Final Report

FEHMARNBELT FIXED LINK
HYDROGRAPHIC SERVICES (FEHY)

Marine Soil - Impact Assessment

Sediment Spill during Construction of the Fehmarnbelt Fixed Link

E1TR0059 - Volume II

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ACRONYMS AND ABBREVIATIONS

Excess concentration:	Concentration in excess of the normal background concentration
SSC:	Suspended Sediment Concentration (mg/l)
Floc:	Number of cohesive grains sticking together
C_d:	Drag coefficient
g:	Gravity (9.82 m/s^2)
ρ:	Density (kg/m^3)
Microns:	Measuring unit. 10^{-6}m
u':	Velocity due to turbulence
k-ε:	Turbulence model
E_x:	Exceedance time of concentration above the value x
f_x:	Fractile. A diameter/concentration for which x percentage of the data is below this value
FEHY:	Fehmarnbelt Hydrographic Services
FEMA:	Fehmarnbelt Marine Biology Services
FEBI:	Fehmarnbelt Bird Services
FeBEC:	Fehmarnbelt Environment Consortium
RAT JV:	Rambøll, Arup and Tec Tunnel Joint Venture

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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).

0 EXTENDED SUMMARY

Most large infrastructure projects in the marine environment require dredging of marine soils. When dredging in the marine environment it is inevitable that part of the dredged material is lost to the surrounding waters. The amount of lost or spilled materials depends on the dredging method and the local soil composition. The spilled material will spread depending on the physical properties of the soil, the amount of spilled material and the local hydrodynamics.

The spilled material will spread with the currents until it finally settles in an area from where it cannot be resuspended. Before reaching a final resting place the sediment may settle and resuspend many times. During the period of settling and resuspension the spilled material will be in excess of the natural background concentration of sediment in the Fehmarnbelt. The following parameters are quantified:

- Increase in suspended sediment concentrations
- Increased sedimentation
- Changes in sea bed sediment grain size distribution due to sedimentation

In the following one assumption of how dredging could be carried out is investigated. The dredging plans will continue to develop over time until the project starts. The selected schemes are thus considered realistic but not necessarily final schemes.

This report covers the analyses of dredging scenarios for two alternatives of the Fixed Link across the Fehmarnbelt:

- Immersed tunnel (E-ME)

- Cable stayed bridge

It should be noted that the cable stayed bridge version applied in this assessment (BE-E, April 2010) is an earlier version compared to the final version (Variant 2 BE-E, October 2010). The final version has a total spill of only about 55% of the earlier version and also a slightly different alignment. The present bridge assessment is thus conservative with respect to effects for the final version.

This report includes:

- Presentation of the earth budgets for dredged materials and spill scenarios

- Results of the experiments made in order to determine settling velocities for spilled dredged materials

- Results of the spill simulations of suspended concentration levels and sedimentation patterns

- Comparison of the simulated spill concentrations with baseline conditions for suspended sediment concentrations

The simulated earth budgets for dredged and filling materials are presented in Table 0.1 and Table 0.2. The tables present the amount of handled material per activity, the expected percentage of material which will be spilled and the amount of spilled material. The budgets are exclusive of remote sand mining for backfilling and production of concrete for structures and elements, as this sand is assumed provided from outside the primary effect area of the local dredging and filling activities.

Table 0.1 Dredging activities for the immersed tunnel

Activity	Spill [%]	Amount [mill m^3]	Amount spilled [mill m^3]
Dredging for tunnel elements	3.5	15.50	0.540
Containment dikes	0.1-0.8	1.20	0.007
Portal and ramps Lolland	0.1-0.7	0.36	0.002
Portal and ramps Fehmarn	0.1-0.7	0.32	0.002
Working harbour Lolland	0.1–0.8	2.87	0.020
Working harbour Fehmarn	0.1-0.8	0.10	0.001
Reclamation	0.5	20.80	0.104
Trench backfilling Lolland	0.1-0.8	3.40	0.015
Trench backfilling Fehmarn	0.1-0.8	3.00	0.013
Restoring sea bed Natura 2000*	0.1-1.0	0.48	0.003
Landscaping reclamation area	0.5-2.0	4.31	0.039
Total amount handled/spilled		**52.34**	**0.746**

*This activity is removed from the project in Oct 2012, but is included in the present simulations, making the spill assessment marginally conservative in this respect.

Table 0.2 Dredging activities for cable stayed bridge (BE-E, April 2010)

Activity	Spill [%]	Amount [mill m^3]	Amount spilled [mill m^3]
Dredging for piers	12	0.54	0.070
Backfilling at piers (sand)	1	0.18	0.002
Dredging of access channels	5	0.35	0.020
Backfilling of access channels	5	0.35	0.020
Scour protection etc.	1	0.05	0.001
Work harbour at Rødby	1	1.19	0.010
Dredging for pylons	12	0.31	0.037
Total amount handled/spilled		**2.97**	**0.160**

The dredging is planned to last six years for the tunnel and three years for the bridge solution. The construction of the bridge is assumed to start on 1 January according to the bridge design consultant. The dredging for the construction of the tunnel is assumed to start simultaneously at both coasts on 13 October according to the tunnel design consultant. The construction work starts with the work harbours and associated access channels. The results will be the same for start times shifted one year.

Numerical simulations of spreading of sediment spill have been prepared using the representative hydrographic year 2005. The flow conditions calculated throughout 2005 have been repeated for each year of the construction period.

Selected results from the simulations of sediment spill are presented in the following. It is noted that the tunnel scenario represents spill amounts at least 7 times larger than that of the bridge. For the tunnel solution the year 2015 is the year with the highest amounts of spillage and thus results from this year are presented in this summary. The results are presented for the summer time because this is the biological growth season and the season for recreational use of the coastal areas. Time series of simulated and measured concentrations are presented at the locations of the stations presented in Figure 0.1.

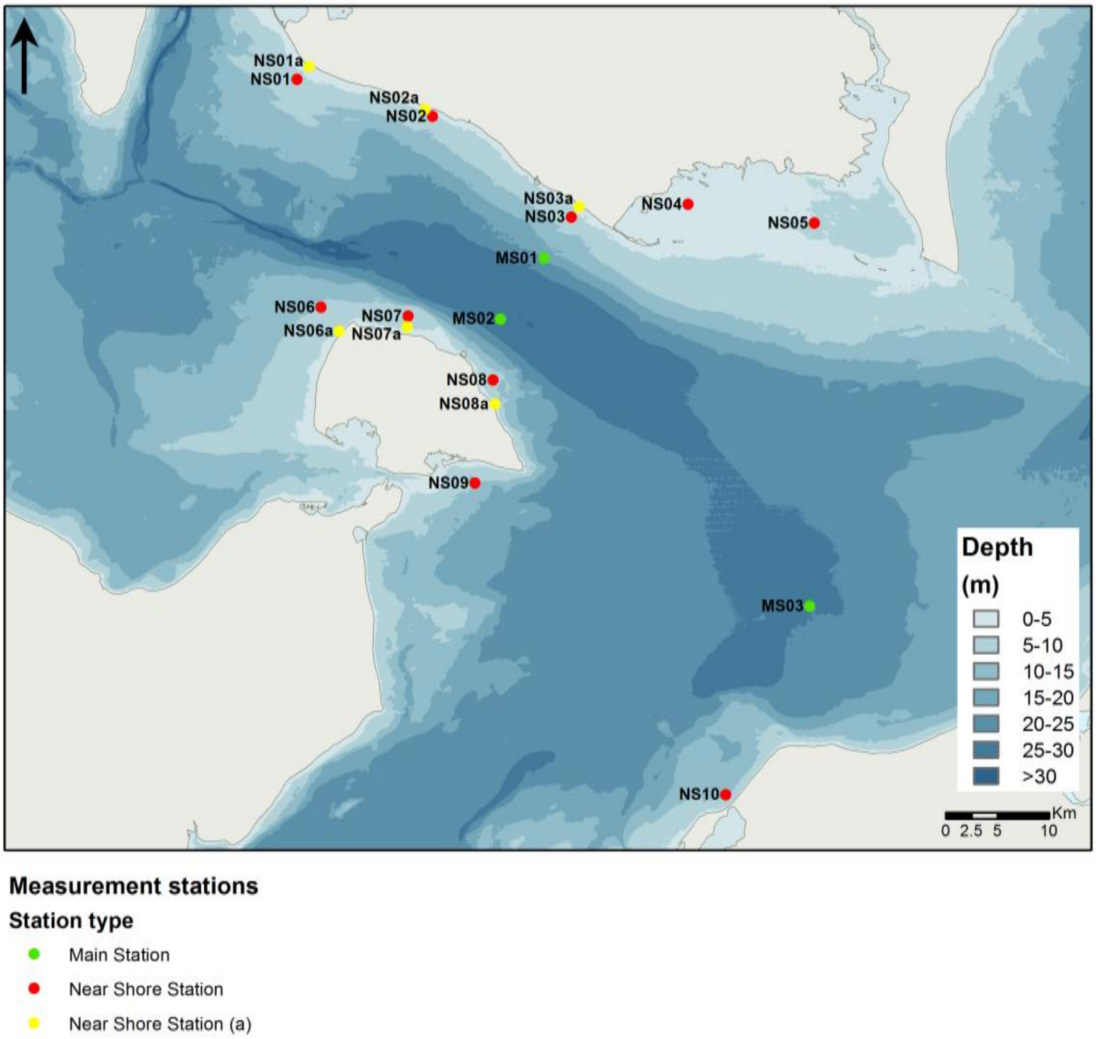

Figure 0.1 *Location of measurement stations from baseline study, which also is used as key stations in impact assessment*

Immersed tunnel

Excess suspended sediment concentrations at the locations NS03, NS04 and NS08 are presented in Figure 0.2 to Figure 0.4.

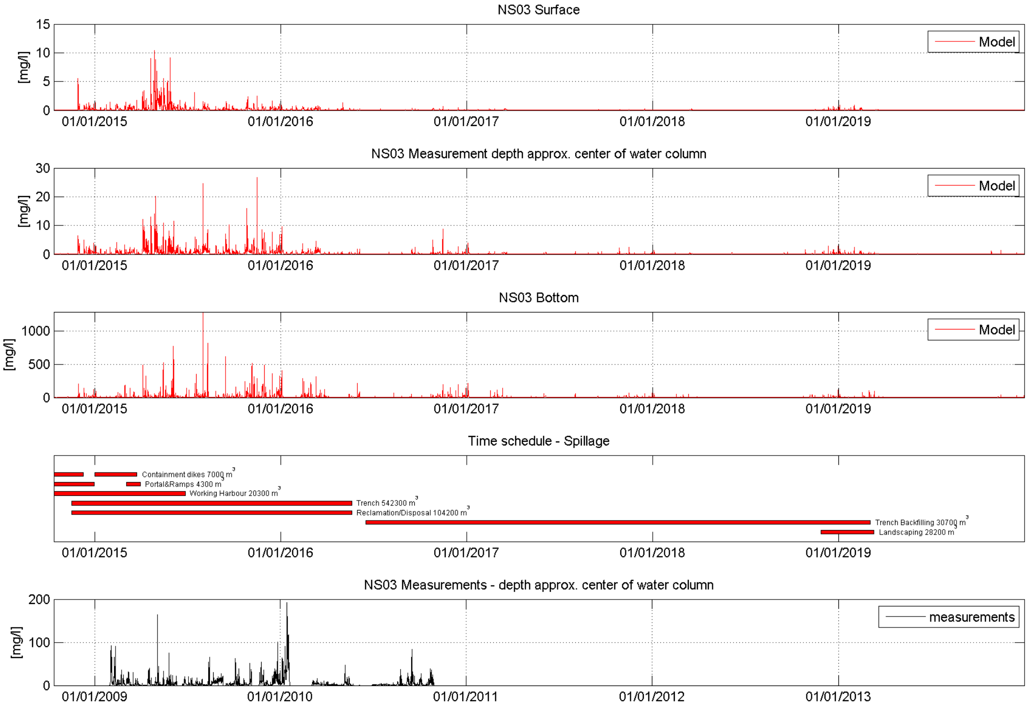

Figure 0.2 *Time series of spilled suspended sediment concentration at station NS03 near Rødbyhavn in three depths (surface, mid level and bottom), along with tunnel dredging schedule. The bottom panel shows the baseline suspended concentration monitored in 2009-2010*

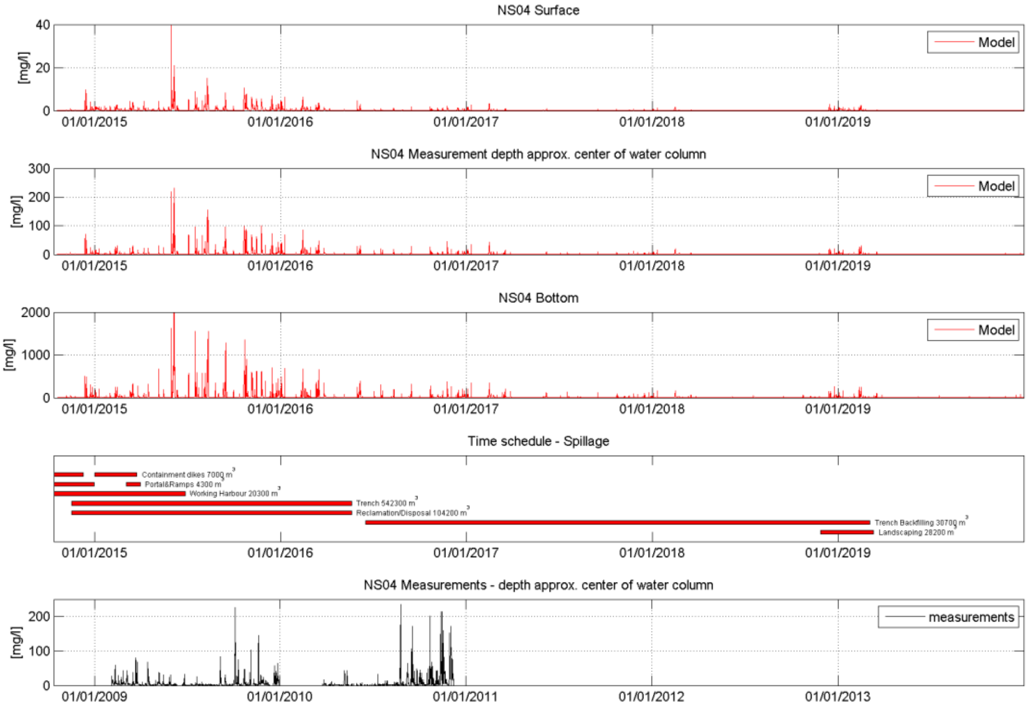

Figure 0.3 *Time series of spilled suspended sediment concentration at station NS04 in Rødsand Lagoon west in three depths (surface, mid level and bottom), along with tunnel dredging schedule. Bottom panel shows the baseline suspended concentration monitored in 2009-2010*

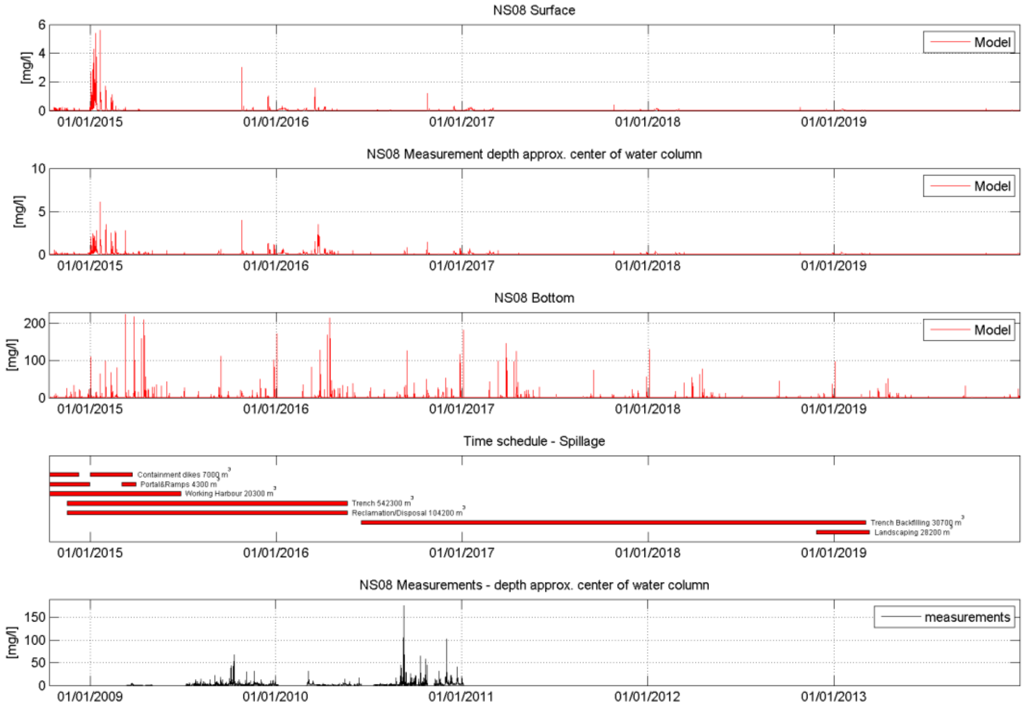

Figure 0.4 Time series of spilled suspended sediment concentration at station NS08 near Puttgarden in three depths (surface, mid level and bottom), along with tunnel dredging schedule. Bottom panel shows the baseline suspended concentration monitored in 2009-2010

The figures show among others the comparison of modelled time series of excess concentrations at mid depth from the years 2015-2019 and the measured concentrations at approx. mid depth from the baseline years 2009-2010 at station NS03 near Rødbyhavn, at NS04 in Rødsand Lagoon and at NS08 near Puttgarden. It appears that the natural background concentration varies in the same way as the excess concentration with re-suspension event during storms. Note that at mid level the background concentration reaches a higher level than the excess concentration.

The time series show the largest excess concentrations in the last months of 2015 and the first months of 2016. The largest excess concentrations at mid level are seen in the Rødsand Lagoon where excess concentrations can reach above 200 mg/l for short periods of time. Away from the Rødsand Lagoon and offshore of the coastal areas excess concentrations are much smaller.

Excess concentrations on the German side are seen to be smaller than on the Danish side, consistent with the smaller amounts of spilled sediment and the milder wave climate here.

The level of excess concentration from dredging decreases in accordance with the decreasing dredging activity. Effects can hardly be detected after summer 2019.

The exceedance time is the percentage of time when the concentration has been above a given value. For instance the exceedance time for 2 mg/l is the percentage of time when the excess concentration exceeds 2 mg/l.

Various maps of exceedance times for the excess concentration are presented for the summer 2015, which is the year with the largest spill, see Figure 0.5 to Figure 0.7.

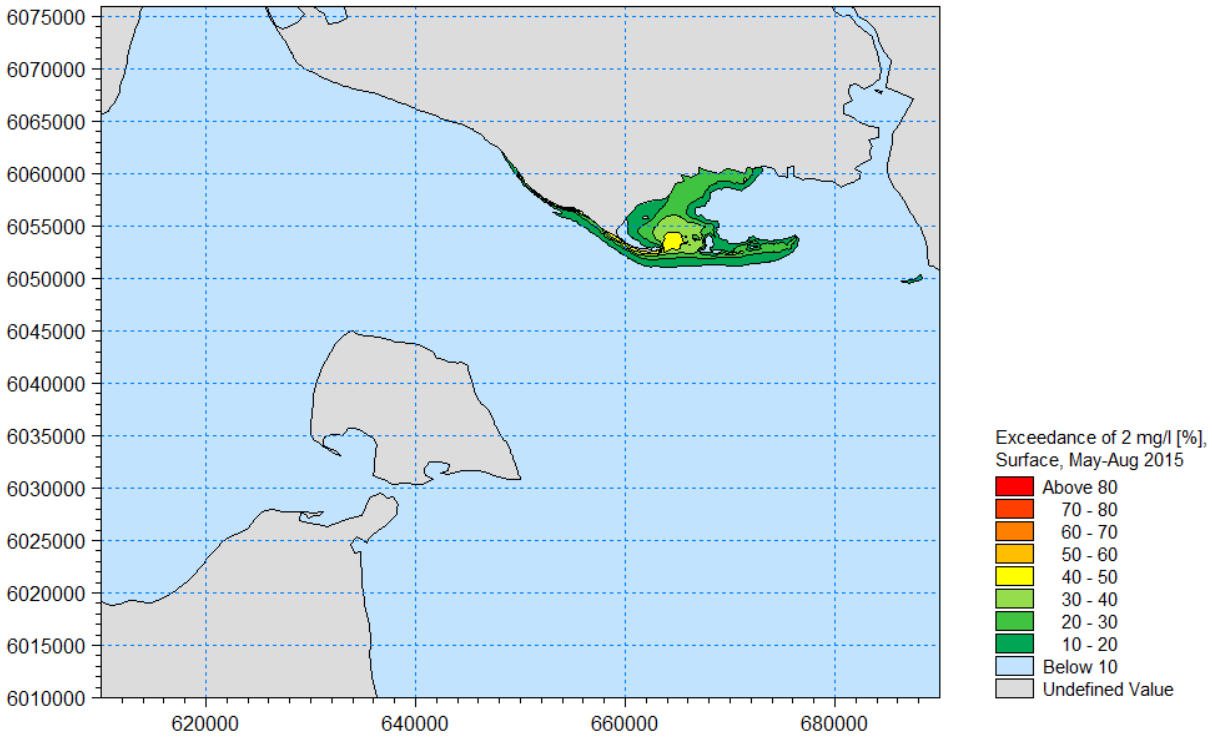

Figure 0.5 Exceedance time of 2 mg/l spilled sediment concentration at the ***surface*** *for the period May – August 2015. Immersed tunnel E-ME*

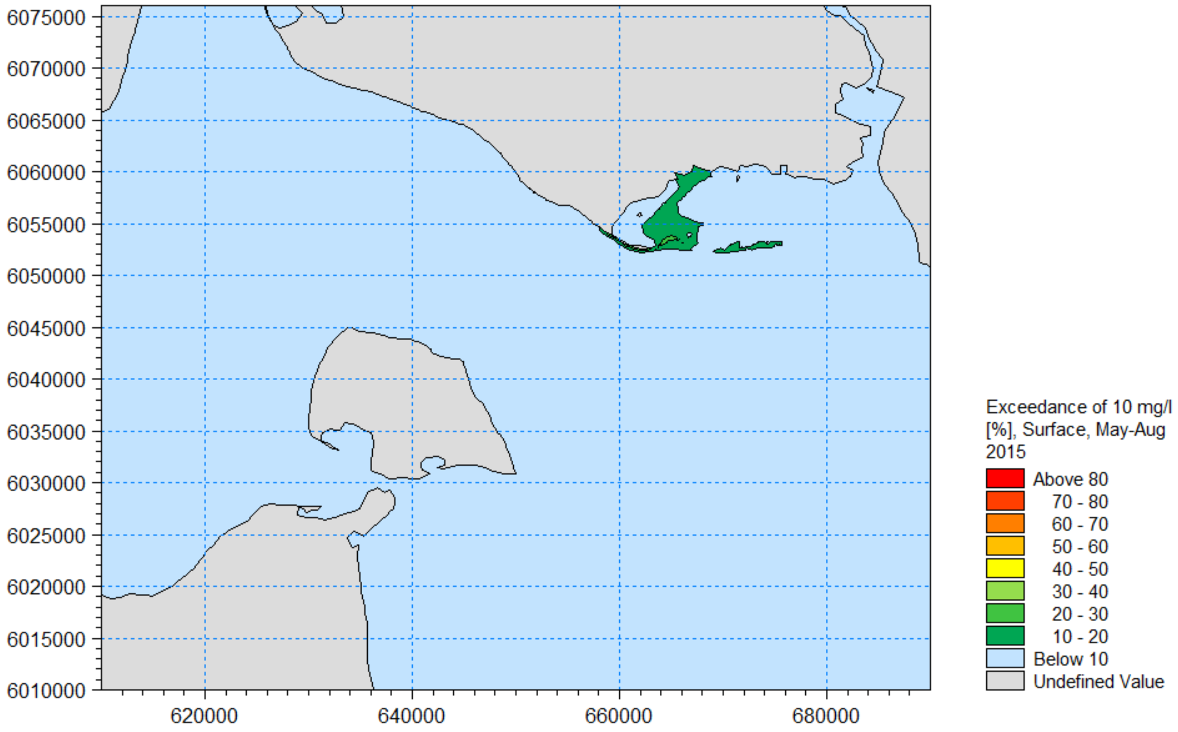

Figure 0.6 Exceedance time of 10 mg/l spilled sediment concentration at the ***surface*** *for the period May – August 2015. Immersed tunnel E-ME*

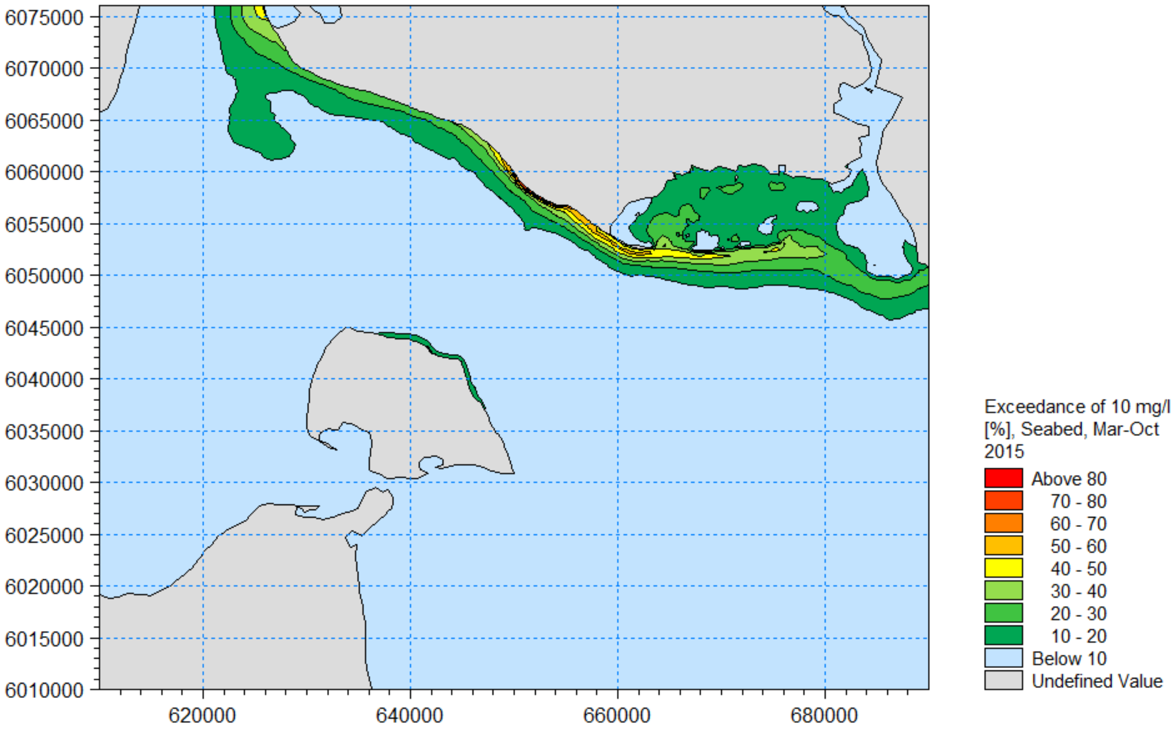

Figure 0.7 Exceedance time of 10 mg/l spilled sediment concentration for the ***lower part*** *of the water column for the period March – October 2015. Immersed tunnel E-ME*

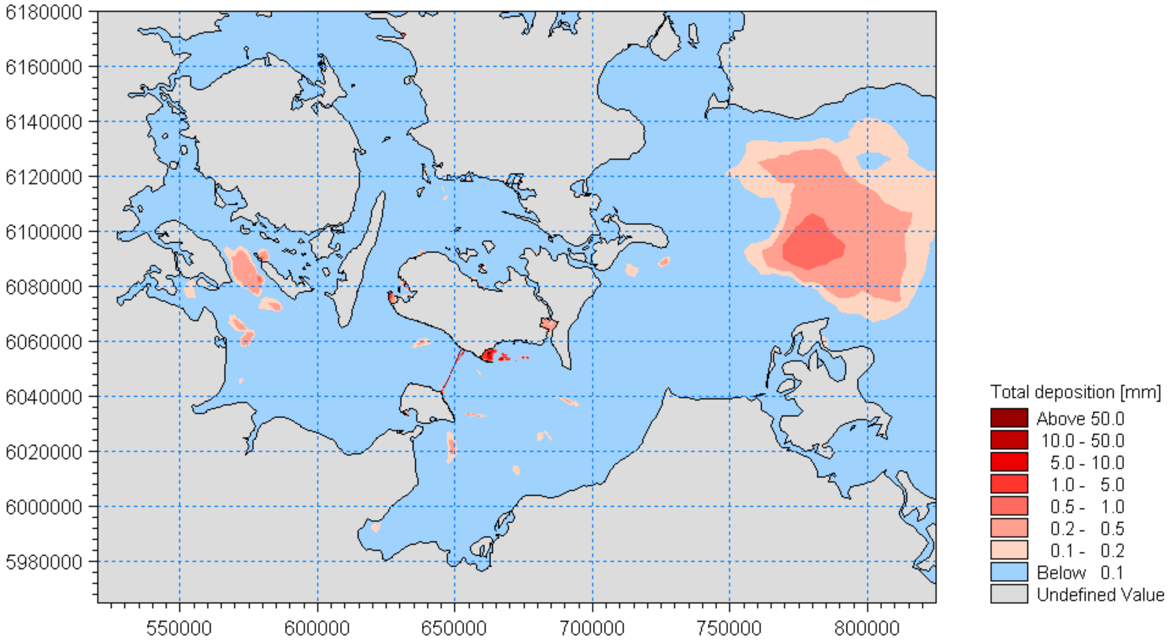

Figure 0.8 Deposition at the end of the dredging period (2014-2019). Immersed tunnel E-ME

The results show that 2 mg/l for the excess concentrations is exceeded more than 20% of the time in the surface near the Lolland coast. The exceedance frequency reaches 40% inside the Rødsand Lagoon during the summer 2015. At no time during the summer 2015 will there be an exceedance of 2 mg/l along the coast of Fehmarn.

Near the bottom excess concentrations are higher. 10 mg/l is exceeded more than 20% of the time during the summer of 2015 along the Lolland coastline from Nakskov Fjord in the west to Gedser Odde in the east with a maximum along the new reclamation at Rødbyhavn of 60%. Inside the Rødsand Lagoon near bottom concentrations exceed 10 mg/l for typically 10-25% of time. The higher exceedance times are partly due to dredging plumes and partly due to resuspension of spilled sediment in the nearshore areas.

The results show little or no sedimentation in the majority of the offshore area in the Fehmarnbelt away from the alignment. Along the tunnel trench sedimentation is seen to be up to 0.5-1.5 cm in a band of about 600 m on each side of the alignment centreline. This sedimentation originates from the coarser part of the spill (the sand). Deposition up to 1 cm is also seen in the sheltered part of the Rødsand Lagoon. An overview of the deposition very close to the alignment is presented in Figure 0.9.

Figure 0.9 Sand deposition along the alignment of the tunnel

The results show that final deposition areas are the Arkona Basin (with up to 1 mm over the six-year period), the deeper parts of southern Lillebælt, the band along the alignment, and Rødsand Lagoon. For comparison the natural sedimentation rates in the Arkona Basin is about 2 mm a year.

Cable stayed bridge

Excess concentrations at NS03, NS04 and NS08 are presented in Figure 0.10 to Figure 0.12.

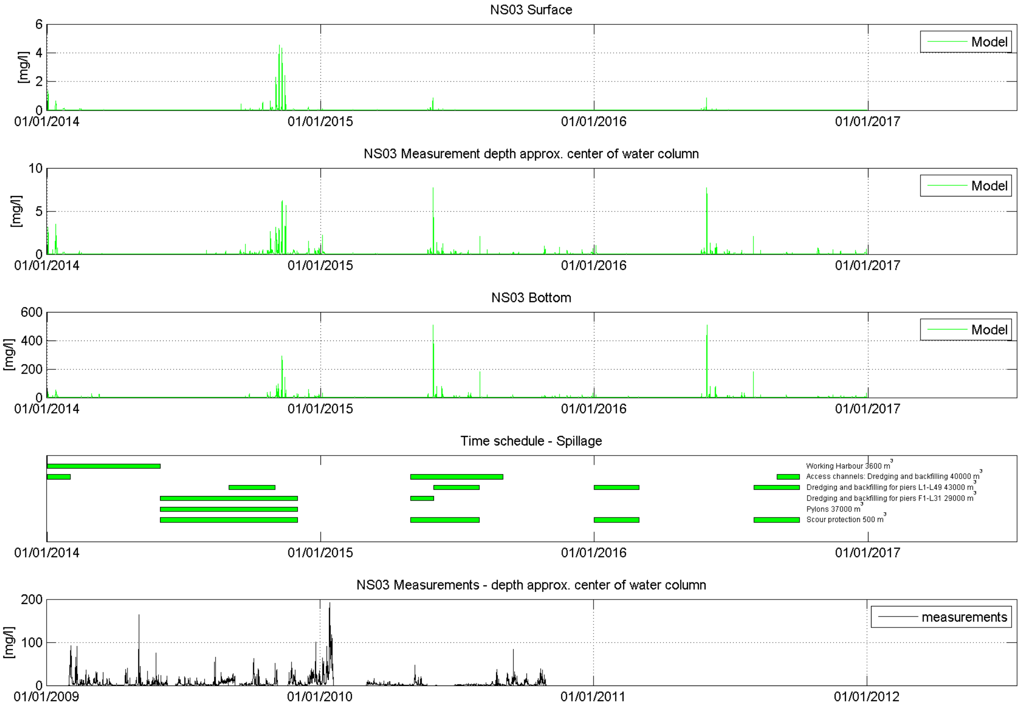

Figure 0.10 Time series of suspended sediment concentration at station NS03 near Rødbyhavn in three depths (surface, mid level and bottom), along with bridge dredging schedule. The bottom panel shows the baseline suspended concentration monitored in 2009-2010

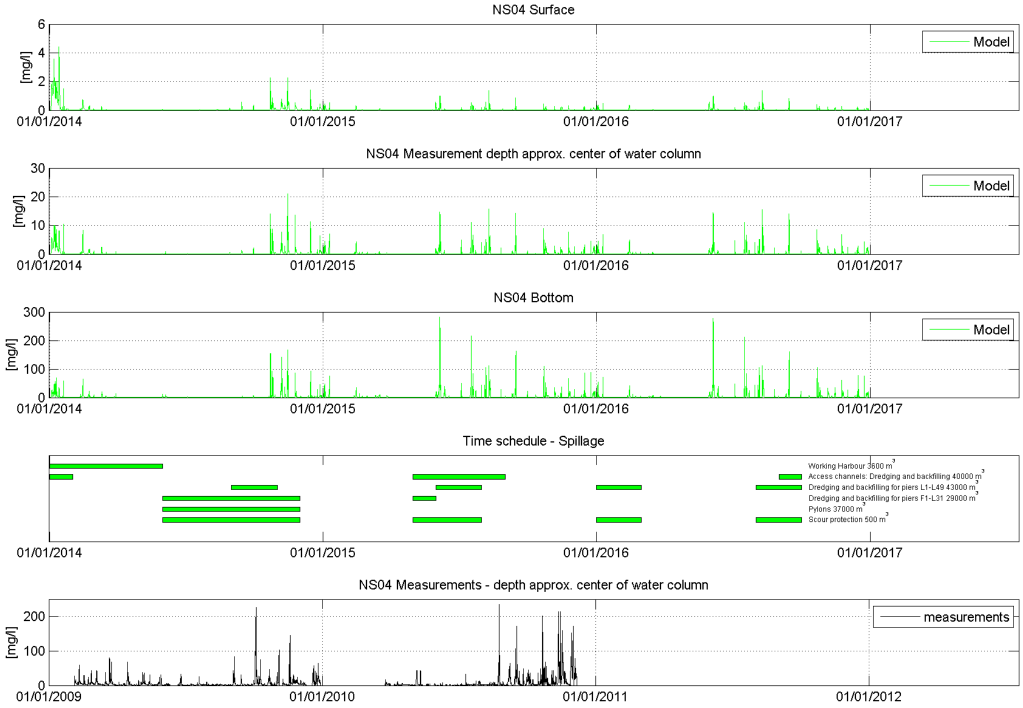

Figure 0.11 Time series of suspended sediment concentration at station NS04 in Rødsand Lagoon west in three depths (surface, mid level and bottom), along with bridge dredging schedule. The bottom panel shows the baseline suspended concentration monitored in 2009-2011

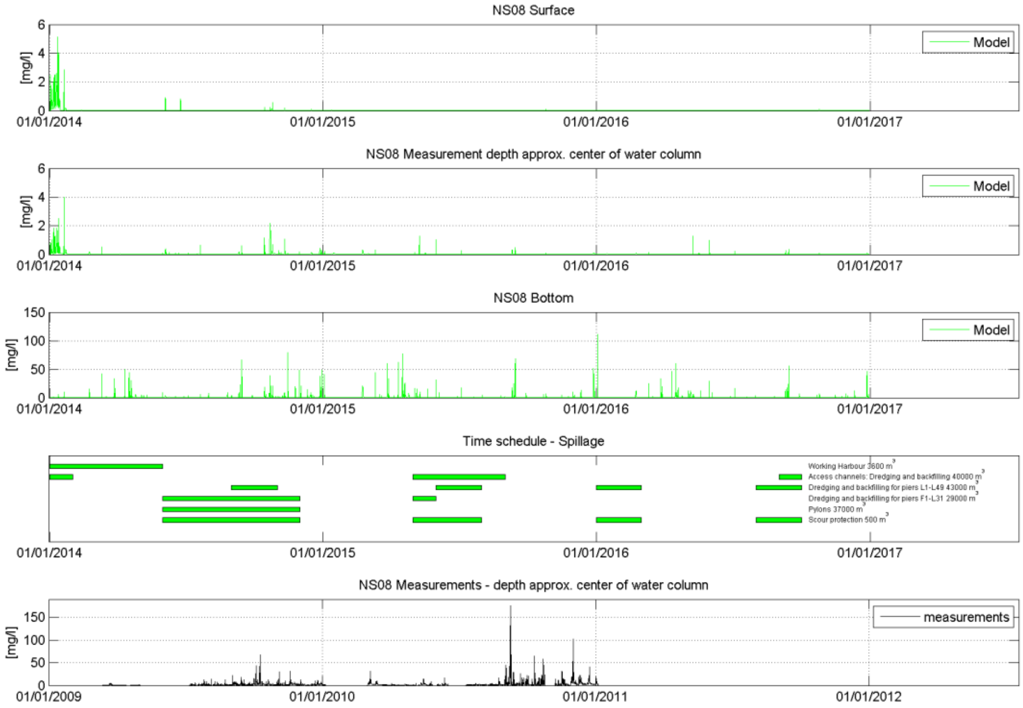

Figure 0.12 Time series of suspended sediment concentration at station NS08 near Puttgarden in three depths (surface, mid level and bottom), along with bridge dredging schedule. The bottom panel shows the baseline suspended concentration monitored in 2009-2011

The results show maximum concentration levels at mid level at about 20 mg/l in the Rødsand Lagoon and smaller away from the lagoon.

Excess concentrations on the Danish side are higher than on the German side due to the milder wave climate on the German side.

Situations with higher excess concentrations are seen to be much less than for the tunnel solutions consistent with the much smaller amount of spilled sediment. Time series at the nearshore stations in the Rødsand Lagoon and NS08 near Puttgarden indicate that excess concentrations will occur up to the end of 2016.

One example of results is presented for the summer time 2014 because this is the biological growth season and the season for recreational use of the coastal areas. Furthermore, 2014 is the year where dredging takes place in shallow waters.

The results show very small excess sediment concentrations. Even near the sea bed excess sediment concentrations from dredging will rarely exceed 10 mg/l in 2014. This is shown in Figure 0.13 The release of spill happens only over a short period of time at a given position before the dredger moves on. Therefore the exceedance time is generally low even though plumes always will be visible around the operation.

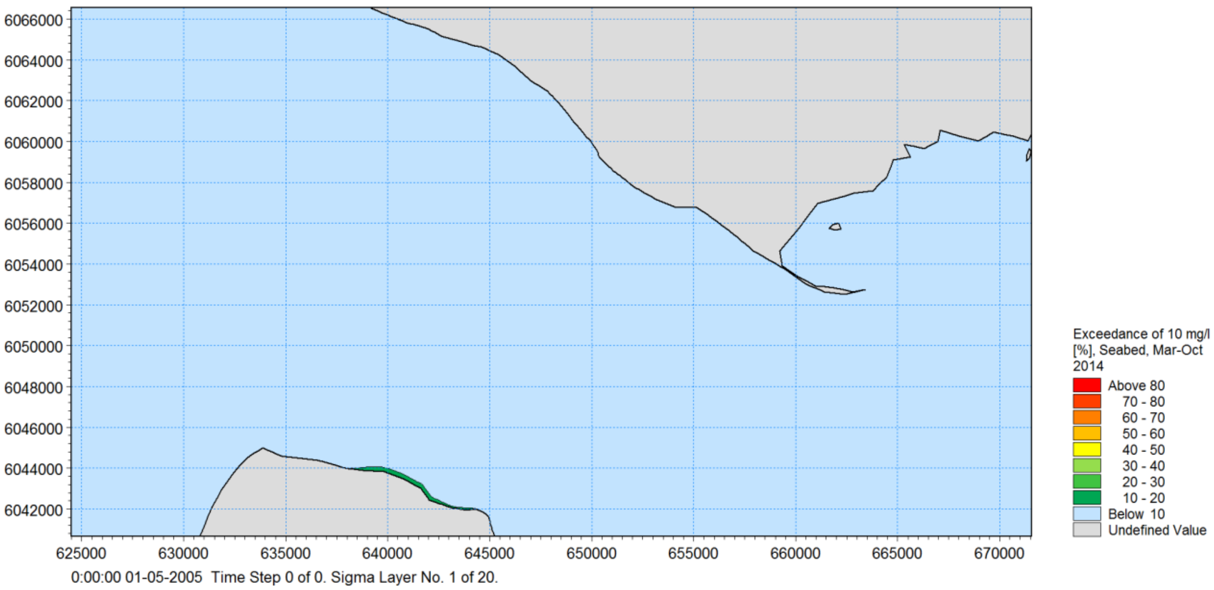

Figure 0.13 *Exceedance time of 10 mg/l in the period March - October for the* ***lower part*** *of the water column. Cable stayed bridge solution, year 1: summer 2014. Dredging occurring at different piers both nearshore and offshore. Most dredging activities are located at the German end of the link*

With respect to deposition the results show that the sand fractions deposit near the alignment. The finer fractions are spread over a large area. Final deposition areas are the Arkona Basin and the sheltered parts of the Rødsand Lagoon, but the layers are very thin. At the alignment 0.5–1.5 cm thick layers of sand will be deposited around the piers, see Figure 0.14 and Figure 0.15.

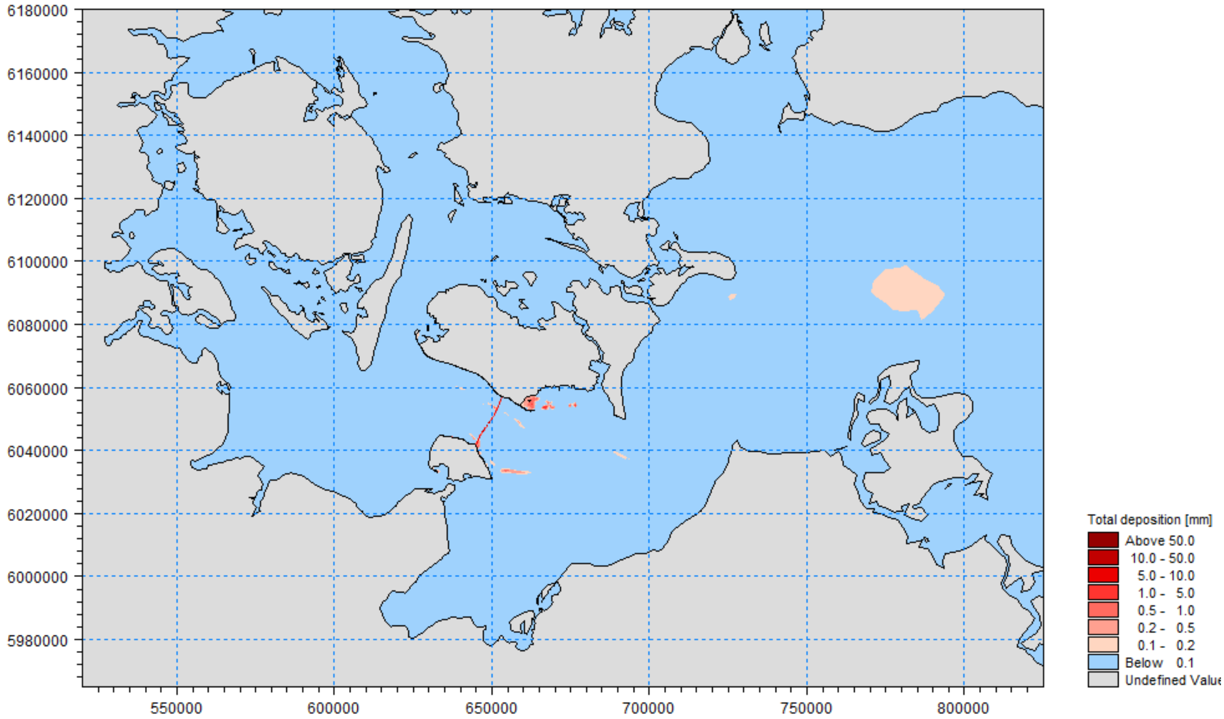

Figure 0.14 Deposition pattern at the end of 2016. Bridge solution. Full modelling area

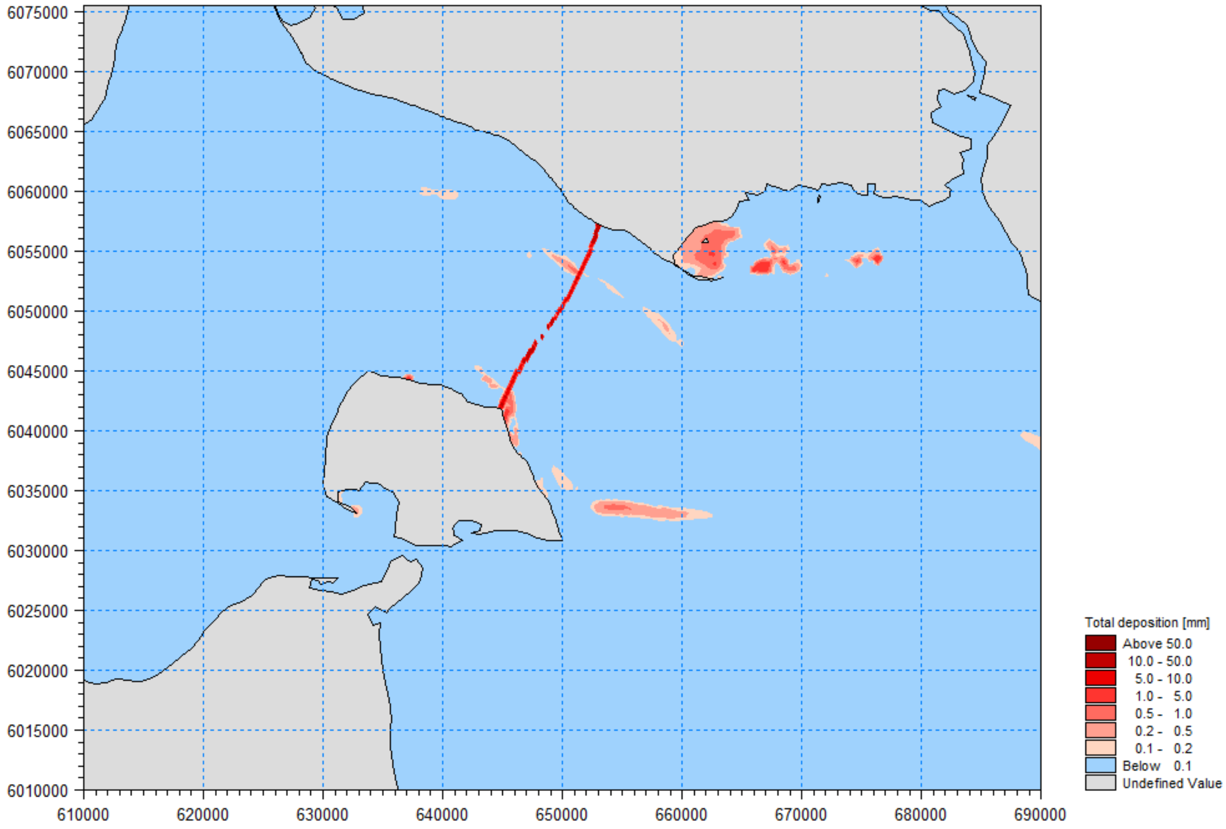

Figure 0.15 Deposition pattern at the end of 2016. Cable stayed bridge solution, local zoom

Comparing baseline conditions with excess sediment concentrations for immersed tunnel

The numerical calculations are carried out based on the hydrographic year 2005. The measurements of suspended sediment are from 2009 – 2010. A direct comparison between measured background concentrations and modelled excess concentrations is thus not possible. In order to assess the order of magnitude of the excess concentrations relative to the background concentrations key statistical parameters are compared. In this connection the key statistical parameters are the exceedance times and the “fractiles”. The 90% fractile (f_{90}) is the concentration in one single point which is exceeded 10% of the time, see Figure 0.16 for an illustration. Fractiles and exceedance times are calculated for the full dredging period and for selected sub periods.

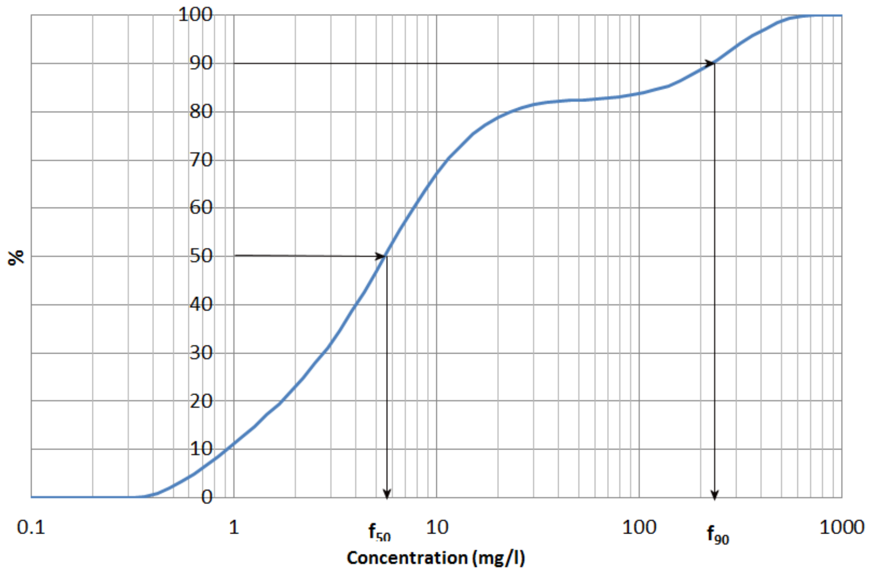

Figure 0.16 Illustration of “fractiles”. The blue curve is the accumulated percentage of all values below a given concentration

Table 0.3 shows the fractiles and exceedance times for the excess concentrations during 2015 at mid depth at various positions. The positions are shown in Figure 0.1.

The table should be read in the following way: the excess concentration that is exceeded exactly 50% of the time (f_{50}) at NS03 is 0.3 mg/l (mid level value). Similarly the concentration that is exceeded exactly 95% of the time (f_{95}) at NS08a is 0.2 mg/l. The percentage of time the excess concentration exceeds 2 mg/l (E_2) at NS03 is 11.3%. Similarly, the percentage of time the concentration exceeds 20 mg/l (E_{20}) at NS03a is 3.2%.

The year 2015 is presented because this year contains the largest amount of sediment spill. The following years of the construction period the spill is at maximum 36% of the spill in 2015.

Table 0.4 presents fractiles and exceedance times for the measured background concentrations for 2009-2010. The locations of the nearshore stations are shown in Figure 0.1. The exceedance frequency E_2 is compared graphically in Figure 0.17.

Table 0.3 *Fractiles, f_{xx}(xx%) in mg/l and exceedance times in %, E_{xx}(xx mg/l) for the excess concentrations for the E-ME tunnel solution in 2015 (mid level values)*

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	0.2	0.4	1.2	4.8	0.6	0.1
NS02	0.2	0.8	1.8	8.3	0.1	0.1
NS03	0.3	1.0	2.2	11.3	0.5	0.1
NS04	0.5	2.3	9.9	26.9	9.8	5.5
NS05	0.2	0.9	2.1	10.6	1.2	0.3
NS06	0.0	0.0	0.1	0.3	0.0	0.0
NS07	0.0	0.0	0.3	0.3	0.0	0.0
NS08	0.0	0.0	0.2	0.6	0.0	0.0
NS09	0.0	0.0	0.1	0.0	0.0	0.0
NS10	0.0	0.0	0.0	0.0	0.0	0.0
NS01a	0.3	1.3	3.7	16.8	2.3	0.8
NS02a	0.3	1.3	2.9	16.3	0.4	0.1
NS03a	2.2	5.4	10.4	51.2	10.5	3.2
NS06a	0.0	0.0	0.1	1.1	0.4	0.2
NS07a	0.0	0.0	0.2	0.6	0.1	0.0
NS08a	0.0	0.0	0.2	2.4	0.1	0.0
MS01	0.0	0.1	0.3	0.2	0.0	0.0
MS02	0.0	0.1	0.4	1.2	0.0	0.0

Table 0.4 *Fractiles, f_{xx}(xx%) in mg/l and exceedance times in %, E_{xx}(xx mg/l) as measured at the measurement stations during 2009-2011(mid level values)*

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	1.1	1.9	10.6	23.1	5.4	2.1
NS02	1.5	3.9	28.9	38.6	13.2	7.8
NS03	2.2	6.3	24.7	53.6	15.7	6.6
NS04	2.5	6.4	34.0	60.8	17.7	9.3
NS05	5.3	15.5	54.6	81.0	34.4	19.8
NS06	1.2	1.7	4.7	19.4	0.7	0.2
NS07	1.4	2.6	8.2	32.1	3.3	1.0
NS08	1.4	2.4	6.9	30.6	2.5	1.1
NS09	1.4	2.3	7.9	30.0	3.8	1.5
NS10	1.3	2.2	7.6	28.5	3.2	1.0
NS01a	4.8	17.0	88.2	67.7	34.6	22.8
NS02a	5.1	30.8	126.1	69.6	38.0	30.3
NS03a	18.2	66.3	302.1	83.9	59.9	48.5
NS06a	2.0	6.9	95.0	49.5	20.8	13.2
NS07a	1.9	4.4	36.3	48.0	15.2	9.5
NS08a	1.1	2.2	18.6	27.8	7.9	4.6
MS01	0.7	1.1	3.5	9.4	0.3	0.0
MS02	0.7	1.0	2.4	6.4	0.3	0.0

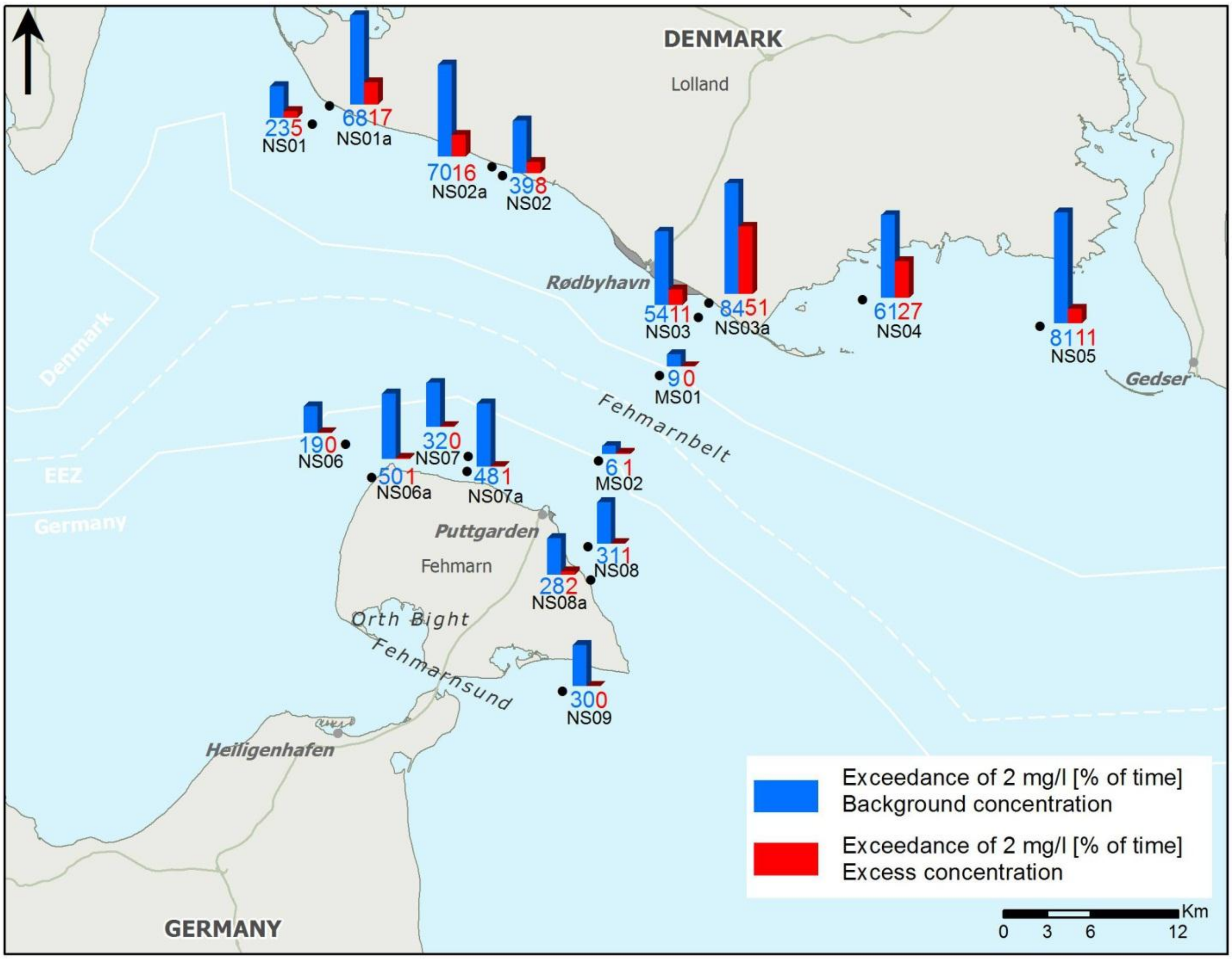

Figure 0.17 Exceedance frequencies, E_2, for the simulated sediment spill for the tunnel scenario for the year 2015 compared with measured background exceedance frequencies. Note the different measurement periods (NS01-NS10: 2009-2010; MS01-MS02: 2009-2011; NS01a-NS08a: Oct 2010/Jan 2011 – May 2011)

The results show that generally the background concentrations are higher than the excess concentrations from the tunnel sediment spill. All background fractiles are generally a factor five or more than the excess concentrations caused by tunnel dredging. Similarly, all exceedance times for background concentrations are higher than the exceedance times cuased by dredging.

