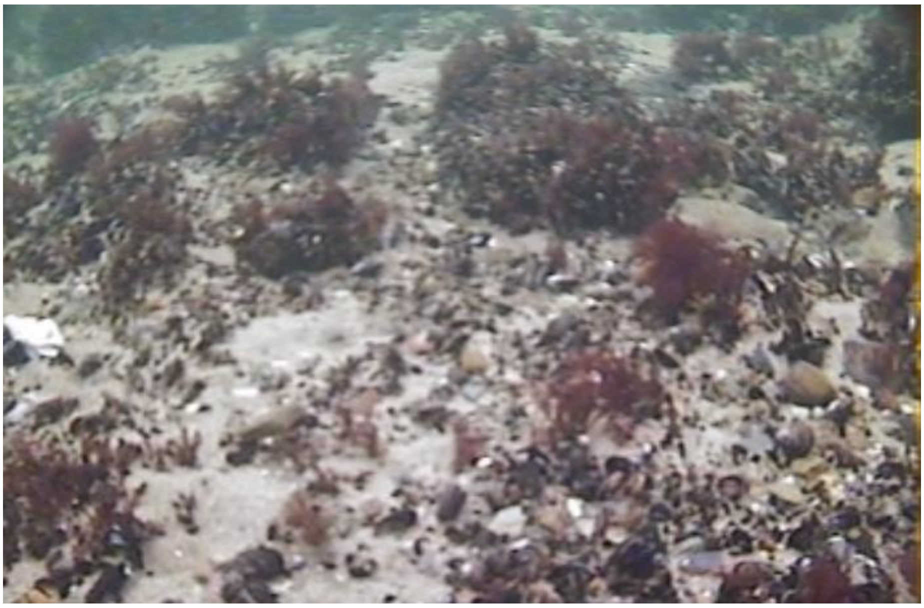


Figure 3.9 Camera shot of the seabed at NS03a

The first high turbidity level event was documented from 8 April 2011 00:00 to 9 April 2011 00:00. Water samples showed sediment concentrations in the range from 32 to 999mg/l. The sampler was located at 3m depth which under normal conditions is outside the breaker zone. On this specific event, it is, however, likely that breaking waves were present as the winds were very strong and the water level was about 0.5m below normal. The wave height (H_{m0}) at MS01 was measured as 2.2m.

Water samples were taken in three periods. Key parameters are listed in Table 3.7 with a full documentation including grain sizes and organic content given in Appendix M.

Table 3.7 Overview of sampling periods

Start of sampling	Number of samples	Interval	Wind direction	Max wind speed	Max concentration
08-04-11 00:00:00	23	1h	W - WNW	16m/s	999mg/l
12-04-11 09:00:00	18	1h	W - WNW	16m/s	548mg/l
28-04-11 12:00:00	23	4h	E - ENE	12m/s	28mg/l

The results of the automatic water samplings are presented in Figure 3.10.

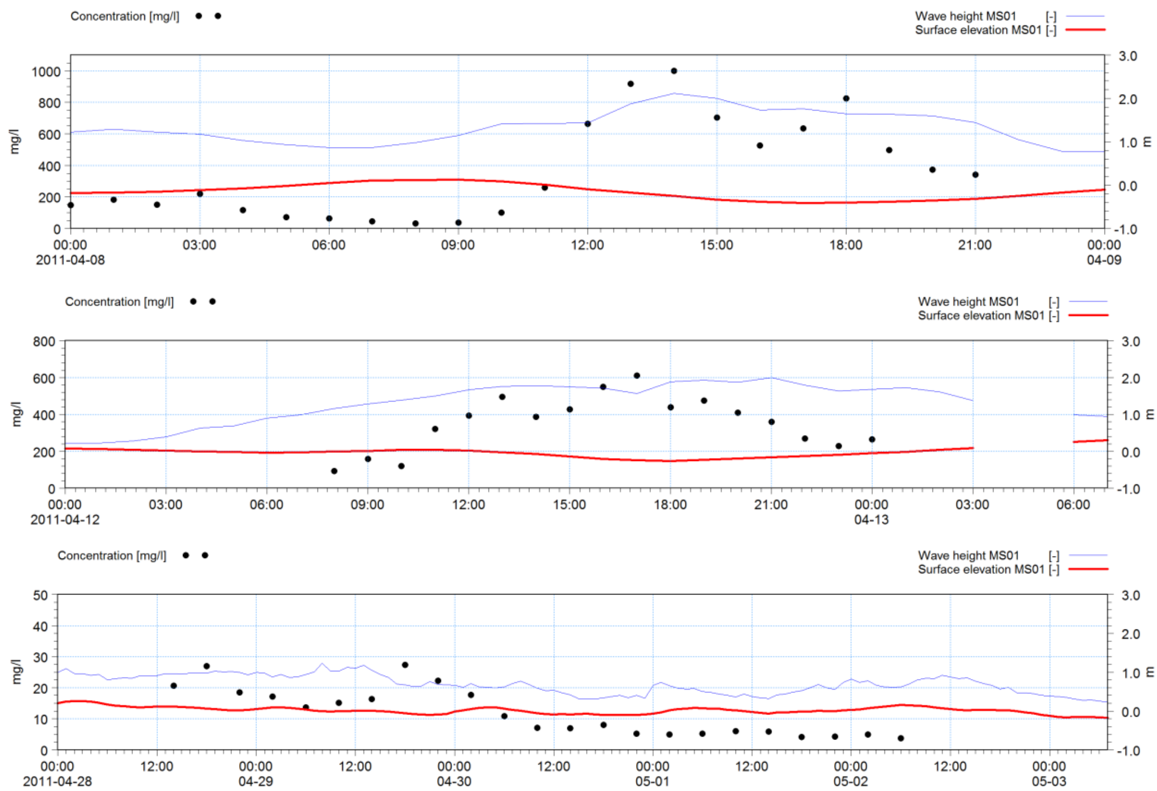


Figure 3.10 Results from automatic water sampling at NS03a. Note different scales on left y-axes

The samples were analysed for grain size especially for determination of the sand content. No direct correlation between the relative sand content and the absolute concentration was found. The highest concentration from the water samples (999.7mg/l) does, however, have a sand content of 39.48% which is among the highest sand contents found.

3.4 Organic Content

No systematic analysis of organic content was included in the analysis from the beginning. Based on the initial analysis, it was, however, found that it would be useful with a number of loss-on-ignition tests. This was done at some stations during the winter 2010/2011 and spring 2011. Further, results from the sediment trap campaign in autumn 2009 were analysed for loss-on-ignition. The results are presented in Table 3.8 and Table 3.9. The analysis was made for 55 water samples and 12 trap samples. The organic content is varying between 0.7% and 72.7%. The largest variation is found when the sediment concentration is below 2mg/l. This coincides with very calm water with low concentrations.

During high energy events, the organic content becomes very low when the concentrations increase. This coincides with an increase of coarse material (sand) in the water column.

The samples that were analysed for organic content were primarily taken in autumn and winter periods. It is assumed that the variation over the year is considerable and the organic content is high during the spring and autumn blooms. Based on the samples done during the present project, it has, however, not been possible to establish any significant variation over the year.

Table 3.8 Overview of analyses of organic matter. Samples were filtered and analysed for loss on ignition

Station ID	Minimum organic content [%]	Maximum organic content [%]	Average organic content [%]	Total number of samples
NS01	15.6	53.1	27.4	4
NS01a	53.8	53.8	53.8	1
NS02	15.8	72.7	34.2	5
NS02a	-	-	-	0
NS03	20.6	70.6	33.5	4
NS03a	0.7	69.2	19.2	33
NS04	18.0	29.7	23.8	2
NS05	18.5	28.3	22.6	4
NS06	36.1	36.1	36.1	1
NS06a	-	-	-	0
NS07	47.9	47.9	47.9	1
NS07a	-	-	-	0
NS08	-	-	-	0
NS08a	-	-	-	0
NS09	-	-	-	0
NS10	-	-	-	0

Table 3.9 Results from the trap campaign. Loss on ignition in %

Station	Period	Organic content, level 1 [%]		Organic content, level 2 [%]		Organic content, level 3 [%]	
NS02	10/11-14/12-2009	6.46	N/A	7.3	7.3	N/A	N/A
NS04	1/9-21/10-2009			4.12	N/A		
	21/10-30/10-2009			20.19	20.02		
	30/10-9/11-2009			19.02	N/A		
	9/11-11/12-2009			15.03	15.44		
NS06	30/10-20/11-2009	16.2	17.7	17.75	N/A	N/A	N/A
	20/11-14/12-2009	N/A	N/A	N/A	N/A	N/A	N/A
NS08	22/9-30/10-2009	19.02	19.02	16.06	16.31	N/A	N/A
	30/10-15/12-2009	13.22	13.53	13.33	13.3	11.9	10.06

3.5 Seabed Sediments

3.5.1 Bed Sampling

Bed sampling was performed covering a large area of the Fehmarnbelt to get information about the grain size distribution at the seabed.

All bed samples are presented in Figure 3.11 with the d_{50} for each sample. The bed samples generally show a large variation which indicates a large diversity in the bed material.

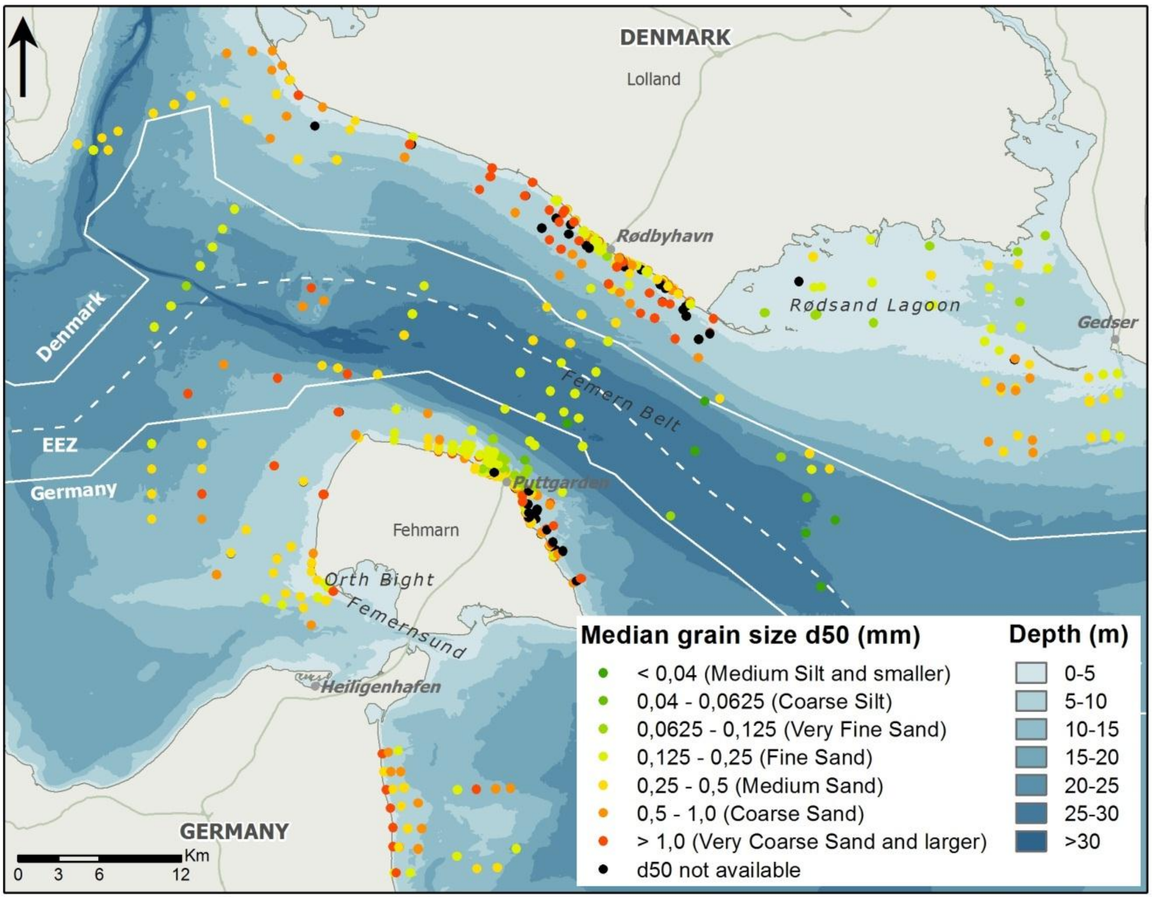


Figure 3.11 Seabed samples collected in the Fehmarnbelt. The d_{50} values are classified in colours according to the description in the legend

3.5.2 Substrate Map

A substrate map has been developed for the wider Fehmarnbelt area encompassing parts of Kiel and Mecklenburg Bays. The interpretation is based on different data sources. In the Fehmarnbelt area including the Lagoon of Rødsand and the coastline around Fehmarn, a high resolution was achieved through the use of aerial photography (in shallow waters) and multibeam data (in deeper waters), classified with Definiens image analysis software and ground-truthed with grain size data from the baseline sampling (see Section 3.5.1). The map is shown in Figure 3.12.

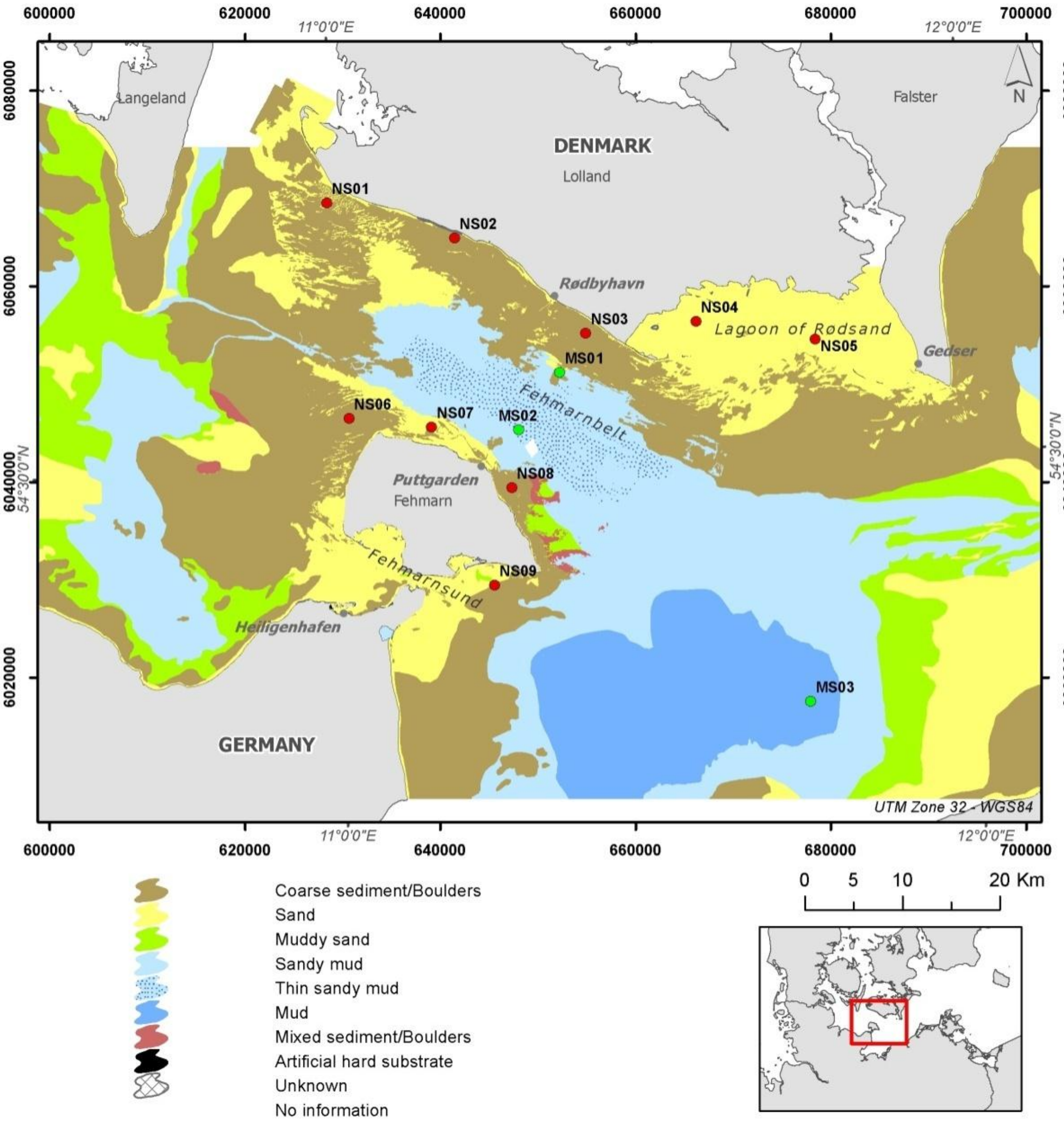


Figure 3.12 Substrate map

From the substrate map, it can be seen that coarse sediment, boulders and sand dominate in the areas of the nearshore stations.

3.5.3 Sample of the Seabed at NS03

At NS03, a core bed sample was taken. A picture of the sample is presented in Figure 3.13. A thin layer of fines in the surface layer is seen, and layers of fines between coarse sediment are identified. This indicates that fines are present to be suspended from the bottom although the sample is generally very coarse.

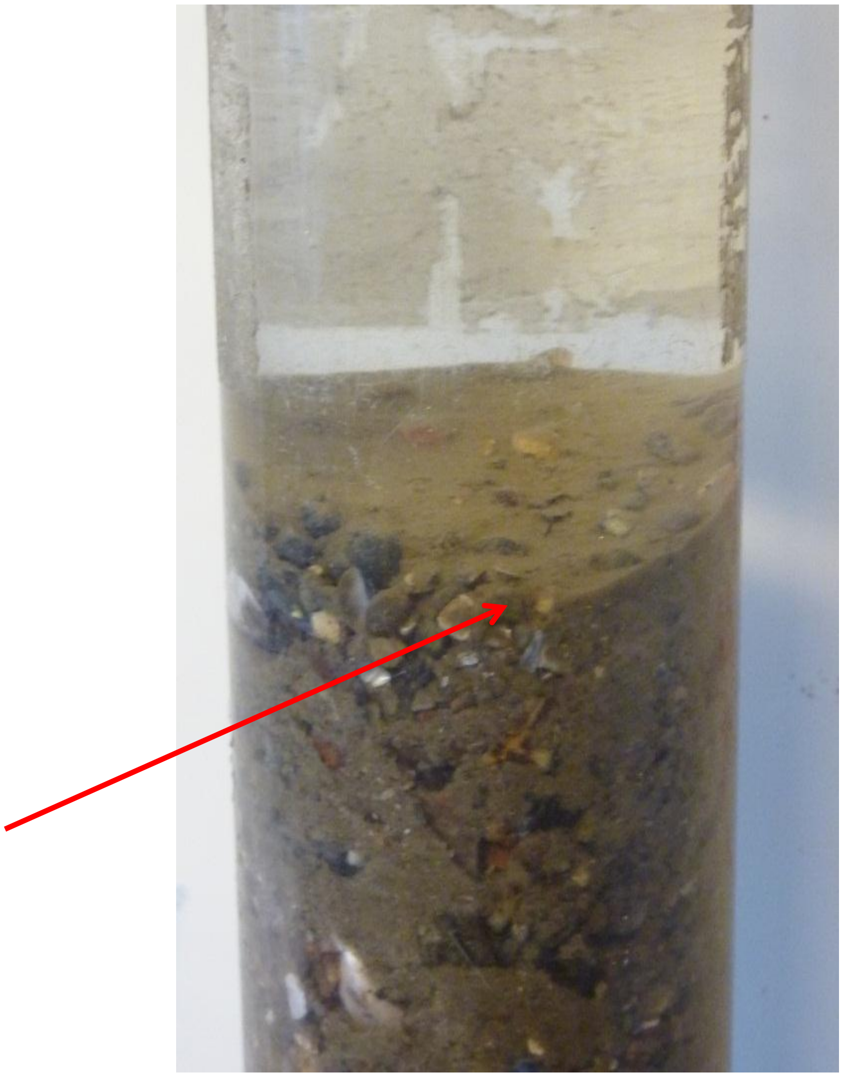


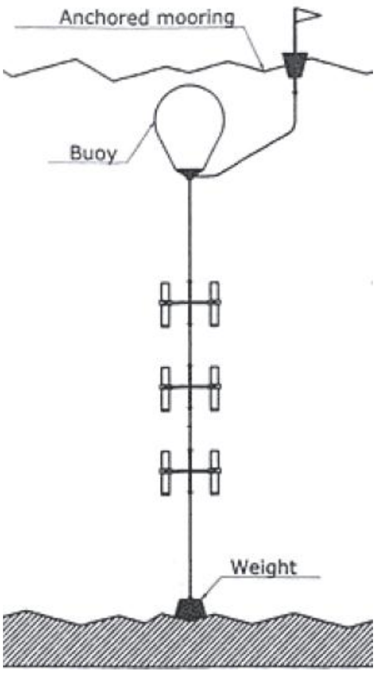
Figure 3.13 Seabed sample at NS03. The seabed consists of a very coarse material of sand and gravels but on the day overlaid with about 1mm thin layer of very fine material (red arrow)

3.6 Sediment Traps

3.6.1 Measurement Set-up

Sediment traps were deployed at nearshore stations NS02, NS04, NS06 and NS08. Two cups at each depth were mounted on a string as shown on Figure 3.14. Depths of the cups are listed in Table 3.10. The trap campaign went on in the period from 01/9-2009 – 15/12-2009. The traps were emptied with intervals of 10-45 days.

After each recovery, the traps were brought into the laboratory to be analysed for total mass of sediment as well as grain size distributions. The trap material was dried, and hereafter loss-on-ignition analysis was performed to ensure that only minerals were analysed. Finally, grain size analysis was performed by sieving the material. In many cases, the trap materials had large part of their constituents in the fine fractions below 63µm, and therefore four representative trap results, one from each trap station, were analysed with laser diffraction to provide information about the entire grain size distribution.



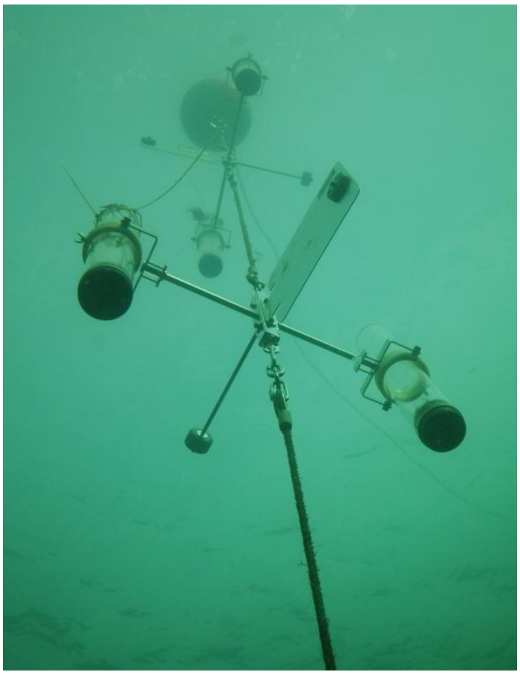


Figure 3.14 Sketch of the trap set-up. The underwater photo shows a trap set-up seen from the position of the lowest set of cups

Table 3.10 Trap set-up levels distance to the seabed. Total depths are seen in Table 3.2

	NS02	NS04	NS06	NS08
Upper cups: distance seabed (m) (level 1)	3.7		7.7	5.9
Mid water cups: distance seabed (m) (level 2)	2.5	0.8	4.5	3.6
Lower cups: distance seabed (m) (level 3)	1.3		1.3	1.3

3.6.2 *Presentation of Trap Data*

The trap results are presented in Table 3.11.

Table 3.11 Results from the trap campaign. Mass given here is the masses after loss of ignition analysis unless anything else is noted. The trap periods, where further analyses have been applied, are marked in green

Station	Period	Mass level 1 (g)		Mass level 2 (g)		Mass level 3 (g)	
NS02	10/11-14/12-2009	32.84	N/A	44.54	44.52	N/A	N/A
NS04	1/9-21/10-2009			62.82	N/A		
	21/10-30/10-2009			1.26	1.15		
	30/10-9/11-2009			4.77	4.82		
	9/11-11/12-2009			37.59	35.43		
NS06	30/10-20/11-2009	1.13	1.44	1.29	N/A	N/A	N/A
	20/11-14/12-2009	0.005*	N/A	0.008*	N/A	0.28*	N/A
NS08	22/9-30/10-2009	11.46	12.93	8.77	9.37	11.91*	11.52*
	30/10-15/12-2009	3.50	3.24	6.08	5.45	5.65	5.79

**) Total mass (no analysis of loss of ignition available)*

Grain size distributions for four representative traps are presented below in Figure 3.15 to Figure 3.18. These distributions are determined by laser diffraction after dispersion of the material in ultrasonic environment.

