Nord Stream AG

# Offshore pipeline through the Baltic Sea

Memo 4.3A-5

Spreading of sediment and contaminants during works in the seabed

September 2008


RAMBØLL

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## List of abbreviations and definitions

| | |
|---|---|
| Bioavailability | The dissolved and chemical forms of a chemical compound that can be taken up by organisms and/or interact with receptors. |
| Desorption | A phenomenon whereby a substance is released from or through a surface. |
| Flocculation | The process by which fine particulates are caused to clump together into floc(s). |
| KP | Kilometres from Russian landfall. |
| PEC | Predicted environmental concentration. |
| PNEC | Predicted no-effect concentration. |
| Pycnocline | A layer across which there is a rapid change in water density with depth. |
| Sorption | The action of either absorption or adsorption. Absorption is the incorporation of a substance in one state into another of a different state (e.g., liquids being absorbed by a solid or gases being absorbed by water). Adsorption is the physical adherence or bonding of ions and molecules onto the surface of another molecule. |
| Source strength | Also termed the spill rate, defines the amount of sediment released per time. |
| Speciation | The transformation process of a chemical in the environment to a species not having the same properties of the pure parent chemical. |
| Cd | Cadmium |
| Hg | Mercury |
| Pb | Lead |
| Zn | Zinc |
| Cu | Copper |
| As | Arsenic |
| Cr | Chromium |
| Ni | Nickel |
| SUM16PAH | Sum of 16 selected Polycyclic Aromatic Hydrocarbons (PAH) |
| TBTIN | Tributyltin - non-specified atoms/molecules bound to tributyltin. |

# 1. Introduction

## 1.1 The Nord Stream project

Nord Stream is a natural gas transmission twin pipeline from Russia to Germany with connections to onshore transmission systems in these two countries, which is to be build by Nord Stream AG. It passes through the exclusive economic zones (EEZ) of five countries: Russia, Finland, Sweden, Denmark and Germany, and the territorial waters of Russia, Germany and Denmark. It will at full capacity provide 55 billion cubic metres (bcm) of natural gas per year to West European consumers. Nord Stream is a priority project in the Trans-European Network – Energy (TEN-E).

The shareholders of Nord Stream AG are OAO Gazprom, Wintershall (a BAsF subsidiary); and E.ON Ruhrgas (an E.ON subsidiary). Soon the company NV Nederlandse Gasunie will join the shareholders group.

Nord Stream AG is based in Zug, Switzerland, with a branch office in Moscow. The company is responsible for the development and construction of the offshore twin pipeline and will be the operator of the gas-transmission system.

The Nord Stream project includes two offshore transmission pipelines between Russia and Germany with an offshore service platform located in the Swedish EEZ north-east of Gotland Island.

## 1.2 Spreading of sediment and contaminants during works in the seabed

A certain disturbance or spill of seabed sediments must be expected in connection with works in the seabed such as rock placement or trenching/dredging.

The sediment will be transported by the current and deposited again after some time. In some areas, the seabed sediment may contain increased levels of chemicals, heavy metals and organic or inorganic pollutants. These substances will be transported with the sediment or may partly be dissolved in the water.

Based on the planned seabed works and a study of the current climate and the sediment characteristics, this memo evaluates the spreading of sediments and contaminants due to works in the seabed in connection with the Nord Stream project. The primary goals are to assess the concentration and duration of suspended sediment and contaminants as well as the resulting net sedimentation.

# 2. Summary

The spreading of sediments and contaminants due to works in the seabed in connection with the Nord Stream project are studied with respect to the following types of activities based on information obtained from Snamprogetti:

- Post- and pre-lay rock placement by fall pipe
- Post-trenching by plough
- Pre-dredging by scoop dredger or excavator

Some disturbance of the seabed must be anticipated in the vicinity of the pipeline due to e.g. trenching spoil heaps, rock piles, and construction of dams. This disturbance has roughly been assessed as being within the order of 100 m from the pipelines and consequently only particles eligible of being transported more than in the order of 100 m away from the pipelines are considered, i.e. clay, silt and very fine sand.

For trenching and dredging the spill rate is found as respectively 2 and 10% of the trench volume applying a continuous average working speed of respectively 300 m/hr and 150 $m^3$/hr. For rock placement the amount of suspension is estimated at ~1 % of the rock volume and the suspension rate is taken to be proportional to an average rock placement rate of 500 T/hr. The resulting spill rate of sediment is app. 20 kg/s for trenching, 1 kg/s for rock placement and 7 kg/s for dredging.

Properties of seabed sediment and contaminants were adopted from PeterGaz Ltd reports, existing databases, literature and new sediment samples along the pipeline corridor.

The spill is distributed according to some of the grain-size samples with the highest content of clay, silt and very fine sand for each country and work type. The associated settling velocities of respectively app. 0.13, 0.40 and 2.41 mm/s are based on flocculated grain sizes reflecting actual measurements from estuaries. The spill is released respectively 5 and 2 m above the seabed for trenching (plough) and rock placement (fall-pipe) reflecting the proximity of the works to the seabed. The spill from dredging is released 2m below the surface.

The chemical compounds found to be present in the Baltic Sea and with the potential to cause ecotoxicological effects are: Cd, Hg, Pb, Zn, Cu, As, Cr, Ni, PAH's and TBTIN. The release of the chemical compounds are based on the $90^{th}$% fractile of the measured sediment bound concentrations for each country and conservative values for desorption and bioactivity.

The risk of causing ecotoxicological effects is assessed by considering the ration between the predicted no-effect concentration (PNEC) and the predicted environmental concentration (PEC) according to the following pattern:

- PEC/PNEC ≤ 1: No adverse effects are anticipated.
- PEC/PNEC > 1: Adverse effects may occur.

It is found that Cu and PAH's are the relatively most toxic chemical compounds.

The general numerical particle analysis model MIKE 3 PA developed by DHI Water – Environment – Health is used to simulate the transport and fate of dissolved and suspended substances in three dimensions. The model uses a Lagrangian-type approach, which involves no other spatial discretisations than those associated with the description of the bathymetry, current and water level fields.

The particle analysis model is forced by hydrodynamic data from 2005, including currents, salinity and temperature, acquired from a numerical 3D model of the Baltic Sea, run by DHI, Denmark. 3 different hydrographical periods (calm, normal and rough) are applied to study the variability in the spreading. Each model result is thus an outcome of specific hydrographical conditions and should be seen as an example of a representative event and not as an exact result of what will actually occur.

For each type of seabed works the following main results are found:

<u>Rock placement by fall-pipe (Sweden, Finland, Russia):</u>

- A total area of about 2 $km^2$ (within a few 100 m of the pipelines) may experience a suspended sediment concentration > 10 mg/l with an average duration of 5 – 8 hrs.
- Any significant net sedimentation (> 1 mm) is expected only in very minor areas beyond the close vicinity of the pipelines (> 100 m away).
- A total area of 100 – 200 $km^2$ (typically within about 5 km from the pipelines) may experience an exceedance of the PNEC value of Cu and PAH for typically ½ - 1 day on average and up to ~3 days at certain locations.
- For contaminants the areas and duration of concentrations > PNEC may vary up to +/-25% from average due to different hydrographical conditions. During rough weather exceedance is seen up to about 10 km from the pipelines in few locations, but the overall exceedance is most significant during calm conditions.

<u>Trenching by plough (Germany, Denmark, Sweden):</u>

- A total area of about 100 $km^2$ (generally within ~1 km of the pipelines) may experience a suspended sediment concentration > 10 mg/l with an average duration of 2 – 5 hrs.

- Any significant net sedimentation (> 1 mm) is expected only in very minor areas beyond the close vicinity of the pipelines (> 100 m away).

- For sediment the areas and durations of suspended concentrations vary less than +/- 20% from average due to different hydrographical conditions. The trend is that calm conditions cause longer exceedance durations covering smaller areas.

<u>Dredging by excavator (Russia):</u>

- A total area of about 6 $km^2$ (generally within a few km of the pipelines) may experience a suspended sediment concentration > 10 mg/l with an average duration of about 12 hrs.

- A total area of 1 - 2 $km^2$ (generally within 1 km of the pipelines) may experience a net sedimentation > 1 mm.

It is concluded that the applied methods for trenching (plough) and rock placement (fall-pipe) mainly causes a disturbance in the close vicinity (within the order of 100 m) of the pipelines.

The suspension of sediment is generally far too minor to produce a visible sediment concentration (> 1 mg/l) in the water more than a few hundred meters away and only primarily in the lower part of the water column. The resulting net sedimentation is therefore also very minor (< 1 mm) when more than a few 100 m from the pipelines.

Since conservative assumptions have been applied for assessing the governing input parameter, the sediment spill rate (1-20 kg/s), the results are considered to be on the safe side and only weakly sensitive to other parameters.

Dredging (only Russian landfall) is expected to cause some visible sediment concentrations and net sedimentation in excess of 1 mm as quantified above.

It is found that a release of the most critical chemical compounds Cobber (Cu) and PAH’s (SUM16PAH).may cause an exceedance of the PNEC values at the major rock placement sites. However, the release of contaminants is based on rather conservative assumptions, including:

- $90^{th}$% fractile of the measured sediment bound concentrations

- High values for desorbtion and bioactivity in the water body

- No decay, settling or biodegradation after release

- Fast average discharge (i.e. little non-productive working time)

The actual observed concentrations are therefore expected to be less. Further it is noted that the main ecotoxicological impact potential of the pipeline project is not caused by an emission of chemicals, but by a redistribution of depositions of chemical compounds already present in the Baltic Sea.

# 3. Type of works in the seabed

Based on references /1-10/ the following types of planned seabed works have been identified:

- Post- and pre-lay rock placement by fall pipe
- Post-trenching by plough
- Pre-dredging by scoop dredger or excavator
- Artificial backfilling by plough

The types of work are described below and the scopes of work are shown in tables in Appendix A: Model basis and on maps in Appendix B: Atlas maps.

## 3.1 Rock placement (fall-pipe)

The designation 'rock placement' covers gravel works where coarse gravel and small stones are placed to locally reshape the seabed to ensure the long term integrity of the pipeline. Rock placement and gravel works are primarily required as follows:

- Support for free-span correction (pre-lay and post-lay)
- Cover (post-lay) as additional stabilisation of the pipeline
- Basements where major pipe sections are welded together (tie-in)

In addition rock placement may also be considered as a means to provide local protection at cable crossings and from dropped or dragged anchors and to some extent ship grounding.

Assuming that the material used for rock placement is very coarse, it is anticipated that any sediment spill from rock placement activities will be related to suspension of the natural sediment duo to the induced momentum of the placed rock material.

The material is assumed to be placed via a pipe, see Figure 3.1, in order to fulfil construction requirements. The rock will consequently not fall freely through the water column, and consequently the induced momentum is reduced. The resulting disturbance of sediment is therefore limited. According to /11/ the resulting impact of rocks striking the pipeline was comparable to a brick being dropped app. 15 cm in air.

Gravel and stones are transported by ship to each particular position where rock-placement is required. The rock material is loaded into the fall pipe by conveyors on the ship. The rock material falls through the water column in the fall pipe. The geometry of each gravel support has been designed according to seabed conditions, bathymetry in the surroundings, currents etc. The lowest part of the fall pipe is equipped with nozzles to allow a precise shaping of each gravel support.

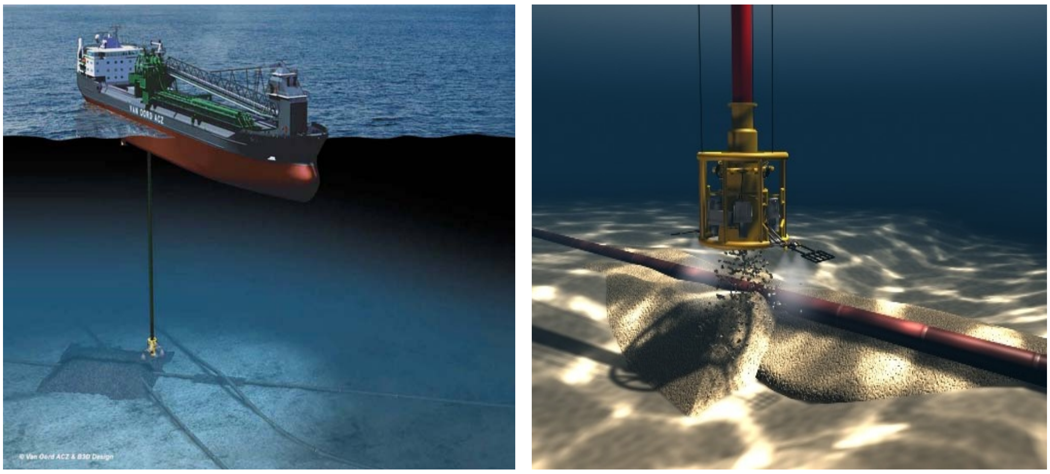


Figure 3.1 Flexible fall pipe vessel and placement of stones, /12/.

Typical examples of rock placements are shown in Figure 3.2, /13/. Rock placement on soft clay with a low bearing capacity or a sloping seabed may compromise the geotechnical stability. Under most circumstances such issues are solved by additional rock placement as counter-fill around the required gravel berms as shown in Figure 3.3, /14/.

In rare occasions, when counter fill is not feasible, special foundations may be placed at the seabed, /15/. Special foundations are light constructions that ensure the necessary support for the pipe under difficult geotechnical conditions. A variety of foundations exist, cf. /16/, but all are light constructions, often pre-fabricated. This includes very few structures being placed with high accuracy at the seabed and is not considered further in this memo.

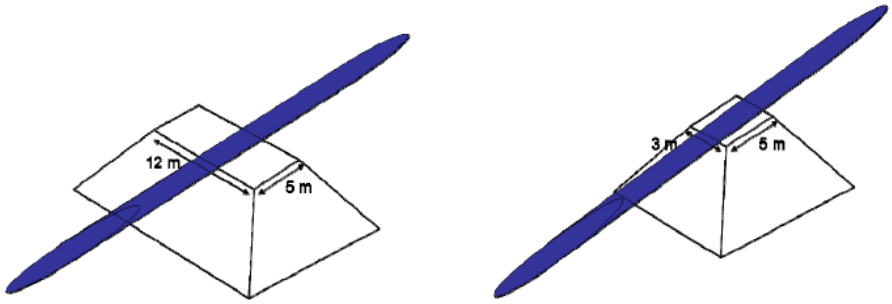



Figure 3.2 Typical pre- and post-lay rock placement, /17/.

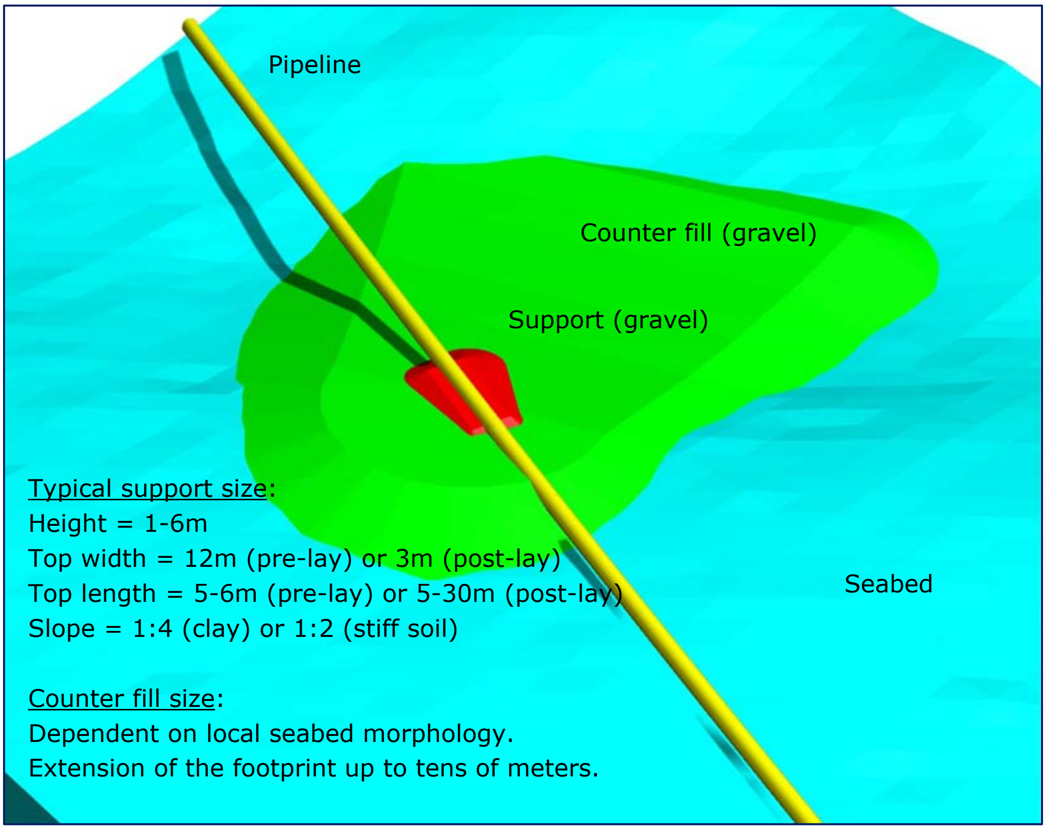


Figure 3.3 Purpose developed counter fill, /18/.