Comparing baseline conditions with excess concentrations for bridge solution

In Table 0.5 and Figure 0.18 the fractiles and exceedance times for the bridge solution are given. It appears that the sediment spill concentrations from the construction of the bridge are low compared to the background when averaged over the entire construction period.

Table 0.5 Fractiles and exceedance times for excess concentrations for the bridge solution 2014-2016

Stations	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	0.0	0.0	0.1	0.1	0.0	0.0
NS02	0.0	0.0	0.0	0.2	0.0	0.0
NS03	0.0	0.0	0.1	0.3	0.0	0.0
NS04	0.0	0.1	0.5	3.8	0.4	0.0
NS05	0.0	0.0	0.1	0.1	0.0	0.0
NS06	0.0	0.0	0.0	0.0	0.0	0.0
NS07	0.0	0.0	0.0	0.0	0.0	0.0
NS08	0.0	0.0	0.0	0.0	0.0	0.0
NS09	0.0	0.0	0.0	0.0	0.0	0.0
NS10	0.0	0.0	0.0	0.0	0.0	0.0
NS01a	0.0	0.0	0.1	0.7	0.0	0.0
NS02a	0.0	0.0	0.0	0.3	0.0	0.0
NS03a	0.0	0.0	0.2	2.0	0.6	0.2
NS06a	0.0	0.0	0.0	0.3	0.1	0.0
NS07a	0.0	0.0	0.0	0.3	0.0	0.0
NS08a	0.0	0.0	0.0	0.8	0.0	0.0
MS01	0.0	0.0	0.1	0.0	0.0	0.0
MS02	0.0	0.0	0.1	0.0	0.0	0.0

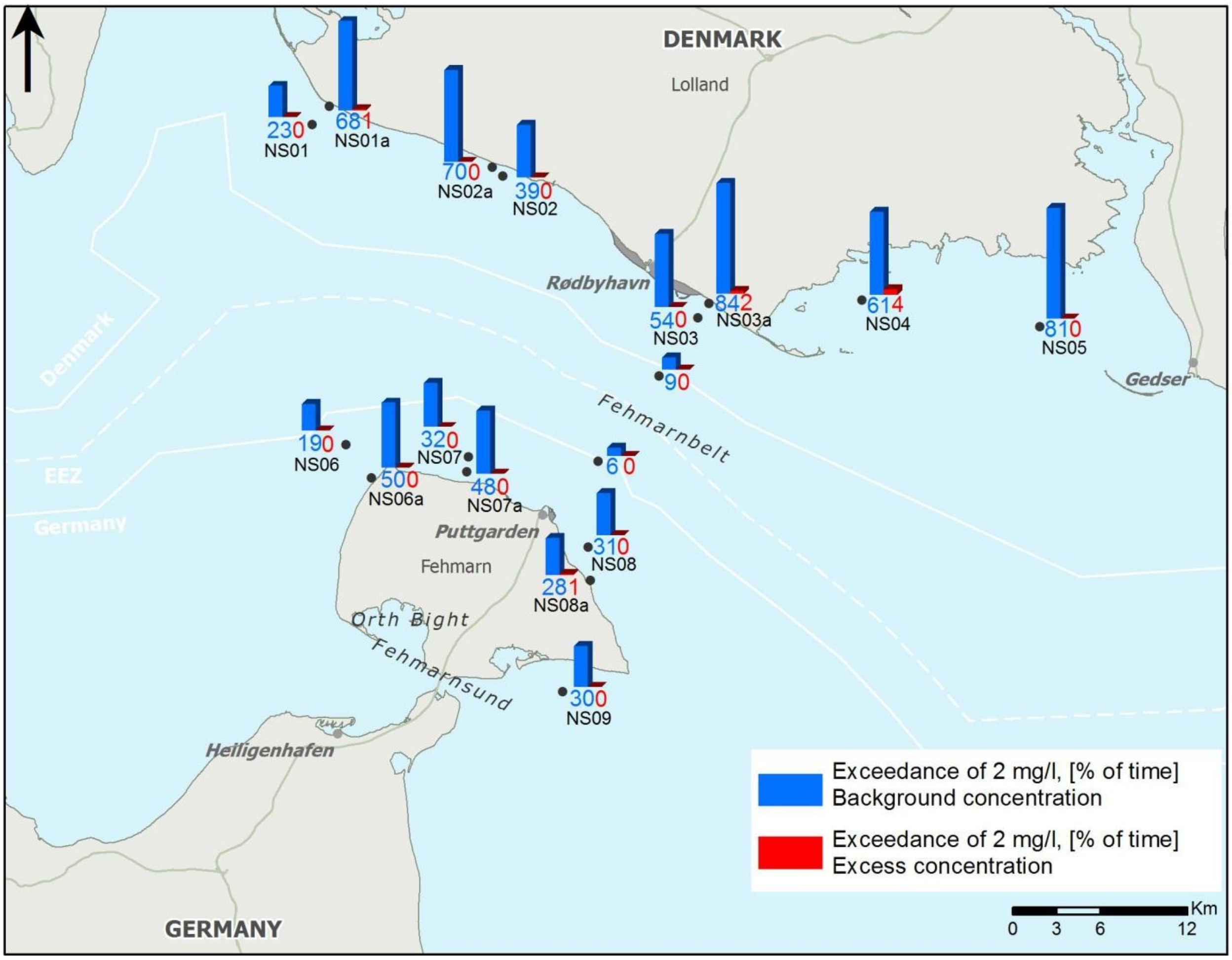

Figure 0.18 Exceedance frequencies, E_2, for the simulated sediment spill for the bridge scenario for 2014 - 2016 compared with measured exceedance frequencies. Note the different measurement periods (NS01-NS10: 2009-2010; MS01-MS02: 2009-2011; NS01a-NS08a: Oct 2010/Jan 2011 – May 2011)

Sediment transport

The suspended sediment concentration levels due to sediment spill vary during the construction period depending on the location of the dredging operations and the current and wave conditions. The concentrations are relatively high along the coastline during the construction of work harbours, access channels and the near coastal parts of the bridge/tunnel, whereas later on, when the construction work is moving offshore, the concentration levels decrease in the nearshore areas. Furthermore, in coastal waters, the waves frequently re-suspend the spilled material. Therefore, in periods relatively high concentrations are seen near the sea bed in the shallow coastal waters. This effect allows for the sediment to travel relatively far along the coastline. In the simulations sediment from the dredging is seen to pass Gedser Odde to the east and Nakskov Fjord to the west due to this effect. On the German side spilled sediment passes around Fehmarn both at the eastern and the western fringe.

The overall sediment spill budget for spilled sediments for the immersed tunnel is outlined in Figure 0.19 which shows the relative sediment fluxes compared to the total spill due to dredging. Note: around 40% of the spilled sediment is sand which deposits close to the corridor.

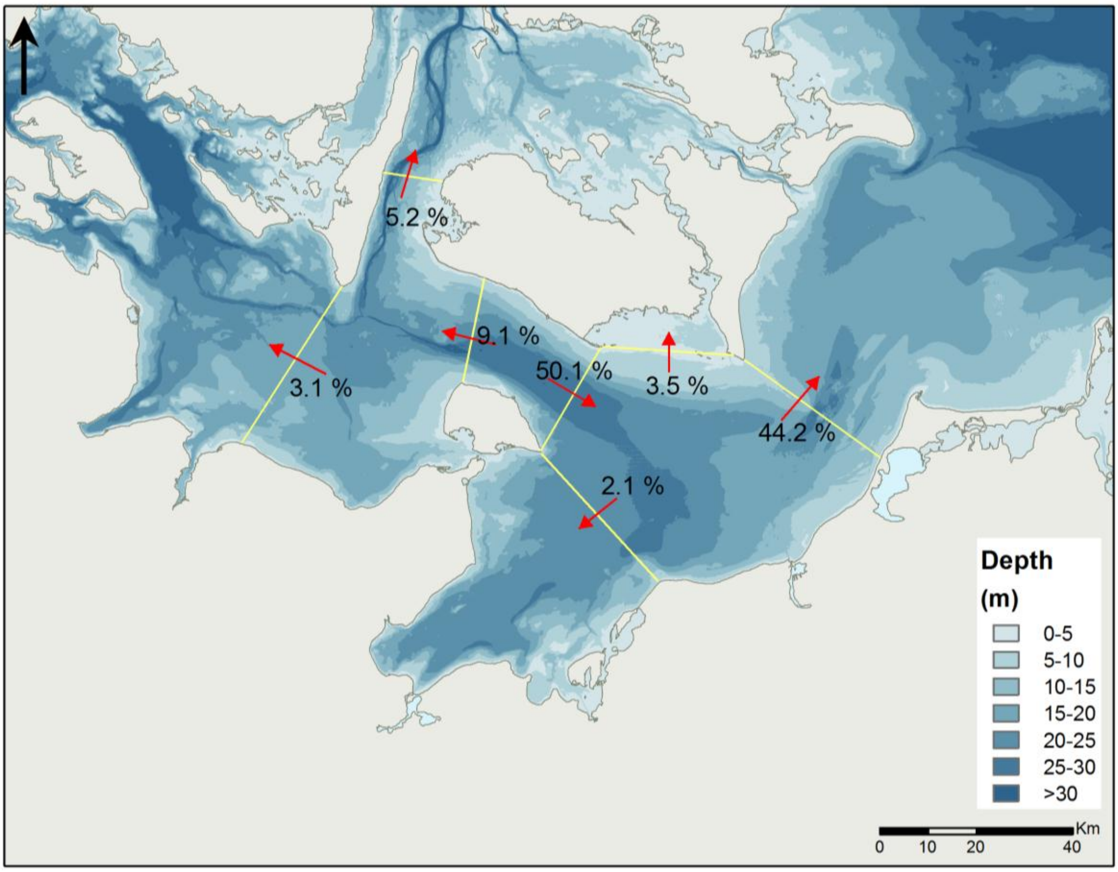

Figure 0.19 Overview of spilled sediment transports for all sediments for the immersed tunnel. The percentages are based on the total spill including coarser fractions. The calculation of sediment transport covers the entire period 2014 – 2019

It is seen that the majority of the spilled sediment travels east consistent with the inflow of saline bottom water from the Kattegat to the Baltic Sea. It is also seen that the majority of the material travelling east continues past Gedser Odde and into the Baltic Sea. Only 3.5% of the totally spilled volume enter the Rødsand Lagoon. Generally, the inflow of sediment from dredging operations to the Rødsand Lagoon is governed by water moving into the lagoon and spilled sediment being available at the entrance to the lagoon. Therefore inflow of sediment requires both rising water levels and that the sediment spill plume has been oriented towards east or sediment is being resuspended from the sea bed along the barrier and near the entrance. Such events are responsible for more than 75% of the sediment entering the Rødsand Lagoon during 2014 and 2015.

The inflow of sediment to the Rødsand Lagoon decreases during the last quarter of 2015 when the dredging for the tunnel trench has reached 2-3 km from shore.

The major effect of dredging on the open coasts disappears shortly after dredging has stopped. However, the sediment temporarily deposited on the sea bed can be resuspended for a long time after dredging has stopped. In the present simulations resuspension can be seen up to 9 months after dredging has stopped. See Figure 0.2 and Figure 0.7 as examples of modelled excess concentrations at NS03 and NS08.

Comparison of solutions

The excess turbidity levels are generally much higher for the tunnel solution than for the bridge.

At the end of the construction period spilled sediments will be present over large areas but in very thin layers. This is the case for both solutions but the layer thicknesses are much smaller for the bridge solution than for the tunnel solution. The deposition of spill reaches up to 50 mm in a narrow band (<1200 m wide) along the tunnel trench and around the bridge piers. The spill at the alignment and at the piers mainly consists of sand. The final deposition of fines will take place in the deeper parts of the Arkona Basin, some areas of the Bay of Mecklenburg, the deep waters off the island of Als and the Rødsand Lagoon, however in very thin layers.

1 INTRODUCTION

This report includes presentation of results of numerical modelling studies undertaken to determine the possible impact from sediment spillage in the Fehmarnbelt during construction of the fixed link.

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, but instead the relative time references from start of construction works (year 0, year 1, etc.), i.e. year 0 corresponds to 2014; year 1 corresponds to 2015 etc.

1.1 Environmental theme

Almost all large infrastructure projects in the marine environment require some degree of dredging of marine soils. When dredging in the marine environment it is inevitable that part of the dredged material is lost into the surrounding waters. The amount of lost materials depends on the dredging method, and the local soil composition. The lost material will spread depending on the physical properties of the soil, the amount of spilled material and the local hydrodynamics.

The spilled material will travel in the water column until it finally settles in an area from where it cannot be resuspended. Before reaching a final resting place the sediment may settle and resuspend many times. During the period of settling and resuspension the spilled material will be in excess of the natural background concentration of sediment in the Fehmarnbelt.

The following parameters are quantified:

- Increase in suspended sediment concentrations
- Reduced water quality (clarity) at bathing beaches during construction
- Increased sedimentation,
- Change in sea bed sediment grain size distribution due to sedimentation

The results will form the basis for evaluating possible impacts on ecology, fish, birds, and mammals, see (FEMA 2013a), (FEMA2013b), (FEMA2013c), (FEHY 2013g), (FEBI 2013a). For Mammals and fish please see the impact reports from Febec and FeMM for Femern A/S.

Possible release of contaminated soils from the dredging operations is treated in (FEHY 2013g).

1.2 Scenarios assessed

Two solutions are considered:

- Immersed tunnel (Version August 2011 E-ME)

- Cable stayed bridge (Version October 2010, alignment BEE)

The two solutions are optimised versions of Immersed tunnel (version November 2010 E-ME) and Cable stayed bridge (version April 2010, alignment BEE), respectively. These two latter versions are the ones which have been studied in detail.

The modelled bridge layout (version April 2010, alignment BEE) is similar to the assessed (version October 2010, alignment BEE) but it includes approximately 100% more sediment spill. An overview of the differences between the two versions is given in Chapter 7.8. The results from the modelling of BEE version April 2010 are representative for the optimised Version 2 BEE of October 2010 as well, but considered to be conservative with regards to sediment spill.

The modelled tunnel layout version November 2010 E-ME is very similar to version August 2011 E-ME, but includes 6% more sediment spill. An overview of the differences is given in Chapter 7.8. The results from the modelling version November 2010 E-ME are valid for the Version August 2011 E-ME as well but considered to be slightly on the conservative side regarding sediment spill.

The objectives of the impact investigations are as follows:

- Quantify the excess concentration due to spillage for each solution
- Quantify the excess deposition patterns due to spillage for each solution

The outcome of the simulations of spreading of spill from dredging activities will subsequently be used to assess the impact on flora and fauna from the construction works as well as the impact on the sea bed morphology in the Fehmarnbelt.

Note that two examples of how dredging could be carried out are investigated. The dredging plans may continue to develop over time until the project starts and the selected schemes are thus considered realistic but not necessarily final schemes.

2 THE FEHMARNBELT FIXED LINK

2.1 General description of the project

The Impact assessment is undertaken for two fixed link solutions:

- Immersed tunnel E-ME (August 2011)
- Cable Stayed Bridge Variant 2 B-EE (October 2010)

2.1.1 The Immersed Tunnel (E-ME August 2011)

The alignment for the immersed tunnel passes east of Puttgarden, crosses the Fehmarnbelt in a soft curve and reaches Lolland east of Rødbyhavn as shown in Figure 2.1 along with near-by NATURA2000 sites.

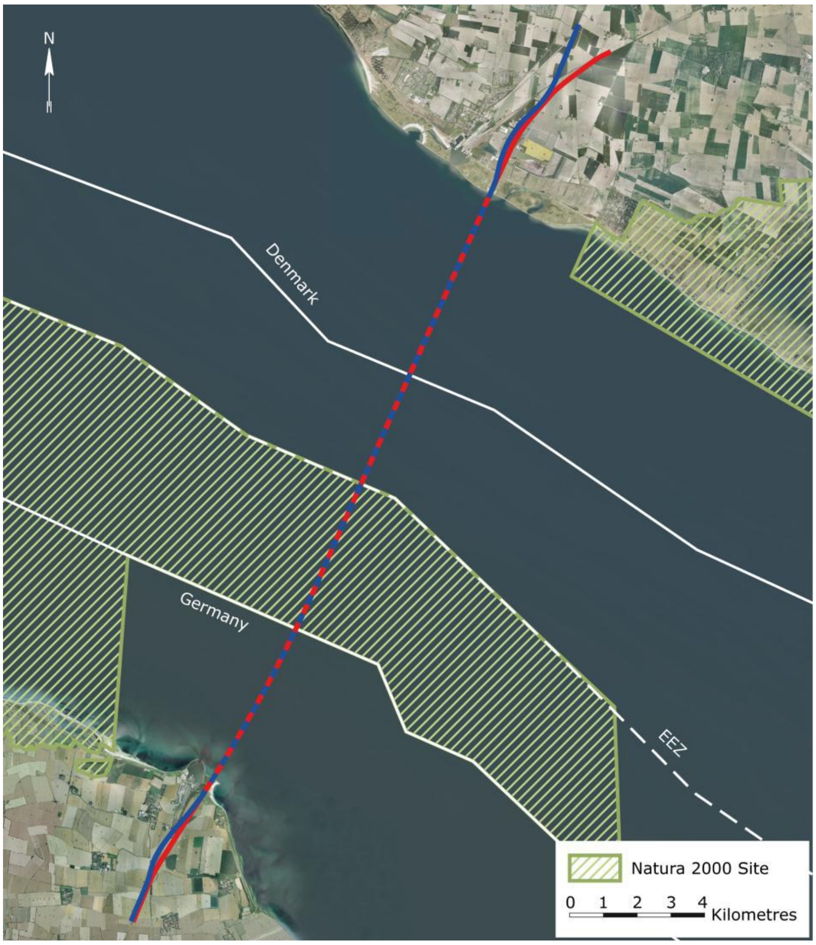

Figure 2.1 Proposed alignment for immersed tunnel E-ME (August 2011)

Tunnel trench

The immersed tunnel is constructed by placing tunnel elements in a trench dredged in the seabed, see Figure 2.2. The proposed methodology for trench dredging comprises mechanical dredging using Backhoe Dredgers (BHD) up to 25m water depth and Grab Dredgers (GD) in deeper waters. A Trailing Suction Hopper Dredger (TSHD) will be used to rip the clay before dredging with GD. The material will be loaded into barges and transported to the near-shore reclamation areas where the soil will be unloaded from the barges by small BHDs. A volume of approx. 14.5 mio. m^3 sediment is handled.

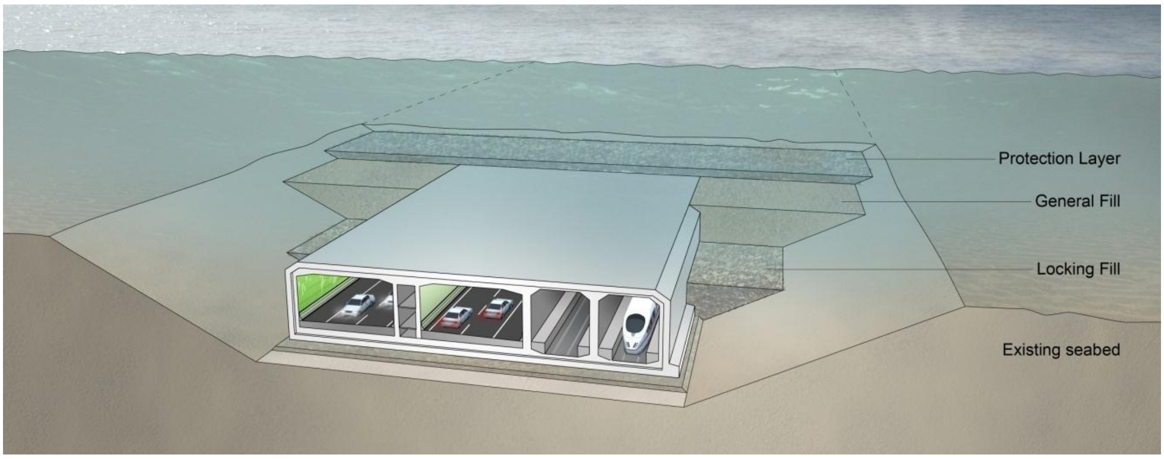

Figure 2.2 Cross section of dredged trench with tunnel element and backfilling

A bedding layer of gravel forms the foundation for the elements. The element is initially kept in place by placing locking fill followed by general fill, while on top there is a stone layer protecting against damage from grounded ships or dragging anchors. The protection layer and the top of the structure are below the existing seabed level except near the shore. At these locations, the seabed is locally raised to incorporate the protection layer over a distance of approximately 500-700m from the proposed coastline. Here the protection layer is thinner and made from concrete and a rock layer.

Tunnel elements

There are two types of tunnel elements: standard elements and special elements. There are 79 standard elements, see Figure 2.3. Each standard element is approximately 217 m long, 42m wide and 9m tall. Special elements are located approximately every 1.8 km providing additional space for technical installations and maintenance access. There are 10 special elements. Each special element is approximately 46m long, 45m wide and 13m tall. After placement of the elements, the tunnel trench will be backfilled with marine material, potentially partly from Kriegers Flak.

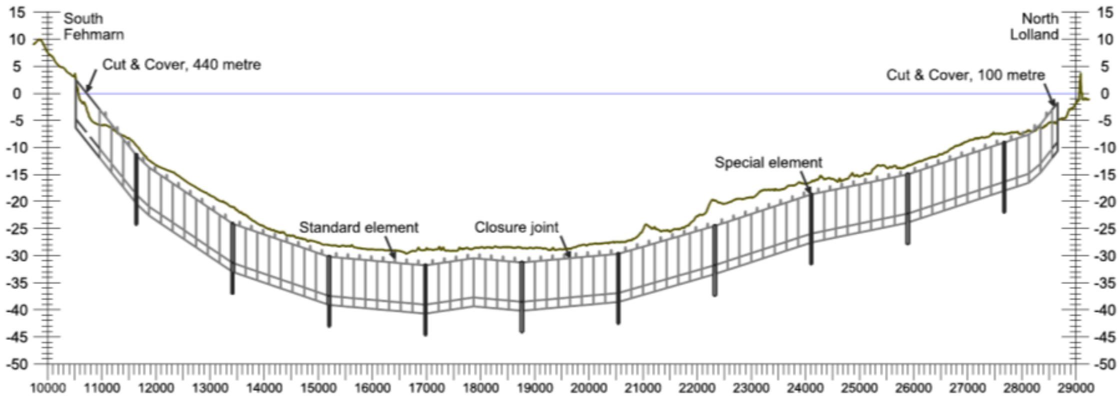

Figure 2.3 Vertical tunnel alignment showing depth below sea level

The cut and cover tunnel section beyond the light screens is approximately 440m long on Lolland and 100m long on Fehmarn. The foundation, walls, and roof are constructed from cast in-situ reinforced concrete.

Tunnel drainage
The tunnel drainage system will remove rainwater and water used for cleaning the tunnel. Rainwater entering the tunnel will be limited by drainage systems on the approach ramps. Fire fighting water can be collected and contained by the system for subsequent handling. A series of pumping stations and sump tanks will transport the water from the tunnel to the portals where it will be treated as required by environmental regulations before being discharged into the Fehmarnbelt.

Reclamation areas
Reclamation areas are planned along both the German and Danish coastlines to accommodate the dredged material from the excavation of the tunnel trench. The size of the reclamation area on the German coastline has been minimized. Two larger reclamations are planned on the Danish coastline. Before the reclamation takes place, containment dikes are to be constructed some 500m out from the coastline.

The landfall of the immersed tunnel passes through the shoreline reclamation areas on both the Danish and German sides

Fehmarn reclamation areas
The proposed reclamation at the Fehmarn coast does not extend towards north beyond the existing ferry harbour outer breakwater at Puttgarden. The extent of the Fehmarn reclamation is shown in Figure 2.4. The reclamation area is designed as an extension of the existing terrain with the natural hill turning into a plateau behind a coastal protection dike 3.5m high. The shape of the dike is designed to accommodate a new beach close to the settlement of Marienleuchte.

Figure 2.4 Proposed reclamation area at Fehmarn

The reclaimed land behind the dike will be landscaped to create an enclosed pasture and grassland habitat. New public paths will be provided through this area leading to a vantage point at the top of the hill, offering views towards the coastline and the sea.

The Fehmarn tunnel portal is located behind the existing coastline. The portal building on Fehmarn houses a limited number of facilities associated with essential equipment for operation and maintenance of the tunnel and is situated below ground level west of the tunnel.

A new dual carriageway is to be constructed on Fehmarn for approximately 3.5km south of the tunnel portal. This new highway rises out of the tunnel and passes onto an embankment next to the existing harbour railway. The remainder of the route of the highway is approximately at level. A new electrified twin track railway is to be constructed on Fehmarn for approximately 3.5km south of the tunnel portal. A lay-by is provided on both sides of the proposed highway for use by German customs officials.

Lolland reclamation area

There are two reclamation areas on Lolland, located either side of the existing harbour. The reclamation areas extend approximately 3.7km east and 3.4km west of the harbour and project approximately 500m beyond the existing coastline into the Fehmarnbelt. The proposed reclamation areas at the Lolland coast do not extend beyond the existing ferry harbour outer breakwaters at Rødbyhavn.

The sea dike along the existing coastline will be retained or reconstructed, if temporarily removed. A new dike to a level of +3m protects the reclamation areas against the sea. To the eastern end of the reclamation, this dike rises as a till cliff to a level of +7m. Two new beaches will be established within the reclamations. There will also be a lagoon with two openings towards Fehmarnbelt, and revetments at the openings. In its final form the reclamation area will appear as three types of landscapes: recreation area, wetland, and grassland - each with different natural features and use.

The Lolland tunnel portal is located within the reclamation area and contained within protective dikes, see Figure 2.5. The main control centre for the operation and maintenance of the Fehmarnbelt Fixed Link tunnel is housed in a building located over the Danish portal. The areas at the top of the perimeter wall, and above the portal building itself, are covered with large stones as part of the landscape design. A path is provided on the sea-side of the proposed dike to serve as recreation access within the reclamation area.

Figure 2.5 Proposed design of tunnel portal area at Lolland

A new dual carriageway is to be constructed on Lolland for approximately 4.5km north of the tunnel portal. This new motorway rises out of the tunnel and passes onto an embankment. The remainder of the route of the motorway is approximately at level. A new electrified twin track railway is to be constructed on Lolland for approximately 4.5km north of the tunnel portal. A lay-by is provided in each direction off the landside highway on the approach to the tunnel for use by Danish customs officials. A facility for motorway toll collection will be provided on the Danish landside.

Marine construction works
The temporary works comprises the construction of two temporary work harbours, the dredging of the portal area and the construction of the containment dikes. For the harbor on Lolland an access channel is also provided. These harbours will be integrated into the planned reclamation areas and upon completion of the tunnel construction works, they will be dismantled/removed and backfilled.

Production site
The current design envisages the tunnel element production site to be located in the Lolland east area in Denmark. Figure 2.6 shows one production facility consisting of two production lines. For the construction of the standard tunnel elements for the Fehmarn tunnel four facilities with in total eight production lines are anticipated.

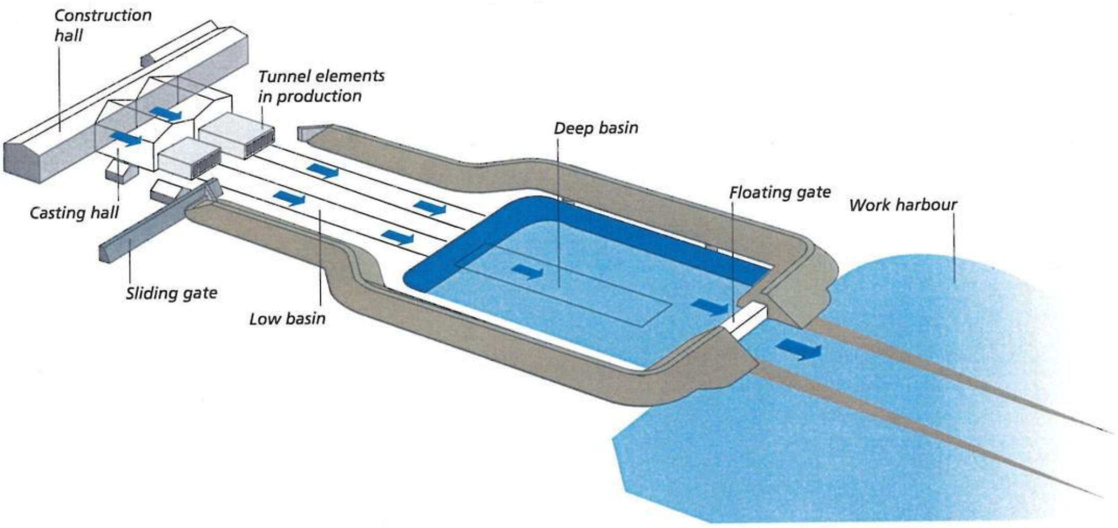

Figure 2.6 Production facility with two production lines

In the construction hall, which is located behind the casting and curing hall, the reinforcement is handled and put together to a complete reinforcement cage for one tunnel segment. The casting of the concrete for the segments is taking place at a fixed location in the casting and curing hall. After the concrete of the segments is cast and hardened enough the formwork is taken down and the segment is pushed forward to make space for the next segment to be cast. This process continues until one complete tunnel element is cast. After that, the tunnel element is pushed into the launching basin. The launching basin consists of an upper basin, which is located at ground level and a deep basin where the tunnel elements can float. In the upper basin the marine outfitting for the subsequent towing and immersion of the element takes place. When the element is outfitted, the sliding gate and floating gate are closed and sea water is pumped into the launching basin until the elements are floating. When the elements are floating they are transferred from the low basin to the deep basin. Finally the water level is lowered to normal sea level, the floating gate opened and the element towed to sea. The proposed lay-out of the production site is shown in Figure 2.7.

Dredging of approx. 4 million m^3 soil is required to create sufficient depth for temporary harbours, access channels and production site basins.

Figure 2.7 Proposed lay-out of the production site east of Rødbyhavn

2.1.2 *The Cable Stayed Bridge (Variant 2 B-EE, October 2010)*

The alignment for the marine section passes east of Puttgarden harbour, crosses the belt in a soft S-curve and reaches Lolland east of Rødbyhavn, see Figure 2.8.

Bridge concept

The main bridge is a twin cable stayed bridge with three pylons and two main spans of 724m each. The superstructure of the cable stayed bridge consists of a double deck girder with the dual carriageway road traffic running on the upper deck and the dual track railway traffic running on the lower deck. The pylons have a height of 272m above sea level and are V-shaped in transverse direction. The main bridge girders are made up of 20m long sections with a weight of 500 to 600t. The standard approach bridge girders are 200m long and their weight is estimated to ~ 8,000t.

Caissons provide the foundation for the pylons and piers of the bridge. Caissons are prefabricated placed 4m below the seabed. If necessary, soils are improved with 15m long bored concrete piles. The caissons in their final positions end 4m above sea level. Prefabricated pier shafts are placed on top of the approach bridge caissons. The pylons are cast in situ on top of the pylon caissons. Protection Works are prefabricated and installed around the pylons and around two piers on both sides of the pylons. These works protrudes above the water surface. The main bridge is connected to the coasts by two approach bridges. The southern approach bridge is 5,748m long and consists of 29 spans and 28 piers. The northern approach bridge is 9,412m long and has 47 spans and 46 piers.

Figure 2.8 Proposed main bridge part of the cable stayed bridge

Land works
A peninsula is constructed both at Fehmarn and at Lolland to use the shallow waters east of the ferry harbours breakwater to shorten the Fixed Link Bridge between its abutments. The peninsulas consist partly of a quarry run bund and partly of dredged material and are protected towards the sea by revetments of armour stones.

Fehmarn
The peninsula on Fehmarn is approximately 580m long, measured from the coastline, see Figure 2.9. The gallery structure on Fehmarn is 320m long and enables a separation of the road and railway alignments. A 400m long ramp viaduct bridge connects the road from the end of the gallery section to the motorway embankment. The embankments for the motorway are 490m long. The motorway passes over the existing railway tracks to Puttgarden Harbour on a bridge. The profile of the railway and motorway then descend to the existing terrain surface.

Lolland
The peninsula on Lolland is approximately 480m long, measured from the coastline. The gallery structure on Lolland is 320m long. The existing railway tracks to Rødbyhavn will be decommissioned, so no overpass will be required. The viaduct bridge for the road is 400m long, the embankments for the motorway are 465m long and for the railway 680m long. The profile of the railway and motorway descends to the natural terrain surface.

Figure 2.9 Proposed peninsula at Fehmarn east of Puttgarden

Drainage on main and approach bridges
On the approach bridges the roadway deck is furnished with gullies leading the drain water down to combined oil separators and sand traps located inside the pier head before discharge into the sea.

On the main bridge the roadway deck is furnished with gullies with sand traps. The drain water passes an oil separator before it is discharged into the sea through the railway deck.

Marine construction work
The marine works comprises soil improvement with bored concrete piles, excavation for and the placing of backfill around caissons, grouting as well as scour protection. The marine works also include the placing of crushed stone filling below and inside the Protection Works at the main bridge.

Soil improvement will be required for the foundations for the main bridge and for most of the foundations for the Fehmarn approach bridge. A steel pile or reinforcement cage could be placed in the bored holes and thereafter filled with concrete.

The dredging works are one of the most important construction operations with respect to the environment, due to the spill of fine sediments. It is recommended that a grab hopper dredger with a hydraulic grab be employed to excavate for the caissons both for practical reasons and because such a dredger minimises the sediment spill. If the dredged soil cannot be backfilled, it must be relocated or disposed of.

Production sites
The temporary works comprises the construction of two temporary work harbours with access channels. A work yard will be established in the immediate vicinity of the harbours, with facilities such as concrete mixing plant, stockpile of materials, storage of equipment, preassembly areas, work shops, offices and labour camps.

The proposed lay-out of the production site is shown in Figure 2.10.

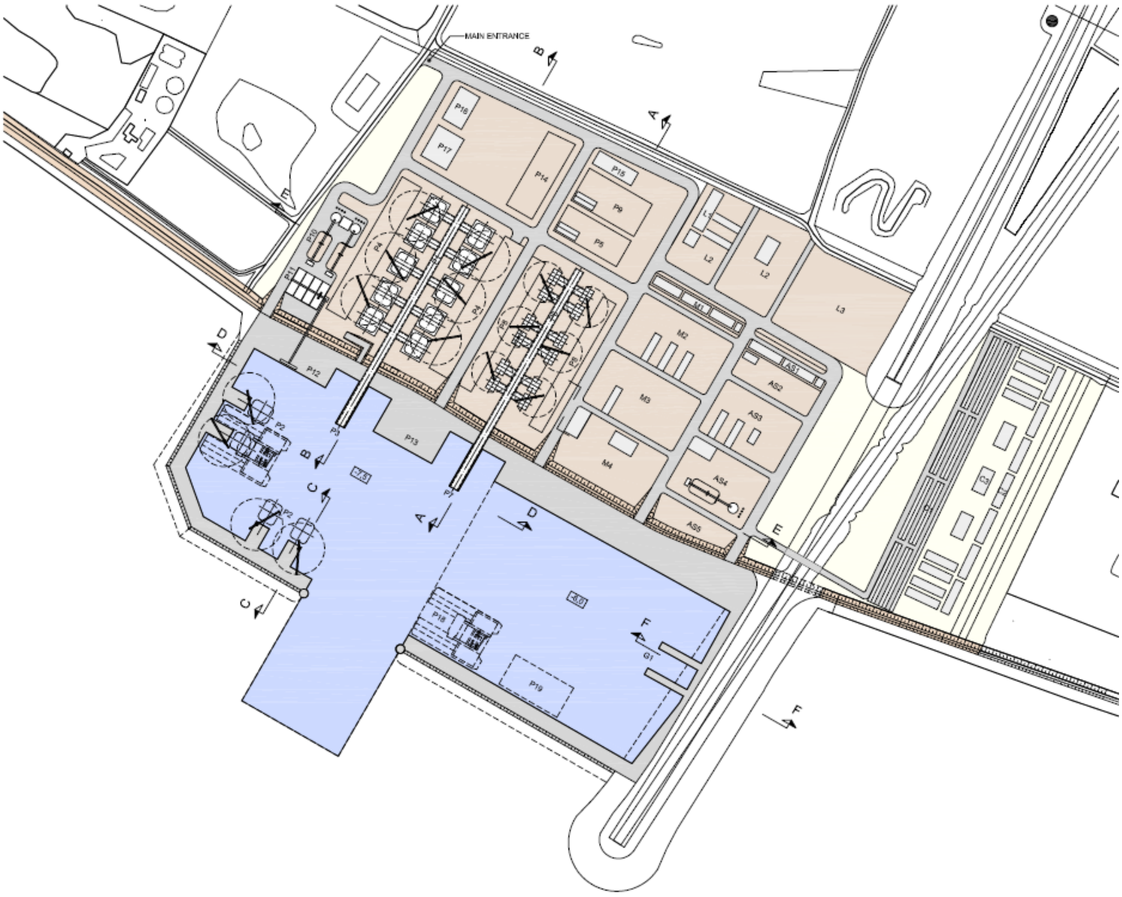

Figure 2.10   Proposed lay-out of the production site at Lolland east of Rødbyhavn

2.2 The Cable stayed bridge version 2 BE-E October 2010

The alignment for the marine section passes east of Puttgarden harbour, crosses the belt in a soft S-curve and reaches Lolland east of Rødbyhavn.

2.2.1 Bridge concept

The main bridge is a twin cable stayed bridge with three pylons and two main spans of 724 m each. The superstructure of the cable stayed bridge consists of a double deck girder with the dual carriageway road traffic running on the upper deck and the dual track railway traffic running on the lower deck. The pylons have a height of 272 m above sea level and are V-shaped in transverse direction. The main bridge girders are made up of 20 m long sections with a weight of 500 to 600 t. A sketch is shown in Figure 2.11.

Caissons provide the foundation for the pylons and piers of the bridge. Caissons are prefabricated placed 4 m below the sea bed. If necessary, soils are improved with

15 m long bored concrete piles. The caissons in their final positions end 4 m above sea level. Prefabricated pier shafts are placed on top of the approach bridge caissons. The pylons are cast in situ on top of the pylon caissons. Protection works are prefabricated and installed around the pylons and around two piers on both sides of the pylons. These works protrude above the water surface. The main bridge is connected to the coasts by two approach bridges. The southern approach bridge is 5,748 m long and consists of 29 spans and 28 piers. The northern approach bridge is 9,412 m long and has 47 spans and 46 piers. The standard approach bridge girders are 200 m long and their weight is estimated to ~ 8,000 t.

Figure 2.11 Bridge layout

2.2.2 *Land works*

A peninsula is constructed both at Fehmarn and at Lolland to use the shallow waters east of the ferry harbours breakwater to shorten the Fixed Link Bridge between its abutments. The peninsulas consist partly of a quarry run bund and partly of dredged material and are protected towards the sea by revetments of armour stones.

Fehmarn
The peninsula on Fehmarn is approximately 580 m long, measured from the coastline. The gallery structure on Fehmarn is 320 m long and enables a separation of the road and railway alignments. A 400 m long ramp viaduct bridge connects the road from the end of the gallery section to the motorway embankment. The embankments for the motorway are 490 m long. The motorway passes over the existing railway tracks to Puttgarden Harbour on a bridge. The profile of the railway and motorway then descend to the existing terrain surface.

Lolland
The peninsula on Lolland is approximately 480 m long, measured from the coastline. The gallery structure on Lolland is 320 m long. The existing railway tracks to Rødbyhavn will be decommissioned, so no overpass will be required. The viaduct bridge for the road is 400 m long, the embankments for the motorway are 465 m long and for the railway 680 m long. The profile of the railway and motorway descend to the natural terrain surface. See Figure 2.12.

Figure 2.12 Example of the approach bridge and the peninsula

2.2.3 Marine construction works

The marine works comprises soil improvement with bored concrete piles, excavation for and the placing of backfill around caissons, grouting as well as scour protection. The marine works also include the placing of crushed stone filling below and inside the protection works at the main bridge.

Soil improvement will be required for the foundations for the main bridge and for most of the foundations for the Fehmarn approach bridge. A steel pile or reinforcement cage could be placed in the bored holes and thereafter filled with concrete.

The dredging works are one of the most important construction operations with respect to the environment, due to the spill of fine sediments. It is recommended that a grab hopper dredger with a hydraulic grab be employed to excavate for the caissons both for practical reasons and because such a dredger minimises the sediment spill. If the dredged soil cannot be backfilled, it must be relocated or disposed of.

2.2.4 *Production sites*

The temporary works comprise the construction of two temporary work harbours with access channels. A work yard will be established in the immediate vicinity of the harbours, with facilities such as concrete mixing plant, stockpile of materials, storage of equipment, preassembly areas, work shops, offices and labour camps.

The proposed layout of the production site is shown in Figure 2.13.

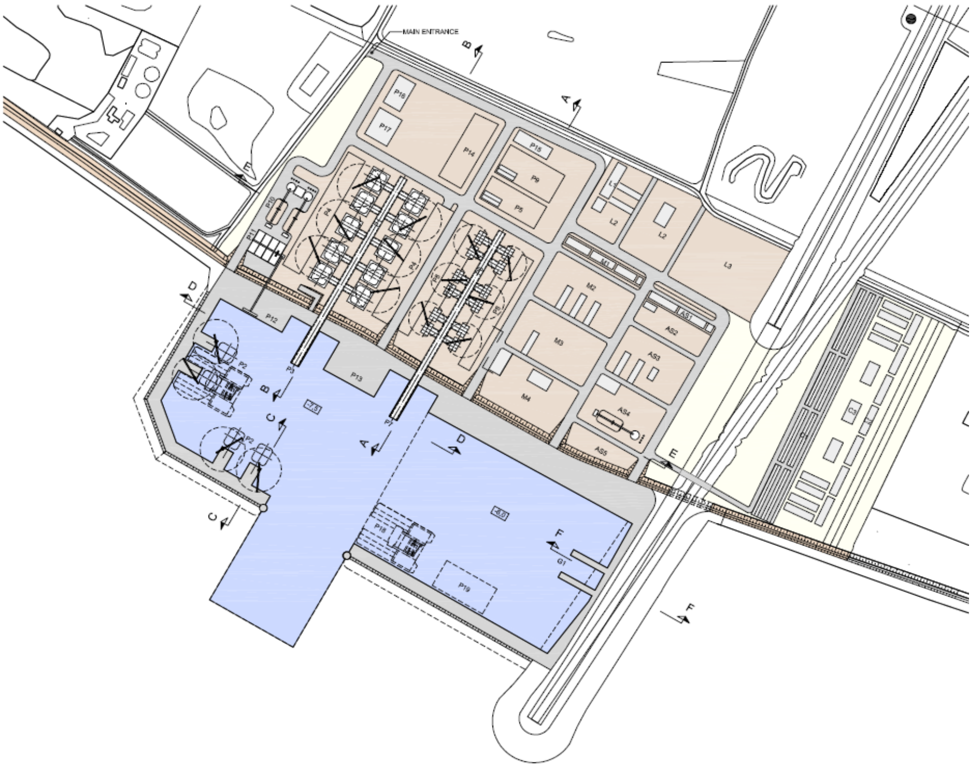

Figure 2.13 Proposed layout of the production site

3 DATA AND METHODS

3.1 List of data available

The following data is available for this study:

- Sediment samples from all geotechnical stations gathered from different depths below the sea bed. See (Location reports. Fugro Engineers. B.V 2009)
- Settling velocity and grain size data from field test conducted in September 2009 using material from geotechnical station A008 (late glacial clay) and A014 (clay till). See Appendix P
- Settling velocity and grain size data from the field test conducted in October 2010 on Paleogene clay. See Appendix P
- Dredging plans, earth balances and spill amounts from RAT JV (Tunnel solutions). See Appendix A
- Dredging plans, earth balances and spill amounts from COWI/Obermeier (Bridge solution). See Appendix B
- Baseline data on suspended sediment concentration (SSC). See (FEHY 2013c)
- Baseline data on the sea bed composition. See (FEHY 2013c)
- Baseline data on current speeds and directions. See (FEHY 2013d)
- Map of marine habitats from Fehmarnbelt marine baseline investigations. See (FEMA 2013c)
- Calibrated numerical model of the hydrodynamics from Fehmarnbelt hydrodynamic studies. See (FEHY 2013a)
- Calibrated wave model from Fehmarnbelt wave studies. See (FEHY 2013e)

Note: Chemical conditions in pore water and pollution of sediments are not part of this report on sediment spill. Reference is given to (FEHY 2013g) for a discussion of possible release of comtaminated sediments during dredging.

3.2 Area of investigation

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 Mecklenburg Bight and further over the shallow Darss Sill into the Arkona Basin of the Baltic Sea.

The hydrodynamic conditions in the Fehmarnbelt are affected by local and remote forcings due to irregular weather patterns and occasional storms with time scales of a few days resulting in varying current conditions. During stable weather conditions, for example in the summer, the flow is in the same direction for weeks. For further information see (FEHY 2013d).

Transport, erosion and deposition of naturally available sediment or spilled sediment during dredging are determined by the hydrodynamic conditions. In periods with rough weather, large waves and strong currents the sediment will be kept in suspension and travel with the flow whereas in periods with calm weather the sediment will settle on the sea bed. Normally the weather is shifting with the irregular weather patterns and therefore the sediment transport happens in a series of events. The sediment will continue being resuspended and re-deposited until it reaches a location where the hydrodynamic forces, waves and currents are so weak that the sediment cannot be resuspended. This location is denoted the final deposition area.

By investigation of the present bed composition in the Fehmarnbelt, see (FEHY 2013c), Figure 3.1, it is expected that the final deposition areas will be locations that naturally contain a large percentage of fine materials. In these areas it must be expected that the spilled sediment can settle without being resuspended. Examples of local accumulation areas of fine sediments are Bay of Mecklenburg, The Arkona Basin, the area just off Heiligen Hafen, and the deeper areas between Bay of Kiel and Lillebaelt.

The investigation area is shown in Figure 3.2.

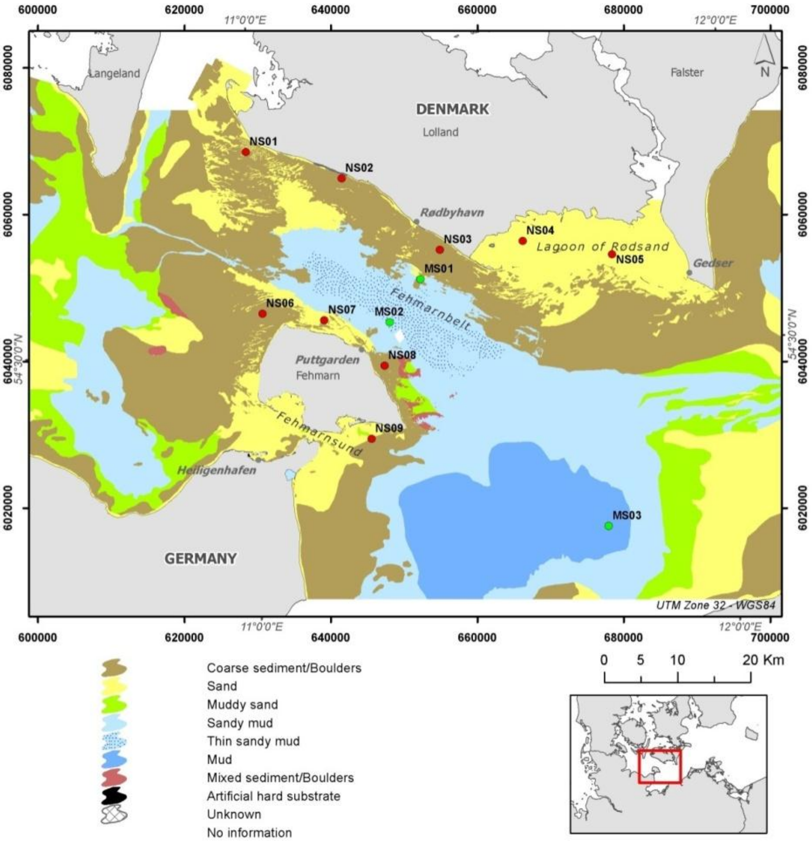

Figure 3.1 Substrate map showing the bed composition

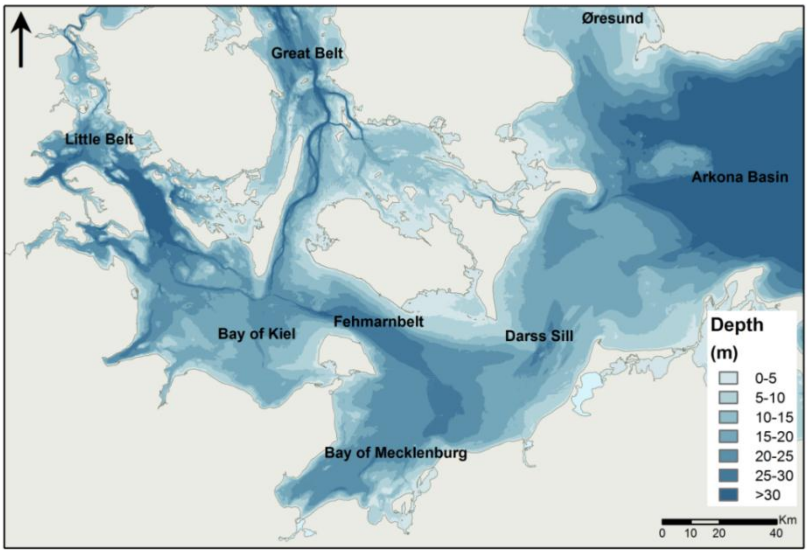

Figure 3.2 The bathymetry map of the Fehmarnbelt region shows the investigation area for the sediment spill assessment

3.3 Background concentrations and visibility of sediment in the water

The concentrations of natural sediment in the Fehmarnbelt have been thoroughly investigated in (FEHY 2013c). The statistics for suspended sediment concentrations as measured during 2009 to 2011 are given in Figure 3.5. This investigation shows that natural concentrations are typically below 2 mg/l in the offshore zone in water depths larger than 6 m. In the nearshore zone, here defined as nearshore-areas where water depths are below 6 m, concentrations vary strongly. In this region concentrations often exceed 100 mg/l. Examples of measured time series of simultaneous suspended concentrations and wind are presented in Figure 3.3 and Figure 3.4.

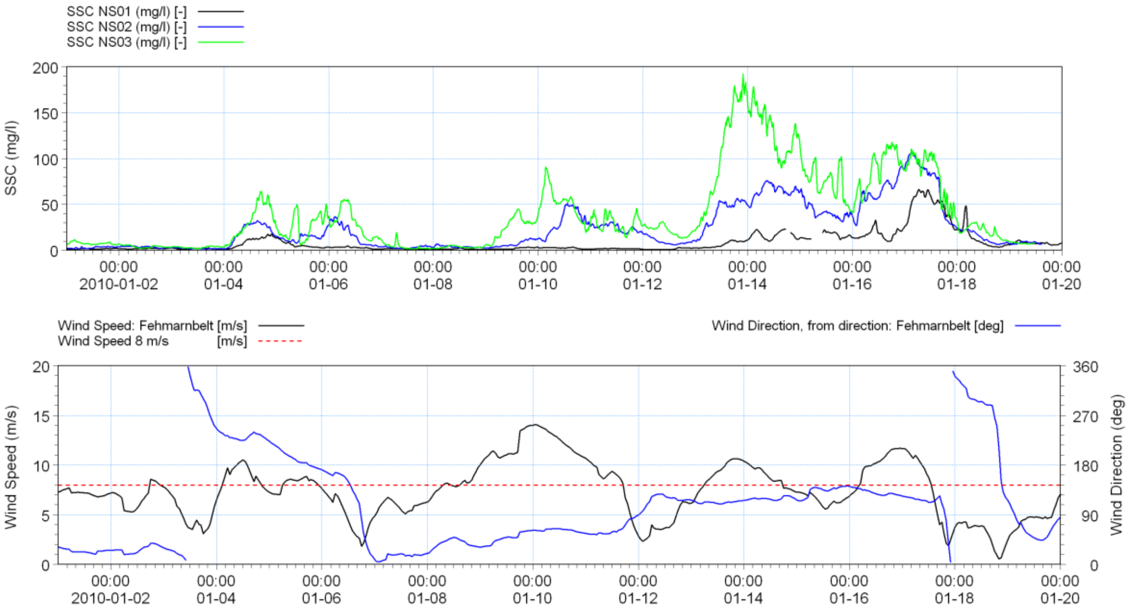

Figure 3.3 Natural concentrations at NS01 – NS03

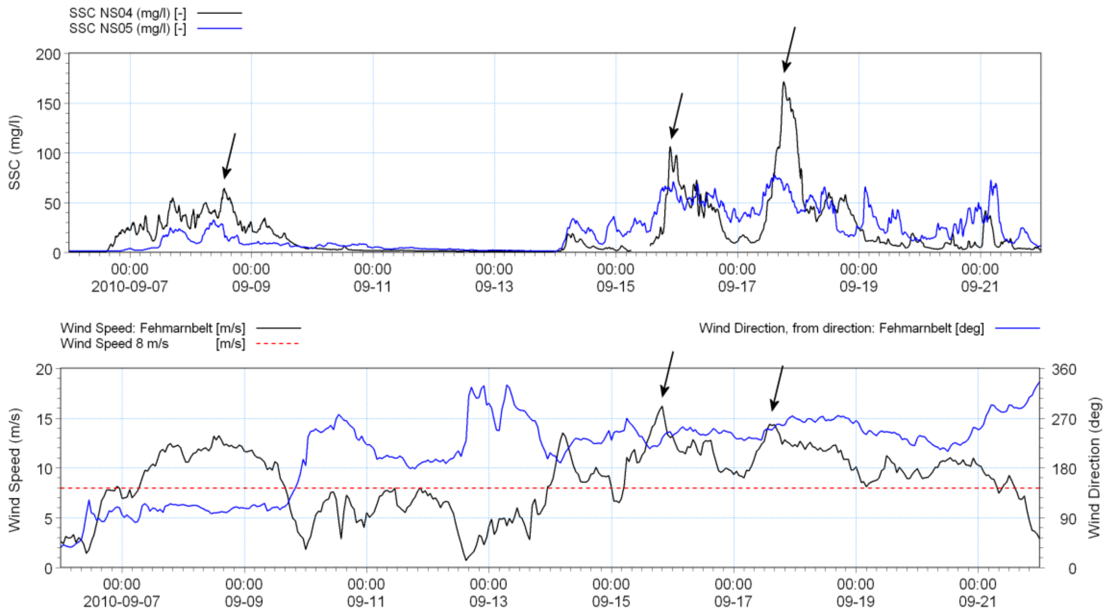

Figure 3.4 Natural suspended sediment concentrations at NS04 – NS05

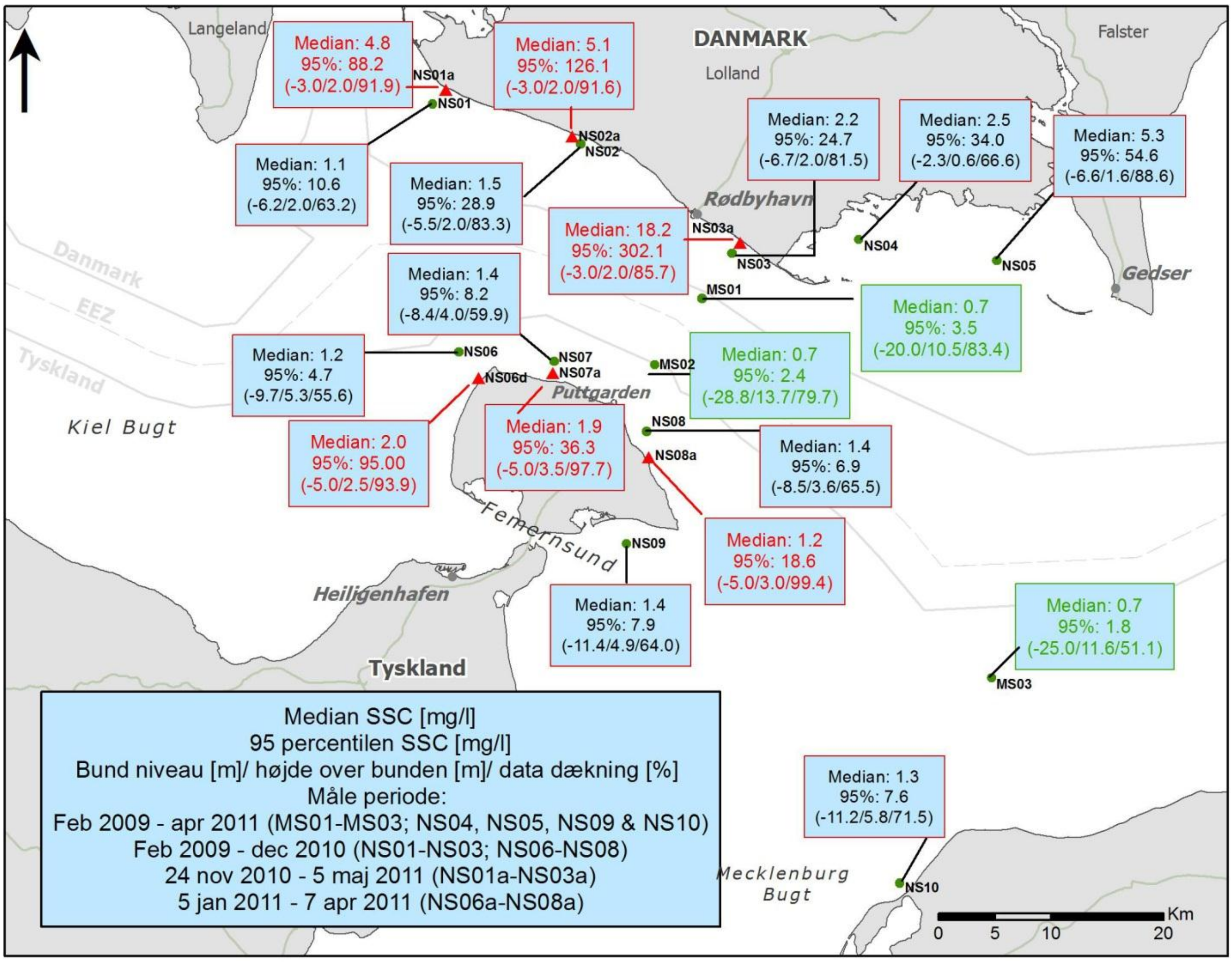

Figure 3.5 Statistics for natural suspended sediment concentrations in the Fehmarnbelt. (FEHY 2013c)

It is shown that the concentration levels in the nearshore regions are closely related to the winds (waves) and currents and that the suspended sediment consists of locally resuspended sediments.