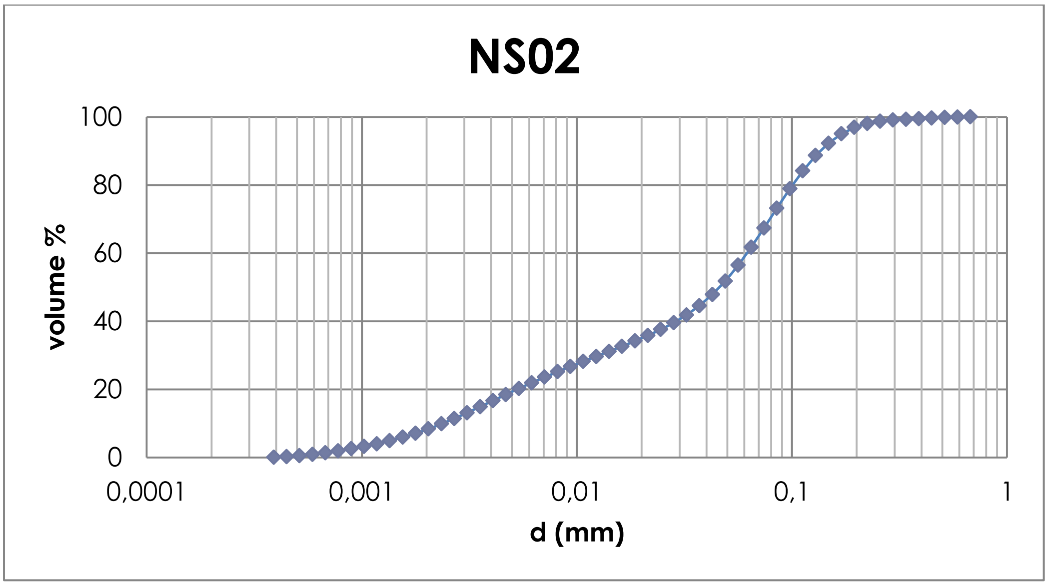


Figure 3.15 Accumulated primary grain size distribution at NS02 at surface level covering the period from 10/11-2009 to 14/12-2009. The primary grain size distribution is performed with laser diffraction analysis. The resulting grain size distribution represents the non-flocculated sediment

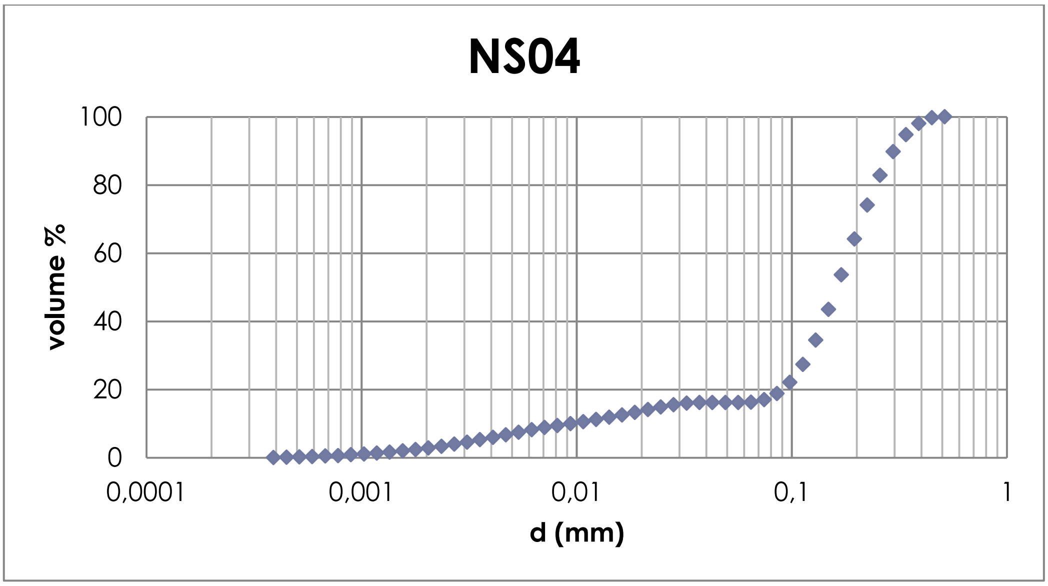


Figure 3.16 Accumulated primary grain size distribution at NS04 at mid water level covering the period from 9/11-2009 to 11/12-2009. The primary grain size distribution is performed with laser diffraction analysis. The resulting primary grain size distribution represents the non-flocculated sediment

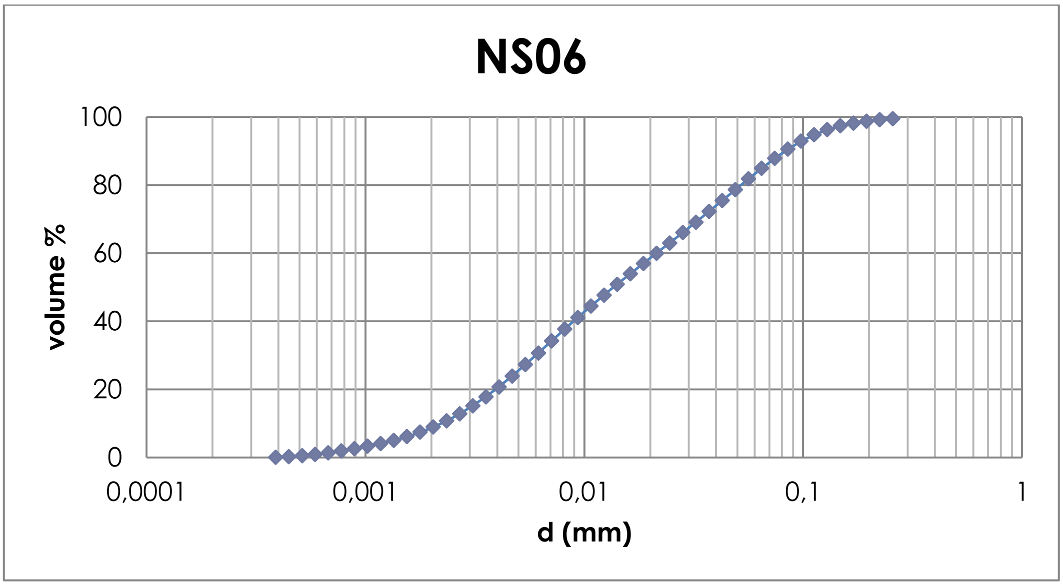


Figure 3.17 Accumulated primary grain size distribution at NS06 at mid water level covering the period from 30/10-2009 to 20/11-2009. The primary grain size distribution is performed with laser diffraction analysis. The resulting primary grain size distribution represents the non-flocculated sediment

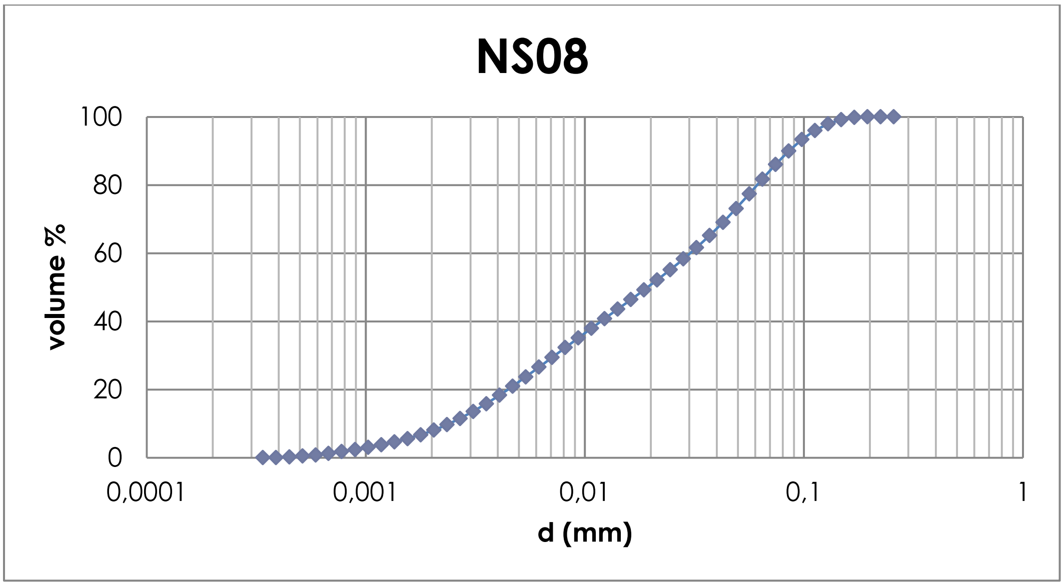


Figure 3.18 Accumulated primary grain size distribution at NS08 at mid water level covering the period from 22/9-2009 to 30/10-2009. The primary grain size distribution is performed with laser diffraction analysis. The resulting primary grain size distribution represents the non-flocculated sediment

3.7 Remote Sensing

3.7.1 Spatial Variation in Sediment Concentrations from Satellite

Remote sensing data can provide unique information about the distribution of suspended sediment. This information may contribute to the understanding of some of the events found in the measurements of turbidity from the nearshore and main stations.

The MERIS satellite data used in this study have a spatial resolution of 300m. Raw data have been processed, and total suspended matter (TSM) (mg/l) has been calculated using the FuB algorithm described in (Schroeder et al. 2007).

The algorithm has been developed and trained on data from turbid parts of the North Sea especially for turbid water (so-called case 2 waters) and has shown to perform better than the standard MERIS level 2 products (Schroeder et al. 2007). An automatic cloud detection procedure has been performed. The automatic cloud detection procedure does not remove all clouds, and this may lead to false TSM values around clouds. A local calibration has not been performed in this study as the images are primarily used to provide information about the spatial distribution of suspended sediment at different hydrodynamic situations rather than exact measures of sediment concentrations.

3.7.2 Presentation of Total Suspended Matter Maps

A data set of processed MERIS data covering the period from the beginning of May 2009 to the end of October 2009 has been evaluated to find images with minimum cloud cover in the Fehmarnbelt. From images with reduced cloud cover, eleven images have been chosen for further analysis (Table 3.12). Mainly images from late summer and autumn 2009 have been selected to cover both high-dynamic situations as well as quiet weather situations.

The TSM extracted from the MERIS data is a result of the concentration in the upper part of the water column. The resulting maps for the selected dates are presented in Appendix D, and two examples can be seen on Figure 3.19 and Figure 3.20. The image from September shows a typical situation with low sediment concentrations, whereas the image from October shows the situation after a storm where higher concentrations are measured. In areas with very low water depths such as the western part of the Lagoon of Rødsand, the reflectance measured by the satellite sensor can be influenced by signals from the sea bottom leading to an increase of the reflectance recorded at the satellite. Therefore, the algorithm may over-estimate the actual suspended matter concentration in very shallow areas in some of the images.

When interpreting the maps and comparing them with values from the suspended sediment concentration time series from the fixed stations, it is worth to remember that the MERIS maps provide information from the upper part of the water column, and that the calculated physical parameter is total suspended matter (eg including chlorophyll *a* and organic matter) and not only sediment. The main advantage of the MERIS satellite images is the ability to provide information about the relative distribution of suspended matter in the Fehmarnbelt area.

In Table 3.12, comments and general observations from the TSM maps and from the SSC time series plots (fixed stations) on corresponding dates are listed.

Table 3.12 Overview of dates of satellite images and comments

MERIS date	Comments TSM maps	Fixed stations comments
1/8-2009	Clouds in the western part of the image are not masked properly resulting in false high concentration values. Very low concentrations in the rest of the image except from an area off the Lagoon of Rødsand in the eastern direction	Very low SSC values
6/8-2009	Low TSM values (below 1.5mg/l)	Very low SSC values
16/8-2009	Low TSM values (below 1.5mg/l)	Generally low values. 10-20mg/l at NS04
19/8-2009	Low TSM values (below 1.5mg/l)	Low SSC values
20/8-2009	Low TSM values (below 1.5mg/l)	Low SSC values
1/9-2009	TSM values below 3.5mg/l	Approximately 10mg/l at NS03. Up to 25mg/l at NS05
20/9-2009	Low TSM values (below 1.5mg/l)	Low SSC values
24/9-2009	Generally TSM below 2mg/l	Up to 80 mg/l at NS05
5/10-2009	High concentrations are seen. In the middle of the Fehmarnbelt up to 5.5mg/l. The spatial distribution shows higher concentrations in the middle of the Fehmarnbelt as well as in Mecklenburg Bight and Kiel Bight compared to the coastal areas	All fixed stations show increased SSC. See time series plot on Figure 6.2, Figure 6.9 and Figure 6.11
9/10-2009	Concentrations are up to 3.5mg/l with a few areas with even higher concentrations. The spatial distribution shows lower concentrations in the middle of the Fehmarnbelt as well as in some spots in Mecklenburg Bight and Kiel Bight. This is a reverse situation compared to four days earlier	Increased SSC on all Danish stations as well as the German NS07-NS08. No increase in Mecklenburg Bight NS09 and NS10
15/10-2009	Generally, concentrations up to 5mg/l with higher concentrations in the coastal zone near Fehmarn. The high concentrations seen east of Falster are probably clouds not detected in the automatic cloud mask and these values should not be interpreted as suspended matter	Increased SSC at NS05 and NS07

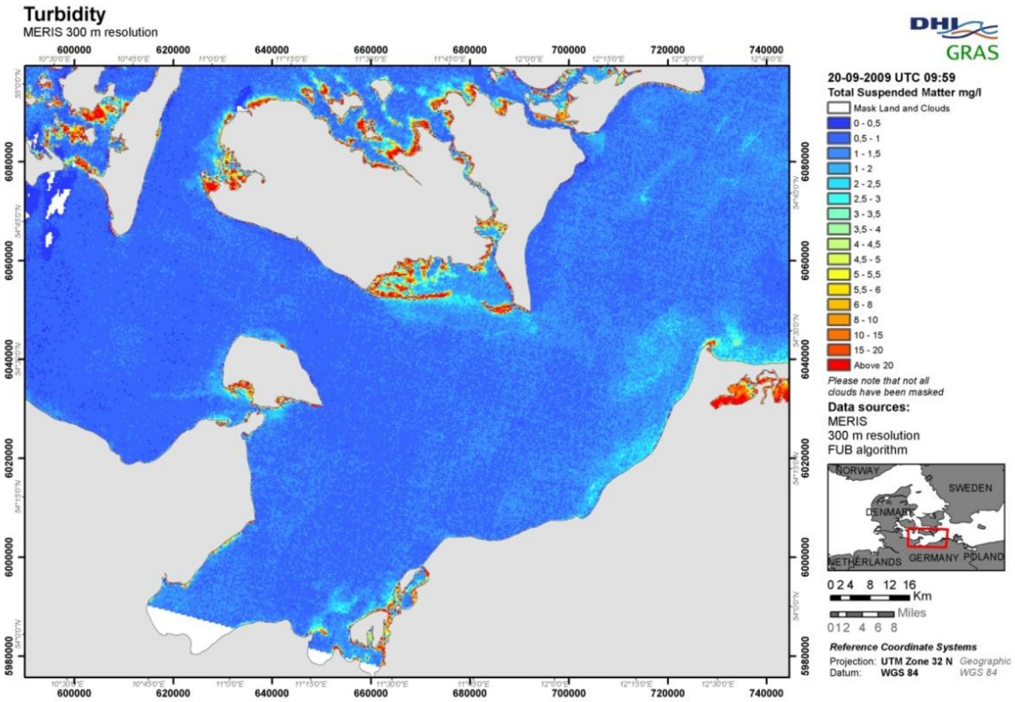


Figure 3.19 Map of TSM derived from MERIS satellite image on 20/9-09. Note that the actual concentration may be over-estimated in shallow areas due to reflectance from the bottom

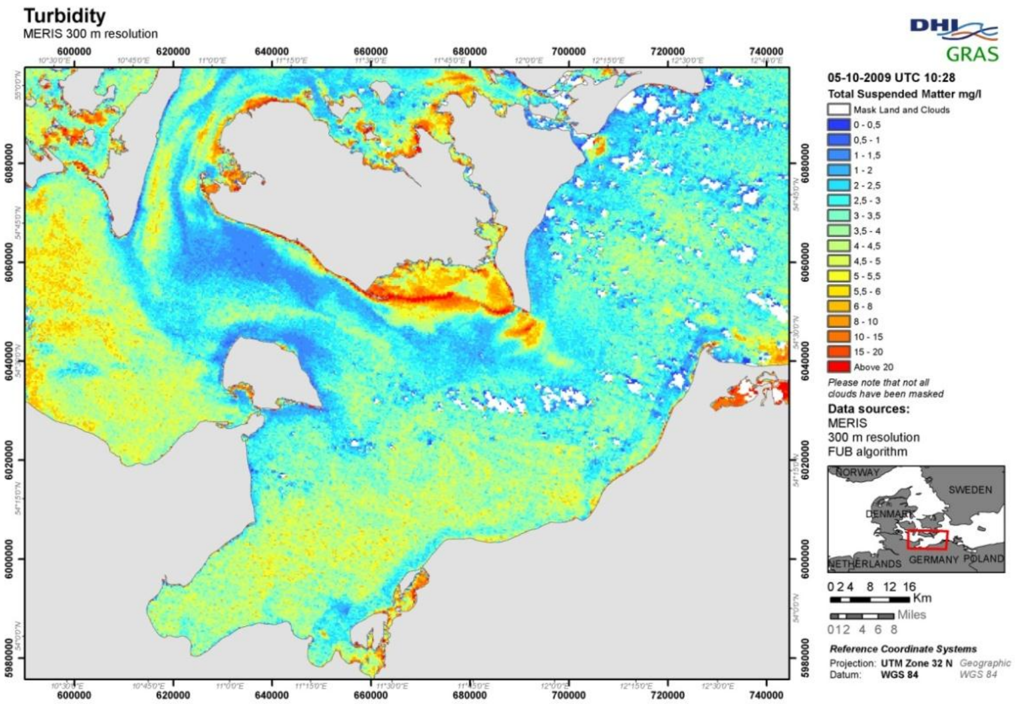


Figure 3.20 Map of TSM derived from MERIS satellite image on 5/10-09. Note that the actual concentration may be over-estimated in shallow areas due to reflectance from the bottom

Generally, there is a good correspondence between high concentrations of TSM in the satellite data and increased SSC at the fixed stations. Furthermore, the satellite images confirm that the sediment concentrations in the Fehmarnbelt are very low most of the time.

On low water, it is known that the reflection reported in satellite images is affected by the seabed. The concentrations shown in Figure 3.19 and Figure 3.20 are therefore probably not correct near the shores.

To clarify whether the signals reported in Figure 3.19 and Figure 3.20 are caused by sediments or have been biased by algae, the fluorescence signal from the main stations has been inspected. Chlorophyll-*a* levels in the Fehmarnbelt were 2–3µg/l on 20 September 2009 (Figure 3.19) and 2–4µg/l on 5 October 2009 (Figure 3.20). These are low concentrations and do imply that the signal is to a large degree caused by sediments. The weather was quite rough on these dates, and the nearshore stations show an increase in sediment levels. MS stations also record increase in sediment levels both at the surface and the bottom. It is therefore concluded that the signal on the images is mainly caused by suspended sediments.

4 INVESTIGATION AREA AND EXTERNAL FORCES

The Fehmarnbelt is part of a narrow transition area between the North Sea/ Kattegat and the Baltic Sea, connecting the southern part of the Great Belt and the Kiel Bight with the Mecklenburg Bight and further over the shallow Darss Sill into the Arkona Basin of the Baltic Sea, see Figure 4.1.

As a narrow but relatively deep strait between Kattegat and the Baltic Sea, the hydrodynamic conditions in the Fehmarnbelt are affected by local and remote forcing. Irregular weather patterns and storms with time scales of a few days are typical for the area.

Generally, the amount of suspended sediment is correlated to the local wave and current conditions. In the shallow parts of the Belt, at water depths smaller than approximately 6m, the waves under storms re-suspend the finer fractions and the currents spread the suspended fines over larger areas. However, the correlations are weak due to the great variation in the composition of the bed material and the scarcity of fines.

4.1 Currents

The remote forcing for the currents is mainly due to the large-scale weather systems, which build up hydraulic pressure gradients due to atmospheric gradients and associated wind fields, which form different wind set-up of the sea levels in the Kattegat and Arkona Basin. When the wind changes, the barotropic pressure gradient manifested by a large-scale sea level slope is not balanced and forces strong return currents through the narrow straits in the transition zone, and in particular through the narrow Fehmarnbelt. A baroclinic pressure gradient between the saline and dense water in Kattegat and the lighter and less saline Baltic Sea is more or less permanent and causes a long-term average outflow near the surface and inflow near the bed, but the meteorological conditions are the main forcing for the current conditions and the water exchange between the Kattegat and the Baltic through the Fehmarnbelt.

In the nearshore zone, waves - primarily locally wind-generated waves - cause wave breaking along the shorelines, which force longshore currents and littoral transport. Local wind forcing may also generate local wind-driven currents. Locally-generated phenomena such as eddies, upwelling and down-welling and Ekman flows also influence the local current pattern.

Mean current speeds in the upper 10m of the water column in the Fehmarnbelt are about 0.3-0.5m/s and slightly lower when approaching the Danish coast. Current speeds in the central part of the Fehmarnbelt exceed 1m/s, see (Hydrographic of the Fehmarnbelt area - Baseline 2011).

4.2 Waves

Waves in the Fehmarnbelt are primarily locally-generated wind waves, and strong correlations were found between wind speed and wave height and between wave period and wave height. The nearby land areas on both sides of the Fehmarnbelt, however, restrict the fetch available for the waves to grow and limit the wave heights for waves from some directional sections depending on the geographical position in the belt.

The waves in the Fehmarnbelt are in general relatively small with significant wave heights rarely exceeding 1.5m. The significant wave height is a measure for the average wave height for the highest one third of the waves in an irregular wave field. The average significant wave height varies from about 0.4m in July to about 0.9m in January with an annual mean value of about 0.5m. The waves are short with mean wave periods primarily in the range of 1.5s - 4.0s.

The wave heights are larger near the Danish coast than near the German coast. The dominant wave direction near the Danish coast is from WSW-WNW with a significant fraction of waves occurring also from directions E-SE. Towards the German side, the directions shift to NNW and E, respectively.