Placement of rock through fall-pipe may reach a discharge of 2000 T/hr according to /12/. However, some non-productive working must be expected e.g. due to weather conditions, displacement of vessels etc. During a rock placement program securing twin pipelines across the Michigan Straits with 24-hr operation and average placement rate of 145 T/hr were obtained, /19/.

## 3.2 Trenching (plough)

Post-lay trenching means that the pipeline is laid onto the seabed and subsequently lowered to the required depth, using a machine moving along and guided by the pipeline. Post-lay trenching in connection with long marine pipelines is often performed by ploughing or jetting.

The jetting technique has a wider influence on the local benthos than the plough, but it leaves behind lower and more dispersed spoil heaps, as most of the finer sediments, i.e., the silt and clay fractions, will likely be brought into suspension, resulting in a sediment flume from the trenching operation. This type of trenching will be avoided in the Nord Stream project.

The plough mechanically moves the material on the seabed, resulting in a V-shaped furrow with the spoil pushed up on either side of the trench. A variety of ploughs are in use for both small- and large-diameter pipelines, normally being pulled by powerful tugs, see Figure 3.4 and Figure 3.5.

The resulting sediment disturbance is very local. However, the spoil heaps can be prominent in harder cohesive soils. The spoil heaps can be used for backfill and therefore can be evened out. Ploughing is fast but may be limited by insufficient pull force in harder soils, /20/. For deep trenches more than one pass may be necessary.

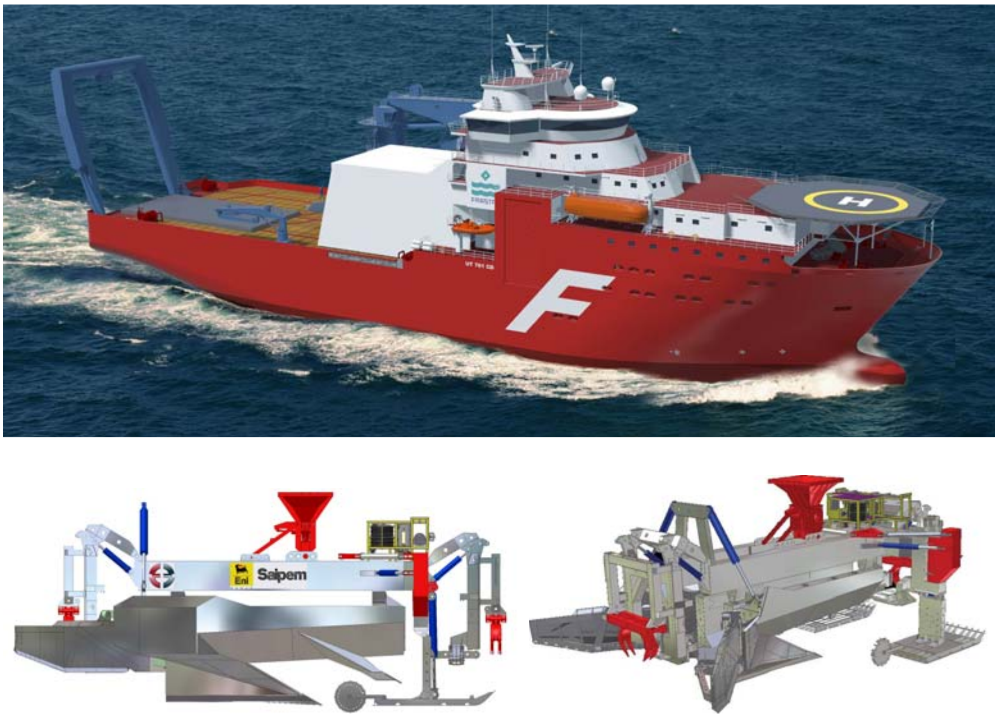



Figure 3.4 Far Samson plough support vessel and PL3 pipeline plough, /21/.

The pipeline plough is deployed onto the seabed from a mother vessel above the pipeline. The pipeline is then lifted by hydraulic grippers into the plough and supported on rollers at the front and rear ends of the plough. The rollers are equipped with load cells to control the loading onto the pipeline during trenching. Towlines are connected to the plough. Between one and three tugboats are used to pull the plough through the seabed, producing the trench. This method causes a limited displacement of seabed sediment, yielding a low overall disturbance of the seabed as well as a low sediment release, see Figure 3.5.

Reported ploughing speed (without non-productive working time) with a VMP plough in very soft clay is 300 – 500 m/hr, /22/. If encountering harder soils a shallower trench may be dug, requiring more passes or a change of plough, /20/.

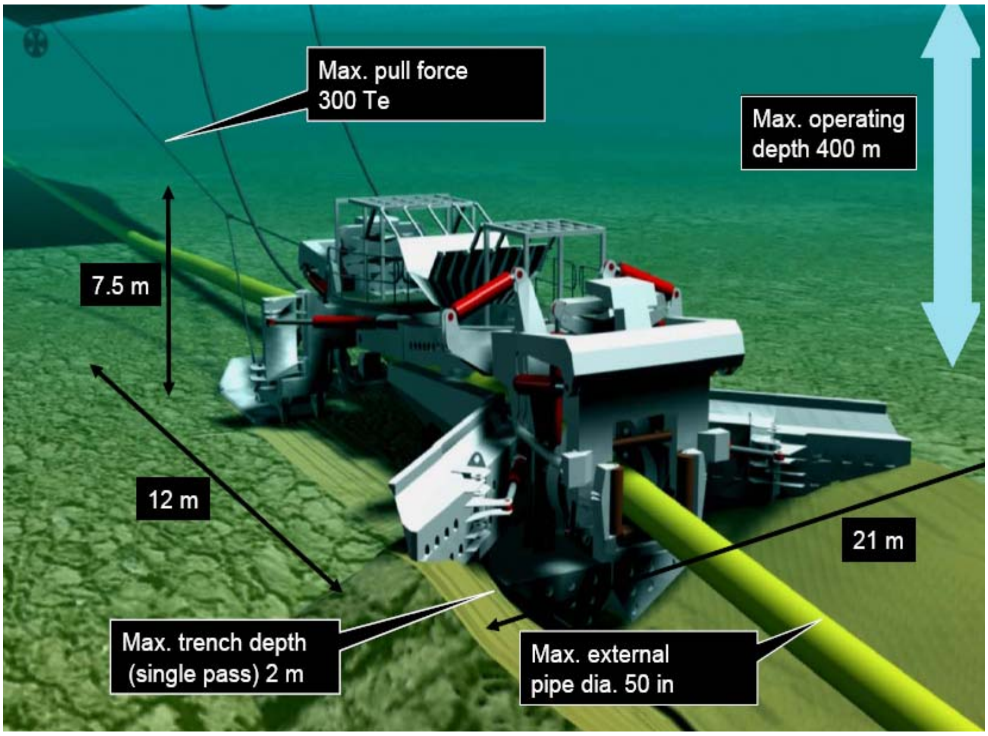



Figure 3.5 Pipeline plough PL2 in operation on the seabed.

## 3.3 Dredging (scoop/excavator)

Dredging means that the pipeline is laid directly into a pre-dredged trench. Pre-dredging can be performed using a variety of mechanical and hydraulic dredgers. The dredged material can be removed and transported to a permanent or preliminary dumping site for later backfilling. The spill can vary substantially, depending on the dredging method and seabed characteristics.

The excavation of the trench in the shallow coastal area is planned to be done by means of a scoop dredger of the type "At Your Service" of the company MPTC with the excavator Liebherr P994 or similar, see Figure 3.6, /23/. The movement of the scoop dredger is facilitated by a system of hydraulic spuds. The excavated soil will be placed to a burrow along the trench in a distance of app. 15 m and then used for backfilling after the pipeline has been laid.

In soft soil the volume is limited by the bucket capacity. The production capacity depends on the cycle time of the bucket and the step procedure of the pontoon. Dredging for landfall is likely within a time frame of a few weeks according to time schedule.

Figure 3.6 The scoop dredger “At Your Service” of the company MPTC, /24/.

## 3.4 Backfilling (plough or artificial)

For safety reasons backfilling of the trench is usually carried out. Backfilling may be carried out by two different methods:

- Backfill ploughing: The material from the edges of the trench is moved mechanically into the trench (Only applicable if spoil heaps are available from previous trenching).
- Artificial backfilling: The material is transported to the site by barges and placed into the trench.

Material ploughed into the trench will mainly be material that has been handled once during the trenching or dredging operation, meaning that some part of the fine fractions have been washed out.

Material transported to the site for artificial backfilling is most likely coarse sand, gravel or crushed rocks. Any fine material would be transported away from the site by currents, making it inappropriate for backfilling, as it increases the required volumes.

In any case, the backfilling material is expected to have limited fine-material content and consequently will not lead to any significant spill compared to the trenching or dredging operation itself. Therefore, spill from backfilling is not modelled specifically.

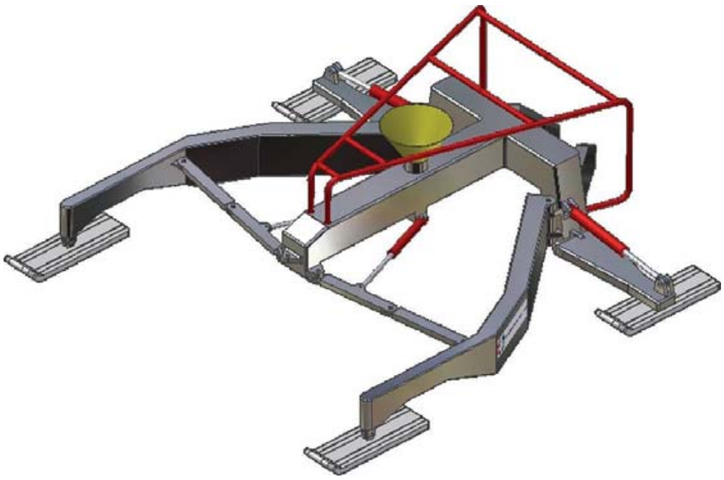


Figure 3.7 Backfill plough – BPL3, /25/.

# 4. Spill release and disturbance of the seabed

The possible disturbance from seabed work is dependant of how much and what kind of sediment is spilled during the works, as well as how fast and where in the water column the spill is released.

## 4.1 Disturbance in the close vicinity of the pipelines

Some disturbance of the seabed must be anticipated in the vicinity of the pipeline (area of seabed works and release of spill) due to e.g. trenching spoil heaps, rock piles, and construction of dams, see Figure 4.1. This disturbance is roughly assessed as being within the order of 100 m from the pipe-lines based on information of trench and rock pile dimensions, see e.g. /26, 27/. Consequently only particles eligible of being transported more than in the order of 100 m away from the pipeline are considered. Normally this means the fine fraction of sediment (clay, silt and possibly very fine sand), cf. section 5.6.

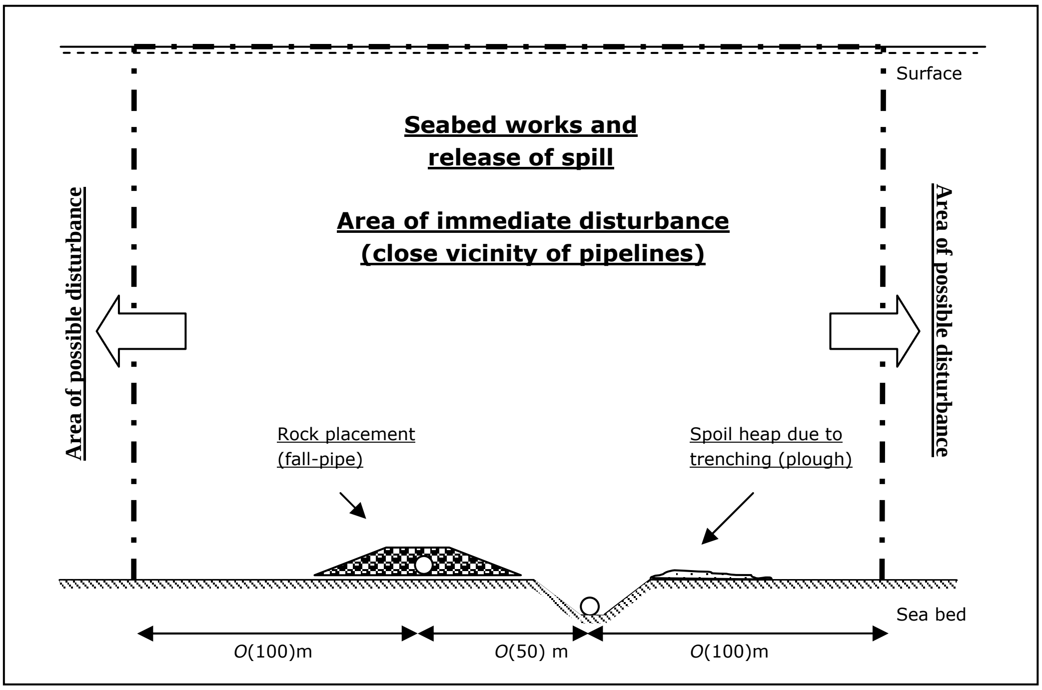



Figure 4.1: Seabed work and disturbance areas.

The disturbances in the close vicinity of the pipelines with regard to seabed works see Figure 4.1, are significantly different from what is caused by any suspended sediment. These areas have been estimated for reference/comparison.

The total footprint area of rock placed on soft soil can be considered as the sum of the footprint of the nominal support and of the footprint of the stabilization counter fill. The footprint area of the nominal pyramid shaped support can be evaluated starting from the area of the top of the gravel heap and assuming a 1:2 side slope, i.e.

$$Area_{\sup port} = (L + 2 \cdot H \cdot Slope) \cdot (W + 2 \cdot H \cdot Slope)$$

Where:

- L = top length
- W = top width
- H = height
- Slope = Side slope

The ratio between nominal support (An) and counter fill (Ac) footprints area have been evaluated as averagely Ac/An = 15, /28/.

A rough estimate of the area of foot print of the pipeline, the rock placements and the trenching are given in Table 4.1. The areas of trenching (trench + spoil heaps) are based on a total corridor (width) of 20 m trench + 2*15 m spoil heaps = 50 m, see Figure 3.5).

In total the area of immediate disturbance is app. 10 $km^2$ per pipeline (in principle part of the pipeline area is overlapped by the rock placement foot prints and trench-ing spoil heaps).

Table 4.1 Area of disturbance in the close vicinity of the pipelines (for 1 pipeline).

| | Pipeline[1] | | Rock placements[2] | | Trenching[3] | |
|---|---|---|---|---|---|---|
| **Country [-]** | **Length [km]** | **Foot print [$km^2$]** | **Sites / Locations [#]** | **Foot print [$km^2$]** | **Length [km]** | **Trench + heaps [$km^2$]** |
| **Germany** | 85 | 0.1 | - | - | 42.8 | 2.1 |
| **Denmark** | 195 | 0.3 | 25 | <0.0 | 16.0 | 0.8 |
| **Sweden** | 447 | 0.6 | 70 | 0.1 | 69.5 | 3.5 |
| **Finland** | 370 | 0.5 | 103 | 0.3 | - | - |
| **Russia** | 123 | 0.2 | 171 | 0.6 | - | - |
| **Total** | **1,220** | **1.7** | **369** | **1.1** | **128.3** | **6.4** |

[1] Based on a pipe diameter of 1.4 m.
[2] Based on estimated geometry of nominal and counter fill rock placements.
[3] Based on a 50 m wide corridor (rough estimate, see Figure 3.5).