The visibility of dredged materials is different offshore, here defined as areas with water depths larger than 6 m, and near shore. Offshore the plumes from dredged materials will be superimposed on a very low natural concentration level and thus the plumes will be visible at the normal visibility level. Nearshore the sediment plumes will be superimposen a natural concentration level that is very variable. During windy periods the background concentrations will be high and thus the plume will be hard to detect whereas during calm periods the plume will be detectable similar to the offshore conditions.

The limit for sediment visibility depends on the light at the time, sediment composition, and colour of the water and the sediment and in shallow waters also the colour of the seabed. Experience from the Øresund study sets the visibility limit to 2 mg/l. During the field tests in September 2009 and October 2010 the sediment plumes were also visible at 2 mg/l. An example from the field test from September 2009 is given in Figure 3.6. For further information see Appendix P. This limit is therefore adopted for the clear water case.

Figure 3.6 Sediment plume from field test October 2009. Concentration 3-4 mg/l. See Appendix P

3.4 Soil conditions along the alignment

3.4.1 Geology

The upper soil in the Fehmarnbelt is dominated by deposits from the latest ice age. On the Danish side the soil is predominantly till and postglacial sand. The clay till is generally very hard in this area with. On the German side the soil is dominated by basin deposits, mainly late glacial clay and gyttja. Both earth types are very fine grained and vary between very soft to very hard. Typical geotechnical properties are given in Table 3.1

In an area near the southern banks paleogene clay has been folded up. Paleogene clay is fine grained but very hard. An overview of the different geological features can be seen in Figure 3.7.

Table 3.1 Overview of geotechnical soil properties. Typical intervals based on borings number A009, A007, A003, and A006

	Plasticity index ()	Water content (%)	Organic content (%)	Density (kN/m^3)	Cone resistance (MPa)
Clay till	6 - 16	8 - 12	1 - 3	22 -24	2 - 40
Paleogene clay	10	8	0 – 1		
Post glacial sand	-	20 - 60	0		0.5 - 8
Melt water sand	-	-	0		
Late glacial clay	7 - 101	26 - 40	1-5	15 - 19	< 3
Gyttja	31 - 61	40 - 80	2 -30	14 - 17	< 1

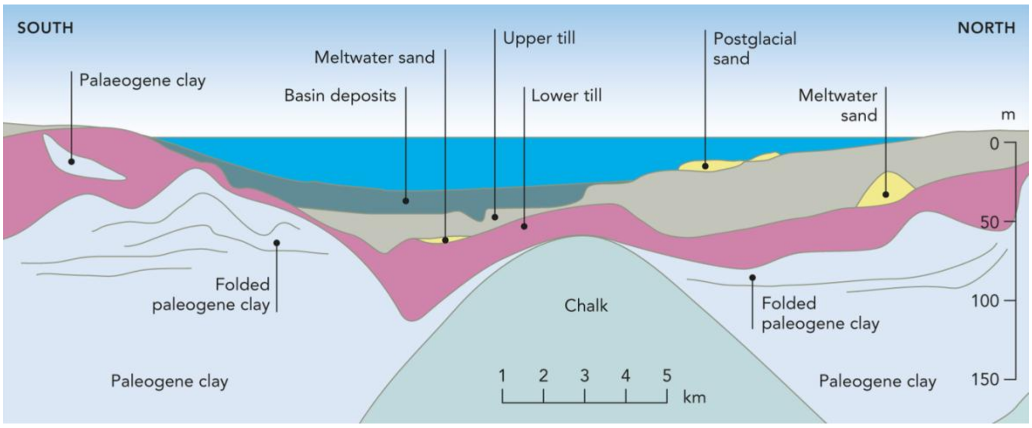

Figure 3.7 Overview of the geology in the Fehmarnbelt www.Fehmarn.dk

3.4.2 Information on grain size distribution

The information on the grain sizes was gathered from 19 geotechnical cores collected during the geotechnical survey, see (Location reports Fugro Engineers. B.V. 2009).The bore hole locations where the cores were sampled are shown in Figure 3.8.

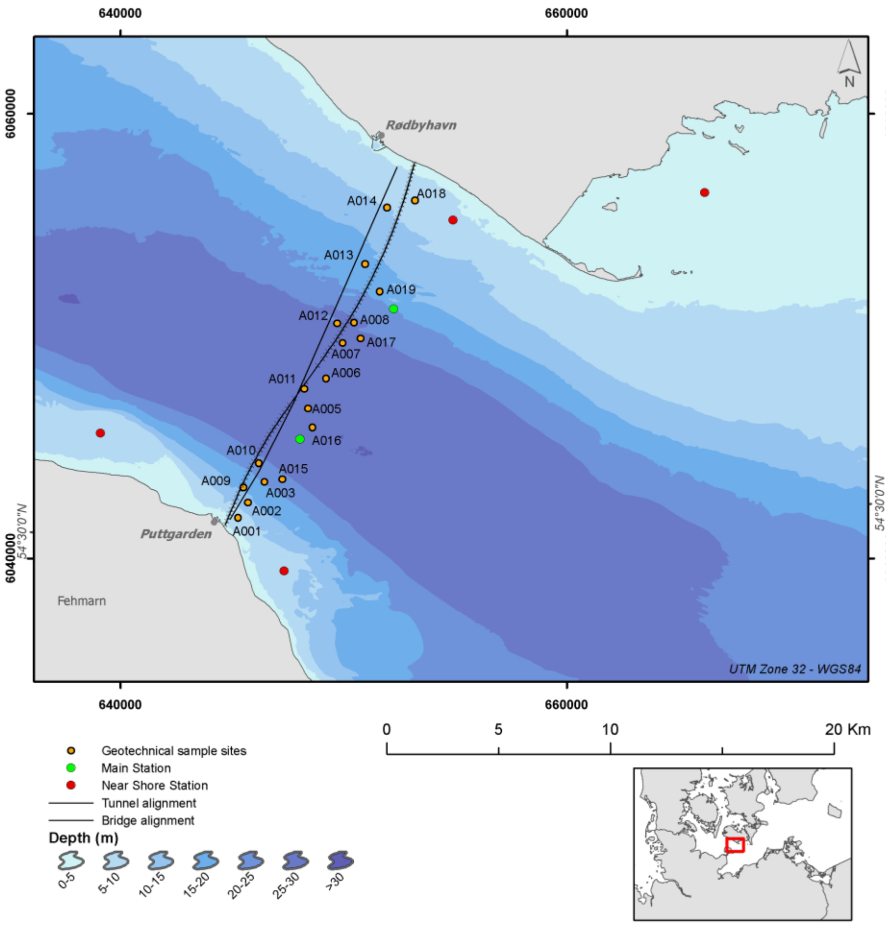

Figure 3.8 Overview of geotechnical borehole locations

Each core penetrated down to a level of between 50 m and 100 m below the seabed. Samples from each layer at each core were taken partly from bag samples (BS) and partly from the actual cores. In total, 45 samples were taken. Further 22 samples were taken from the 2 m cores gathered during FEMA’s survey in autumn 2010. See (FEMA 2013c).

All samples not consisting of pure sand were analysed for particle size distributions by means of laser diffraction analysis. The sand samples were sieved. In Figure 3.9 to Figure 3.12, particle size distributions from some of the most common soil types are given based on laser diffraction analysis. Particle size distributions for all samples can be found in Appendix D.

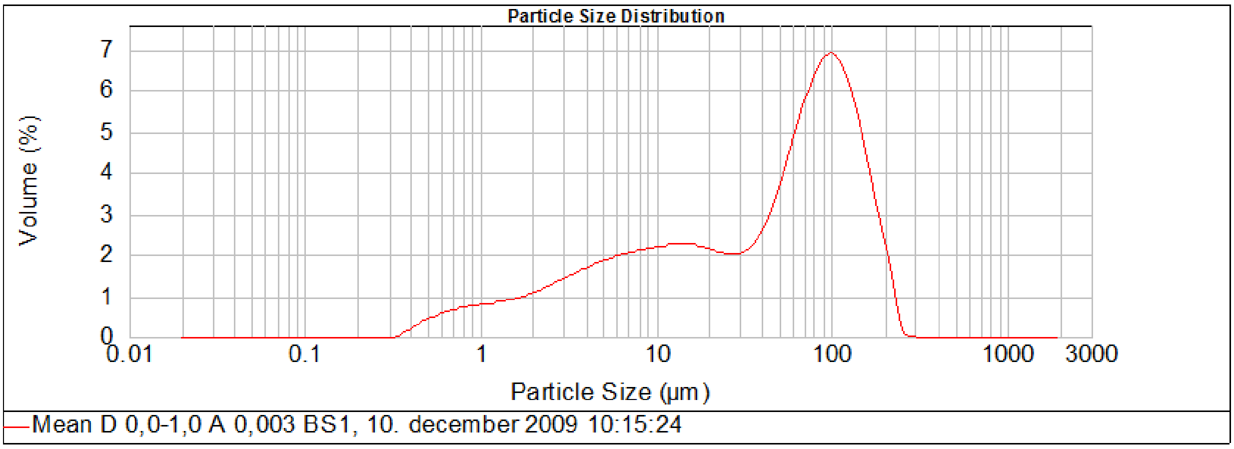

Figure 3.9 *Particle size distribution from sample No 2 (A003 BS1). Postglacial marine sand/gravel unit. Clay: < 0.002 mm, silt: 0.002mm-0.063 mm, sand:>0.063 mm. Sample taken 0.5 m below sea bed*

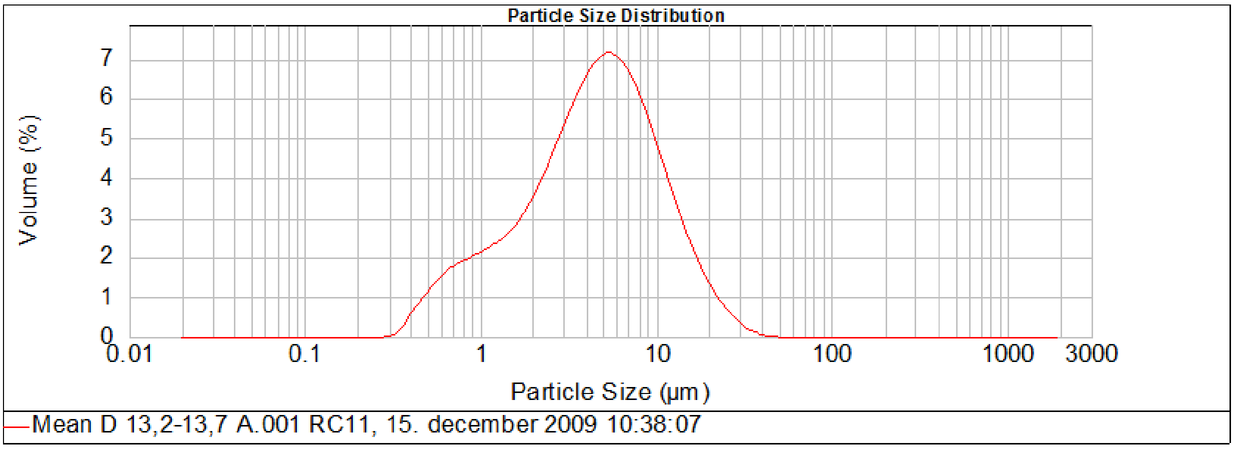

Figure 3.10 *Particle size distribution from sample No 11 (A001 RC11). Post/late glacial marine/fresh-water clay. Clay: < 0.002 mm, silt: 0.002mm-0.063 mm, sand:>0.063 m. Sample taken 13.4 m below sea bed*

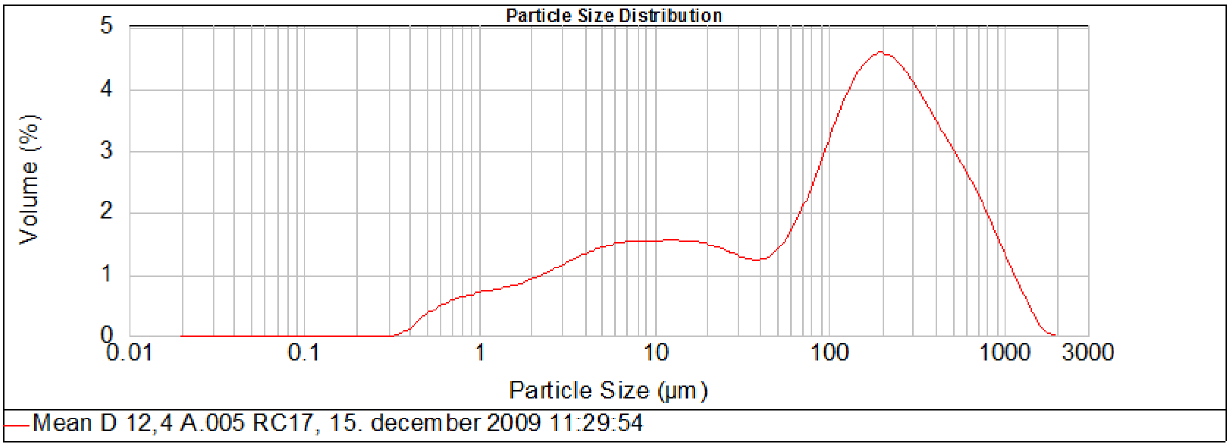

Figure 3.11 *Particle size distribution from sample No 5 (A005 RC17). Lower quaternary upper – upper glacial unit (till). Clay: < 0.002 mm, silt: 0.002 mm- 0.063 mm, sand:>0.063 mm. Sample taken 12.4 m below sea bed*

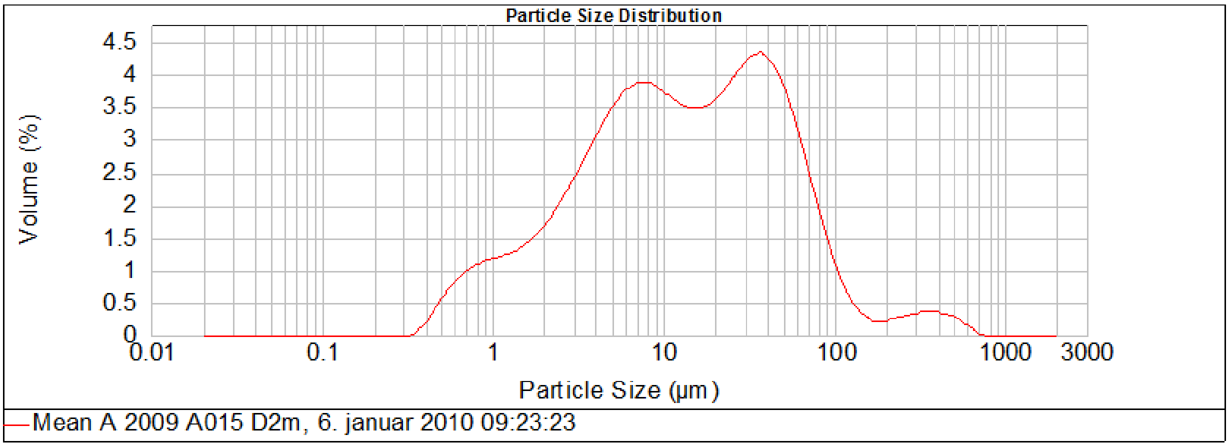

Figure 3.12 Particle size distribution from sample No 55 (A015). Postglacial marine/freshwater gyttja. Clay: < 0.002 mm, silt: 0.002 mm-0.063 mm, sand:>0.063 mm. Sample taken 2.0 m below sea bed

Note that all samples analysed by laser diffraction have been dispersed to primary particles. Therefore the grain size distribution for the cohesive particles shows finer particles compared to similar tests performed in the field where flocculation will occur. The tests should therefore be used to assess the amount of fines and the potential for fine particles rather than for assessing the exact grain size distribution in the field.

3.5 Spill modelling

The spreading of spilled sediment for the entire dredging operation has been simulated in a set of numerical models for the two different Fixed Link scenarios. The plans for earth works, including dredging, disposal, temporal storage, build-in of material in ramps and reclamations, etc. form the basis for the so-called “spill scenarios” being the interpretation of the dredging work in the numerical model.

The spill amounts are determined by the type of dredging equipment and working procedures. The type of spilled sediment (clay, sand etc.) is determined by the geological conditions at the dredging location. The geological conditions are mapped in great detail, see Chapter 3.3.

The numerical model for simulation of spreading of the sediment operates with four fractions of the dredged material. The distribution of sediment (in fractions) varies strongly from location to location. The geological conditions and the selected, representative fractions are described in Chapter 5.1.1.

The amounts and locations of earth handling which result in sediment spills are described for each of the two Fixed Link scenarios by RAT JV for the tunnel scenario and COWI/Obermeier for the bridge scenario. The earth works are documented in Appendix A and Appendix B. Summaries of the plans for the earth works are presented in Chapter 5.1.1.

The hydrographic year 2005 has been used as basis for the simulation of the spreading of the spilled sediment. The year 2005 was chosen as a hydrodynamically representative year based on comparisons of the currents at the locations of the main stations MS01 and MS02, see (FEHY 2013d). Comparisons of current speeds and directions are presented in Figure 3.13.

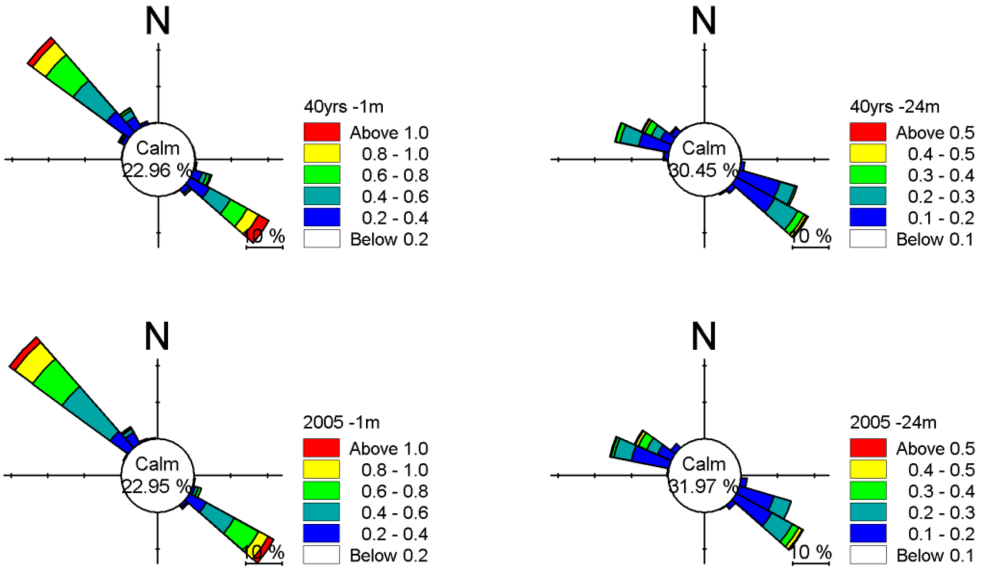

Figure 3.13 Modelled current speeds from the position of main station 2. Currents for the year 2005 (bottom), compared to an average over the period 1970–2010, see (FEHY 2013d)

In Figure 3.14, the long term flow statistics derived on a monthly basis are compared to the statistics for the year 2005. It is seen that the year 2005 represents the overall trends well, but that smaller variations compared to the monthly averages do occur.

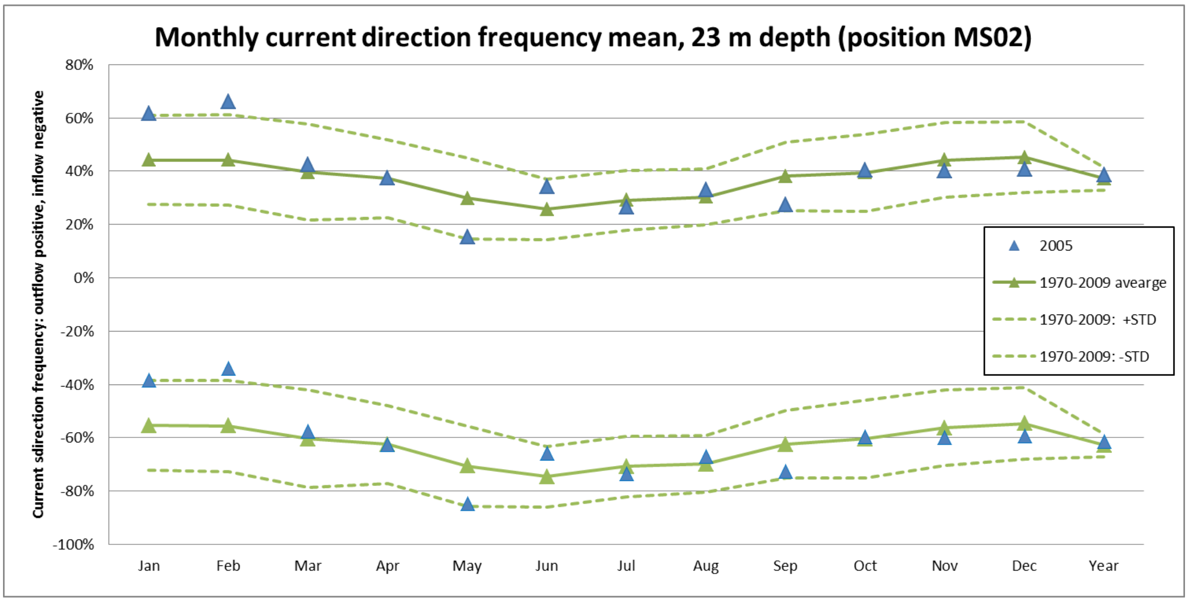

Figure 3.14 Flow statistics (inflow and outflow) from the year 2005 compared to the average flow from 1970–2009

In Figure 3.15 an overview of the modelled hydrodynamics and the applied wind is given for the location of main station 1.

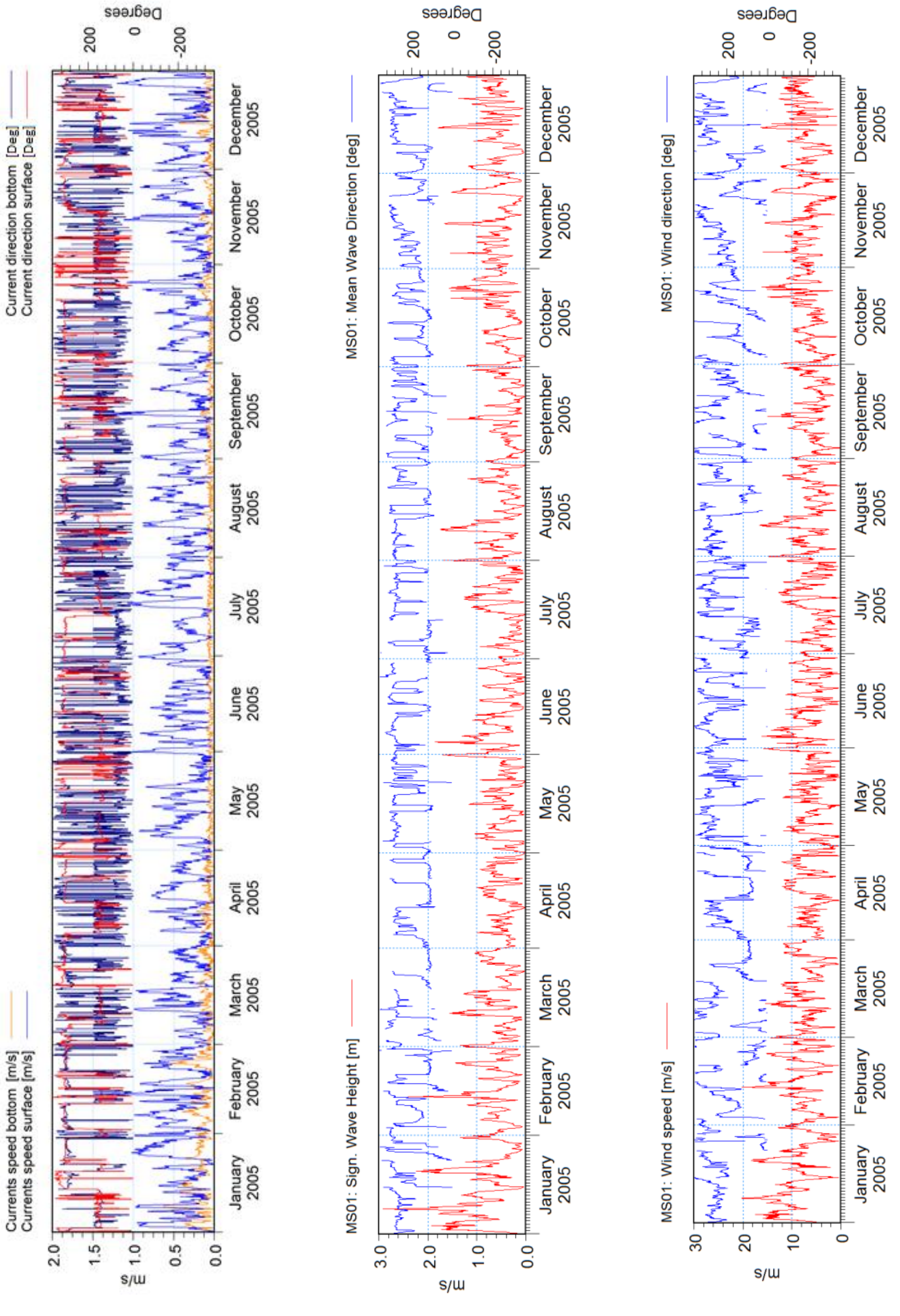

Figure 3.15 Overview of hydrodynamics and wind conditions at MS01 in 2005

3.5.1 *Hydrodynamic modelling*

Model set-up and model parameters
A set-up of the 3D hydrodynamic model MIKE FM HD 3D, with the following characteristics has been established:

Coverage:	from Kattegat to the Baltic Sea, see Figure 3.17
Horisontal resolution:	varying from approximately 100 m to 2000 m
Vertical resolution:	20 layers equally distributed over the local depth
Boundary conditions:	extracted from the regional hydrodynamic model
Turbulence closure:	Smagorinsky/k-ε
Bed roughness:	0.0005 m
Horisontal dispersion factor	0.001
Vertical dispersion factor	0.01

The use of a so-called sigma grid in the vertical direction, see Figure 3.16, in combination with boundary conditions and 3D fields of salinity and temperature extracted from the regional hydrodynamic model, see (FEHY 2013a), ensures an accurate representation of the near-bed current speeds.

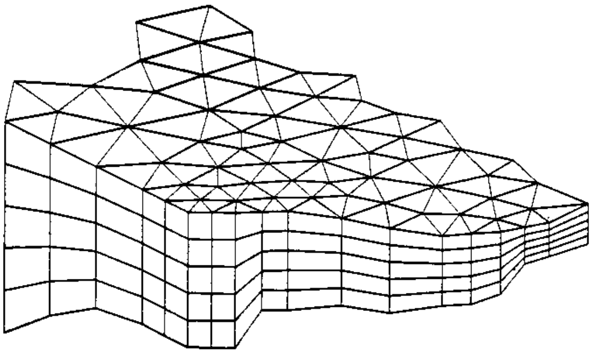

Figure 3.16 Example of a 3D triangular grid using the Flexible Mesh solution technique and sigma grid. A sigma grid is a grid where the vertical grid spacing varies with the water depth

The model set-up applied for the study of spilled sediment is similar to the one used for studying the natural sediment transport capacity in the Fehmarnbelt, See (FEHY 2013e).

In order to reproduce the plumes a finer horisontal resolution has been adopted around the Fixed Link and the entrances to the Rødsand Lagoon. The refined computational mesh in the Fehmarnbelt is shown in Figure 3.17 and Figure 3.18. The hydrodynamic model with the sigma layer has been calibrated and validated against measured currents from 2009. The comparison with measurements is documented in (FEHY 2013d).

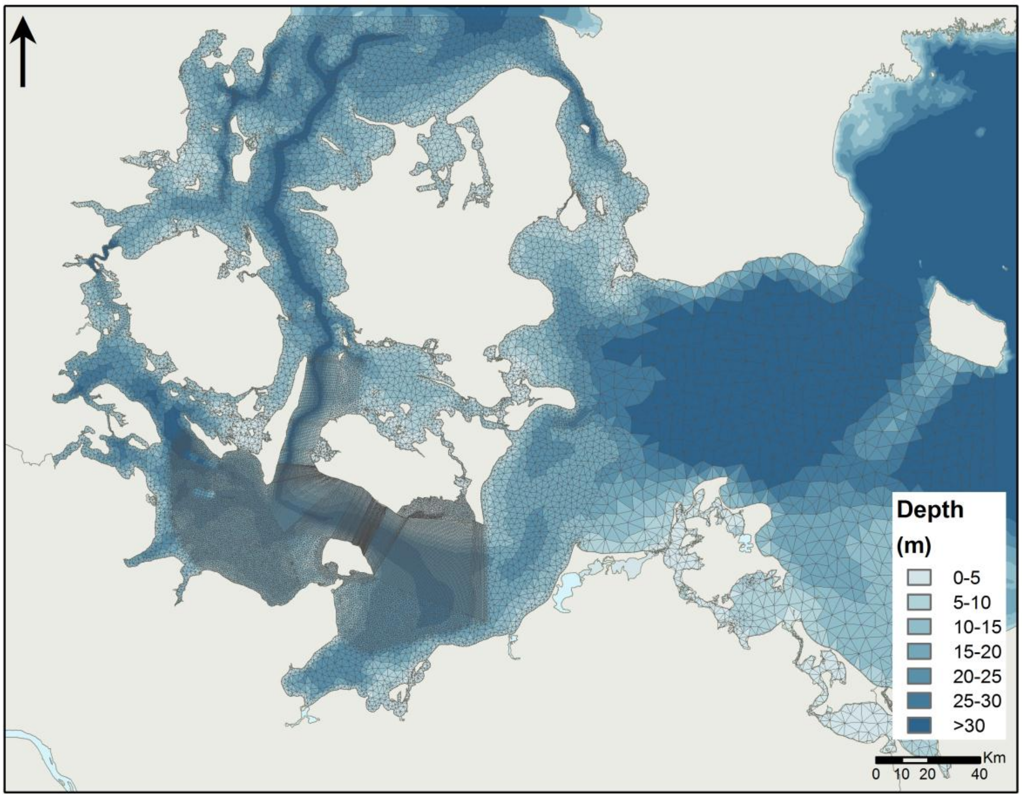

Figure 3.17 Coverage and horisontal computational mesh for the hydrodynamic model

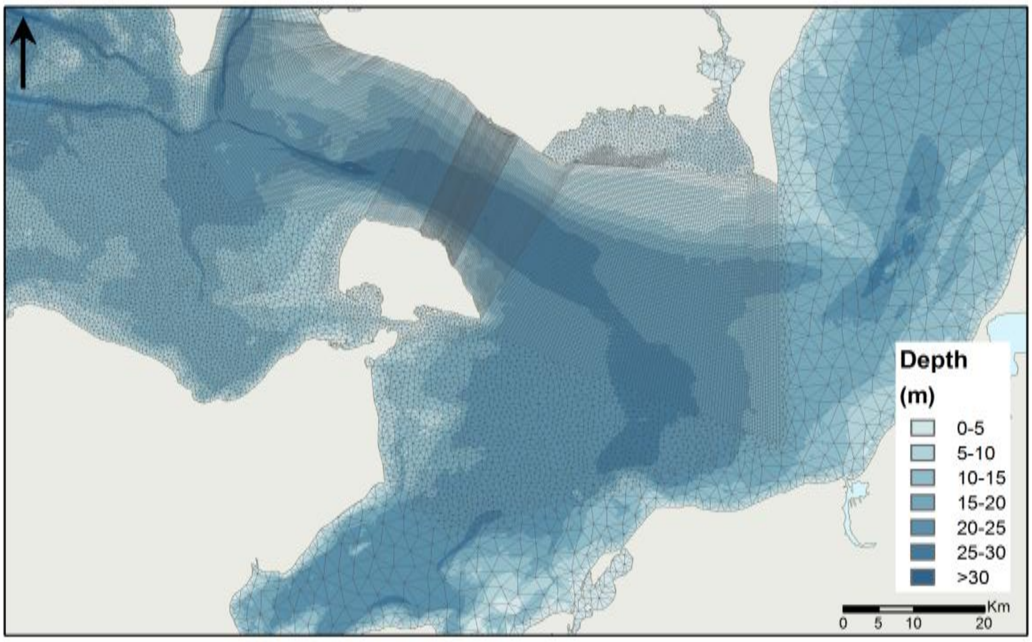

Figure 3.18 A zoom in the horisontal mesh in the Fehmarnbelt. The finest mesh has a resolution of about 100 m

3.5.2 *Wave simulations*

Purpose

Waves stir up sediment from the sea bed and allow it to be transported by the currents. Similarly, waves will keep sediment in suspension. In shallow waters even very small waves will keep sediment in suspension. Therefore waves have been simulated for the representative year of 2005 and the wave fields are used as basis for simulation of the spreading and deposition of spilled sediments.

Wave model setup

The wave conditions are modelled in two steps:

1. Regional wave model covering the entire Baltic Sea for boundary generation

2. Local high resolution wave model covering an area of the Fehmarnbelt that is identical to the area of the sediment spill model

The purpose of 1) is to supply boundary conditions for the local high resolution model, while the purpose of 2) is to provide detailed wave conditions of importance for the sediment spreading study.

The regional wave model is run for the period 1989-01-01 to 2009-01-01 (20 years) resulting in a long-term detailed description of the wave conditions in and near the project area. The local model is only run for the modelling period 2005-01-01 to 2006-01-01. The model bathymetry of the local model is identical to the hydrodynamical mesh presented in Figure 3.17.

The mesh is highly refined in the link corridor and along the coastal areas adjacent to Rødby and Puttgarden harbours in order to properly resolve the bathymetrical features of importance for the waves. Details about the setup and verification of the wave model can be found in (FEHY 2013e). The simulated wave roses are illustrated in Figure 3.19, but can also be found in Appendix F.

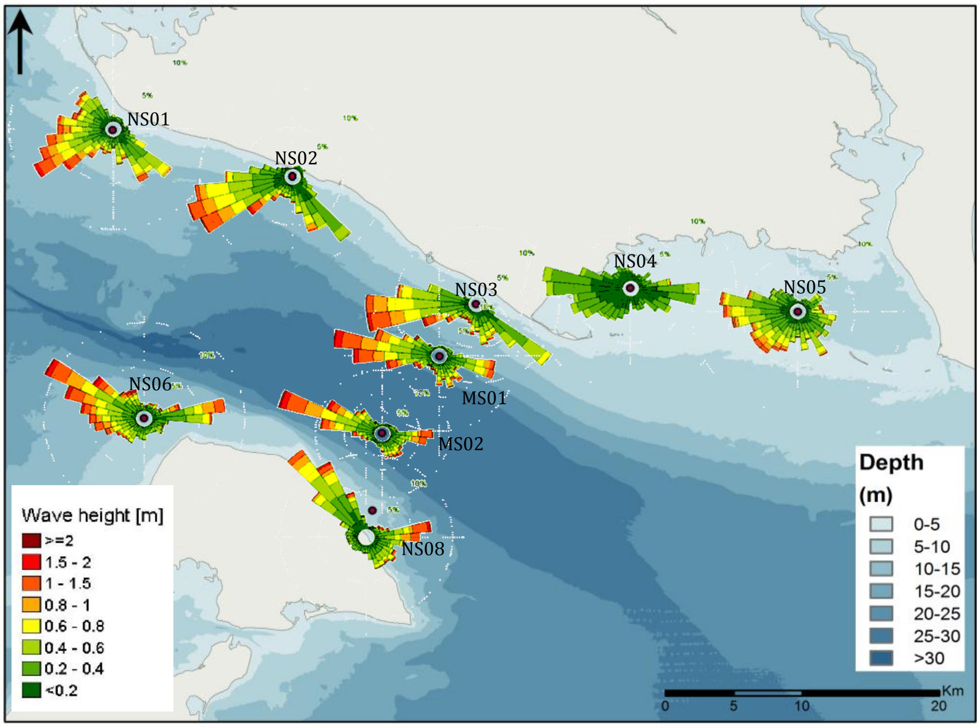

Figure 3.19 Wave roses from 2005. Significant wave heights

3.5.3 *Spreading of spilled sediment*

The spilled sediment will be spread by the currents. The silt and clay fractions have very low settling velocities and will therefore stay in suspension for a long time and may be transported over long distances. The fine sediments may deposite if the currents drop, but will be re-suspended when the nearbed currents and thereby shear stress exceed the critical threshold. The sand fractions and above settle quickly and are less susceptible to further movements at the sea bed and will thus deposit close to the dredging location.

From a sediment transport point of view the most important parameters for spreading of spilled fine sediment in the silt-clay fractions are:

- Settling velocity of the sediment
- Critical Shear Stress for deposition (below which sediment settles)
- Critical Shear Stress for erosion (above which sediments are resuspended)

With respect to sand fractions, grains at the sea bed will start to move when the so called Shields number is higher than 0.05.

Model set-up and model parameters

The spreading of fine spilled sediments has been simulated with the 3D model MIKE3 FM Mud Transport (MT).

MIKE 3 FM MT is integrated with MIKE 3 FM Hydrodynamics (HD) and takes into account:

- The actual release of sediments spilled during the dredging work as a function of time, location, soil conditions and dredger as defined in the spill scenarios
- Advection and dispersion of the suspended sediment in the water column as a function of the 3D flow field calculated with MIKE 3 HD
- Settling of the spilled sediment
- Erosion of the spilled sediment

The contribution from the surface waves to the bed shear stress is included in order to account for the resuspension of the sediment especially in the nearshore zone.

The sediment transport simulations are prepared for the spilled material only. No natural background concentrations are included in the simulations and thus the model output can be considered as the maximum excess concentrations.

In Appendix C a short description of MIKE 3 MT is presented.

The sediment that is spilled will not be uniform and the fine cohesive sediments will form flocs that settle faster than the single grains. The sediment is therefore divided into five fractions in order to cover the range of particle sizes from clay-silt-sand. The spreading of the four finest fractions is simulated with MIKE 3 MT. The fifth fraction represents medium sand and is handled separately.

Each fraction simulated with MIKE 3 MT is defined by its settling velocity and its critical shear stress for deposition.

The bed shear stresses are calculated from the time series of near-bed currents and waves using a parameterised version of Fredsøe's boundary layer model, see (Fredsøe 1984), for combined waves and currents.

The sand fraction will settle within 100 m – 600 m from the alignment with the bulk inside 100 m. The travelling distance depends on the current speed and, the water depth and height over the sea bed where the sediment is released. In shallow water or low current speeds the travelling distance will be short. For the present calculations the sand fraction is placed on the bed in a 200 m wide band around the alignment just after it is spilled. The sand fraction will only be transported during rare events of strong near bed currents larger than 0.2-0.3 m/s. The transport capacity along the alignment is documented in (FEHY 2013e). The transport capacity of sand is low 0-40 m^3/m/year, and the spilled sand will only slowly move further away and will be mixed with the natural sand on the sea bed. It can be discussed if parts of this fraction are re-dredged because it settles inside the dredging area. This will be the case in many areas and thus the deposition patterns directly at the alignment should be considered conservative.

Table 3.2 shows the settling velocities and critical shear stresses for deposition for each of the fractions which describe the spilled sediments. The critical shear stress for deposition is the shear stress below which deposition will occur.

Table 3.2 Settling and deposition parameters

Fraction No	Sediment type	Settling velocity [mm/s]	Critical shear stress for Deposition [N/m^2]
1	Medium sand	15	0.36
2	Fine sand/silt	2.9	0.3
3	Clay flocs	0.56	0.07
4	Clay flocs	0.07	0.06
5	Clay flocs	0.03	0.05

The settling velocities are based on an extensive analysis of soil data from the site, see next section. Generally, the values of the critical shear stress for deposition are between 0.06 N/m^2 and 0.1 N/m^2, but can be different depending on the sediment properties (Soulsby et. al 2000). The critical shear stress for erosion is set to 0.3 N/m^2. This value is in line with experience from other sites that have critical shear stresses for erosion between 0.15 N/m^2 and 0.35 N/m^2 for newly deposited mud (Soulsby et. al 2000) and (Van Rijn 2007). (Lumborg 2005) found the critical shear stress to be 0.3 N/m^2 in Øresund. Sediments that settle in the shallow western part of Rødsand where eelgrass is present cannot be resuspended. This trapping effect was implemented in the model as an increase in the critical shear stress for erosion based on the eelgrass coverage, see (FEMA 2013c). The applied shear stress map is shown in Figure 3.20. The yellow colour represents areas where the critical shear stress is 0.3 N/m^2.

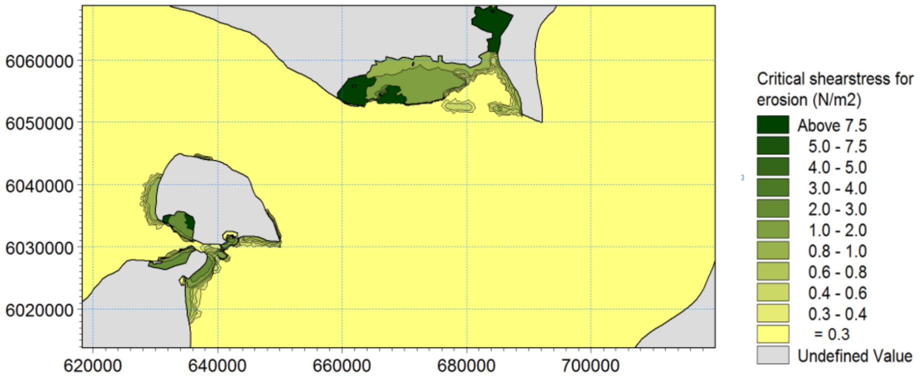

Figure 3.20 Applied map for critical shear stress for erosion. Light yellow is areas with critical shear stress for erosion = 0.3 N/m^2.

Effects of filter feeders (mussels) are not included in the model. Filter feeders would have increased the sedimentation and lowered concentrations near the sea bed in areas where filter feeders are present.

Wave driven currents are not included. Wave driven currents would have increased resuspension and advection of sediment in the nearshore zone during rough weather.

Representative settling velocities

The settling velocities must be known in order to simulate the spreading of material spilled during the dredging works. Representative settling velocities are derived partly from the geotechnical borehole samples and partly from the full scale spill experiments in the field. The geotechnical samples provide a description of the variability in the soil along the corridor whereas the two spill experiments provide observed in situ settling velocities. The present section describes how the analysis in the laboratory of the geotechnical samples and the measurements in the field have been combined to provide representative settling velocities.

The settling velocities of the soil samples were estimated by taking a very small portion of the geotechnical samples, suspend it in water, with properties similar to the actual Fehmarnbelt water, to a concentration of approximately 50 mg/l and prepare a settling velocity test in a so-called Owen tube test (Owen 1988). The Owen tubes are shown in Figure 3.21.

Figure 3.21 Owen tubes

Owen tube tests were performed for 19 representative geotechnical samples with a large amount of material finer than sand. For pure sand samples settling velocities were calculated based on their primary grain size distribution only.

In the laboratory the soil sample was disintegrated by shaking the material in a half-filled 0.5 L plastic container imitating the disintegration of the soil expected to occur during the dredging work. The shaking continued until all material was disintegrated. This mixture was used for the Owen tube tests and in this way the effect of breakup mode was included. An example of the results is given in Figure 3.22.

The Owen tube tests were extended from 64 min, which is the standard length of a test, to 180 min to cover a larger portion of the settling velocity distribution. However, the extended period was not sufficient to describe the entire sample. In the example presented in Figure 3.22, almost 30% of the fine fractions had not settled after three hours in the Owen tube. Extending the test period was not an option due to possible flocculation in the tube during the experiment. Thus, an alternative procedure must be applied for the material being too fine to be analysed in the Owen Tube. In the 180 min long tests no observations were made that could indicate hindered settling or extensive flocculation.

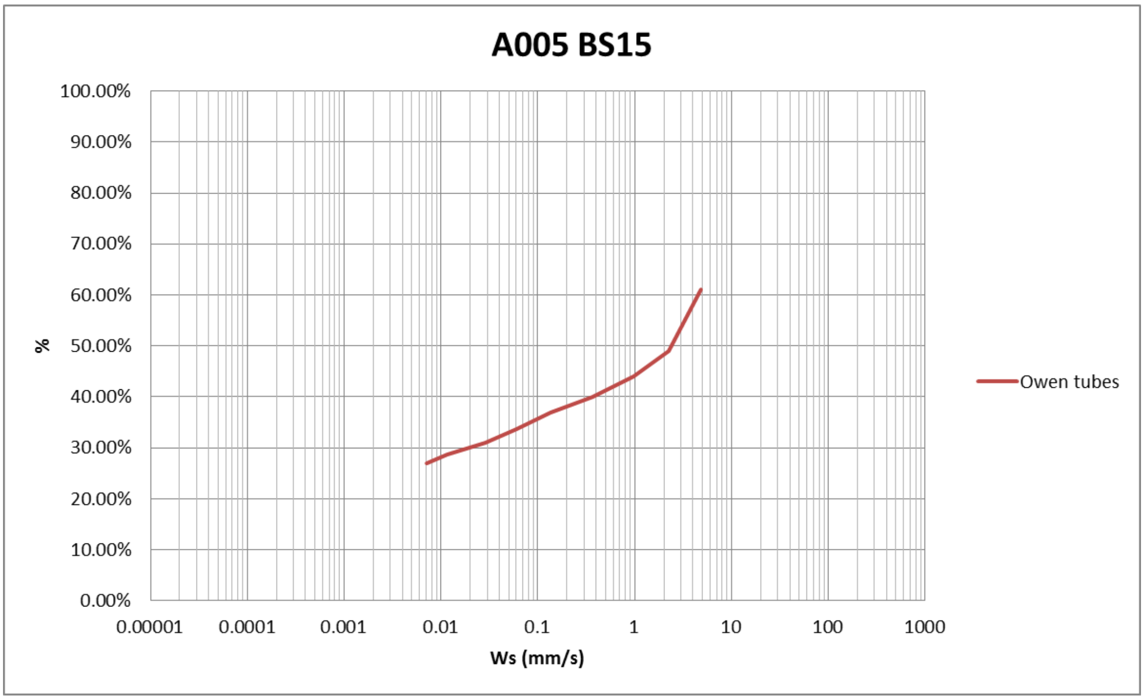

Figure 3.22 An example of results of settling velocity tests, borehole location A005, see Figure 3.8, Bag Sample 15 (clay till)

The settling velocities in the ranges not covered by the Owen tube tests have been calculated using Stoke's law. Stoke's law requires knowledge of grain size, density and viscosity of the water.

Stoke's law:

$$W_s = \frac{\left(\frac{\rho_s - \rho_w}{\rho_w}\right) g(fd)^2}{18v}$$

In which ρ_s is the sediment density, ρ_w is the density of water, g is gravity, d is grain size, f is a flocculation factor and ν is the kinematic viscosity. W_s is settling velocity. The flocculation factor is applied to account for the expected flocculation of the finest particles.

Analysis of the primary grain size distributions reveals a significant portion of extremely fine fractions, see Appendix D. An example is given in Figure 3.23.

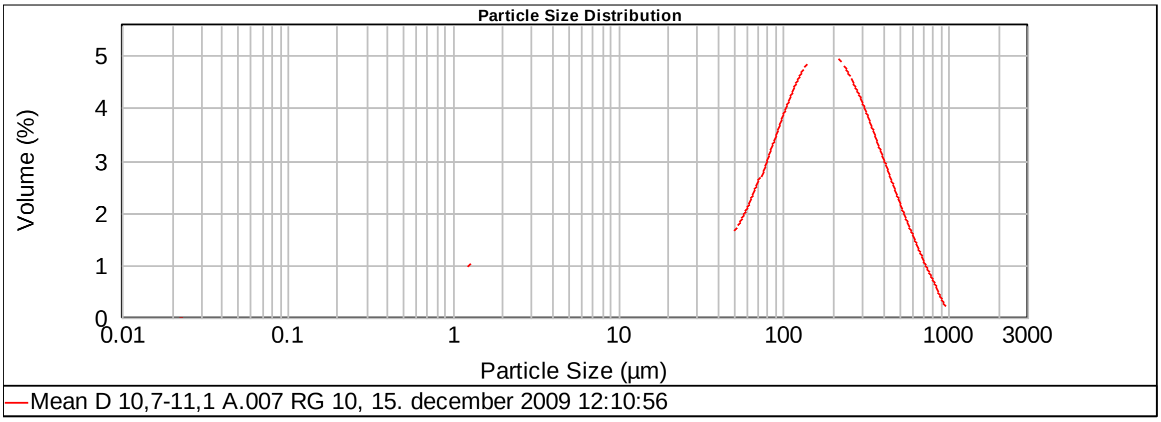

Figure 3.23 Primary grain size distribution at station A007 11.1 m below sea bed (clay till)

However, such conditions do not exist in nature and in situ measurements must be applied. The spill experiment from October 2010 was made with Paleogene clay and sand close to geotechnical station A002, see Figure 3.8. The measurements showed an increase in the median grain size by a factor of 3 over a period of time for low concentrations similar to the ones expected away from the construction area, see (Mikkelsen and Peirup 1998). The spill test from September 2009 (see Appendix P) was made with late glacial clay and clay till close to the geotechnical sites A008 and A014 (see Figure 3.8) and showed a slow increase in median grain sizes by a factor of between 2 and 15 over a period of 1h and 37 minutes.

The 2010 experiment shows results equivalent to the 2009 measurements after 50 minutes for Paleogene clay. None of the conducted experiments were long enough to determine the final flocculation level. However, the 2009 experiment is considered the best estimate due to the length of the so-called Lagrangian tests, see Appendix P. In Figure 3.24 and Table 3.3 the values from the 2009 test are given. A description of the field tests can be found in Appendix P.

Table 3.3 *Overview of flocculation factors from the 2009 spill test (Baseline for Suspended Sediment, Sediment Spill, related Surveys and Field Experiments, March 2011). Left side is grain size in mm. Right side is flocculation factors. Example: Fact = d_{50}(t=1h37min)/d_{50}(t=0). Fractile is a diameter corresponding to a certain percentage of material below this. Example: d_{30} is the diameter for which 30% of the material has diameters below this*

Fractiles	t = 0 min [mm]	t = 50 min [mm]	t = 1h37min [mm]	fact 0 min	fact 50 min	fact 1h 37min
d_{10}	<0.00273	0.004	0.008	-	-	-
d_{20}	0.003	0.010	0.023	1.0	3.0	7.2
d_{30}	0.007	0.017	0.061	1.0	2.5	9.0
d_{40}	0.009	0.029	0.131	1.0	3.3	15.1
d_{50}	0.015	0.058	0.211	1.0	4.0	14.5
d_{60}	0.022	0.124	0.296	1.0	5.7	13.6
d_{70}	0.037	0.199	0.345	1.0	5.4	9.4
d_{80}	0.073	0.276	0.394	1.0	3.8	5.4
d_{90}	0.177	0.355	0.428	1.0	2.005	2.4
Average				1.000	3.708	9.6

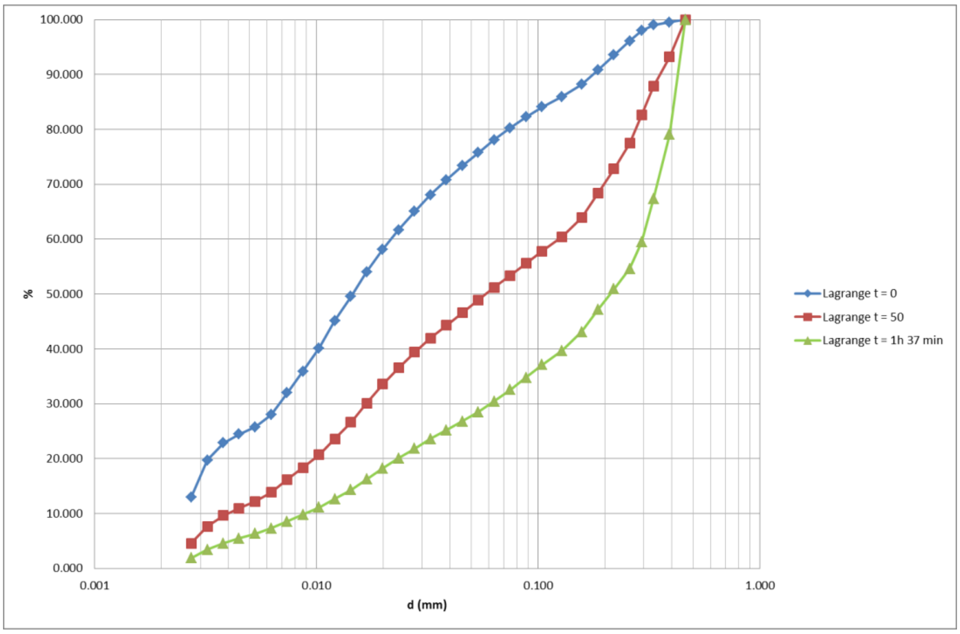

Figure 3.24 *Accumulated grain size distributions for late glacial clay in the plume at different times in the spill experiment undertaken in September 2009 measured with the LISST. Clay limit is 0.002 mm, silt limit is 0.063 mm. Above this is fine sand*

As shown above the particles of the very fine material build flocs with a size about 10 times larger than the particles. The density of the flocs varies with the size of the flocs. For very fine particles or small flocs it is assumed that the floc density is close to the grain density. The same assumption is made for very coarse material. In between there is a range where the sediment flocs are composed of any number of grains. In Figure 3.25 the red line illustrates the Owen tube test results and the blue line illustrates Stoke’s law without various modifications to the primary grain size. The purple line illustrates Stoke’s law applied for the primary particle distribution and modified for flocculation/breakup mode by the described factor of 10.

The purple line shows the lower limit of settling velocities observed in nature. It is documented in literature, that the primary grain size distribution measured by Malvern laser analysis underestimates the frequency by up to a factor of 3 for grain sizes less than 10 microns, see (Konert 1997). The explanation lies in the Malvern assuming a spherical geometry of the grains. A floc of random geometry will reflect a different amount of light than a sphere with the same volume. The lower limit of settling velocities is therefore connected to the lower limit of the distribution found in the Owen tube tests by scaling. This scaling accounts for the variation in floc density and the error originating from the Malvern laser analysis procedure. The lower limit 0.007 mm/s corresponds to a diameter of approximately 2 microns. Diameters below this have not been referenced in literature on natural sediments and none of the field measurements show settling velocities less than 0.1 mm/s.

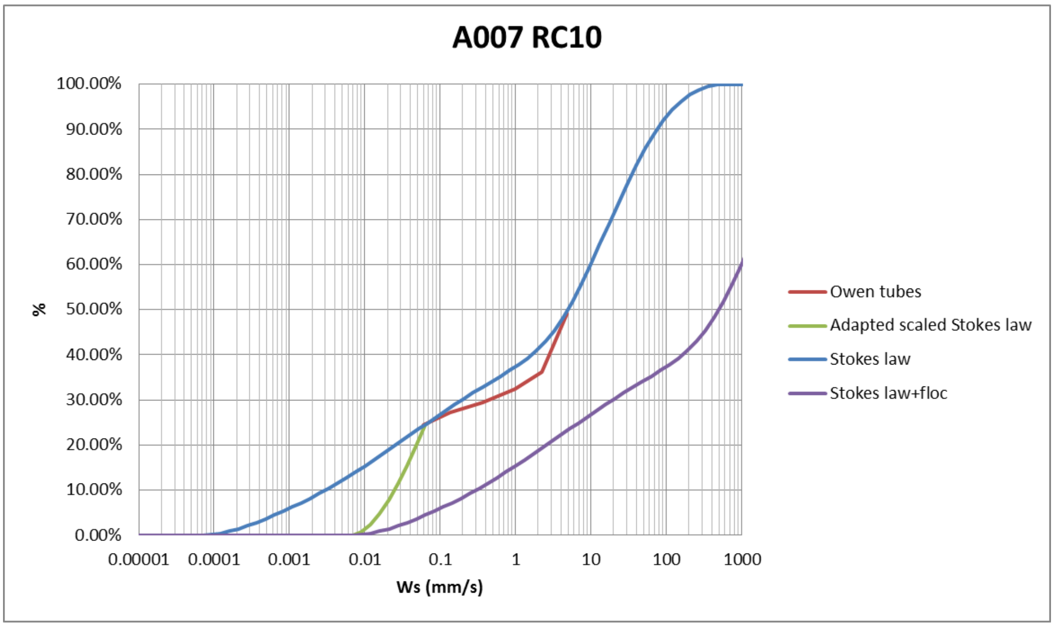

Figure 3.25 *Result of settling velocity tests (borehole location A007, see Figure 3.8, RC10 Core 10 (clay till)).The red line represents results from 180-min Owen tube test. The blue line shows the settling velocities for primary particles calculated using Stoke's law with a density of 2650 kg/m^3. The purple line shows the settling velocities for primary particles calculated using Stoke's law and grain sizes corrected for flocculation/breakup mode (factor 10) and a density of 2650 kg/m^3. Green line shows the settling velocities for primary particles calculated using Stoke's law, corrected for flocculation and scaled to match the results from the Owen type*

Representation of soil types in the numerical model

The numerical model simulates the spreading of specific grain sizes and settling velocities. Seven soil types are present:

- Paleogene clay
- Late glacial clay
- Gyttja
- Clay till
- Late glacial sand/silt
- Post glacial sand
- Glacial melt water sand

The soil distribution varies across the Fehmarnbelt. Figure 3.7 shows an overview of the geology across the Fehmarnbelt. In Table 3.4 an overview of the soil types and the amount of each soil dredged for the tunnel solution along the trench is given.

Table 3.4 Distribution of soil types to be dredged for the tunnel

Type	Gyttja	Late glacial clay	Paleogene clay	Clay Till	Late glacial sand/silt	Post glacial sand	Glacial melt water sand
%	4	28	4	51	9	4	0.5

Every soil type holds a unique distribution of grain sizes. Each of these grain size distributions is represented by a number of fractions in the model. Each fraction is characterised by a specific settling velocity and each fraction represents an interval of the grain sizes. Thus, each fraction represents a certain amount of sediment. A total of five fractions were chosen to represent the grain size distributions. Table 3.5 presents the five fractions described by the estimates of characteristic settling velocities and grain sizes found from the geotechnical samples using laboratory techniques.

Table 3.5 Estimate of representative settling velocities and diameters as found from laboratory tests of the geotechnical samples. The percentages of sediment are partly measured in Owen tubes (fraction 0-3) and partly estimated from primary grain size distribution and Stoke's law (fraction 4) and modified as described. Calculations using Stoke's law assumed 10^{o}C and a density of 2650 kg/m^3. All diameters are calculated from settling velocities using Stoke's law. Note: the density is uncertain and known to be overestimated for fractions 2 and 3. These grain sizes are put in brackets

	Ws0	Ws1	Ws2	Ws3	Ws4
W [mm/s]	15.00	2.9	0.56	0.07	0.03
d [µm]	147	65	(28)	(10)	7
Average [%]	39.3	14.7	11.3	17.5	17.3

The grain size distributions between the individual fractions for all tested soil samples can be found in detail in Appendix D. Results from Owen tube tests are shown in Appendix E. Table 3.6 gives an overview of the overall average fraction distribution of the dredged soil types for the tunnel. Settling velocities are adopted from Table 3.5.