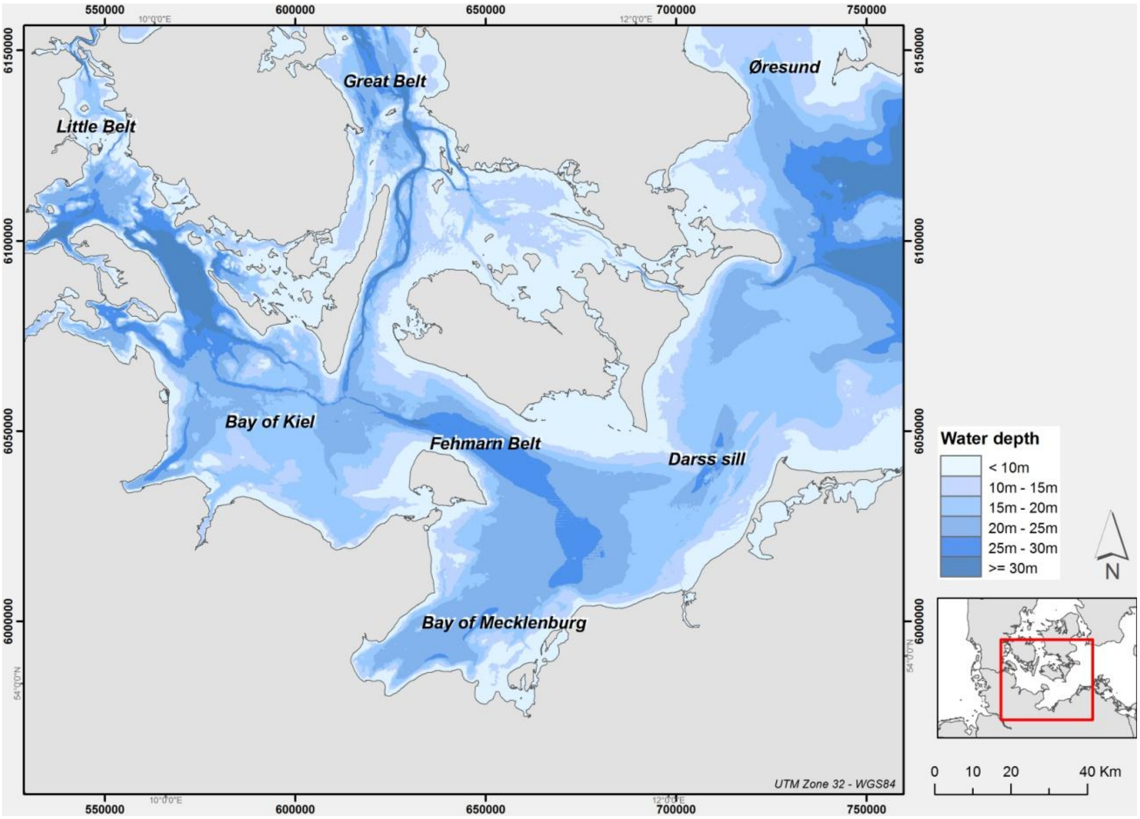


Figure 4.1 Bathymetry of the Fehmarnbelt region

5 CALCULATION OF SEDIMENT CONCENTRATION

5.1 Quality Check and Filtering

In order to prepare the NTU time series from the fixed stations for the further analysis, it is necessary to identify erroneous parts of the signals. Errors can originate from air bubbles, algae, seaweed, fish larvae, some chemicals, small fish and a number of other things (Downing, J. 2006). This section and Appendix N provide an overview of the procedures which have been used to eliminate erroneous signals. Finally, a discussion with possible explanations of the large percentage of noisy signals during spring and summer periods will be presented.

In case the suspended sediment event is the result of local re-suspension, the turbidity level will increase rapidly and decrease more slowly. The duration will follow the meteorological or hydraulic conditions that caused the event. The event usually has a time scale of at least some hours. An example of this is shown in Figure 5.1.

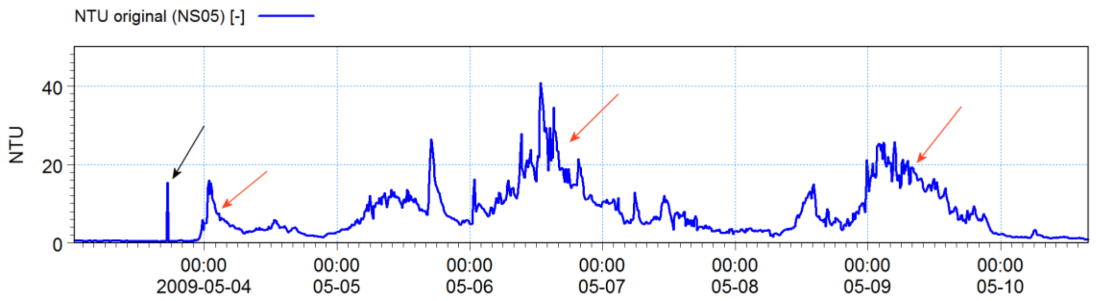


Figure 5.1 Typical measurement signal from NS05. Red arrows are signals corresponding to suspended sediment. The black arrow is most likely a signal from something else

Noise and undesired peaks have been removed using both visual and numerical methods. The reasons for the undesired spikes and the methods used to eliminate them are described in Appendix N.

5.2 Correlation between NTU and SSC

5.2.1 Testing of Instrument Dependency

A laboratory facility was used to establish a correlation between the measured NTU and the actual suspended sediment concentrations. First, a test was made to see if each instrument needed individual calibration parameters. The test was made by mounting five different Wetlabs NTUsb instruments in a black container with clean water with the same salinity as found in the Fehmarnbelt. Sediment from geotechnical station A008 (UTM coordinate: 650457m E, 6050595 m N) collected during the spill test was slowly added. Sediment originated from sediment cores and contained very little or no organic material. No attempt was done to remove any organic content. During the calibration test, water samples were taken and analysed for SSC. The NTU and the analysed SSC are compared. The results from the five tested instruments are shown in Figure 5.2. It is concluded that the differences of the slopes are within the expected uncertainty range of the measurement. The correlation between SSC and NTU for the present material is SSC [mg/l] = 3.5 × NTU.

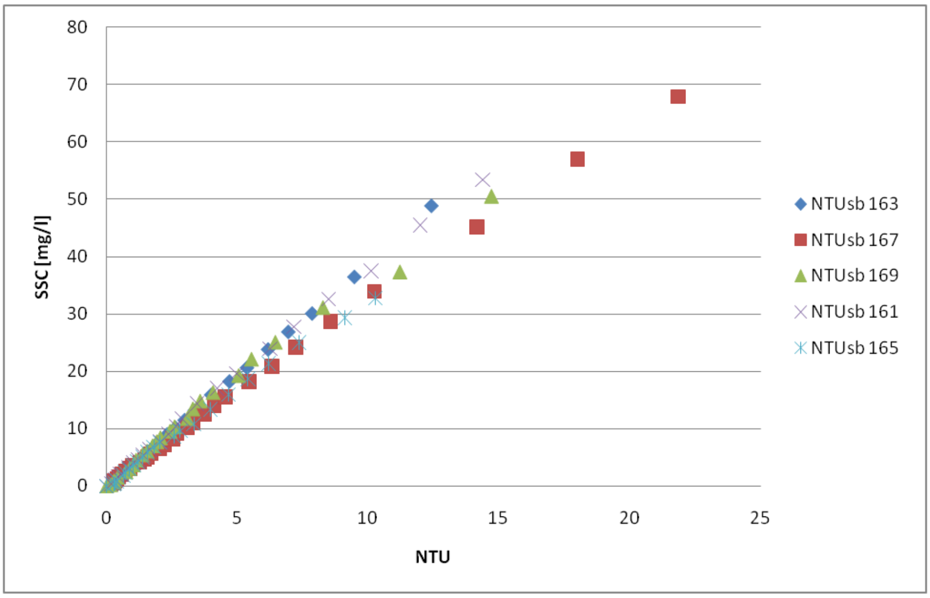


Figure 5.2 Comparison of calibration of five NTUsb instruments. Equation for all instruments together is SSC [mg/l] = 3.5 NTU

Similar tests have been performed in the Fehmarnbelt at NS06 by mounting two measuring devices at the same location at the same time. The NTU values measured by different instruments reflect the same NTU values as seen in Figure 5.3.

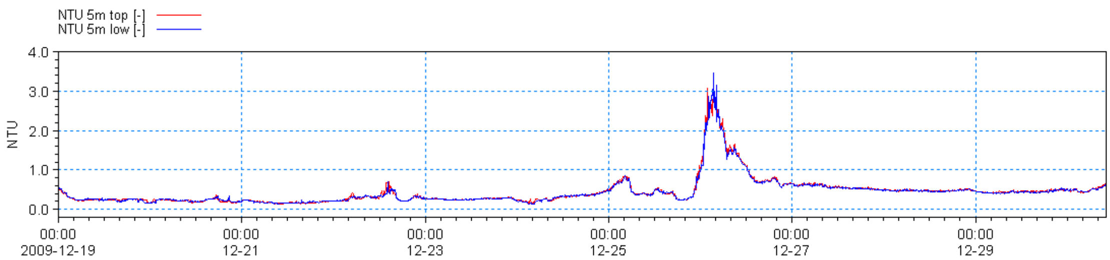


Figure 5.3 Test of the instrument dependency at NS06 where two instruments were mounted at the wire just above each other. The two instruments measure identical signals

5.2.2 *Correlation based on Water Samples at NS01 –NS10 and MS01 – MS03*

Ideally, calibration of the NTU should be based on the water samples taken at each station. However, there is a lack of water samples with high concentrations. The water samples collected from nearshore stations (up till re-deployment) and main stations are plotted in Figure 5.4 together with the measured NTU at the time of sampling. The correlation factor between NTU and SSC is found based on water samples to be in the range from 1.9–3.4, i.e. SSC [mg/l] = factor × NTU. As mentioned earlier, the very low concentrations seen in the water samples leave too small amounts of sediment to perform analysis of organic matter. Bed samples and fluorescence measurements, however, indicate that the organic content during most of the year is very low.

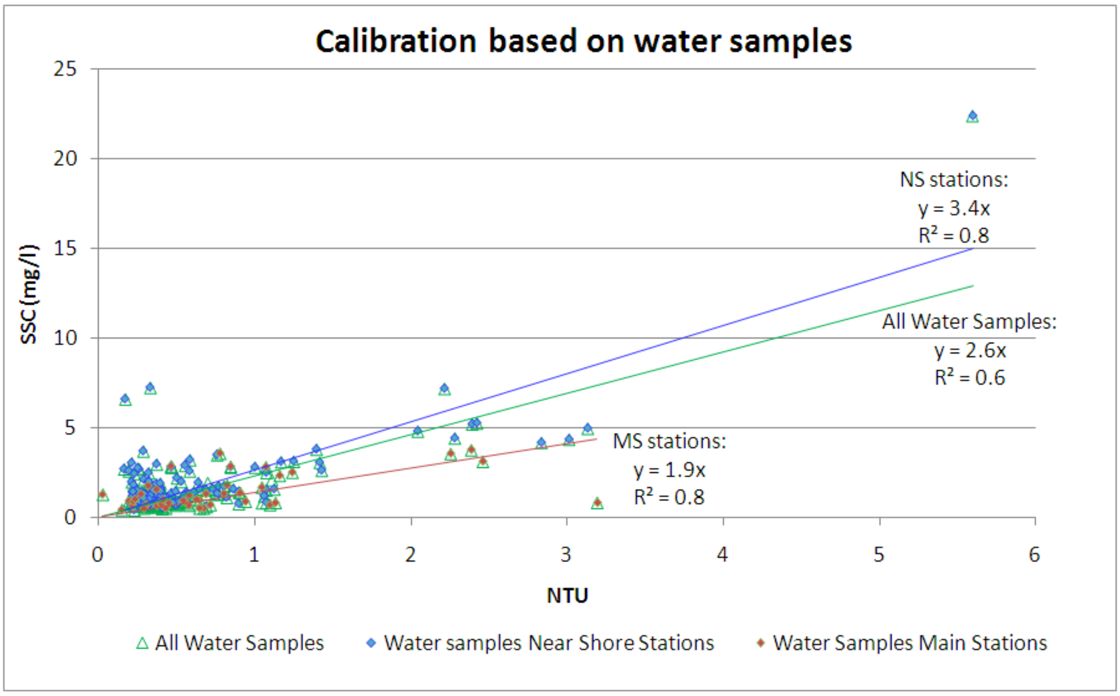


Figure 5.4 *Suspended sediment concentrations from water samples and corresponding NTU measurements from 2009 for nearshore stations, main stations and all stations. The linear regression lines through (0.0) are presented*

5.2.3 *Correlation based on Water Samples at NS03a*

The automatic ISCO water sampler has provided data for calibration of the shallow water nearshore stations at NS03a. This calibration is presented in Figure 5.5.

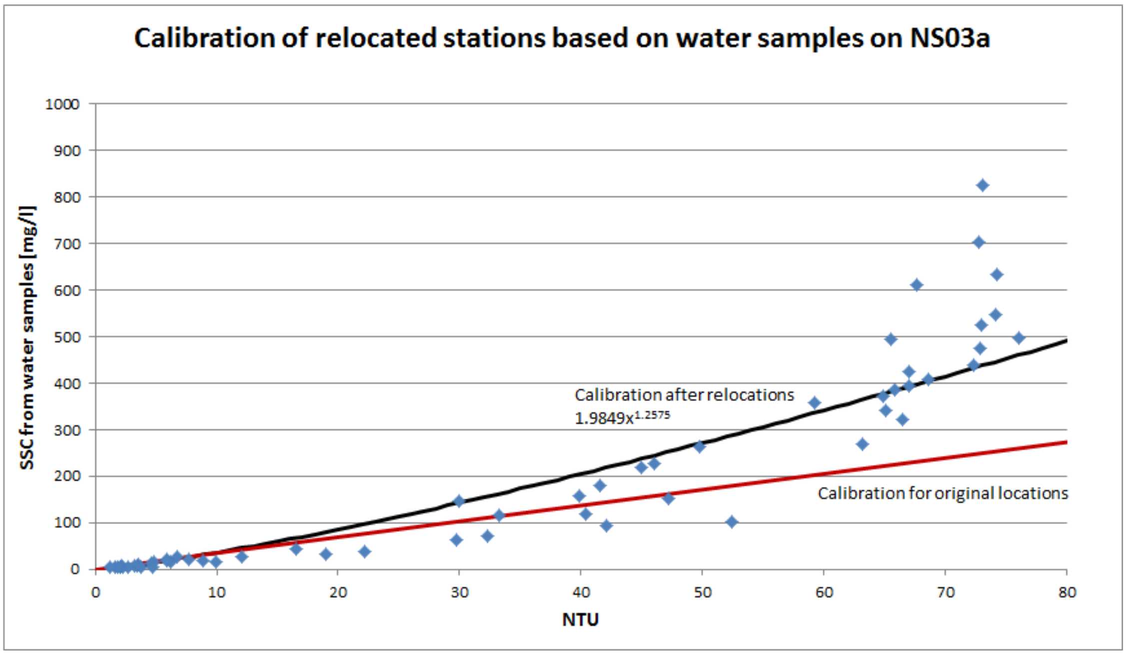


Figure 5.5 *Correlation between NTU and SSC at station NS03a. The calibration curve shown as a black line is used for all relocated stations. The calibration used for original locations is shown in red for comparison purposes*

The calibration correlation is the best possible using a power function. Exponential correlations and other functions have lower RMS values. Note that the highest SSC values occur during a storm on 8 April 2011, where the waves are breaking at the measuring station. During this period, DHI is not totally convinced that the NTU signal is correct. It might have been influenced by bubbles, or simply saturated. Offshore H_s was 2.2m and the water depth at the station was 2.8m; see Figure 3.10 (top plot). If the highest SSC values, originating from this event, are removed in Figure 5.5, a good correlation occurs.

In Figure 5.5, the correlation between extracted water samples and corresponding NTU values is displayed along with the calibration curve for the original positions. It is seen that the original calibration for NS01-NS10 is almost identical with the calibration curve for NS01a-NS03a and NS06a-NS08a for concentrations less than approximately 50mg/l. However, it is clear that it is not possible to use the same calibration curve at the new locations during high energy events. When the concentration exceeds 50mg/l, the calibration presented in Figure 5.4 under-estimates the actual concentrations, and thus a separate calibration curve is needed for these shallow water measurements. This curve is presented as the black curve in Figure 5.5. It appears that there is substantial scatter, and measured NTU can be converted to SSC with ±50%.

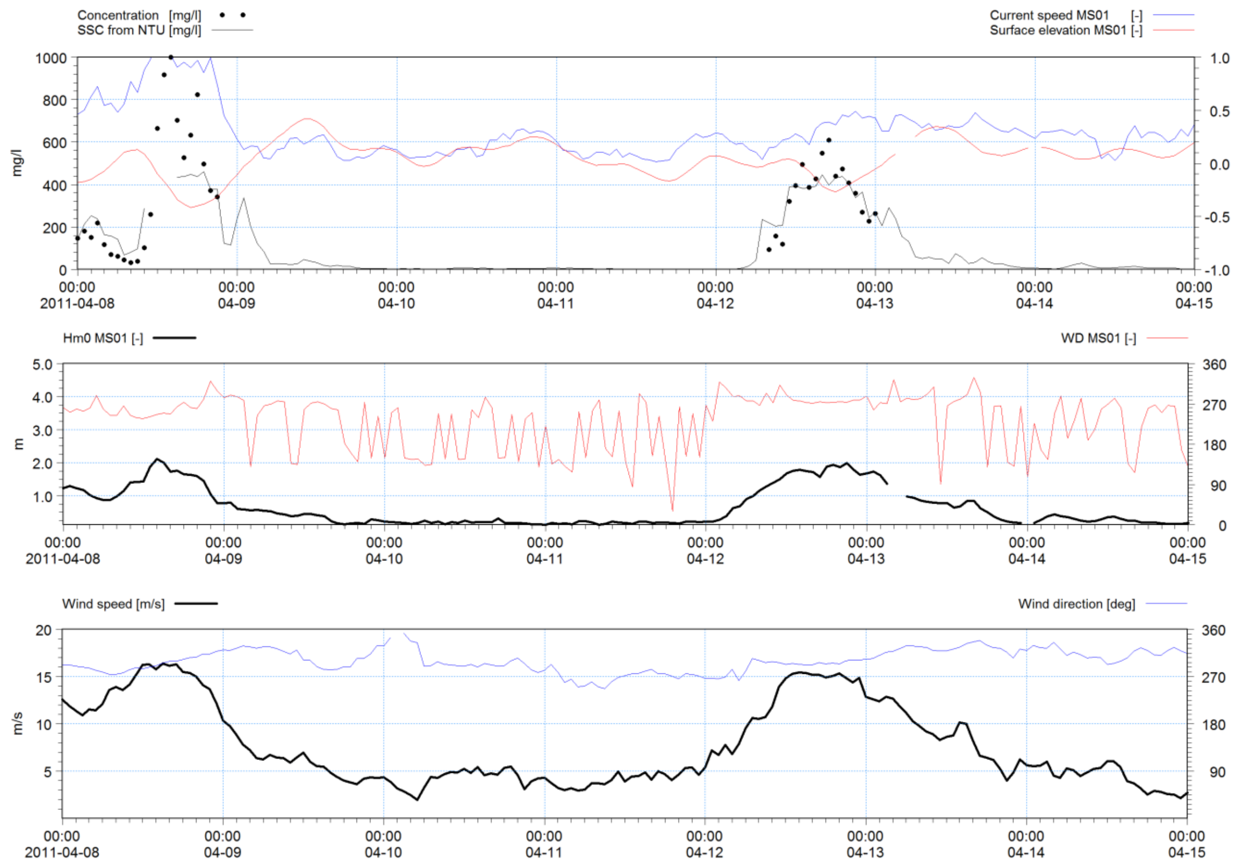


Figure 5.6 Final calibration of the rough weather periods. The results from the water samples together with the calibrated NTU signal are shown in the upper panel. Concentration is SSC

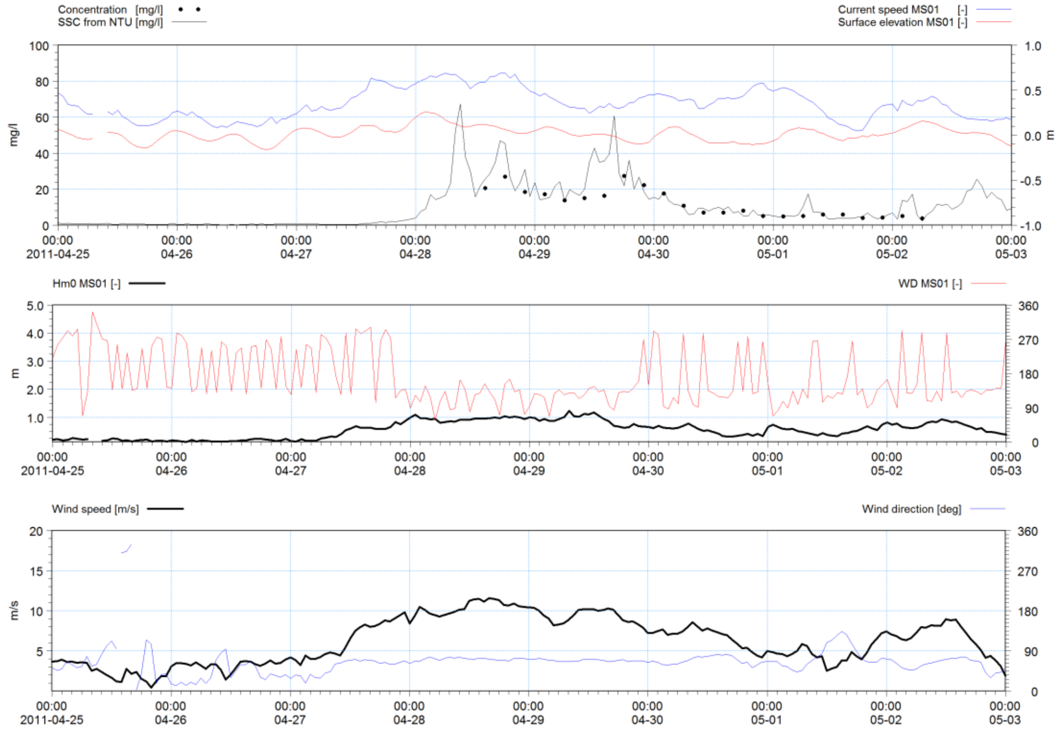


Figure 5.7 Final calibration of the rough weather periods. The results from the water samples together with the calibrated NTU signal are shown in the upper panel. Concentration is SSC

The uncertainty is due to varying grain size distribution and air bubbles in the surf zone. In Figure 5.8, the variation of organic content and sand content in the suspended sediment is given.

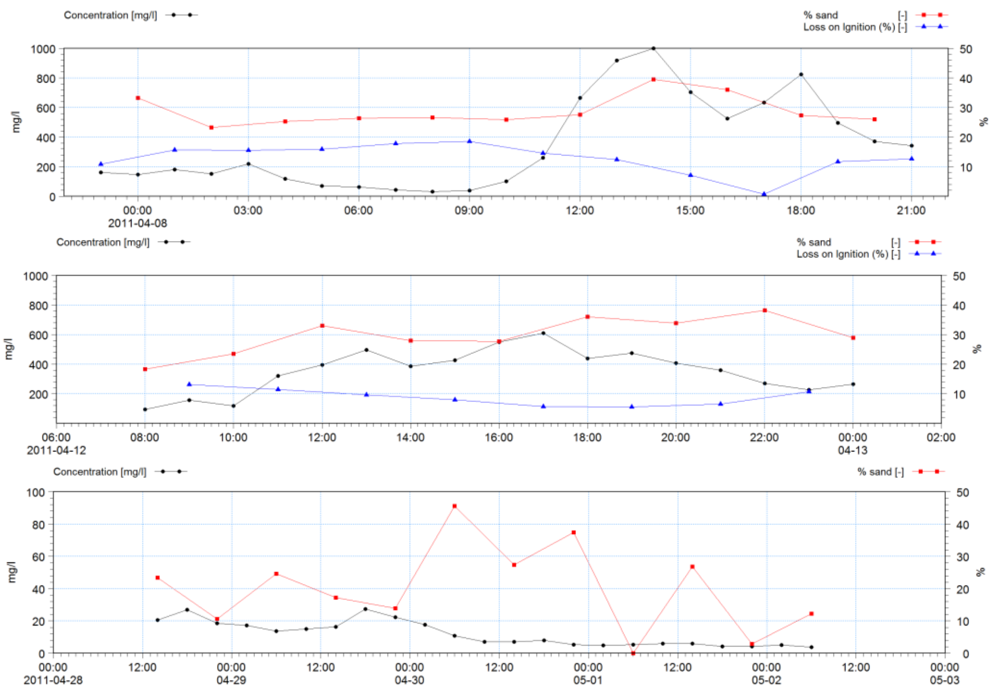


Figure 5.8 *Analysis of the collected water samples for organic content (loss-on-ignition) and sand content. Concentrations are total suspended matter*

5.2.4 Correlation based on Different Types of Sediments

Calibration of NTU is known to be dependent on the specific material characteristics, and a site-specific calibration of each measuring station is therefore tested. From the sediment trap campaign, there is site-specific information about the actual trapped sediment at four stations; NS02, NS04, NS06 and NS08. Based on material from the traps, laboratory tests have been performed to gain information of the calibration for each specific type of bed material. Beside the four sediment trap samples, a number of selected and different subsea bed materials have been analysed. Correlations between SSC and NTU are presented in Figure 5.9.