## 4.2 Spill rate for trenching and dredging operations

For particles eligible of being transported more than in the order of 100 m away from the pipeline a spill rate is applied as input to the numerical modelling simulations. Seabed works that are disturbing the seabed sediments are regarded as a source of sediment suspension moving with e.g. the dredger. The spill rate, $S_{rate,sed}$ [kg/s], defines the actual amount of sediment that is released per second during the sea bed works. It is given as time series of coordinates (*x,y,z*) e.g. for the dredge along with the spill rate. For trenching and dredging the spill rate is found as a percentage of the trench volume, i.e.:

$$S_{rate,sed,tre} = U_{activity} \cdot V_{no\min al} \cdot P_{spill} \cdot \rho_{material}$$

Where

- $U_{activity}$ = average trenching/dredging speed, [m/s]
- $V_{no\min al}$ = nominal volume of the trench, [m$^3$/m]
- $P_{spill}$ = percentage spill, [%]
- $\rho_{material}$ = in situ density of the spilled sediment, [kg/m$^3$]

Experience from the Great Belt and Oresund Bridge projects in Denmark show that the total spill percentage for scoop type dredging operations can be kept below 5% of the dredged volume, /29/. For this type of operation the sediment is lifted through the water column and placed on a barge or dam. This result has to been seen in comparison with the seabed type and dredging methods. Consequently the spill is taken higher at 10%.

Applying an average dredging capacity of 150m$^3$/hr (based on an anticipated 3 weeks of dredging for Russian landfall) gives an average spill rate of 7 kg/s during the entire dredging work period. The spill from the near-shore dredging activities is assumed to be released 2 m below the surface (conservative) signifying that the spill may occur throughout the water column.

Reported ploughing speed (without non-productive working time) in very soft clay is 300 – 500 m/hr, /22/. If encountering harder soils a shallower trench may be dug, requiring more passes or a change of plough, /20/. As a result an average ploughing speed (including non-productive working time) of 300 m/hr is applied.

No recordings of spill are available for trenching operations. However, trenching by plough involves much less handling of the sediment since it is not lifted through the water column and placed on a barge or dam. The plough mechanically moves the material on the seabed, resulting in a V-shaped furrow with the sediment pushed up on either side of the trench. The resulting sediment disturbance is very local, allowing little contact with the surrounding water and consequently the spill is assumed as 2 % of the total volume.

Applying an average nominal trench volume of 6.9 $m^3$/m, as specified in the design documents, /30/, the resulting sediment spill rate at trenching speed of 30 m/hr is app. 20 kg/s (depending on seabed porosity), which is distributed among the fine fractions of sediment only and released averagely 5 m above the seabed.

## 4.3 Spill rate for rock placement

The material used for rock placement is very coarse (mean grain diameter $d_{50}$ = 6 cm, /31/). Hence it is anticipated that any sediment spill from rock placement activities is related to suspension of the local sediment caused by the induced momentum of the placed material.

The rock may be covered with a small amount of fine material that may be washed of during placement (all though minimal if the rocks comes from a quarry). Assuming that 50 % of the surface area of the rocks is covered with 0.1 mm of fines of which 50% is washed of, would give a spill equivalent to about 0.1% of the rock volume. An amount of this size is regarded as being within the uncertainty in the overall assessment and not addressed further.

For rock placement the amount of suspension is taken to be proportional to the placed rock volume and the suspension rate is taken to be proportional to the placement rate.

The amount of suspension is based on an energy approach assuming that the kinetic energy from the impacting stones is converted to potential energy of suspended sediment, see Figure 4.2.

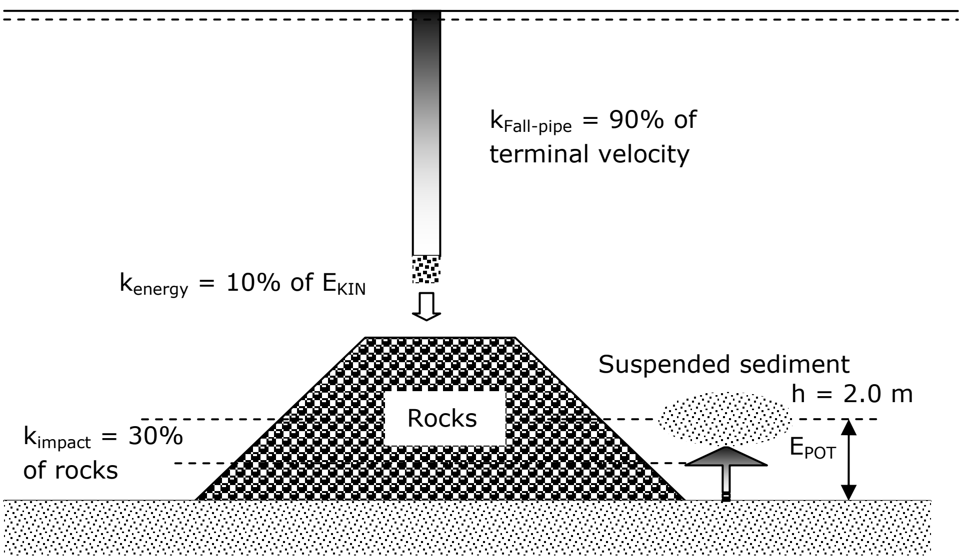


Figure 4.2 Principle for calculating sediment suspension during rock placement.

The total kinetic (impact) energy, $E_{kin}$ [Nm], of the falling rocks is equal to:

$$E_{kin} = \frac{1}{2} \cdot M \cdot v^2$$

where:

- $M$ = mass of rock, [kg]
- $v$ = velocity of the falling rock, [m/s]

However, only a fraction of the energy, $k_{energy}$ in this case set to 10%, is actually available for lifting the sediment. The remaining energy is lost to water flow, water-sediment friction, turbulent dispersion, etc.

The falling rock will reach a constant velocity, called the equilibrium velocity, $V_e$, [m/s], if they were falling freely through the water, determined by, /12/:

$$V_e = \sqrt{\frac{4}{3 \cdot C_D}} \cdot \sqrt{g \cdot \Delta D}$$

where:

- $\Delta$ = relative buoyant density of the object, [-]
- D = nominal rock diameter, [m]
- $C_D$ = drag coefficient, [-]; function of Reynolds number and the shape of the stone, generally in the range 0.5 -1.5.

To account for the reduced velocity inside the fall-pipe the velocity has been reduced to 90% ($k_{fall-pipe}$) of the above.

Further it is assumed that the impacting stones constitute on average 30% ($k_{impact}$) of the total placed volume, i.e. that the impact from the subsequent placement is absorbed by the initial layers of rock and/or the pipeline.

The impact energy of the falling rocks is converted to potential energy, $E_{pot}$ [Nm], of suspended sediment according to:

$$E_{pot} = M \cdot g \cdot h$$

The average suspension height above the seabed, $h$, is taken at 2 m, representing the rather light disturbance. Using a higher suspension height would require more energy thus reducing the amount that would be suspended.

The suspended mass of sediment (averagely 2 m above the seabed) is found by equating the potential energy of the sediment with the kinetic energy of the falling rocks:

$$M_{susp.sediment} = \frac{\frac{1}{2} \cdot M_{falling-rock} \cdot k_{impact} \cdot \left(V_e \cdot k_{fall-pipe}\right)^2 \cdot k_{energy}}{g \cdot h}$$

The equivalent spill rate during rock placement is obtained by substituting the mass of the falling rocks with the placement rate of rocks, $r_{rock-placement}$ [kg/s], i.e.:

$$S_{rate,sed,roc} = \frac{\frac{1}{2} \cdot r_{rock-placement} \cdot k_{impact} \cdot \left(V_e \cdot k_{fall-pipe}\right)^2 \cdot k_{energy}}{g \cdot h}$$

Placement of rock through fall-pipe may reach a discharge of 2000 T/hr according to /12/. However, some non-productive periods must be expected e.g. due to weather conditions, loading of rocks, positioning of the vessels etc. During a rock placement program securing twin pipelines across the Michigan Straits with 24-hr operation an average placement rate of 145 T/hr were achieved, /32/. Consequently an average discharge of 500 T/hr is assumed.

The rock placement rate is mainly governing for the suspended sediment concentrations since the net sedimentation will only be slightly affected. A faster release will generally result in higher maximum concentrations of suspended sediment but a shorter duration. In this study the released amounts are relatively small and it is therefore regarded as most critical with a fast release.

Areas with hard sea bed (e.g. rock or glacial till) are regarded as erosion areas not eligible of suspension of fine sediments, the spill from rock placement in these areas are thus neglected.

Using the above approach and a nominal rock diameter of 6 cm, /33/, gives a terminal (impacting) velocity of 2.5 m/s of the rocks. Applying a placement rate of 500 T/hr gives a spill rate for rock placement of ~1kg/s.

In comparison, the <u>observed</u> terminal velocity of 12.5 cm rocks being deposited by fall-pipe in the Michigan straits was 0.6 – 0.9 m/s, /34/. This is app. a factor 3 slower even though the rocks are bigger. Since the impacting energy is proportional to the square of the velocity, the above energy and hence suspension should be app. a factor of 10 lower. Consequently the above assumption is regarded as conservative.

The sensitivity of the spill rate to falling rock velocity is illustrated in Figure 4.3. In order to further validate the applied rates, a laboratory study is on-going to quantify the sediment release during rock placement.

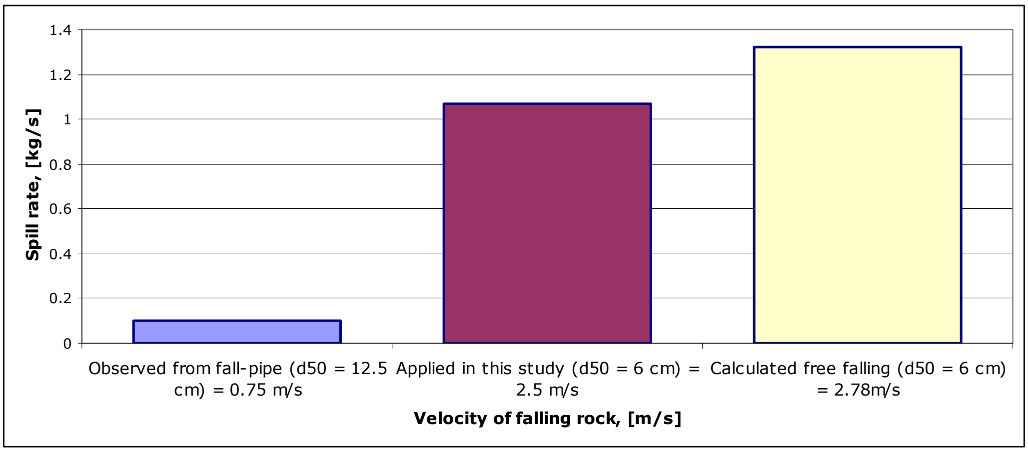



Figure 4.3: Sensitivity of spill rate to falling rock velocity.

The influence of a possible pycnocline (rapid change in water density with depth) is not included in the initial vertical distribution since the sea bed works and spill are executed below this depth and/or in areas where no significant layering occurs (near-shore). However, pycnoclines are present in the hydrodynamic basis, and the effect of these is therefore included in the spreading simulations.

# 5. Suspended sediment

The main sediment parameter governing the distance each particle travels is the settling velocity. Particles that come into suspension during works in the seabed need to be sufficiently fine-grained or light-weight to remain in suspension for longer period of time.

## 5.1 Grain-size classification

The Wentworth grain-size classification scheme shown in Figure 5.1 is used for the description of the grain-size distribution, /35/.

| Millimeters (mm) | | Micrometers (µm) | Phi (ϕ) | Wentworth size class | | Rock type |
|---|---|---|---|---|---|---|
| | 4096 | | -12.0 | | | |
| | | | | Boulder | Gravel | Conglomerate/ Breccia |
| | 256 | | -8.0 | | | |
| | | | | Cobble | | |
| | 64 | | -6.0 | | | |
| | | | | Pebble | | |
| | 4 | | -2.0 | | | |
| | | | | Granule | | |
| | 2.00 | | -1.0 | | | |
| | | | | Very coarse sand | Sand | Sandstone |
| | 1.00 | | 0.0 | | | |
| | | | | Coarse sand | | |
| 1/2 | 0.50 | 500 | 1.0 | | | |
| | | | | Medium sand | | |
| 1/4 | 0.25 | 250 | 2.0 | | | |
| | | | | Fine sand | | |
| 1/8 | 0.125 | 125 | 3.0 | | | |
| | | | | Very fine sand | | |
| 1/16 | 0.0625 | 63 | 4.0 | | | |
| | | | | Coarse silt | Silt | Siltstone |
| 1/32 | 0.031 | 31 | 5.0 | | | |
| | | | | Medium silt | | |
| 1/64 | 0.0156 | 15.6 | 6.0 | | | |
| | | | | Fine silt | | |
| 1/128 | 0.0078 | 7.8 | 7.0 | | | |
| | | | | Very fine silt | | |
| 1/256 | 0.0039 | 3.9 | 8.0 | | | |
| | | | | Clay | Mud | Claystone |
| | 0.00006 | 0.06 | 14.0 | | | |

Figure 5.1 The Wentworth grain-size classification scheme, /35/.

## 5.2 Flocculation

Particles smaller than sand (<0.063 mm), i.e., silt and clay, are usually cohesive and tend to flocculate and form aggregates when released in seawater. Thereby, a more coarse-grained size distribution with somewhat lower particle densities is formed /36, 37/.

The fragility of the aggregates varies depending on the creation. Strong high-density aggregates may originate from compression of above-lying sediments and be re-leased during dredging, while fragile low-density aggregates may form in the water column. The break-up of strong density aggregates requires considerable amounts of energy. The resulting size distribution is usually well sorted with typical aggregate sizes between 0.01–0.2 mm (approximately coarse silt – fine sand) and very small content of primary particle sizes /36-38/.

An increase in particle size will increase the settling velocity, but this increase may to some degree be counter-balanced by the decrease in density. The variation in settling velocity, therefore, is found to increase not only with respect to aggregate size but also with aggregate density /36, 37/.

According to /36/ the timescale of flocculation of lime in Oresund, Denmark, is within the order of 50 minutes. Since the chalk compound of the lime does not flocculate according to /39/, this timescale may be conservative compared with clay and silt sediments. Given that clay has electrical charges, flocculation is expected to occur with at least the same speed. This means that even during a relatively high persistent current speed of e.g. 10 cm/s most flocculation will take place within approximately 300 m of the release location.

Low to medium concentration of suspended sediment and low turbulence appear to promote flocculation, whereas high concentration and high turbulent shear promote breakdown of the aggregates by, e.g. collision, /37/. The main flocculation is thus assessed to take place once the large particles have settled and the turbulence arising from any seabed activity has decreased. The time after the sea bed works, therefore, is expected to yield favourable conditions for flocculation.

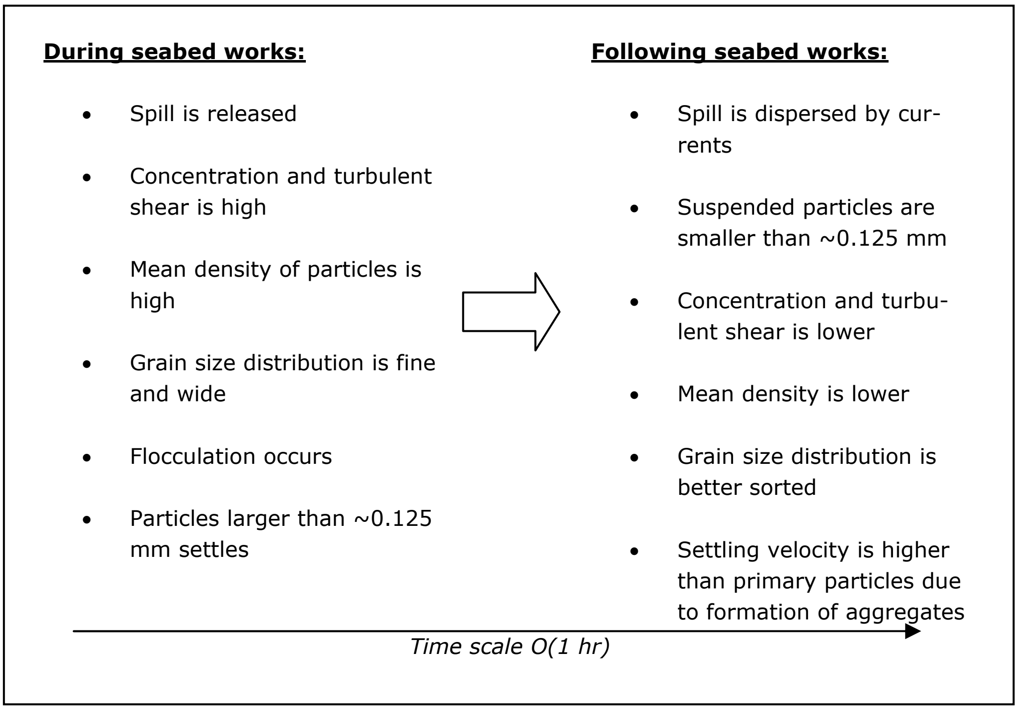



Figure 5.2 Conditions of the spilled suspended sediment during and following seabed works.

