EIA FOR THE FEHMARNBELT CROSSING – THE WORLD'S LONGEST IMMERSED TUNNEL

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An 18 km long immersed tunnel is going to be built between Denmark and Germany. The construction works include dredging for the tunnel trench and reclamation of areas in the coastal zone. The paper discusses the baseline conditions and the potential impacts on the aquatic environment of the dredging works. Focus is on sediment spill from the soil handling and methods to investigate the effects of additional turbidity in the water.

Keywords: sediment spill, settling velocities, modelling of sediment spreading, light attenuation, ecological modelling

THE FEHMARNBELT CROSSING

The Fehmarnbelt is about 18 km wide at its narrowest point with water depth up to 30 m. At this point, a fixed connection is planned for both rail and road. One of many environmental requirements is that changes in salinity and the exchange of water between the North Sea and the Baltic Sea must be insignificant. This aspect together with many other considerations such as navigation safety and impacts on migrating birds have led to the decision that the connection is going to be a tunnel below seabed level. The overall dimensions of the tunnel elements are a height of 9-12 m and a width of 42 m. A protection layer covers the elements. The dredging of a tunnel trench and the establishment of temporal work harbours including casting basins require handling of in total (both dredging and reclamation) 55 mill. m^3 soil. The excess amounts of soil will be built into landscaped reclamations primarily at the Danish side. These reclamations will include artificial beaches and lagoons, see Brøker and Mangor (2012) for a discussion of these features. The location of the Fehmarnbelt, a sketch of the engineer landscape on the Danish side and a sketch of the tunnel element cross section are shown in Figure 1. The connection is planned to open in 2021.

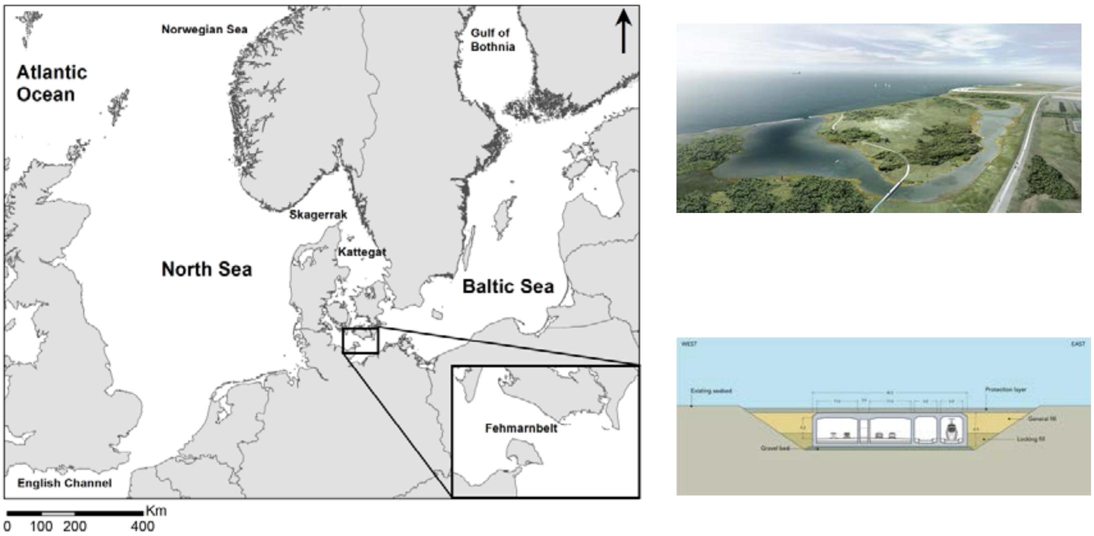

Figure 1. Overview of the water bodies surrounding the Fehmarnbelt, the architect's sketch of the artificial land shape on the Danish side and a sketch of the tunnel elements.

The present paper gives a brief introduction to the methods applied for the environmental impact assessment. For further information reference is given to http://vvmdocumentation.femern.com/.

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HYDROGRAPHIC AND SEDIMENT CONDITIONS

The Fehmarnbelt is one of the narrow straits that connect the North Sea and the Baltic Sea, see Figure 1. The hydrographic conditions are dominated by the meteorological conditions and the fresh water inflow to the Baltic Sea from rivers and streams. The narrow Danish straits include sills that restrict the inflow of saline water from the North Sea to the Baltic Sea. The Fehmarnbelt is located just where these complex conditions result in stratified flow during long periods but also periods where the flow is well mixed. The astronomical tide is very limited with a maximum range of 0.08 m. The wind rose based on 63 years' of measurements, and current roses based on 2 years' of measurements 5 m and 27 m below mean sea level, position MS02, as well as wave roses based on 2 years' of measurements in position MS01 are shown in Figure 2. It appears that the strong westerly winds generate significant wave heights up to about 2 m. The near bed currents only rarely exceed 0.4 m/s and the mean current is going towards the Baltic Sea whereas currents in the upper part of the water column reach above 1.2 m/s and are in average flowing out of the Baltic Sea.