The first field test was conducted in September 2009 at the geotechnical stations A008 and A014 (Figure 3.8). The test was conducted in a calm period with low current speeds below 0.1 m/s. Concentrations away from the ship were generally below 5 mg/l in the plume. The dredged material was clay till or late glacial clay. See (FEHY 2013c).

Owen tube tests taken in the plume of spilled material dredged at station A008 (Figure 3.8) (Late glacial clay) showed median values for settling velocities between 0.05 mm/s and 0.4 mm/s, see (FEHY 2013c).

Table 3.6 shows median settling velocities at approximately 0.07 mm/s for late glacial clay.

Owen tube tests in the plume from material dredged at station A014 (Figure 3.8) (clay till) showed median values for settling velocities between 0.17 mm/s and 1.04 mm/s.

Table 3.6 shows median settling velocities at approximately 2.15 mm/s for clay till.

Note that during this field test the material had been stirred in the tank of the dredger at very high concentrations for a period of time and thus the material is expected to be more flocculated than it would have been during a normal dredging operation. Therefore median settling velocities measured in the field during this test are probably overestimated. For further information see Appendix P.

The second field test was carried out in October 2010 near geotechnical station A002 (Figure 3.8). This test was carried out in stronger currents over 0.3 m/s. Owen tube tests in the plume showed median values for settling velocities around 0.2 mm/s. For further information see Appendix M.

Table 3.6 shows median settling velocities at approximately 0.04 mm/s for paleogene clay. Results from the field experiment, however, showed that the dredged and spilled material was coarser than the geotechnical sample from station A002 (Figure 3.8). During the investigations for the Øresund connection (Edelvang 1998) median settling velocities of dredging spoils were measured at 0.01–0.06 mm/s. This is similar to the values found for late glacial clay, gyttja and paleogene clay.

Table 3.6 Representative distribution of fractions for various soil types and the overall average distribution of the actual dredged amount of each type

	Ws0	Ws1	Ws2	Ws3	Ws4	Ws_{50} (mm/s)
W [mm/s]	15.00	2.92	0.56	0.07	0.03	
Paleogene clay	14.6%	11.1%	13.9%	13.9%	46.6%	0.04
Late glacial clay	23.4%	11.8%	11.2%	35.1%	18.5%	0.07
Gyttja	11.8%	9.9%	15.7%	30.7%	31.9%	0.05
Clay till	44.5%	16.8%	9.2%	11.2%	18.3%	2.15
Late glacial sand/silt	62.7%	13.9%	17.2%	6.3%	0.0%	5.37
Post glacial sand	50.0%	14.8%	21.7%	4.0%	9.4%	2.93
Glacial melt water sand	89.8%	4.6%	2.5%	0.2%	3.0%	8.27
Overall average	39.3%	14.7%	11.3%	17.5%	17.3%	

4 ASSESSMENT OF 0 ALTERNATIVE

The 0 alternative is defined as the situation without a fixed link to which all impacts are compared.

All impacts from the construction period are compared to the baseline situation 2009/2011. The excess sediment concentrations and the sediment deposition from the dredging are compared with the relevant base line measurements.

Apart from occasional maintenance dredging of the access channel the continuation of the ferry traffic does not impose any generation of spill or need for dredging.

5 ASSESSMENT OF IMPACTS OF MAIN TUNNEL ALTERNATIVE

The results from the simulations of spreading and deposition of spilled sediments are presented in this section for the year with the highest spill. For the tunnel alternatives this is 2015. The results for the remaining years can be found in Appendix G – Appendix M.

The following analysis and illustrations of the results are presented for each:

Maps of Suspended Sediment Concentration at the surface for the period from 1 May to 1 September.

- Exceedance time of 2 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)

- Exceedance time of 5 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)

- Exceedance time of 10 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)

- Exceedance time of 20 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)

Maps of Suspended Sediment Concentration at the bottom for the period from 1 March to 1 November.

- Exceedance time of 10 mg/l, 1/3-1/11 for just above the sea bed (bottom layer in the numerical model results)

- Exceedance time of 20 mg/l, 1/3-1/11 for just above the sea bed (bottom layer in the numerical model results)

- Exceedance time of 50 mg/l, 1/3-1/11 for just above the sea bed (bottom layer in the numerical model results)

If the exceedance time is less than 10% for 2, 5 or 10 mg/l in the entire area the illustration for 5, 10 or 20 mg/l, respectively is not shown. As seen in the appendices H-P this is especially the case for the later construction years when the dredging activities are less intense.

Maps of sediment deposition for each dredging scenario:

- Deposition at the end of the construction period
- Maximum deposition during the construction period
- Deposition at the end of selected years

The exceedance levels are defined as the limit for visibility (2 mg/l) as well as threshold values for assessment of marine biology (5, 10, 20 and 50 mg/l).

The results are shown both for a local area in the Fehmarnbelt and for a larger area when relevant.

Time series of the modelled concentrations from the spill at mid-water are compared with measured median concentrations from the baseline study, see (FEHY 2013c). Mid water is chosen because baseline measurements were undertaken approximately at this position in the water column. The locations of the turbidity stations are shown in Figure 5.1.

A budget for the transport of the spilled sediment has also been established. The budget gives the percentage of the spill which ends up in the Rødsand Lagoon, which passes through the Sound of Langeland and the Darss Sill. The deposition areas at the end of the construction periods are determined.

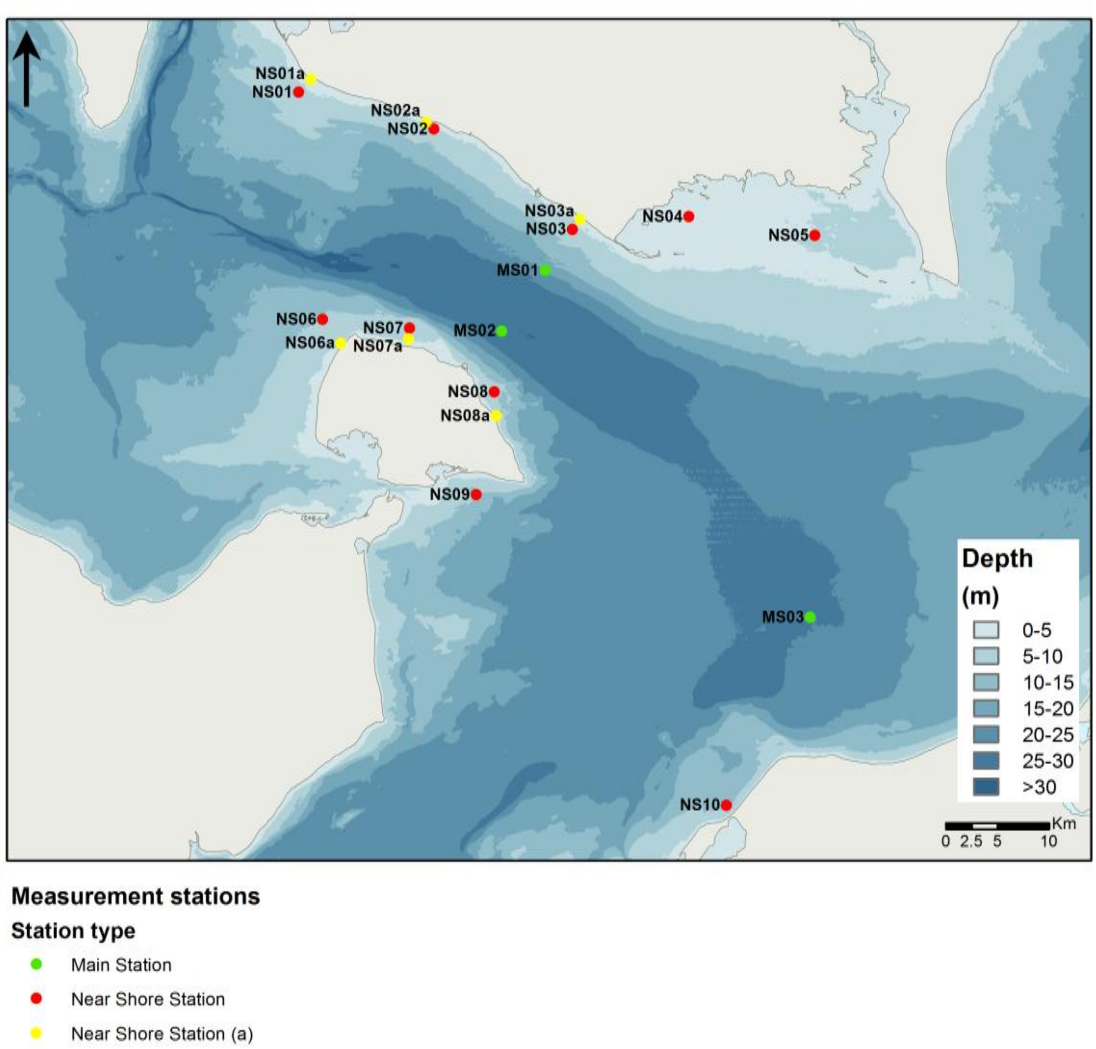

Figure 5.1 Location of nearshore (NS) and main stations (MS), (FEHY 2013c)

5.1 Magnitude of pressure

5.1.1 Spill scenario

Purpose
The purpose of this section is to define the spill scenario determined by the earth balances, spill percentages and the associated settling velocities that depend on the soil type.

Earth balance
This scenario includes an immersed tunnel in a dredged trench, reclamations at Rødby and Puttgarden, construction of two work harbours and the construction of a

production facility for production of the tunnel elements. The total amounts of handled materials are given in Table 5.1. Specifications of handled materials, amounts and spill percentages can be found in Appendix A.

Table 5.1 Dredging activities for the immersed tunnel E-ME

Activity	Spill [%]	Amount [mill m^3]	Amount spilled [mill m^3]
Dredging for tunnel elements	3.5	15.50	0.540
Containment dikes	0.1-0.8	1.20	0.007
Portal and ramps Lolland	0.1-0.7	0.36	0.002
Portal and ramps Fehmarn	0.1-0.7	0.32	0.002
Working harbour Lolland	0.1–0.8	2.87	0.020
Working harbour Fehmarn	0.1-0.8	0.10	0.001
Reclamation	0.5	20.80	0.104
Trench backfilling Lolland	0.1-0.8	3.40	0.015
Trench backfilling Fehmarn	0.1-0.8	3.00	0.013
Restoring sea bed Natura 2000*	0.1-1.0	0.48	0.003
Landscaping reclamation area	0.5-2.0	4.31	0.039
Total amount handled/spilled		**52.34**	**0.746**

*This activity is removed from the project in October 2012 but is included in the simulations, making the spill assessment marginally conservative in this respect.

The total construction period is 6 years. Table 5.3 includes an overview of the earth works. The details of the dredging time schedule can be seen in Appendix A.

The tunnel alignment (denoted E-ME) is given in Figure 5.2. The production facility will be located just east of the alignment at the Danish Coast. A sketch of a possible production facility is shown in Figure 5.3. An overview of the reclamations is presented in Figure 5.4.

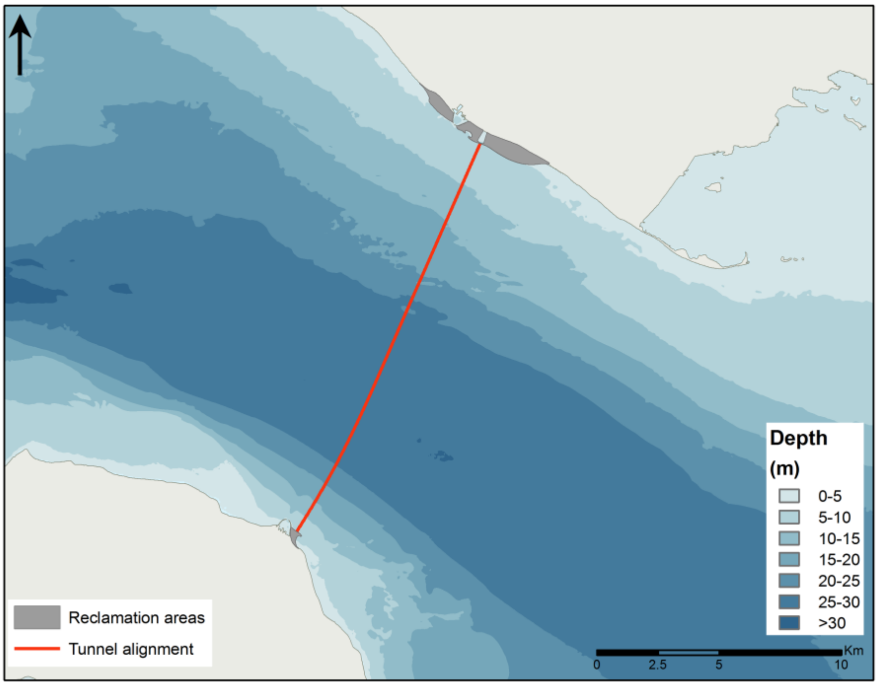

Figure 5.2 Tunnel alignment

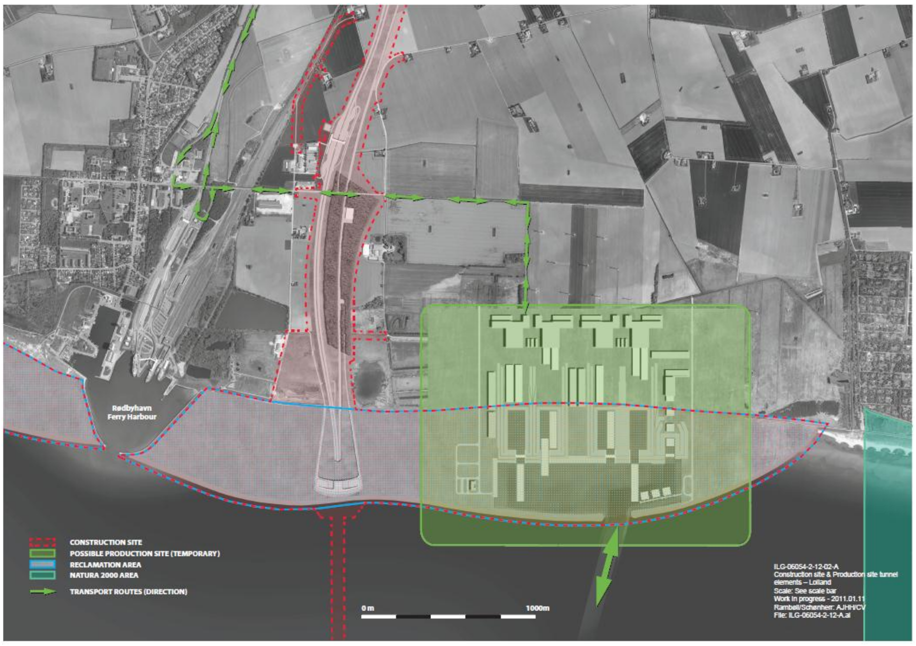

Figure 5.3 Sketch of the production facility just east of the tunnel alignment

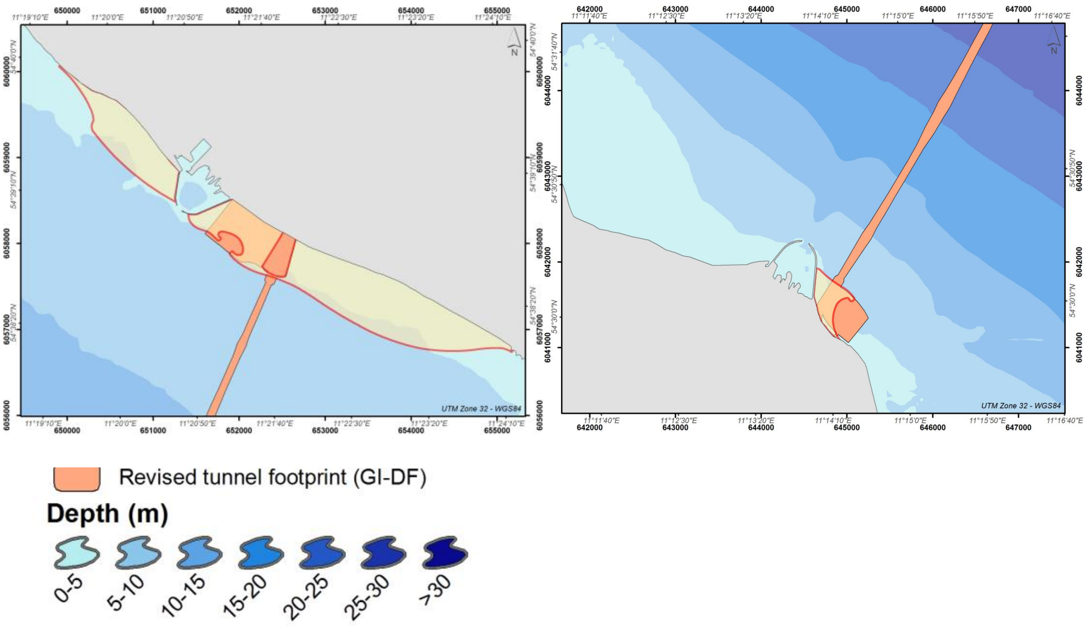

Figure 5.4 Overview of reclamations. Left: Denmark. Right: Germany

The spill scenario is based on the following assumptions, see also Table 5.2. Dredging is performed by trailer hopper suction dredgers, grab dredgers and backhoe dredgers.

- The backfilling follows the description presented in the construction plan and is a mixture of sand from Kriegers Flak, local clay till and rocks from quarries
- No offshore disposal will be done

- Backfilling will be done using a grab dredger. The timing will follow the construction plan

- Smoothing the underwater slopes will be done using a trailer suction hopper dredger. Landscaping inside the reclamation areas and above the waterline will be done using dumpers

The full construction plan is presented in Appendix A and a simple overview of the time plan is given in Table 5.3 and Figure 5.5.

Table 5.2 Overview of equipment and spill percentages for immersed tunnel E-ME

Activity	Equipment	Distribution in the water column	Spill percentage (%)
Dredging for tunnel elements	Backhoe dredgers and grab dredgers	Evenly distributed	3.5
Containment dikes	Backhoe dredgers and grab dredgers	Evenly distributed	0.1-0.8
Portal and ramps Lolland	Backhoe dredgers and grab dredgers	Evenly distributed	0.1-0.7
Portal and ramps Fehmarn	Backhoe dredgers and grab dredgers	Evenly distributed	0.1-0.7
Working harbour Lolland	Backhoe dredgers and grab dredgers	Evenly distributed	0.1–0.8
Working harbour Fehmarn	Backhoe dredgers and grab dredgers	Evenly distributed	0.1-0.8
Reclamation	Backhoe dredgers	Evenly distributed	0.5
Trench backfilling Lolland	Grab dredgers	Evenly distributed	0.1-0.8
Trench backfilling Fehmarn	Grab dredgers	Evenly distributed	0.1-0.8
Restoring sea bed Natura2000	Grab dredgers	Evenly distributed	0.1-1.0
Landscaping reclamation area	Trailer suction hopper dredgers and dumpers	Evenly distributed	0.5-2.0

Note that the activity "Restoring Natura 2000" is removed from the project in October 2012 but is included in the present spill simulations, making the spill assessment marginally conservative in this respect.

Table 5.3 Overview of the time schedule of earth handling for the immersed tunnel E-ME

Immersed tunnel with production facility and sandmining	Year	2014				2015												2016												2017												2018												2019											
	month	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Activity	Amount spilled																																																																
	[mill m^3]																																																																
Dredging for tunnel elements	0,54			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																																												
Containment dikes	0,007		▨	▨	▨	▨	▨	▨																																																									
Portal and ramps Lolland	0,002				▨			▨																																																									
Portal and ramps fehmern	0,002		▨	▨	▨																																																												
Working harbor lolland	0,02			▨	▨	▨	▨	▨	▨	▨	▨																																																						
Working harbor fehmarn	0,0007		▨	▨																																																													
reclamation	0,104			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																																											
Trench backfilling lolland	0,015																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨														
Trench backfilling fehmarn	0,013																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨														
Restoring natura 2000	0,003																																																			▨	▨	▨	▨	▨									
Landscaping reclamation area	0,039																																																			▨	▨	▨	▨	▨									
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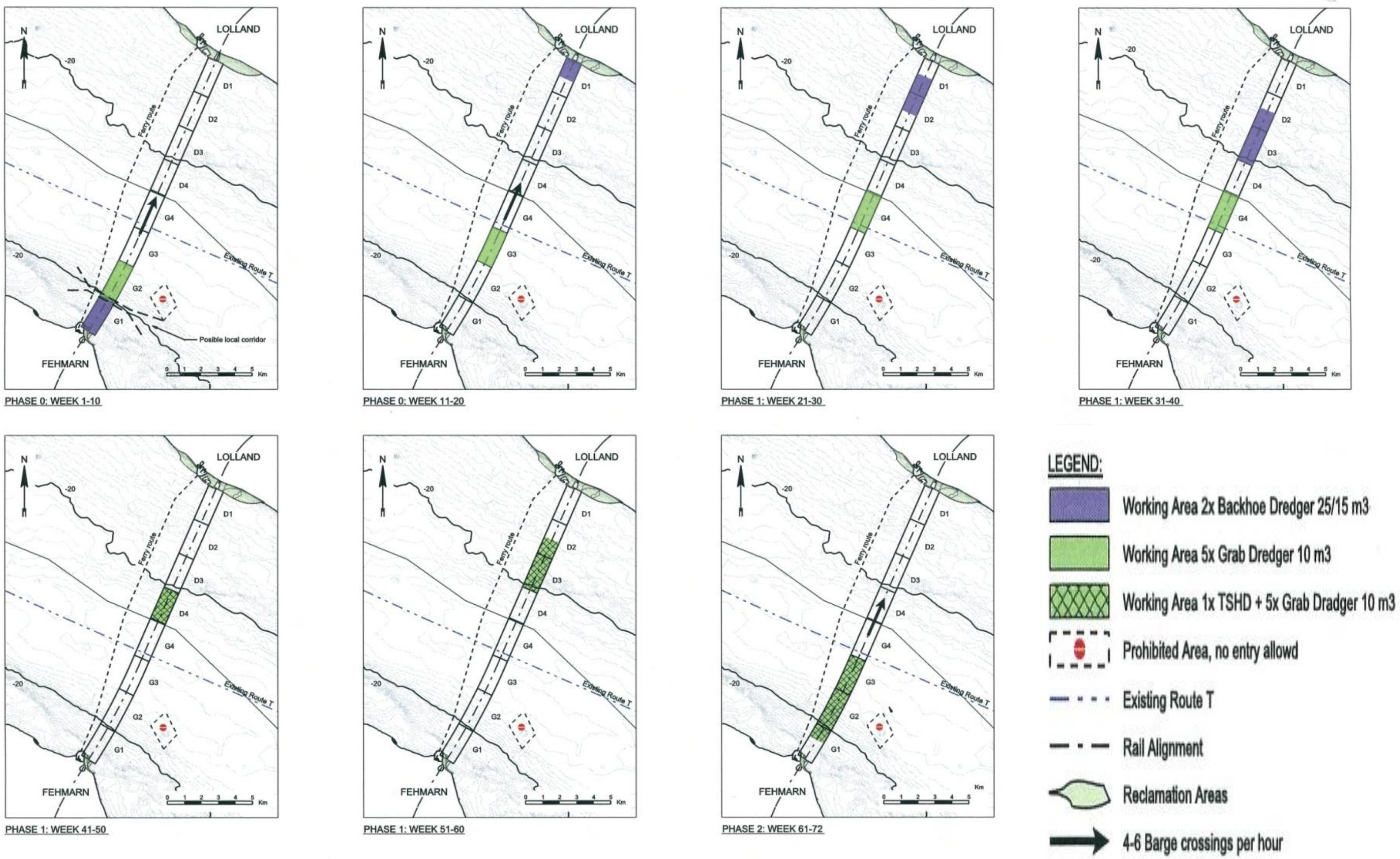
Note that the activity “Restoring Natura 2000” is removed from the project in October 2012 but is included in the present spill simulations, making the spill assessment marginally conservative in this respect.



PHASE 0: WEEK 1-10

PHASE 0: WEEK 11-20

PHASE 1: WEEK 21-30

PHASE 1: WEEK 31-40

PHASE 1: WEEK 41-50

PHASE 1: WEEK 51-60

PHASE 2: WEEK 61-72

Figure 5.5 *Overview of dredging plan for tunnel trench. See (Rambøll – Arup – Tech JV. Technical note. Description of the offshore activities. August 2011). Trench dredging starts 1 January 2015*

Dredging operations

The amount of sediment spill depends on the soil types and the chosen equipment. At present there are plans for using clamshell dredgers, backhoe dredgers, and hopper suction dredgers assisted by barges. Backhoe dredgers and clamshell dredgers will be used for the main part of the tunnel dredging. For the backhoe dredgers and the clamshell dredgers the spill will occur partly at the bottom due to the disturbance from the grab, partly in the water column due to water flowing over the free surfaces in the grab and partly at the surface due to water draining of the barge. For practical purposes the spill is considered uniformly distributed over the water column. Conceptual drawings are given in Figure 5.6 and Figure 5.7.

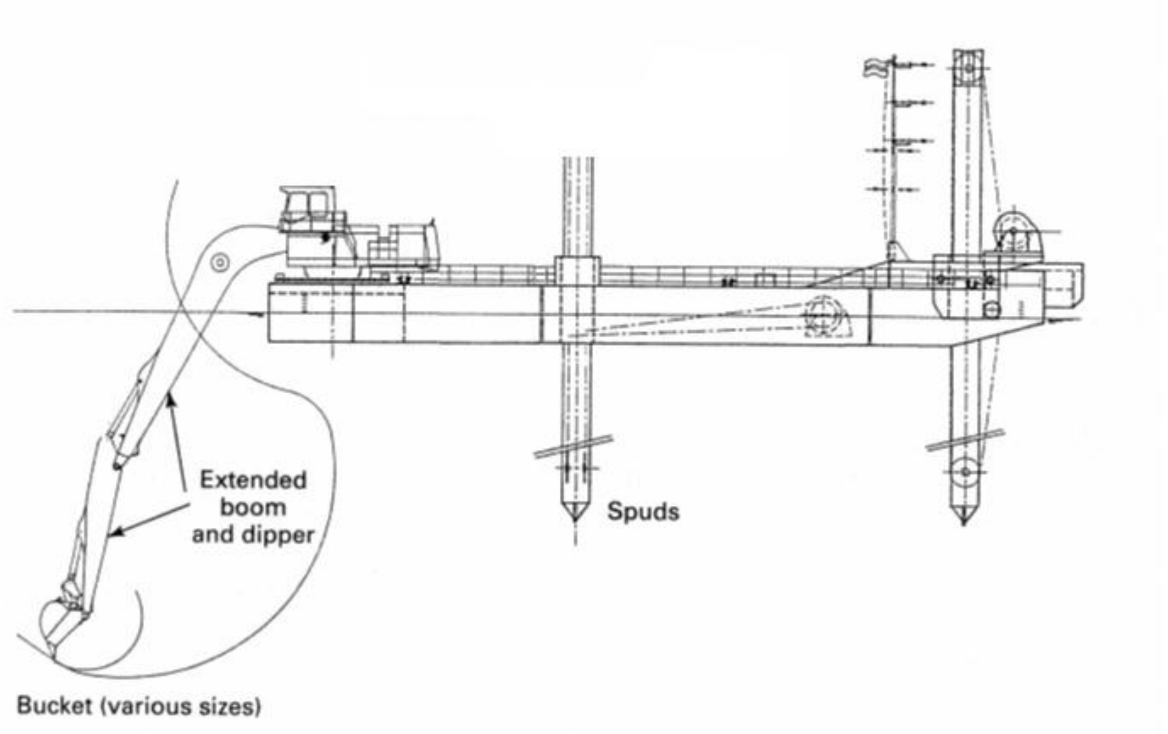


Figure 5.6 Conceptual drawing of a backhoe dredger from (R.N. Bray, Bates, A. D., Land, J.M. 1997)

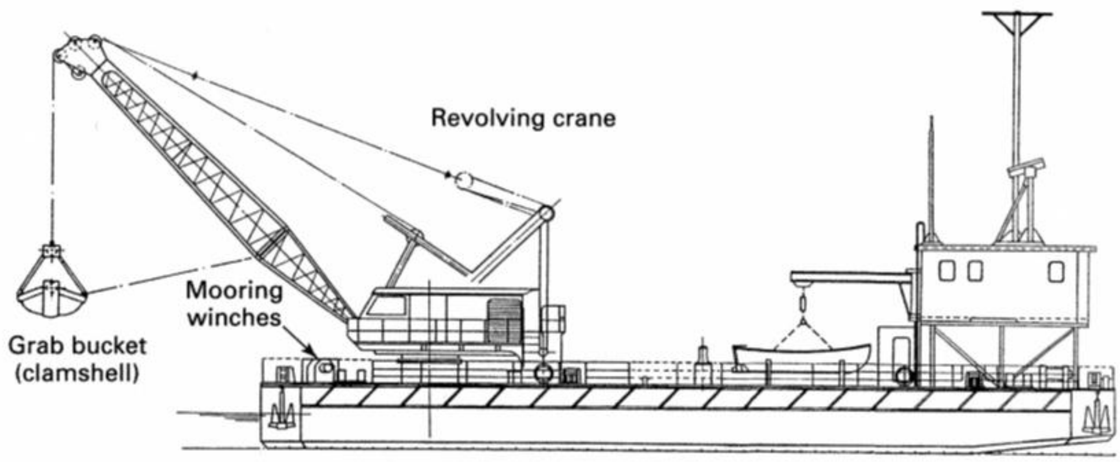


Figure 5.7 Conceptual drawing of a clam shell grab dredger from (R.N. Bray, Bates, A. D., Land, J.M. 1997)

The spilled sediment consists of everything which is present in the dredged soil. However, boulders, larger lumps of sediment and coarse sand fractions will settle close to the dredger and it is only the finer sediment which is carried away.

5.2 Effect of pressure

5.2.1 Suspended sediments

Examples of instantaneous results
The hydrography of the Fehmarnbelt is very complicated with rapidly shifting currents and waves. The simulations are designed to simulate the dredging operations as close to reality as possible. In the following some snapshots of results from the E-ME tunnel are presented to illustrate the results.

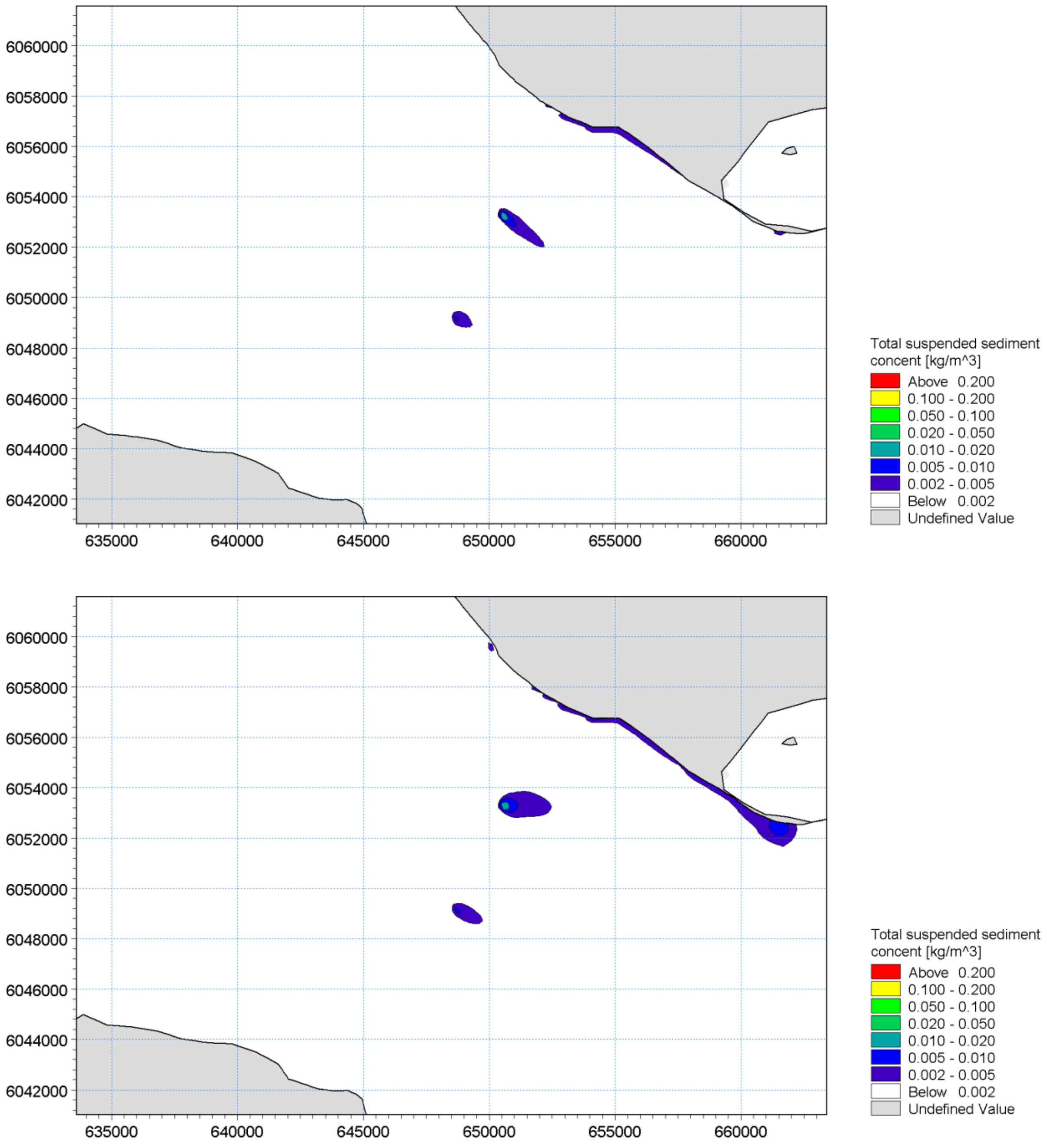


Figure 5.8 Illustration of suspended sediment plume pattern. 2 active dredgers. Concentration near land is resuspension. Upper plot is surface concentration, lower plot is bottom concentration. 10/9 2015 06:00:00

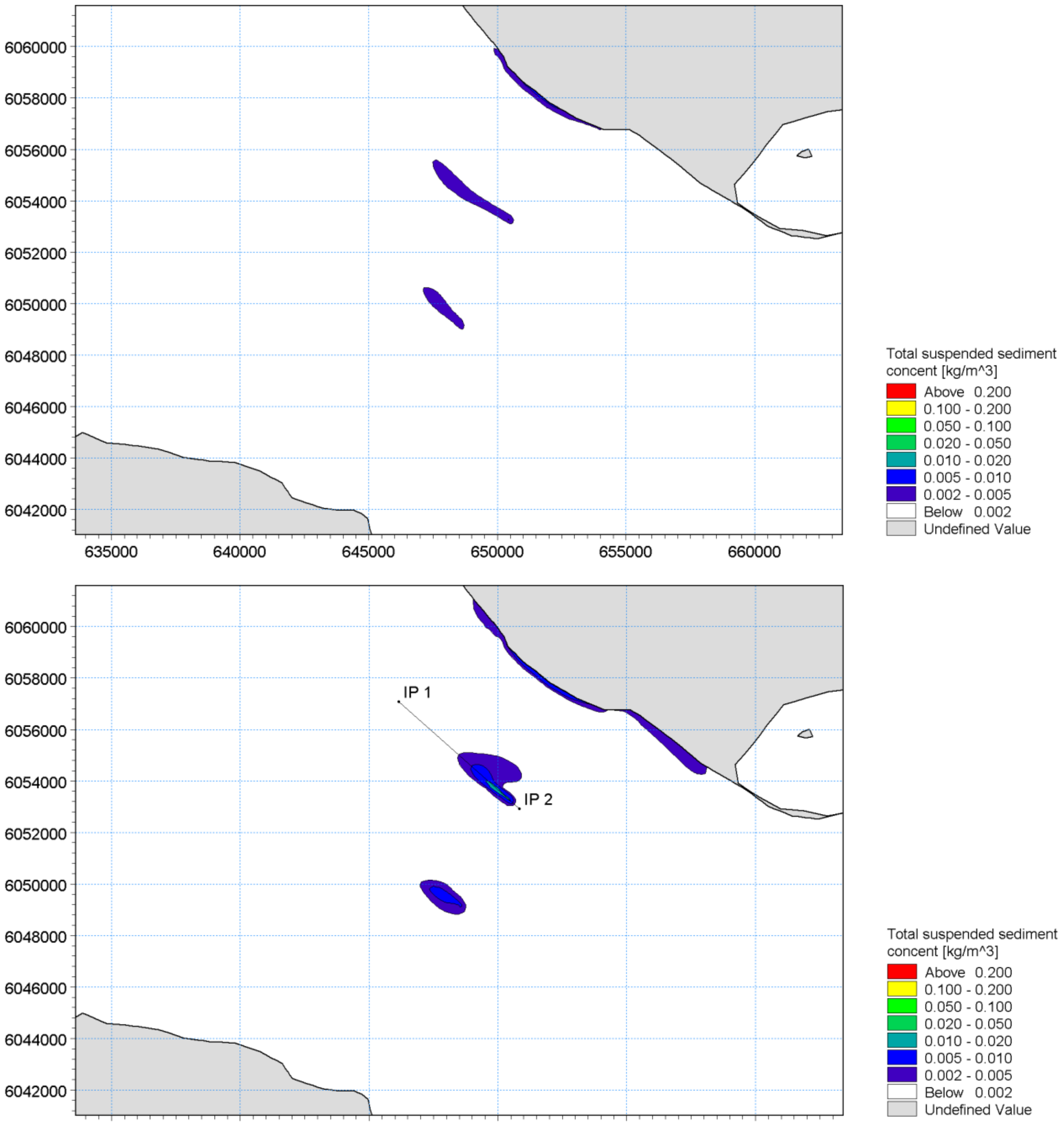


Figure 5.9 Illustration of suspended sediment plume pattern. 2 active dredgers. Concentration near land is resuspension. Upper plot is surface concentration, lower plot is bottom concentration. 10/9 2015 12:00:00

The vertical variation in the plumes is modelled in great detail. In the following two figures vertical cross sections of the plumes are presented. The cross section is taken at the plume centreline.

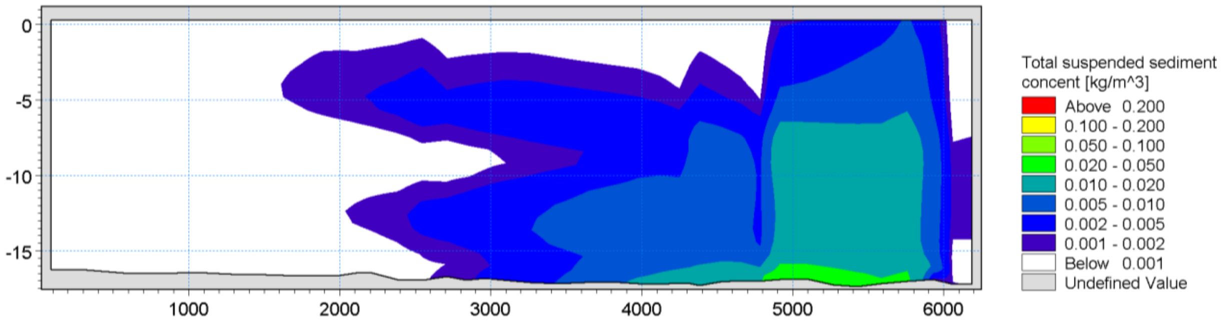


Figure 5.10 Illustration of vertical suspended sediment plume pattern. 10/9 2015 12:00:00. West-going current. Cross section along an W-E line marked in Figure 5.9. Dredger located at the eastern end

The results show a great variability in the plume patterns. The concentration at a given point is always the sum of the present plume concentration, resuspended spilled sediment and background concentration. This is especially seen in Figure 5.9. It is also seen that only a minor part of the sediment plume will be visible at the surface. In Figure 5.11 an overview of different plume locations at different times is given along with the maximum plume extension down to 3 m below the surface. The figure illustrates that there will be visible plumes all the time during the construction period. However, as the dredgers move along the trench the suspended sediment concentrations from the plumes will only be present at specific points for a short period of time.

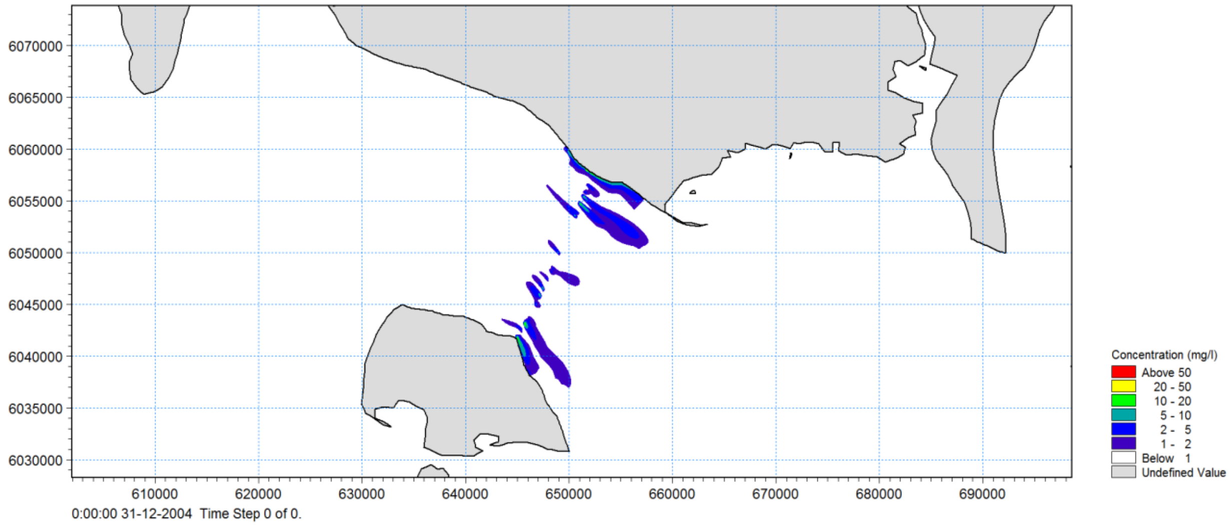


Figure 5.11 Oveview of plume extensions at various points in time during 2015

Time series of concentration for the tunnel solution

Time series of excess sediment concentration at the locations of nearshore stations NS01, NS03, NS04, NS05, NS06, NS08 and the relocated nearshore stations NS01a, NS02a, NS03a, NS06a, NS07a, NS08a are presented for the tunnel solution. The modelled excess concentration time series are shown for bottom, mid depth and surface. Suspended sediment has been measured at approx. mid depth at the nearshore stations. The measured background concentrations from the base line surveys 2009-2011 are shown for comparison. Dredging operations are indicated in the bottom of the plots. The results including measured background concentrations can be found in Appendix I for all stations.

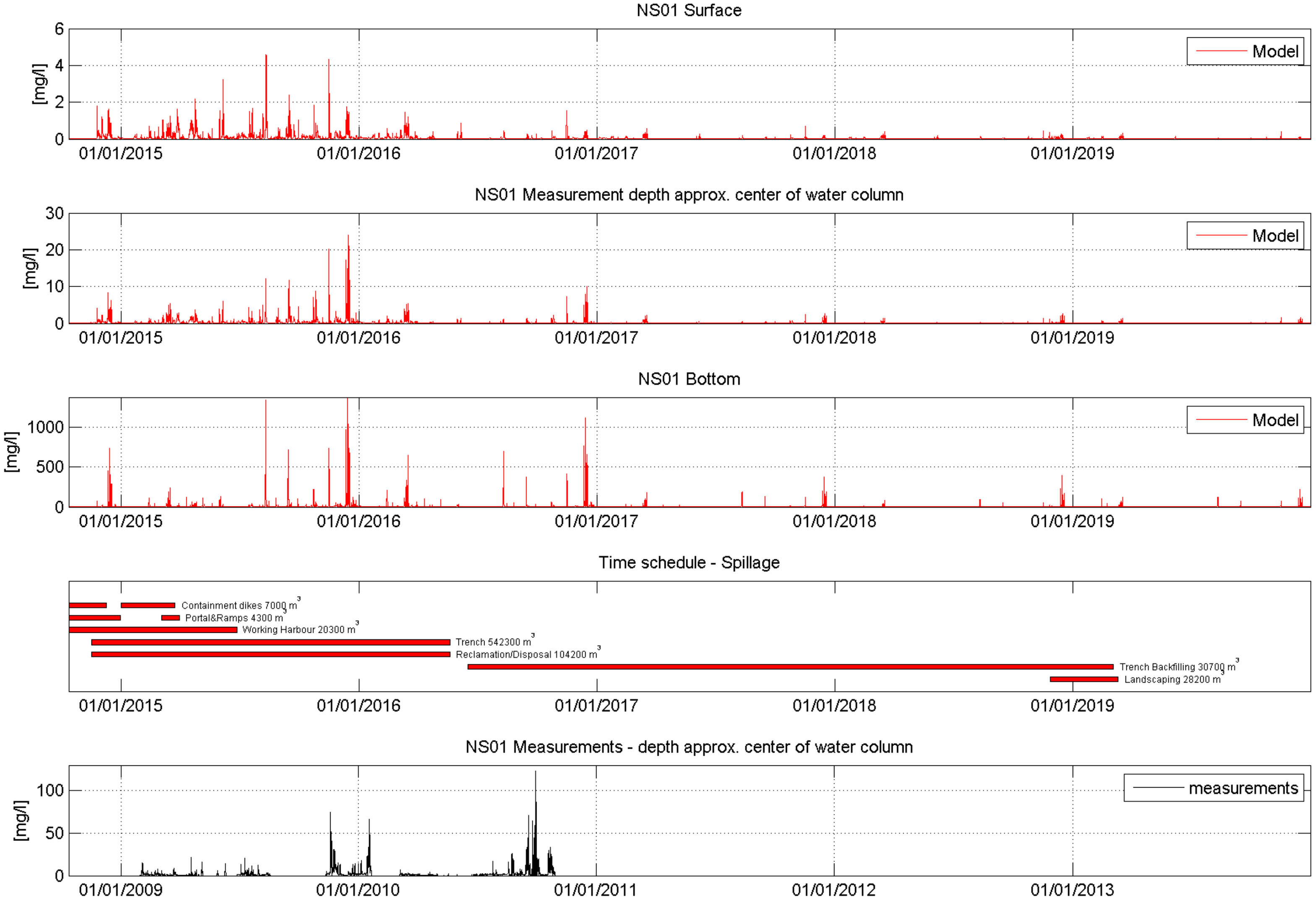


Figure 5.12 Time series of suspended sediment concentration at station NS01 for tunnel solution. Note: different scales are applied

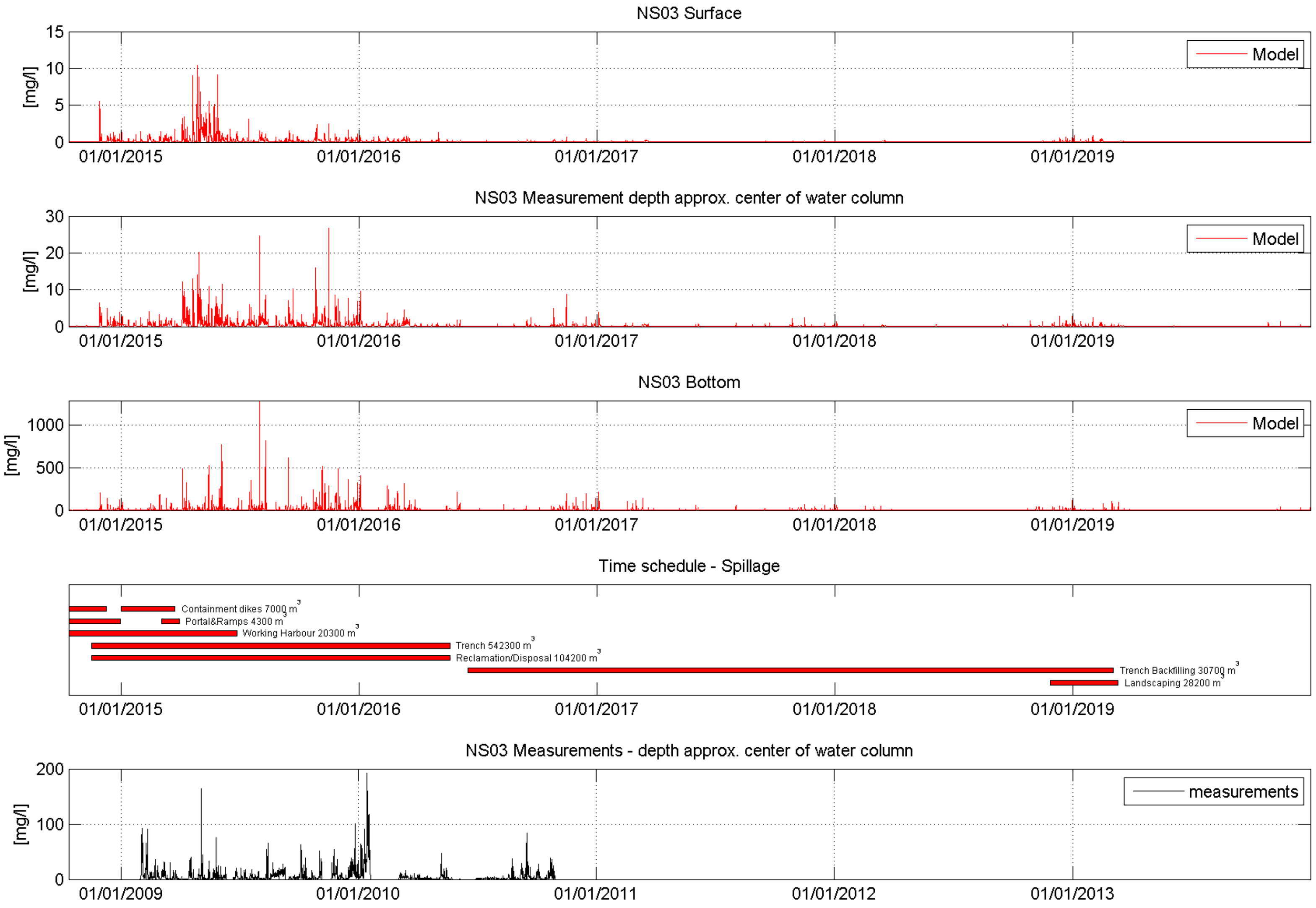


Figure 5.13 Time series of suspended sediment concentration at station NS03 for tunnel solution. Note: different scales are applied

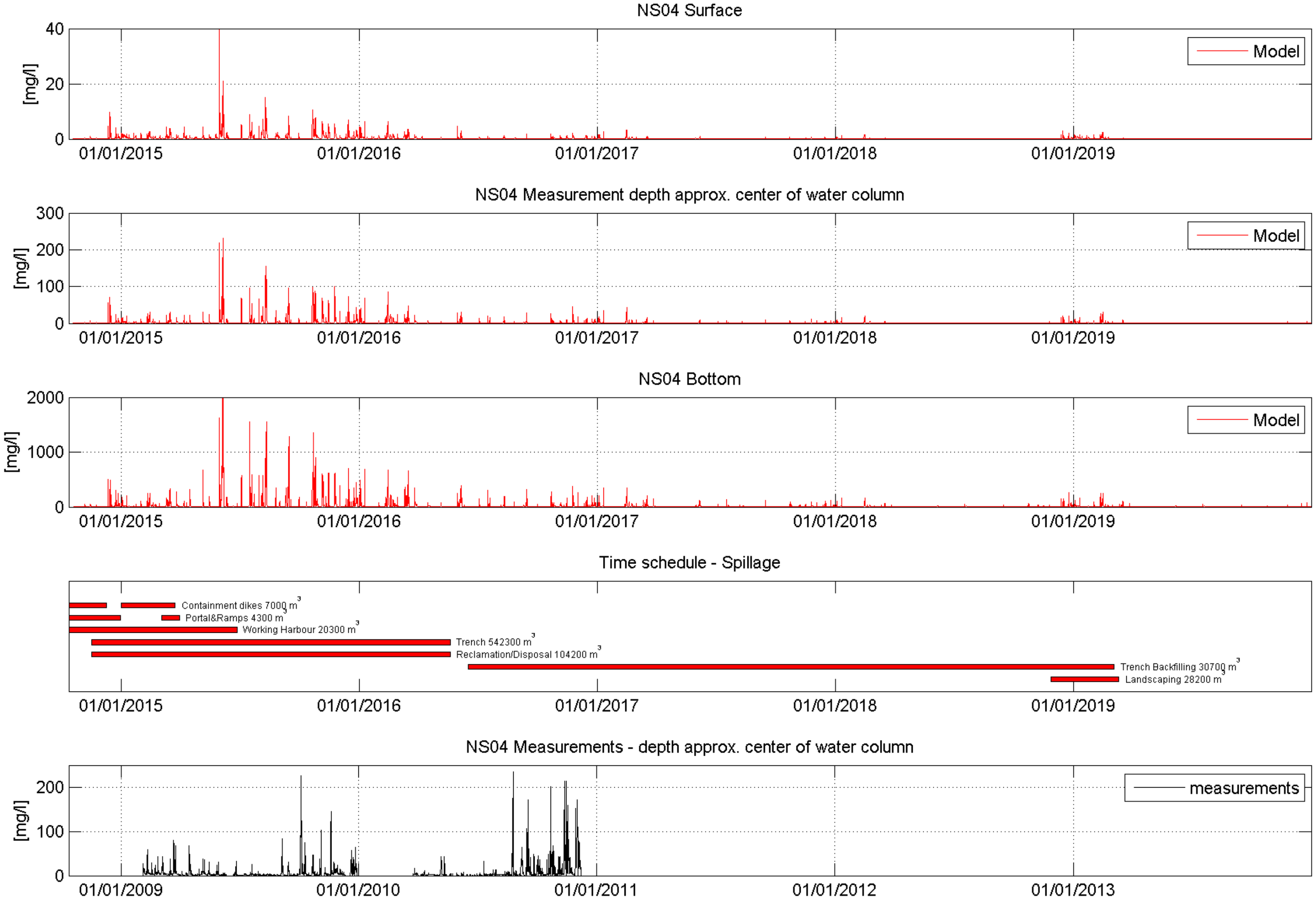


Figure 5.14 Time series of suspended sediment concentration at station NS04 for tunnel solution. Note: different scales are applied

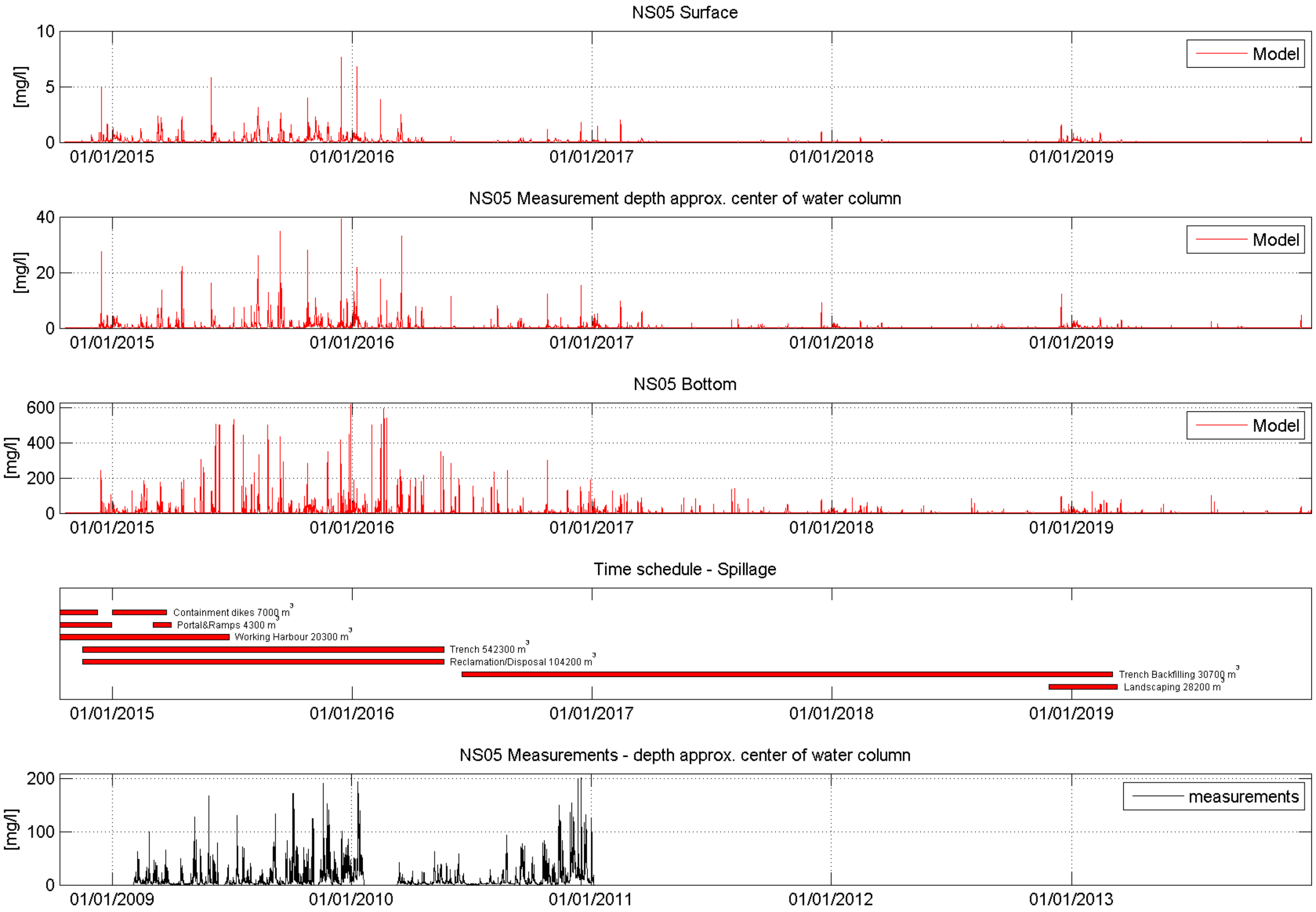


Figure 5.15 Time series of suspended sediment concentration at station NS05 for tunnel solution. Note: different scales are applied