The importance of flocculation may be demonstrated by the relationship shown in Figure 5.3, /40/. The flocculation factor, F, is the ration of the settling velocity of flocculated sediment, $w_f$, to that of the chemically dispersed sediment, $w_{sd}$. At the clay to silt boundary, $d_{50} = 0.004 mm$ , the flocculated settling velocity is app. a factor 25 higher than that of the primary particles.

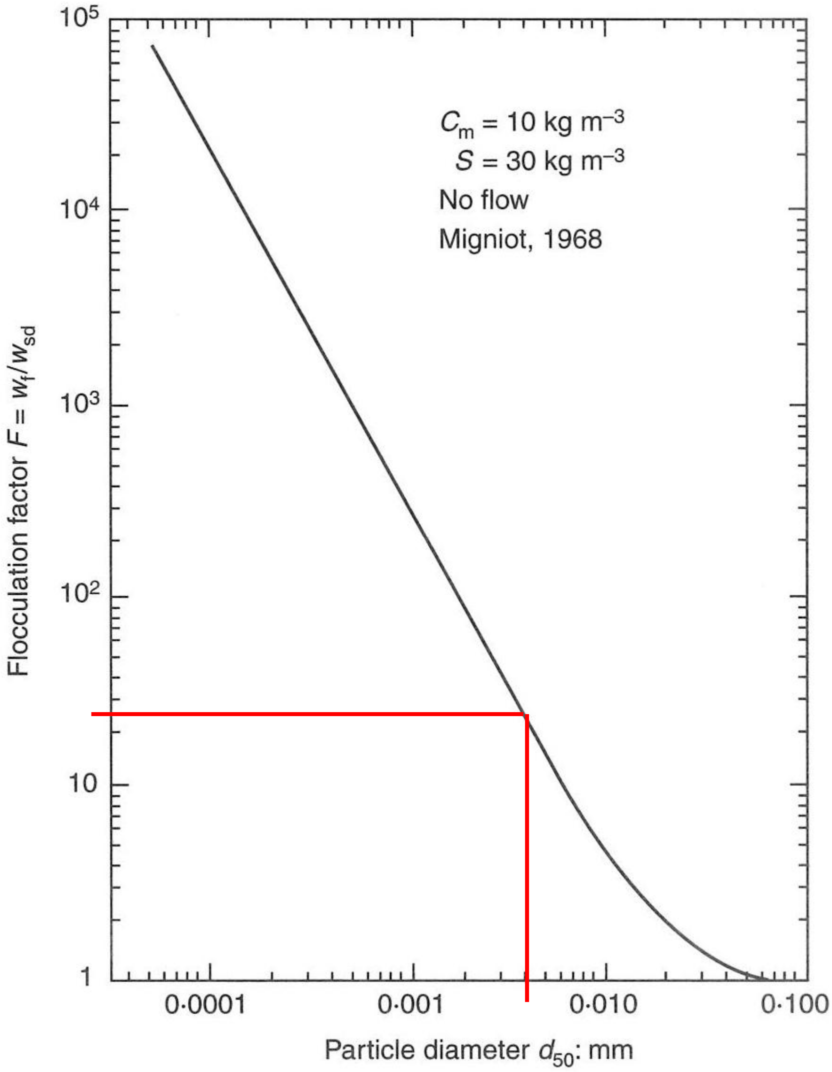



Figure 5.3 Flocculation factor, F, as a function of median particle diameter.

## 5.3 Grain-size fractions

Acknowledging that fine-grained suspended particles form low-density aggregates with a consequent increase in settling velocity, it is assumed that particles <0.004 mm (clay) behave like 0.04 mm spheres and particles between 0.004–0.063 mm (silt) behave like 0.063 mm spheres. Particles between 0.063-0.125 mm (very fine sand) do not form aggregates, and therefore a mean diameter of 0.08 mm is used. Particles larger than 0.125 mm (fine sand) will settle within close vicinity of the pipeline due to a high settling velocity.

In this way the flocculated aggregate sizes are represented by grain-size fractions of 0.040, 0.063 and 0.094 mm with correspondingly reduced density of the clay and silt fractions, see Table 5.1. This is within the typical aggregate sizes of 0.01–0.2 mm according to /36-38/.

Table 5.1 Sediment properties in the Gulf of Finland, the Baltic Proper and the western Baltic applied for calculation of settling velocities.

| **Sediment property** | | **Clay** | **Silt** | **Very fine sand** |
|---|---|---|---|---|
| Primary particle size | $d_n$ [mm] | < 0.004 | 0.004 - 0.063 | 0.063 - 0.125 |
| **Mean aggregate size** | **$D_n$ [mm]** | **0.030** | **0.040** | **0.080** |
| Mean aggregate density | $\rho_s$ [kg/m$^3$] | 1650 | 2150 | 2650 |
| Vol. Conc. | c [-] | 0.01 | 0.01 | 0.01 |

## 5.4 Hindered settling

Immediately following some activity in the seabed, the sediment concentration can be very high. In high concentrations when many particles settle simultaneously the settling velocity is slower than for single grains. The reduction in fall velocity, $\omega_s$ ,for sand grains as function of the volume concentration, *c*, can be estimated by the following expression, /41/.

$$\omega_s = \omega_{s0} \cdot (1-c)^n$$

Where

- $n = 4.35 \cdot R^{-0.03}$ $\quad 0.2 < R < 1$
  $n = 4.45 \cdot R^{-0.10}$ $\quad 1 < R < 500$
  $n = 2.39$ $\quad 500 < R$

- $R$ = the grain Reynolds number, see below.

Within a short distance of the pipeline the larger particles have settled and the smaller particles have undergone some dispersion, causing a reduction in the concentration. For a volume concentration of about 1% (~10 kg/m$^3$), the reduction in settling velocity for fine sand grains is less than 5%. The concentration is expected to be less than 1% in most of the affected area, but it may be higher close the seabed for some period of time. As a result the average settling velocity is reduced by approximately 5%.

## 5.5 Water properties

The settling velocity also depends on the water viscosity which is a weak function of temperature. At low water temperature the viscosity is high, resulting in a small settling velocity.

In fresh water the flocculation processes are reduced, which also reduces the settling velocities, $\omega_s$, due to the smaller/fewer aggregates. This effect is evaluated by Krone's experiments and can be described by the following expression, /42/.

$$\omega_s = \omega_{s0} \cdot (1 - c_1 \cdot e^{S \cdot c_2})$$

Where *S* is salinity and $c_1$ and $c_2$ are calibration parameters. Using the default values 0.5 and -0.33 respectively, /42/, shows that salinity only plays a significant role on flocculation at salinities below approximately 5 psu. This effect is therefore mainly important in parts of the Gulf of Finland.

The applied and calculated water properties for three separate parts of the Baltic Sea: the Gulf of Finland, Baltic Proper and the western Baltic, are shown in Table 5.2.

Table 5.2 Water properties in the Gulf of Finland, the Baltic Proper and the western Baltic applied for calculation of settling velocities.

| **Water Properties** | **Temperature** | **Salinity** | **Density** | **Dyn. Visc.** | **Kin. Visc.** |
|---|---|---|---|---|---|
| **Area** | **T [°C]** | **S [psu]** | **$\rho_w$ [kg/m$^3$]** | **μ [Ns/m$^2$ x 10$^{-3}$]** | ***v* [m$^2$/s x 10$^{-6}$]** |
| Gulf of Finland | 2.0 | 5.0 | 1004.0 | 1.665 | 1.659 |
| Baltic Proper | 5.0 | 7.0 | 1005.6 | 1.515 | 1.507 |
| Western Baltic | 8.0 | 9.0 | 1006.9 | 1.386 | 1.376 |

## 5.6 Settling velocity

Generally, large particles have high settling velocities, meaning that the particles settle rapidly after their release, while fine-grained particles have low settling velocities, allowing a wider spreading of the sediment. Organic matter usually has low settling velocities due to low density. Therefore, mainly the fine fractions and the organic content of the sediment will be transported from the vicinity of the pipeline to the surroundings during works in the seabed.

When a sphere moves through a fluid, it accelerates due to gravity and eventually reaches a maximum velocity called the settling velocity, $\omega_s$ [m/s]. An estimate of the settling velocity of a single particle in a fluid can be calculated according to Stokes' law. Stokes' law applies to very small values of the grain Reynolds number and considers the dependence on diameter and density of the particles and the density of the fluid, /41/. Another expression of the settling velocity is given by Fredsøe, which takes into account the variation in drag coefficient, $c_D$, with the grain Reynolds number, /41/, and is therefore preferred.

$$\omega_{s,Stokes} = \frac{\left(\frac{\rho_s}{\rho_w} - 1\right) g d^2}{18\upsilon} \qquad \omega_{s,Fredsøe} = \sqrt{\frac{4(1 - \frac{\rho_s}{\rho_w}) g d}{3 c_D}}$$

Where

- $d$ = the grain diameter, [m]
- $\upsilon$ = the kinematic viscosity, [m$^2$/s]
- $\rho_w$ = the density of seawater, [kg/m$^3$]
- $\rho_s$ = the density of sediment, [kg/m$^3$]
- $c_D = 1.4 + \frac{36}{R}$ = the drag coefficient, [-]
- $R = \frac{\omega_s \cdot d}{\nu}$ = the grain Reynolds number, [-]

The resulting settling velocities according to Fredsøe, /41/, of the mean aggregate sizes, adjusted for hindered settling and salinity dependent flocculation (clay and silt only) are shown in Table 5.3.

Table 5.3 Settling velocity according to Fredsøe, /41/, of mean aggregates, adjusted for hindered settling and salinity dependent flocculation (clay and silt only).

| | Settling velocity of mean aggregates, $\omega_s$ [mm/s] | | |
|---|---|---|---|
| **Area** | **Clay** | **Silt** | **Very fine sand** |
| Gulf of Finland | 0.11 | 0.35 | 2.20 |
| Baltic Proper | 0.13 | 0.40 | 2.41 |
| Western Baltic | 0.14 | 0.45 | 2.63 |

## 5.7 Sensitivity and measurements

Whether a high or a low settling velocity is most critical depends on what parameter is being studied. Applying a low settling velocity will result in a longer duration of suspension (and thus wider spreading) which then results in a thinner layer of net sedimentation over a larger area. Applying a high settling velocity gives a thicker layer of net sedimentation in a more concentrated area due to shorter durations/transport of suspension sediment. The governing parameter for assessing the impact is the spill rate and emphasis is put on applying the most realistic settling velocity.

The mean settling velocity of natural sediments has been estimated from measurements of the particle flux and mass concentration of sediments in Øresund, /43/. During calm conditions with low concentrations the mean diameter was small (~0.008 mm) and the mean settling velocity was correspondingly low, estimated at 0.04mm/s. However, during rough periods where re-suspension occurs, causing a higher concentration of suspended sediment, the mean grain sizes were somewhat larger (~0.02 – 0.03mm) and the settling velocity will therefore also be higher.

The conditions during seabed works causes a local increase in concentration of suspended sediment which favours flocculation, and the conditions are therefore regarded as comparable to the rough conditions described in Øresund. Therefore the mean aggregate grain sizes in Table 5.1 (~0.03 – 0.04mm) are assessed as realistic.

The calculated settling velocities in Table 5.3 match well with what has been observed in the Elbe, Tamar and Dollard estuary of roughly between 0.05–10 mm/s according to /37/.

The settling velocities in Table 5.3 are regarded as appropriate values for this study since they reflect actual measurements from estuaries and Øresund as well as experimental results (see Figure 5.3).

The possible extent of spreading may be assessed using the settling velocities in Table 5.3 and a persistent current speed of say 5 cm/s (which is fast for the near-seabed currents in the Baltic Sea, /44/). Under such conditions the clay particles will settle within ~2000 m from the pipelines when released 5 m above the seabed, while very fine sand will settle within ~100 m from the pipelines (or less if the current fluctuates or is not perpendicular to the pipeline).

Applying for instance a 50% slower settling velocity would allow the particles to travel twice as far (e.g. up to ~4000m). However, this takes longer time which results in a higher dispersion and thus lower concentrations. Based on the above discussion it is assessed that the fraction of sediment with such low settling velocities will be too minor to produce any significant concentration of suspended sediment.

## 5.8 Grain-size distribution

The distribution of the considered grain-size fractions at the locations of seabed works are based on samples of surface and sub-surface sediment collected and analysed at a large number of locations along the pipeline route, /45/.

The applied distributions for each country and seabed work type are summarized in Table 5.4. The trenching areas are generally located at shallow areas or near-shore and thus have a higher content of sand, while rock placement areas may be in deep locations with higher porosity and higher content of fines. Dredging is only performed close to shore and thus also has some content of sand.

In general the sediment sample with the highest content of fines (clay and silt), i.e. the highest spreading potential, has been applied as representative for each area. In the Gulf of Finland this means that the entire fraction is clay and silts, see also Memo /46/ for further assessment of the sediment properties in the Gulf of Finland.

Table 5.4: Grain size distribution and porosity for rock placement, trenching and dredging areas.

| | Percentage content of nominal wet volume [%] | | | | |
|---|---|---|---|---|---|
| **Location** | **Clay** | **Silt** | **Very Fine Sand** | **Total fines** | **Porosity** |
| Germany - Trenching | 1 | 4 | 19 | 24 | 28 |
| Denmark - Trenching | 1 | 4 | 19 | 24 | 28 |
| Denmark - Rock placement | - | - | - | - | - |
| Sweden - Trenching | 28 | 21 | 8 | 57 | 30 |
| Sweden - Rock placement | 29 | 4 | 1 | 34 | 67 |
| Finland - Rock placement | 30 | 3 | 0 | 33 | 67 |
| Russia - Rock placement | 30 | 3 | 0 | 33 | 67 |
| Russia - Dredging | 5 | 11 | 17 | 33 | 38 |

# 6. Suspended contaminants

Chemical compounds with the potential to cause ecotoxicological effects on the Baltic ecosystems and/or bioaccumulate have been deposited over centuries on the seabed of the Baltic Sea. During the establishment of the gas pipeline, sediments will be re-suspended, thus mobilising some of these chemical compounds, with the potential to cause adverse effects on organisms inhabiting the Baltic Sea.

The main ecotoxicological impact potential of the pipeline project, therefore, is not caused by an emission of chemicals in the traditional sense, but by a redistribution of depositions of chemical compounds already present in the Baltic Sea.

## 6.1 Sediment bound concentrations

The distribution and concentrations of sediment bound chemical compounds in the Baltic Sea have been analysed and described as presented in /47/. Further analyses are based on a large number of field measurements available in /48-50/. From these studies the relevant substances known to be present and with the potential to cause ecotoxicological effects have been identified as listed below.

- Cd Cadmium
- Hg Mercury
- Pb Lead
- Zn Zinc
- Cu Copper
- As Arsenic
- Cr Chromium
- Ni Nickel
- SUM16PAH Sum of 16 selected Polycyclic Aromatic Hydrocarbons (PAH)
- TBTIN Tributyltin

Chemicals (other than listed above) known to bioaccumulate but incapable of causing measurable effects on lower organisms are characterised by estimation of half-life by fishing (removal with biomass caught by fishing vessels), and/or by comparison with the yearly input of chemicals to the Baltic Sea, see /51/.

The data has large spatial variations in concentrations and coverage. Therefore, as a conservative measure, the $90^{th}$% fractile of the measured concentrations for each country have been adopted for this study, see Table 6.1. The concentrations include the total amount of contaminants contained in the bulk sediment (i.e. from both grains and pore water).

Table 6.1 90$^{th}$% fractile concentrations ($c_{90\%}$) of the considered chemical compounds in each country based on /48-50/, DW = Dry Weight.

| Chemical Compound | $c_{90\%,De}$ [mg/kg DW] | $c_{90\%,Dk}$ [mg/kg DW] | $c_{90\%,Se}$ [mg/kg DW] | $c_{90\%,Fi}$ [mg/kg DW] | $c_{90\%,Ru}$ [mg/kg DW] |
|---|---|---|---|---|---|
| Cd | 1.50E+00 | 6.91E-01 | 5.59E+00 | 1.76E+00 | 5.48E-01 |
| Hg | 4.66E-01 | 6.43E-02 | 1.69E-01 | 6.60E-02 | 1.38E-01 |
| Pb | 6.83E+01 | 5.64E+01 | 6.87E+01 | 3.87E+01 | 1.30E+01 |
| Zn | 2.30E+02 | 1.82E+02 | 7.61E+02 | 3.60E+02 | 1.16E+02 |
| Cu | 1.60E+02 | 4.12E+01 | 1.15E+02 | 9.66E+01 | 3.16E+01 |
| As | 2.16E+01 | 1.52E+01 | 3.05E+01 | 1.55E+01 | 7.10E+00 |
| Cr[1] | 4.04E+01 | 3.87E+01 | 6.91E+01 | 5.85E+01 | 2.37E+01 |
| Ni | 9.74E+01 | 3.43E+01 | 8.49E+01 | 5.50E+01 | 3.33E+01 |
| SUM16PAH | 2.00E-01 | 2.10E+00 | 3.37E+00 | 7.70E-01 | 9.07E-02 |
| TBTIN[2] | 3.40E-03 | 6.50E-03 | 3.59E-02 | 7.04E-02 | 7.04E-02 |

[1] Not included in national survey in Finland. Figure indicates the overall number for the Baltic Sea.