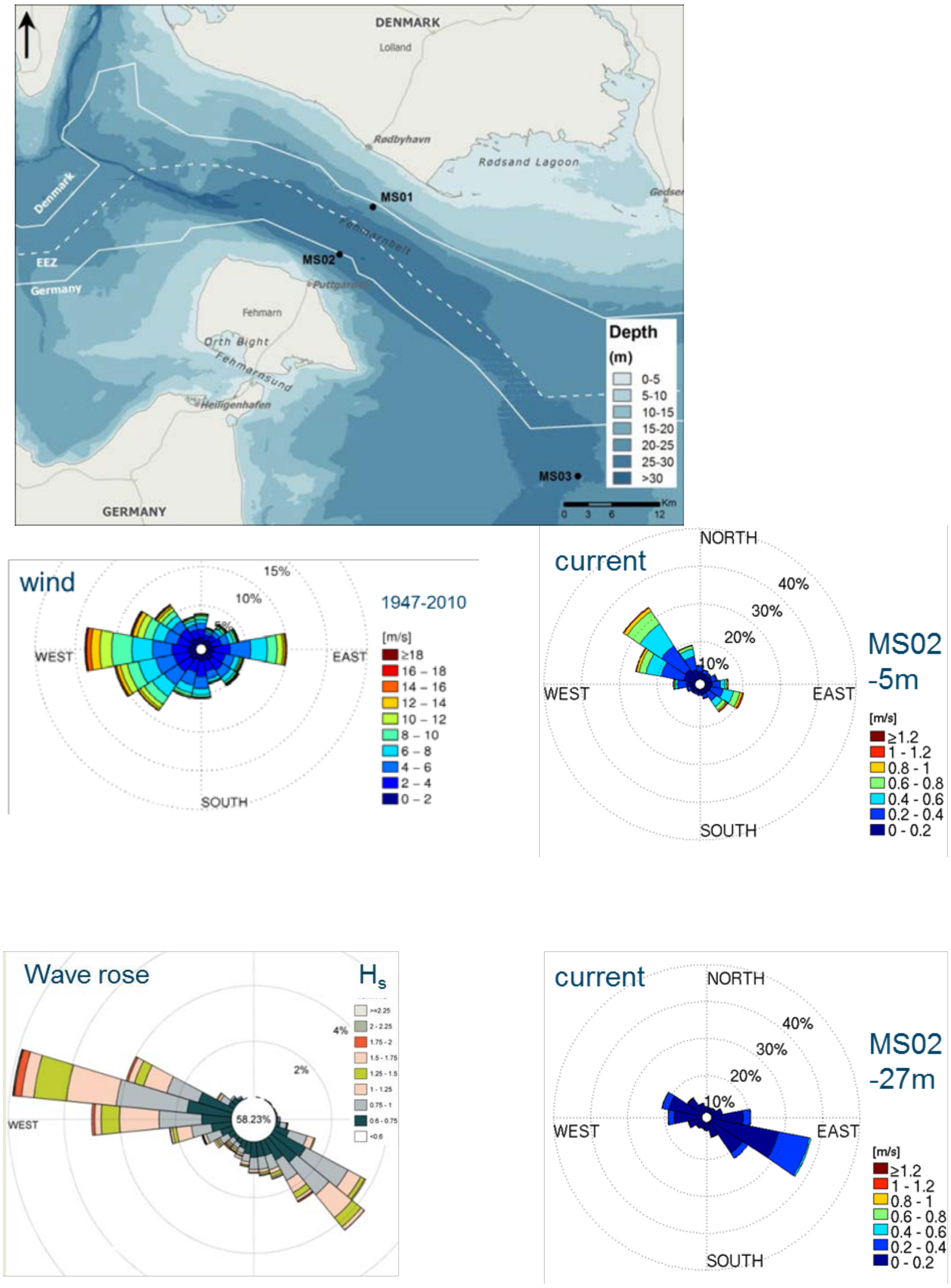


Figure 2. Overview of hydrographic stations, wind rose, wave rose and current roses at two water depths.

The sea bed in the Fehmarnbelt consists of glacial deposits. The near shore active zone is generally covered with loose sand whereas the sea bed in deeper water generally consists of hard till, which in places is covered by thin layers of sand. The sand forms active sand waves or lunate shaped bed forms.
The natural suspended sediment concentrations are generally low in the Fehmarnbelt. The turbidity has been measured in 17 locations scattered over the area of interest. The measurements are made over a two-year period with in total 11 measurement stations at the same time. The turbidity measurements have been calibrated against water samples, see FEHY (2013a) for a discussion of variability of the calibration with sediment properties for this specific case. The median and the 95 percentile suspended sediment concentrations are shown in Figure 3 along with an example of simultaneous time series of suspended sediment concentrations. The measurements show that the natural suspended concentrations are typically low, less than 2 mg/l outside of 8 m water depth and can reach 200-500 mg/l in the active near shore zone and in the shallow coastal lagoons.