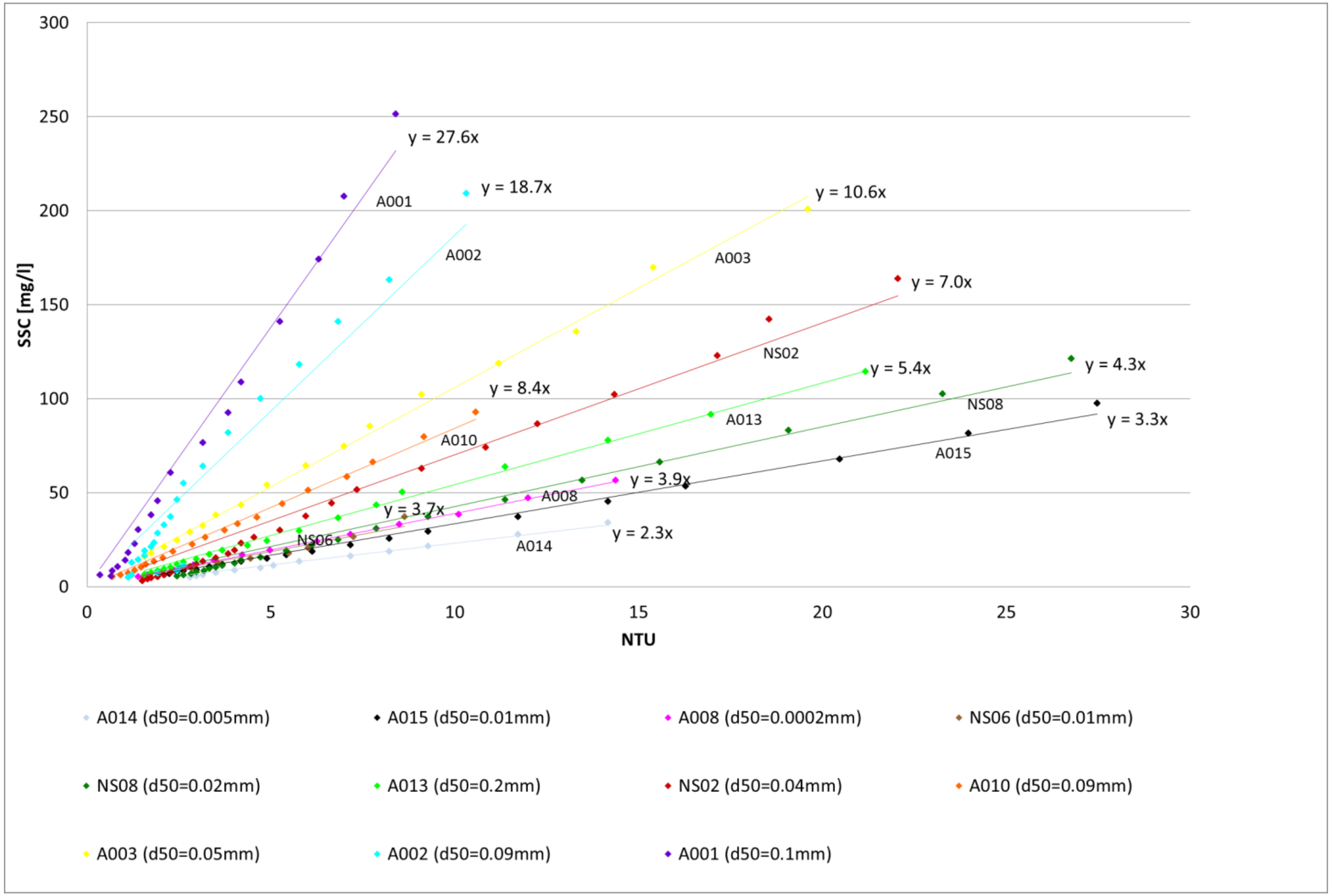


Figure 5.9 *Range of correlation curves based on laboratory experiments. Grain size distributions for the samples are presented in Appendix C and in Figure 3.15 to Figure 3.18 for subsea samples and traps, respectively. D_{50} and $\sqrt{d_{84}/d_{16}}$ are calculated based on particle sizes derived from the laser diffraction analysis*

The correlation factors vary with an order of magnitude between the fine sediments and the coarser sediments. From the different calibration curves presented in Figure 5.9, it can be concluded that it is not possible to find one correlation which is representative in calm situations, where the suspended sediment is fines only and rough situations, where a mixture of fines and sand is brought into suspension. However, during rough weather the suspended matter will consist of a mixture of fine and coarse material, and thus the actual calibration factor will never reach the highest level. During storms, it is believed that the sediment distribution at mid water, where the NTU's are located, will be dominated by finer sediments and thus the possible error from using a fixed calibration coefficient of 3.4 is up to 50%.

5.2.5 Final Calibration

From the above analysis of water samples and laboratory calibrations of different sediments along with evaluation of traps, it is concluded that it is not possible to find a universal correlation factor that covers both the fines and sand.

The correlation factors found from water samples are 3.4 and 1.9 at the nearshore stations with water depth larger than ~6m and the main stations, respectively. These factors are confirmed by the findings in the laboratory for a larger range of suspended concentrations. Further, the analysis of the traps indicates that fine suspended concentrations have similar distributions at the nearshore locations. It is therefore concluded that the correlation factors measured in-situ shall be applied, i.e. 3.4 and 1.9, respectively. The correlation factors reflect that the suspended sediment is finer at the main stations than at the nearshore stations. This is also consistent with the absence of wave influence at the main stations, which means that less coarse material is brought into suspension here. This is especially true for the measurements in the middle and top of the water column. The correlation factors are valid for grain sizes less than $\simeq$0.063mm. During rough events where sand is brought into suspension, the concentrations based on NTU measurements and using the correlation factors derived from the water samples will be under-estimated. However, emphasis is on the concentrations of fines which stay in suspension for a long time.

For NTU instruments placed closer to the coast (NS01a – NS03a and NS06a-NS08a), a different pattern of concentrations was found. During rough weather events, a considerable amount of sand was found in the samples and thus a different calibration needed to be established. This was done by establishment of an automatic water sampler (ref Section 0). The results from this revealed that the linear calibration applied at the main stations and at the original nearshore locations is valid. However, when the concentrations rise above approximately 50mg/l, a power function does describe the conversion better. Therefore for nearshore stations placed close to land, the following function was applied: $SSC = 1.98 \times NTU^{1.26}$. This calibration was applied for all the data acquired after re-deployment at lower water depths (NS01a – NS03a and NS06a – NS08a).

The applied relations between SSC and NTU are given in Table 5.1.

Table 5.1 Applied relations between SSC and NTU for stations at different water depths

Water depth	Relation between NTU and SSC	Stations
0m – 5m (except Rødsand)	$SSC = 1.9849 \times NTU^{1.2575}$	NS01a, NS02a, NS03a, NS06a, NS07a, NS08a
5m – 10m (and Rødsand lagoon)	SSC = 3.4 x NTU	NS01 – NS10
Above 10m	SSC = 1.9 x NTU	MS01 – MS03

5.3 Time Series of Suspended Sediment, Fixed Stations

The correlation factors have been applied to all time series from nearshore and main stations, and calculated SSC values are available in the Fehmarnbelt database. Hereafter, a low-pass filter has been applied as described in Section 5.1. Time series of the nearshore SSC values can be found in Appendix E, and an example from NS03 is shown in Figure 5.10. Time series from the main stations are presented in Appendix F.

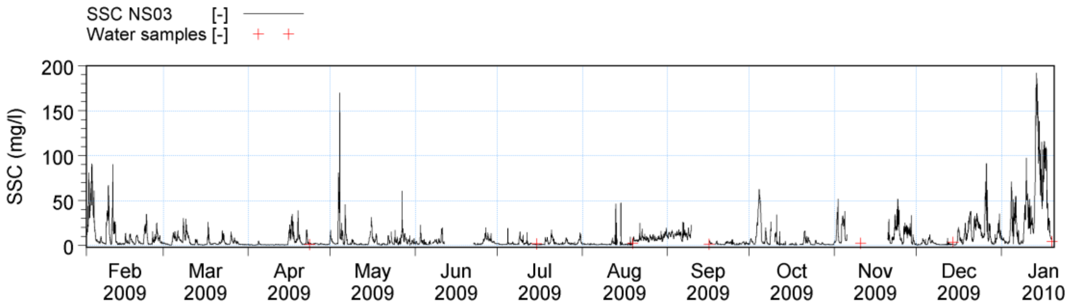


Figure 5.10 Example of Suspended Sediment Concentration (SSC) from NS03 during 2009. Overview of all nearshore stations can be found in Appendix E

The water samples presented in Table 3.6 are plotted on the time series of SSC presented in Appendices E and F. The water samples show a generally good agreement with the SSC values. Unfortunately, most of the values represent low concentrations below 5mg/l. Except for a few points, the correspondence between the concentrations measured by the fixed stations and concentrations provided from water samples show the same SSC levels.

5.4 Spatial Distribution of Suspended Sediment from Cruises

A total of 96 profiles of turbidity (along with other parameters) have been measured during each of the monthly cruises undertaken in 2009 and 2010. The cruises last for 7 days and the stations are visited during this period. All profile data are marked with the exact time of the measurement and stored in the Data Handling Centre. The turbidity is measured with a similar OBS type instrument as used at the fixed stations.

The measured turbidity has been converted into suspended sediment concentrations using the correlations between turbidity and concentrations found for the main stations. It is noted that the correlation factor found for the main stations is lower than the factors found for the nearshore stations. This is because the suspended sediments are generally finer in deeper water than in more shallow areas.

Examples of suspended sediment profiles from selected cruises and profiles are shown in Figure 5.12 through Figure 5.16. Locations are given in Figure 5.11.

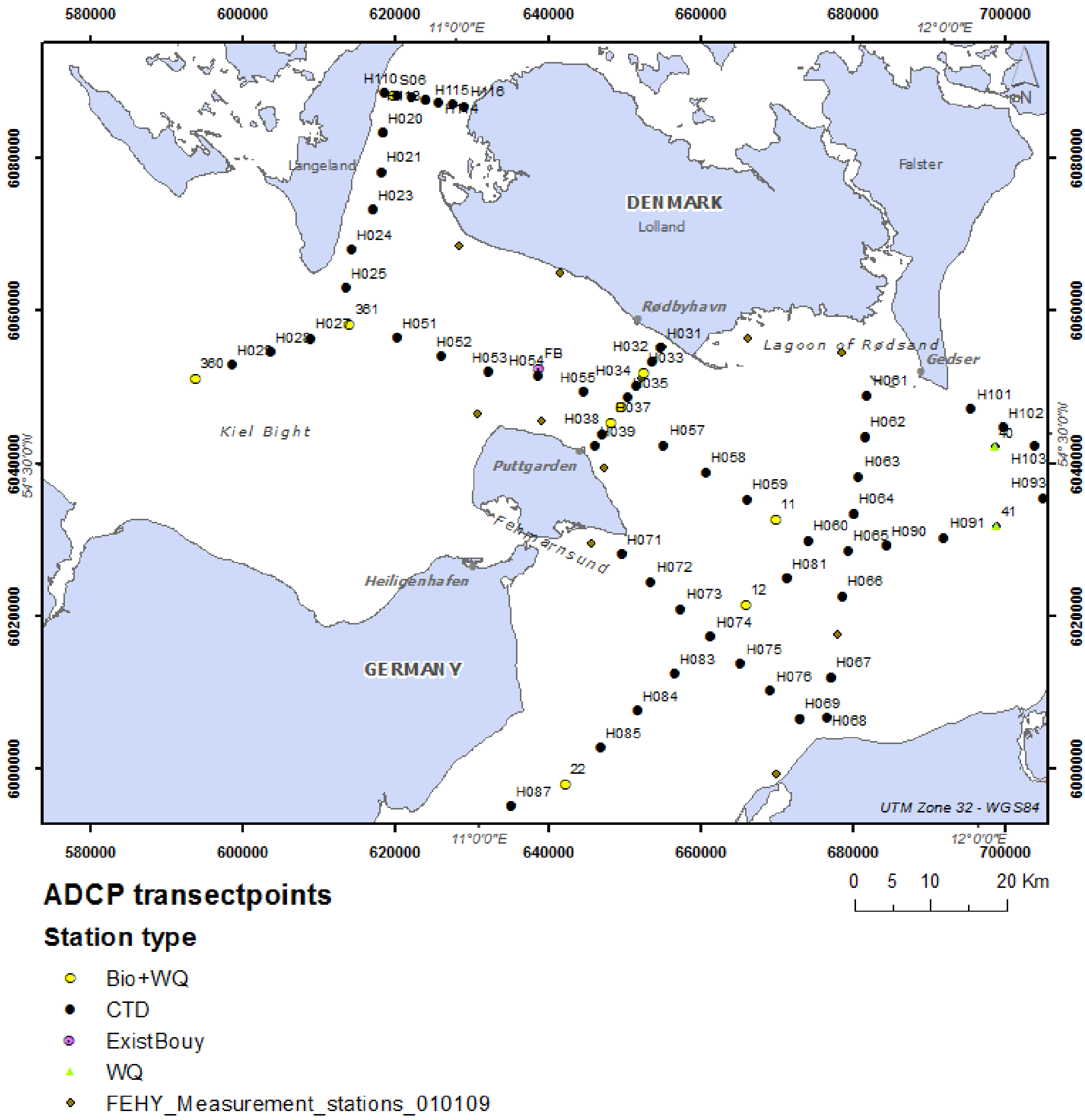


Figure 5.11 Location of cruise stations

Average suspended concentrations have been calculated for the upper 5m and the lower 5m for each measured profile. Suspended sediment concentrations for the upper and lower 5m derived from turbidity profile measurements are presented in Appendix J for all cruises.

Generally, the turbidity levels and thereby the suspended sediment concentrations are low, below 2mg/l during the cruises. However, the measurements from the cruise undertaken in the period 11–16 January 2010 showed somewhat higher values of turbidity over a large area. The spatial distributions of suspended concentrations from this cruise are presented in Figure 5.17 and Figure 5.18.

A north-easterly storm with wind speeds up till 14m/s occurred during the 3 days prior to the cruise. During the cruise, the wind turned to east south-easterly directions and exceeded 10m/s. The current speeds were generally low below

0.3m/s at MS01 during the cruise. The increased turbidity level was clearly caused by the waves generated by the strong wind prior to and during the cruise.

The overviews of suspended sediment concentrations derived from the turbidity profiles measured during the cruises may under-estimate the concentrations at the most shallow profile locations. This is because the correlation between turbidity and concentrations found from the main stations has been applied for all profiles.

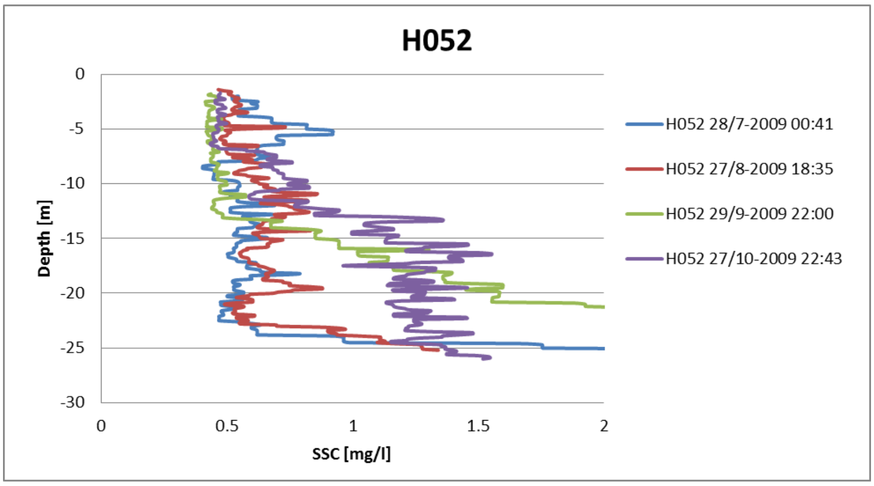


Figure 5.12 Example of SSC profile from the cruise stations. Location H052

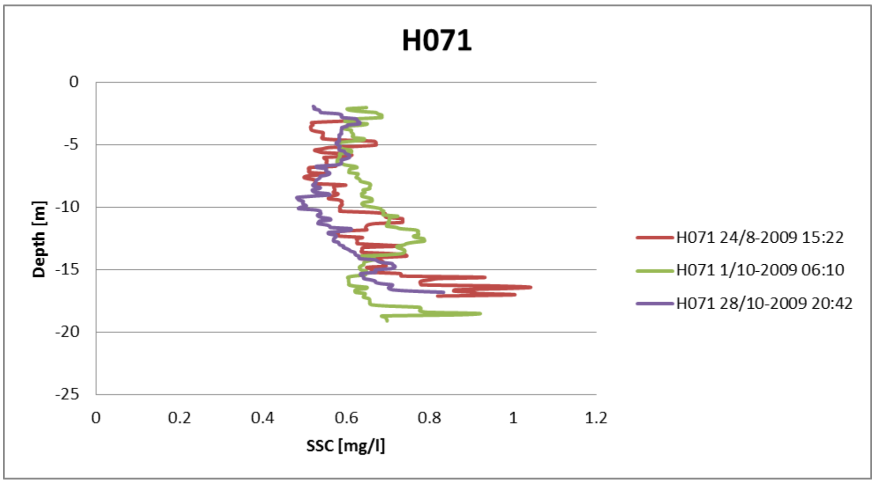


Figure 5.13 Example of SSC profile from the cruise stations. Location H071

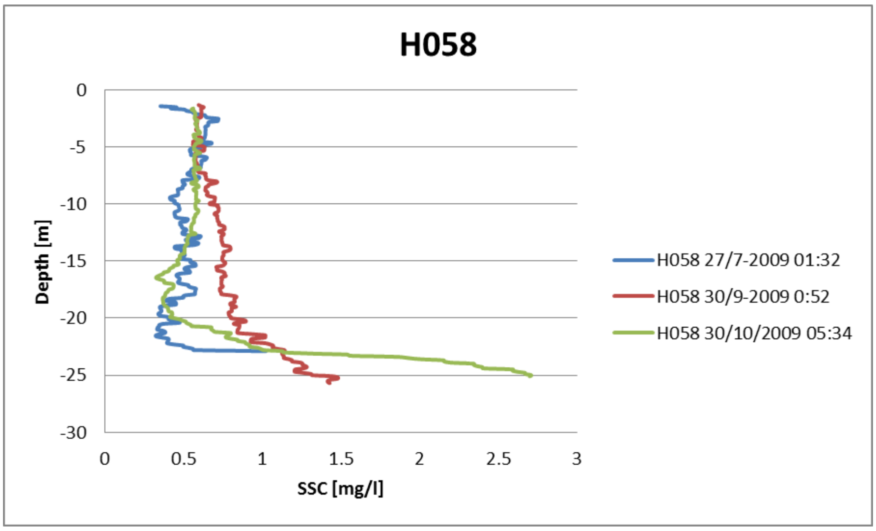


Figure 5.14 Example of SSC profile from the cruise stations. Location H058

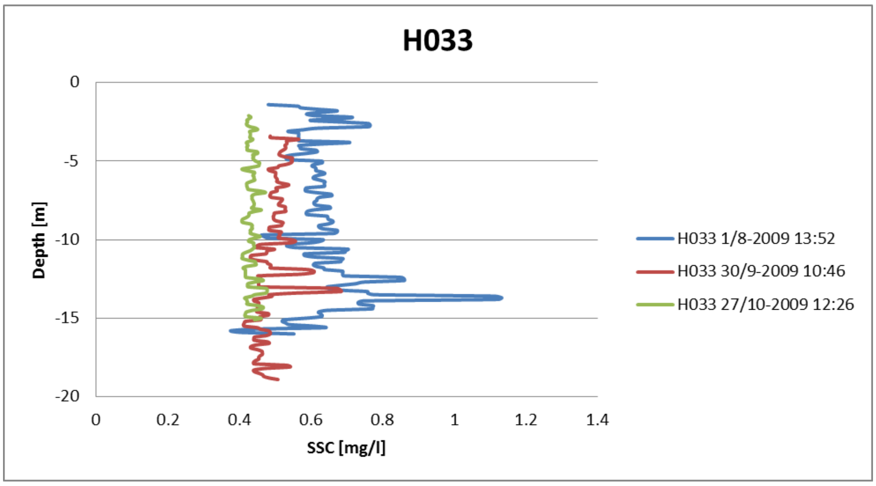


Figure 5.15 Example of SSC profile from the cruise stations. Location H033

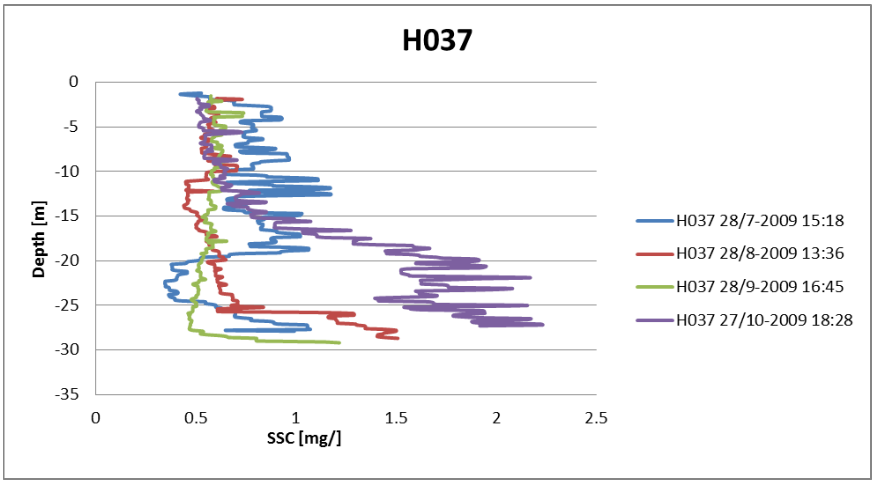


Figure 5.16 Example of SSC profile from the cruise stations. Location H037

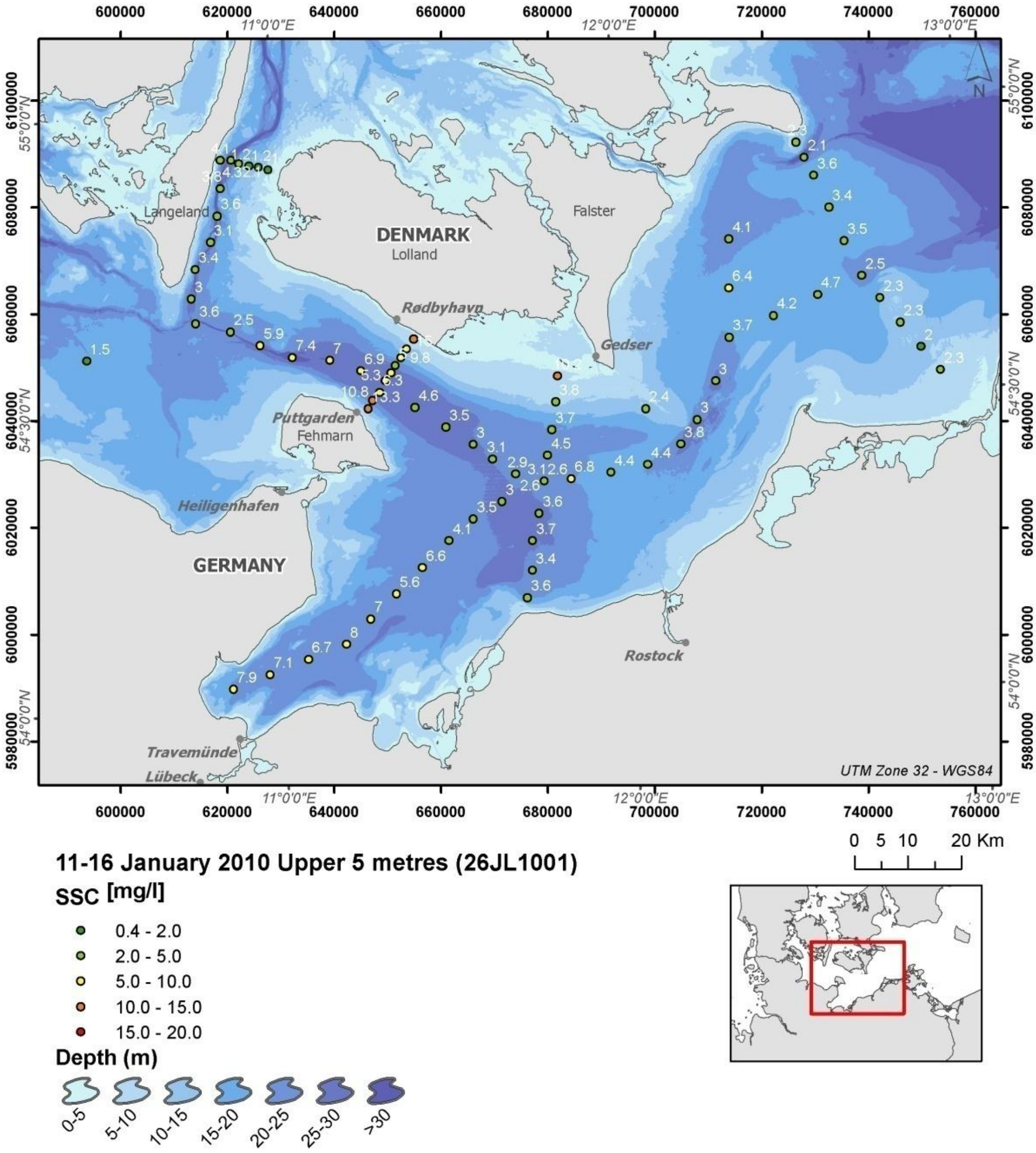


Figure 5.17 Example of spatial distribution of suspended sediment concentrations derived from turbidity profile measurements during the cruise 11-16 January 2010. Concentrations averaged over the upper 5m of each profile