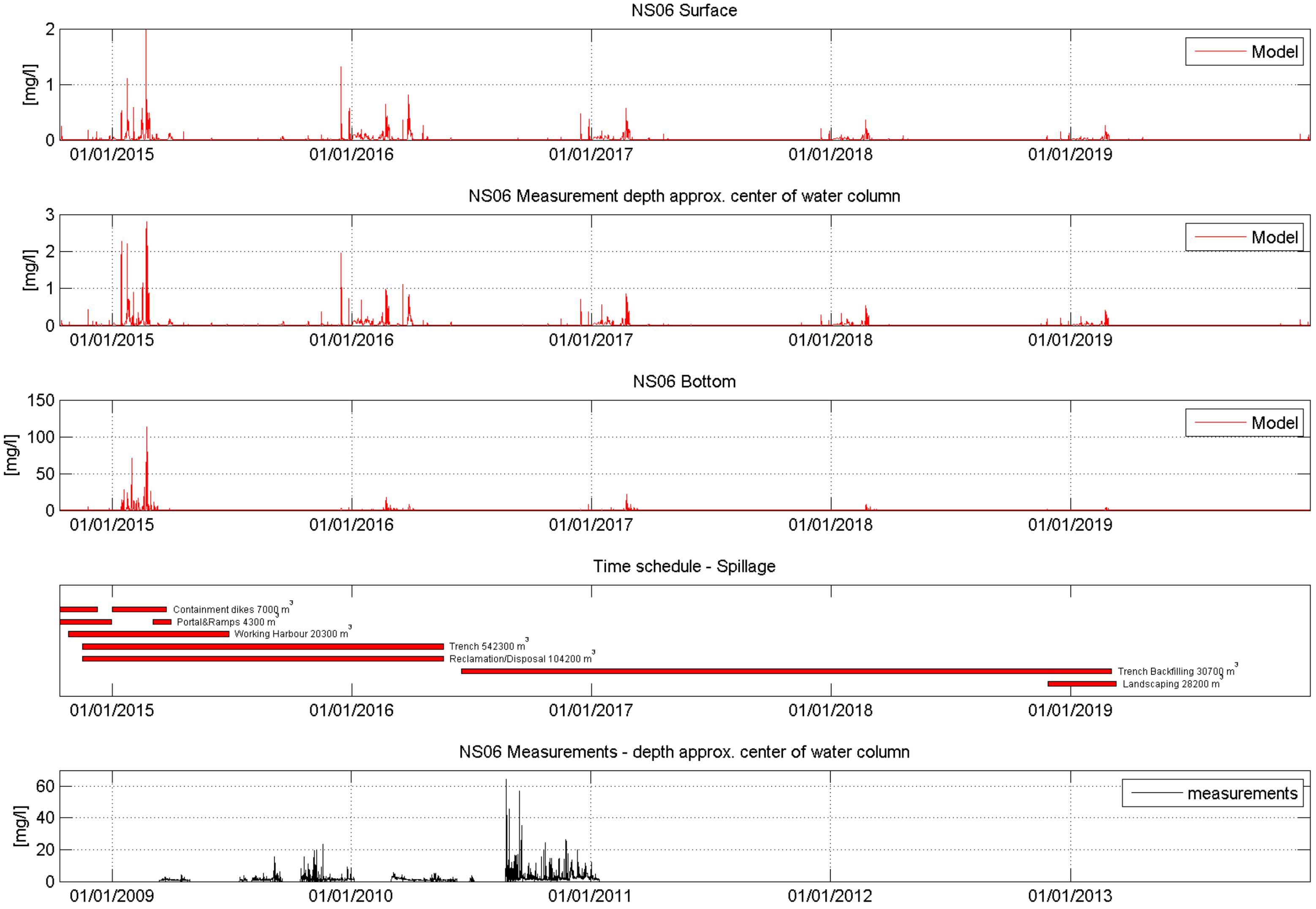


Figure 5.16 Time series of suspended sediment concentration at station NS06 for tunnel solution. Note: different scales are applied

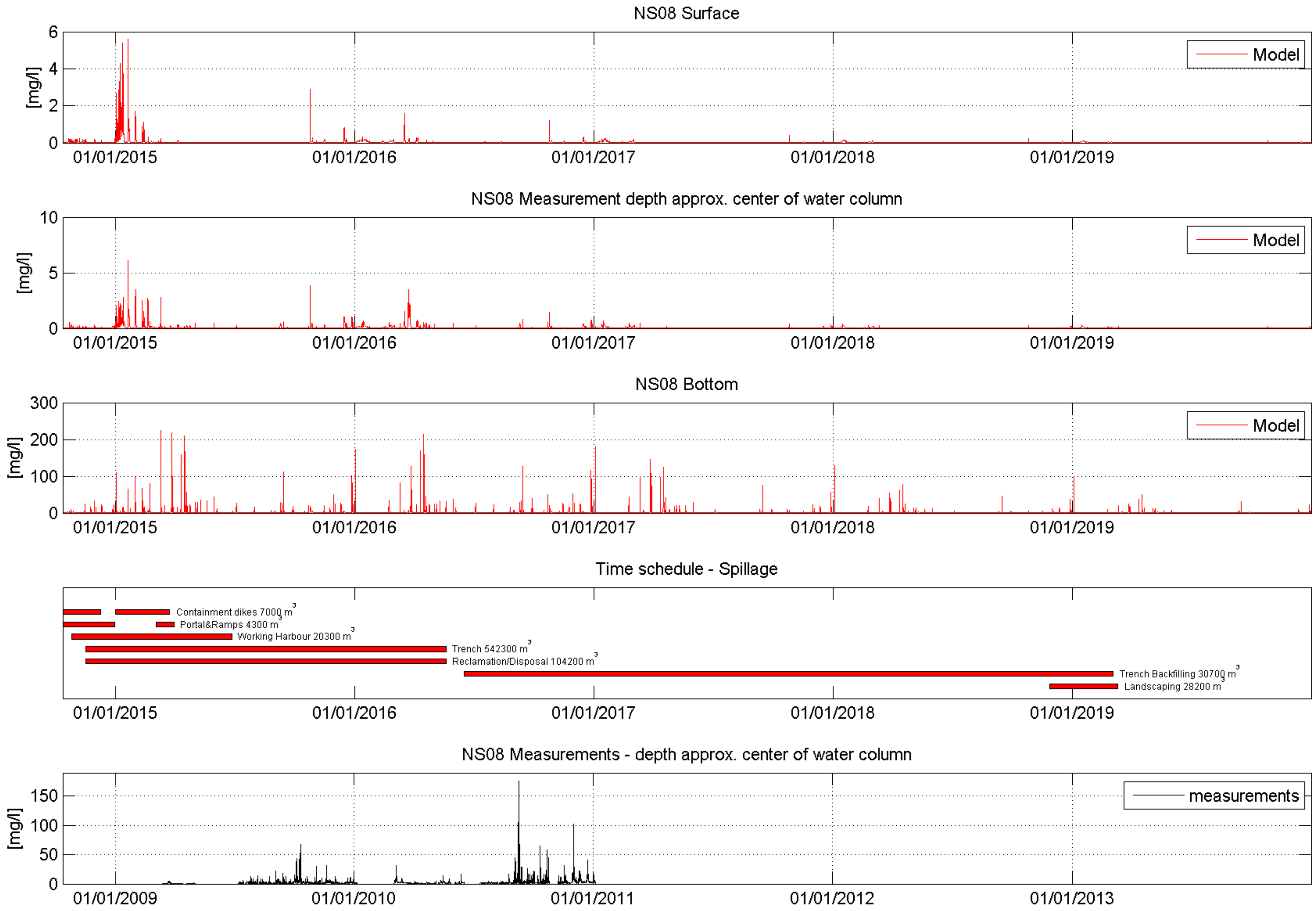


Figure 5.17 Time series of suspended sediment concentration at station NS08 for tunnel solution. Note: different scales are applied

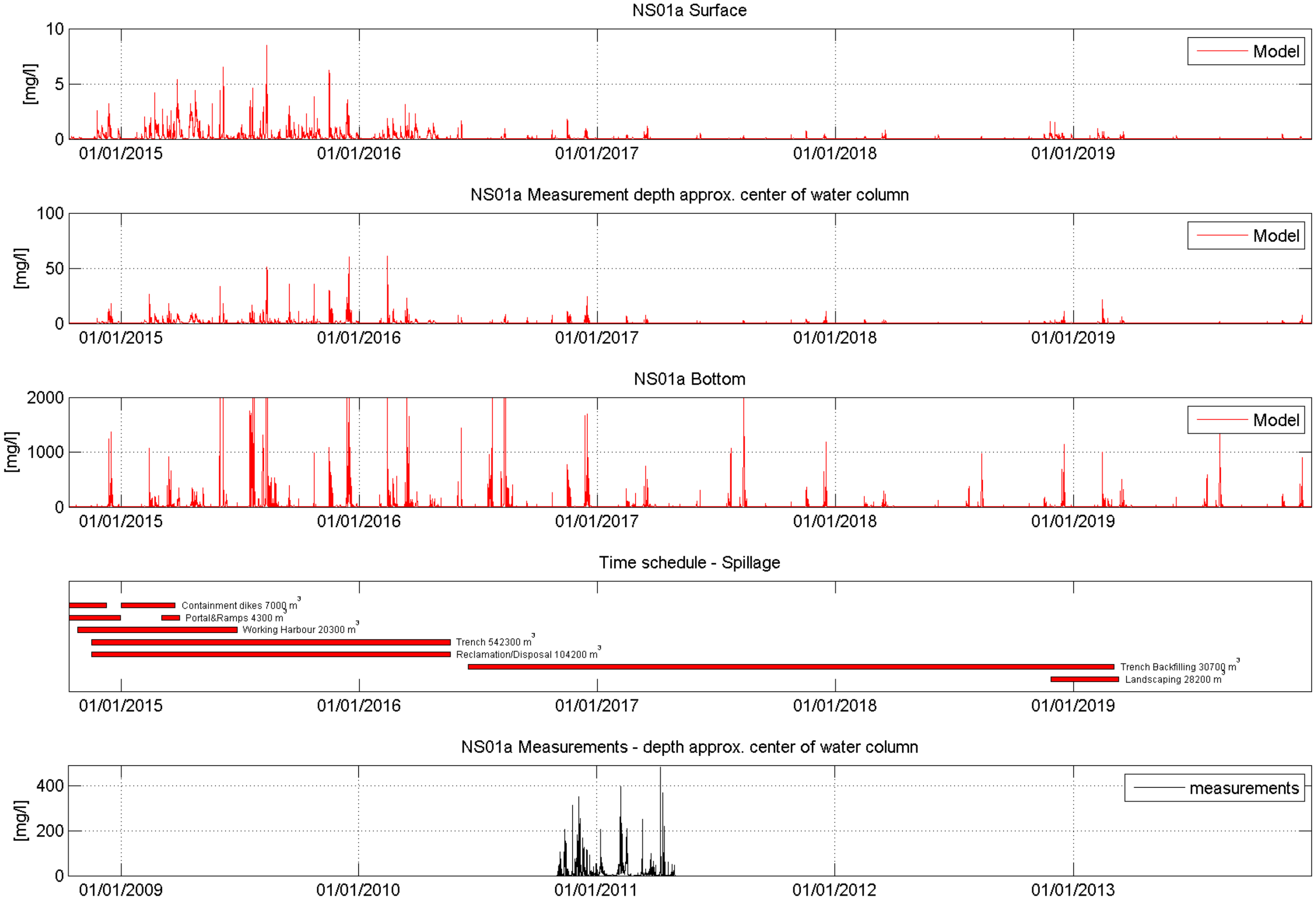


Figure 5.18 Time series of suspended sediment concentration at station NS01a for tunnel solution. Note: different scales are applied

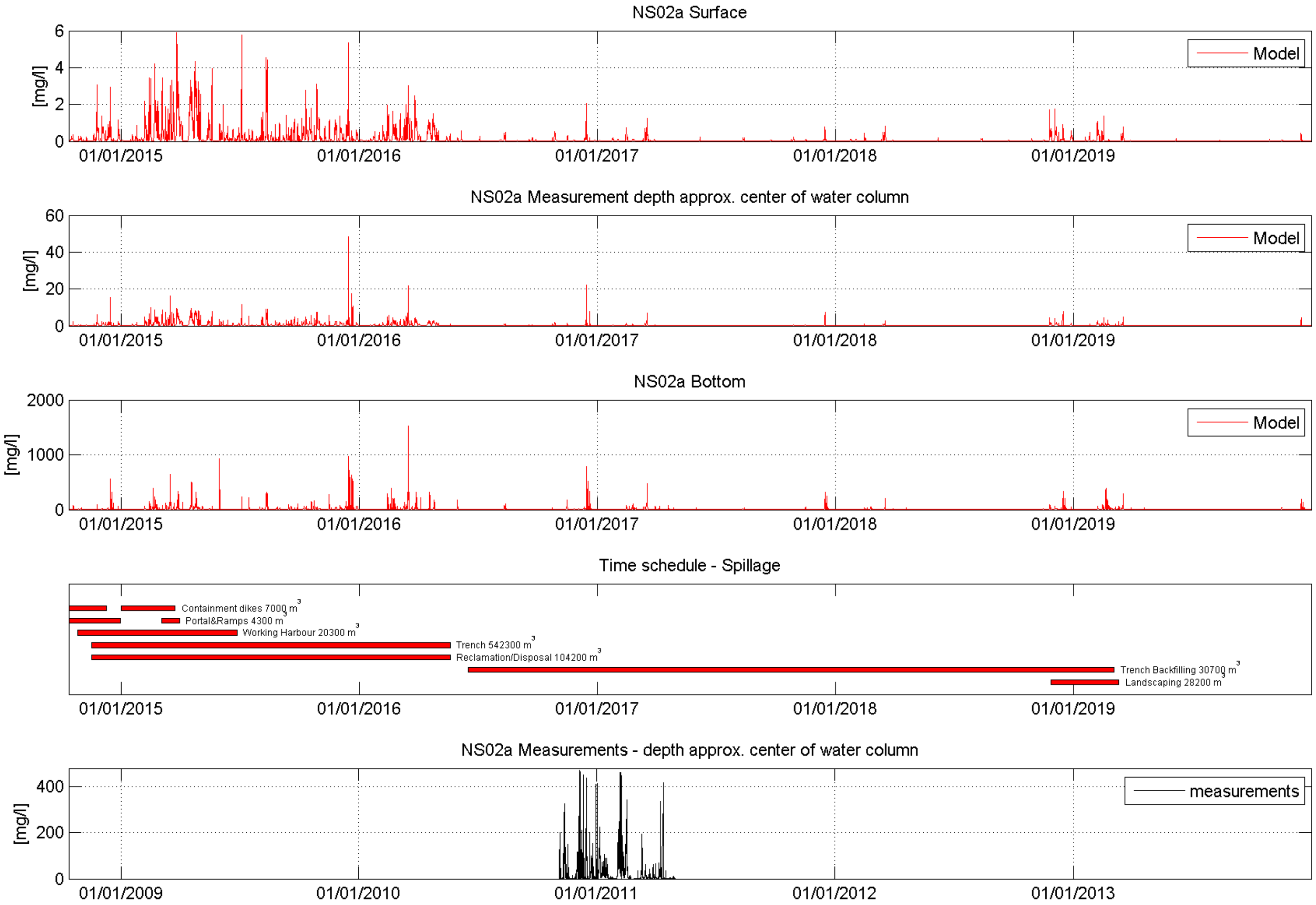


Figure 5.19 Time series of suspended sediment concentration at station NS02a for tunnel solution. Note: different scales are applied

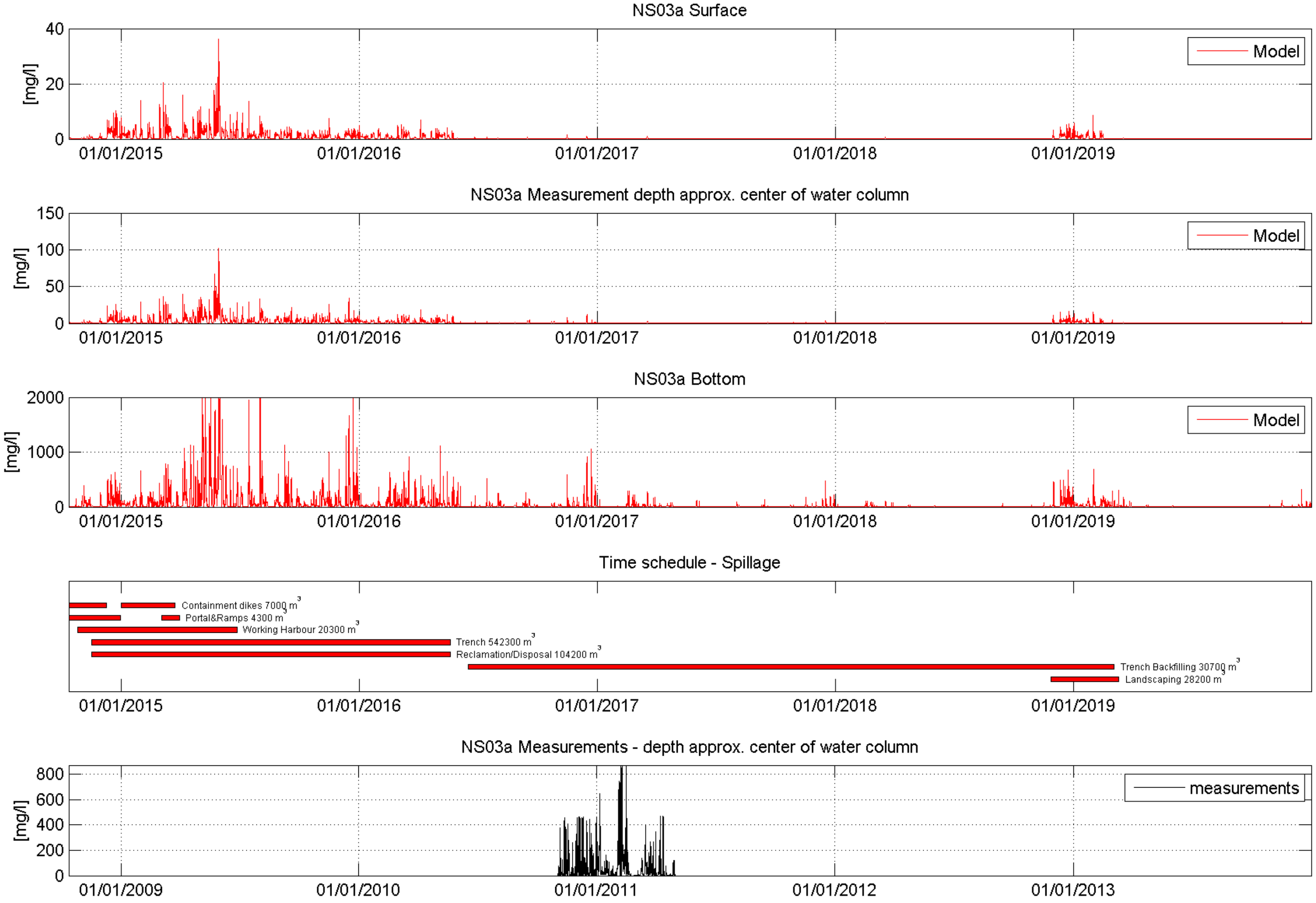


Figure 5.20 Time series of suspended sediment concentration at station NS03a for tunnel solution. Note: different scales are applied

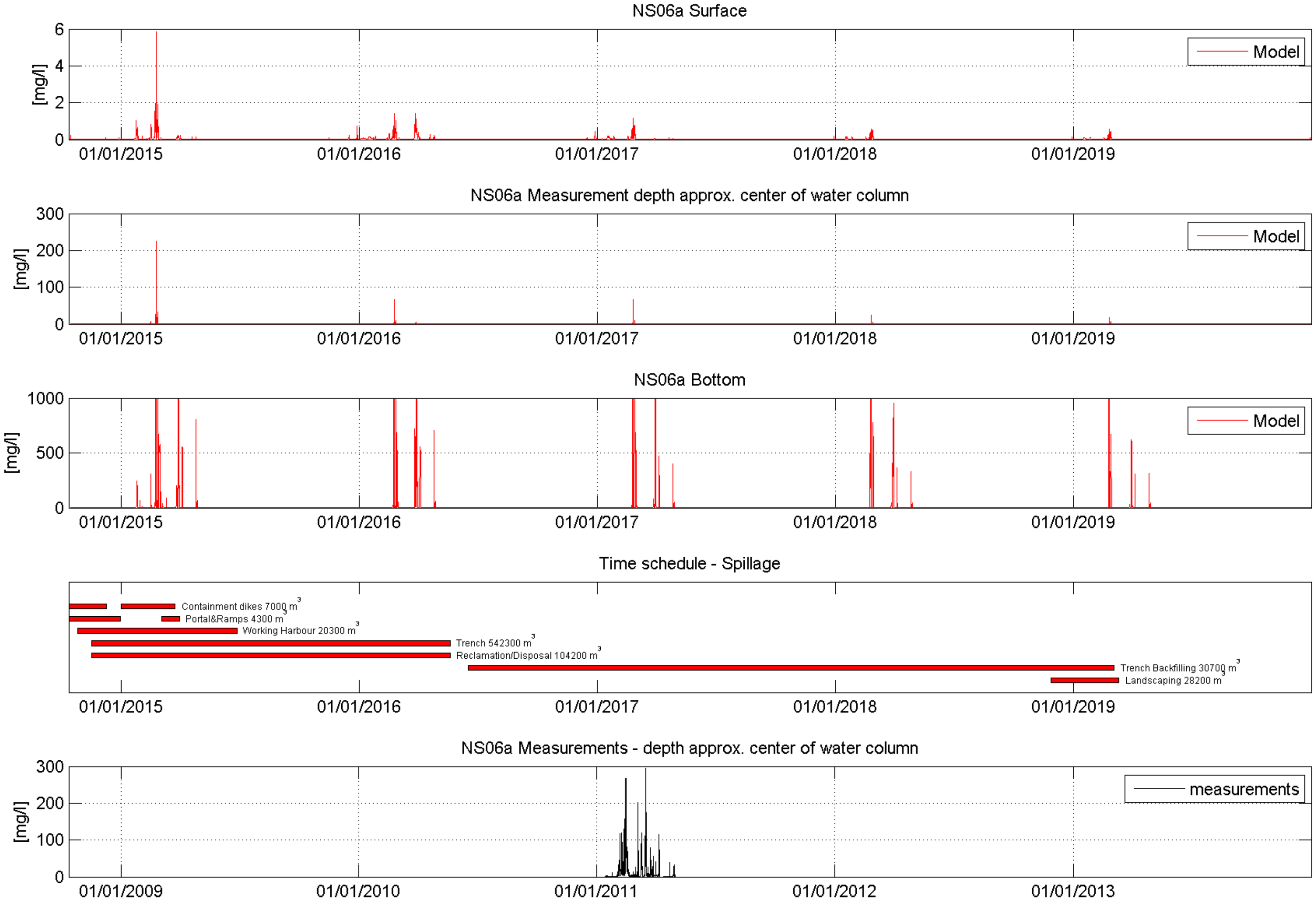


Figure 5.21 Time series of suspended sediment concentration at station NS06a for tunnel solution. Note: different scales are applied

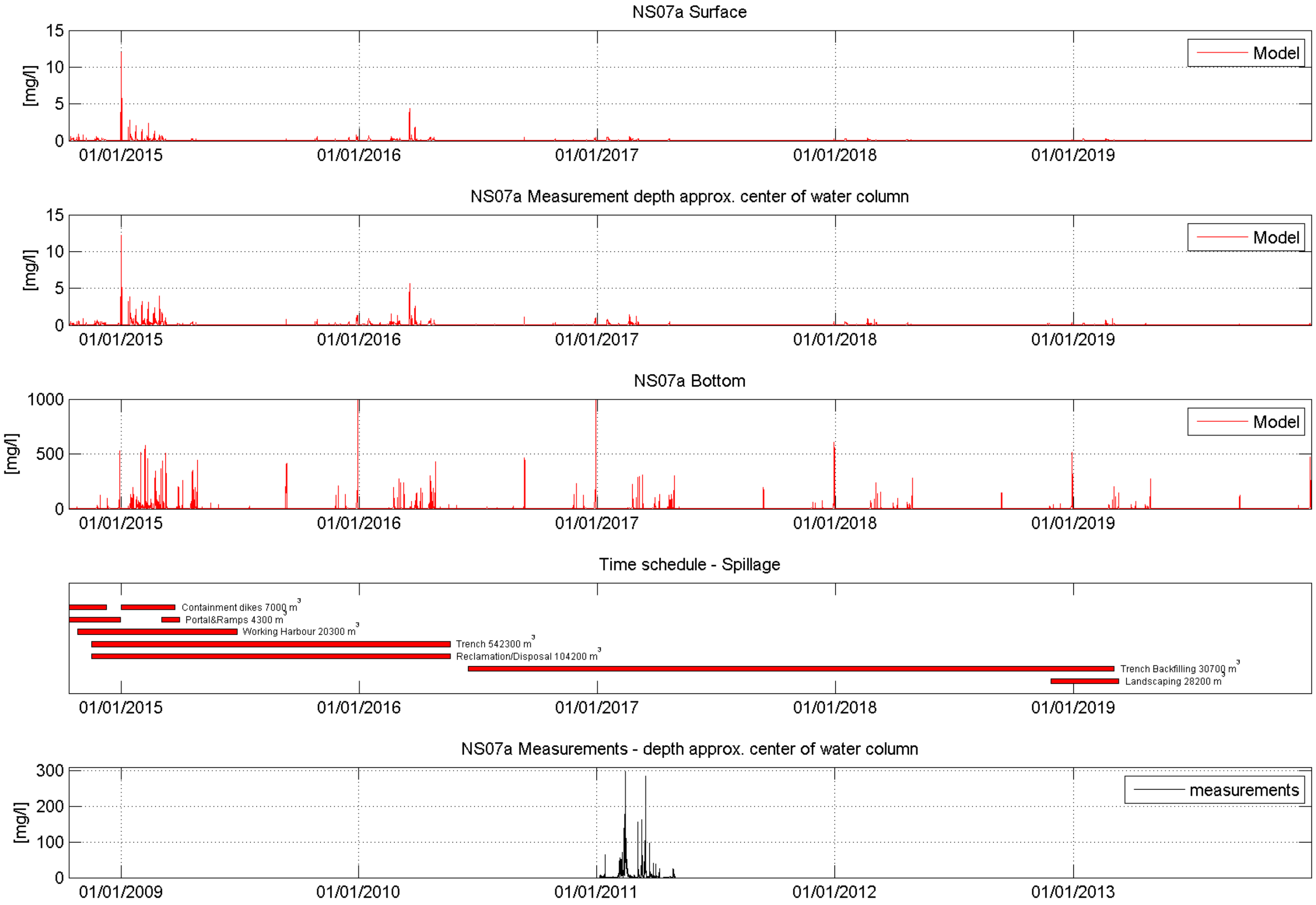


Figure 5.22 Time series of suspended sediment concentration at station NS07a for tunnel solution. Note: different scales are applied

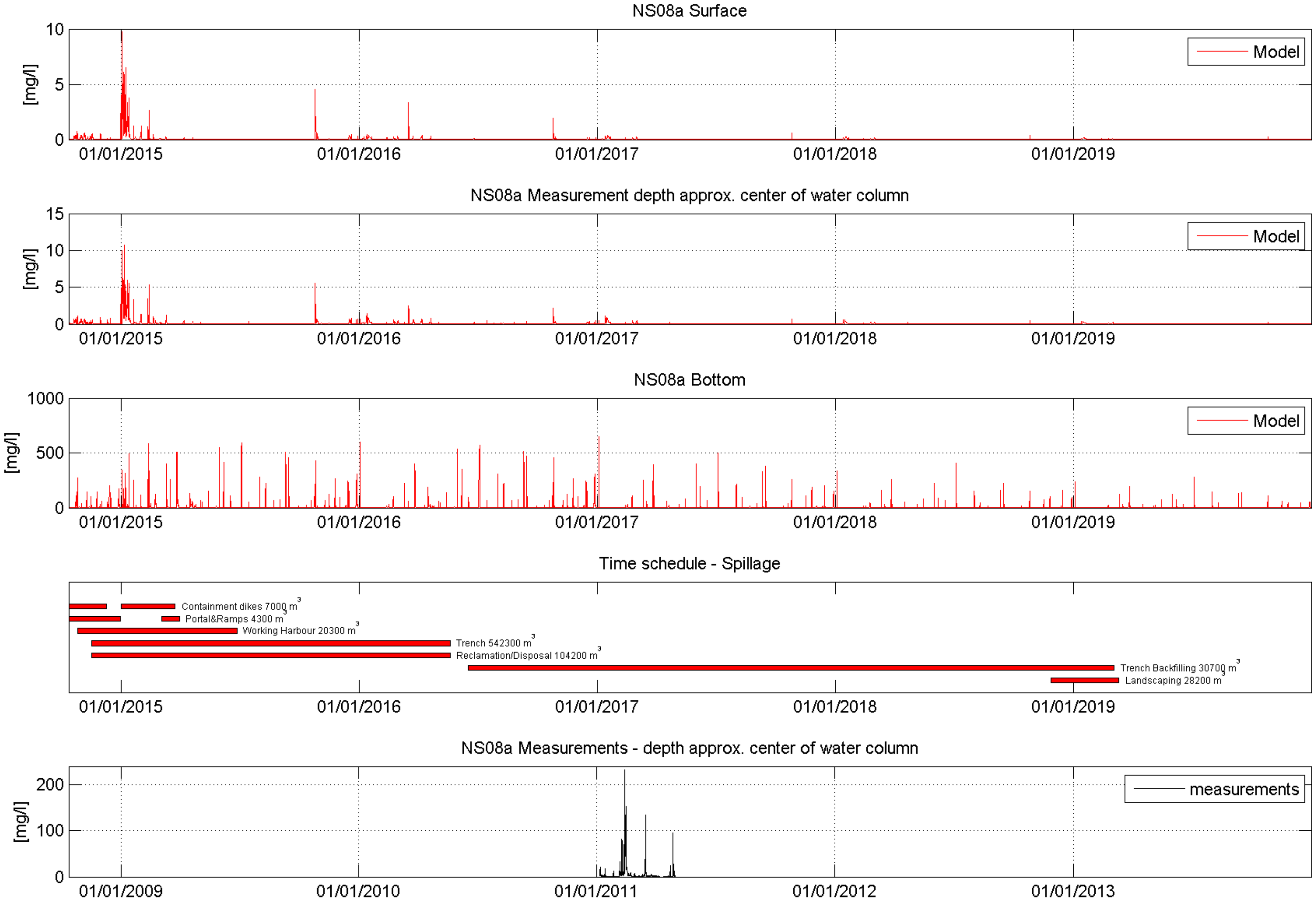


Figure 5.23 Time series of suspended sediment concentration at station NS08a for tunnel solution. Note: different scales are applied

The time series show the largest excess concentrations in the last months of 2015 and the first months of 2016. Largest excess concentrations at midwater are seen in the Rødsand Lagoon where excess concentrations can reach above 150 mg/l for short periods of time and at the nearshore stations where concentrations at midwater can reach 800 mg/l over short periods of time. Away from the Rødsand Lagoon and offshore of the coastal areas excess concentrations are smaller.

Excess concentrations on the German side are seen to be smaller than at the Danish side consistent with the smaller amounts of spilled sediment and the milder wave climate here.

The level of excess concentration from dredging decreases in accordance with the decreasing dredging activity. Effects can hardly be detected after summer 2019.

The important information that can be derived from the time series plots is that the high excess concentrations occur during situations with strong waves and currents that resuspend already deposited spilled sediment and prevent sediment in suspension to settle at the sea bed.

Excess concentrations are generally smaller than the background concentration. In some cases maximum levels reach the same levels as the background concentrations.

Exceedance times of concentration limits for tunnel solution
In this section selected exceedance times for the tunnel solution are given. All results can be found in Appendix G.

The exceedance time is the percentage of time the excess concentration has been above a given value in a given time series. For instance the exccedance time for 2 mg/l is the percentage of time the concentration in a given time series is above 2 mg/l.

The exceedance time is presented for the summer of 2015 since this is the year with the largest spill.

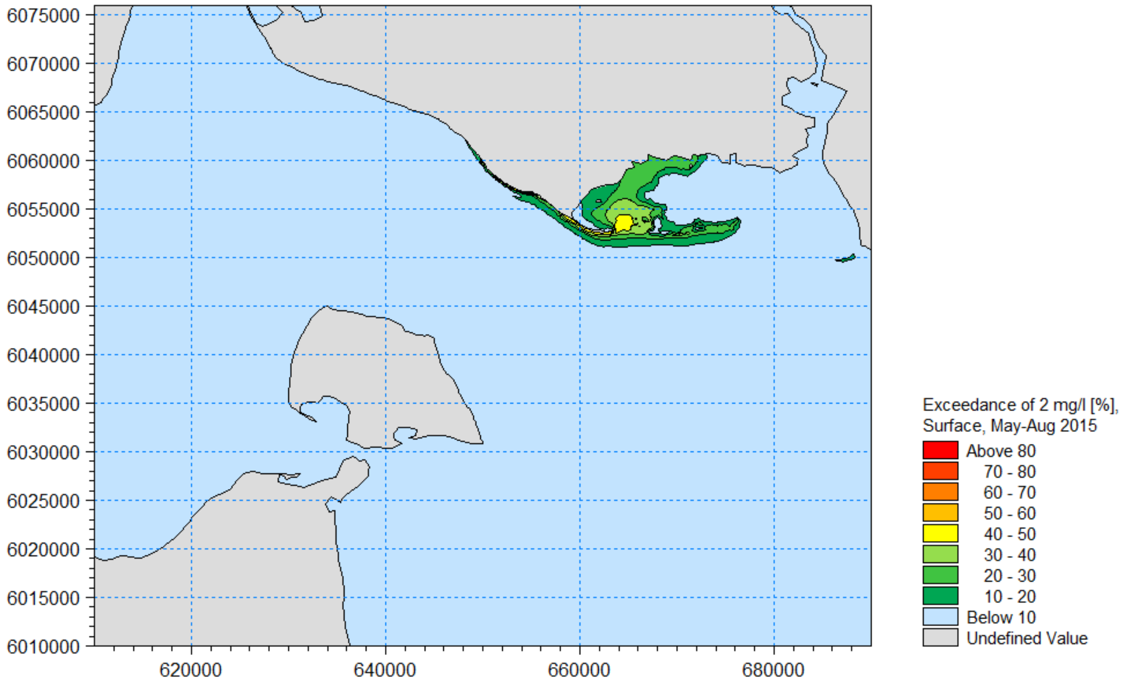


Figure 5.24 *Exceedance time of 2mg/l, 1/5-1/9 2015 for the surface (top layer in the numerical model results). E-ME Tunnel solution*

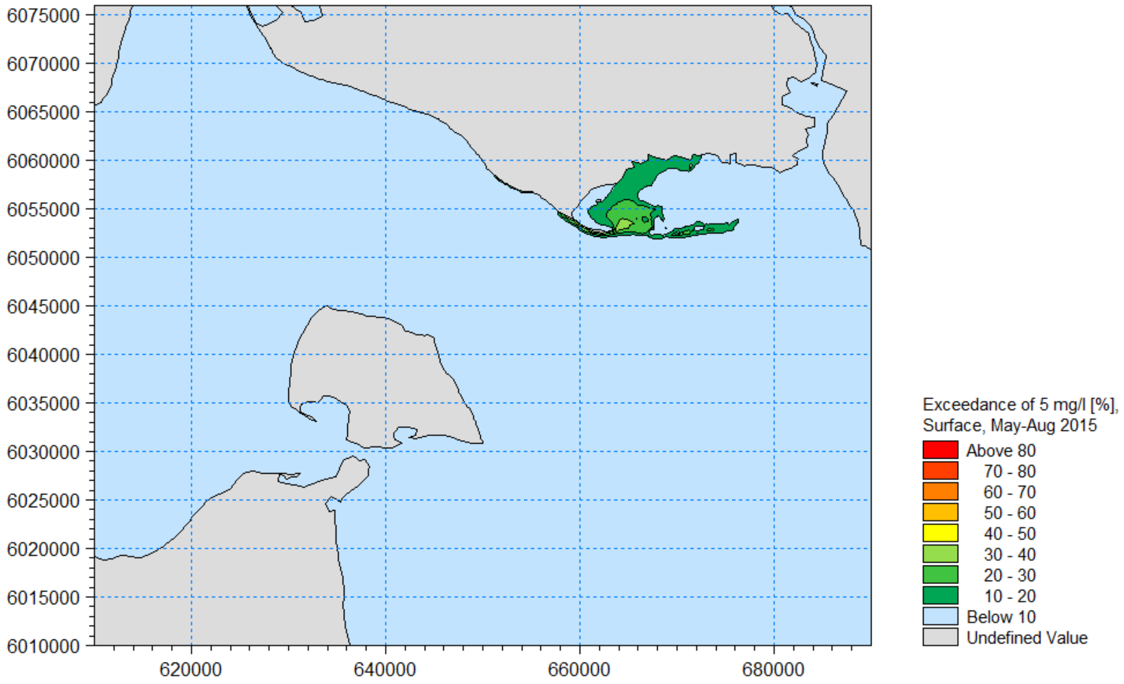


Figure 5.25 *Exceedance time of 5 mg/l, 1/5-1/9 2015 for the surface (top layer in the numerical model results). E-ME Tunnel solution*

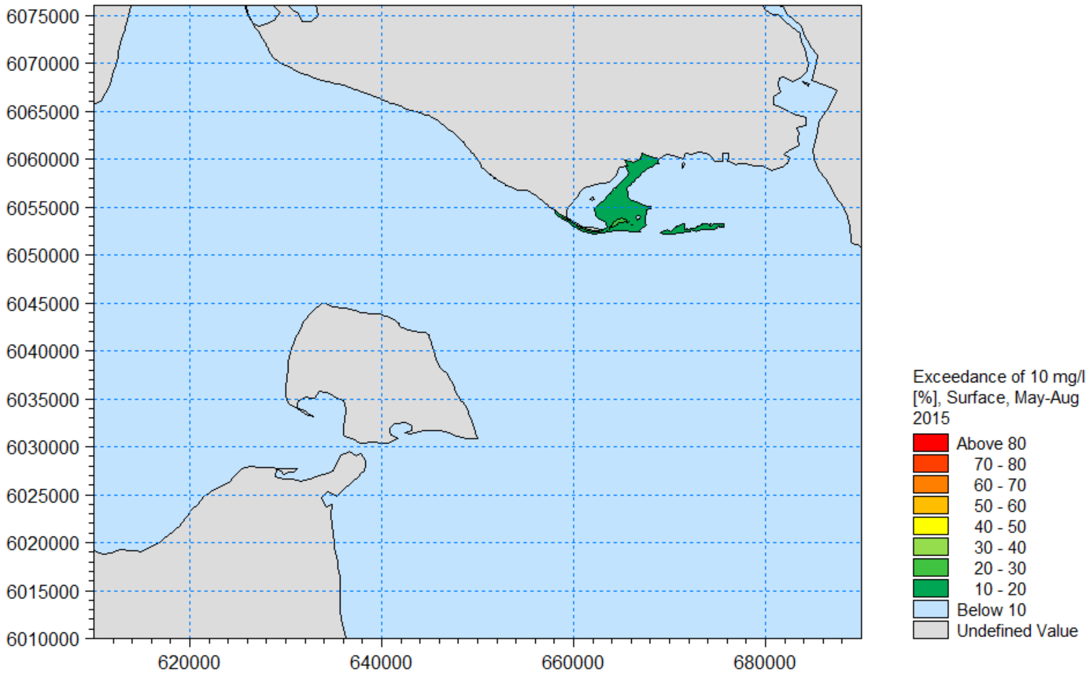


Figure 5.26 Exceedance time of 10 mg/l, 1/5-1/9 2015 for the surface (top layer in the numerical model results). E-ME Tunnel solution

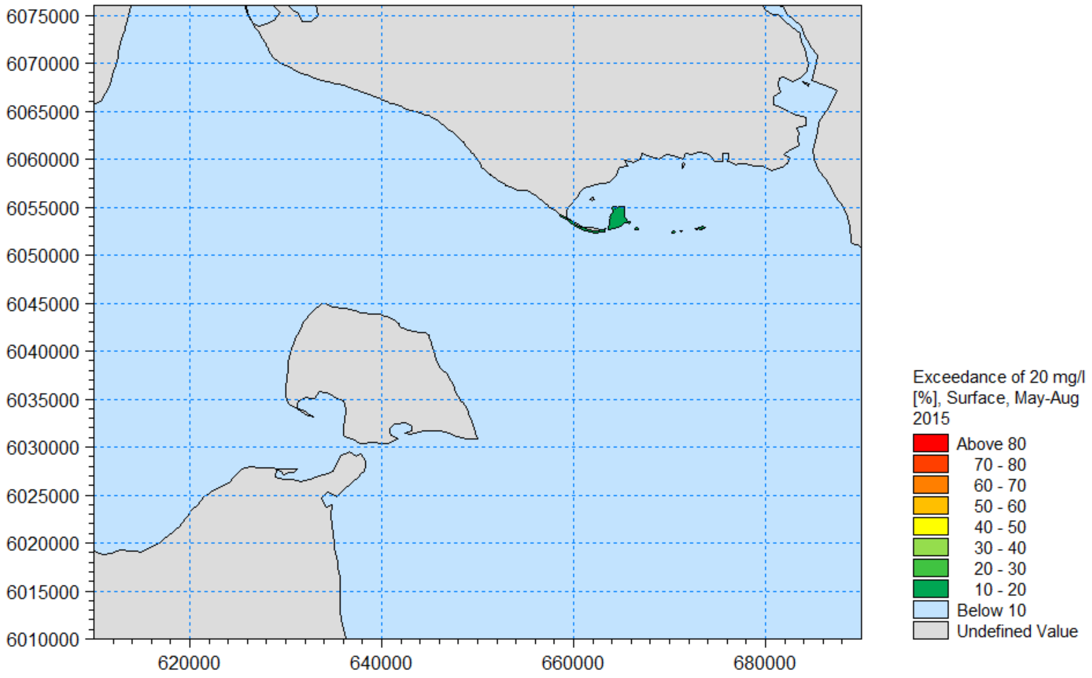


Figure 5.27 Exceedance time of 20 mg/l, 1/5-1/9 2015 for the surface (top layer in the numerical model results). E-ME Tunnel solution

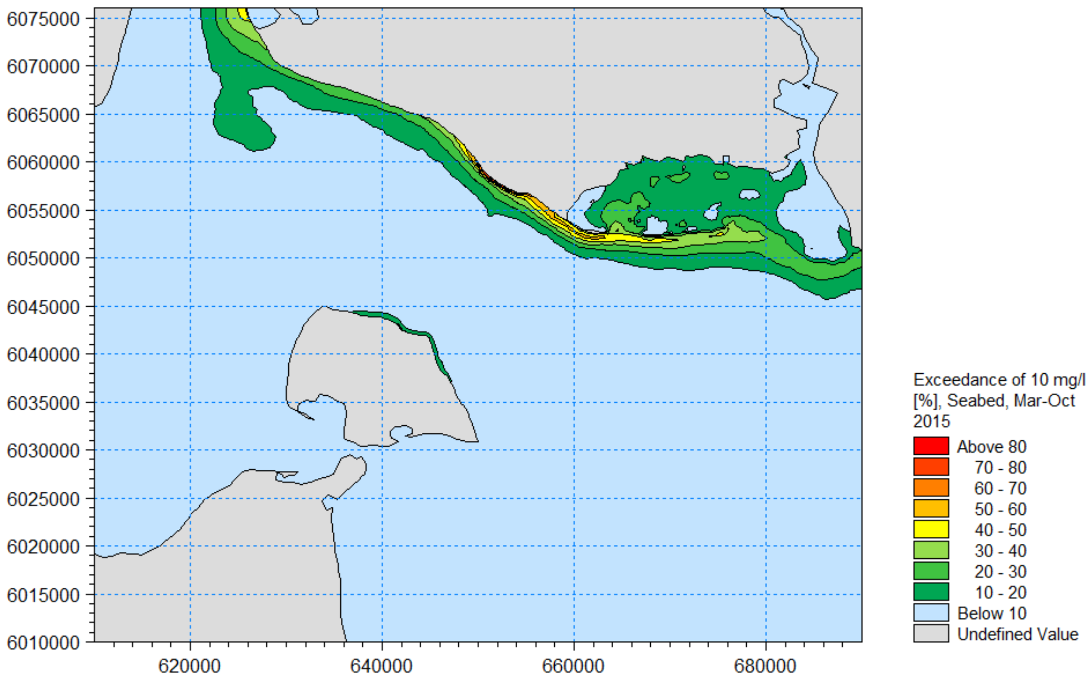


Figure 5.28 *Exceedance time of 10 mg/l, 1/3-1/11 2015 for just above the sea bed (bottom layer in the numerical model results). E-ME Tunnel solution*

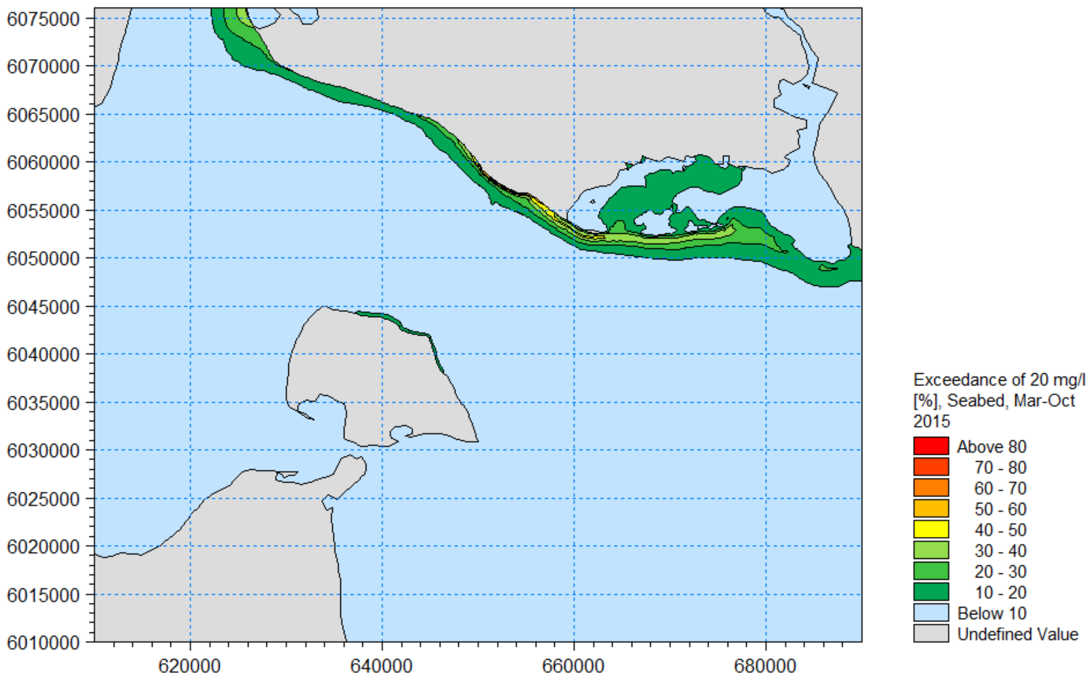


Figure 5.29 *Exceedance time of 20 mg/l, 1/3-1/11 2015 for just above the sea bed (bottom layer in the numerical model results). E-ME Tunnel solution*

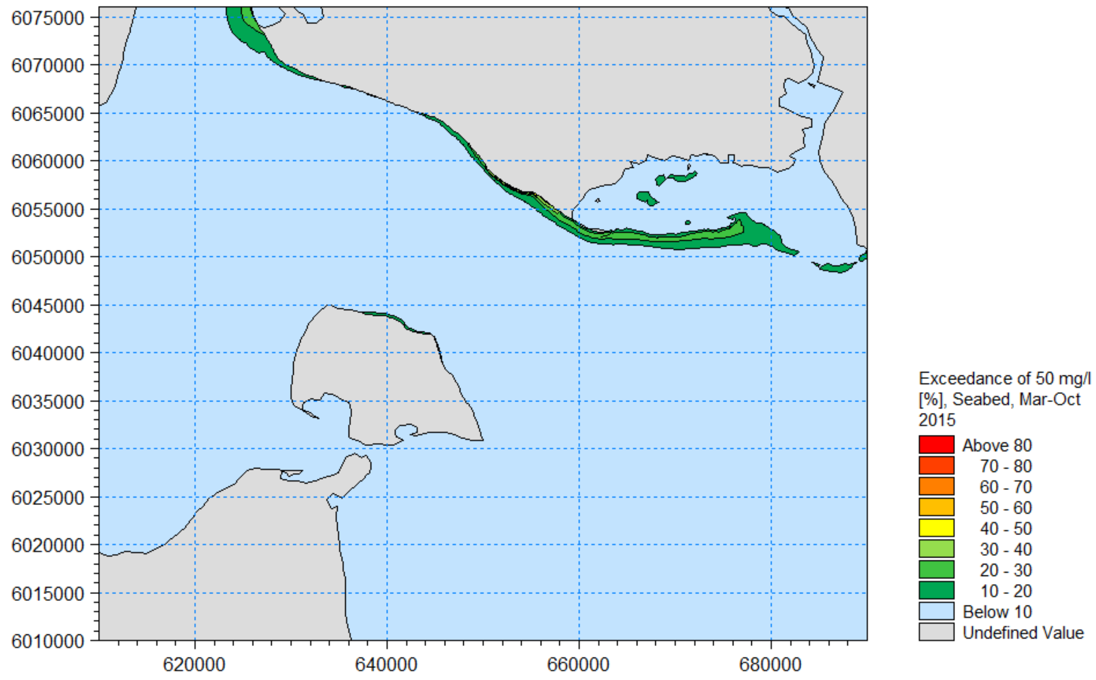


Figure 5.30 Exceedance time of 50 mg/l, 1/3-1/11 2015 for just above the sea bed (bottom layer in the numerical model results). E-ME Tunnel solution

Near the surface excess concentrations are most visible in Rødsand Lagoon and along the barrier island between the lagoon and the Fehmarnbelt. The results show that the visibility limit of 2 mg/l is exceeded up to 30% of the time near the surface in the Rødsand Lagoon and very close to the Danish Coast. Higher exceedance levels are only seen in Rødsand Lagoon and along the barrier island. Concentrations above 20 mg/l are never exceeded for more than 10% of the time.

Near the bottom excess concentrations are significantly higher. The exceedance level of 10 mg/l is exceeded up to 60% of the time along the Danish coastline and near the Rødsand Lagoon. Near the German coasts exceedances between 10% and 20% are seen. The higher exceedances are due to resuspension of sediment in the nearshore areas. Deposited sediment are resuspended and mixed with spilled sediment in the water column. Larger exceedance values are only exceeded in limited areas but concentrations of above 50 mg/l are seen up to 20% of the time at the Danish and German coasts.

The area with elevated concentrations stretches from the entrance to Nakskov Fjord to Gedser Odde and from the eastern tip to the western tip of Fehmarn Island. In Figure 5.31 the exceedance of 2 mg/l is presented in days.

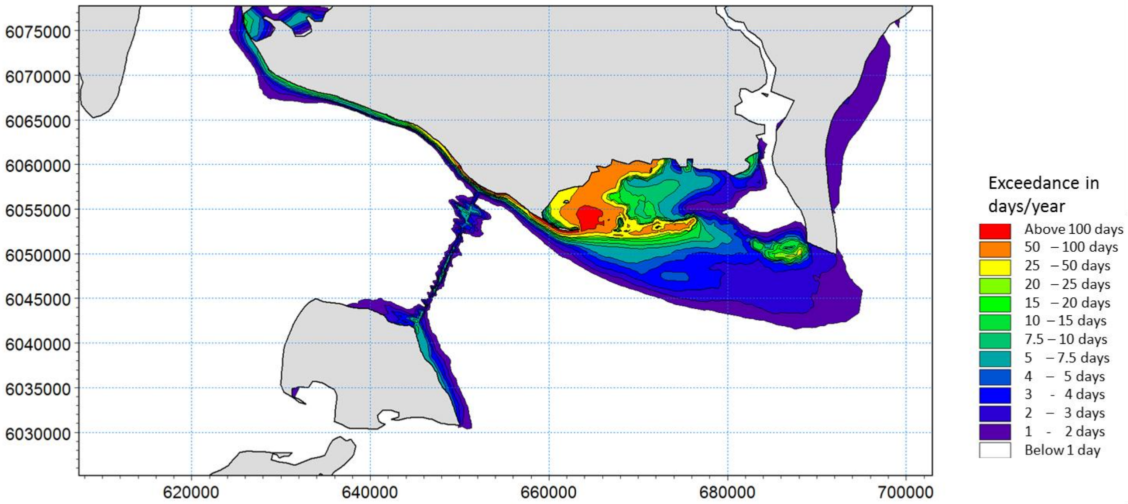


Figure 5.31 Exceedance of 2 mg/l in days/year for 2015

It is seen that excess sediment plumes from dredging will be visible at a given position up to 7.5 days in the offshore region. Results also show that there is a clear difference between nearshore and offshore conditions. The nearshore band extends around 3 km offshore. Inside this band resuspension will be the dominant factor for the concentration of suspended sediments. Outside this band the direct plumes from the dredging operation are dominant. Results also show that plumes from dredging operations occurring more than 3 km offshore will rarely hit the coastline.

In the coastal zone the visibility limit of 2 mg/l is exceeded for up to 100 days a year on the Danish coast and only less than 7.5 days on the German coast. Here the visibility is mainly due to resuspension.

Sediment transport patterns
In order to quantify sediment pathways or flow patterns of the spilled material the overall sediment budget for sediment below 63 microns is given in Figure 5.32 for the E-ME Tunnel solution. The figure shows the average travelling patterns for the sediment over the entire construction period. Larger plots can be found in Appendix K.

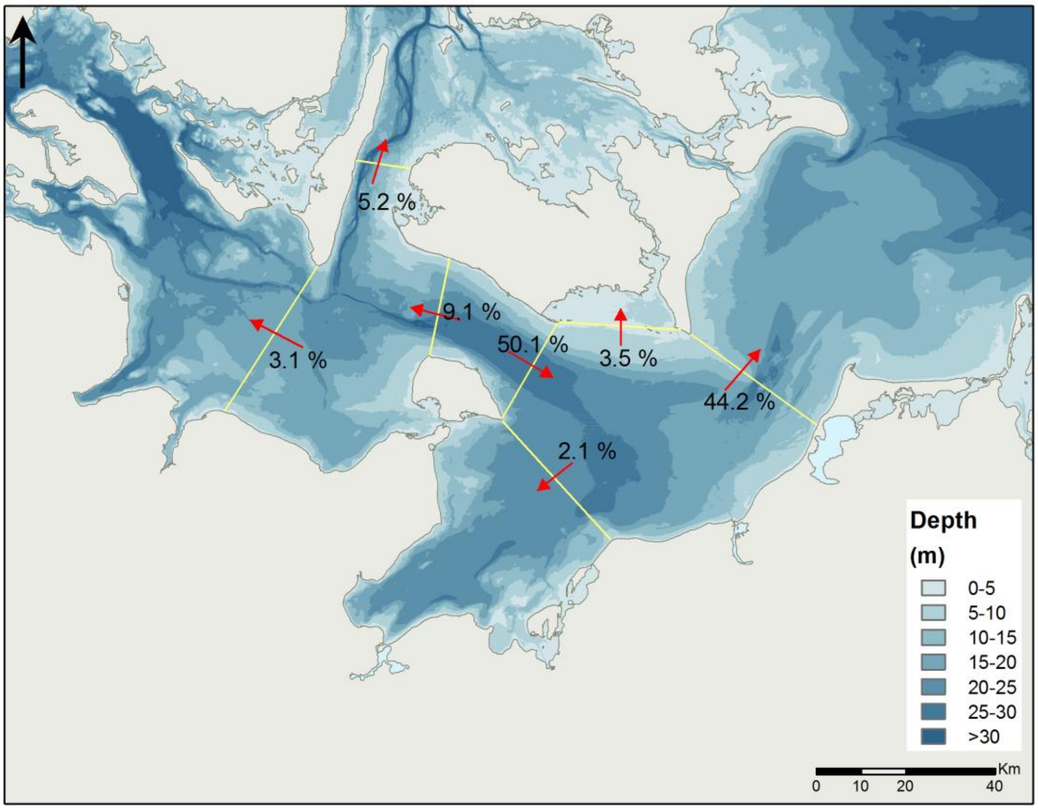


Figure 5.32 Sediment transport patterns for all sediment for the E-ME Tunnel solution

About 40.8% of the total amount of spilled sediment remains close to the alignment. Of this sediment approximately 90% is sand that will settle and remain close to the construction.

59.2% of the sediment leaves the area between Fehmarn and Lolland. 44.2% of this travels east past Darss Sill and into the Baltic Sea. 3.5% enters the Rødsand Lagoon and 2.1% enters the Bay of Mecklenburg. The east bound flow of sediment to the Baltic Sea is due to the frequent dense saline inflow of bottom water where the sediment concentrations are high.

The west bound flow of water from the Baltic also carries sediment but in smaller concentrations. 5.2% travels west into the Storebælt and the Lillebælt. 3.1% travels south of Langeland and 4.9% travels into the Kattegat.

Note that this calculation shows the transport pattern summed up for the entire dredging period. Due to the shifting currents and resuspension events variations in the distribution of spilled sediments will be seen over time.

Statistical time series analysis for tunnel solutions

The simulations of excess concentrations from sediment spill are carried out based on the hydrographic year 2005. The available baseline measurements are from 2009-2010.

In order to measure the simulated excess concentrations relative to the background concentrations fractiles and exceedance times have been applied.

Fractiles are defined as for example: the 10% fractile (f_{10}) is the concentration which is not reached 10% of the time. A conceptual definition sketch is given in Figure 5.33.

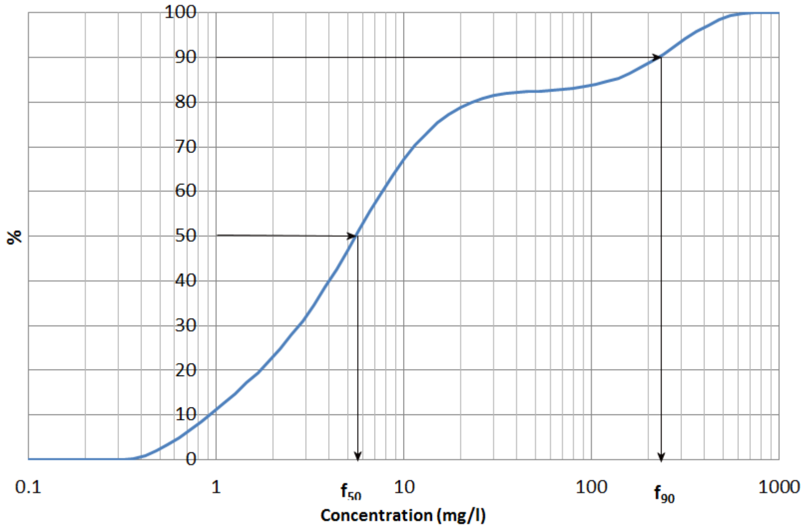


Figure 5.33 Definition of fractiles. Blue curve is the accumulated percentage of all values below a given concentration. Fractiles f_{50}, and f_{90} are given as examples

Exceedance times are defined as the percentage of time the concentration has been above a given value. For instance the exceedance time E_2 for 2 mg/l is the percentage of time the concentration is above the threshold level of 2 mg/l. See Figure 5.34 for a conceptual definition. Note, this is the same definition as applied for 2D maps of exceedance time presented in the sections above.