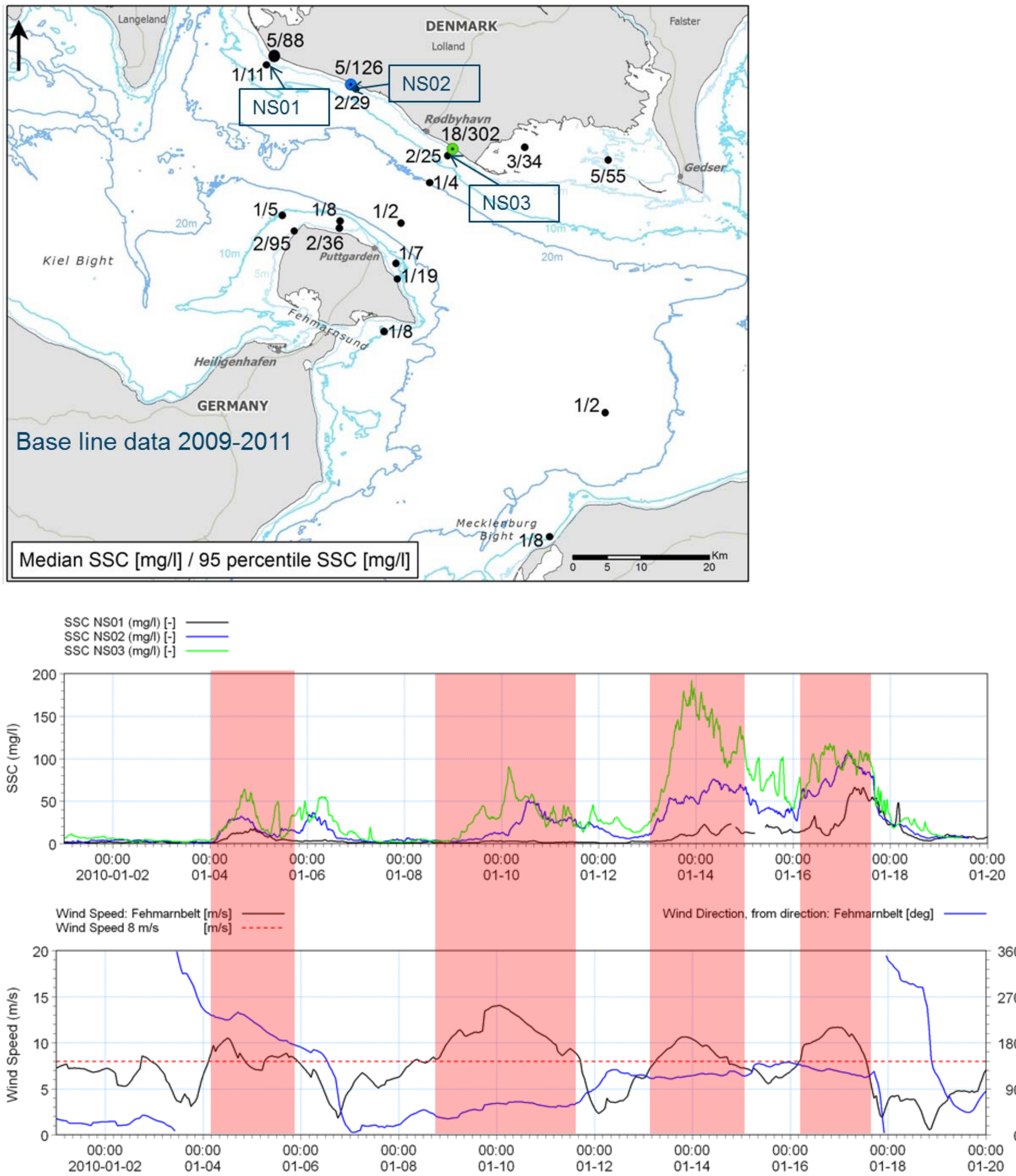


Figure 3. Left: median and 95 percentile suspended sediment concentrations at mid depth measured over more than 4 months per location. Right: illustration of the strong correlation between wind speed (lower figure) and suspended sediment concentrations (upper figure).

ECOLOGICAL CONDITIONS

The ecological conditions in the Fehmarnbelt were studied during two years and included all important ecosystem components: water quality, benthic flora and fauna, fish, marine mammals and seabirds. The main impact of sediment spill is reduced light availability for marine plants, and this issue is therefore the focus of this paper.

The water quality in the Fehmarnbelt is in general good with an average secchi depth of 7.1m, Chl a concentration of app. 5 mg m^{-3} and inorganic N of app. 80 mg m^{-3} (FEMA-FEHY 2013).

Hard bottom areas suitable for macroalgae colonisation are found scattered in the coastal areas with highest densities along the coast of Lolland in Denmark and at Staberhuck (Natura 2000 site) at the north-eastern part of the island Fehmarn in Germany. The macroalgae can be divided into five communities, named by their dominating species (FEMA 2013). *Fucus* sp. dominated areas are found at depths between 1–5 m, but only at a few locations, mainly on the western part of Fehmarn. *Furcellaria lumbricalis* together with *Coccotylus* /*Phyllophora* dominate at depths between 2–8 m and are widely distributed along the Lolland coast. The perennial redalgae *Phycodrys rubens* and *Delesseria sanguinea* are found at depths between 5–19 m and are widely distributed in the area. In deeper water between 12–19 m the perennial brown algae *Saccharina latissima* is also a characteristic species. Many sites are also dominated by filamentous, opportunistic algae (the filamentous algae community).

The flowering plant communities (eelgrass, tasselweed/dwarf eelgrass) were widely distributed within the soft bottom dominated areas of western Rødsand Lagoon and Orth Bight (for location see Figure 1). Due to the soft bottom and sheltered conditions in these areas both communities occurred with high coverage (> 50%). Both areas are part of different Natura 2000 sites (Rødsand and Eastern Kiel Bight). In Rødsand Lagoon the eelgrass is food for a large number of overwintering swans.

TOOLS FOR THE SEDIMENT SPILL IMPACT ANALYSIS

The impact of the dredging work is predicted using numerical models for simulation of hydrodynamics, waves, spreading of the sediment spill from the dredging and reclamation works, its impact on the light conditions and the resulting impact on pelagic and benthic primary production. The effects on higher trophic levels like birds and marine mammals have been assessed based on the outcome of these simulations. An overview of the modelling complex is shown in Figure 4. The hydrodynamic model and wave model are calibrated and validated against measurements whereas key parameters for the sediment model, the light reduction model and the ecological model are measured in the field and in the laboratory as briefly described in the following.

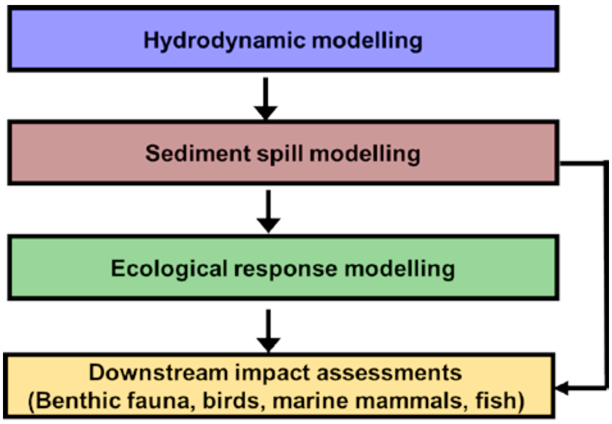


Figure 4. Illustration of the connection between various numerical modelling tools.

Hydrodynamics

The complex hydrodynamic conditions through the Danish straits are modelled in a 3D regional model (MIKE 3), which gives boundary conditions to a 3D local model. For details of the modelling tools, see FEHY (2013b and 2013c). The regional model is driven by meteorological data, wind, air pressure, temperature, fresh water inflow and water levels along the open boundary in the North Sea from even bigger models. Both models use a flexible mesh in the horisontal plan whereas the regional model uses a fixed resolution of 1 m in the vertical direction below 10 m depth and 10 “sigma layers” above 10 m

and the local model uses 20 sigma layers all over the model domain. This combination ensures that the overall stratification is well reproduced on the regional scale and that the velocity profiles are well reproduced in the local model area.
Figure 5 shows the extent of the regional and the local model areas and the flexible mesh in the local model area. The resolution in the horisontal direction varies between 100 m and 5000 m. Further,
Figure 5 shows examples from the model calibration: measured and modelled salinity 5 m and 32 m below the sea surface for one year and two examples of the measured and modelled vertical distribution of salinity in the Fehmarnbelt. An independent model validation was undertaken using dedicated monitoring data from 2009. Both the regional and the local model area are coved also with spectral wind wave models (MIKE SW), see FEHY (2013d) for a model description.
The analysis of sediment spill effects has been based on a representative hydrographic year which is modelled in regional and local models. The hydrographic year 2005 has proven to be representative with regards to in- and out flow to the Baltic Sea, to stratification and to the seasonal variation of storm events. This year has been used for testing of seasonal variability of effects of spill as well as for impact assessments of realistic spill scenarios with durations up till 7 years in which case the hydrographic year has been repeated and used as basis for the sediment spreading simulations for all seven years.