[2] Not included in national survey in Russia. Figure indicates the number for Finland.

## 6.2 Desorption and bioactivity

In order to cause toxicological effects a chemical compound has to be bioavailable, that is dissolved and in a chemical form that can be taken up by organisms and/or interact with receptors. Two factors limit the ecotoxicological impacts in the aquatic compartment:

1. Sorption: By sorption, the amount of chemical compounds released from re-suspended sediments is limited. The chemical compound settles with the sediment, thus decreasing the available bioactive concentration.

2. Speciation: Through various processes a chemical can be transformed in the environment to a species not having the same properties of the pure parent chemical. Metals, for instance, can form chlorides, bromides, sulphides and other species that are generally regarded as species not contributing to the ecotoxicological impact potential of the parent compound (in regard to metals, here the free metal ion).

To account for the above-mentioned factors, two factors are applied:

1. Desorption, quantifying the fraction of chemical compound in bound sediment that will desorb during re-suspension; and

2. Bioactivity, quantifying the fraction of desorbed chemical compound capable of being taken up by aquatic organisms and/or interacting with receptors.

The factors accounting for desorption and bioactivity are generalised for metals and lipophilic organic chemicals. In regard to metals, it is estimated that 50% of the sediment content is desorbed to form dissolved species by re-suspension, while for lipophilic organic chemicals it is estimated that 10% is desorbed to free dissolved form by re-suspension. The bioactivity for metals is set to 25%, indicating that only 25% of the dissolved species are present as the free ion according to the free ion activity approach, see /52/. For lipophilic organic chemicals, it is assumed that 100% of the free-dissolved form contributes to the impact potential. The values are summarized in Table 6.2.

Table 6.2 Desorption, bioactivity and PNEC values of the considered chemical compounds.

| Chemical compound | Desorption[1] [%] | Bioactivity[2] [%] | PNEC (µg/l) | PNEC Reference |
|---|---|---|---|---|
| Cd | 50 | 25 | 0.115 | /53/ |
| Hg | 50 | 25 | 0.025 | /53/ |
| Pb | 50 | 25 | 0.1 | /53/ |
| Zn | 50 | 25 | 0.56 | /53/ |
| Cu | 50 | 25 | 0.02 | /53/ |
| As | 50 | 25 | 0.01 | /54/ |
| Cr | 50 | 25 | 0.47 | /55/ |
| Ni | 50 | 25 | 2.2 | /53/ |
| SUM16PAH | 10 | 100 | 0.00009 | /53, 56, 57/ |
| TBTIN | 10 | 100 | 0.0005 | /56/ |

[1] The desorption of a given compound is estimated conservatively as 50% for metals [a)] and 10% for lipophilic organic chemicals [b)].

[2] The fraction of the desorbed chemical having biological activity, thus contributing to ecotoxicity is 100% for organic chemical [c)] and 25% for metals [d)] due to speciation.

[a)] The fraction of inorganic chemicals desorbed resulting in free dissolved metal species is limited by sorption, absorption and incorporation. Indications are that the release of sediment contaminants by re-suspension can not be estimated applying existing models, /58/.

[b)] The fraction of organic chemicals desorbed is limited by sorption, absorption and salting effect. Indications are that the release of sediment contaminants by re-suspension can not be estimated applying existing models or measured applying existing simulation methods, /58/. Estimate is based on Mackay Level 1 for fraction dissolved in water in standard EQC environment, /59/.

[c)] Maximum possible value – Absolute worst case.

[d)] Realistic worst case. The fraction of any of the metals present as the free ion (in accordance with the Free Ion Activity Model, /52/) is estimated to maximum 25%, /60/.

## 6.3 Release rate to the water body

Based on the above, the release rate of contaminants from the sediment to the water body during a spill, $S_{rate,cont}$ [mg/s], may be expressed (for each compound) as:

$$S_{rate,cont} = S_{rate,sed} \cdot c_{90\%} \cdot Desorption \cdot Bioactivity$$

where:

- $S_{rate,sed}$ [kg/s], is the sediment spill rate, see Section 4
- $c_{90\%}$ [mg/kg DW], is the sediment bound concentration, see Table 6.1
- For desorption and bioactivity, see Section 6.2

This includes the very conservative assumption of applying the 90th % fractile for the concentration of contaminants which makes the release rather sensitive to the spill rate of sediment. The spilled contaminants are treated as dissolved particles, i.e. without any settling velocity.

## 6.4 Ecosystem effects (PEC/PNEC)

The release of each chemical compound leads to an increased concentration in the water body with the potential to cause ecotoxicological effects. In order to quantify this risk the ration between the predicted no-effect concentration (PNEC) and the predicted environmental concentration (PEC) is applied.

- The predicted no-effect concentration (PNEC) = estimated lower limit of the concentration range in the water body known to cause effects

- The predicted environmental concentration (PEC) = estimated exposure concentration in the water body based on spill and spreading

The PEC/PNEC ratio is thus interpreted as follows:

- PEC/PNEC ≤ 1: No adverse effects are anticipated.

- PEC/PNEC > 1: Adverse effects may occur.

The PNEC values for the considered substances are shown in Table 6.2.

## 6.5 Relative toxicity

The actual toxicity (or impact potential) in the ecosystem of each compound may be seen as a function of two components:

A. The desorbed and bioactive fraction of the sediment bound concentration

B. The predicted no-effect concentration in the water (PNEC).

By considering the ratio between these two components, here termed the relative toxicity $R_{tox}$ [m$^3$/kg], it is possible to compare the toxicity of the different compounds. The relative toxicity is thus found as:

$$R_{tox} = \frac{c_{90\%} \cdot Desorption_i \cdot Bioactivity}{PNEC_i}$$

The odd unit ($m^3$/kg) is a result of dividing a sediment bound concentration (mg/kg) with a water body concentration (µg/l or $mg/m^3$).

The relative toxicity of each chemical compound is presented in Figure 6.1 and Table 6.3 for each country. Red indicates the most critical compound, yellow the second most critical, and green the third most critical compound in each country.

It is apparent that copper, arsenic and SUM16PAH are the most critical compounds with almost all other compounds being at least a factor 10 less critical than the most critical compound in each country. The significance of the PAH's is mainly caused by the very low PNEC value since the concentration is much lower than e.g. Cu and As.

In practice this means that if the PNEC value of e.g. the second most critical compound is not exceeded, then it needless to consider the remaining less critical compounds.

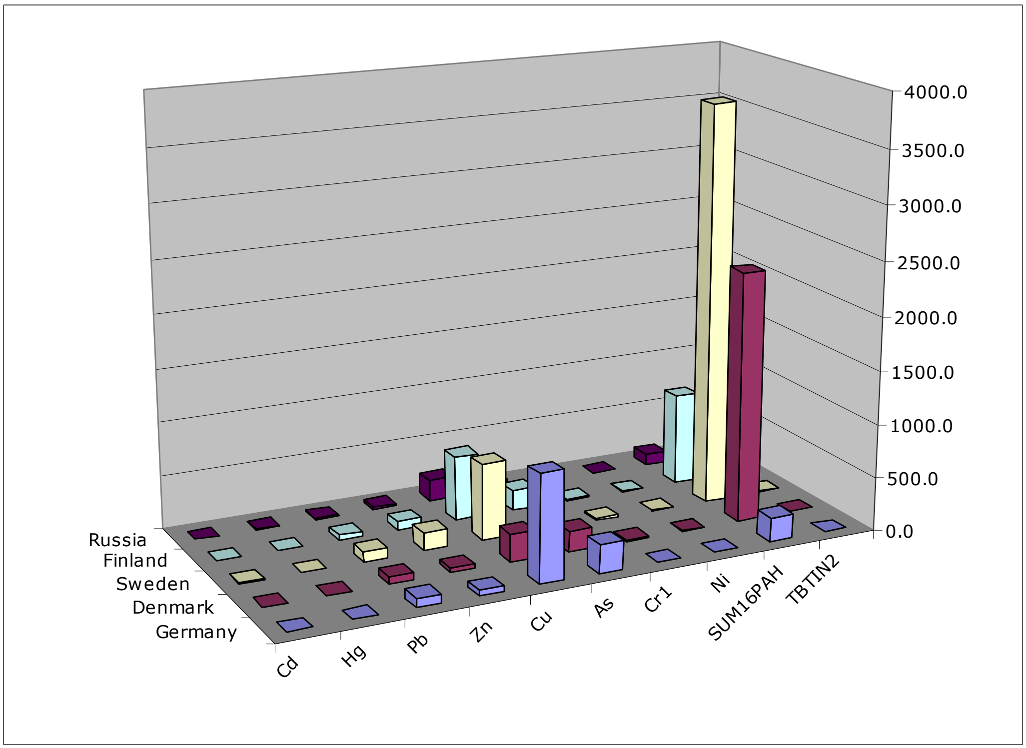



Figure 6.1 Country-specific relative toxicity of the considered chemical compounds.

Table 6.3 Country-specific relative toxicity of the considered chemical compounds. Red indicates the most critical compound, yellow the second most critical, and green the third most critical compound in each country.

| Compound | $R_{tox,Ge}$ | $R_{tox,De}$ | $R_{tox,Sw}$ | $R_{tox,Fi}$ | $R_{tox,Ru}$ |
|---|---|---|---|---|---|
| | [$m^3$/kg DW] | [$m^3$/kg DW] | [$m^3$/kg DW] | [$m^3$/kg DW] | [$m^3$/kg DW] |
| Cd | 1.6 | 0.8 | 6.1 | 1.9 | 0.6 |
| Hg | 2.3 | 0.3 | 0.8 | 0.3 | 0.7 |
| Pb | 85.4 | 70.5 | 85.9 | 48.4 | 16.3 |
| Zn | 51.3 | 40.6 | 169.9 | 80.4 | 25.9 |
| Cu | 1000.0 | 257.5 | 718.8 | 603.8 | 197.5 |
| As | 270.0 | 190.0 | 381.3 | 193.8 | 88.8 |
| Cr[1] | 10.7 | 10.3 | 18.4 | 15.6 | 6.3 |
| Ni | 5.5 | 1.9 | 4.8 | 3.1 | 1.9 |
| SUM16PAH | 222.2 | 2333.3 | 3744.4 | 855.6 | 100.8 |
| TBTIN[2] | 0.7 | 1.3 | 7.2 | 14.1 | 14.1 |
| **Sum** | **1649.9** | **2906.6** | **5137.5** | **1816.8** | **452.7** |

# 7. Particle analysis model

The spreading of material is evaluated using the general numerical particle analysis model MIKE 3 PA developed by DHI Water – Environment – Health. The model is forced by hydrodynamic data including currents, salinity and temperature for representative hydrographical periods.

## 7.1 MIKE 3 PA description

The numerical particle analysis model MIKE 3 PA is used to simulate the transport and fate of dissolved and suspended substances in three dimensions. The substances can be discharged or accidentally spilled in estuaries, coastal areas or in the open sea.

MIKE 3 PA requires that current velocities and water level are prescribed in time and space in a computational grid covering the model area. This information is provided, e.g., as results from a hydrodynamic model simulation.

The simulated substances can be pollutants of any kind, for instance suspended sediment, chemicals or nutrients. The spilled material is represented by a large number of particles, each of a specific mass. The mass can change during the simulation due to decay. The particles are released at a source point for discharge (e.g., the location of trenching) and successively moved as the simulation progresses.

The model uses a Lagrangian-type approach, which involves no other spatial discretisations than those associated with the description of the bathymetry, current and water level fields. Some advantages of a Lagrangian-type model are:

- No numerical diffusion
- No accumulation of sub-grid effects
- Effective in resolving narrow plumes

Each particle is within a time step moved a distance equal to the current velocity multiplied by the time step, which represents the advection. In the *z*-plane, the particles are in addition moved a distance equal to the settling velocity multiplied by the time step.

The particles are also successively moved a random distance, representing the dispersion that accounts for the non-resolved flow processes. The dispersion is prescribed in three dimensions. In a Lagrangian model the dispersion coefficients are independent of the time step and the grid size.

The resulting movement along each axis during a time step $\Delta t$ can be described by:

$$X = X_0 + u \cdot \Delta t + [R]_{-1}^{1}\sqrt{6D_l \Delta t} \cdot \frac{u}{|\vec{U}|} + [R]_{-1}^{1}\sqrt{6D_t \Delta t} \cdot \frac{v}{|\vec{U}|}$$

$$Y = Y_0 + v \cdot \Delta t + [R]_{-1}^{1}\sqrt{6D_l \Delta t} \cdot \frac{v}{|\vec{U}|} + [R]_{-1}^{1}\sqrt{6D_t \Delta t} \cdot \frac{u}{|\vec{U}|}$$

$$Z = Z_0 + (w + V_{sett}) \cdot \Delta t + [R]_{-1}^{1}\sqrt{6D_v \Delta t}$$

Where:

| | |
|---|---|
| $u, v, w$ | = current velocity along *x*, *y* and *z*-axis |
| $\lvert\vec{U}\rvert = \sqrt{u^2 + v^2}$ | = current velocity |
| $[R]_{-1}^{1}$ | = random number within the range -1 to 1 |
| $V_{sett}$ | = settling velocity |
| $D_l, D_t$ | = longitudinal and transverse dispersion coefficient |
| $D_v$ | = vertical dispersion coefficient |

A detailed technical description of the MIKE 3 PA module is given in /42/.

## 7.2 Hydrodynamic basis

The hydrodynamic basis for the MIKE 3 PA simulations is acquired from an existing model setup of the numerical hydrodynamic model MIKE 3 by the Danish National Environmental Research Institute as a part of the Danish national monitoring programme. A description of the model and setup are given in /44/.

The hydrodynamic data includes current, temperature, salinity and water level and is available as three-dimensional grid data. The data has a horizontal resolution of 3 nautical miles, a vertical resolution of 1 m to a depth of 210 m (surface layer ~2.5 m) and covers the entire Baltic Sea including Danish waters. For the inner Danish waters and German waters the data is available in 1 nautical miles horizontal resolution. The data is available with a temporal resolution of one and six hours.

For the near-shore area where bathymetric features and flow patters may not be properly resolved in the regional model a high resolution local model has been set up based on a more detailed bathymetry and boundary conditions/forcing extracted from the regional model, cf. /44/.

## 7.3 Simulation periods

The speed and direction of the natural currents in the Baltic Sea is determining the extent of the spreading of sediment. The currents vary continuously due to e.g. wind and air pressure. Naturally the exact extent of the spreading will depend on the hydrographical conditions at the point in time when the spill is actually released.

Based on an analysis of the currents in the Baltic Sea three different time periods have been defined representing calm, average and rough conditions in relation to spreading of sediment, /44/:

- Calm conditions (weak currents): Apr. 28th. – May 28th 2005
- Normal conditions (average currents): Sep. 26th. – Oct. 26th. 2005
- Rough conditions (strong currents): Nov. 21st. – Dec. 21st. 2005

These periods are used to study the variability in the spreading associated with different hydrographical conditions. In the event that a spill scenario (seabed work) exceeds the duration of 1 month then the hydrographical periods are looped.

Stormy conditions are not considered since severe weather will usually prevent the execution of any seabed works.

## 7.4 Concentration Resolution

The Lagrangian approach allows the PA model to be set up in a finer horizontal resolution than specified in the hydrodynamic basis. In order to properly resolve the concentration of particles in the vicinity of the pipeline, the horizontal resolution around the pipeline is refined. The applied resolution in the spreading analyses is typically between 50-200 m, depending on the type of application and geographical coverage.

## 7.5 Background concentration

The background concentration is defined as 0, meaning that the natural transport processes are not taken into consideration. In this way the model results identify/isolate the excess concentration due to the seabed activities.

# 8. Model simulations

Based on the planned works in the seabed the associated spill has been assessed. By investigating the properties of suspended sediment and possible seabed contaminants the following input for analysing the spreading have been defined. The resulting scenarios have been simulated using the above described particle analysis model in order to assess the extent of the spreading.