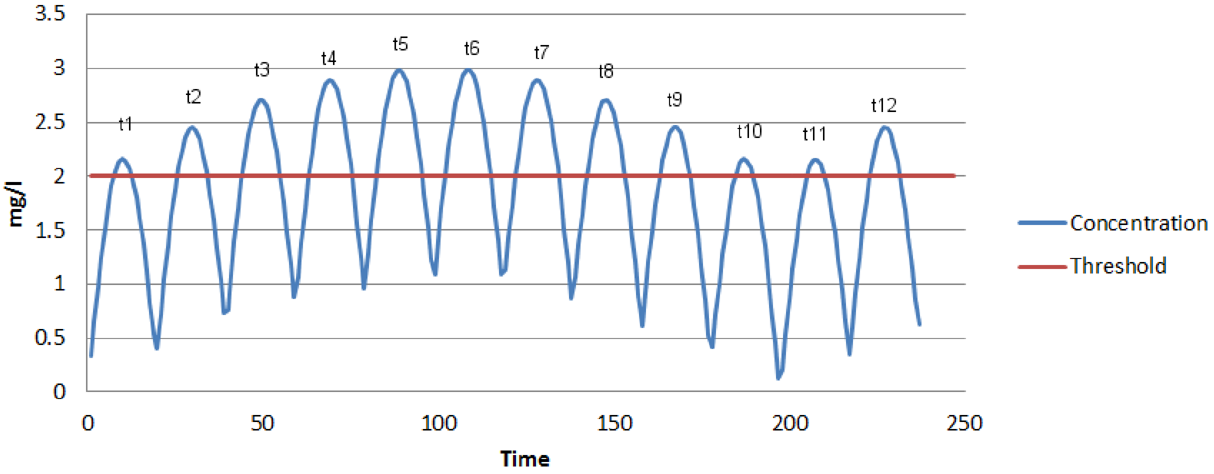


*Figure 5.34 Definition of exceedance time. E_2 = sum (t1:t12)/(total time)*100 (t1 is the time between the first up-crossing and the first down-crossing)*

In Table 5.4, the fractiles and exceedance times at the location of each of the near-shore stations are given for the entire construction period. All statistical results can be found in Appendix N.

Table 5.4 *Fractiles and exceedance times for excess concentration, E-ME Tunnel solution 2014-2019*

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	0.0	0.0	0.1	1.4	0.1	0.0
NS02	0.0	0.0	0.1	1.9	0.1	0.0
NS03	0.0	0.0	0.1	2.6	0.1	0.0
NS04	0.0	0.0	0.5	11.0	3.2	1.5
NS05	0.0	0.0	0.1	3.5	0.4	0.1
NS06	0.0	0.0	0.0	0.1	0.0	0.0
NS07	0.0	0.0	0.0	0.1	0.0	0.0
NS08	0.0	0.0	0.0	0.2	0.0	0.0
NS09	0.0	0.0	0.0	0.3	0.0	0.0
NS10	0.0	0.0	0.0	0.0	0.0	0.0
NS01a	0.0	0.0	0.2	5.2	0.6	0.2
NS02a	0.0	0.0	0.1	4.3	0.2	0.0
NS03a	0.0	0.0	0.5	15.7	2.3	0.6
NS06a	0.0	0.0	0.0	0.5	0.1	0.1
NS07a	0.0	0.0	0.0	0.2	0.0	0.0
NS08a	0.0	0.0	0.0	0.5	0.0	0.0
MS01	0.0	0.0	0.1	0.1	0.0	0.0
MS02	0.0	0.0	0.1	0.3	0.0	0.0

In Table 5.5 the fractiles and exceedance times for the baseline measurements for the period 1 February 2009 to 1 May 2011are presented. Note: different periods for various locations.

Table 5.5 Fractiles and exceedance times for fixed station measurements 01.02.2009 – 01.01.2011 (NS01-03 01.02.2009 – 01.11.2010, NS01a-03a 01.11.2010-01.05.2011, NS06a-08a 05.01.2011-01.05.2011)

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	1.09	1.85	10.59	23.06	5.40	2.05
NS02	1.48	3.91	28.86	38.62	13.15	7.78
NS03	2.20	6.31	24.66	53.57	15.72	6.57
NS04	2.46	6.36	34.04	60.78	17.69	9.33
NS05	5.33	15.46	54.62	81.03	34.44	19.83
NS06	1.17	1.71	4.74	19.37	0.71	0.17
NS07	1.36	2.59	8.22	32.08	3.27	0.99
NS08	1.39	2.36	6.92	30.64	2.54	1.10
NS09	1.38	2.30	7.94	30.03	3.77	1.45
NS10	1.30	2.25	7.60	28.53	3.22	1.02
NS01a	4.83	17.04	88.18	67.75	34.63	22.84
NS02a	5.08	30.79	126.12	69.57	38.05	30.28
NS03a	18.22	66.32	302.06	83.93	59.91	48.49
NS06a	1.96	6.94	95.00	49.50	20.81	13.20
NS07a	1.87	4.38	36.26	47.99	15.20	9.49
NS08a	1.15	2.22	18.60	27.85	7.94	4.64
MS01	0.7	1.1	3.5	9.4	0.3	0.0
MS02	0.7	1.0	2.4	6.4	0.3	0.0

The largest concentrations occur in 2015. The fractiles and exceedance times for this year alone are given in Table 5.6.

Table 5.6 Fractiles and exceedance times for excess concentration, for E-ME Tunnel solution 2015

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	0.2	0.4	1.2	4.8	0.6	0.1
NS02	0.2	0.8	1.8	8.3	0.1	0.1
NS03	0.3	1.0	2.2	11.3	0.5	0.1
NS04	0.5	2.3	9.9	26.9	9.8	5.5
NS05	0.2	0.9	2.1	10.6	1.2	0.3
NS06	0.0	0.0	0.1	0.3	0.0	0.0
NS07	0.0	0.0	0.3	0.3	0.0	0.0
NS08	0.0	0.0	0.2	0.6	0.0	0.0
NS09	0.0	0.0	0.1	0.0	0.0	0.0
NS10	0.0	0.0	0.0	0.0	0.0	0.0
NS01a	0.3	1.3	3.7	16.8	2.3	0.8
NS02a	0.3	1.3	2.9	16.3	0.4	0.1
NS03a	2.2	5.4	10.4	51.2	10.5	3.2
NS06a	0.0	0.0	0.1	1.1	0.4	0.2
NS07a	0.0	0.0	0.2	0.6	0.1	0.0
NS08a	0.0	0.0	0.2	2.4	0.1	0.0
MS01	0.0	0.1	0.3	0.2	0.0	0.0
MS02	0.0	0.1	0.4	1.2	0.0	0.0

Inspection of the tables shows that generally the background concentrations are higher than the excess concentrations and the exceedance values are generally exceeded for much longer times in the measured time series.

Figure 5.35 shows the exceedance time for 2 mg/l of the background concentrations and of the excess concentrations (due to spill in the entire construction period) for all the measurement stations. All comparisons are made at the water depth where the measurements are made.

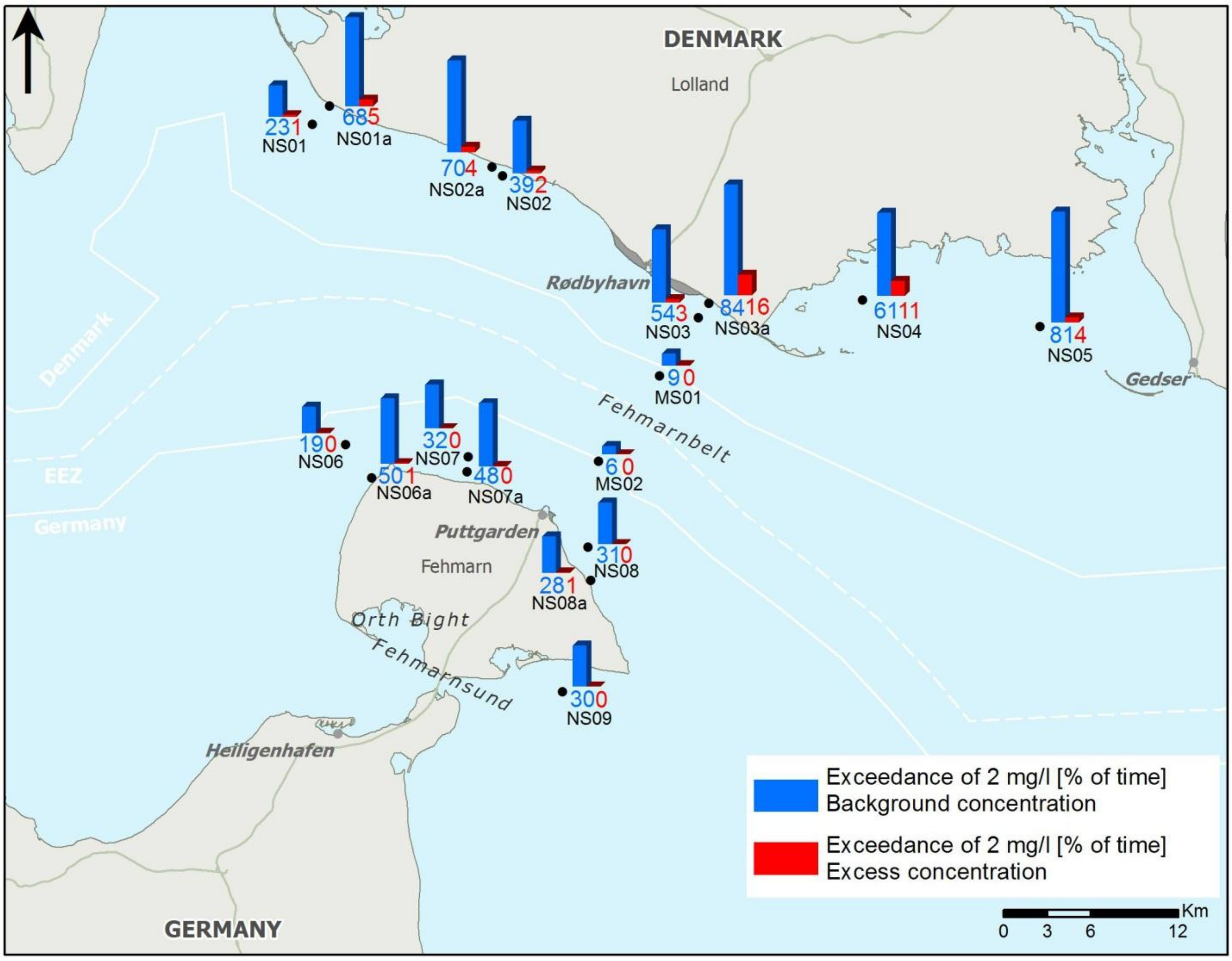


Figure 5.35 Comparison between exceedance time of 2 mg/l for the background and the excess concentrations at the measurement stations during the entire tunnel construction period (2014-2019)

The comparison shows that the frequency of background concentrations above 2 mg/l is always at least 5 times larger than the excess frequency due to dredging when the entire construction period is considered. The excess frequency is largest along the coast of Lolland (NS01a-03a) and inside the Rødsand Lagoon (NS04 and NS05). Along the coast of Fehmarn the excess concentration only exceeds 2 mg/l for less than 1 % of the time at a few stations.

Figure 5.36 shows the exceedance time of 2 mg/l for the background concentrations and for the excess concentrations due to spill in the year 2015 for all the measurement stations. The comparison shows that the exceedance time for the visibility limit except for NS03a is less than half of the exceedance time for the natural visibility limit of 2 mg/l.

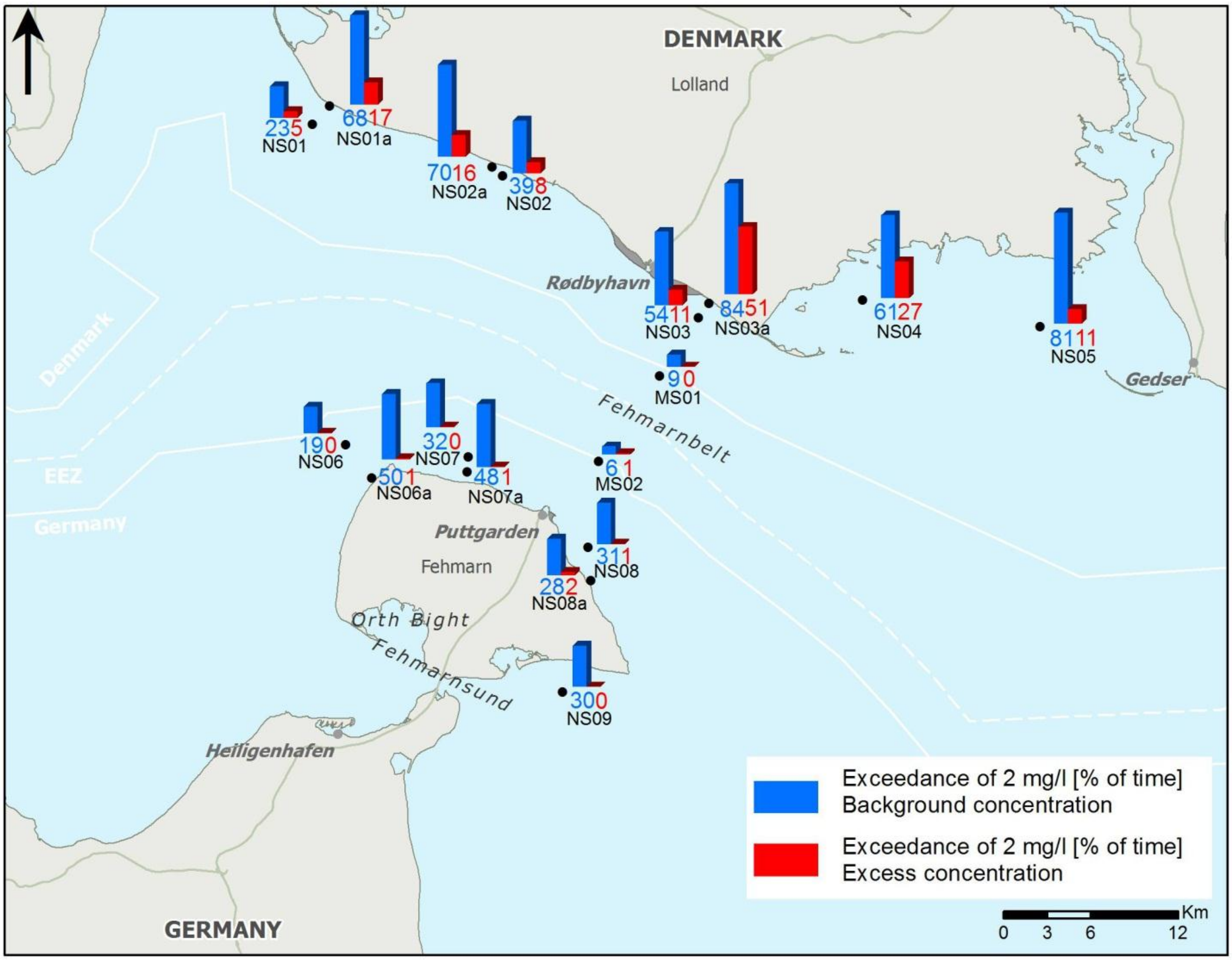


Figure 5.36 Comparison between exceedance time of 2 mg/l for the background and the excess concentrations at the measuring stations during 2015

Except for the period where the dredger is actually dredging in the nearshore zone the high concentration events will occur when the hydrodynamic conditions are rough. This means that at least part of the time where the visibility limit is exceeded by excess concentration is simultaneous with natural resuspension events. It will therefore be hard to detect a visual difference in the appearance of the water and thus the effect of dredging is considered insignificant in such cases.

In Rødsand there will only seldomly be sediment plumes from dredging and thus any concentrations seen here are the result of resuspension. Since resuspension of natural material will happen at the same time as resuspension of the dredged material the frequencies will not change much. Seen from a “visual appearance” point of view the natural frequency of sediment events with concentrations above 2 mg/l is so high that a slight increase in frequencies or concentration levels will not be detectable.

Bathing water

Bathing beaches exist on both sides of the Fehmarnbelt. The quality of the bathing beaches is related to the visual appearance of the water and the composition of the sea bed. The visual appearance of the water can be impacted by the dredging activities in two ways:

- Directly, because the dredging plume hits coastal areas

- Indirectly, because previously dredged materials remain on the bed and is re-suspended after the dredging operation has moved offshore

The maximum excess concentrations during the first summer (2015) at the surface are given in Figure 5.37.

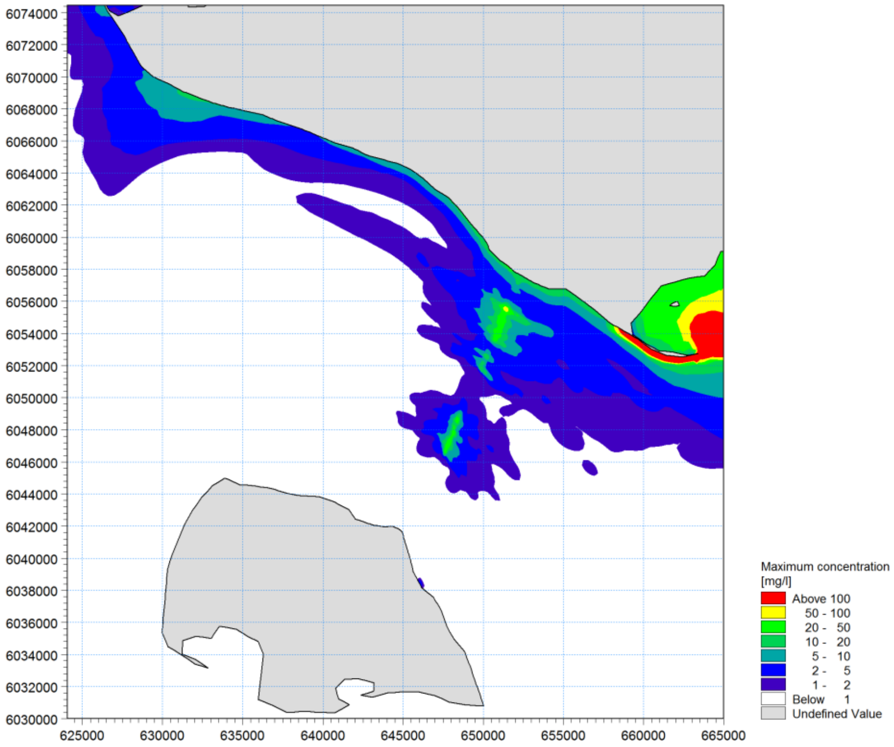


Figure 5.37 Maximum suspended sediment concentrations at the surface during the period 1/5-2015 – 1/9-2015

This shows that the plumes from dredging will be located at least 6 km offshore of the German coast during summertime and that the German coast is never affected directly. This is illustrated in Figure 5.38 which shows typical plumes from May 2015. It is seen that the plume travels parallel to the coast.

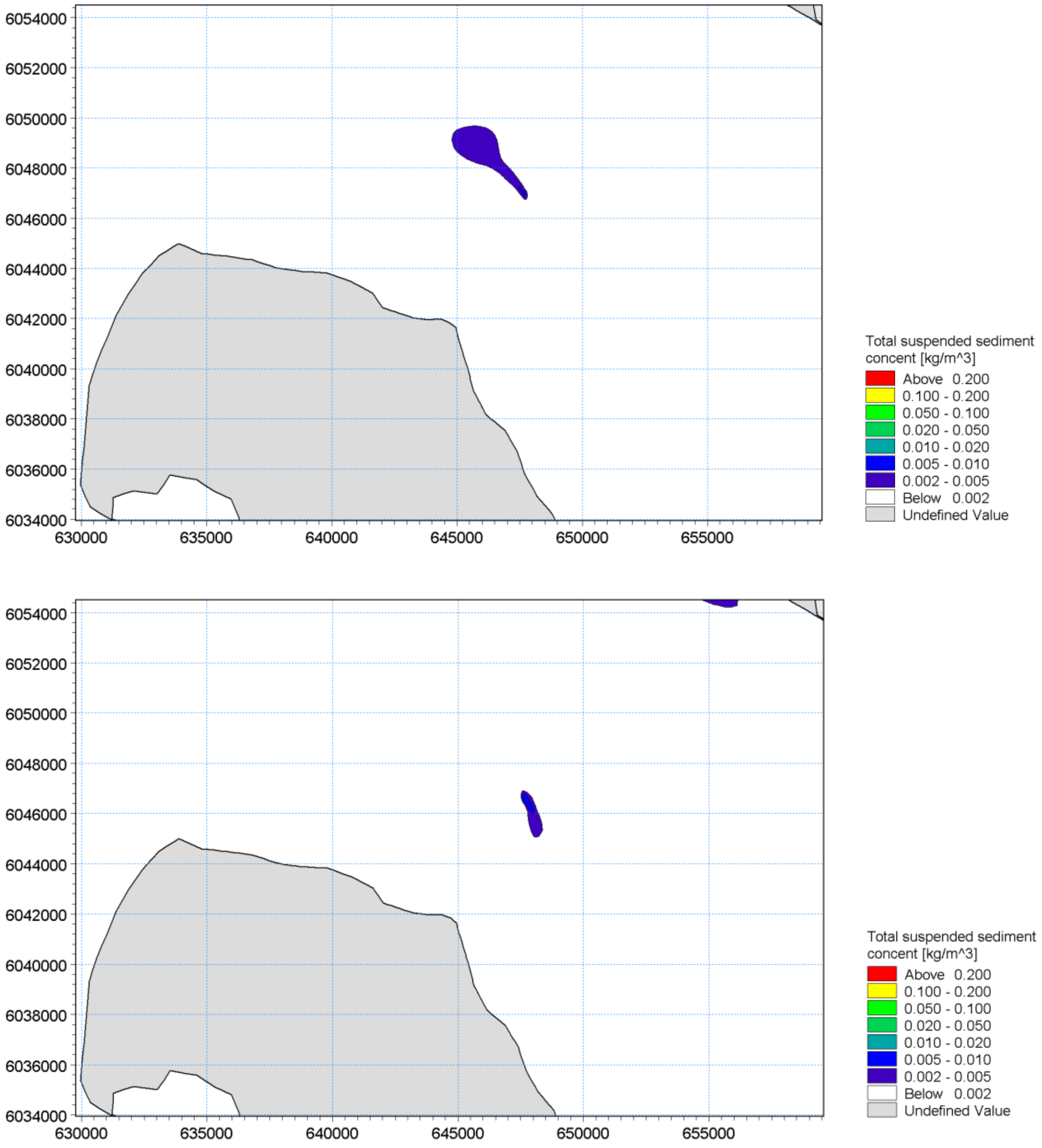


Figure 5.38 Typical suspended sediment plumes from May 2015at the German nearshore area (top east-going currents, bottom west-going currents)

The composition of the sea bed depends on the level of wave action. In the bathing areas the sea bed consists of sand because the beaches are subject to waves. Suspended fine sediments may settle temporarily in these areas. Any deposited fine sediment will be rapidly removed during wave events and thus the sea bed composition will not be altered. However, over short periods between the events small amounts of fine sediments may be observed on the sea bed.

On the Danish side the dredging for the tunnel trench takes place at least 3 km offshore during summertime. During 2015 reclamation occurs during the entire year. This will occur directly in the nearshore zone. The timing of the dredging operation can be found in Figure 5.5. The spill from the reclamation will travel along the coastline and hence resuspension and excess concentrations are seen along the coastline during wave events. In Figure 5.24 the exceedance time of 2 mg/l at the surface is presented. This shows that no significant extra exceedance is present near the beaches on the western side of the alignment. On the eastern side exceedance times are seen to be up to 30 %. The extra sediment in the water on the Danish side is mainly due to resuspension of sediment. Direct effects of plumes from offshore activities hitting the coastline are not detected during the bathing season. This is also illustrated in Figure 5.39 which shows snapshots of typical plumes in May 2015.

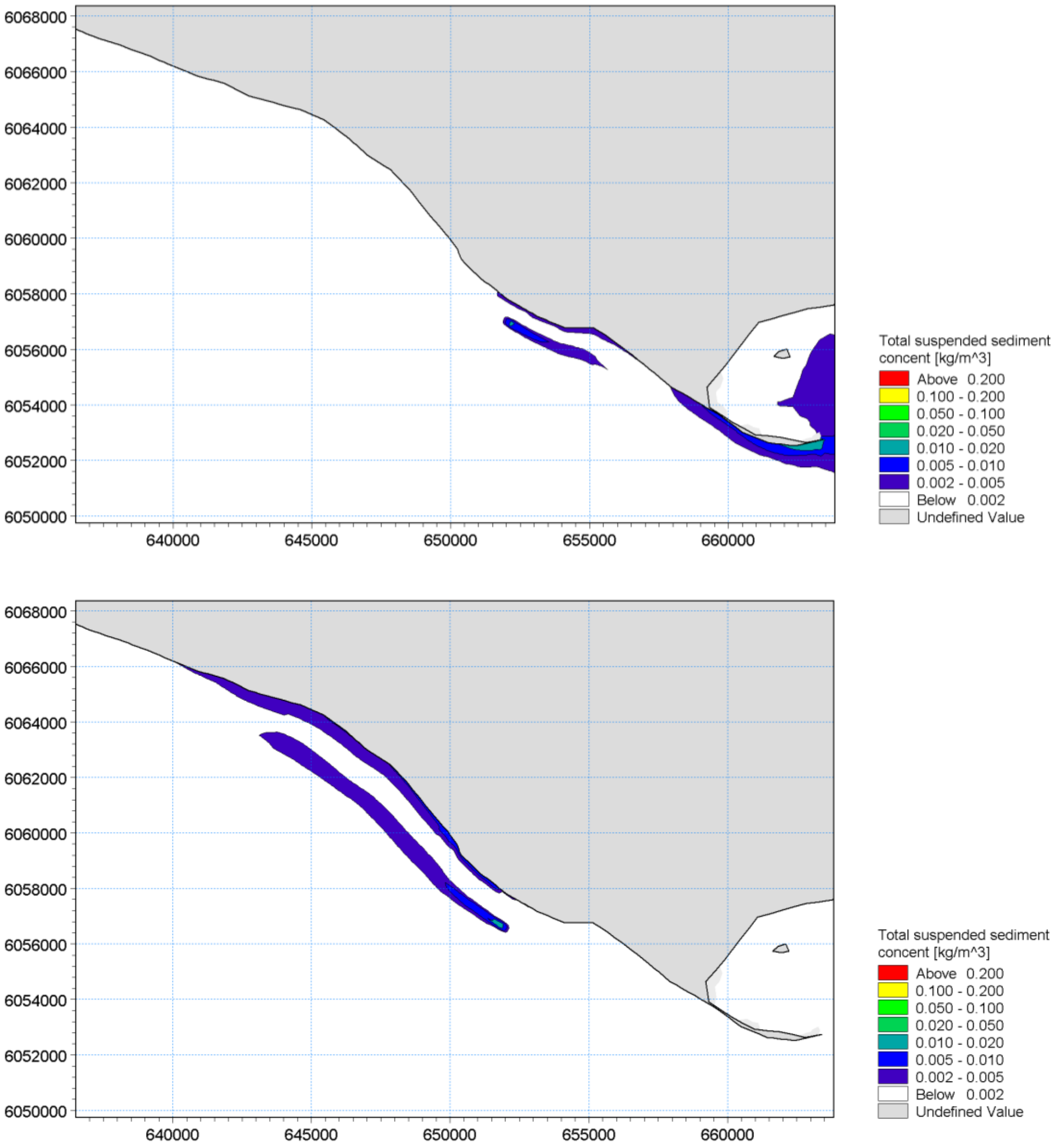


Figure 5.39 *Typical suspended sediment plumes from May 2015 at the Danish coast (top east-going currents, bottom west-going currents)*

The indirect effect illustrated in Figure 5.31 at the Danish coast will appear at times when the wind is onshore and waves are present. This is the same conditions that will cause natural resuspension. The spill from the reclamation work will settle locally and take part in the resuspension events. Time series of winds and natural concentration levels as measured in NS01-NS03 and NS06-08 as well as modelled excess concentrations at the same locations for year 2015 are shown in Figure 5.40 - Figure 5.45.

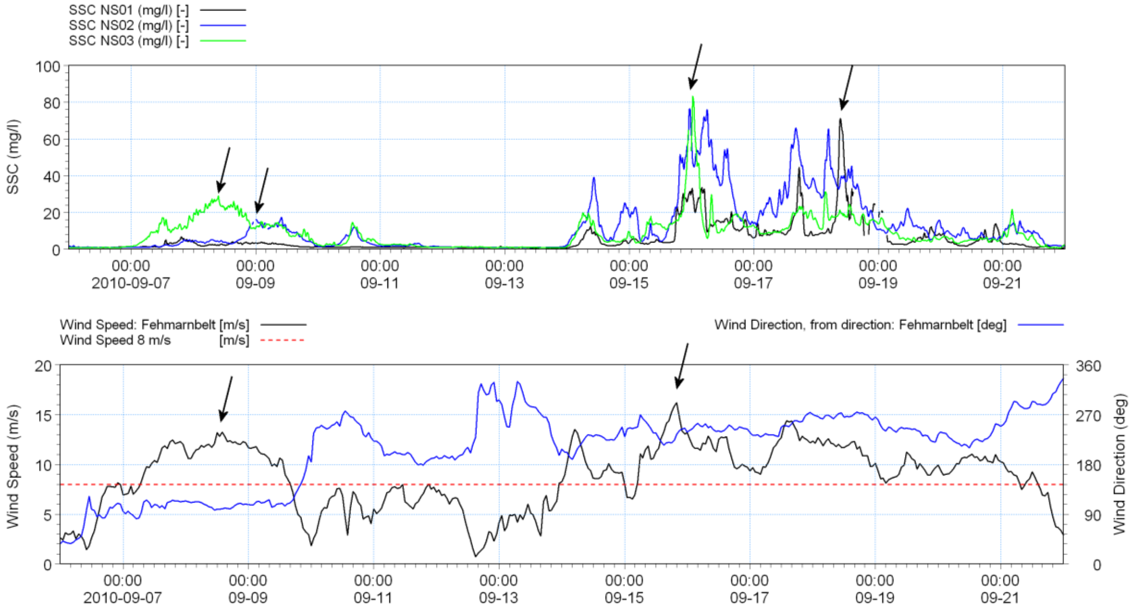


Figure 5.40 Time series of natural suspended sediments as measured at NS01 – NS03 and wind speed and direction. Upper panel: SSC at NS01, NS02, NS03. Lower panel: wind speed and direction. September 2010

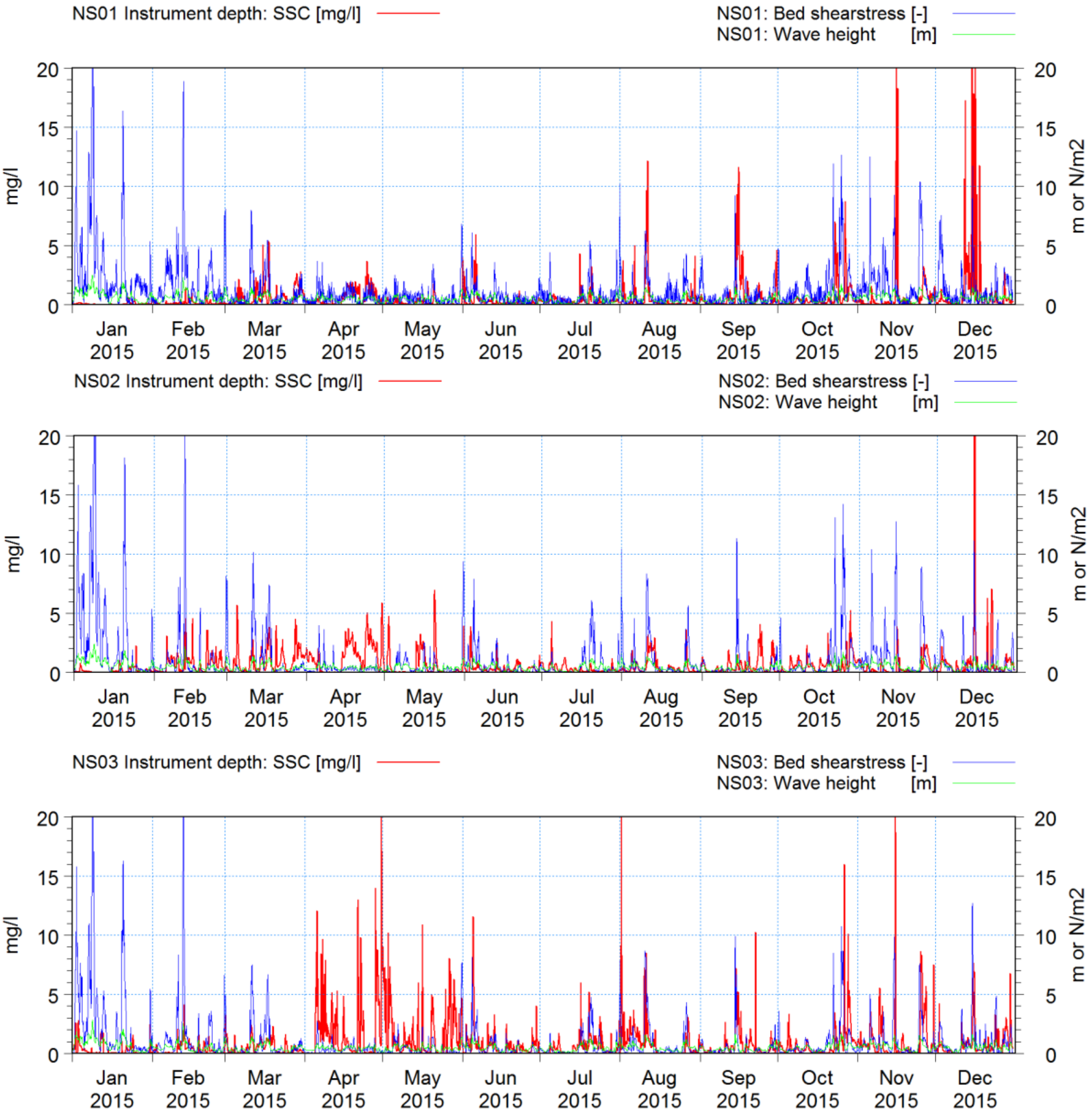


Figure 5.41 *Time series of modelled suspended excess sediment concentrations, shear stresses and waves at NS01- NS03 during 2015 for tunnel solution*

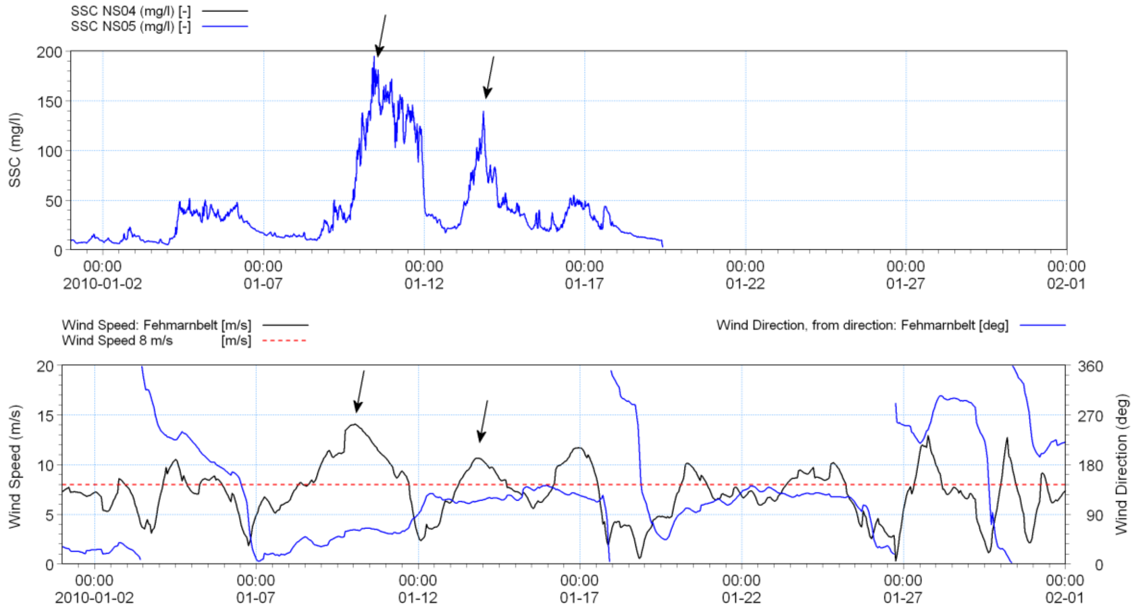


Figure 5.42 Time series of measured suspended sediment concentrations and winds at NS04-NS05. Upper panel: SSC at NS04, NS05. Lower panel: wind speed and direction. January 2010

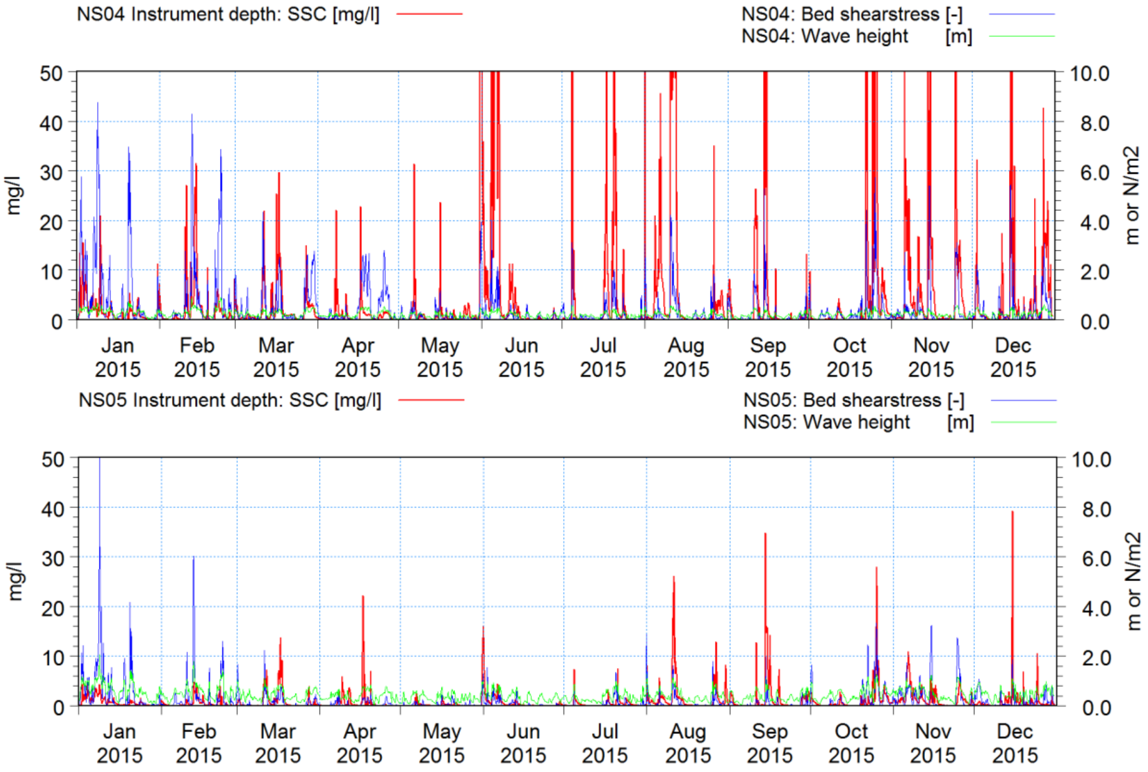


Figure 5.43 Time series of suspended excess concentrations and shear stresses and waves at NS04-NS05. Spilled sediments modelling 2015 for tunnel solution

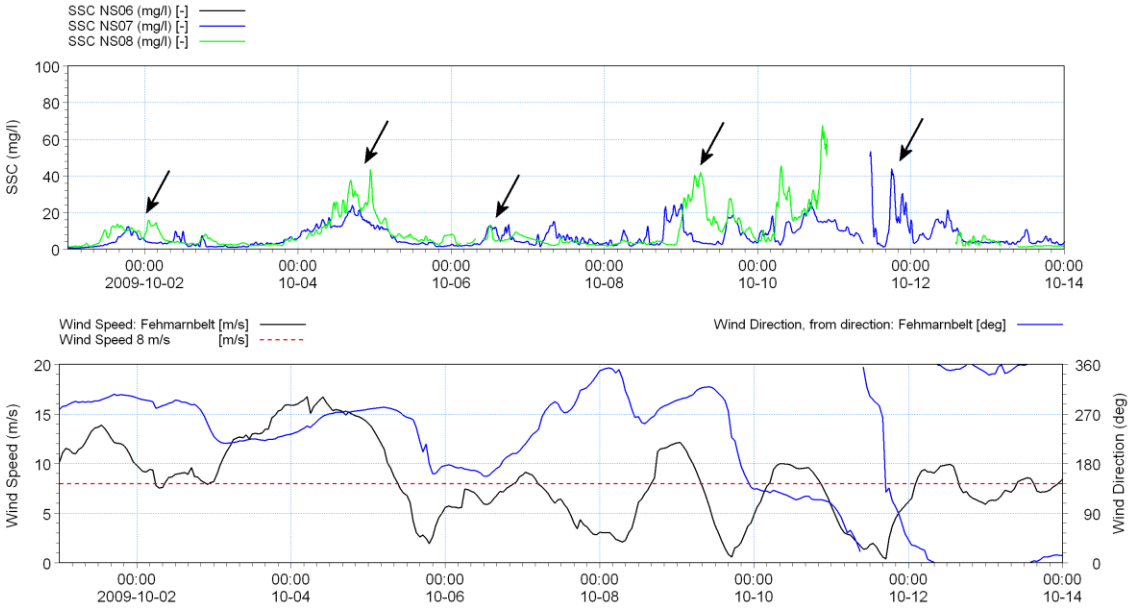


Figure 5.44 Time series of measured natural suspended excess concentrations s at NS07 – NS09 and wind speed and direction. Upper panel: SSC at NS06, NS07, NS08. Lower panel: wind speed and direction. October 2009

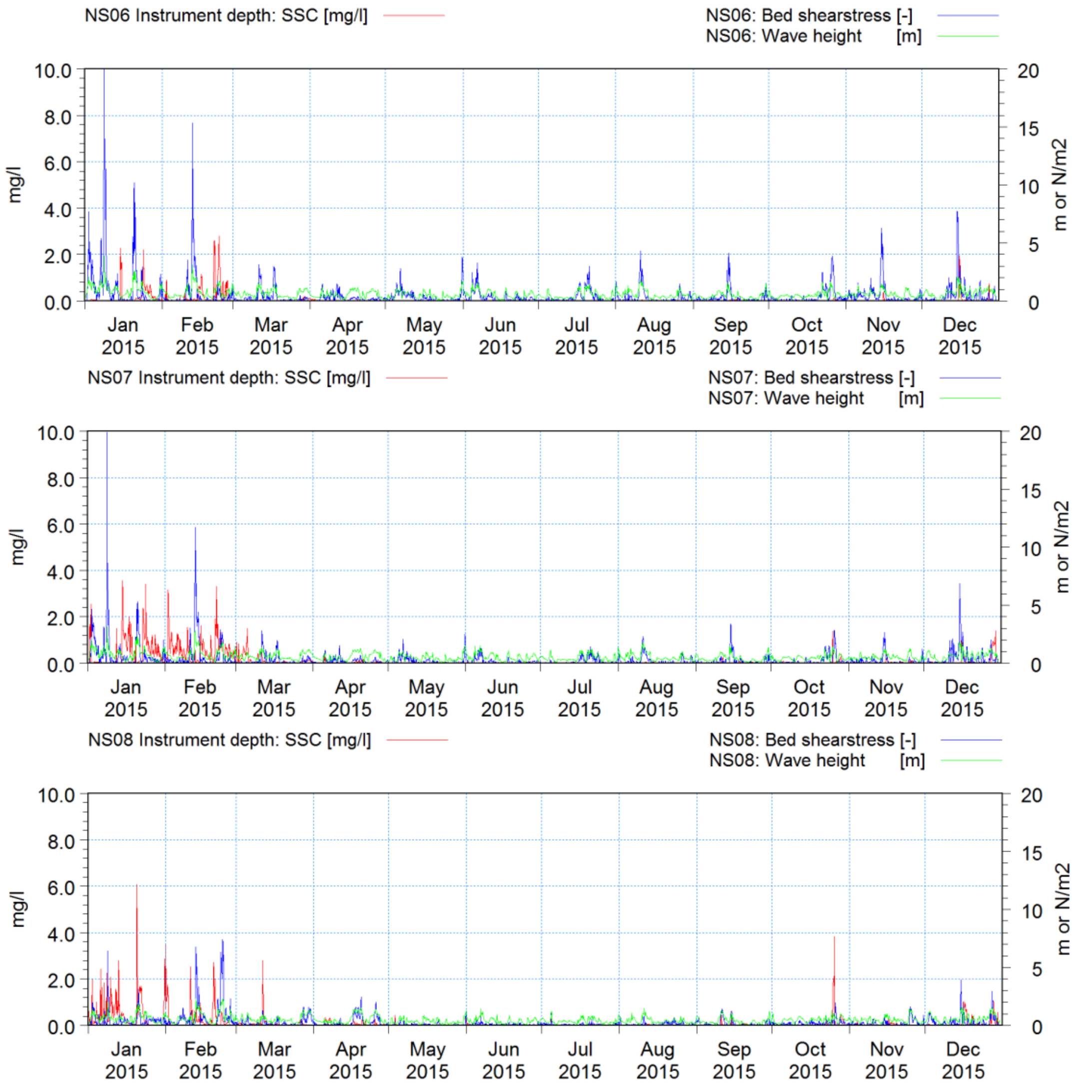


Figure 5.45 Time series of suspended excess concentrations, shear stresses and waves at NS06 – NS08. Spilled sediments modelling 2015 for tunnel solution

These figures illustrate that high excess concentrations often occur simultaneously with natural high concentrations in the nearshore zone. Only when the dredger is dredging in the nearshore zone (spring 2015) and there is a direct impact of the plume from the dredging deviations from this pattern are seen.

According to (FEHY 2013c) the natural median concentration levels are above the visibility limit of 2 mg/l. In windy periods many of the stations have background concentrations well above 100 mg/l. Therefore when combining the effect of natural sediment and added sediment due to dredging the effect on the appearance will be small. In calm weather there will be no sediment in the water and thus no impact can be detected. See Figure 5.12.

The same argument can be applied on the German side and though background concentrations are slightly lower here concentrations still reach over 100 mg/l near the coast during onshore winds. It will thus be hard to detect an extra amount of sediment in the water that is already unclear.

In conclusion, there will be no impact during calm weather and during rough weather there may be some extra sediment available but due to the already high concentrations of sediment in the water it will be undetectable for the human eye.

5.2.2 Deposited sediments

Deposition maps for tunnel solution

In Figure 5.46 to Figure 5.47 the deposition patterns at the end of the construction period are given. The plots illustrate where the spilled sediment will deposit eventually. The deposition is presented in mm with the assumption that the fine sediment deposits at the sea bed with a dry density of 300 kg/m^3 corresponding to weakly consolidated fine sediments. The sand deposits with a dry density of 1590 kg/m^3. All deposition maps can be found in Appendix L.

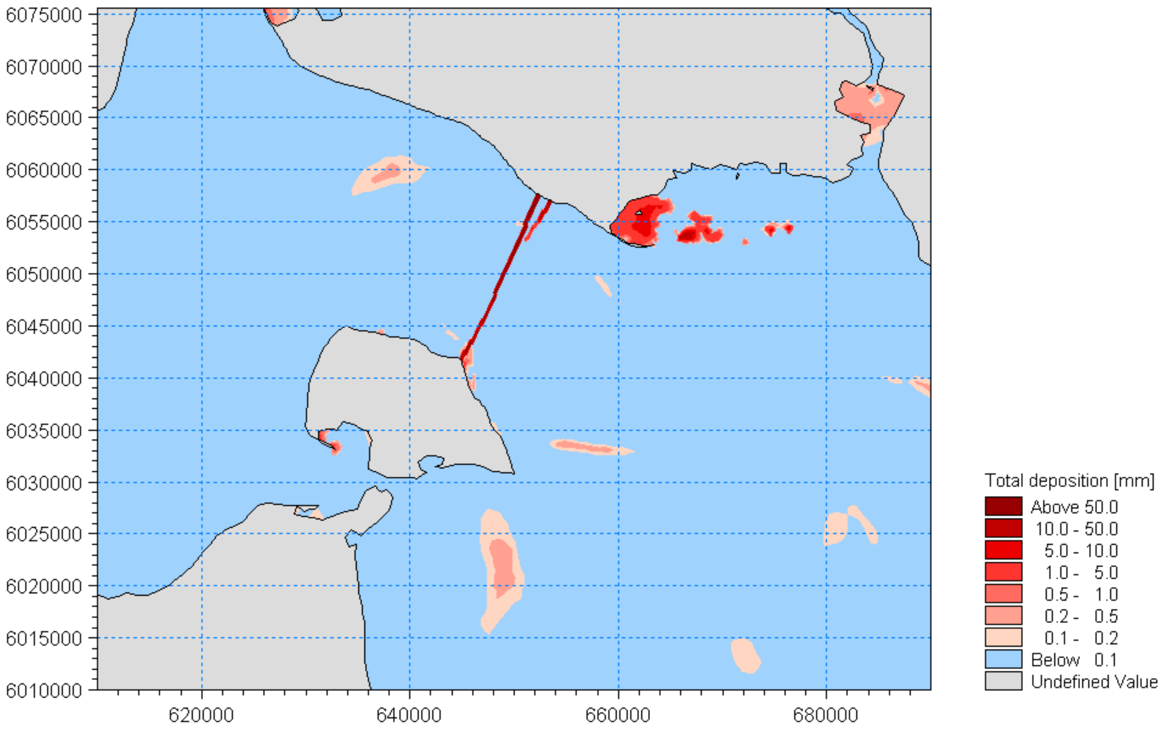


Figure 5.46 Deposition pattern at the end of 2019. E-ME Tunnel solution

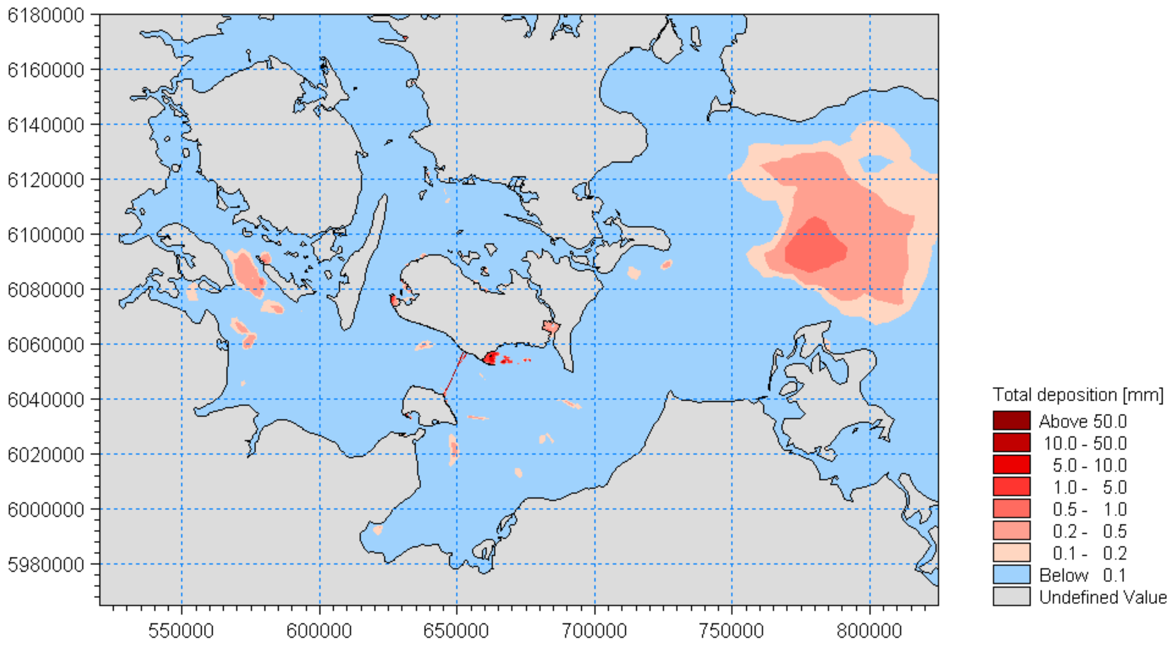


Figure 5.47 Deposition pattern at the end of 2019. E-ME Tunnel solution. Full modelling area

The results show little or no sedimentation in the majority of the offshore area in the Fehmarnbelt away from the alignment. At the alignment sedimentation is seen to be about 5 cm. This sedimentation originates from the coarser part of the spill (the sand fractions) that is less mobile. In reality the spilled sand fractions will deposit within 200-600 m from the dredging operation. This is illustrated in Figure 5.48 in which the sand is equally distributed within this distance from the alignment.

Figure 5.48 Illustration of sand deposition along the tunnel alignment

Deposition is also seen in the sheltered part of the Rødsand Lagoon by up to 1 cm.

The results show that final resting places are the Arkona Basin, the edges of Bay of Mecklenburg and in the deeper waters in the Southern Lillebælt between Als and Ærø. It is emphasised that these deposits are very thin and less than 1 mm. Natural deposition in the Arkona Basin is approximately 10 mm over the construction period and thus the effect of the tunnel represents an excess deposition of 10%, see (Christiansen et. al 2002).

Maximum temporary depositions for the tunnel solutions

In the following the maximum temporal deposition patterns are presented. These plots represent the maximum deposition height that occurs at a given point and time over the entire simulation period. The plots serve as an illustration of the mobility of the sediment. All the results can be found in Appendix L.

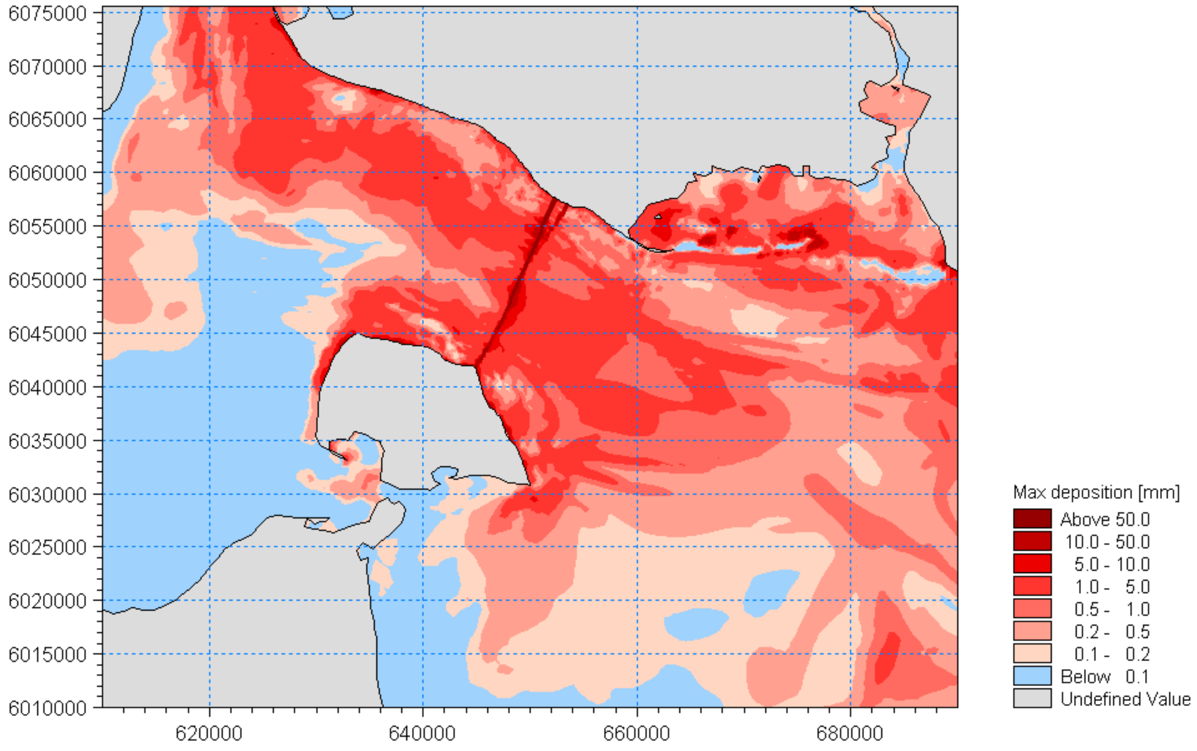


Figure 5.49 Maximum temporary deposition heights for the E-ME Tunnel solution

The results show that large areas are subject to temporal sedimentations of 1 mm along the coasts of Lolland and Fehmarn as well as in the Rødsand Lagoon and along the east and west side of Fehmarn. However, the depositions are temporary and in combination with the deposition plots for the entire construction period it illustrates that the sediment is deposited and resuspended many times before it reaches the final resting places.

5.3 Transboundary impacts

Some small deposition is recorded in the deposition area in the Arkona Basin. This is partially a Swedish area. However, natural deposition in this area is 2.2 mm/year or approximately 1 cm over the construction period, see (Christiansen et. Al. 2002) and thus the deposition from the dredging activities is insignificant. Some sediment also travel further into the Baltic Sea. However, the sediment consists of the finest fractions and similar to the de-position patterns in the Arkona Basin it will be spread over a large area and form an extremely thin layer. For practical purposes this will not be measurable. In the water column this amount will come at so low concentrations that it will be practically impossible to measure.

5.4 Mitigation and compensation measures

5.4.1 General

Mitigation measures must aim at limiting the excess concentrations due to spillage. Four kinds of mitigation measures are available:

- Limiting the actual spill at the dredging operation
- Limiting the spreading from the dredging area
- Limiting spreading of material to certain sensitive areas
- "Intelligent dredging" using knowledge of hydrodynamics to dredge in periods with minimum effects on the environment

5.4.2 Limiting the actual spill at the dredging operation

Limiting the actual spill at the dredging operation can be done by choosing methods that imply a minimum spill. Generally, this means avoiding dredging methods using overflow. For instance cutter suctions or hopper suction dredgers often use this method. Similarly, relocating sediment should be done using fall pipes.

This mitigation method has already been implemented to a high degree in the dredging plan.

5.4.3 Limiting the amount of spill which leaves the working area

Limiting the spill which leaves the dredging or deposition area requires that the work area can be sealed off either by silt curtains, bubble curtains or by a dike. The latter is applied in the construction of the work harbours and for the reclamations for both the tunnel and the bridge. Silt curtains and bubble curtains can only be applied in relatively calm hydrodynamic conditions and thus this is probably not an option in the strong currents of the Fehmarnbelt.

Potentially the spill from the land reclamation at Rødbyhavn could be reduced by a mechanical unloading of the barges. At present the unload is assumed to take place via split barges inside a dike with navigation openings.