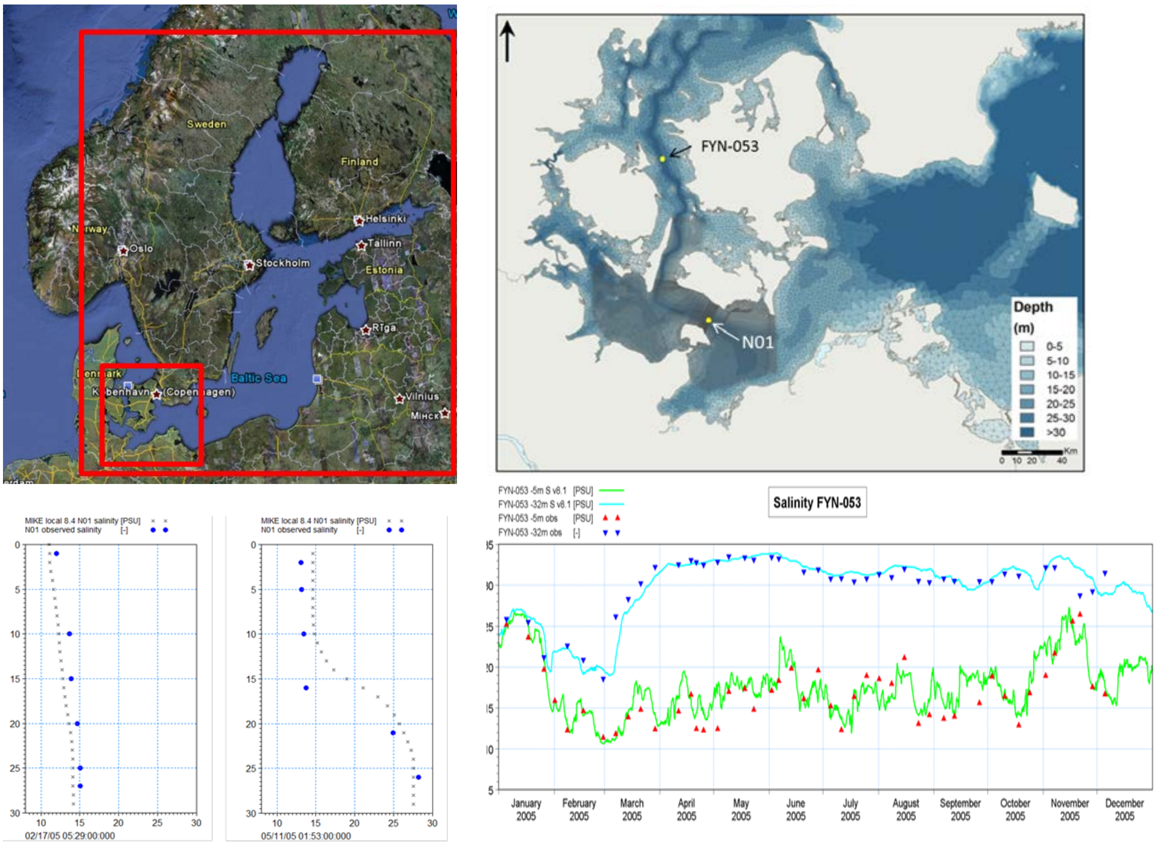


Figure 5. Upper left: the extent of the regional hydrodynamic model. Upper left: the local numerical model area showing computational mesh. Lower left: comparison of measured and modelled salinity at the station M01 at a point in time with no stratification and one with stratification. Lower right: comparison of measured and modelled salinity near surface and bottom at the station FYN-53.

Sediment Spreading

The spreading of losses of sediment from the soil handling is simulated in a 3D advection-dispersion model (MIKE MT) which uses the same resolution as the hydrodynamic model and covers the so-called local model area, see Figure 5. For a description of the model, see FEHY (2013e). The deposition and erosion processes are described as proposed by Krone (1962) and Parchure and Metha (1985) and bed shear stresses in the combined wave-current conditions are calculated using the model of Fredsøe (1981). The settling velocity of the sediment grains is a key parameter in determining the extent both of the sediment plumes around the construction works but also the migration of the fines when these are re-suspended during events of strong currents which in the near shore zone may be combined with wave action. The settling velocities have been determined partly by testing of soil samples from the geotechnical boreholes and partly from measurements in the field in connection with full scale spill experiments in the field. The geology along the alignment as determined based on geotechnical cores is shown in Figure 6. It appears that the tunnel trench will be dredged in various layers of glacial deposits. In total 76 samples from the relevant layers have been tested in the laboratory for primary particle distribution and distribution of settling velocity by 3 hours' long Owen type tests. In the full scale experiment slurry of dredged material with the estimated spill rates of about 20 kg/s of spill sediment was released near the surface. The variation in the floc size was measured in the plume using a LISTT for in situ measurements. These field experiments showed that during the first one-two hours after the release the primary particles formed flocs with stable sizes. An example of the development of the grain size distribution just after the release is shown in Figure 7. The distribution of settling velocities for each of the representative soil types is constructed from the experiments, see an example in Figure 7. Each soil type is represented in the numerical model by 5 fractions each characterized by a settling velocity. The initial hours where the flocs form have been neglected in the numerical model set-up. The distribution on the 5 fractions for each soil type is listed in Table 1. For further discussion of the representative settling velocities, see Bundgaard et al (2011).