## 8.1 Model basis

In general a scenario has been established for each seabed work type (rock placement, trenching and/or dredging) and each country. For Finland additional rock placement scenarios are included representing both the east and the west pipelines as well as the alternative route at Kalbadagrund.

A summary of the basis and input for the model simulations are given in Appendix A: Model basis, including the following parameters:

- ID: Scenario identification name
- Location(s): Overall location(s) of scenario
- Route: Route alignment and pipeline considered
- Activity: Type of seabed work considered
- Method: Applied method for seabed work
- Speed: Speed of seabed work (average)
- Scope: Distance or locations covered
- Volume: Volume of trench or rocks handled
- Duration: Time of execution of seabed works
- Spill: Spill percentage relative to volume of trench or rock
- Parameters: Sediment and contaminants are separate scenarios
- Weather: Weather periods considered (calm, normal, rough)
- Atlas map(s): Atlas map(s) showing the seabed works and results of modelling
- Reference(s): Main references from the design (Snamprogetti)

## 8.2 Hydrographical conditions

Some of the scenarios have been modelled for 3 different hydrographical periods (calm, normal and rough), see section 7.3, to study the variability in the spreading. The model result is thus an outcome of specific hydrographical conditions and should be seen as an example of a representative event and not as an exact result of what will actually occur.

The same hydrographical periods are used for all activities implying that the conditions may not be equally 'calm', 'normal' or 'rough' at all locations. Further, the seabed works vary widely in duration and water depth, causing variations in the hydrographical influence, which affects the extent of the spreading. When the dominant current flows parallel to the pipelines then the spreading will be concentrated along the pipe and less significant away from the pipes.

It is unrealistic that the hydrographical conditions would be equally calm, normal or rough in all locations during construction works of this size, and consequently the applied calm, normal and rough periods are considered as representative realistic scenarios.

## 8.3 Scenario input

The input for each scenario is shown in the tables below, specifying the length or number of locations, the duration of seabed work and the amount of suspended sediment.

Table 8.1: Scenario TRE_GE: Trenching in Germany

| **Scenario: TRE_GE** | **From** | **To** | **Length** | **Duration** | **Suspended sediment** |
|---|---|---|---|---|---|
| **Area** | **KP [km]** | **KP [km]** | **[m]** | **[days]** | **[T]** |
| Germany | 1139 | 1143 | 4,000 | 0.6 | 1,053 |
| | 1156.5 | 1180 | 23,500 | 3.3 | 6,188 |
| | 1180 | 1194.493 | 14,493 | 2.0 | 3,816 |
| | 1194.493 | 1195.27 | 777 | 0.1 | 205 |
| **Total** | | | **42,770** | **5.9** | **11,262** |

Table 8.2: Scenario TRE_DE_N: Trenching in Denmark (North of Bornholm route)

| **Scenario: TRE_DE_N** | **From** | **To** | **Length** | **Duration** | **Suspended sediment** |
|---|---|---|---|---|---|
| **Area** | **KP [km]** | **KP [km]** | **[m]** | **[days]** | **[T]** |
| Denmark | 1049 | 1051 | 2,000 | 0.3 | 527 |
| | 1063 | 1076 | 13,000 | 1.8 | 3,423 |
| | 1101 | 1102 | 1,000 | 0.1 | 263 |
| **Total** | | | **16,000** | **2.2** | **4,213** |

Table 8.3: Scenario TRE_DE_S: Trenching in Denmark (South of Bornholm route)

| **Scenario: TRE_DE_S** | **From** | **To** | **Length** | **Duration** | **Suspended sediment** |
|---|---|---|---|---|---|
| **Area** | **KP [km]** | **KP [km]** | **[m]** | **[days]** | **[T]** |
| Denmark | 1046.1 | 1053 | 6,900 | 1.0 | 1,489 |
| **Total** | | | **6,900** | **1.0** | **1,489** |

Table 8.4: Scenario ROC_DE_N: Rock placement in Denmark (North of Bornholm route)

| Scenario: ROC_DE_N | | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type | [$m^3$] | [-] | [days] | [T] |
| Pre-Lay | Static | 1,672 | 25 | - | - |

Table 8.5: Scenario TRE_SW: Trenching in Sweden

| Scenario: TRE_SW | From | To | Length | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Area | KP [km] | KP [km] | [m] | [days] | [T] |
| Gotland | 523.97 | 526.92 | 2,950 | 0.4 | 755 |
| | 527.05 | 527.86 | 810 | 0.1 | 207 |
| | 529 | 532.17 | 3,170 | 0.4 | 811 |
| | 537.08 | 537.88 | 800 | 0.1 | 205 |
| | 542.6 | 547.82 | 5,220 | 0.7 | 1,336 |
| | 556.01 | 559.88 | 3,870 | 0.5 | 991 |
| Midsjö | 802.11 | 823.79 | 21,680 | 3.0 | 5,550 |
| | 829.28 | 832.43 | 3,150 | 0.4 | 806 |
| | 833.66 | 841.55 | 7,890 | 1.1 | 2,020 |
| Hoburg | 878.9 | 886.35 | 7,450 | 1.0 | 1,907 |
| | 912.23 | 924.4 | 12,170 | 1.7 | 3,115 |
| **Total** | | | **69,160** | **9.6** | **17,704** |

Table 8.6: Scenario ROC_SW: Rock placement in Sweden

| Scenario: ROC_SW | | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type | [$m^3$] | [-] | [days] | [T] |
| Pre-Lay | Tie-in | 12,000 | 1 | 1.8 | 166 |
| | Static | 4,545 | 4 | 0.7 | 63 |
| Post-Lay | Static | 17,771 | 29 | 2.7 | 239 |
| | Fatigue | 6,171 | 34 | 0.9 | 78 |
| | Dynamic | 1,794 | 2 | 0.3 | 25 |
| **Total** | | **42,281** | **70** | **6.3** | **570** |

Table 8.7: Scenario ROC_FI_W: Rock placement in Finland (West pipe)

| Scenario: ROC_FI_W |  | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type/Phase | [m³] | [-] | [days] | [T] |
| Pre-Lay | Tie-In | 12,000 | 1 | 1.8 | 166 |
|  | Phase 1 | 45,495 | 12 | 6.8 | 615 |
| Post-Lay | Phase 2 | 84,288 | 52 | 12.6 | 1,122 |
|  | Phase 3 | 12,239 | 21 | 1.8 | 169 |
|  | Spot gravel | 1,127 | 17 | 0.2 | 16 |
| **Total** |  | **155,149** | **103** | **23.3** | **2,088** |

Table 8.8: Scenario ROC_FI_E: Rock placement in Finland (East pipe)

| Scenario: ROC_FI_E |  | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type/Phase | [m³] | [-] | [days] | [T] |
| Pre-Lay | Tie-In | 12,000 | 1 | 1.8 | 166 |
|  | Phase 1 | 5,736 | 7 | 0.9 | 39 |
| Post-Lay | Phase 2 | 59,369 | 38 | 8.9 | 751 |
|  | Phase 3 | 6,535 | 28 | 1.0 | 54 |
|  | Spot gravel | 892 | 17 | 0.1 | 12 |
| **Total** |  | **84,532** | **91** | **13** | **1,023** |

Table 8.9 Scenario ROC_KAL_W: Rock placement in Finland (Kalbadagrund alternative, West pipe)

| Scenario: ROC_KAL_W |  | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type | [m³] | [-] | [days] | [T] |
| Pre-Lay | Tie-In | 12,000 | 1 | 1.8 | 166 |
|  | Phase 1 | 28,518 | 9 | 4.3 | 352 |
| Post-Lay | Phase 2 | 97,166 | 45 | 14.6 | 1,314 |
|  | Phase 3 | 14,903 | 25 | 2.2 | 110 |
|  | Spot gravel | 1,127 | 17 | 0.2 | 16 |
| **Total** |  | **153,714** | **97** | **23.1** | **1,957** |

Table 8.10: Scenario ROC_KAL_E: Rock placement in Finland (Kalbadagrund alternative, East pipe)

| Scenario: ROC_KAL_E | | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type | [m³] | [-] | [days] | [T] |
| Pre-Lay | Tie-In | 12,000 | 1 | 1.8 | 166 |
| | Phase 1 | 5,974 | 4 | 0.9 | 39 |
| Post-Lay | Phase 2 | 61,028 | 37 | 9.2 | 795 |
| | Phase 3 | 11,423 | 31 | 1.7 | 83 |
| | Spot gravel | 892 | 16 | 0.1 | 8 |
| **Total** | | **91,317** | **89** | **13.7** | **1,091** |

Table 8.11: Scenario ROC_RU: Rock placement in Russia

| Scenario: ROC_RU | | Rock volume | Number of sites | Duration | Suspended sediment |
|---|---|---|---|---|---|
| Activity | Type | [m³] | [-] | [days] | [T] |
| Pre-Lay | Static | 30,652 | 23 | 4.6 | 186 |
| Post-Lay | Static | 42,906 | 69 | 6.4 | 529 |
| | Fatigue | 6,903 | 28 | 1.0 | 29 |
| | Buckling | 559,548 | 52 | 83.9 | 6,337 |
| **Total** | | **640,008** | **172** | **96.0** | **7,081** |

Table 8.12: Scenario DRE_RU: Dredging in Russia

| Scenario: DRE_RU | To | Length | Volume | Duration | Suspended sediment |
|---|---|---|---|---|---|
| KP [m] | KP [m] | [m] | [m³] | [days] | [T] |
| 0 | 458 | 458 | 33,884 | 9.4 | 3,388 |
| 458 | 610 | 152 | 9,324 | 2.6 | 932 |
| 610 | 965 | 355 | 18,889 | 5.2 | 1,889 |
| 965 | 1100 | 135 | 5,588 | 1.6 | 559 |
| 1100 | 1430 | 330 | 5,379 | 1.5 | 538 |
| 3291 | 4767 | 1,476 | 10,887 | 3.0 | 1,089 |
| **Total** | | **2,906** | **83,951** | **23.3** | **8,395** |

## 8.4 Post-processing

The spill for rock placement and trenching is released rather close to the seabed, cf. section 4, making it unlikely to be suspended higher than 10 m. Contaminants being dissolved in the water without any settling velocity may however be spread across the entire water column.

Since the water depth varies greatly across the Baltic Sea then the concentration may vary substantially through the water column. Therefore, the results for depth averaged concentrations of suspended sediment and contaminants are post-processed to represent all suspended matter as contained in the lower 10 m layer, thus regarding the remaining water column as clean. In this way the results represent comparable values including all suspended matter. Dredging at landfall in Russia (DRE_RU) is except from this due to local areas of water depth less than 10 m).

The post-processing leads to an increase of the concentrations and considered conservative.

# 9. Spreading of sediment

The results of the model simulations are analysed in terms of the seabed sedimentation and suspended sediment quantified by the following measures:

- Total amounts of suspended sediment
- Area and average duration of suspended sediment concentration
- Area of seabed sedimentation and average sedimentation rate

## 9.1 Total amounts of suspended sediment

An overview of the total suspended sediment in each scenario is shown in Figure 9.1. For all countries the amount totals app. 50,000 T (for 1 pipe without alternatives) with the highest contributions from the trenching and dredging works.

All the suspended sediment is assumed to be of the fine fractions and distributed according to the grain-size distributions for each country and work type shown in Table 5.4.

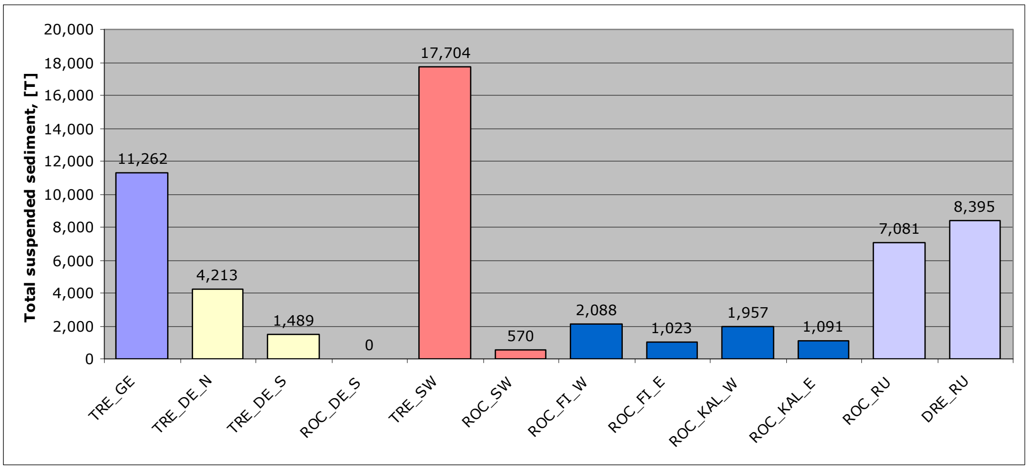



Figure 9.1 Total amounts of suspended sediment in each scenario.

## 9.2 Area and average duration of suspended sediment concentrations

The areas and average duration of a suspended sediment concentration > 1 mg/l are shown on maps in Appendix B: Atlas maps. A excess concentration of 1 mg/l will hardly be visible in the water since normally occurring concentrations in the Baltic Sea is typically in the range of 1 – 4 mg/l during normal weather and even higher during stormy conditions, /46/. Therefore the sediment clouds shown on the Atlas Maps may be regarded as the maximum extent of the sediment spreading (for the applied weather conditions). The following assessments are based on the maps in Appendix B: Atlas maps.

For trenching the sediment generally settles within 2 km of the pipelines. Only on few occasions of strong currents perpendicular to the pipeline the sediment may travel up to about 5 km away. The duration of a 1 mg/l concentration is generally in the range of 1 -24 hours, after which conditions returns to normal.

For rock placements the sediment spreading is even slighter (mainly due to the lighter disturbance of the seabed compared to trenching). The 1 mg/l concentration is seen a maximum of 1-2 km away from the pipelines and usually with a duration less than 12 hours.

Dredging is the seabed work type with the largest disturbance of the seabed and is associated with the largest spill, however only relevant for the landfall areas. As a result of the higher current speed at the coastal areas, and the higher spill, the suspended sediment concentration > 1 mg/l is seen up to 7 – 8 km from the pipeline.

The areas of suspended sediment concentration > 1 and 10 mg/l are shown in Table 9.1 along with the average duration. It is seen that the trenching activities generally affects the largest areas. If considering a concentration > 10 mg/l the part from rock placement is only a few $km^2$ in total. The landfall dredging activities constitutes a large part compared to the short distance covered.

Table 9.1 Area and average duration of suspended sediment concentrations.

| | Suspended sediment[1] | | | |
|---|---|---|---|---|
| **Normal weather** | **Area of concentration > 1 mg/l** | **Area of concentration > 10 mg/l** | **Avg. duration of concentration > 1 mg/l** | **Avg. duration of concentration > 10 mg/l** |
| **ID** | **[km²]** | **[km²]** | **[hr]** | **[hr]** |
| TRE_GE | 99.0 | 31.1 | 6.5 | 2.0 |
| TRE_DE_N | 29.1 | 10.2 | 11.3 | 3.4 |
| TRE_DE_S | 11.8 | 4.1 | 10.5 | 3.0 |
| ROC_DE_S | - | - | - | - |
| TRE_SW | 275.9 | 72.6 | 12.3 | 4.9 |
| ROC_SW | 9.3 | 0.2 | 7.3 | 6.0 |
| ROC_FI_W | 33.3 | 0.4 | 10.4 | 7.6 |
| ROC_FI_E | - | - | - | - |
| ROC_KAL_W | 31.0 | 0.1 | 9.4 | 4.5 |
| ROC_KAL_E | - | - | - | - |
| ROC_RU | 81.1 | 1.8 | 12.0 | 5.2 |
| DRE_RU | 35.6 | 5.6 | 11.7 | 12.8 |
| **Average** | **-** | **-** | **10.2** | **5.5** |

- Not modelled.

[1] Average concentration 0 - 10 m above the seabed (including all suspended particles), cf. section 8.4.

## 9.3 Area of seabed sedimentation and average sedimentation rate

The resulting net sedimentation once all particles have settled are shown on maps in Appendix B: Atlas maps.

A net sedimentation in excess of 1 mm (yellow and red colours) is seen to occur almost only for dredging in Russia. For trenching and rock placement the majority of the sediment will settle within close vicinity (few 100 m) of the pipeline. Only very minor net sedimentation (< 1 mm) is observed in areas up to a few kilometres from the pipelines.

The areas of net sedimentation > 1 mm and > 10 mm and the average sedimentation rate > 1 mm (assuming a local average settling duration of 12 hours following the cessation of seabed activity) are summarized in Table 9.2.