5.4.4 Limiting the access of spilled materials to sensitive areas

Physically retaining the spilled material from entering sensitive areas requires that the access to the area is limited. The entrance to Rødsand Lagoon is not well suited for the use of either silt curtains or bubble curtains. Technically it would be possible to construct a temporal sand dike extending from the western barrier island. However, the effects of temporally reduced exchange of water should be quantified.

5.4.5 Intelligent dredging using knowledge of hydrodynamic conditions to dredge in periods with minimum impacts

The flow of sediment into sensitive areas is governed by the general flow patterns. If the flow patterns can be predicted and mechanisms for inflow of sediment are known it is possible to design a dredging scheme that, to some extent, does not impact the sensitive areas.

Analysis of the results from the present scenario shows that for this combination of the timing of spill and spill locations dredging further away than approx. 3 km from the Danish coast gives little inflow to the lagoon from sediment plumes. However, it appears that inflow happens both due to direct plumes and due to sediment which has deposited in front of the lagoon and is re-suspended when east-going currents change to west-going currents and the water level rises. In this situation the amount of inflowing sediment depends on the history: how much sediment has temporarily deposited in front of the lagoon and is available for entering the lagoon. This information may be used to manage dredging to minimise the impact on the Rødsand Lagoon.

In the present dredging plans no dredging takes place closer to the coastline during the summertime to avoid unclear water during the bathing season.

With regards to avoiding sedimentation in the sand wave areas it is an advantage to dredge in periods where the currents in the belt are frequently high. During these periods sediment will not settle very often and thus the sand waves will experience a minimum of sedimentation. The high current events usually occur during October to March.

With regard to marine life the growth season for flora is spring and summer. Eelgrass and seaweed is generally located in shallow water and therefore the effect in these areas may be minimised by limiting spill here in the growth season.

The sensitive periods for fish are generally during winter.

The selection of optimum dredging periods for fish, fauna and marine life should be based on the findings in the impact reports from FEMA, FEBI and FEbec.

5.5 Decommissioning

Decommissioning and removal of the Fehmarnbelt Fixed Link tunnel structures and installations are envisaged to comprise the following actions, see Femern A/S (2011):

- The tunnel tubes shall be stripped for equipment and cabling etc., flooded, and the entrances sealed to prevent unauthorised access
- Decommissioning and removal / demolition of tunnel entrance structures, portal buildings and road and railway structures
- The reclaimed areas are designed to maintain or even improve the conditions for flora and fauna and therefore it is unlikely that these areas after 120 years of "natural environmental development" will be required to be modified back into their original conditions. For this a comparison can be made to the existing sea dikes on both the Lolland and Fehmarn side, which were established in the 1870s

None of these actions are expected to pose any significant spillage into the marine environment and thus no suspended sediment effects are expected.

6 ASSESSMENT OF IMPACTS ON MAIN BRIDGE ALTERNATIVE

The results from the simulations of spreading and deposition of spilled sediments are presented in this section for the year with the highest spill. For the bridge alternative it is 2014. The results for the remaining years can be found in Appendix G – Appendix M.

The following analysis and illustrations of the results are presented for each:

Maps of Suspended Sediment Concentration at the surface for the period from 1 May to 1 September.

- Exceedance time of 2 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)
- Exceedance time of 5 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)
- Exceedance time of 10 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)
- Exceedance time of 20 mg/l, 1/5-1/9 for the surface (top layer in the numerical model results)

Maps of Suspended Sediment Concentration at the bottom for the period from 1 March to 1 November.

- Exceedance time of 10 mg/l, 1/3-1/11 for just above the sea bed (bottom layer in the numerical model results)
- Exceedance time of 20 mg/l, 1/3-1/11 for just above the sea bed (bottom layer in the numerical model results)
- Exceedance time of 50 mg/l, 1/3-1/11 for just above the sea bed (bottom layer in the numerical model results)

If the exceedance time is less than 10% for 2, 5 or 10 mg/l in the entire area the illustration for 5, 10 or 20 mg/l, respectively is not shown. As seen in Appendix G – Appendix M this is especially the case for the later construction years when the dredging activities are less intense.

Maps of sediment deposition for each dredging scenario:

- Deposition at the end of the construction period
- Maximum deposition during the construction period
- Deposition at the end of selected years

The exceedance levels are defined as the limit for visibility (2 mg/l) as well as threshold values for assessment of marine biology (5, 10, 20 and 50 mg/l).

The results are shown both for a local area in the Fehmarnbelt and for a larger area, when relevant.

Furthermore, time series of the modelled concentrations from the spill at mid-water are compared with measured median concentrations from the baseline study, see

(FEHY 2013c). Mid water is chosen because baseline measurements were undertaken approximately at this position in the water column. The locations of the turbidity stations are shown in Figure 5.1.

6.1 Magnitude of pressure

Earth balance bridge solution

The overall budget for dredged material and amounts of spill from each major element in the earth handling are presented in Table 6.1.

Table 6.1 Dredging activities for the bridge solution

Activity	Spill [%]	Amount [mill m^3]	Amount spilled [mill m^3]
Dredging for piers	12	0.54	0.070
Backfilling at piers (sand)	1	0.18	0.002
Dredging of access channels	5	0.35	0.020
Backfilling of access channels	5	0.35	0.020
Scour protection etc.	1	0.05	0.001
Work harbour at Rødby	1	1.19	0.010
Dredging for pylons	12	0.31	0.037
Total amount handled/spilled		**2.97**	**0.160**

The spill scenario is established based on the following assumptions:

- Dredging is performed by a cutter suction dredger with a capacity of 400 m^3/h
- Backfilling around the piers takes place two weeks after completion of dredging for the individual pier. The backfilling follows the description presented in the construction plan and is a mixture of sand from Kriegers Flak, local clay till and rocks for scour protection
- Access channels for the innermost piers are established in parallel with the work harbour. Material which is dredged for the access channels and work harbour is deposited on land and re-used for backfilling of the access channels
- Backfilling will be done using a fall pipe in order to minimise spill. The timing will follow the construction plan

The full construction plan is presented in Appendix B and a simple overview of the time schedule is given in Table 6.3.

The bridge alignment (BEE) of the individual piers is illustrated in Figure 6.1.

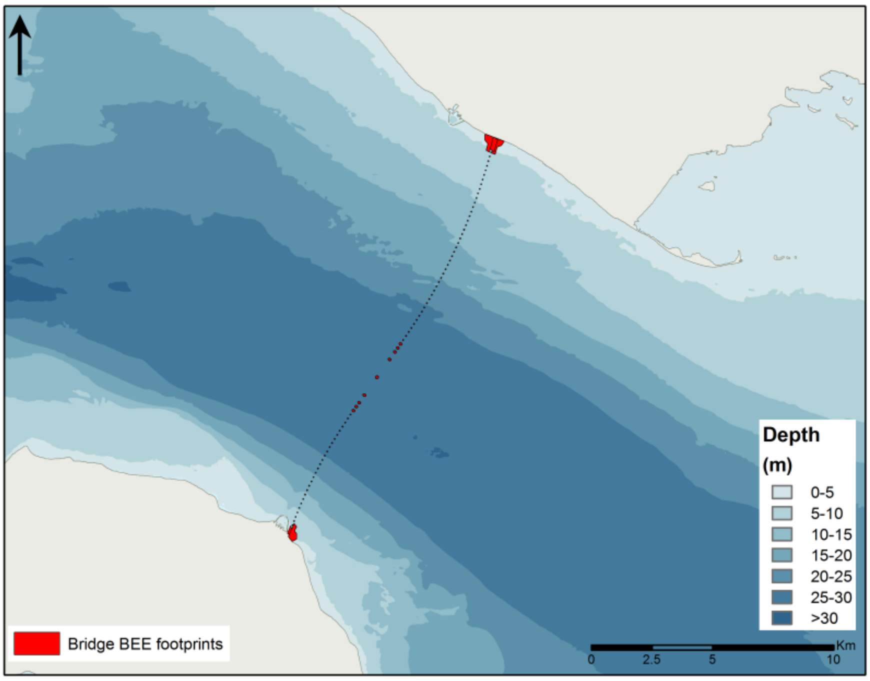


Figure 6.1 Locations of bridge piers (alignment BEE, April 2010)

The bridge consists of 83 piers and pylons in the water. The shapes, location and size of the individual piers are taken into account when generating the spill files.

Table 6.2 gives an overview of the applied equipment and the corresponding spill profiles.

Table 6.2 Overview of equipment and spill characteristics

Activity	Equipment	Distribution in the water column	Spill percentage
Dredging for piers	Cutter suction	Spill at the drag head near the bottom and at the surface due to overflow	Bottom: 2% Overflow: 10%
Backfilling around piers	Barge with fall pipe	Spill 2 m above sea bed	1%
Placement of scour protection	Barge with fall pipe	Spill 2 m above sea bed	1%
Dredging for access channels	Backhoe	Equally distributed over the water column with additional spill at the barge	Water column: 2% Barge: 3%
Backfilling of access channels	Backhoe	Equally distributed over the water column with additional spill at the barge	Water column: 2% Barge: 3%
Construction of work harbour	Various	Equally distributed over the water column	1%
Disposal	Barge with fall pipe	Spill 2 m above the sea bed	3%

Table 6.3 Overview of the time schedule of earth handling for the bridge connection

Bridge connection	Year	2014												2015												2016											
	Months	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Activity	Amount spilled [mill m^3]																																				
Dredging and backfilling for piers, L49 - L38	0.009									■	■																										
Dredging an backfilling for piers, L37 - L26	0.010																		■	■																	
Dredging and backfilling for piers, L25 - L14	0.012																									■	■										
Dredging and backfilling for piers, L13 - L01	0.013																																■	■			
Dredging and backfilling for piers, F31 - F28	0.004										■																										
Dredging and backfilling for piers, F27 - F25	0.002						■																														
Dredging and backfilling for piers, F24 - F22	0.002											■																									
Dredging and backfilling for piers, F21 - F19	0.003																	■																			
Dredging and backfilling for piers, F18 - F01	0.018						■	■	■	■																											
Pylons	0.037						■	■	■	■	■	■																									
Dredging of access channels	0.020	■																																			
Backfilling of access channels	0.020																	■	■	■	■													■			
Scour protection etc.	0.001						■	■	■	■	■	■						■	■	■						■	■						■	■			
Work harbour, Rødby	0.010	■	■	■	■	■	■																														
Total spill	**0.160**																																				

Dredging operations
The amount of sediment spill depends on the soil types and the chosen equipment. At present there are plans for using backhoe dredgers, and cutter suction dredgers assisted by barges. Dredging for bridge piers will be conducted using a cutter suction dredger. For the hydraulic dredgers like the cutter suction dredger and the hopper suction dredger the spill will occur at the cutter head near the bottom and at the surface due to overflow. A conceptual drawing of a cutter suction dredger is given in Figure 6.2.

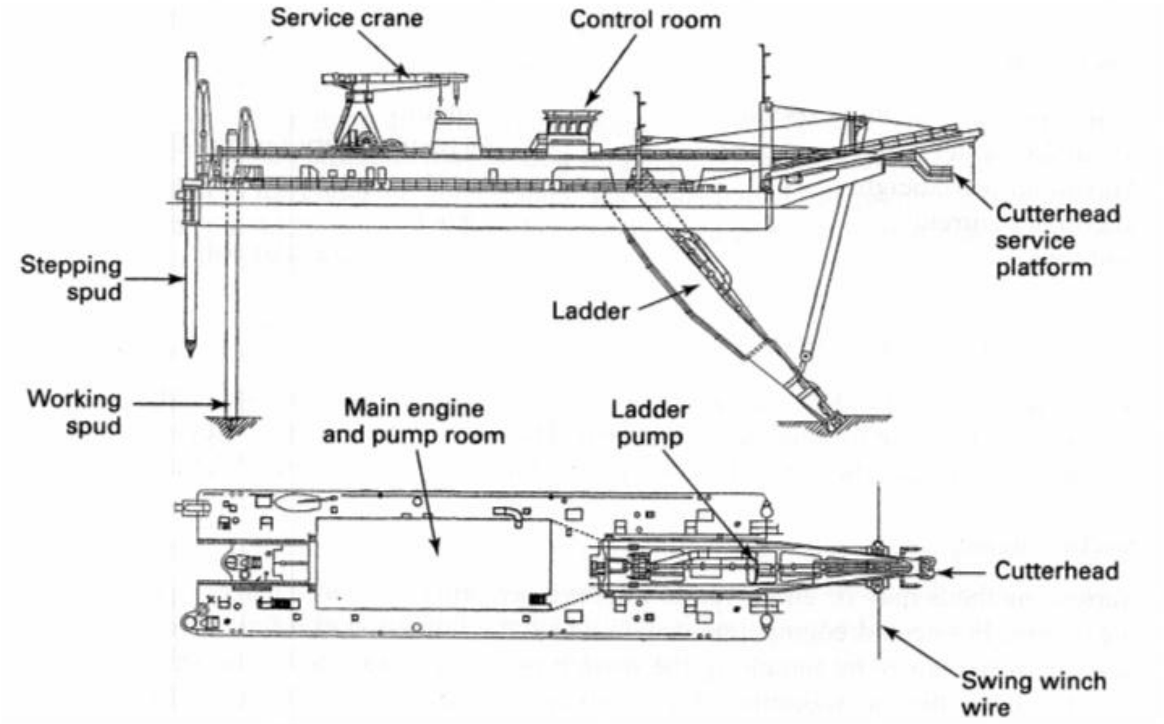


Figure 6.2 Conceptual drawing of a cutter suction dredger from (R.N. Bray, Bates, A. D., Land, J.M. 1997)

For the backhoe dredgers the spill will occur partly at the bottom due to the disturbance from the grab, partly in the water column due to water flowing over the free surfaces in the grab and partly at the surface due to water draining of the barge. For practical purposes the spill is considered uniformly distributed over the water column.

6.2 Effect of pressure

6.2.1 Suspended sediments

Time series of concentrations for the bridge solution
In the following the time series at the locations of the NS01, NS03, NS04, NS05, NS06, and NS08 nearshore stations are presented for the bridge solution. Results from all nearshore stations including average background concentrations can be found in Appendix J.

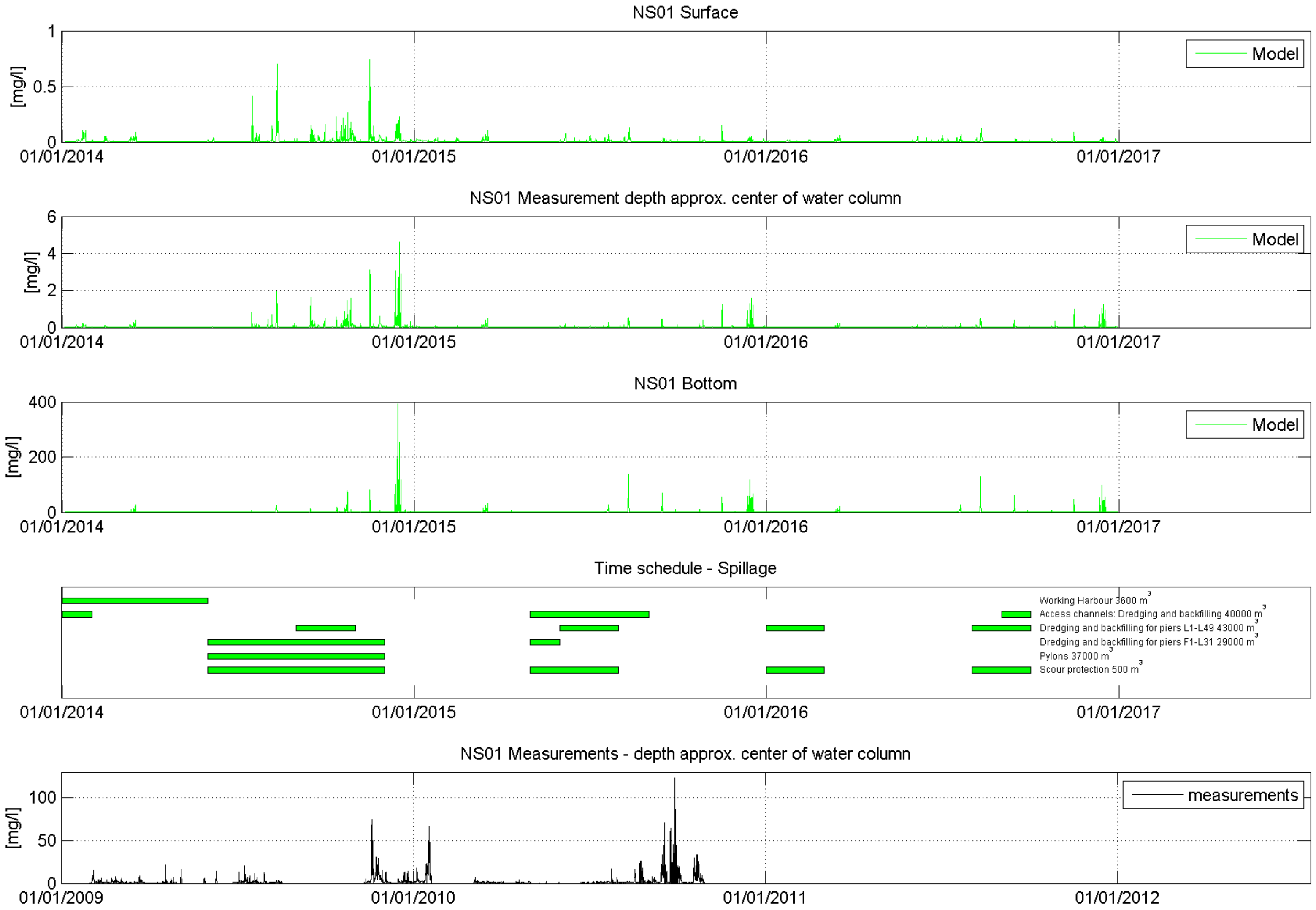


Figure 6.3 Time series of suspended sediment concentration at station NS01 for bridge solution. Note: different scales are applied

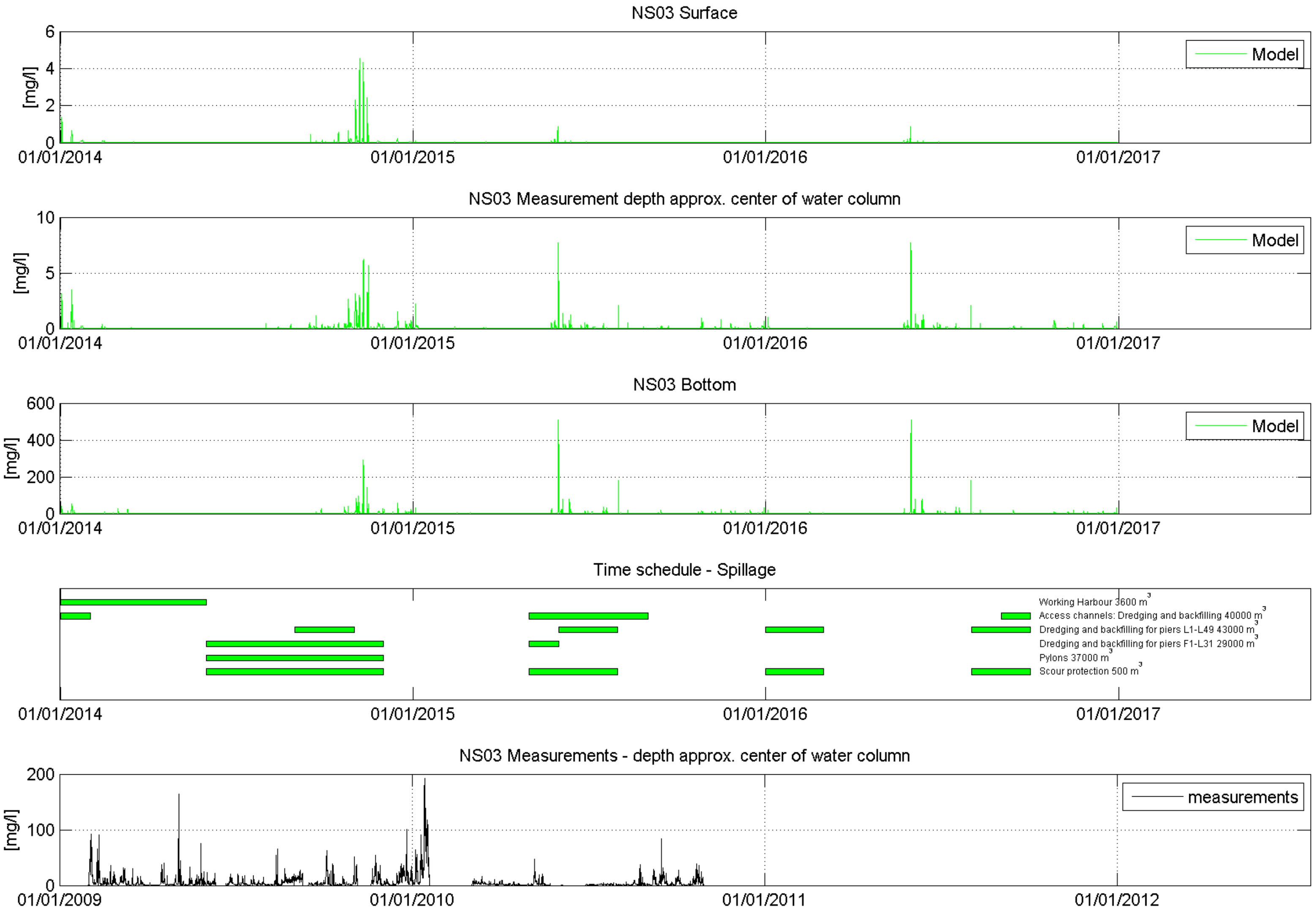


Figure 6.4 Time series of suspended sediment concentration at station NS03 for bridge solution. Note: different scales are applied

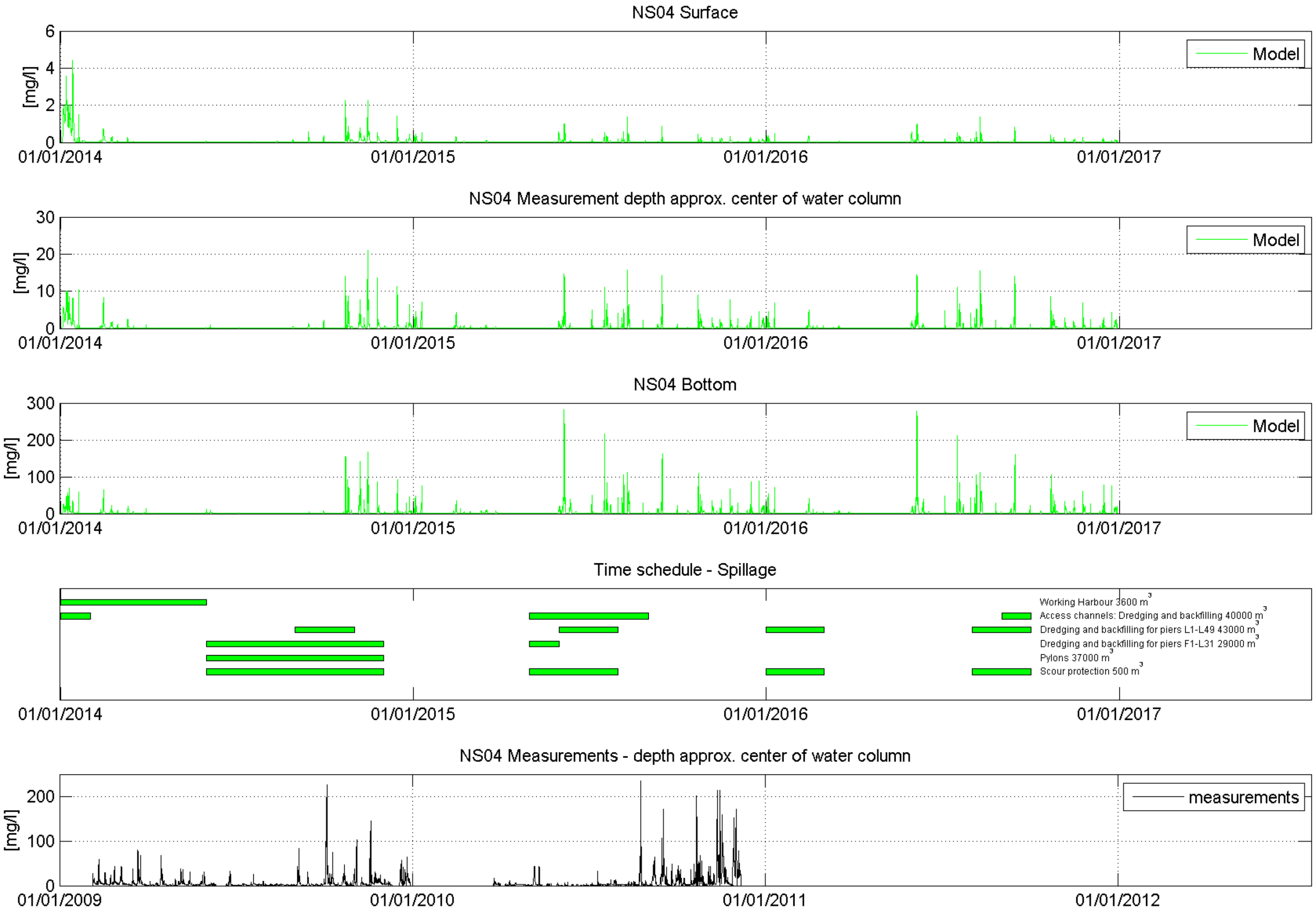


Figure 6.5 Time series of suspended sediment concentration at station NS04 for bridge solution. Note: different scales are applied

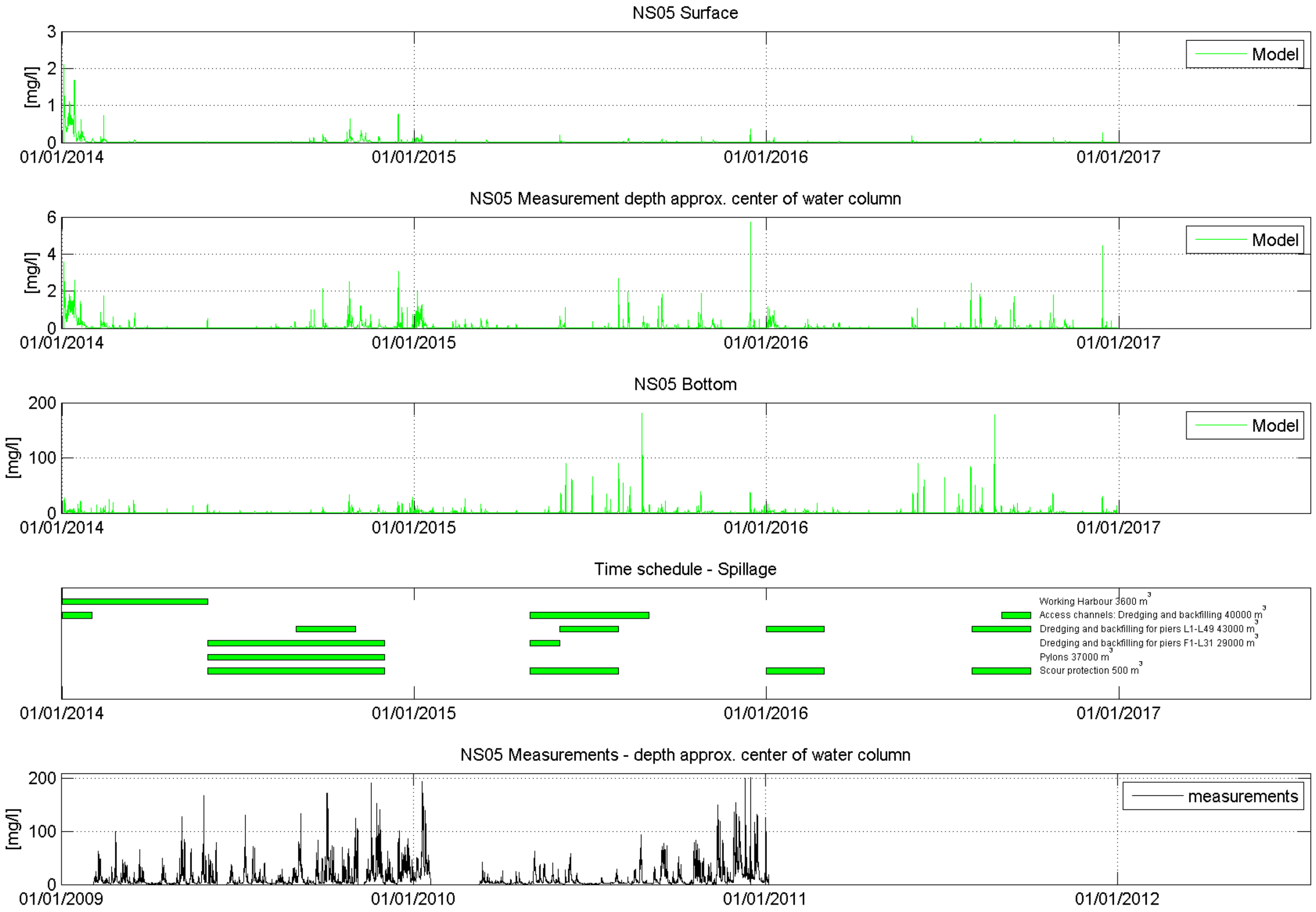


Figure 6.6 Time series of suspended sediment concentration at station NS05 for bridge solution. Note: different scales are applied

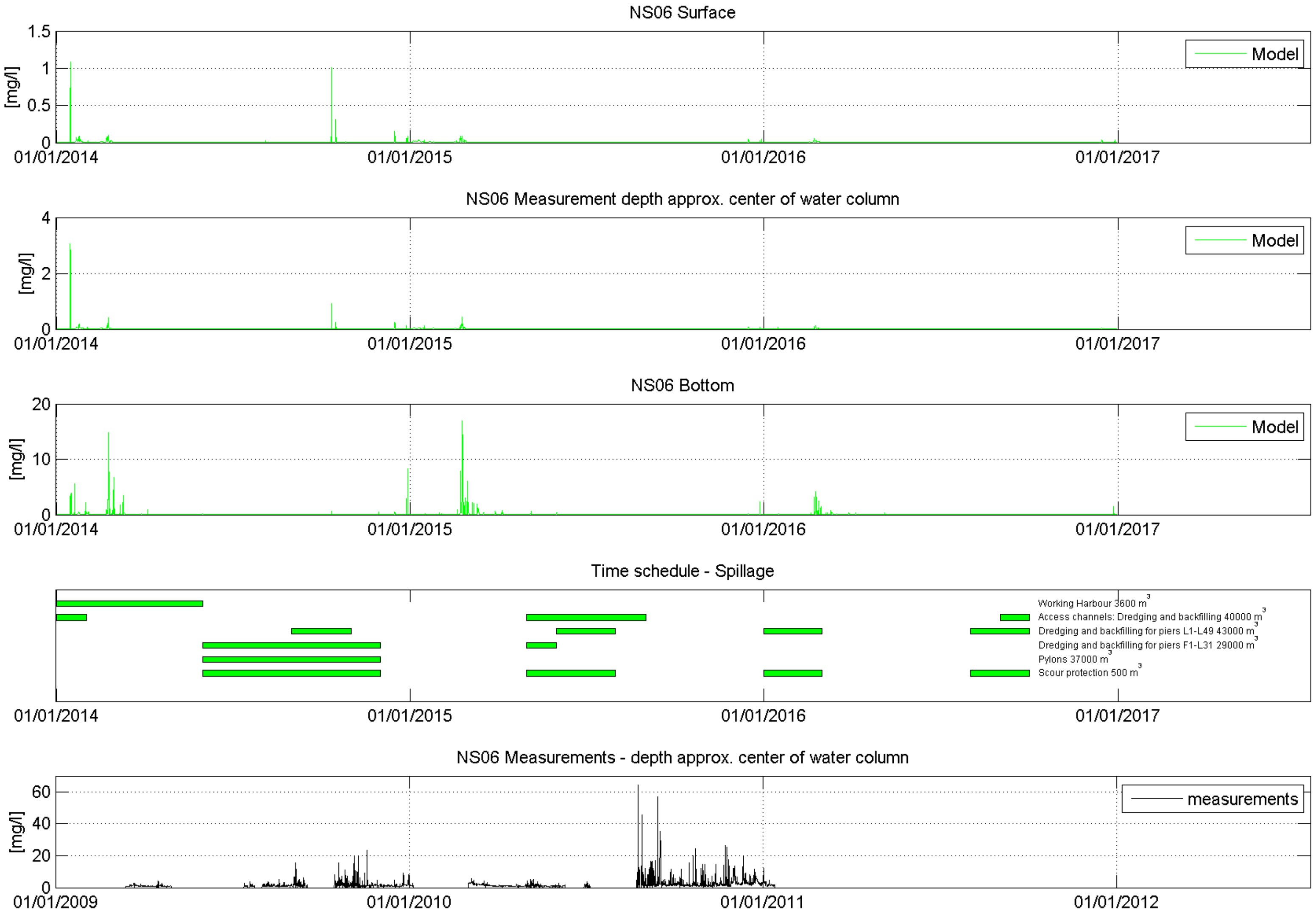


Figure 6.7 Time series of suspended sediment concentration at station NS06 for bridge solution. Note: different scales are applied

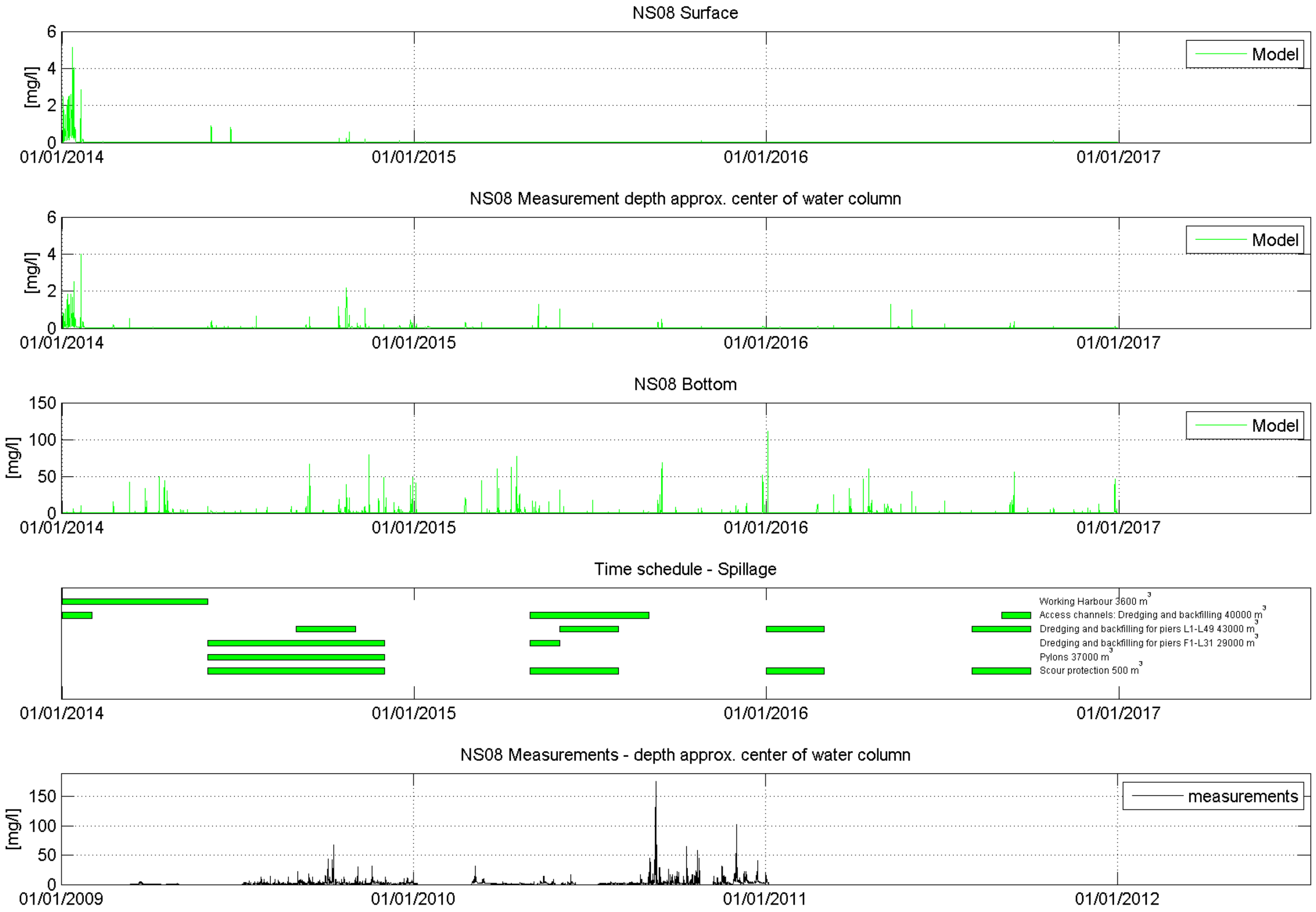


Figure 6.8 Time series of suspended sediment concentration at station NS08 for bridge solution. Note: different scales are applied

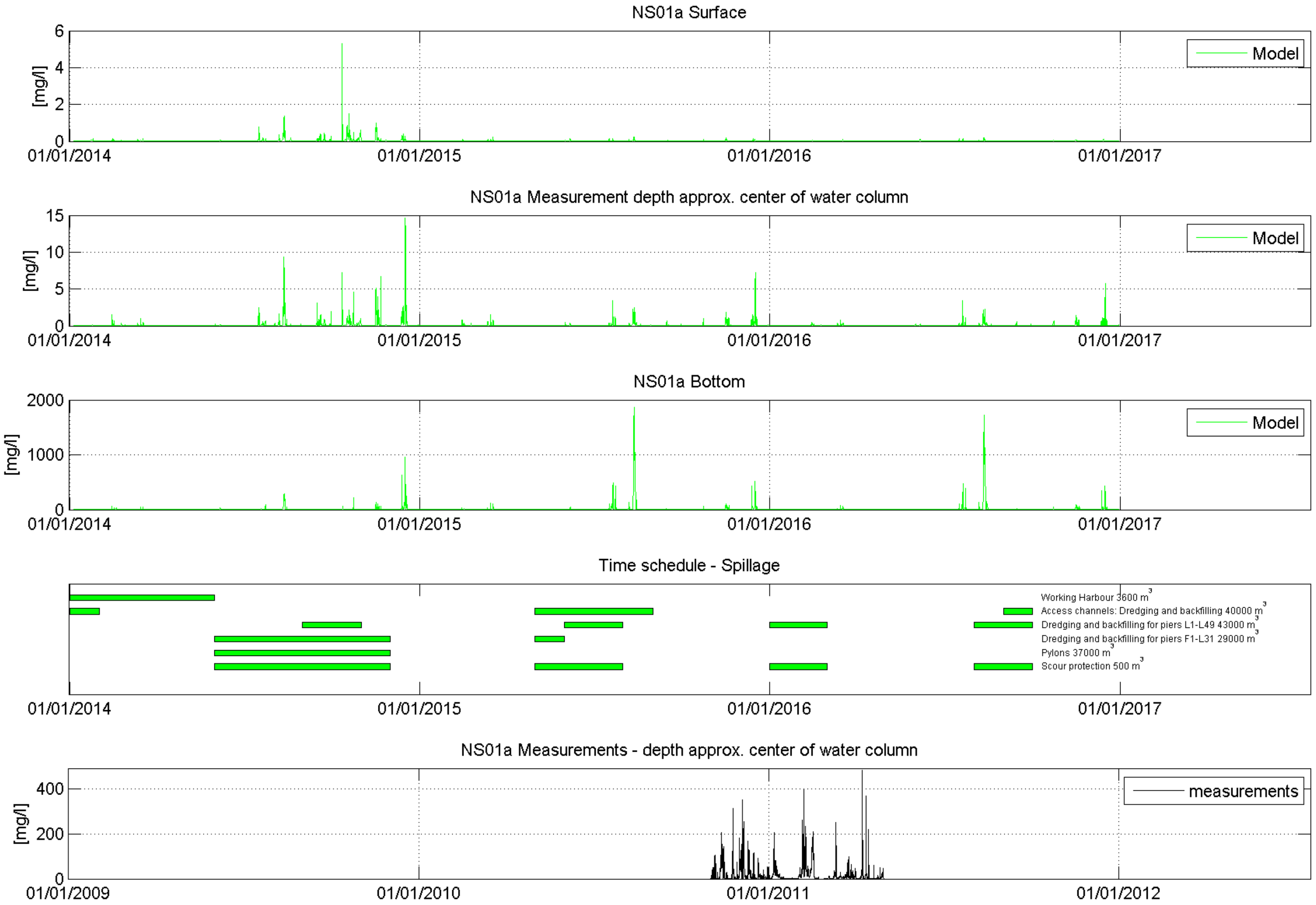


Figure 6.9 Time series of suspended sediment concentration at station NS01a for bridge solution. Note: different scales are applied

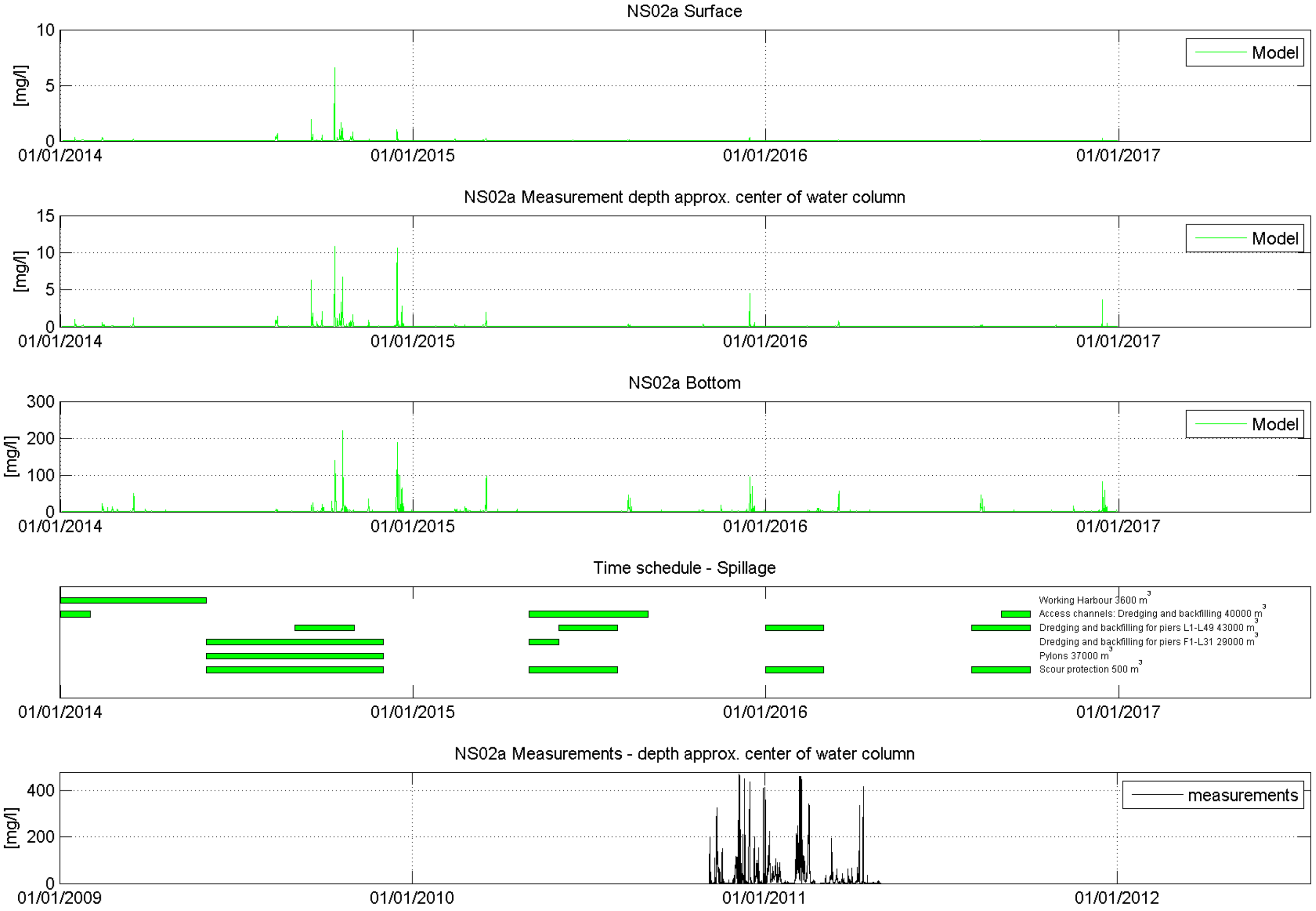


Figure 6.10 Time series of suspended sediment concentration at station NS02a for bridge solution. Note: different scales are applied

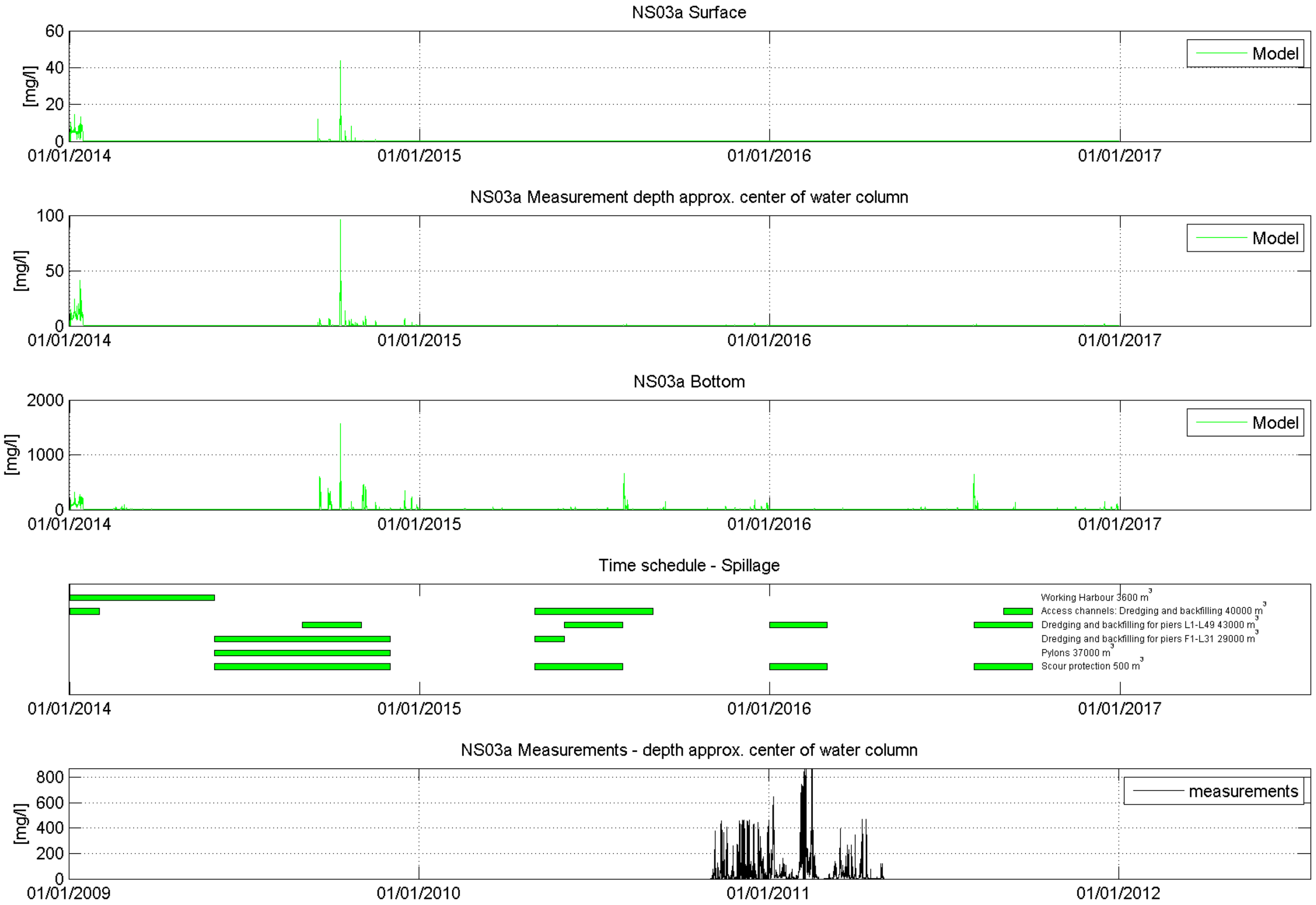


Figure 6.11 Time series of suspended sediment concentration at station NS03a for bridge solution. Note: different scales are applied

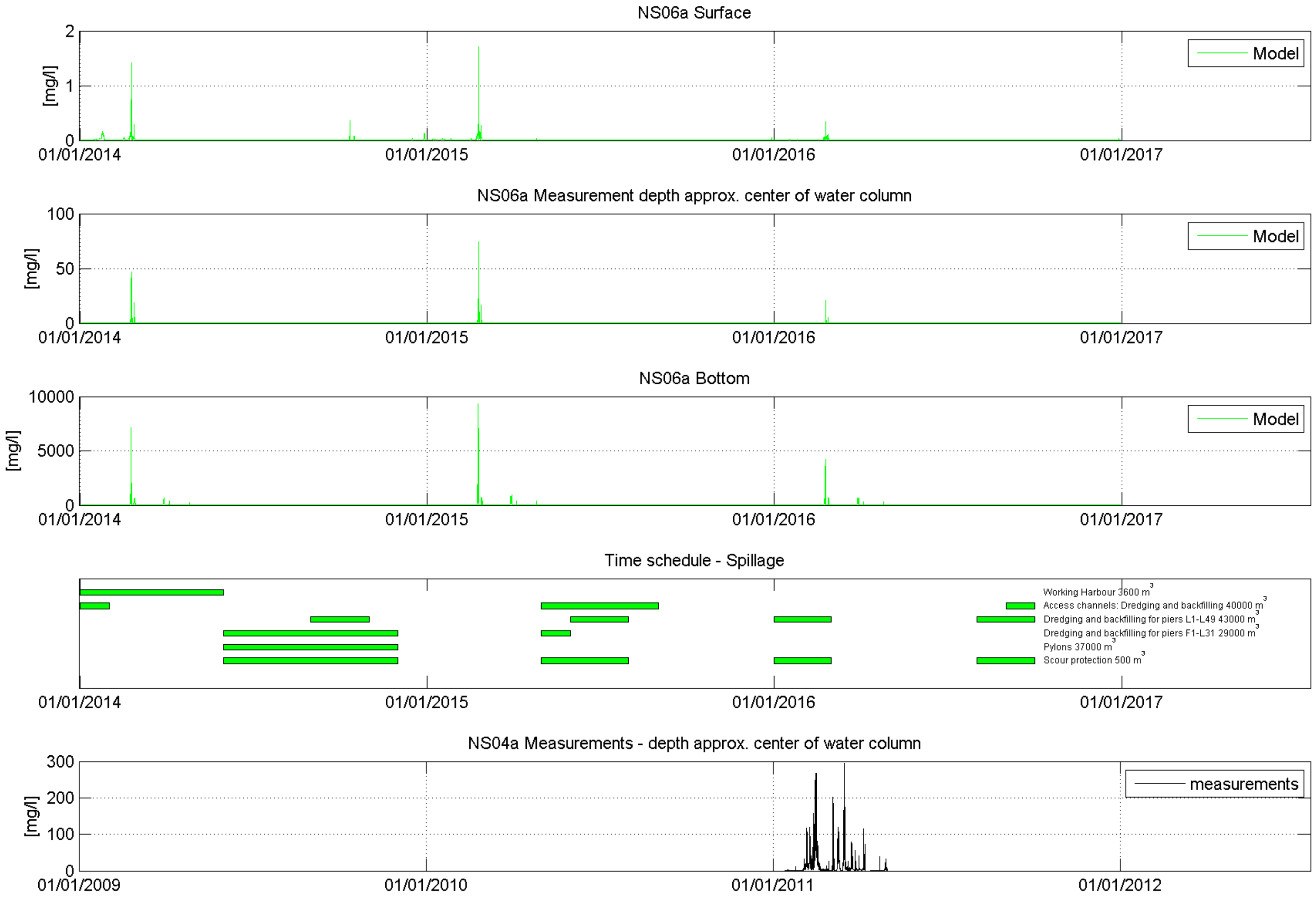


Figure 6.12 Time series of suspended sediment concentration at station NS06a for bridge solution. Note: different scales are applied

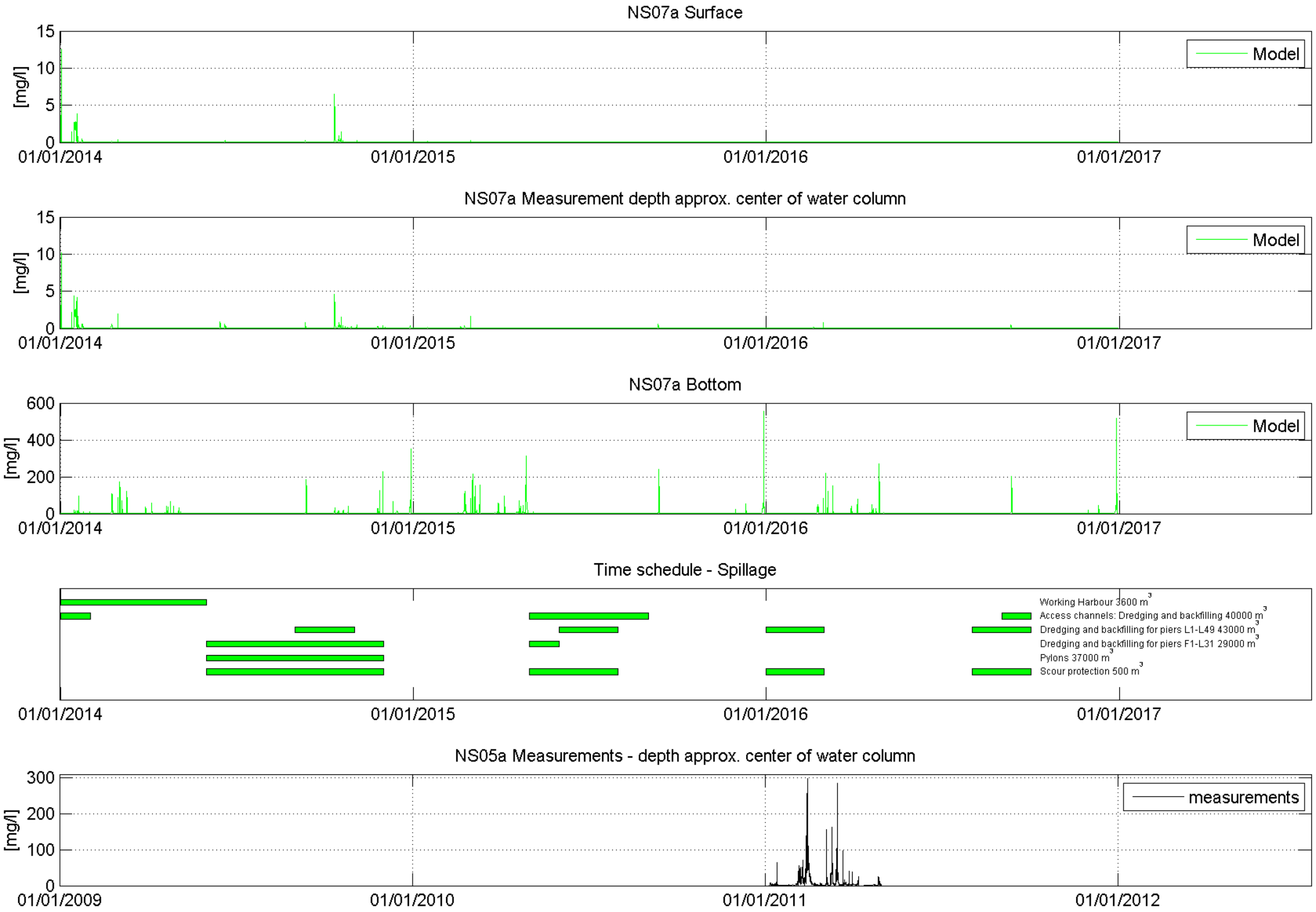


Figure 6.13 Time series of suspended sediment concentration at station NS07a for bridge solution. Note: different scales are applied

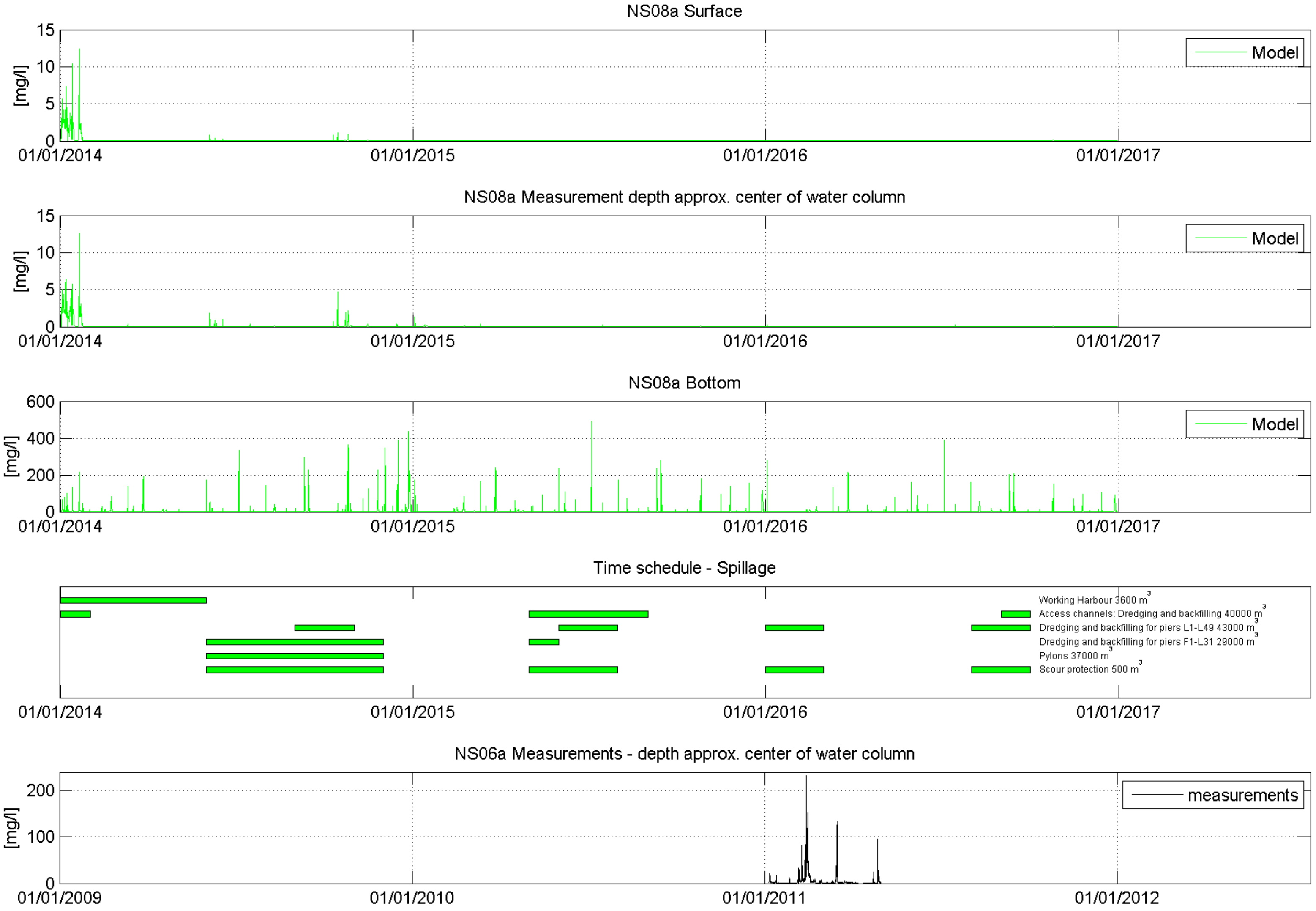


Figure 6.14 Time series of suspended sediment concentration at station NS08a for bridge solution. Note: different scales are applied

The results show temporal maximum concentration levels at midwater above 150 mg/l in the Rødsand Lagoon similar to the tunnel solutions and smaller away from the lagoon.