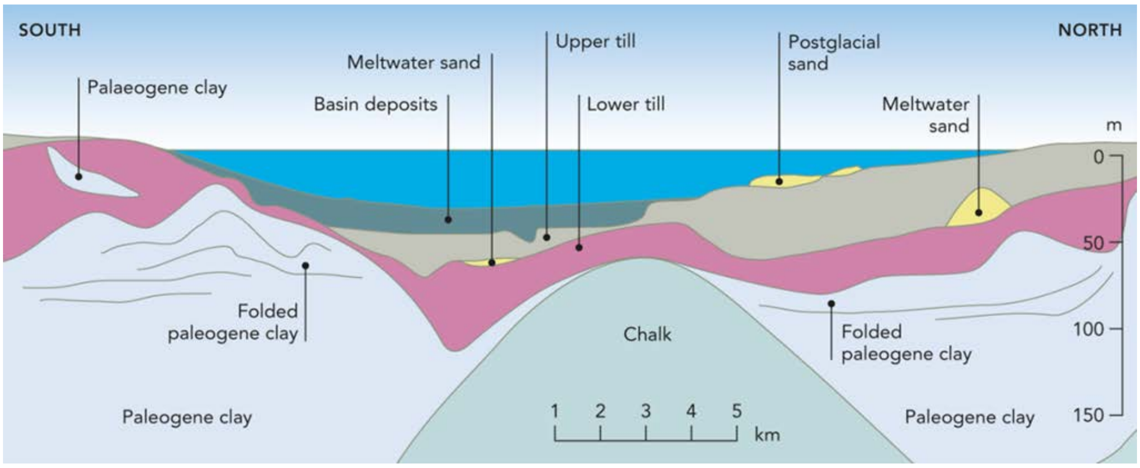


Figure 6. Overview of geology across the Fehmarnbelt.

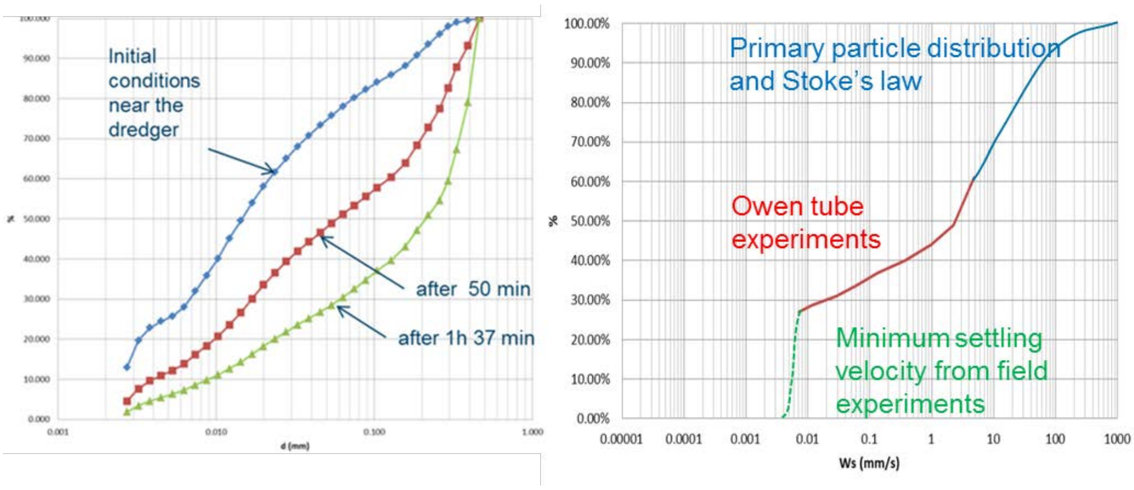


Figure 7. Left: measured grain size distribution in the plume from a trial dredging. Right: example of distribution of settling velocities based on primary particle sizes, experiments in Owen types and measurements in the field.

Table 1. Distribution on fractions.

fraction	0	1	2	3	4
w [mm/s]	15	2.92	0.56	0.07	0.03
d [mm]	0.147	0.065	0.028	0.01	0.007
Paleogene clay	0.15	0.11	0.14	0.14	0.47
Late glacial clay	0.23	0.12	0.11	0.35	0.19
Gyttja	0.12	0.10	0.16	0.31	0.32
Clay till	0.45	0.17	0.09	0.11	0.18
Late glacial sand/silt	0.63	0.14	0.17	0.06	0.00
Post glacial sand	0.50	0.15	0.22	0.04	0.09
Glacial melt water sand	0.90	0.05	0.03	0.00	0.03

Ecology

Ecological modelling (MIKE ECOlab) was used to quantify the impacts arising from spilled sediment on water quality, benthic flora (FEMA 2013b). Dredging activities are variable in intensity, spatial scope and duration during a project period and thus impacts on light attenuation and growth depend on the timing of the activities and the sensitivity of the different species. The ecological model describes the relationships and interaction between sediment, light availability and primary producers, between nutrients and primary producers, as well as the interrelationship and inter-specific competition between three distinct groups of producers; pelagic phytoplankton, benthic macroalgae (three different groups) and rooted vegetation (eelgrass).

Light attenuation due to sediment spill. Sediment spilled during dredging vary in composition and therefore also in their optical properties, where the organic content, size distribution and shape of particles are important for the mass-specific light attenuation (Baker and Lavelle 1984, Bowers and Binding 2006, Woźniak et al. 2010). The attenuation of light is the combined effects of two processes in the water column, namely the scattering of light and absorption of light. The scatter of light scales to cross-sectional area of particles (living and dead, inorganic), while the mass-specific scatter (b*) including a diffraction effect is a function of the diameter of a (spherical) particle and the density of the particle (Bowers and Binding 2006). Besides area, surface properties of particles such as their refractive index are important for the mass-specific scatter.

Three experiments with different sediment types from the alignment area were carried out in order to measure mass specific light attenuation by different size fractions of sediment from the Fehmarnbelt.

Quantifying impact of changes in light conditions on marine primary production. The model simulates growth of four model species of benthic flora that represent eelgrass and three different form-functional groups of macroalgae. Effect of light on growth rate is described by saturation functions, where light requirements differ between the defined groups: eelgrass (*Zostera marina*), filamentous macroalgae (model species is *Ceramium virgatum*) with high light requirements and most abundant in shallow water, coarsely branched macroalgae (model species is *Furcellaria lumbricalis*) having intermediate light requirements and living in the depth range 2 to 8-10 m and coarsely branched folious macroalgae (model species is *Delesseria sanguinea*) having the lowest light requirements and living in the depth range 8-19 m.