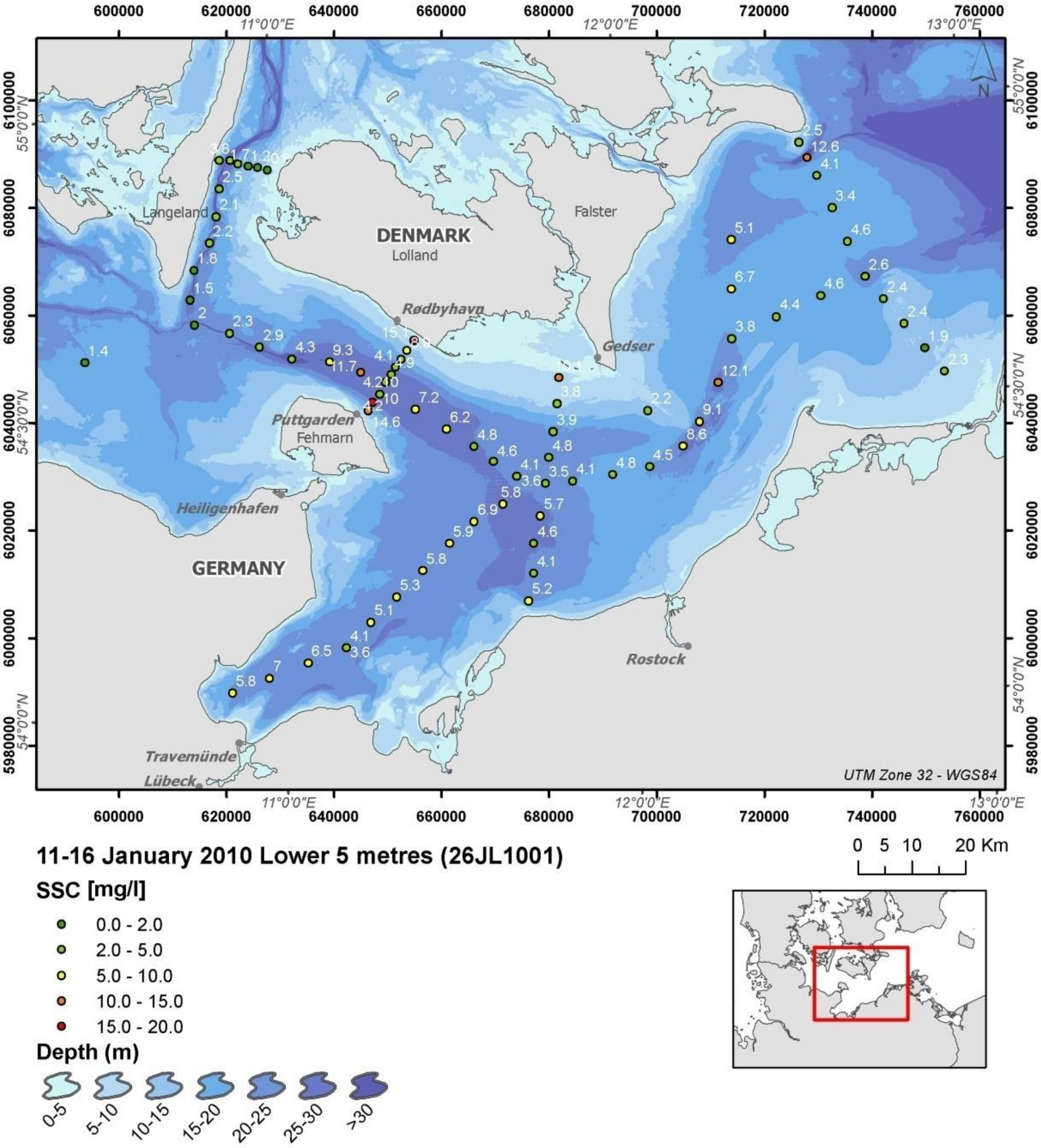


Figure 5.18 Example of spatial distribution of suspended sediment concentrations derived from turbidity profile measurements during the cruise 11-16 January 2010. Concentrations averaged over the lower 5m of each profile

6 CORRELATION BETWEEN SUSPENDED SEDIMENT CONCENTRATIONS AND HYDROGRAPHIC DATA

Time series of SSC data from the fixed stations, time series of modelled wind (StormGeo: WRF, 1/2-2009 – 01/06-2011) and current speed and directions from the main stations are evaluated to illustrate and discuss relations between the hydrographic parameters and SSC. The significant wave height and direction are determined by the wind. The wind was used as an overall parameter instead of the significant wave height measured at the main stations. The waves at the main stations are not necessarily representative for the nearshore stations as the NS stations are close to land and sheltered for some wind directions.

Time series plots of suspended concentrations for all fixed stations on a monthly basis together with wind and currents are presented in Appendices G and H.

First, an evaluation is made to see if the sediment is locally suspended from the seabed or if the events are part of regional re-suspension events. If the sediment concentrations measured at the nearshore stations and main stations are a result of regional re-suspension events, it would be possible to find a delay in the sediment concentrations signal from station to station that would be defined by the wind and current directions. Furthermore, it is evaluated whether there is a certain level of dynamics that need to be present to see a rise in the SSC.

The Danish nearshore stations NS01, NS02 and NS03 are located on the southern coast of Lolland, whereas NS04 and NS05 are located within the Lagoon of Rødsand, see location in Figure 3.1. The German nearshore stations NS06, NS07, and NS08 are located at the northern part of Fehmarn. NS09 is placed south-east of Fehmarn, whereas NS10 is placed about 40km south-east of Fehmarn next to the German mainland. The two latter German stations are not expected to act in the same way. However, they have been merged into one group to reduce the number of plots.

NS01, NS02 and NS03

The turbidity measurements at NS03 generally show higher concentrations of suspended sediment during rough events compared to NS01 and NS02. The lowest concentrations are seen at NS01.

Figure 6.1 shows an example of a number of typical events where high concentrations of suspended sediment are measured at stations NS01, NS02 and NS03. On 4 March 2009, the concentration has its maximum at NS02 at about 8am followed by a maximum in NS01 at 11am. The NS03 reaches its first maximum at 5pm the same day. Four days later, another event can be identified on 8 March 2009. At 11am, the maximum concentrations are reached at NS01 and NS03, and 2 hours later the maximum concentration at NS02 is reached. On 9 March 2009, the high SSC seems to be due to a combination of wind just below 8m/s and strong currents.

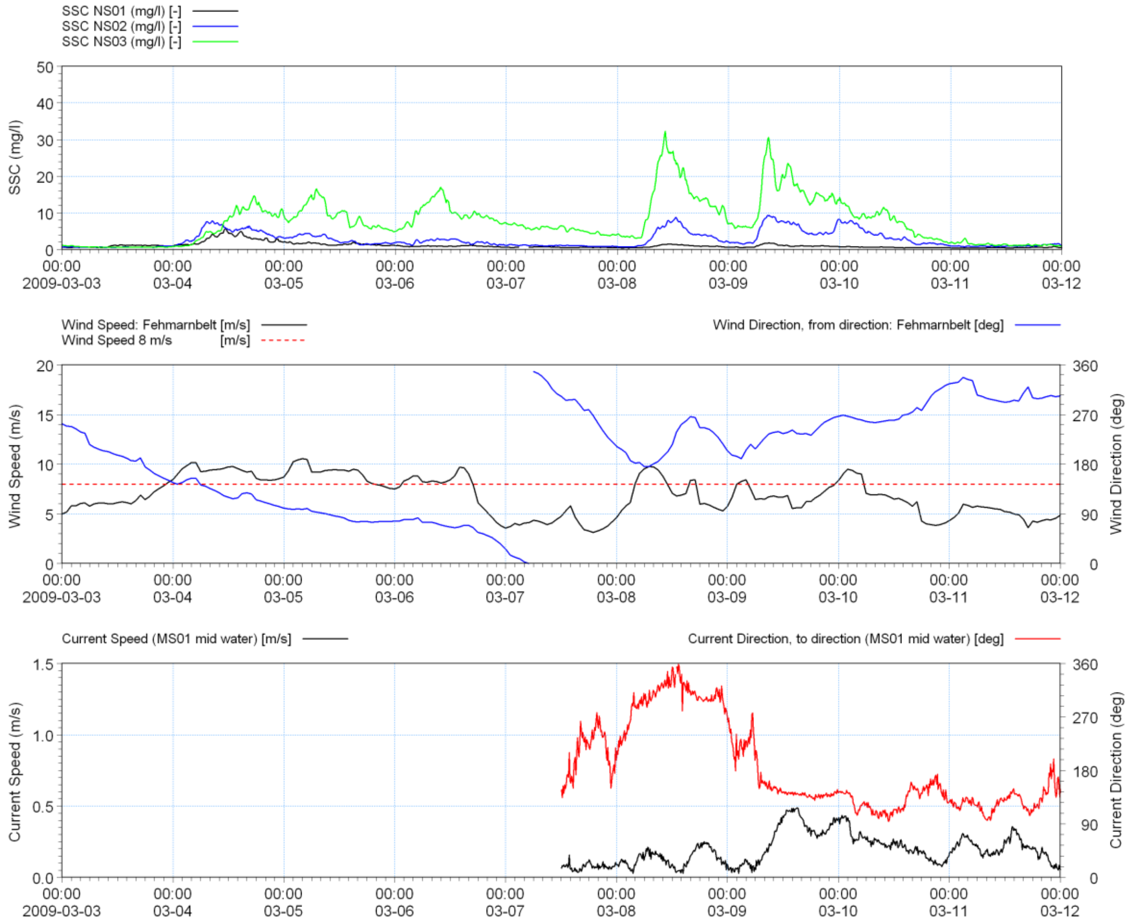


Figure 6.1 Upper panel: SSC at NS01, NS02, NS03. Middle panel: wind speed and direction. Lower panel: current speed and direction. March 2009

Figure 6.2 shows another typical example of high-concentration event at NS02 and NS03. No useful data are available from NS01 in this period. During a storm event in the beginning of October, a high concentration of suspended sediment is seen at the two stations. A very fine correspondence between the wind speed and the concentrations of sediment at both stations indicates an immediate effect of the storm, and the sediment must be suspended locally as the wave energy increases due to the rise in wind energy. The small increase on 10 October may be due to a combination of strong currents and wind from easterly directions which expose NS03 to waves.

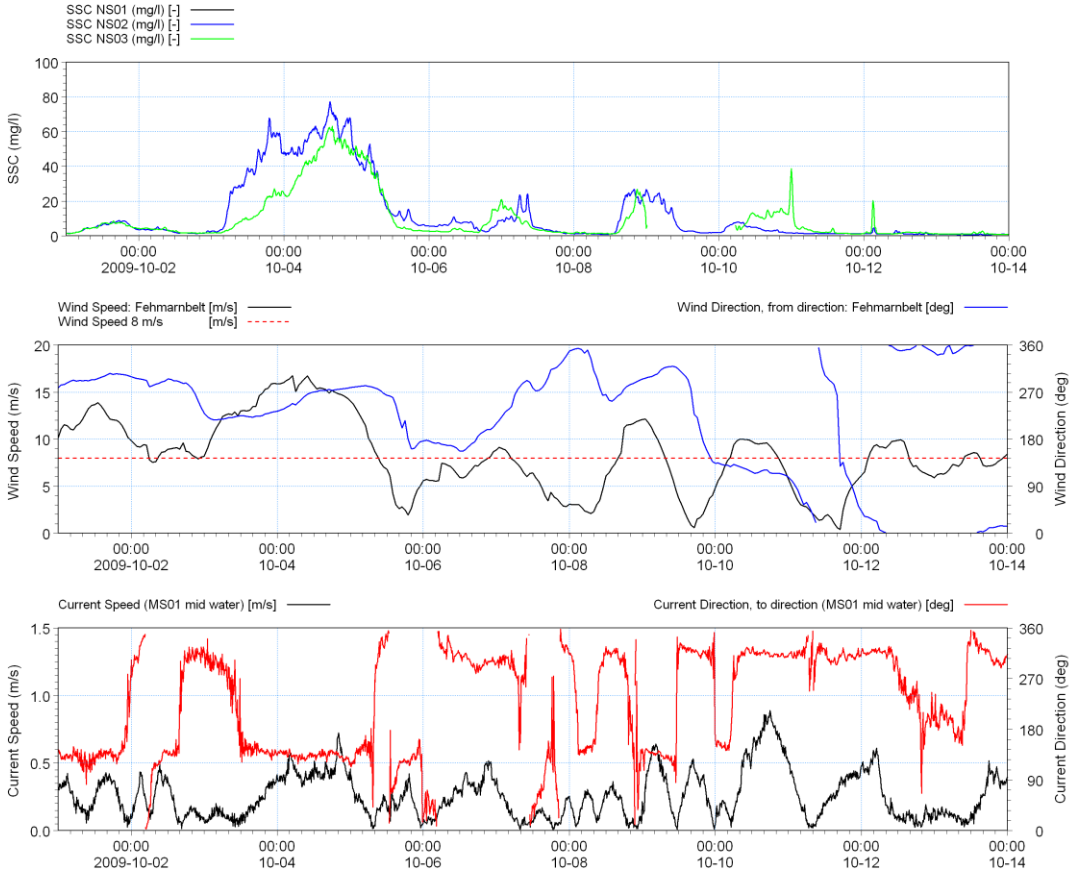


Figure 6.2 Upper panel: SSC at NS01, NS02. Middle panel: wind speed and direction. Lower panel: current speed and direction. October 2009

These examples of neighbouring measurements of sediment concentrations indicate that the variations in sediment concentrations are defined by local re-suspension events rather than regional transport patterns.

Time series of SSC at the Danish nearshore stations, in combination with wind speed and direction and current speed and direction at MS01, show an increase in concentration when the wind speed rises above approximately 8m/s. However, the wind direction is also an important parameter. NS01, NS02 and NS03 are generally exposed to wind coming from south-eastern and western directions. The wind direction and the duration of high wind speeds are often the explanation of why the effects of identical wind speeds result in differences in concentrations. After long high-dynamic conditions, the SSC level is generally higher compared to periods where high wind speed is rare. An example is presented in Figure 6.3, where the wind speed reached 14m/s on 10 January 2010 and the corresponding SSC at NS02 and NS03 reached 50mg/l and 100mg/l. In the following period on 14 January 2010, the maximum wind speed was 10m/s, whereas the SSC reached values of 75mg/l and almost 200mg/l at NS02 and NS03. This illustrates that it is not possible to correlate SSC directly to wind speed and direction. In this case, the event on 10 January 2010 most likely mobilised an amount of sediment. During the event on 14 January, the concentrations raised even higher despite the wind direction being parallel to the shore. This shows that the event on 10 January left back a layer of easily erodible sediments that were easily re-suspended on 14 January.

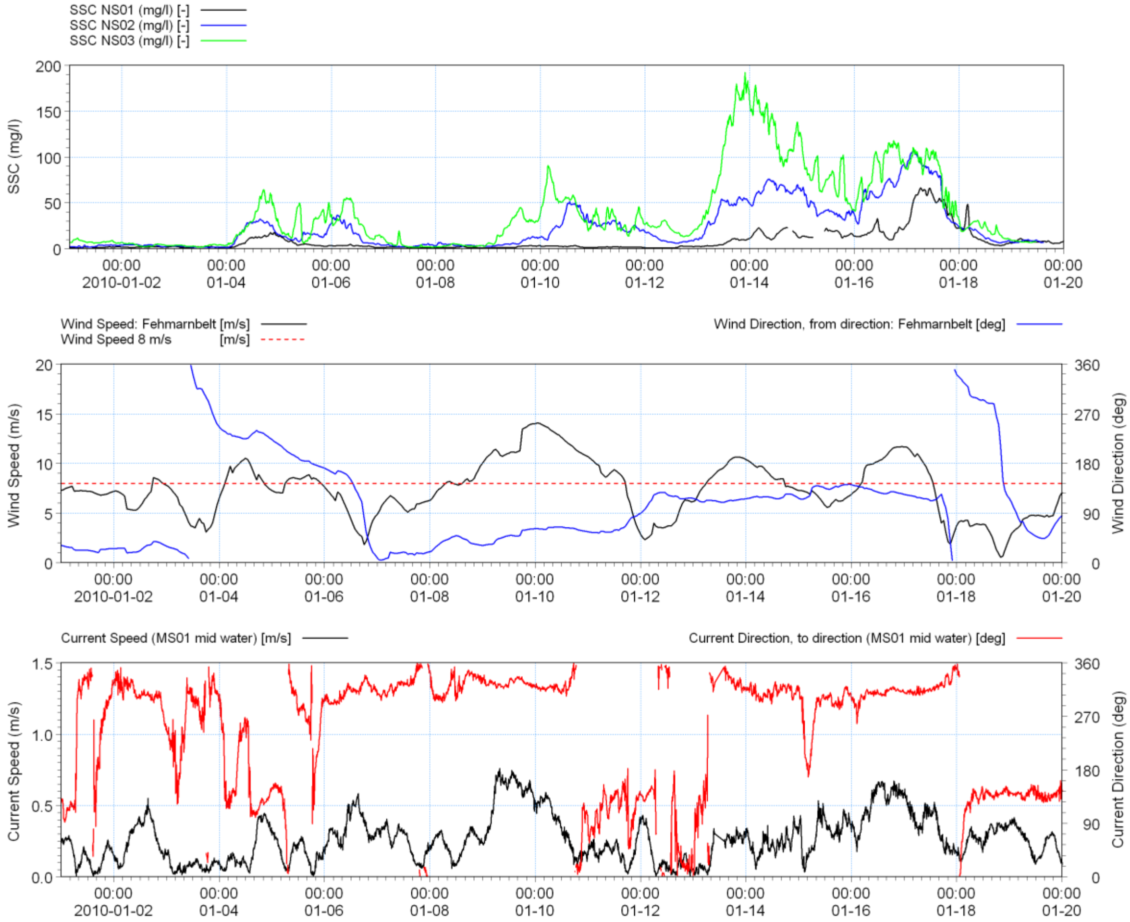


Figure 6.3 Upper panel: SSC at NS01, NS02, NS03. Middle panel: wind speed and direction. Lower panel: current speed and direction. January 2010

Figure 6.4 shows another example of a series of typical high-concentration events measured during September 2010 at stations NS01, NS02 and NS03. On 7 September 2010, a gradually increasing easterly and south-easterly wind speed from 8m/s reaching to its peak at 13.2m/s on 8 September 2010 at 12pm has been observed for MS01. During this period, a north-westerly going current through the Fehmarnbelt was identified. Due to this, the SSC at NS03 rises earlier compared to NS01 and NS02, and it reaches its maximum concentration of 29mg/l on 8 September at 9:40am followed by NS02, which reaches its maximum concentration of 16.2mg/l on 9 September at approximately 00:10. The SSC at NS01 is observed to be lower than the other two stations and generally stay below 6mg/l during the first half of September 2010. It is also noted that when the wind speed starts to fall below the threshold value of 8m/s on 9 September at 4pm, the SSC for both NS02 and NS03 gradually decrease. During the second half of September 2010, from 14–21 September 2010, stronger south-westerly and westerly wind conditions with wind speeds of 8–16m/s were experienced. During this period, a south-easterly going current through the Fehmarnbelt was observed. Several high SSC peaks are observed especially when the wind speed reaches 13m/s and above with the highest SSC observed for both NS02 and NS03 at approximately 80mg/l on 16 September at 00:00. SSC for NS01 has an almost similar trend as NS02 and NS03 but with a lower concentration. The maximum SSC for NS01 is only observed on 18 September at 9:20am.

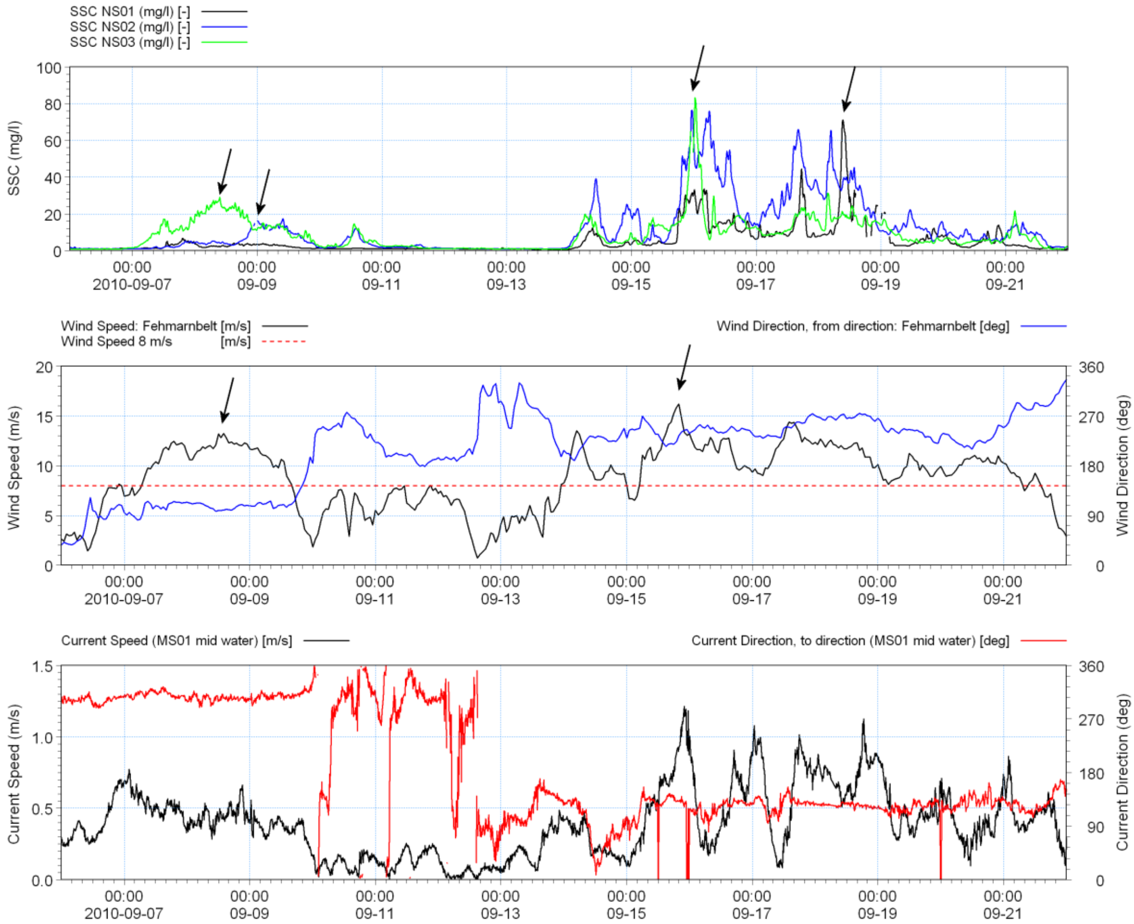


Figure 6.4 Upper panel: SSC at NS01, NS02, NS03. Middle panel: wind speed and direction. Lower panel: current speed and direction. September 2010

NS04 and NS05

NS04 and NS05 are located in the Lagoon of Rødsand. NS04 is in a sheltered place behind the extension of the Hyllekrog barrier. NS05 is placed at a more exposed place in the middle of the entrance to the Lagoon of Rødsand. The time series from NS04 and NS05 show that NS05 measures larger concentrations compared to NS04 during severe events.