The total area of net sedimentation > 1 mm for all seabed works is about 2 km$^2$, with most of it (1.2 km$^2$) arising from the dredging activities at landfall, Russia. The average sedimentation rate is less than 1 mm/hr for all the seabed works. However, a higher sedimentation rate is expected in the close vicinity of the pipelines.

An area of < 0.1 km$^2$ indicates that the amount of suspended sediment is too small to cover any significant area with a net sedimentation > 1 mm. The close vicinity of the pipelines may experience a net sedimentation > 1 mm, however this is not considered further as this is within the area of possible immediate disturbance of the seabed, cf. section 4.1.

Table 9.2 Area of seabed sedimentation and average sedimentation rate.

| | Seabed sedimentation | | |
|---|---|---|---|
| Normal weather | Area of net sedimentation[1] > 1 mm | Area of net sedimentation > 10 mm | Avg. sedimentation[1,2] rate > 1 mm |
| ID | [km$^2$] | [km$^2$] | [mm/hr] |
| TRE_GE | < 0.1 | < 0.1 | 0.1 |
| TRE_DE_N | 0.3 | < 0.1 | 0.2 |
| TRE_DE_S | < 0.1 | < 0.1 | < 0.1 |
| ROC_DE_S | - | - | - |
| TRE_SW | 0.2 | < 0.1 | 0.1 |
| ROC_SW | < 0.1 | < 0.1 | < 0.1 |
| ROC_FI_W | < 0.1 | < 0.1 | < 0.1 |
| ROC_FI_E | < 0.1 | < 0.1 | < 0.1 |
| ROC_KAL_W | < 0.1 | < 0.1 | < 0.1 |
| ROC_KAL_E | < 0.1 | < 0.1 | < 0.1 |
| ROC_RU | 0.2 | < 0.1 | 0.1 |
| DRE_RU | 1.2 | 0.3 | 0.9 |
| **Average** | - | **-** | **0.1** |

- Not modelled.

[1] Assuming a porosity of 0.6 (1 kg/m$^2$ ~ 1 mm).

[2] Assuming a local average settling duration of 12 hr succeeding the passing of a seabed activity.

The extent of the spreading is also influenced by the grain-size distributions, cf. Table 5.4. High clay content (typical for rock placement sites) allows a longer suspension time of the particles compared to silt and sand (typical for trenching and dredging sites).

## 9.4 Sensitivity of hydrographical conditions on sediment spreading

The sensitivity of hydrographical conditions on sediment spreading has been studied for the case of trenching in Sweden (the scenario with the highest spill), by simulating the same scenario for 3 different periods representing calm, normal and rough conditions, cf. section 7.3. Sweden has the longest total stretch of trenching and the results may be seen as representative of the overall sensitivity of sediment spreading modelling.

The results are shown in Table 9.3, indicating a relatively weak sensitivity. The areas and durations of suspended concentrations vary less than +/- 20% from average. This is regarded as a consequence of sediment settling, in combination with the spill occurring fairly close to the seabed. The trend is that calm conditions cause longer exceedance durations that covers smaller areas.

Table 9.3 Suspended sediment during calm, normal and rough hydrographical periods.

| | Suspended sediment[1] | | | |
|---|---|---|---|---|
| **Scenario: TRE_SW** | **Area of concentration > 1 mg/l** | **Area of concentration > 10 mg/l** | **Avg. duration of concentration > 1 mg/l** | **Avg. duration of concentration > 10 mg/l** |
| **Weather** | **[km$^2$]** | **[km$^2$]** | **[hr]** | **[hr]** |
| Calm | 200.2 | 67.6 | 12.8 | 6.6 |
| Normal | 275.9 | 72.6 | 12.3 | 4.9 |
| Rough | 266.8 | 70.4 | 11.1 | 5.1 |
| **Average** | **247.6** | **70.2** | **12.1** | **5.5** |

[1] Average concentration 0 - 10 m above the seabed (including all suspended particles), cf. section 8.4.

# 10. Spreading of contaminants

The spreading of contaminants are analysed in terms of the suspended contaminant concentrations quantified by the following measures:

- Total amounts of suspended, desorbed and bioactive contaminants
- Time series at the largest rock placement sites
- Area and average duration of contaminant concentrations > PNEC

## 10.1 Total amounts of suspended, desorbed and bioactive contaminants

The total suspended, desorbed and bioactive amounts of the 4 most critical chemical compounds (Zn, Cu, As and SUM16PAH), see section 6.5, in each scenario is shown in Figure 10.1. Contaminants are only considered in the rock placement areas since the trenching and dredging areas are erosion areas without any significant degree of contamination, /61/.

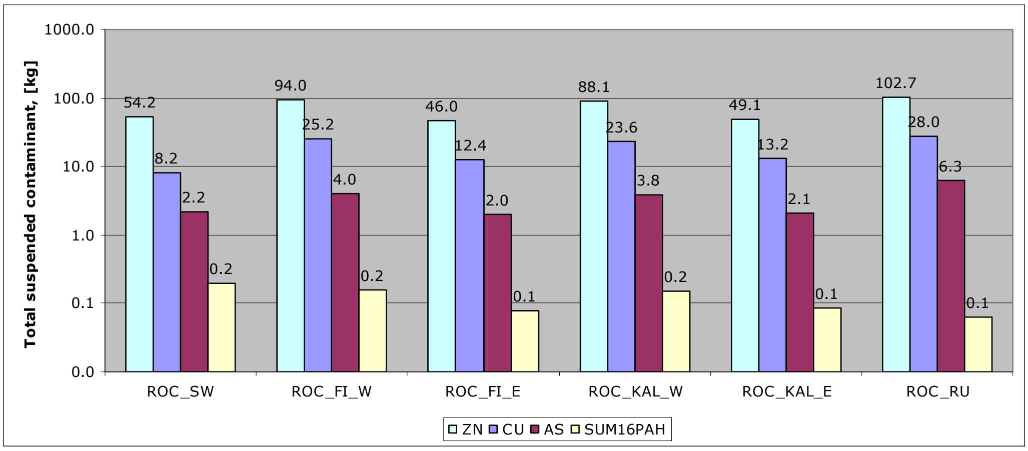



Figure 10.1 Total amounts of suspended, desorbed and bioactive Zn, Cu, As and SUM16PAH.

## 10.2 Time series at the largest rock placement sites

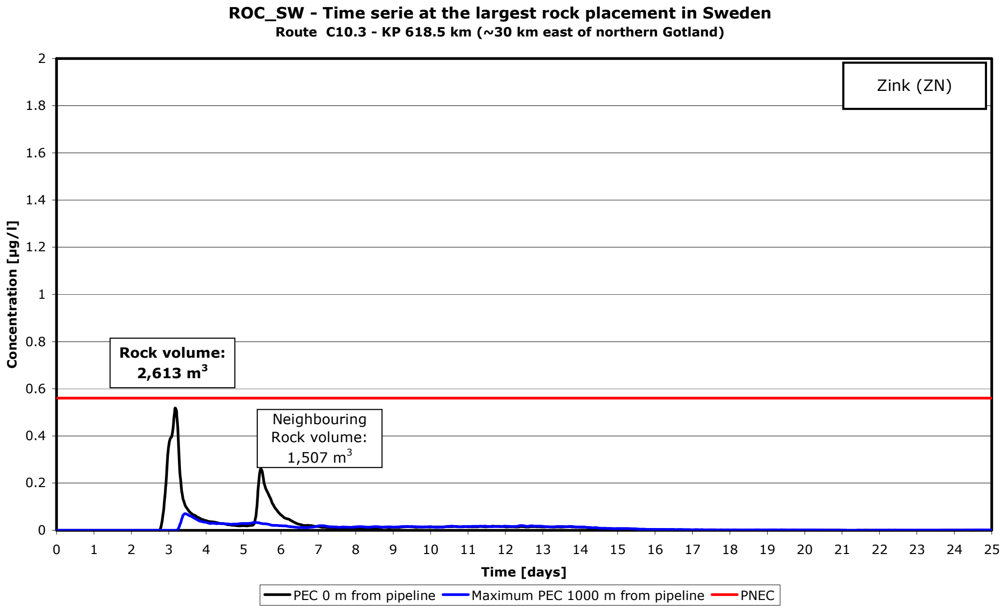
Time series of contaminant concentrations at the largest rock placement sites in each country have been extracted from the model results and plotted against the PNEC value, see Figure 10.2, Figure 10.3 and Figure 10.4.

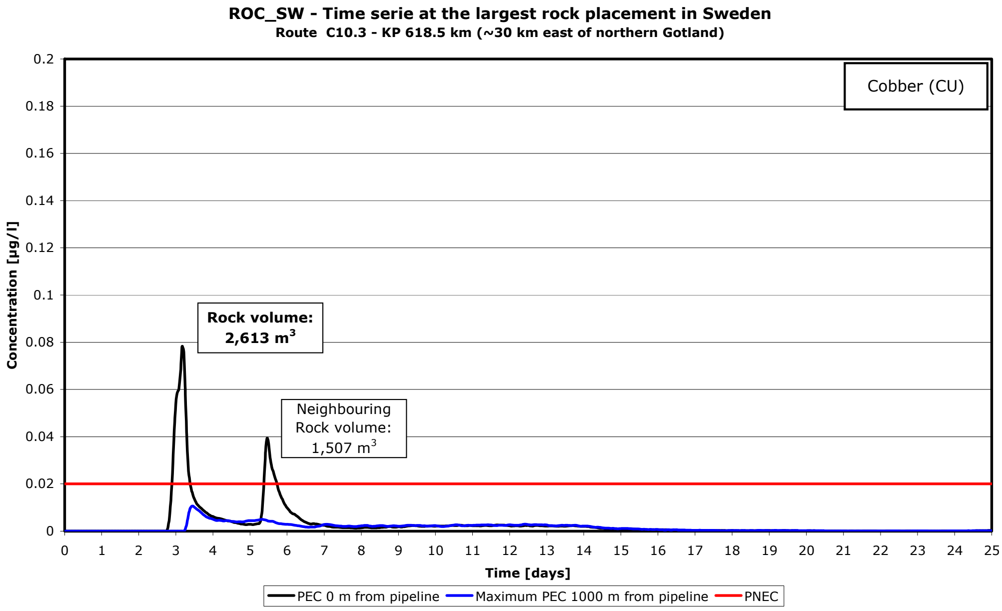
For Zn it is seen that the PNEC value are not exceeded at any time, while As is only exceeded less than 1000 m from the pipeline. Therefore only the compounds with a relative toxicity higher than As are considered further, i.e. Cu and SUM16PAH, see section 6.5.

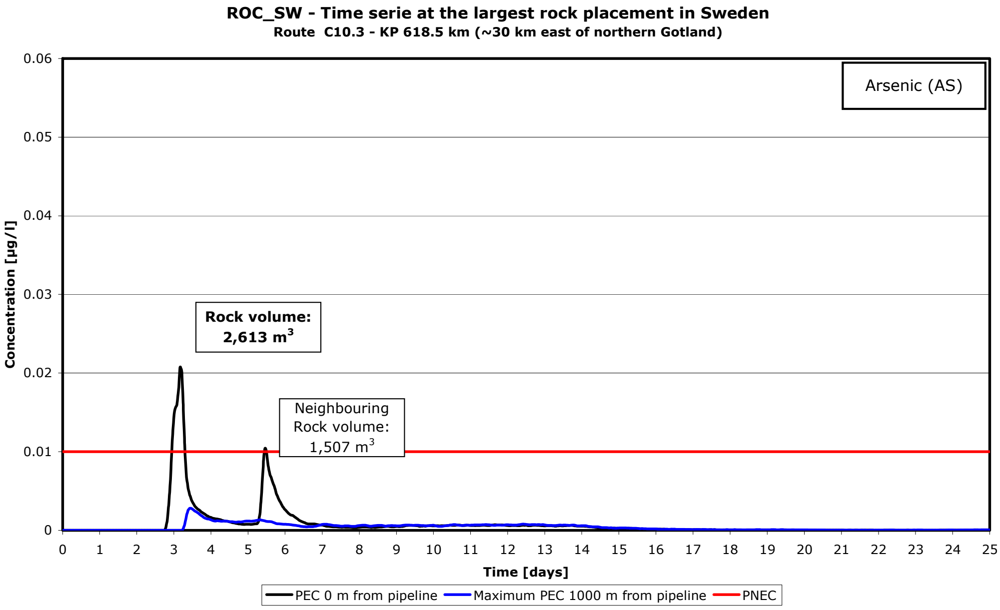
The extracted time series are from the largest rock placements in each country (sometimes with additional influence from neighbouring rock placements) and hence represent the locations with the highest release of contaminants. In comparison the average rock placement volumes are 439 $m^3$ in Sweden, 1,403 $m^3$ in Finland and 3,721 $m^3$ in Russia.

The durations that the PNEC are exceeded at the pipeline is typically around 1 - 3 days which is approximately the same duration as it takes to place the rocks. Hence, any critical concentration has diminished shortly after the finalization of the rock placement due to natural spreading.

The maximum PEC 1000 m away from the pipelines is exceed only for the 1 or 2 most critical compounds (Cu and/or SUM16PAH) for even shorter durations.


ROC_SW - Time serie at the largest rock placement in Sweden
Route C10.3 - KP 618.5 km (~30 km east of northern Gotland)
Zink (ZN)
Rock volume: 2,613 m3
Neighbouring Rock volume: 1,507 m3
Concentration [µg/l]
Time [days]
PEC 0 m from pipeline
Maximum PEC 1000 m from pipeline
PNEC


ROC_SW - Time serie at the largest rock placement in Sweden
Route C10.3 - KP 618.5 km (~30 km east of northern Gotland)
Cobber (CU)
Rock volume: 2,613 m3
Neighbouring Rock volume: 1,507 m3
Concentration [µg/l]
Time [days]
PEC 0 m from pipeline
Maximum PEC 1000 m from pipeline
PNEC