The benthic flora is quantified in terms of biomass (e.g. g C m^{-2}). In their whole life stage eelgrass and macroalgae remain fixed at the bottom. Loss occurs by sloughing of aged leaves, by respiration (C and nutrients returned to inorganic pools) and by loss to the detritus pool. Besides light efficiency, nutrient requirements, source of nutrients (water, sediment and water) and substrate are the main factors that differentiate the groups in the model. Sub-optimal conditions in any limiting factor will result in growth rates below the maximum. The joint dependence of nutrients, temperature and light is defined by separate growth limiting factors, that range from 0 to 1, where a value of 1 means the factor does not limit growth (i.e. light is at optimum intensity, nutrients are available in excess, etc.). The limiting factors are then combined with a maximum growth rate at a reference temperature.

Initially, benthic flora species are allowed to grow everywhere although being restricted by requirements to light, sediment quality, nutrients etc. After a model warm-up period they sustain only where sediment conditions, nutrient and light conditions are appropriate. Distribution and biomass of macroalgae are thereby intrinsic model outputs. Figure 8 shows the conceptual outline of the ecological model and the key processes.

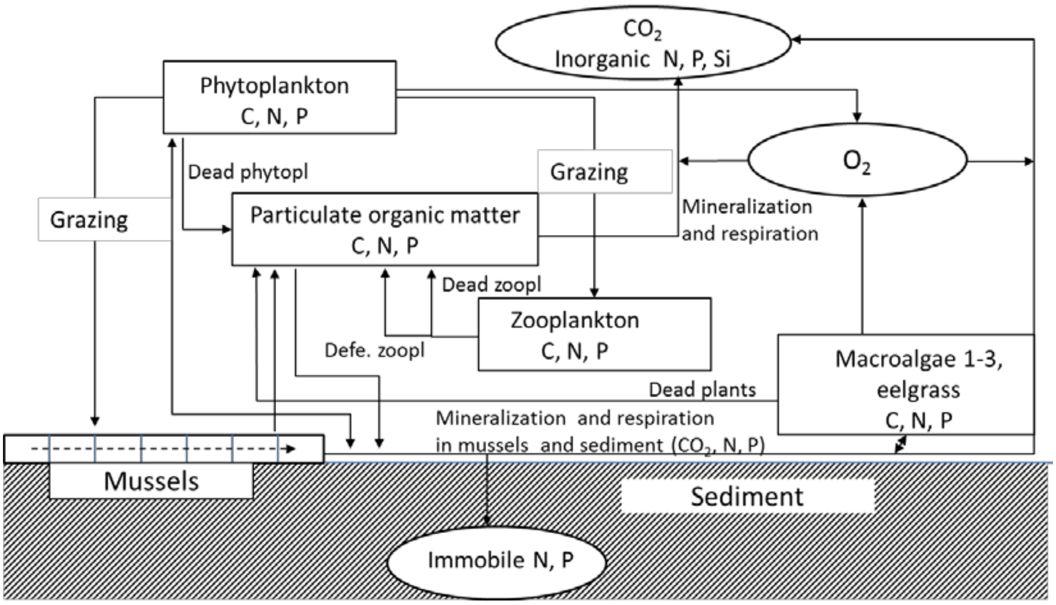


Figure 8. Concept of the ecological model.

Effects of filter feeders, bio-turbation and consolidation of deposited fines have been neglected which result in conservative estimates of impacts from the sediment spill.

SENSITIVITY

The above outlined model complex has been used to test the sensitivity of the aquatic environment to losses of sediment from the construction works. Below is given two examples of such sensitivity tests. The Rødsand Lagoon on the Danish coast is an approximately 40 km by 15 km shallow area covered for large parts with eelgrass. The lagoon is located more than 6 km east of the planned dredging works. The lagoon is protected by low sandy barrier islands which are flooded only in connection with low depressions passing on the North Sea, the Danish waters and the Baltic Sea. The daily exchange of water is also dominated by the meteorological conditions as the tidal variation is almost negligible. This has formed a very special environment and the area is protected as a Natura 2000 site. The impact of light reduction on the growth of eelgrass in the lagoon has been tested for a) seasonal variability in the sediment spill in the fixed link alignment and b) for the amount of sediment spill which enters the lagoon. The amount spilled is indirectly a way to understand if spill from the tunnel trenching and reclamation works is more critical in the near shore zone than further away from the shore. The spilled sediment migrates along the coast towards east and west initially and subsequently during each event where the critical bed shear stress for erosion is exceeded. After a period of time the fine fractions of the spilled sediments build up in front of the lagoon. In subsequent events with wave action, rising water level and flow towards the lagoon fine sediments are carried into the lagoon. Inside the lagoon the extra sediment increases the turbidity and thereby reduces the light at the bottom available for photosynthesis and growth of eelgrass.
Figure 9 shows the resulting reduction in eelgrass biomass in the lagoon at the end of the growth season (1 September). Four different constant spills are tested: all are released 1 km from the coast, and continue during a 3-month period. The reduction in eelgrass biomass is about 3 times larger if sediment is spilled during the main growth period in spring and summer than during autumn and winter.

Figure 10 shows similarly the reduction in eelgrass biomass as a function of the distance of the spill from the coast. In this case the spill rate is constant over nine months starting 1 December but tests are made for spill 1 km, 3 km and 8 km from the coast line. The part of the spill which enters the lagoon decreases with distance from shore of the release point. The reduction in eelgrass biomass is predicted to be 2.5 times larger when the release point is 1 km from the shoreline compared to 8 km from the shoreline.