The wind speed threshold level of 8m/s seems to be valid also in the lagoon. When the wind speed exceeds 8m/s, the SSC is rising and suspension events are seen. An example can be seen in Figure 6.5. This example also shows that the concentration at NS05 is not always larger compared to NS04. A possible explanation for the larger SSC measured during the storm in beginning of October 2009 can be the low water depths at NS04 (only 1.5m), and hence the very high energy at the bottom when very large waves appear. Re-suspension of sediment at NS04 and NS05 within the Lagoon of Rødsand will be somewhat influenced by the wind blowing from north-easterly to south-easterly and from south-westerly directions.

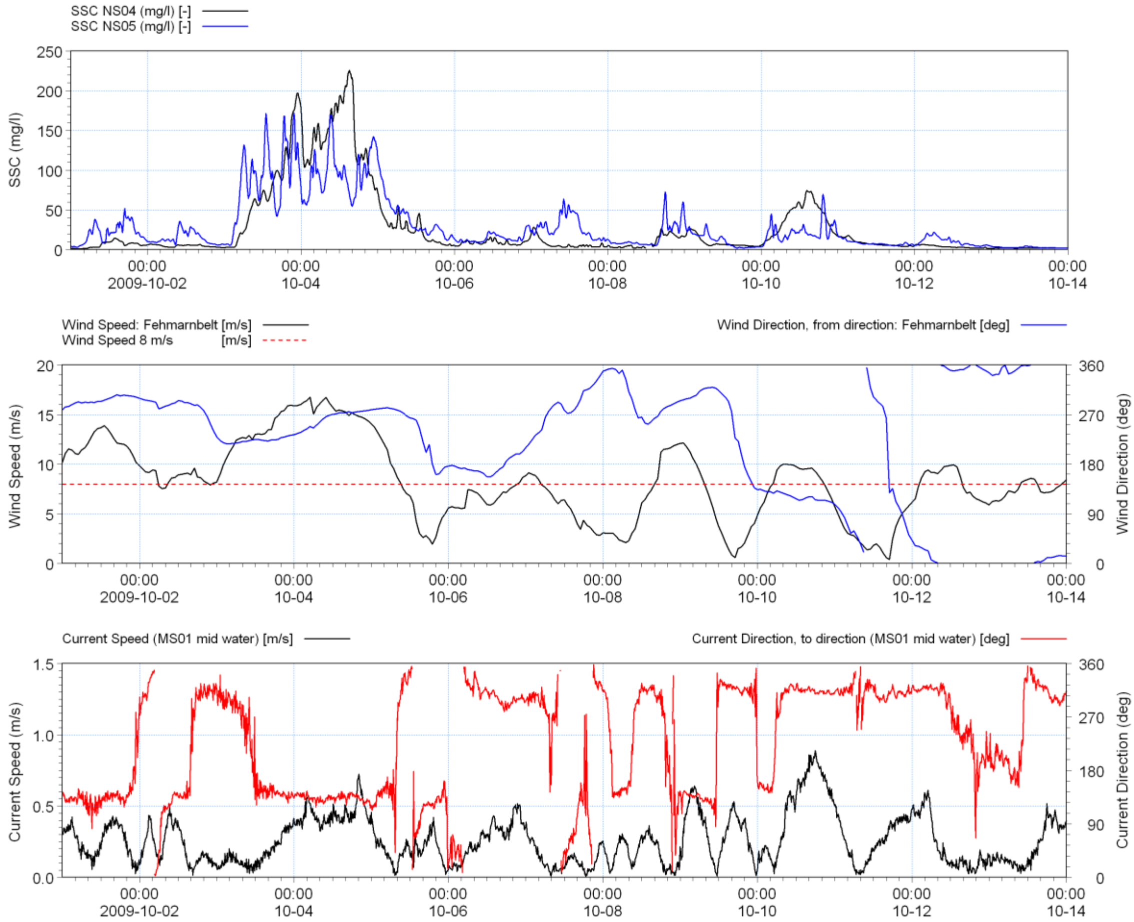


Figure 6.5 *Upper panel: SSC at NS04, NS05. Middle panel: wind speed and direction. Lower panel: current speed and direction. October 2009*

From the above examples and the time series presented in Appendix H, it seems that the suspended sediment concentrations at the Danish nearshore stations are induced by the waves and not by the current. From the wind rose presented in Figure 6.8, it can be seen that the Danish nearshore stations are quite exposed to common wind directions in the area. In Section 7.2.2, further statistics are provided to underline this relation between wind and SSC at the Danish nearshore stations.

Figure 6.6 shows the suspended sediment concentrations measured during January 2010 at stations NS05 only, as no data were available for NS04 for this period. The maximum suspended sediment concentration of 195mg/l has been observed on 10 January 2010 at approximately 10:30am when the north-easterly wind with magnitude of 14m/s blows towards the Lagoon of Rødsand. A second high peak of SSC measuring 140mg/l occurred on 13 September 2010 around 8:10pm during the south-easterly wind condition with wind speed of 11m/s blowing towards the Lagoon of Rødsand.

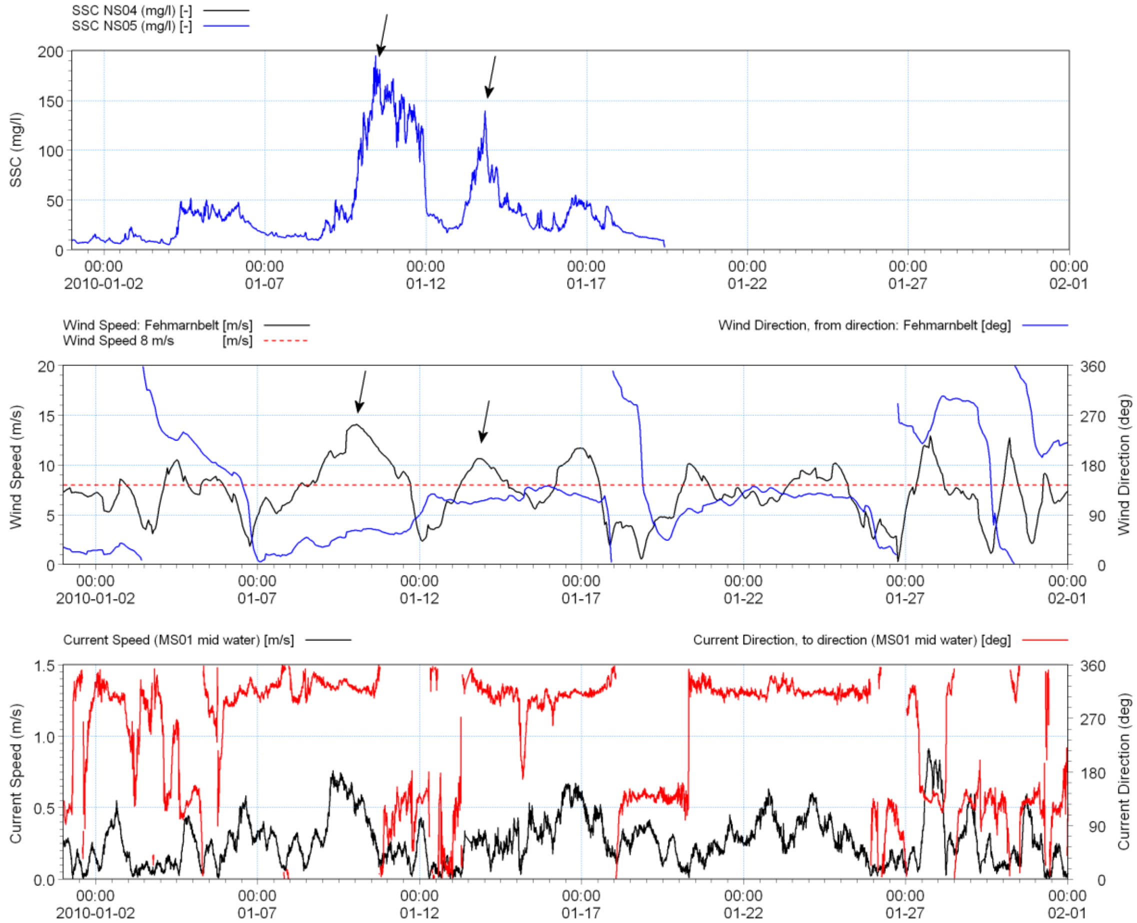


Figure 6.6 Upper panel: SSC at NS04, NS05. Middle panel: wind speed and direction. Lower panel: current speed and direction. January 2010

Figure 6.7 shows an example of suspended sediment concentrations measured during September 2010 at stations NS04 and NS05. From 7 September 2010, dominant easterly and south-easterly wind speeds of 8m/s to 13m/s have been observed for MS01 which lasted for about two days. During this period, NS04 is observed to experience higher level of SSC as compared to NS05 due to its location which is more exposed to the south-easterly winds and wind-induced waves. From 14 September 2010 onwards, the SSC for both NS04 and NS05 gradually increase with the stronger south-westerly winds, and the concentrations are kept in suspension until around 21 September 2010 when the wind speeds drop below 8m/s.

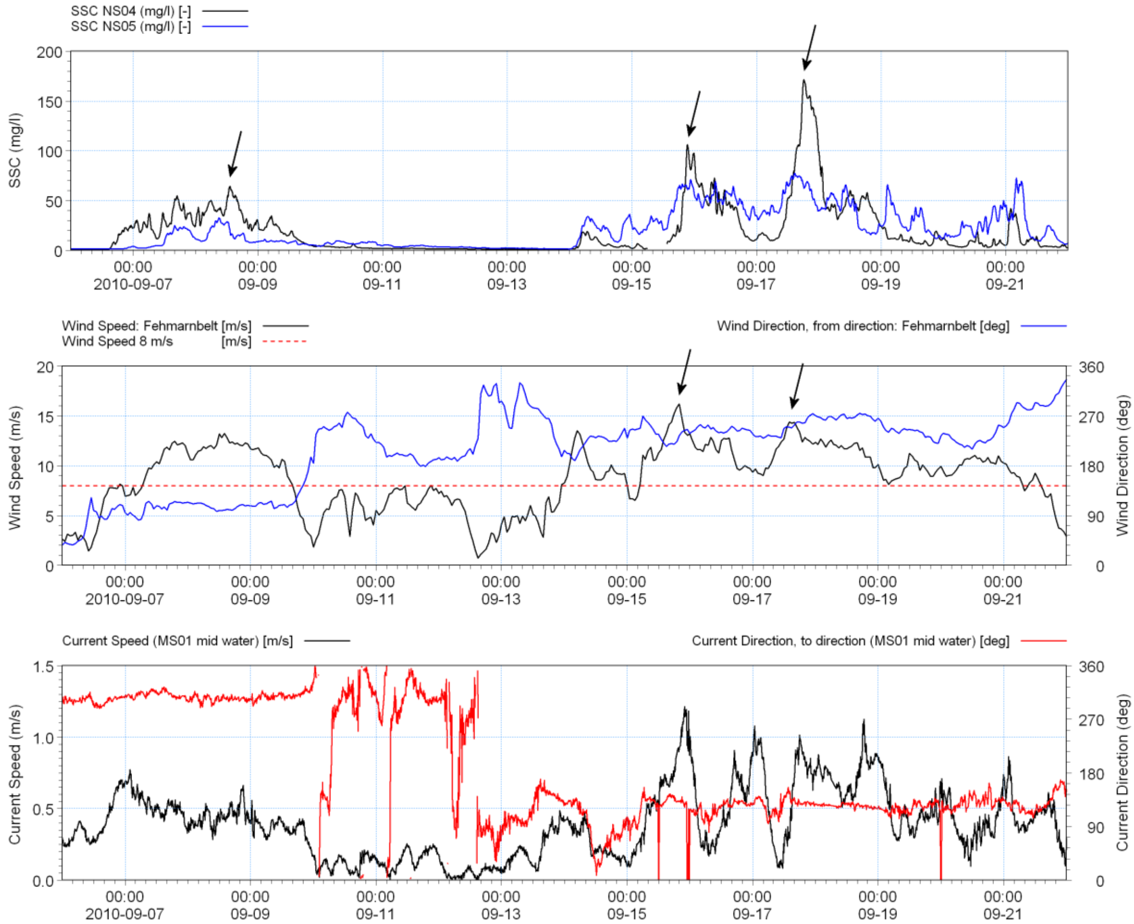


Figure 6.7 *Upper panel: SSC at NS04, NS05. Middle panel: wind speed and direction. Lower panel: current speed and direction. September 2010*

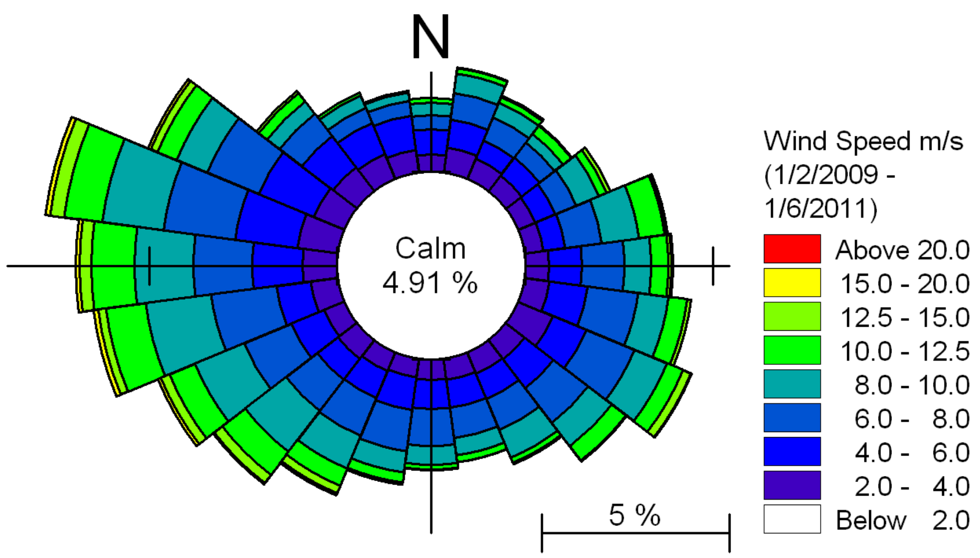


Figure 6.8 *Wind rose from the Fehmarnbelt. The period covered is 1/2-2009 – 1/6-2011 (Storm Geo: WRF)*

NS06, NS07 and NS08
The suspended sediment concentrations are generally much lower at the German nearshore stations than at the Danish stations. Until September 2009, the concentrations hardly exceed 10mg/l at NS06, NS07 and NS08. From September until the end of December 2009, the concentrations of suspended sediment reached 50mg/l, but only occasionally. This similar trend can be seen for the year 2010 as well, but the suspended sediment concentration has been seen.

For NS06, NS07 and NS08, there is no clear connection to a certain wind speed. Visually, the SSC fluctuations seem to be more randomly distributed and not related to wind speed to the same degree as the Danish nearshore stations. One explanation of this might be the geographical location of the German nearshore stations. Apart from NS06, all German nearshore stations are partly or fully sheltered from the most dominating wind directions coming from westerly directions. NS06, NS07 and NS08 are also partly sheltered by Fehmarn for wind directions from south-east. Contrary to the Danish nearshore stations where there is a strong correlation between waves and SSC, suspended sediment concentrations at the German nearshore stations are better correlated to the current speed. The German stations are generally located at larger water depth than the Danish ones and measure SSC 3.6m-5.3m above the bed compared to 2m above the bed at the nearshore stations (NS01-NS03). The short-period waves in the Fehmarnbelt do not contribute significantly to the bed shear stress at the water depths at NS06-NS08.

Figure 6.9 shows the time series plot from the first half of October. SSC data from NS07 and NS08 are available and useful for that period. The black arrows on the time series plot show the events where a clear relation to the current speed is seen.

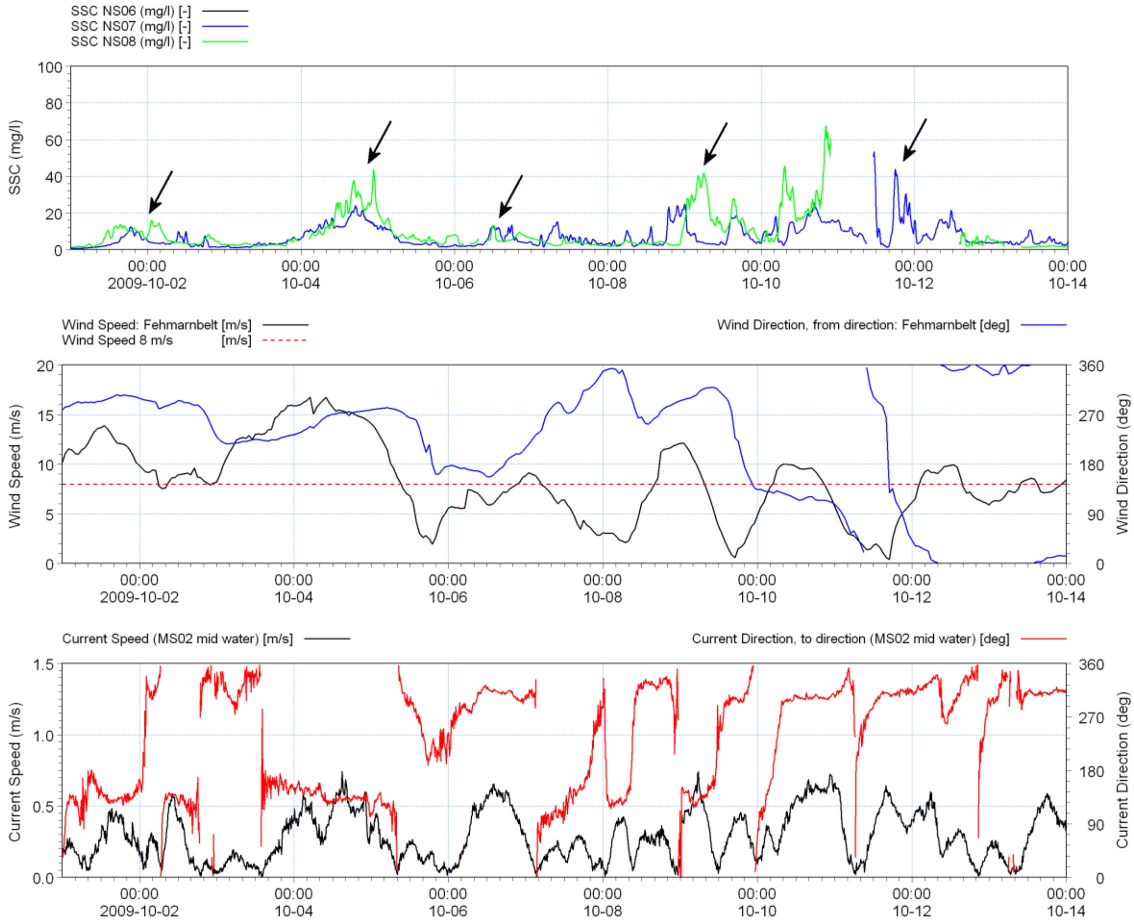


Figure 6.9 *Upper panel: SSC at NS06, NS07, NS08. Middle panel: wind speed and direction. Lower panel: current speed and direction. October 2009*

Another factor seen to have a relation to the SSC at the German nearshore stations is when the current in the Fehmarnbelt changes direction. When the current direction changes, it is seen that a regional circulation arises in the Fehmarnbelt and that the circulation brings bottom water from the Belt up in the water column. This bottom water is then circulated towards the coast. Suspended sediment may be brought to the nearshore stations by this mechanism. The result is that regionally-generated re-suspension of sediment can be measured at the nearshore stations. An example of a sediment concentration event that might come from a situation like this is presented in Figure 6.10.

On 18 November in the evening, a strong current is bringing sediment in suspension at the nearshore stations and the main station 2. The circulation starts at 10am on 19 November, where the current direction changes and bottom water is brought in circulation from MS02. The regional suspension is measured at the nearshore stations between 10am and 5pm on 19 November. At 6pm the current direction changes again and the circulation stops or changes its direction.

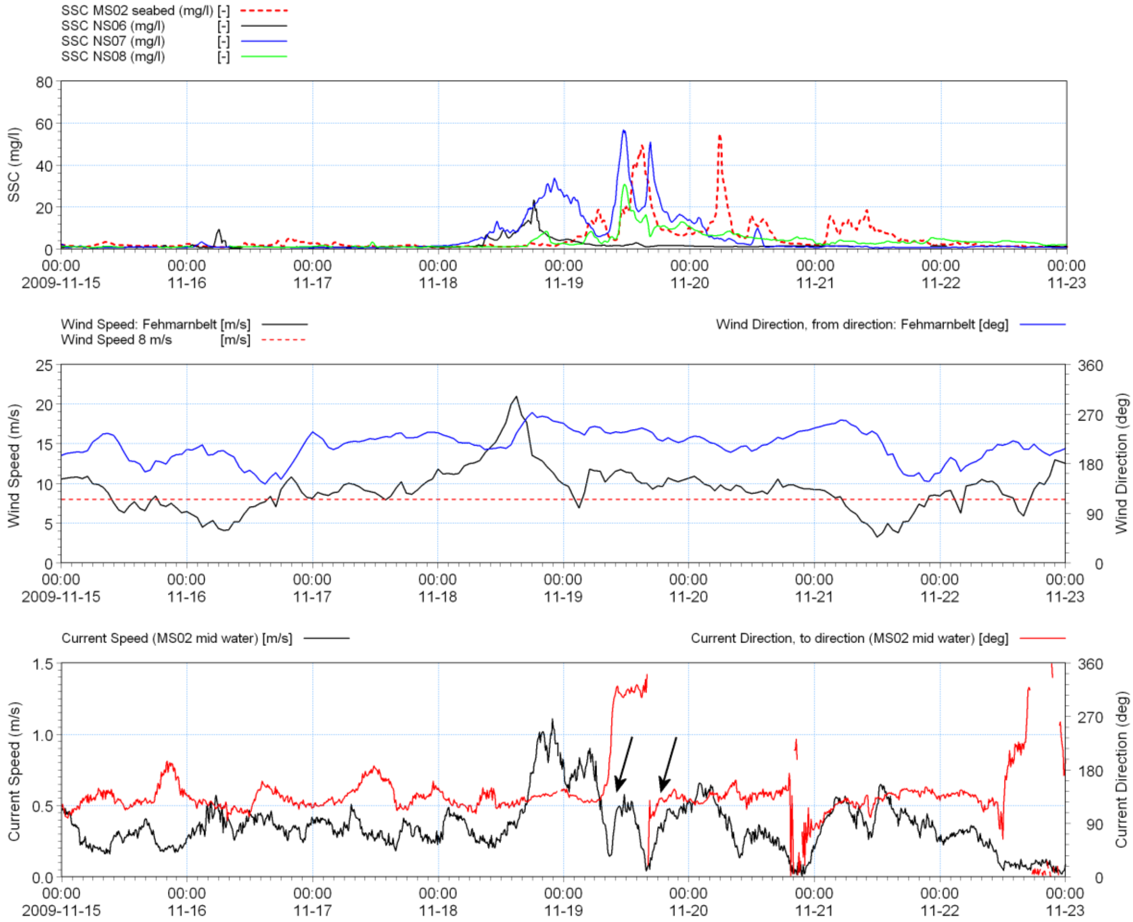


Figure 6.10 Upper panel: SSC at MS02, NS06, NS07, NS08. Middle panel: wind speed and direction. Lower panel: current speed and direction. November 2009

NS09 and NS10

From the time series plots, it can be seen that the NS09 and NS10 follow the same trend as the other German nearshore stations with very low concentrations until the beginning of October. After that, only a few events appeared with concentrations up to 50mg/l. The rest of the time, the concentrations were very low at about 2-4mg/l. An example of the October storm is presented on Figure 6.11.

The suspended concentrations at the German nearshore stations are more influenced by current and not by waves as on the Danish side. This can partly be explained by the dominating wind directions and partly by the fact that the German nearshore stations are placed at larger depths (see Table 3.2) and higher above the bed and thereby not so influenced by waves.