Excess concentrations on the Danish side are higher than on the German side due to the milder wave climate on the German side.

Situations with higher excess concentrations are seen to be much less than for the tunnel solutions consistent with the much smaller amount of spilled sediment. Time series at the nearshore stations in the Rødsand Lagoon and NS08 indicate that effects of dredging can be detected at the end of 2017. Most other stations indicate that no significant excess concentrations are found after the summer of 2016.

Exceedance times of concentration limits for bridge solution

In Figure 6.15 to Figure 6.18 exceedance times for the bridge solution are presented. All results can be found in Appendix H.

As observed in the figures the construction of the bridge results in very small excess concentrations. Sediment will only be visible at the surface for less than 10% of the time. Even at the sea bed, sediment concentrations will rarely exceed 10 mg/l.

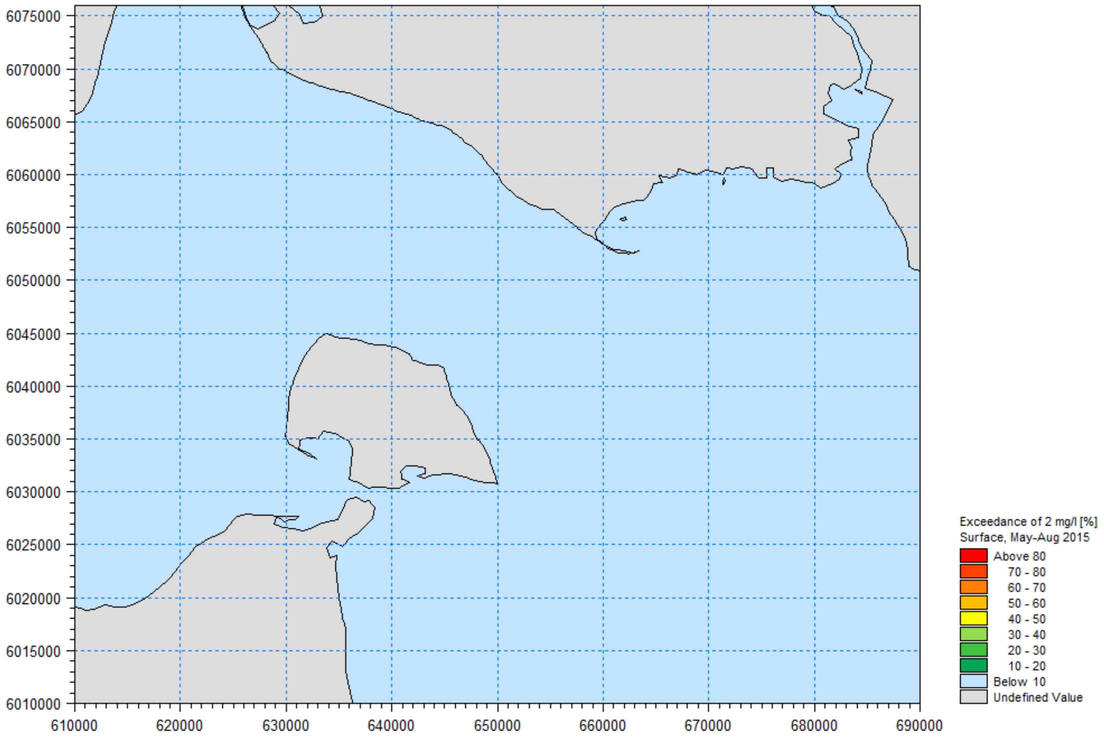


Figure 6.15 Exceedance time of 2 mg/l, 1/5-1/9 2014 for the surface (top layer in the numerical model results) for bridge solution

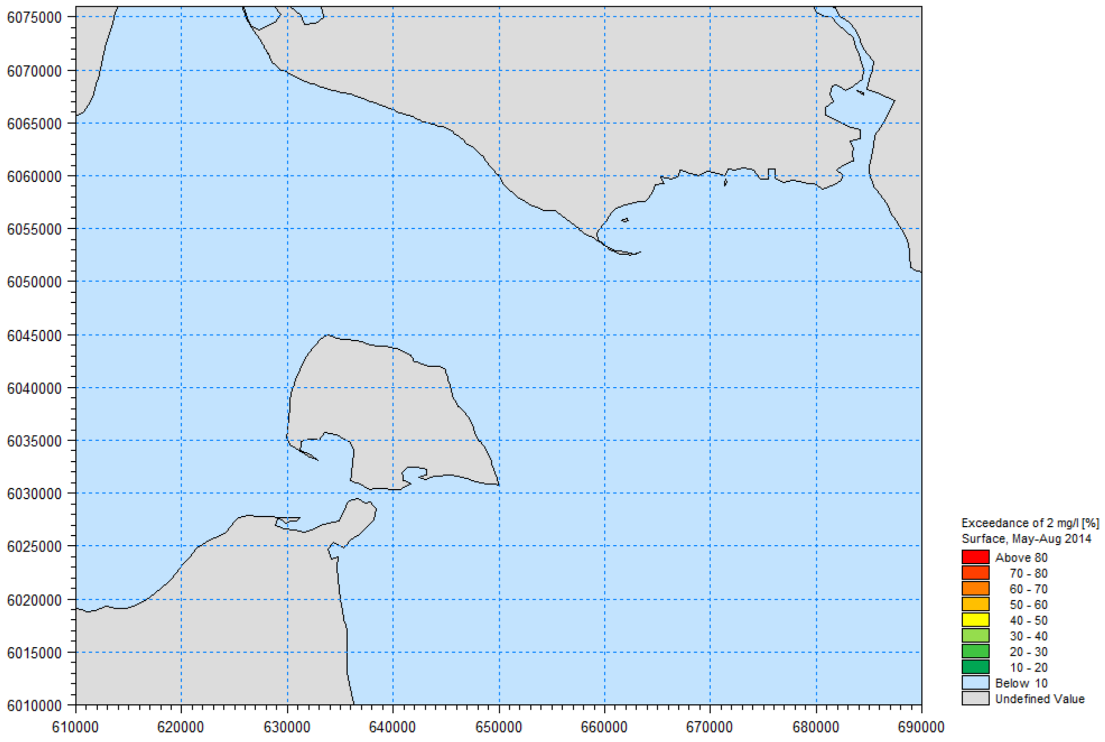


Figure 6.16 *Exceedance time of 2 mg/l, 1/5-1/9 2015 for the surface (top layer in the numerical model results) for bridge solution*

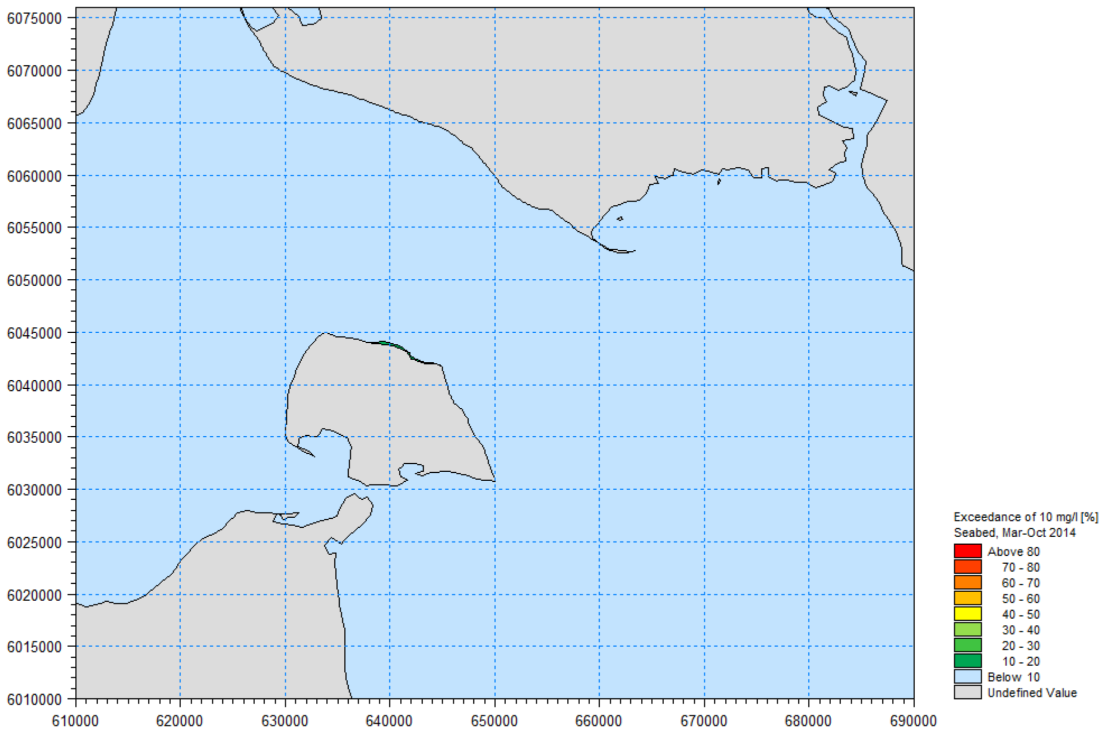


Figure 6.17 *Exceedance time of 10 mg/l, 1/3-1/11 2014 for just above the sea bed (bottom layer in the numerical model results) for bridge solution*

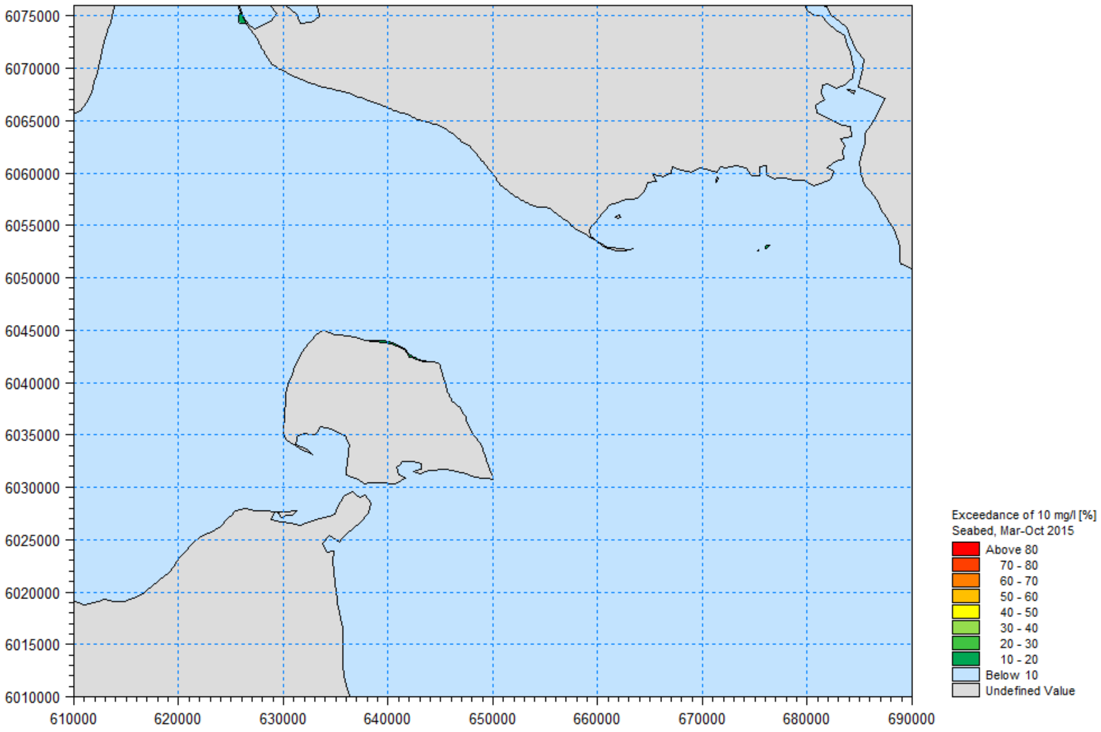


Figure 6.18 Exceedance time of 10 mg/l, 1/3-1/11 2015 for just above the sea bed (bottom layer in the numerical model results) for bridge solution

Statistical time series analysis for the bridge solution

In Table 6.4 and Table 6.5 the fractiles and exceedance times of excess concentrations and baseline conditions for each of the nearshore stations are listed. All the statistical results can be found in Appendix O.

Table 6.4 Fractiles and exceedance times for excess concentration, for Bridge solution 2014-16

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	0.0	0.0	0.1	0.1	0.0	0.0
NS02	0.0	0.0	0.0	0.2	0.0	0.0
NS03	0.0	0.0	0.1	0.3	0.0	0.0
NS04	0.0	0.1	0.5	3.8	0.4	0.0
NS05	0.0	0.0	0.1	0.1	0.0	0.0
NS06	0.0	0.0	0.0	0.0	0.0	0.0
NS07	0.0	0.0	0.0	0.0	0.0	0.0
NS08	0.0	0.0	0.0	0.0	0.0	0.0
NS09	0.0	0.0	0.0	0.0	0.0	0.0
NS10	0.0	0.0	0.0	0.0	0.0	0.0
NS01a	0.0	0.0	0.1	0.7	0.0	0.0
NS02a	0.0	0.0	0.0	0.3	0.0	0.0
NS03a	0.0	0.0	0.2	2.0	0.6	0.2
NS06a	0.0	0.0	0.0	0.3	0.1	0.0
NS07a	0.0	0.0	0.0	0.3	0.0	0.0
NS08a	0.0	0.0	0.0	0.8	0.0	0.0
MS01	0.0	0.0	0.1	0.0	0.0	0.0
MS02	0.0	0.0	0.1	0.0	0.0	0.0

Table 6.5 Fractiles and exceedance times for nearshore measurements 01.02.2009 – 01.01.2011 (NS01-03 01.02.2009 – 01.11.2010, NS01a-03a 01.11.2010-01.05.2011, NS06a-08a 05.01.2011-01.05.2011)

Station	f_{50}[mg/l]	f_{75}[mg/l]	f_{95}[mg/l]	E_2 [%]	E_{10}[%]	E_{20}[%]
NS01	1.09	1.85	10.59	23.06	5.40	2.05
NS02	1.48	3.91	28.86	38.62	13.15	7.78
NS03	2.20	6.31	24.66	53.57	15.72	6.57
NS04	2.46	6.36	34.04	60.78	17.69	9.33
NS05	5.33	15.46	54.62	81.03	34.44	19.83
NS06	1.17	1.71	4.74	19.37	0.71	0.17
NS07	1.36	2.59	8.22	32.08	3.27	0.99
NS08	1.39	2.36	6.92	30.64	2.54	1.10
NS09	1.38	2.30	7.94	30.03	3.77	1.45
NS10	1.30	2.25	7.60	28.53	3.22	1.02
NS01a	4.83	17.04	88.18	67.75	34.63	22.84
NS02a	5.08	30.79	126.12	69.57	38.05	30.28
NS03a	18.22	66.32	302.06	83.93	59.91	48.49
NS06a	1.96	6.94	95.00	49.50	20.81	13.20
NS07a	1.87	4.38	36.26	47.99	15.20	9.49
NS08a	1.15	2.22	18.60	27.85	7.94	4.64
MS01	0.7	1.1	3.5	9.4	0.3	0.0
MS02	0.7	1.0	2.4	6.4	0.3	0.0

The results show that excess concentrations are generally much smaller than the normal background concentrations and the exceedance times are also much smaller than the baseline background exceedance times.

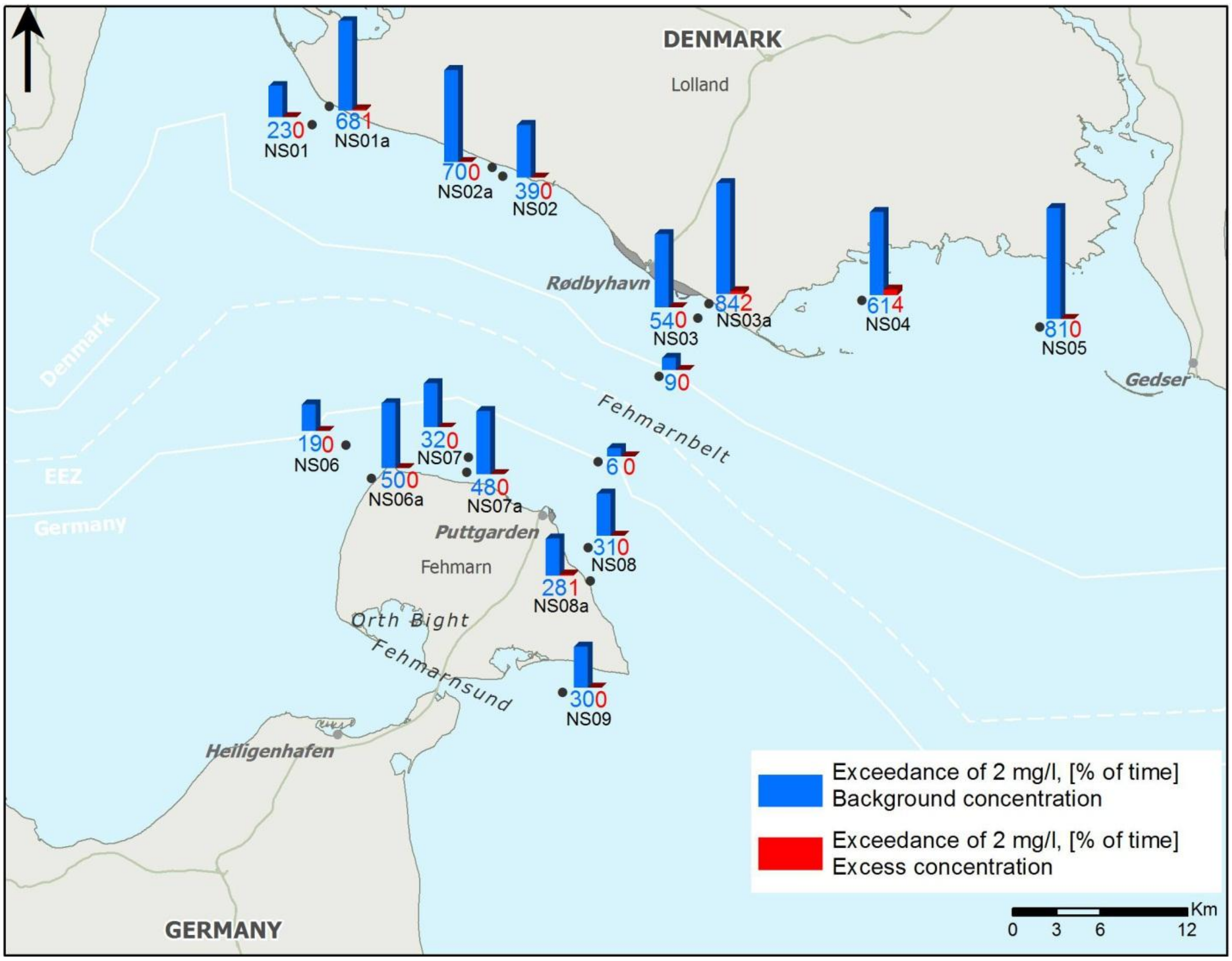


Figure 6.19 Comparison of excess concentrations for bridge solution versus background concentrations at mid level for all stations. Exceedence time in % for 2 mg/l. 2014 - 2016

The background concentrations at the nearshore stations compared to the background concentrations are given in Figure 6.19. All comparisons are made at mid-water where the measurements are made.

The comparison shows that the frequency of background concentrations above 2 mg/l is always significantly larger than the excess frequency due to dredging. Apart from the period where the dredger is dredging in the nearshore zone the high concentration events will occur when the hydrodynamic conditions are rough. This means that a part of the excess frequency will occur at the same time as the natural resuspension events. It will therefore be impossible to detect a visual difference in the appearance of the water and thus the effect of dredging is considered insignificant in this area.

Bathing water

The bathing water is affected in the same way as described in 6.2.1. However, the amount of sediment spilled in the bridge scenario is 10 times less than in the tunnel scenario and there are no large reclamations. Furthermore, sediment is spilled in much shorter intervals. The likelihood of a plume hitting the beaches is thus much smaller. The only operations that might give a direct impact on the beaches are the construction of the work harbour, and the access channels and according to the present plan these will be constructed during wintertime. Therefore there will be no impact on the bathing water during the bathing season.

6.2.2 Deposited sediments

Deposition maps for the bridge solution

In Figure 6.20 and Figure 6.21 the deposition patterns at the end of the construction period are presented. The plots illustrate where the deposited sediment eventually settles. All results from deposition maps can be found in Appendix M.

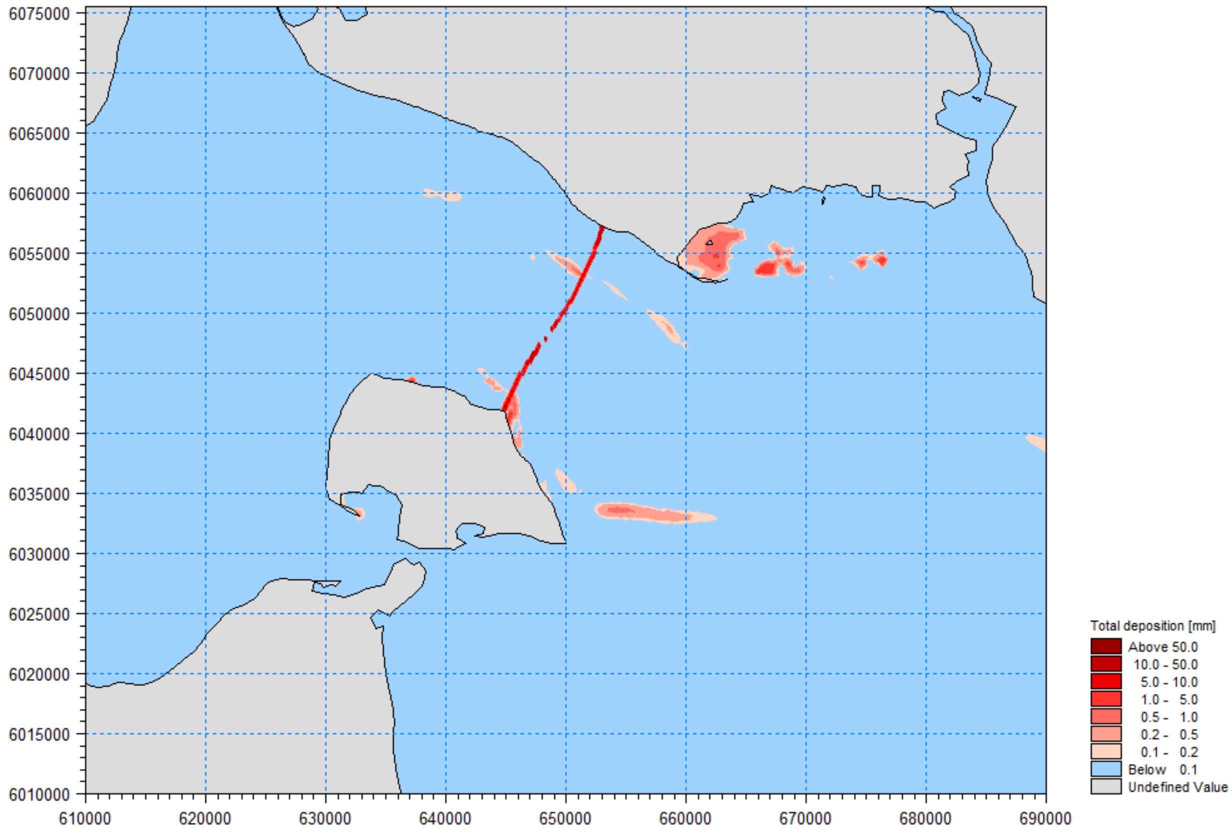


Figure 6.20 Deposition pattern at the end of 2016. Bridge solution

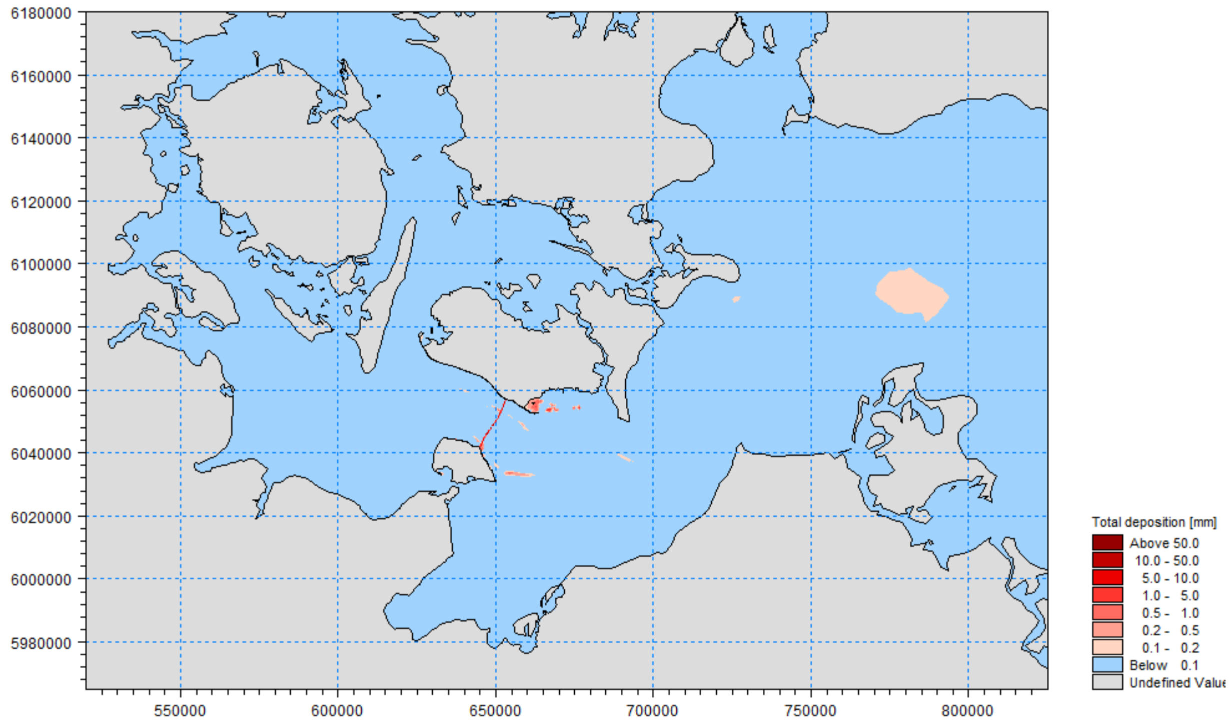


Figure 6.21 Deposition pattern at the end of 2016. Bridge solution. Full modelling area

The results show that only very small amounts of sediment are left at the alignment and this sediment consists mainly of the sand fraction. The finer fractions are spread over a wider area. Final resting places are seen to be the Arkona Basin, the edge of the Bay of Mecklenburg and the sheltered parts of the Rødsand Lagoon. Note that the sediment is spread in a very thin layer over a large area. Generally, maximum deposition heights are below 1 mm. Natural deposition in the Arkona Basin is above 1 cm over the same period and thus the excess deposition due to dredging is less than 10% over the construction period, see (Christiansen et. Al. 2002). At the alignment 1 cm to 5 cm may be reached. This sedimentation originates mainly from the coarser part of the spill (the sand fraction) that is less mobile. In reality the spilled sand fraction will deposit within 200-600 m from the dredging operation. This is illustrated in Figure 6.22 where the sand fraction is equally distributed within this distance from the alignment.

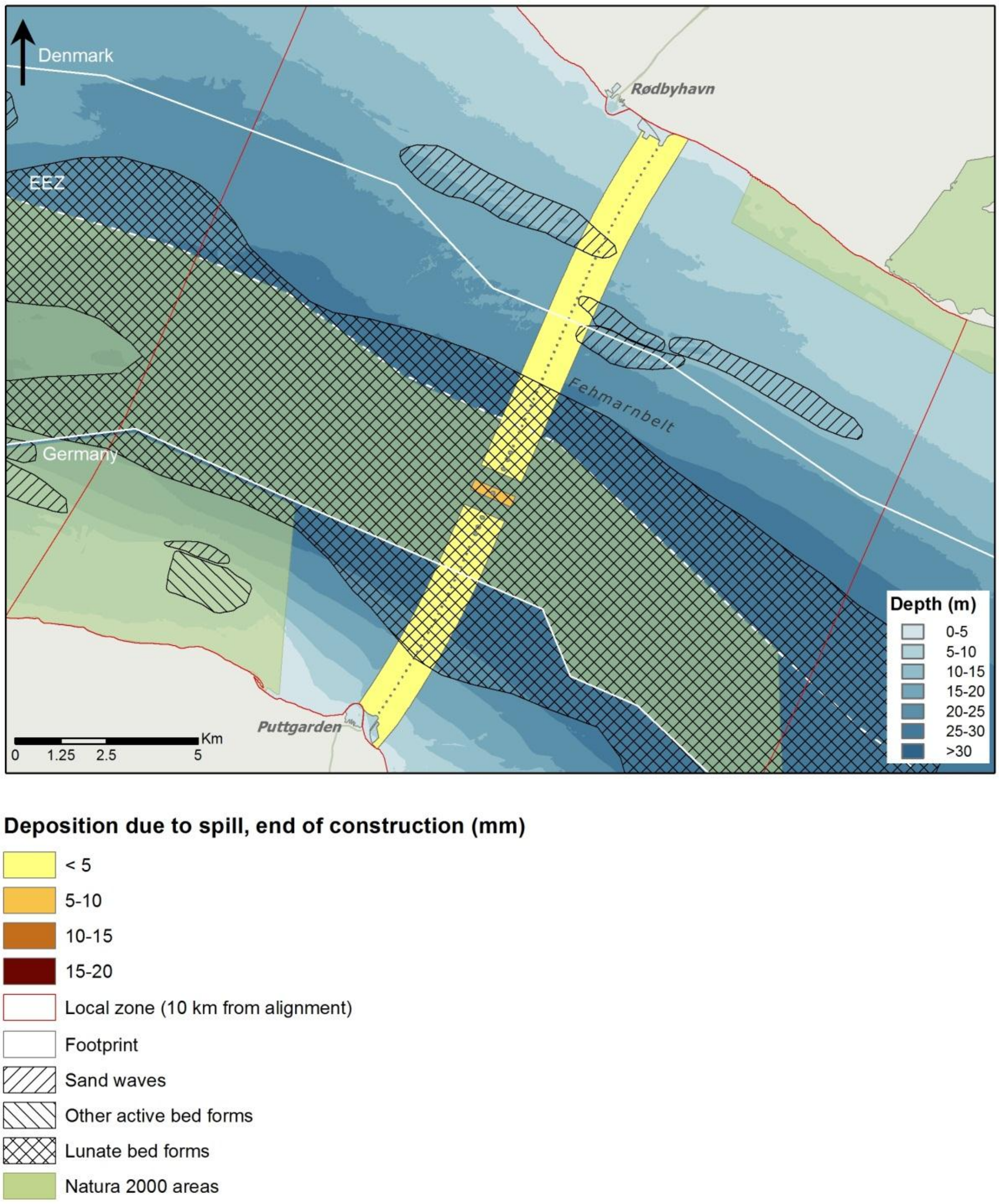


Figure 6.22 Illustration of deposition of sand along the alignment for BEE April 2010

Maximum temporary depositions for the bridge solution
Similarly the maximum temporary deposition pattern is presented for the bridge solution. All results can be found in Appendix M.

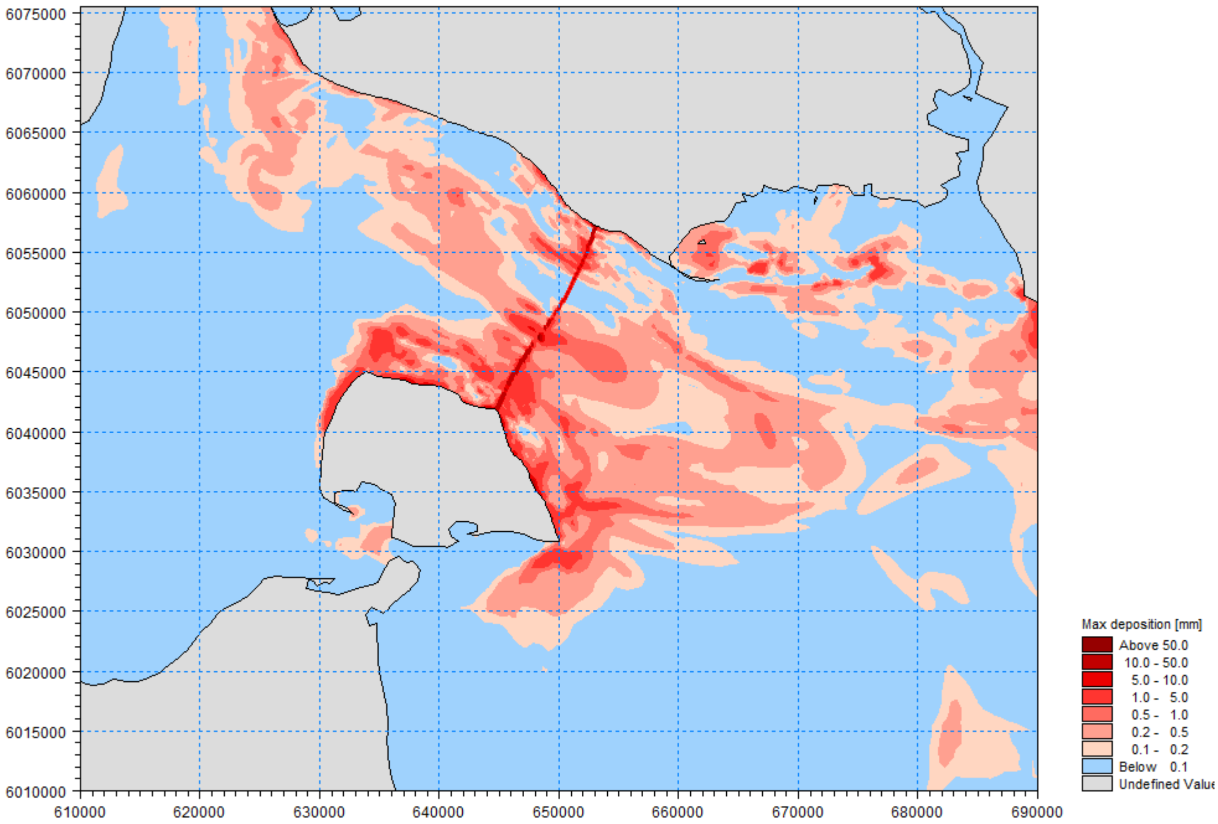


Figure 6.23 Maximum deposition heights for the bridge solution

As for the tunnel solutions the results show that large areas are subject to temporal sedimentation. Temporal sedimentation of 1 mm along the coasts of Lolland and Fehmarn as well as in the Rødsand Lagoon and along the east and west side of Fehmarn is observed. However, the depositions are temporary and the plots illustrate that the sediment is deposited and resuspended many times before it reaches the final resting places. No significant differences are seen between the two tunnel scenarios.

6.3 Transboundary impacts

Some small deposition is recorded in the deposition area in the Arkona Basin. This is partially a Swedish area. However, natural deposition in this area is 2.2 mm/year or approximately 1 cm over the construction period, see (Christiansen et. Al. 2002) and thus the deposition from the dredging activities is insignificant. Some very small portion of sediment travels further into the Baltic Sea. However, the sediment consists of the finest fractions and similar to the depositional patterns in the Arkona Basin it will be spread over a large area and form a very thin layer. For practical purposes this will not be measurable.

6.4 Mitigation and compensation measures

See Section 5.4.

6.5 Decommissioning

Decommissioning of the bridge is expected to comprise of the following elements, see (Femern A/S 2011).

The decommissioning and removal of the Fehmarnbelt Bridge structures and installations are assumed to comprise the following:

- Stripping of equipment and cabling
- Removal of roadway surfacing
- Removal of railway tracks and ballast material
- Dismantling of the bridge superstructure by e.g. reversal of the construction methods and transportation of the bridge girder components to shore for further demolition and scrapping
- In situ demolition of the pylons by cutting into elements with a reasonable weight that can be handled by cranes. Cutting by e.g. water jetting and flame cutting of rebar or diamond wire cutting. The elements are transported to shore for further demolition
- Removal of the pylon caissons by in situ demolition of the plinth, de-ballasting and refloating of the caisson and transportation in floating condition to a near-shore location for further demolition. Demolition of the base plate and lower parts of the walls in dry dock
- Dismantling of the piers with a Heavy Lift Vessel and by cutting the connection to the caisson. Transportation to shore for further demolition
- The caissons are removed by removal of internal ballast material, removal of scour protection and backfill material around the caisson and lifting of the caissons with a Heavy Lift Vessel and transportation to shore for further demolition
- Pile inclusions for soil improvement are situated below the natural sea bed. Removal is, therefore, not required
- Structures on land and the peninsulas are removed using conventional demolition methods

Spillage is expected from removal of scour protection and backfilling material. However, this material has been washed out during placement and the spill is thus expected to predominantly consist of coarse material.

Some backfilling material will be required to fill up the excavations from the piers. This material will probably be sand in combination with the existing backfilling material. In both cases the spillage will be limited. The effect to suspended sediment conditions from decommissioning of the bridge is thus expected to be insignificant

7 COMPARISON OF BRIDGE AND TUNNEL MAIN ALTERNATIVES

7.1 Deposition patterns

The deposition reaches 50 mm around the tunnel trench for both tunnel solutions and around the piers of the bridge solution. For all alternatives, accumulation of spilled sediment will occur in the Rødsand Lagoon. Furthermore, it is noted that sediment may occasionally and temporarily deposit in large areas, but is resuspended by waves and currents. Maximum bed thicknesses for these temporal depositions are up to 1 mm. The sediment will keep depositing and eroding until it reaches a final resting place. Final resting places are seen to be the deeper parts of the Arkona Basin, some areas of the Bay of Mecklenburg and the deep waters off the island of Als. The amount of sediment is approximately 10 times larger for the tunnel than for the bridge. The spill is spread over a large area and settles in thin layers. The deposition patterns are similar for the bridge and the tunnel solutions. The thin deposition layer for the tunnel will be even thinner for the bridge.

7.2 Suspended sediment

The suspended sediment concentration levels due to sediment spill vary during the construction period depending on the location of the dredging operations and the current and wave conditions. Generally, the concentrations tend to start at high levels along the coastline during the construction of work harbours, access channels and the inner parts of the bridge/tunnel, whereas later on, when the construction work is moving offshore, the concentration levels decrease. In coastal waters, waves prevent the spilled material from settling and resuspend material from the bed. Therefore, in periods relatively high concentrations are seen near the sea bed in the shallow coastal waters. Especially at the Danish coast this effect is seen as it is more exposed to waves than the German coast. This effect allows the sediment to travel relatively far along the coastline before settling. Sediment is seen passing Gedser Odde to the east and Nakskov Fjord to the west due to this effect. On the German side sediment passes around Fehmarn both at the eastern and western ends. Note that due to the nearshore locations these effects are only temporal. In open waters, suspended sediment concentrations are considerably lower.

The turbidity levels are much higher for the tunnel than for the bridge and turbidity levels are significantly higher when the construction works take place in the nearshore zones compared to the deeper parts for the tunnel and bridge, respectively.

The overall sediment budgets for the tunnel solutions show that approximately 50% of the spilled sediment travels east consistent with the inflow of saline water from the Kattegat to the Baltic Sea. It is also seen that the majority of the material travelling east continues past Gedser Odde and into the Baltic Sea. About 41% remains near the dredging area. Only 3.5% of the totally spilled mass enters the Rødsand Lagoon.

Note that during the hydrographic year 2005, the sediment will travel as described. During other years, the details of concentration and sedimentation patterns will be different. However, analysis of the hydrodynamics shows that 2005 can be considered to represent average conditions.

7.3 Statistical analysis

Statistical analysis of the excess concentration levels compared to the measured background concentration levels shows that the baseline concentrations represent higher concentration and duration of situations with high concentration. The situations with high excess and baseline concentrations will occur simultaneously. Therefore none of the solutions give rise to a significant impact on the already present concentration levels.

7.4 Impact times

It is seen that on the open coasts the major effects of dredging disappear shortly after dredging has stopped. However, the sediment temporarily deposited on the sea bed can be resuspended for a long time after dredging has stopped. In the present simulations effects can be seen up to 9 months after dredging has stopped. See Figure 5.12 and Figure 5.17.

7.5 Inflow to the Rødsand Lagoon

Generally, the inflow of sediment to the Rødsand Lagoon is governed by water moving into the lagoon and sediment being available at the entrance to the lagoon. Therefore inflow of sediment requires both rising water levels and that the sediment spill plume is oriented towards east or sediment is being resuspended from the sea bed along the barrier and near the entrance. Such events are responsible for more than 75% of the sediment entering the Rødsand Lagoon during 2014 and 2015. This is illustrated in Figure 7.1 and Figure 7.2.

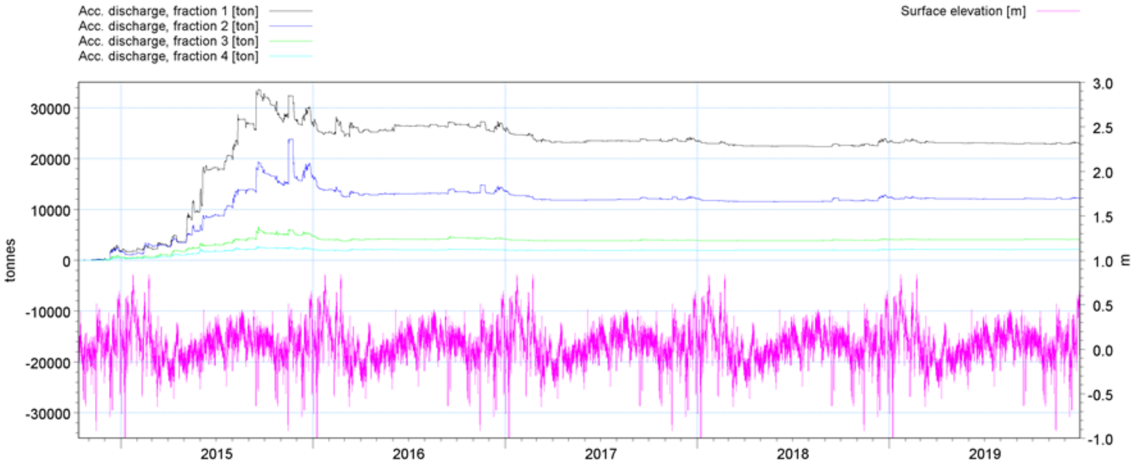


Figure 7.1 Inflow of sediment to Rødsand Lagoon compared to the water level variations. Tunnel solution

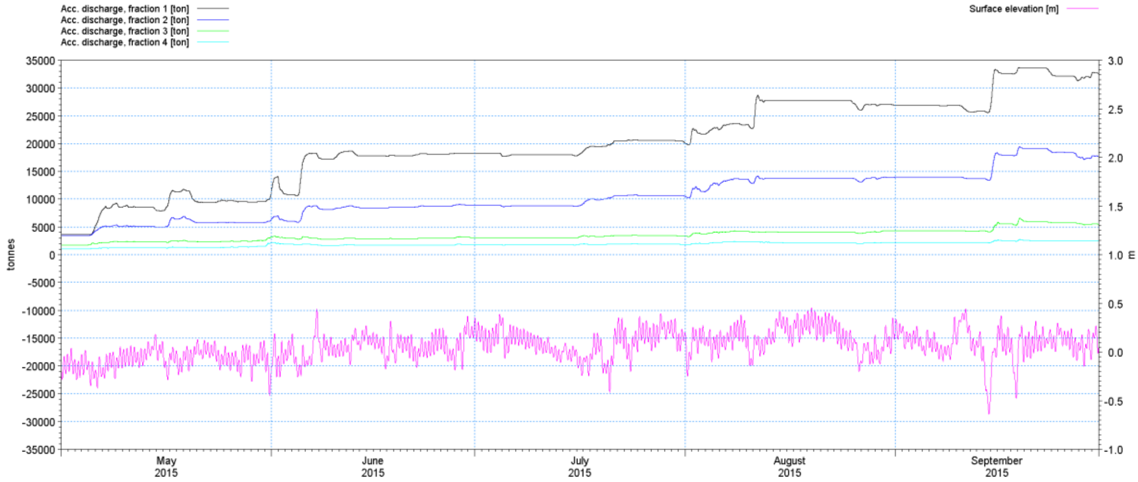


Figure 7.2 Inflow of sediment to Rødsand Lagoon compared to the water level variations. Zoom

In case of the tunnel solution the inflow of sediment to the Rødsand Lagoon stops during the last quarter of 2015 when the dredger has moved 3 km offshore. The effect is the same for both solutions but the amounts are much smaller in the bridge scenario.

7.6 Comparison of tunnel and bridge alternatives with ferry operation

The ferry operation will not pose any significant change to the results from the tunnel and bridge scenarios. Some short term local resuspension due to propeller wash may be experienced near the harbour entrances.

7.7 Comparison of tunnel and bridge alternatives without ferry operation

The ferry operation will not pose any significant change to the results from the tunnel and bridge scenarios.

7.8 Comparison with latest layouts

7.8.1 Tunnel

The most recent tunnel layout is denoted E-ME/August 2011. The applied layout for the spill simulations is denoted E-ME Nov 2010. The differences in terms of spillage are presented in Table 7.1.

Table 7.1 Overview of differences between present and applied tunnel layouts with regards to spill volumes

Activity	E-ME August 2011	E-ME November 2010
Trench dredging	0.507 mill m^3	0.540 mill m^3
Reclamations	0.104 mill m^3	0.104 mill m^3
Dikes/P&R/Harbour	0.032 mill m^3	0.032 mill m^3
Backfilling and landscaping	0.060 mill m^3	0.070 mill m^3
Total dredging volume	0.703 mill m^3	0.746 mill m^3

From Table 7.1 it is seen that the main difference comes from the spilled volumes during dredging of the tunnel trench. Here the applied dredging scenario holds an excess 6% spill relative to the latest layout. A similar figure is seen for the backfilling. The applied spill scenario is thus 6% on the conservative side with regards to spill. The location of the access channel near Rødbyhavn is slightly changed.

7.8.2 Bridge

The most recent bridge layout is denoted 'Variant 2 BE-E, October 2010'. The applied layout for the spil simulations is denoted 'BE-E April 2010'. The differences are summarized below and can be seen in Figure 7.3. The simulated variant differs from the final Var. 2 (October 2010) as follows:

- It had a slightly more S-shaped alignment
- It did not have marine ramps but the approach bridge extended all the way to land (3 extra piers in total)
- One additional pier had a ship protection caisson at the two transfers to the main bridge
- The main bridge span was 900 m compared to 724 m span in the October 2010 version
- The main pylon had a diameter of 80 m compared to 72 m in the October 2010 version

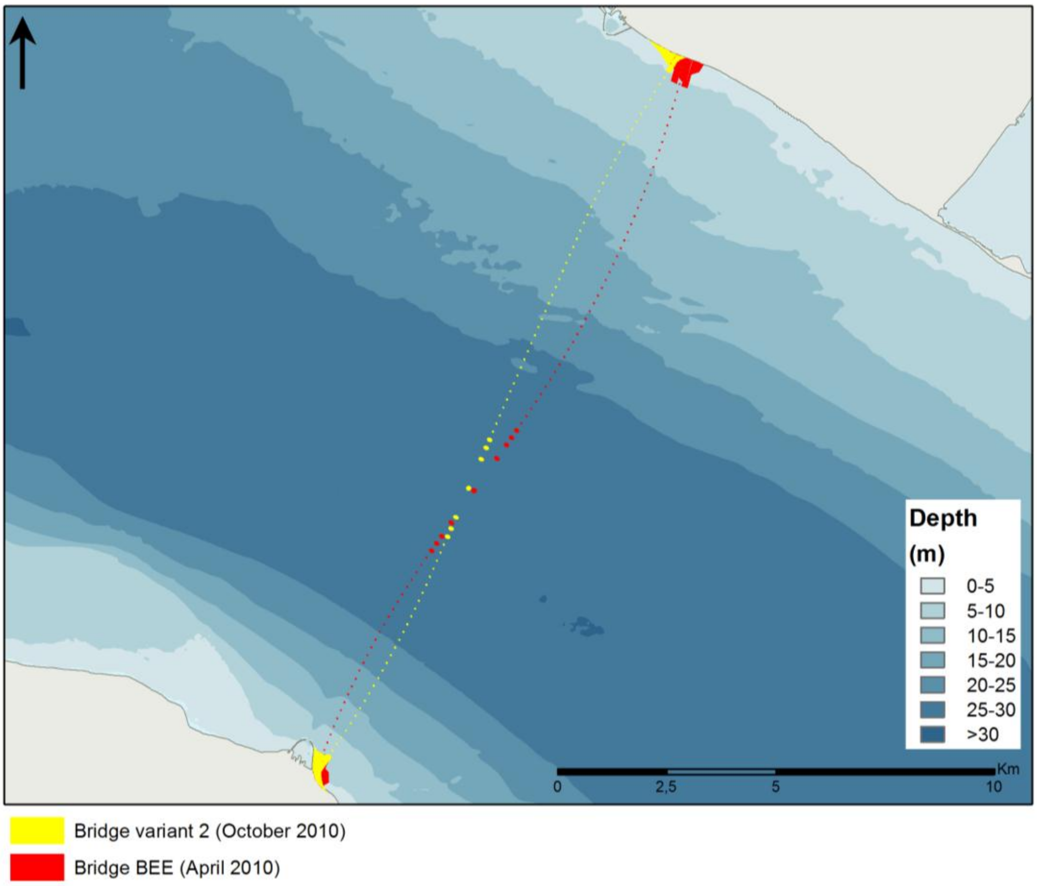


Figure 7.3 Overview of differences between Variant 2 October 2010 and Variant BE-E April 2010

In terms of spill the differences are given in Table 7.2.

Table 7.2 Overview of differences between present and applied bridge layouts with regards to spill volumes

Activity	Amount Spilled BE-E April 2010 [mill m^3]	Amount spilled Var2 BE-E October 2010 [mill m^3]
Dredging for piers	0.070 mill m^3	0.015 mill m^3
Backfilling at piers (sand)	0.002 mill m^3	0.000 mill m^3
Dredging of access channels	0.020 mill m^3	0.000 mill m^3
Backfilling of access channels	0.020 mill m^3	0.000 mill m^3
Scour protection etc.	0.001 mill m^3	0.000 mill m^3
Work harbour at Rødby	0.010 mill m^3	0.000 mill m^3
Reclamations	0.000 mill m^3	0.002 mill m^3
Production facility	0.000 mill m^3	0.034 mill m^3
Dredging for pylons	0.037 mill m^3	0.037 mill m^3
Total amount spilled	**0.160** mill m^3	**0.088 mill m^3**

The difference in terms of spill is approximately 0.072 mill m^3. This constitutes a total reduction in spillage of 45%.

The simulated scenario (‘Variant BE-E April 2010’) holds two times as much spilled material as the assessed scenario (‘Var2 October 2010’) and thus the spill simulations are very conservative compared to the assessed scenario. The distribution of sediment in the two cases is almost the same. On the Danish side the production facility holds a slightly larger amount of sediments than the access channels and the work harbour at Rødbyhavn. On the German side the work harbour and the reclamations hold slightly more spilled sediments than the access channels. However, these changes will not give a significant change. The major difference is the smaller amount dredged offshore. The sediment spilled here will have a tendency to travel away from the alignment in deeper waters and thus the difference will mainly be seen in the offshore deposition patterns and the exceedance patterns near the piers. There the simulated layout is a good approximation in the coastal zone and a conservative approximation offshore.

8 KNOWLEDGE GAPS

The present model complex includes the following elements:

- Wave model
- Hydrodynamic model
- Sediment model

The first two models were calibrated to match the general currents and waves in the Fehmarnbelt. The majority of the sediment related model parameters for the sediment model are based on measurements in the field, laboratory tests and literature values.

Sediment related parameters are difficult to measure in the field. Uncertainty is attached to settling velocities, flocculation, critical shear stress for erosion and deposition and consolidation of fine spilled sediments. Central estimates have been applied throughout the modelling and two spill experiments have been made in the field to calibrate the spill modelling. These experiments supported the selected parameters, however, the variability of the parameters should be realised and more experimental work would reduce the uncertainty on the final modelling work.

Background concentration of suspended sediment has been measured in 18 locations spread over the Fehmarnbelt and the Rødsand Lagoon. These measurements form the basis for comparison with the modelled excess concentrations. The modelling work clearly illustrates the extent of plumes from earth handling, but the re-suspension of initially deposited spilled sediment and the (simultaneously) re-suspension of natural sediment and their interaction are poorly understood. This will typically lead to an over-estimation of the impacts of spill on the water quality as exceedance frequencies of excess concentrations are compared directly with natural exceedance frequencies even though these re-suspension events to a large extent happen at the same time.

9 REFERENCES

John, A., Challinor, S.L., Simpson, M., Burt, T.N., Spearman, J. (April 2000). Scoping the assessment of sediment plumes arising from dredging. Funders report/IP/40

Bray, R.N., Bates, A. D., Land, J. M. (1997). Dredging. A handbook for engineers. Arnold

Burt, N. (1986). Field Settling Velocities of Estuary Muds. In Estuarine Cohesive Sediment Dynamics. Edited by Mehta, A.J. pp 126-150

Christiansen, C., Edelvang, K., Emeis, K., Graf, G., Jähmlich, S., Kozuch, J., Laima, M., Leipe, T., Löffler, A., Lund-Hansen, L.C., Miltner, A., Pazdro, K., Pempkowiak, J., Shimmield, G., Shimmield, T., Smith, J., Voss, M., Witt, G. (2002). Material transport from the nearshore to the basinal environment in the southern Baltic Sea I. Processes and mass estimates. Journal of arinine systems 35

COWI/Obermeier Spill Workplan. Email correspondence of 22/3 2010. COWI ID: A4429-O-LET-257 Excavation Information - Questions from DHIDankers, P.J.T. (2002)

Dankers, P.J.T (2002). The behaviour of fines released due to dredging. A literature review. TUDelft 2002

Edelvang, Karen (1998). In-situ settling velocities and concentrations of suspended sediment in spill plumes, Øresund, Denmark. In Vollmer, M. and Grann, H., Editors. Large-scale Constructions in Coastal Environments, Springer, Berlin, pp 181–189

FEHY (2013a). "Fehmarnbelt Fixed Link, Marine Water: Hydrography of the Fehmarnbelt Area - Impact Assessment". Doc No E1TR0058, Volume II

FEHY (2013b). "Fehmarnbelt Fixed Link, Marine Soil. Sea Bed Morphology of the Fehmarnbelt Area – Impact assessment". Doc No E1TR0059, Volume I

FEHY (2013c). "Fehmarnbelt Fixed Link, Baseline for Suspended Sediment, Sediment Spill, related Surveys and Field Experiments". Doc No E1TR0057

FEHY (2013d). "Fehmarnbelt Fixed Link. Marine Water Baseline. Hydrography of the Fehmarnbelt Area". Doc No E1TR0057, Volume II.

FEHY (2013e), "Fehmarnbelt Fixed Link. Marine Soil, Sea Bed Morphology of the Fehmarnbelt Area – Baseline". Doc No E1TR0056, Volume I

FEHY (2013f). "Fehmarnbelt Fixed Link. Marine Soil, Sea bed Morphology of the Fehmarnbelt Area – Impact Assessment". Doc No E1TR0059, Volume I

FEHY (2013g). "Fehmarnbelt Fixed Link EIA. Marine Soil - Baseline. Seabed Chemistry of the Fehmarnbelt Area". Doc No E1TR0056, Volume II

FEMA (2013a). "Fehmarnbelt Fixed Link. Water Quality and Plankton of the Fehmarnbelt Area – Impact Assessment. Doc No E2TR0021, Volume III

FEMA (2013b). ″Fehmarnbelt Fixed Link EIA. Benthic Fauna in the Fehmarnbelt Area – Impact Assessment. Doc No E2TR0021, Volume II

FEMA (2013c). ″Fehmarnbelt Fixed Link EIA. Fauna and Flora – Baseline. Habitat Mapping of the Fehmarnbelt Area″. Doc No E2TR0020, Volume III

FEBI (2013a). "Fehmarnbelt Fixed Link EIA. Fauna and Flora – Baseline. Waterbirds of the Fehmarnbelt Area – Impact Assessment″. Doc No E3TR0015, Volume I

Femern A/S (2011). Consolidated technical report. Draft 3.3. September 2011

Fredsøe, J. (1984). "Turbulent boundary layer in wave-current motion″. J Hydr Eng, A S C E, Vol 110, HY8, pp 1103-1120

Geotechnical Report, Investigation Data Fixed Link across Fehmarn Belt Germany and Denmark. "Location reports. Fugro Engineers. B.V 2009″

Konert, M. Vandenberg, J. (1997). Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. Sedimentology 44, 523-535

Lumborg, U. (May 2005). Modelling the deposition, erosion, and flux of cohesive sediment through Øresund. Journal of Marine systems

Mikkelsen, O. and Pejrup, M. (1998). Comparison of Flocculated and Dispersed Suspended Sediment in the Dollard Estuary. In Black, K.S., Paterson, D.M & Cramp, A. (eds) Sedimentary Processes in the Intertidal Zone. Geological Society, London, Special Pup. 139, pp 199-209

Miljøpåvirkninger i forbindelse med anlæg af Øresundsforbindelsen. Øresundskonsortiet (May 2000)

Owen, M.W. (1988). Determination of the settling velocities of cohesive muds. HR Wallingford

Rambøll – Arup – Tech JV. (August 2011). Technical note. Description of the offshore activities

Smagorinsky, J. General Circulation Experiment with Primitive Equations, Monthly Weather Review, 91. No. 3, pp. 99-164

Van Leussen, W. (1994). Estuarine Macroflocs and their Role in Fine-grained Sediment Transport. Utrecht University

Van Rijn, L.C. (2007). Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed load transport. Journal of hydraulic engineering, ASCE, Vol 133, No. 6, 649 -667

Whitehouse, Richard, Soulsby, Richard, Roberts, William and Mitchener, Helen (2000). Dynamics of Estuarine Muds. HR Wallingford

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