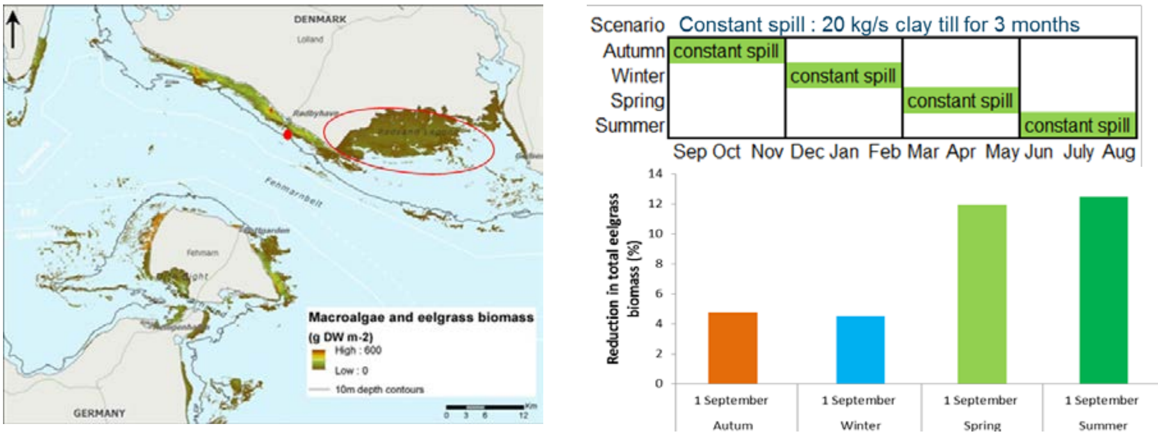
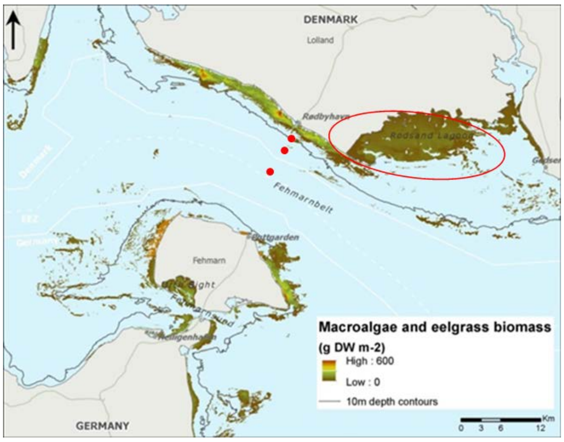


Figure 9. Sensitivity of eelgrass in Rødsand Lagoon to the timing of spill. Left: eelgrass biomass in the lagoon and the release point of sediment spill. Right upper: illustration of spill periods. Right lower: reduction in biomass at the end of the growth season in case of spill in the autumn, the winter, spring or summer.



Scenario: Constant spill: 20 kg/s clay till from December to end of August, 1 km, 3 km and 8 km from the Danish Coast

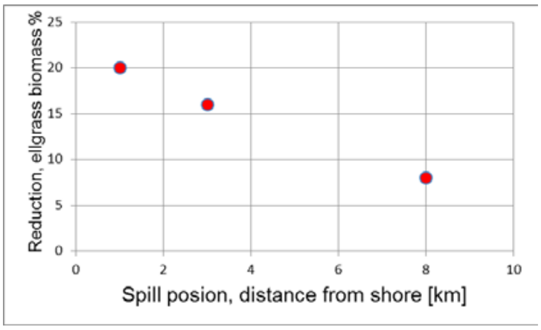


Figure 10. Modelled reduction in eelgrass biomass in Rødsand Lagoon as a function of the distance of the spill from the Danish Coast (due to different amounts of sediment entering the lagoon).

TESTING OF A REALISTIC SCENARIO

The environmental impact assessment developed to obtain approval of the project included the testing of the full construction period with regards to effects of the sediment spill. The majority of the construction activities which leads to sediment spill are expected to be concentrated within a two-year period in the beginning of the construction period. A part of a realistic spill scenario is sketched out in Figure 11. Each and every spill operation is represented in the spill model with exact location, dredged soil type, distribution over the water column of the sediment spill, spill rate and start and end of the operation. The spill simulations provide time series of the (temporal) deposition on the sea bed as well as suspended concentrations over the water column and over the entire model area for the entire construction period. These results are utilised in the ecological model which leads to quantification of among other parameters the development of the eelgrass. The results from the models are also analysed statistically. Figure 12 and Figure 13 show examples of analysed results: the exceedance of the 2 mg/l during the first year with most dredging activity for the lost sediment at the locations where the background concentrations have been measured as part of the baseline, the simulated reduction of eelgrass at the end of the growth season in the worst year and the final deposition of the lost sediments at the end of construction after 7 years (FEMA 2013c). The latter figure illustrates how the fine lost sediment is transported to natural deposition areas.

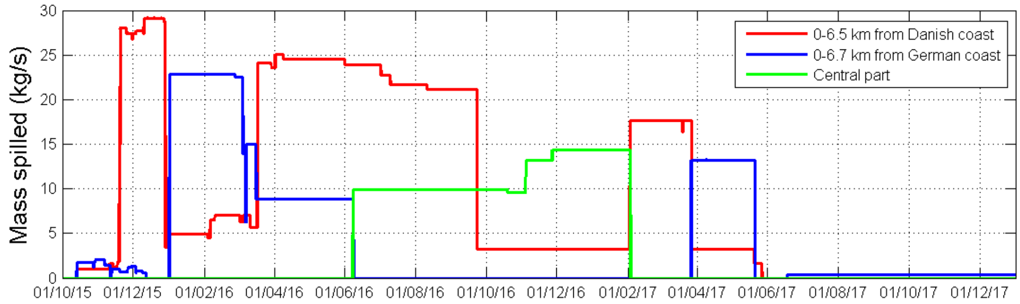


Figure 11. Overview of the spill during part of the construction period for a realistic spill scenario.