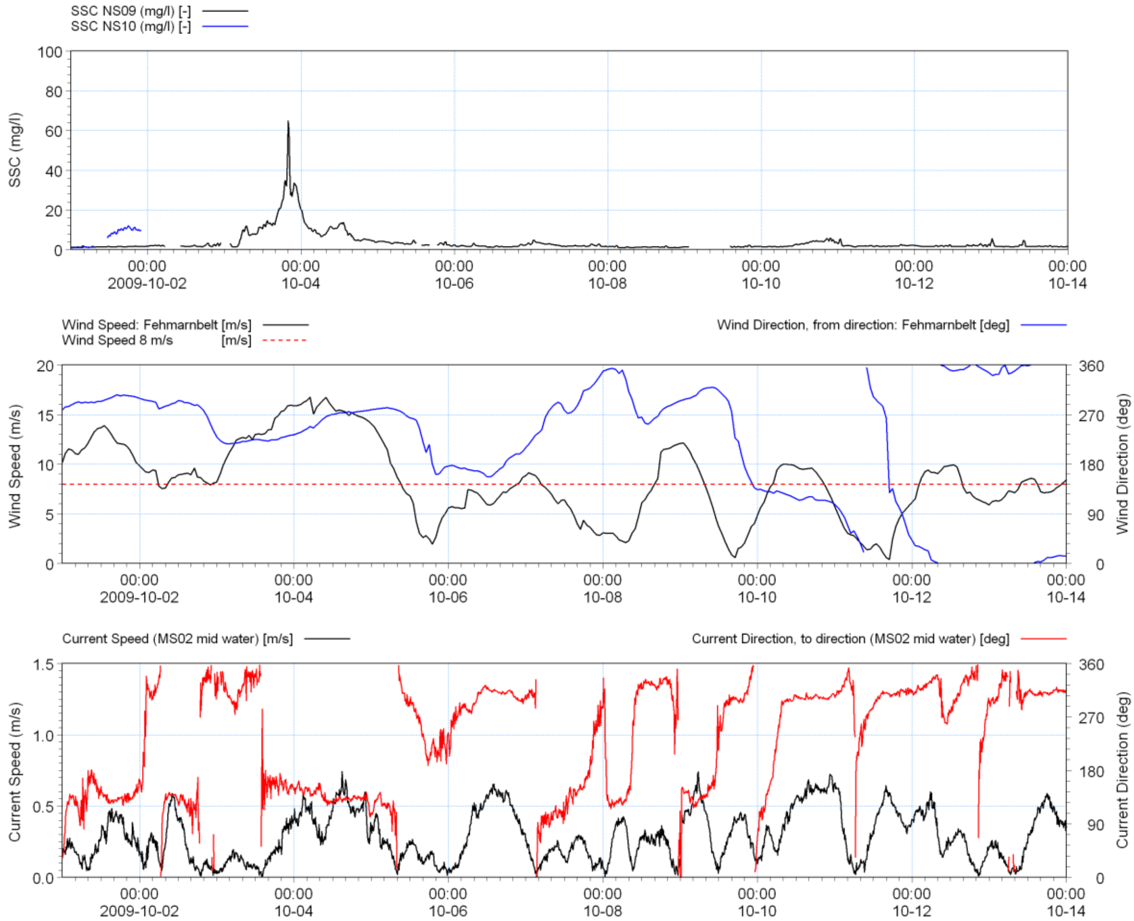


Figure 6.11 Upper panel: SSC at NS09, NS10. Middle panel: wind speed and direction. Lower panel: current speed and direction. October 2009

NS01a, NS02a, NS03a

The suspended sediment concentrations at the relocated nearshore locations (NS01a – NS03a, all located at about 3m of water depth) show a much more dynamic behaviour than the measurements acquired at the original location. Suspended sediment concentrations up to 500mg/l are regularly obtained during rough weather. An example is given in Figure 6.12, where wind speeds are reaching 20m/s. It is seen that the concentrations are very low (1-5mg/l) during the calm period, but once the wind speed rises, the concentrations increase considerably. Based on analyses of the water samples extracted at NS03a, a considerable amount up to 40% of the sediment is sand. This sand settles out very quickly after the wind has decreased, but the concentrations are still in the order of 100mg/l during a longer period. This is most likely the fines that have very low settling velocities and thus remain in the water column also during calmer weather.

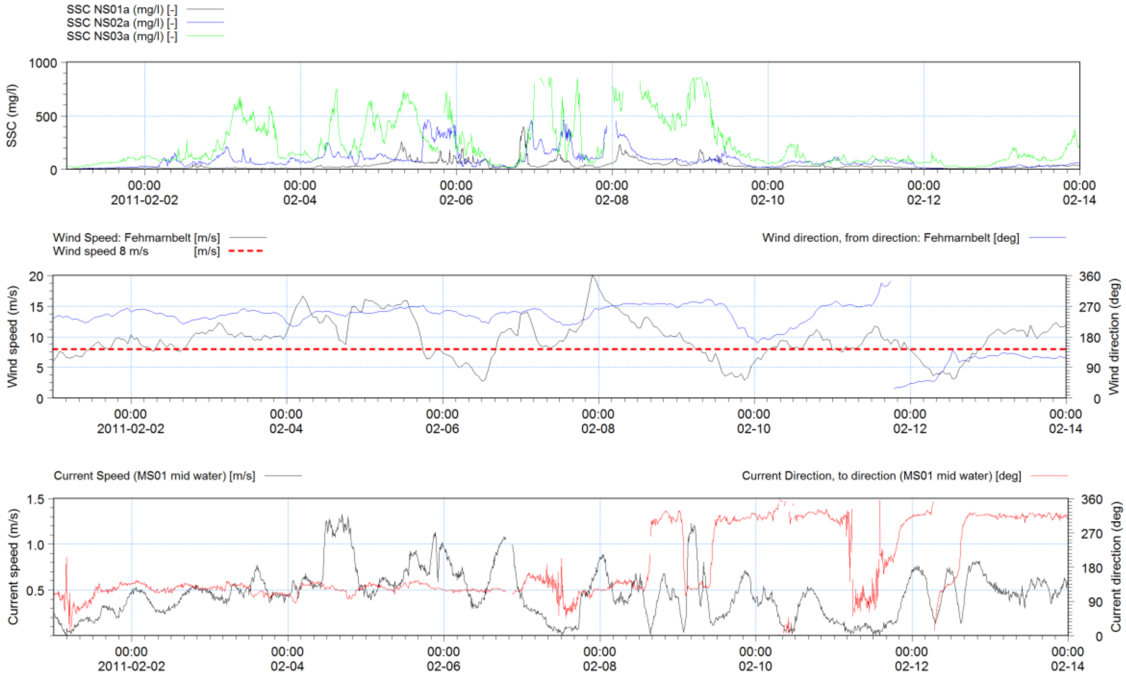


Figure 6.12 Upper panel: SSC at NS01a, NS02a, NS03a. Middle panel: wind speed and direction. Lower panel: current speed and direction. February 2011

NS06a, NS07a, NS08a

NS06a – NS08a on the German side of Fehmarnbelt show lower concentrations than at the Danish nearshore locations. This is due to the fact that the German stations are located at deeper water (about 5m for NS06a-NS08a), which makes the effect of waves less important. Still the concentrations at the more nearshore locations show an increase compared to the original locations (NS06-NS08). During wind events, concentrations up to about 200mg/l are seen. The concentrations drop back to background level fairly quickly after the wind events, which suggests a certain amount of sand in suspension.

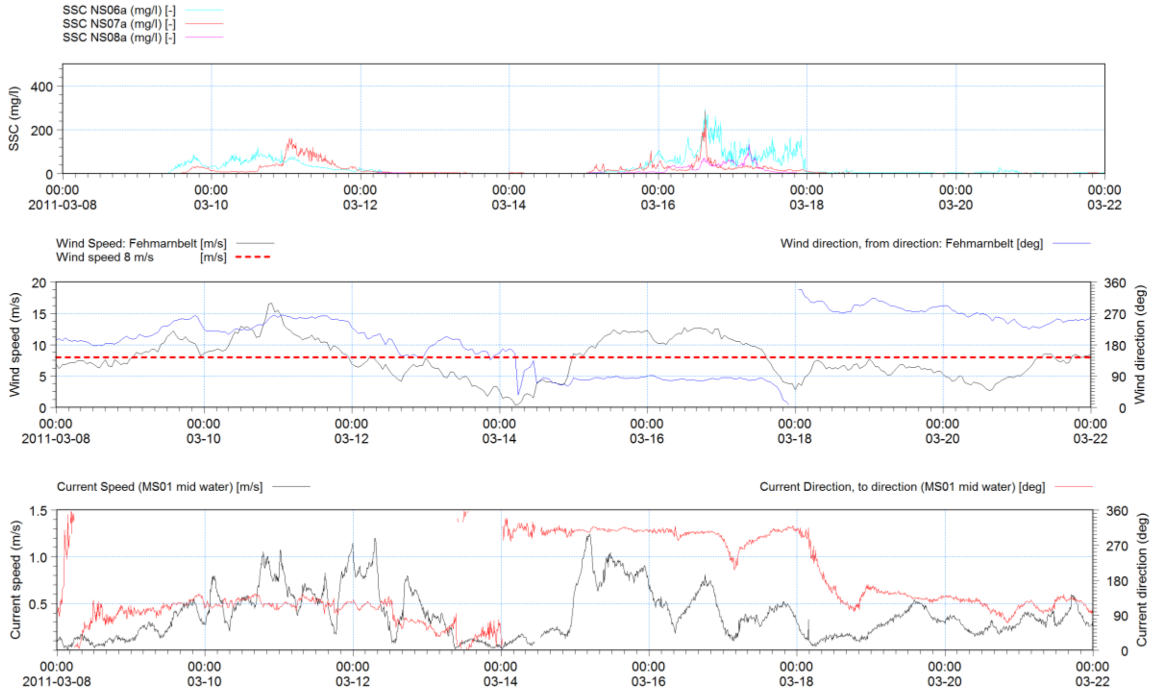


Figure 6.13 Upper panel: SSC at NS06a, NS07a, NS08a. Middle panel: wind speed and direction. Lower panel: current speed and direction. March 2011

MS01, MS02 and MS03

Monthly time series plots from the main stations are presented in Appendix G. The background concentrations of suspended sediment at the main stations near the corridor are very low; most of the time between 1-2mg/l for the entire water column. However, in the autumn and winter months, the frequency of occurrence of events with higher concentrations increases. Suspension events are seen at MS01 with SSC up to 30mg/l at all three measurement levels a couple of times from October 2009 till January 2010. During this period, the concentrations are generally higher at the bottom and at the mid water level compared to the surface level. The rest of the measurement period, the SSC levels are low, below 5mg/l. When the concentration rises at MS02 in September 2009, it is mainly seen at the lower measurement level with quite a few events with concentrations up to 30mg/l and even a few events up to 50mg/l. Both for MS02 and MS03, there is a tendency that the surface concentrations are higher than the mid water level. The measurements, however, show that the suspended sediment concentrations are low most of the time. At MS03, an increase in the concentrations near the seabed is seen in the winter months as well.

7 SUSPENDED SEDIMENT CONCENTRATION STATISTICS

7.1 Overall Statistics of SSC

Figure 7.1 shows an overview of selected statistical parameters for the nearshore and the main stations along with depths and data coverage after quality assurance has removed part of the original data. The data coverage varies between ~50% and 100% with an average of 77%. The main loss of data is due to the spring plume, which results in noisy data which have been discarded.

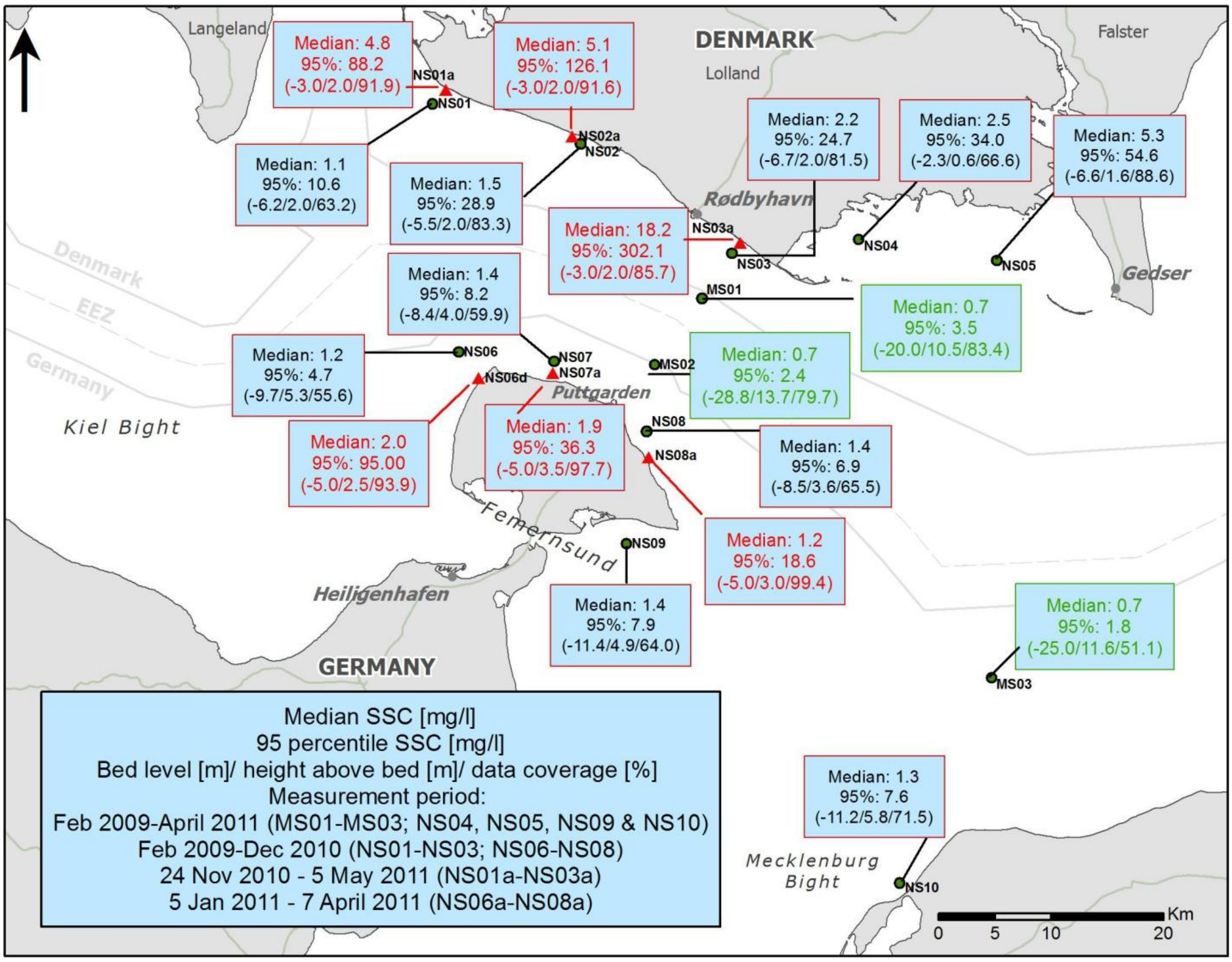


Figure 7.1 Overall statistics for the measurements of suspended sediment concentration at the nearshore stations and the main stations. 'Median' is the value which is exceeded in 50% of the observations. The values presented at the main stations are from the mid water measurements

The median concentrations are generally low; less than 2mg/l for water depths larger than 6m and less than 5.3mg/l for water depths smaller than 6m. The 95 percentile (the concentration exceeded 5% of the time) is high, in the range from 30mg/l to 330mg/l for water depths smaller than 6m. For water depths larger than approximately 6m, the 95 percentile is much lower; in the range 1.7mg/l to 9.3mg/l. Clearly, the natural content of suspended sediment reaches high levels in the coastal zone and in the Rødsand Lagoon when loose sediments are re-suspended by waves and currents.

Table 7.1 Overall statistics for the measurements of suspended sediment concentration from the main stations from the periods noted in the table

Measurement station	MS01 (7/3-09 - 1/5-11)			MS02 (29/3-09 – 1/5-11)			MS03 (30/3-09 – 1/5-11)		
	surface	mid water	seabed	surface	mid water	seabed	surface	mid water	seabed
Mean SSC [mg/l]	2.1	1.2	1.8	1.9	1.0	2.7	1.4	0.9	3.0
Median SSC [mg/l]	1.5	0.7	1.0	1.6	0.7	1.8	1.3	0.7	1.6
95 percentile (SSC [mg/l])	5.0	3.5	5.4	4.6	2.4	7.3	2.4	1.8	7.6
Data coverage (%)	49.3	83.4	87.9	69.3	79.7	75.7	75.8	51.1	59.5

7.1.1 Seasonal Variations

Table 7.2 Seasonal statistics of measurements of suspended sediment concentration for the nearshore stations

	NS01	NS02	NS03	NS04	NS05	NS06	NS07	NS08	NS09	NS10
	Spring 2009/2010/2011: March, April and May									
Mean SSC [mg/l]	**1.1**	**1.6**	**3.9**	**6.0**	**7.6**	**1.2**	**1.6**	**1.6**	**1.6**	**1.6**
Median SSC [mg/l]	**0.8**	**1.1**	**1.8**	**2.6**	**3.9**	**1**	**1.1**	**1**	**1.2**	**1.2**
95% SSC [mg/l]	**2.3**	**4.5**	**13.2**	**24.2**	**28.8**	**2.7**	**3.8**	**4.1**	**3.8**	**3.8**
Data coverage (%)	**49.0**	**62.7**	**69.9**	**70.8**	**90.8**	**51.1**	**48.2**	**51.8**	**64.2**	**68.7**
	Summer 2009/2010: June, July and August									
Mean SSC [mg/l]	**2**	**3.1**	**3.2**	**3.1**	**7**	**1.6**	**1.7**	**1.6**	**1.4**	**1.4**
Median SSC [mg/l]	**1.2**	**1.5**	**1.7**	**1.8**	**3.1**	**1**	**1.3**	**1.4**	**1.1**	**1.1**
95% SSC [mg/l]	**7.2**	**11.7**	**10**	**6.5**	**28.7**	**3.3**	**3.9**	**2.9**	**2.4**	**2.9**
Data coverage (%)	**59.6**	**83.9**	**75.2**	**81.3**	**94.1**	**29.1**	**31.2**	**58**	**70.7**	**81**
	Autumn 2009/2010: September, October and November									
Mean SSC [mg/l]	**7.4**	**10**	**6.7**	**13.5**	**18.2**	**2.2**	**3.2**	**4.3**	**2.6**	**2.2**
Median SSC [mg/l]	**2.8**	**2.3**	**2.9**	**4**	**8.4**	**1.5**	**1.7**	**1.8**	**1.5**	**1.4**
95% SSC [mg/l]	**28.4**	**46.4**	**22.8**	**58.4**	**67.3**	**5.9**	**10.7**	**14**	**6.6**	**7**
Data coverage (%)	**40.6**	**76.6**	**68.7**	**94.3**	**95.2**	**78.7**	**97.3**	**86.9**	**81.5**	**80.4**
	Winter 2009/2010: December and 2010/2011: January and February									
Mean SSC [mg/l]	**3.4**	**11.3**	**17.7**	**13.3**	**24.7**	**2.5**	**4.7**	**3.8**	**4.9**	**3.9**
Median SSC [mg/l]	**1.5**	**4**	**6.8**	**6.1**	**14.1**	**1.8**	**2.5**	**2.2**	**2.6**	**2.1**
95% SSC [mg/l]	**13.1**	**46.8**	**76.1**	**40.8**	**85.4**	**7.4**	**17.4**	**11.9**	**18.3**	**13**
Data coverage (%)	**37.4**	**37.3**	**37.2**	**24.3**	**75.6**	**31.9**	**31.8**	**32.0**	**42.6**	**58.5**

Table 7.3 Seasonal statistics of suspended sediment concentration for the nearshore stations in shallow waters

	NS01a	NS02a	NS03a	NS06d	NS07a	NS08a
	Spring 2011: March and April					
Mean SSC [mg/l]	**11.0**	**10.5**	**36.2**	**12.3**	**7.6**	**2.9**
Median SSC [mg/l]	**3**	**2.6**	**7.9**	**3.1**	**2.6**	**1.4**
95% SSC [mg/l]	**36.8**	**39.3**	**171.3**	**63.6**	**30.5**	**6.2**
Data coverage (%)	**94.7**	**95.9**	**92.8**	**57.1**	**60.6**	**61.7**
	Summer 2011: June, July and August					
Mean SSC [mg/l]	-	-	-	-	-	-
Median SSC [mg/l]	-	-	-	-	-	-
95% SSC [mg/l]	-	-	-	-	-	-
Data coverage (%)	-	-	-	-	-	-
	Autumn 2010: September, October and November					
Mean SSC [mg/l]	**15.3**	**3.2**	**44.9**	-	-	-
Median SSC [mg/l]	**2.7**	**1.0**	**11.6**	-	-	-
95% SSC [mg/l]	**103.1**	**13.7**	**158.9**	-	-	-
Data coverage (%)	**21.9**	**20.2**	**20.0**	-	-	-
	Winter: December 2010 and January and February 2011					
Mean SSC [mg/l]	**24.2**	**47.5**	**97.1**	**12.6**	**8.8**	**7.7**
Median SSC [mg/l]	**8**	**15.2**	**36.1**	**2.4**	**1.9**	**1.5**
95% SSC [mg/l]	**99**	**208.9**	**432.1**	**68.5**	**43**	**40.4**
Data coverage (%)	**89.8**	**88.9**	**80.7**	**50.0**	**59.6**	**60.4**

7.2 Suspended Sediment Concentrations related to Wind Statistics

The analysis in Section 6 showed that the relation between the suspended sediment concentrations and the wind speed increases with decreasing water depth and is strong for water depths smaller than approximately 6m. However, also the duration and wind direction seem to play a role for the amount of sediment brought into suspension. Various hypotheses have been tested on the data set to describe the relation between the SSC and the dynamics in the area. It has not been possible to find a certain way to describe it, but below a few examples is presented. In the end of this section, statistics based on wind and SSC are presented.

7.2.1 Direct Correlation of Wind and SSC

From the above presentation of time series of SSC data and corresponding data of wind, it is indicated that there is a relation between the local dynamics, the bottom material and the turbidity. Especially wind speeds above 8m/s result in higher turbidity at the nearshore stations at the Danish site.

Figure 7.2 and Figure 7.3 show simultaneous measurements of SSC and wind speed squared for NS01 and NS03. Only wind directions where the stations are fully exposed are presented.