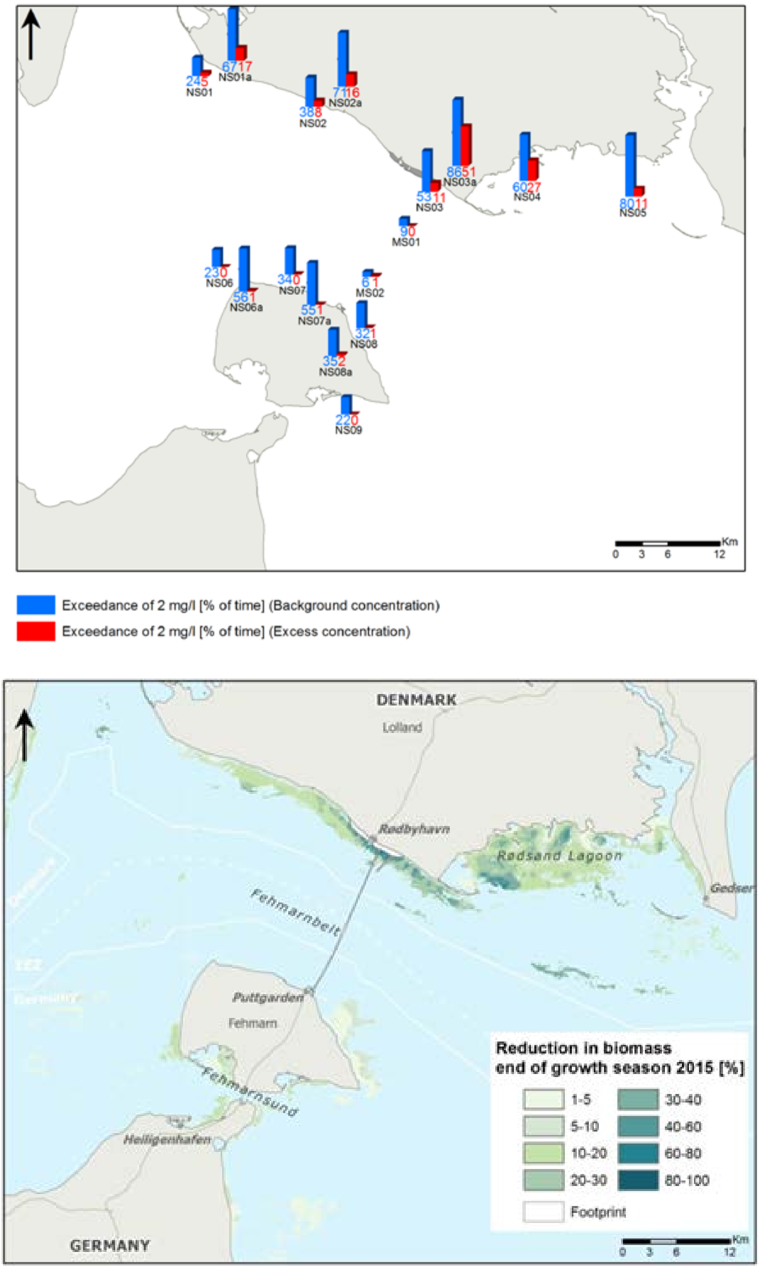


Figure 12. Examples of results from simulation of a realistic spill scenario. Upper plot: Exceedance of 2 mg/l from the lost sediment during the first year of dredging compared to measured exceedance of 2 mg/l. lower plot: Reduction in benthic biomass at the end of the first growth season (FEMA 2014c).

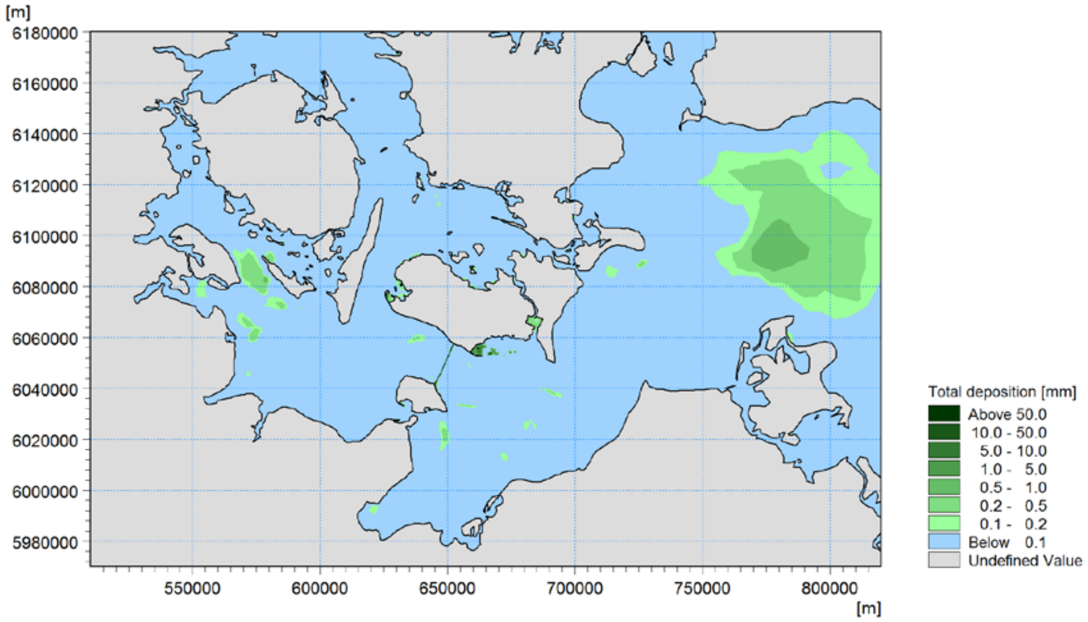


Figure 13. Simulated deposition thickness of spilled sediment at the end of the construction period.

CONCLUSIONS

The detailed model set-up for simulation of hydrographic conditions, spreading of lost sediments and ecological key parameters has proven to be an efficient tool for undertaking sensitivity testing of different spill locations, timing of spill and comparisons of complete spill scenarios.

The simulation of a realistic construction scenario has demonstrated that the fixed link between Denmark and Germany can be built with only minor temporal effects except in areas where the structures occupy the sea bed or the coast lines. The sediment plumes from the soil handling will be visible during construction but only in short periods of time at the same locations and thereby with only minor effects on benthic flora and fauna as well as on bathing water quality in these areas.

Further, the modelling of the ecological response to the loss of sediment has illustrated that at this location the impact of a spill can appear long after release, due to the transport including several re-suspension events. This emphasises the need in this case for controlling the spill amounts according to a predetermined acceptable dose analysis, instead of monitoring effects and based on observed changes in the environment to correct the construction scheme if unacceptable impacts are observed.

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