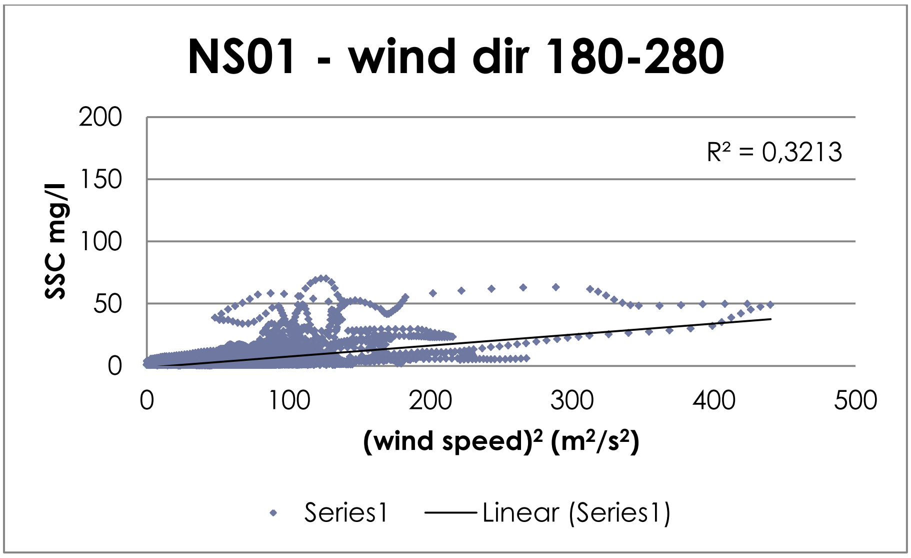


Figure 7.2 *Correlation of SSC and wind speed data from NS01 for the wind corridor between 180 and 280 degrees. Based on data from 1/2-2009 – 31/1-2010*

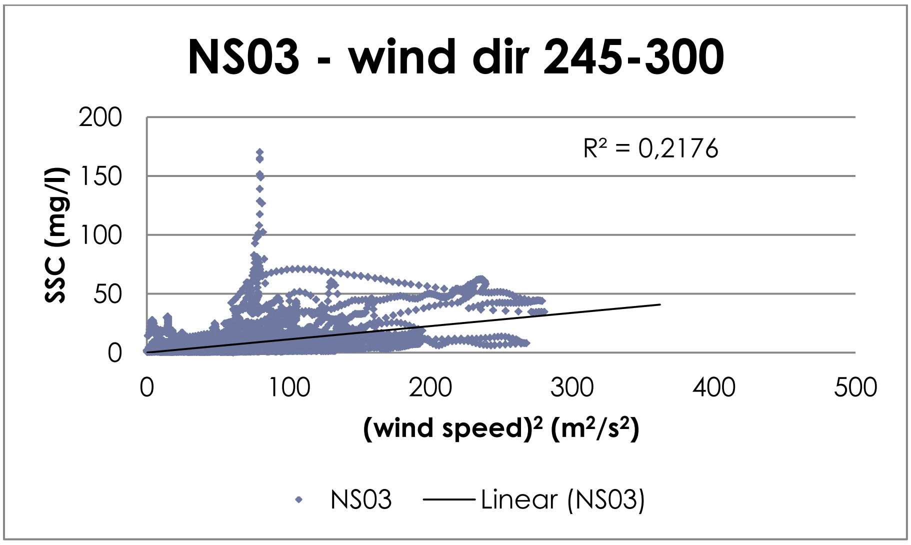


Figure 7.3 *Correlation of SSC and wind speed data from NS03 for the wind corridor between 245 and 300 degrees. Based on data from 1/2-2009 – 31/1-2010*

It is seen from Figure 7.2 and Figure 7.3 that there is hardly any direct correlation between wind speed and SSC. The reason for this can be that sediment first brought into suspension will take a while to resettle after the wave dynamics have been reduced. Furthermore, from the time series it appears that the level of suspended concentrations varies from time to time. The duration of the wind event plays a role here. Finally, the local re-suspension from the bottom will also be related to other factors and dynamics such as bottom roughness, current speed, availability of sediment, etc. One determining factor could be the duration of the event where high waves occur. If only the bottom is influenced by waves for a short period of time, then the sediment may not be brought into suspension or it might not be brought up in the water column to the level of the NTU measurement stations.

The effect of the duration parameter in correlation of the data sets has been tested by an extraction of maximum values each 24 hours. For each 24 hours, the maximum SSC values have been extracted, and in the same 24 hours the maximum wind speed has been extracted. The resulting data set is hereafter correlated. The data have been sorted in typical wind corridors for each location. Examples of resulting correlation plots are found in Figure 7.4 and Figure 7.5. No significant correlations are found.

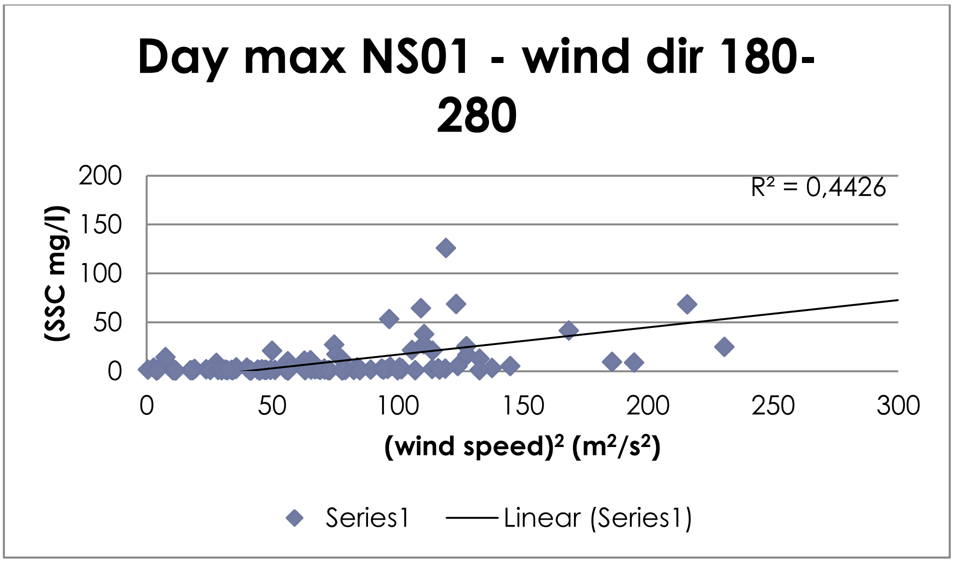


Figure 7.4 *Correlation based on 24-hour maximum values of SSC and wind speed at NS01 in a wind corridor between 180 and 280 degrees. Based on data from 1/2-2009 – 31/1-2010*

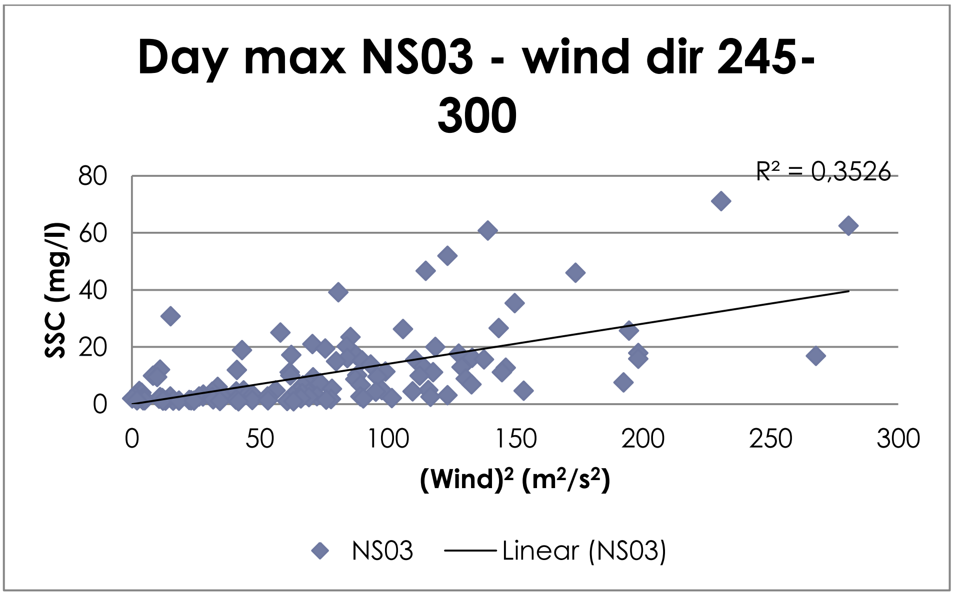


Figure 7.5 *Correlation based on day maximum values of SSC and wind speed in a wind corridor between 245 and 300 degrees. Note that one outlier has been removed from the data set with a SSC value of 170 and a squared wind level of 84m^2/s^2. Based on data from 1/2-2009 – 31/1-2010*

Both time series plots and the example of correlations shown in this section indicate that the wind and thereby the wave energy is an important factor for the turbidity. However, many factors determine the turbidity, and it has proven not to be possible to set up a simple relation between this dynamic parameter and the turbidity. The mapping of bed sediments in the Fehmarnbelt has revealed that in large areas, the seabed is hard and there is a scarcity of loose fine sediments (Figure 3.11). This is illustrated in Figure 7.6 and Figure 7.7, where it is seen that there is only a very thin layer of fines available at NS02 and NS03 and none at NS01. Below this layer, only coarser material is available. Several surveys with underwater video and diver inspections reveal that the surface material composition changes over time. During calm periods, a thin layer of fines can accumulate. After rough periods, the bed consists entirely of coarse sediments. No areas with extensive amounts of fine-grained sediment have been located in the nearshore zone. It should be noted that it is evident from diver inspections that the bed is extremely diverse. Over a few metres patches with seaweed, boulders and loose sediments can be found.

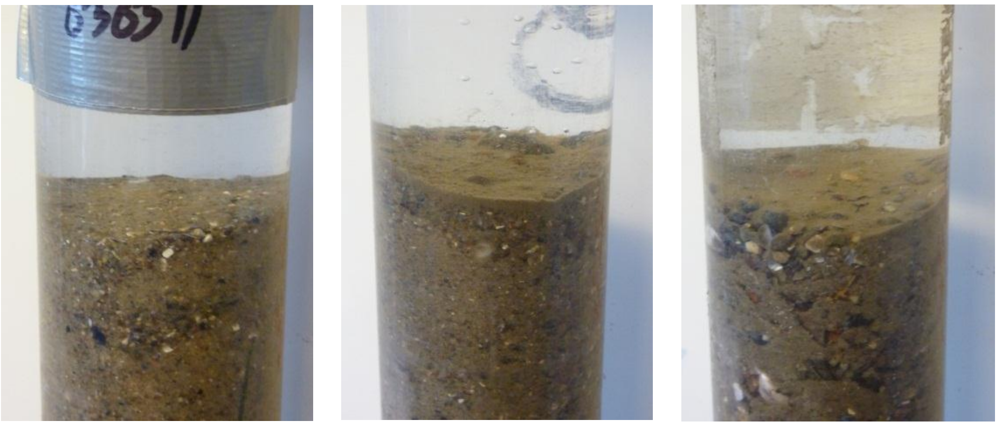


Figure 7.6 Tubes taken at NS01 (left), NS02 (centre) and NS03 (right). All pictures are shown in Appendix K

Figure 7.7 Tubes taken at NS01a (left), NS02a (centre) and NS03a (right). All pictures are shown in Appendix K

The variations in the suspended sediment concentrations are therefore determined by the hydrographic conditions as well as the availability of fines. Therefore, focus will be on statistical calculations and presentation of the data measured from February 2009 to May 2011 in the Fehmarnbelt.

7.2.2 Wind Statistics and SSC

The frequency of exceedance of certain concentrations of suspended sediment has been analysed for wind speed and direction.

Table 7.4 presents the wind statistics. Table 7.5 shows the frequency of exceedance of 10mg/l for NS03 for specific wind speed and directions.

Table 7.4 *Table summarising the wind statistics for the period 1/2-2009 – 24/11-2010. Wind statistics: STORM model from the Fehmarn area. Wind speed is in m/s, wind direction in degrees*

Wind stat					
Wind dir/Wind speed	**0-5**	**5-10**	**10-15**	**15-20**	**Sum**
0-30	2.1%	3.2%	0.3%	0.0%	5.6%
30-60	2.1%	2.2%	0.5%	0.0%	4.8%
60-90	2.0%	4.3%	1.3%	0.1%	7.7%
90-120	2.8%	5.5%	1.1%	0.0%	9.4%
120-150	2.8%	4.8%	1.0%	0.0%	8.6%
150-180	2.2%	3.7%	0.3%	0.0%	6.2%
180-210	2.1%	4.4%	0.6%	0.0%	7.2%
210-240	2.3%	5.6%	2.0%	0.1%	10.0%
240-270	2.9%	7.7%	2.4%	0.2%	13.3%
270-300	4.1%	8.3%	2.6%	0.2%	15.3%
300-330	3.0%	3.6%	0.7%	0.0%	7.4%
330-360	2.3%	2.2%	0.1%	0.0%	4.6%
Sum	**30.7%**	**55.5%**	**13.1%**	**0.7%**	**100.0%**

Table 7.5 *Wind statistics 1/2-2009 – 24/11-2010 and SSC levels at nearshore station NS03. Wind speed is in m/s, wind direction in degrees. Wind statistics: STORM model. Example: The SSC exceeds 10mg/l 23.0% of the time. Under conditions where the wind speed is between 10-15m/s and the wind direction is between 270-300 degrees, concentrations above 10mg/l are measured 1.1% of the time*

SSC >10mg/l					
Wind dir/Wind speed	**0-5**	**5-10**	**10-15**	**15-20**	**% > 10mg/l**
0-30	0.3%	0.6%	0.3%	0.0%	1.2%
30-60	0.3%	0.6%	0.6%	0.0%	1.5%
60-90	0.2%	0.8%	1.0%	0.1%	2.1%
90-120	0.2%	1.4%	1.0%	0.0%	2.6%
120-150	0.4%	0.7%	0.7%	0.0%	1.8%
150-180	0.2%	0.5%	0.1%	0.0%	0.8%
180-210	0.3%	1.0%	0.3%	0.0%	1.5%
210-240	0.2%	1.9%	1.6%	0.2%	4.0%
240-270	0.2%	1.5%	1.1%	0.1%	2.9%
270-300	0.3%	0.8%	1.1%	0.1%	2.3%
300-330	0.3%	0.7%	0.3%	0.0%	1.3%
330-360	0.2%	0.5%	0.2%	0.0%	0.9%
% > 10mg/l	**3.2%**	**11.1%**	**8.2%**	**0.5%**	**23.0%**

Similar tables for all nearshore stations are presented in Appendix I.

If this approach is extended to averaging the concentrations for different onshore wind speeds with 1m/s intervals, then the correlations given below can be found.

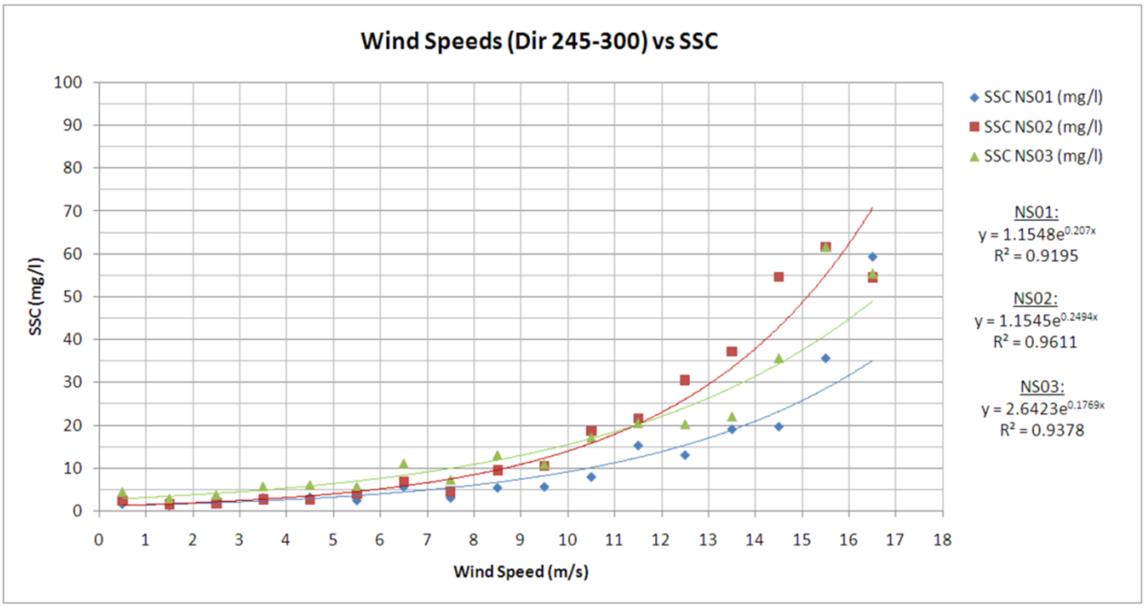


Figure 7.8 Statistical correlation between onshore wind speeds and concentration levels NS01-NS03

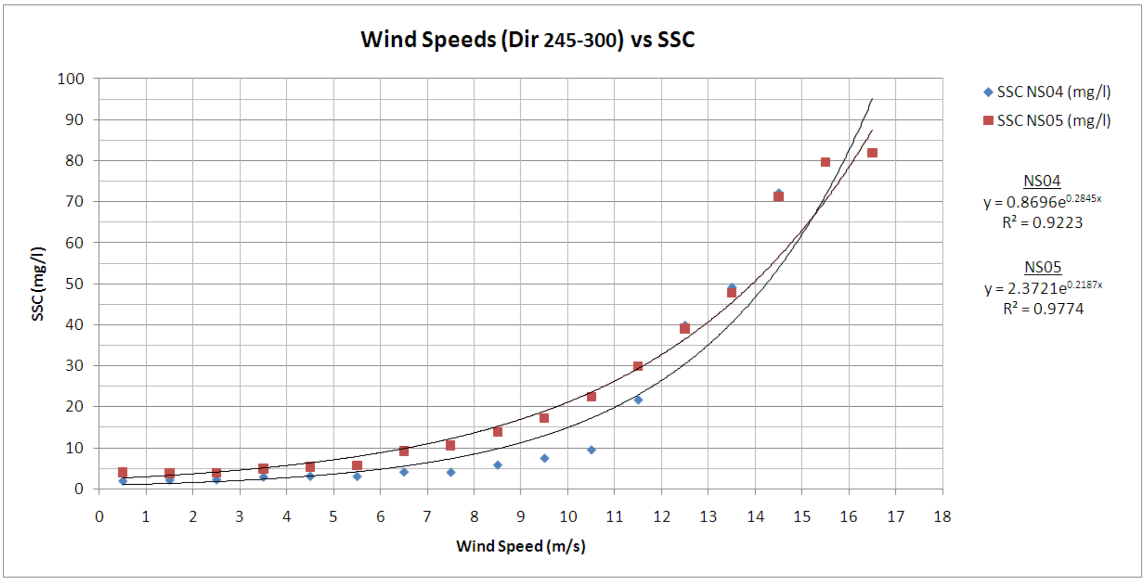


Figure 7.9 Statistical correlation between onshore wind speeds and concentration levels NS04-NS05

All figures can be found in Appendix L.

8 PRESENT PRESSURES

Details regarding disposal sites and amounts and sand-mining areas and amounts can be seen in (Seabed Morphology of the Fehmarnbelt area - Baseline 2011).

The ferries between Rødby and Puttgarden stir up sediment when they enter and leave the harbours. The amount is unknown but the effect in terms of suspended sediment plumes can be clearly seen on aerial photos. The ferries depart every half hour. Other ship traffic has similar effects in shallow water.

The local fishing industry induces a pressure when trawling. Trawls will rip the bed and cause sediment re-suspension. It will also loosen the top of the bed and make it more vulnerable for erosion.

Figure 8.1 and Figure 8.2 show known human pressures in the German and Danish part of the Fehmarnbelt.

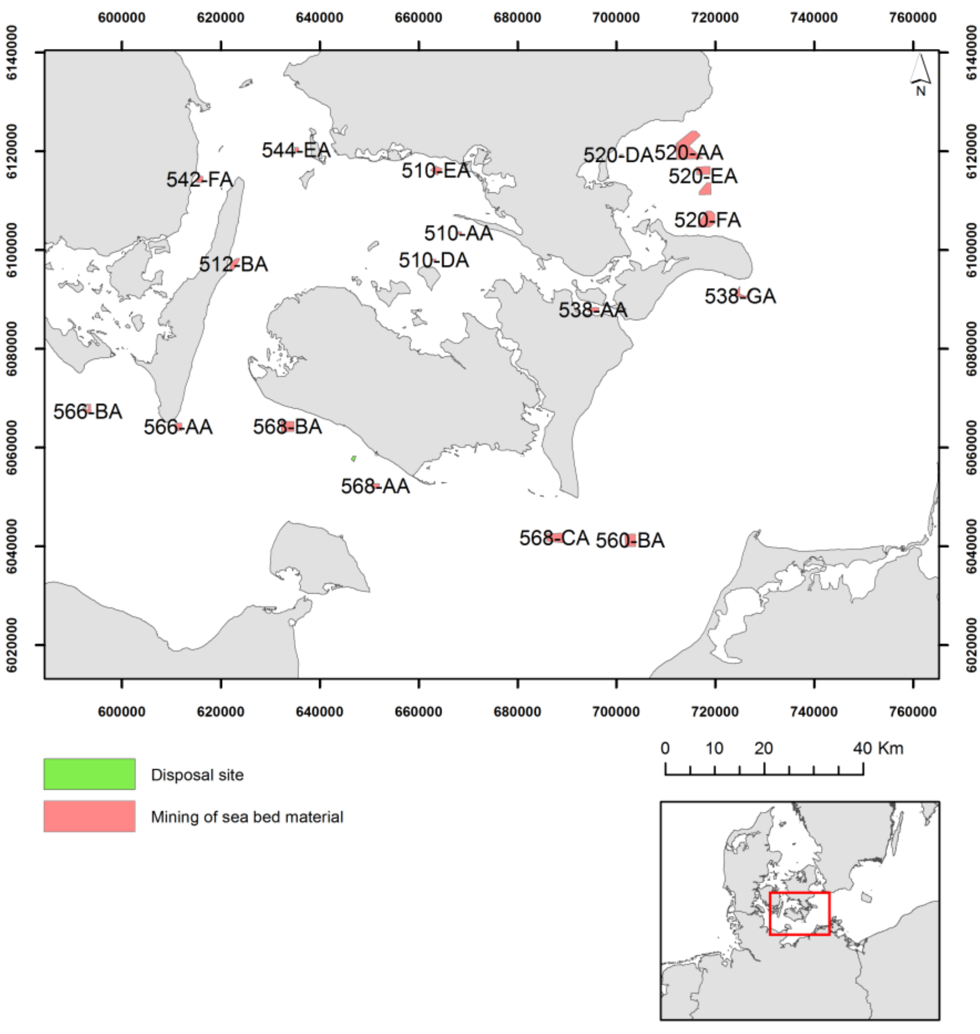


Figure 8.1 Known human pressures in the German part of the Fehmarnbelt (map modified from www.bsh.dk)

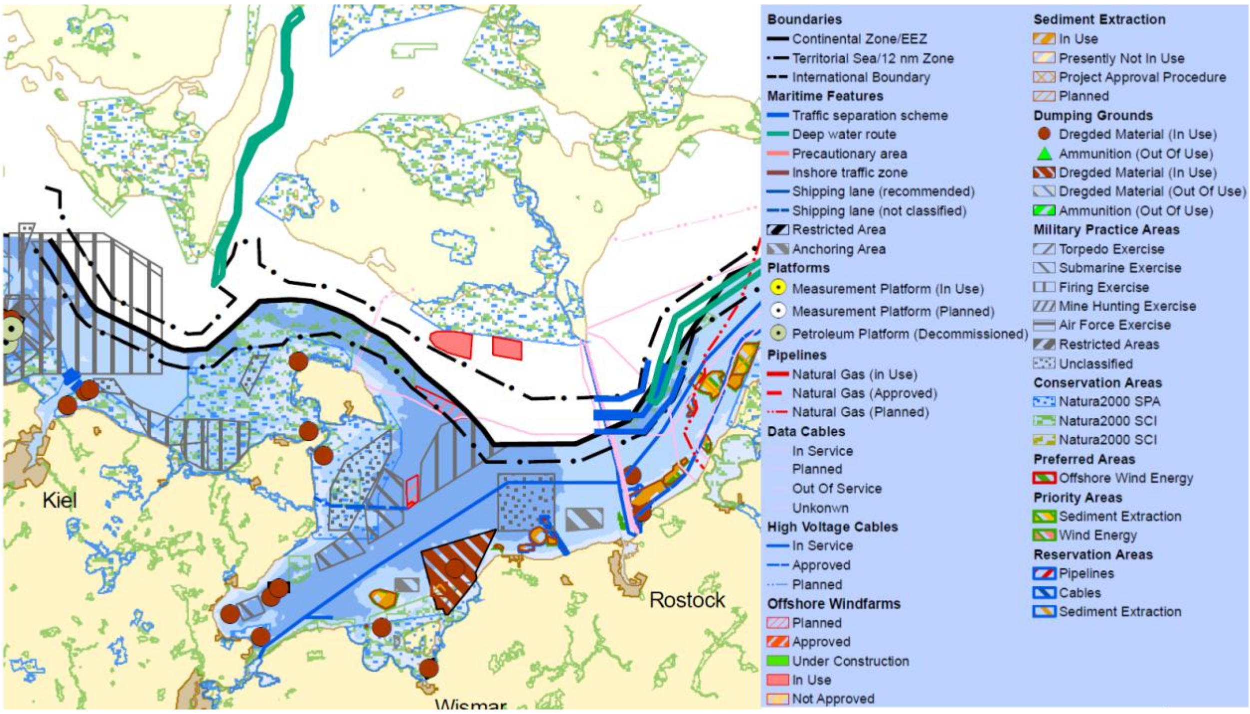


Figure 8.2 Known human pressures in the German part of the Fehmarnbelt (map modified from www.bsh.de)

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