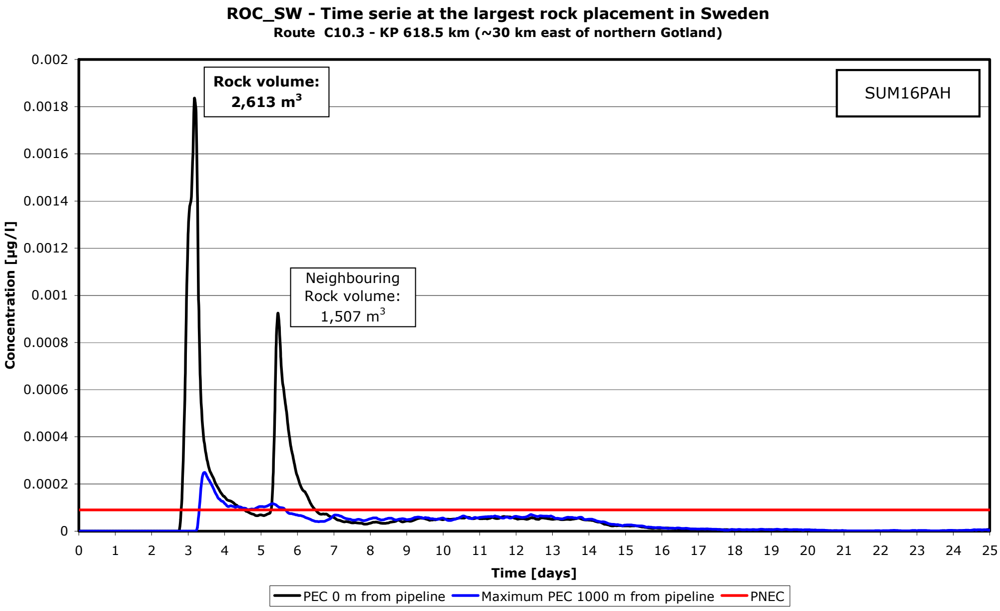
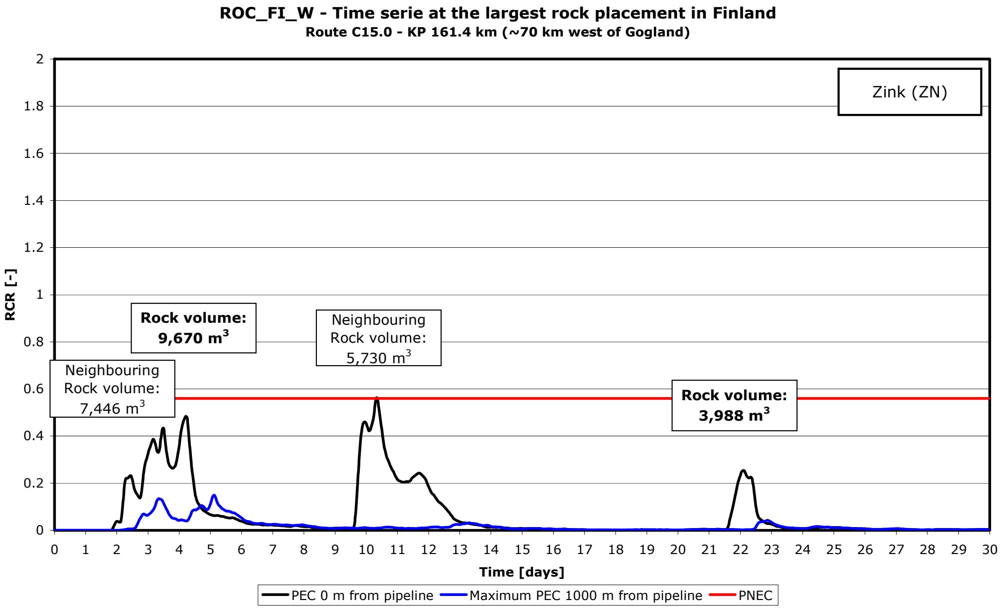
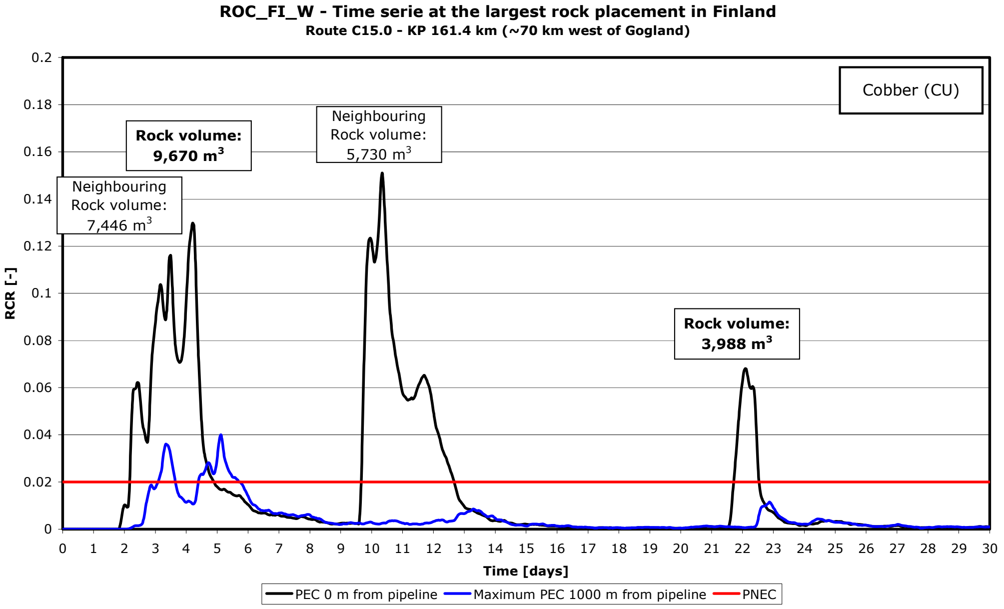



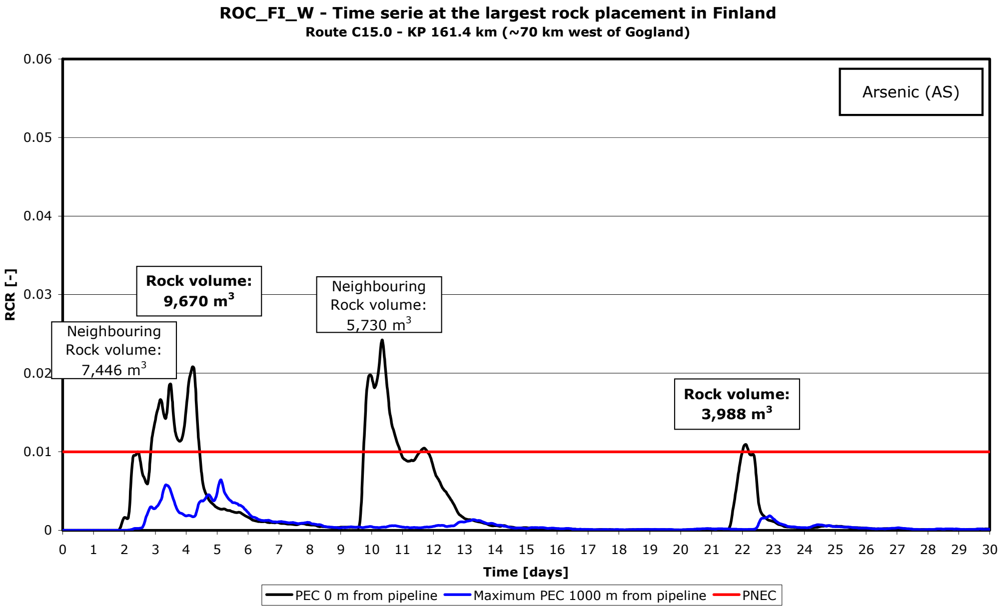

Figure 10.2 Time series at the largest rock placement site in Sweden.



ROC_FI_W - Time serie at the largest rock placement in Finland
Route C15.0 - KP 161.4 km (~70 km west of Gogland)
Zink (ZN)
Rock volume: 9,670 m3
Neighbouring Rock volume: 5,730 m3
Neighbouring Rock volume: 7,446 m3
Rock volume: 3,988 m3
RCR [-]
Time [days]
PEC 0 m from pipeline
Maximum PEC 1000 m from pipeline
PNEC

ROC_FI_W - Time serie at the largest rock placement in Finland
Route C15.0 - KP 161.4 km (~70 km west of Gogland)
Cobber (CU)
Rock volume: 9,670 m3
Neighbouring Rock volume: 5,730 m3
Neighbouring Rock volume: 7,446 m3
Rock volume: 3,988 m3
RCR [-]
Time [days]
PEC 0 m from pipeline
Maximum PEC 1000 m from pipeline
PNEC



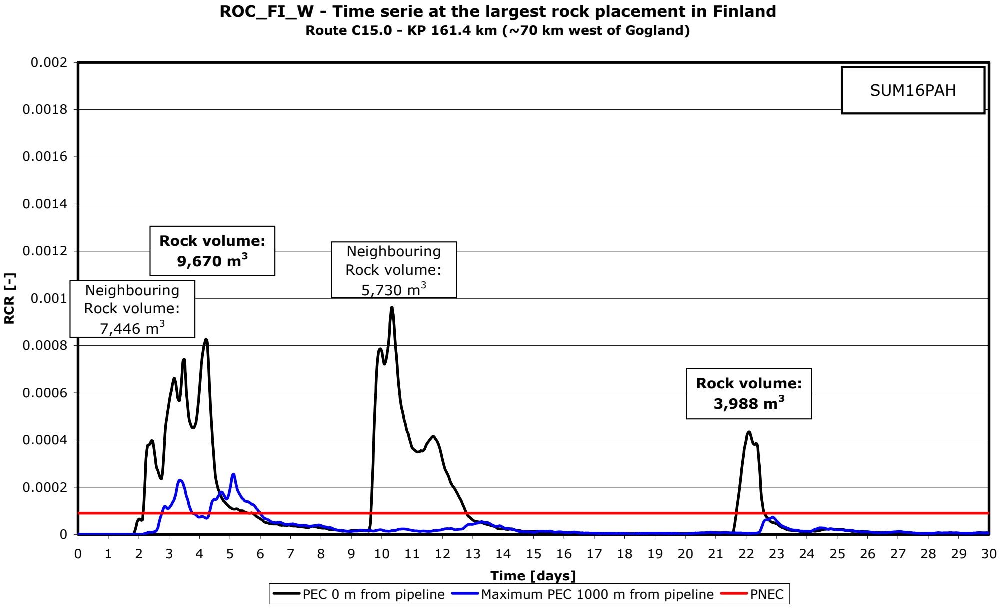
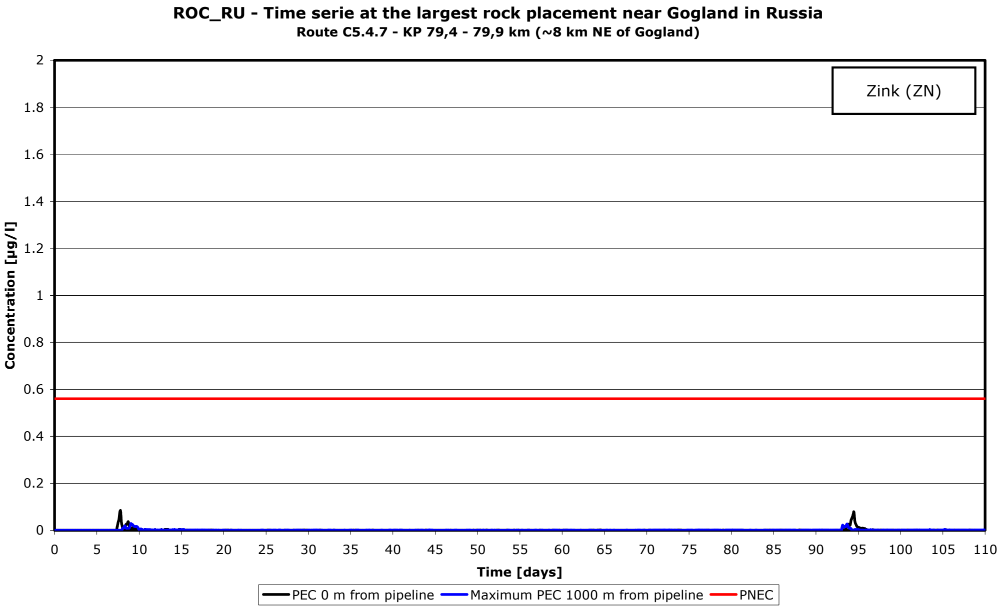
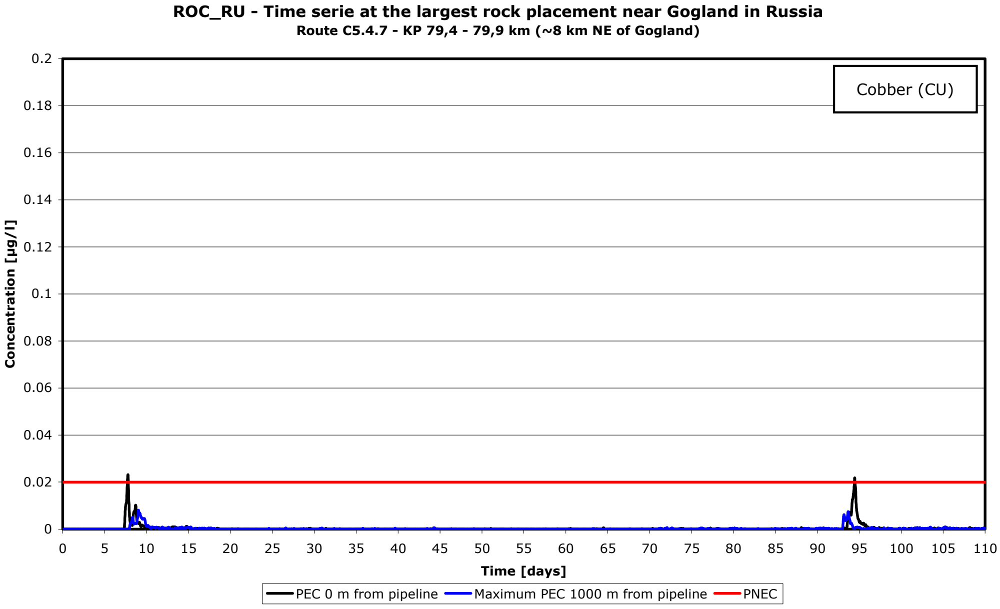
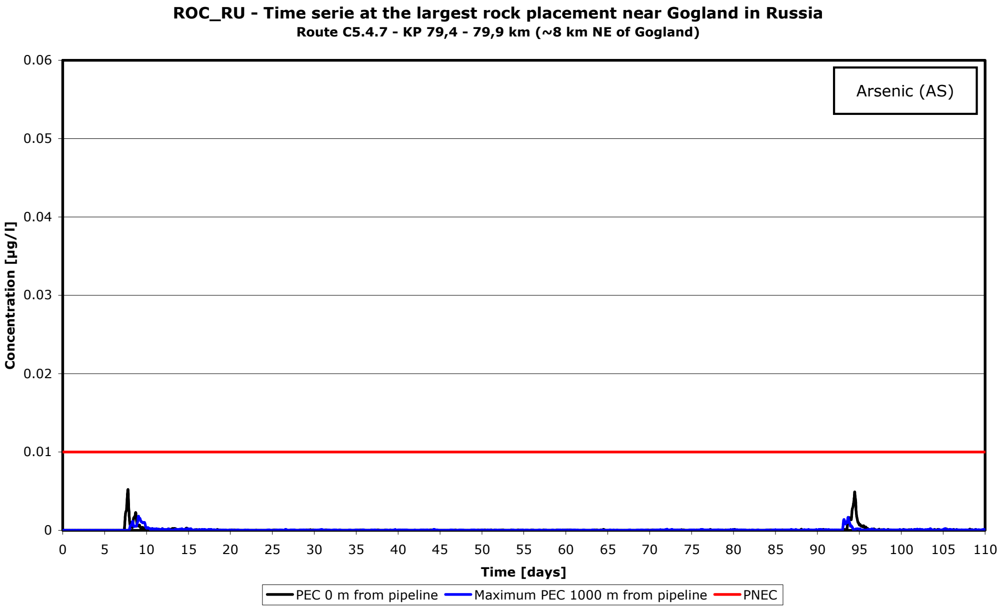




Figure 10.3 Time series at the largest rock placement site in Finland.


ROC_RU - Time serie at the largest rock placement near Gogland in Russia
Route C5.4.7 - KP 79,4 - 79,9 km (~8 km NE of Gogland)
Zink (ZN)
Concentration [µg/l]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
Time [days]
PEC 0 m from pipeline
Maximum PEC 1000 m from pipeline
PNEC


ROC_RU - Time serie at the largest rock placement near Gogland in Russia
Route C5.4.7 - KP 79,4 - 79,9 km (~8 km NE of Gogland)
Cobber (CU)
Concentration [µg/l]
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
Time [days]
PEC 0 m from pipeline
Maximum PEC 1000 m from pipeline
PNEC



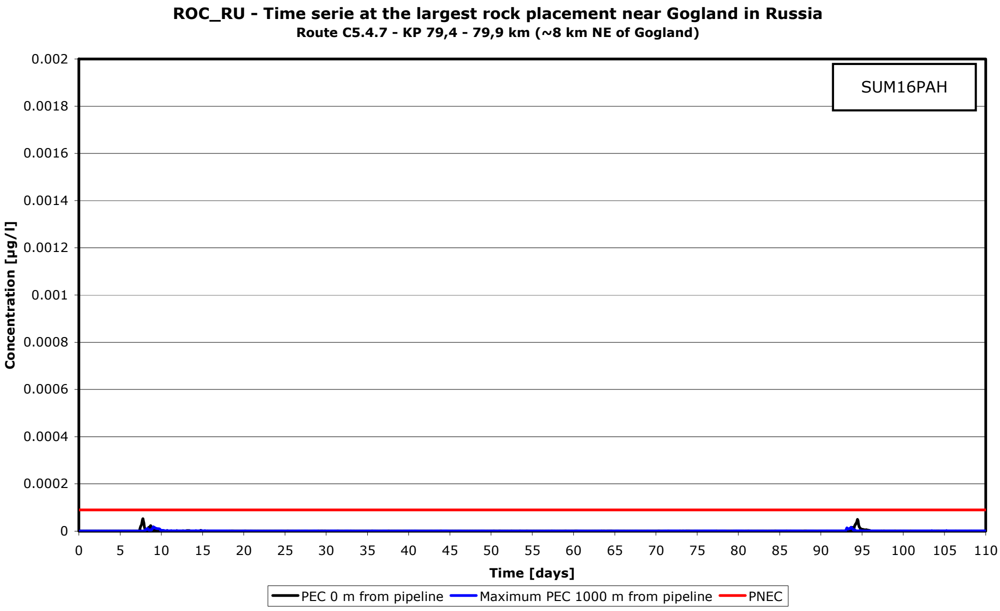




Figure 10.4 Time series at the largest rock placement site in Russia.

## 10.3 Area and average duration of suspended contaminants

The maximum concentrations of Cu and SUM16PAH are shown on maps in Appendix B: Atlas maps. The locations of the affected areas are highly sensitive to the current speed and direction since the contaminants are treated as dissolved particles that do not settle.

The PNEC is exceeded for yellow and red colours only which generally occurs only within app. 5 km of the pipelines. In very few locations during rough weather with strong currents perpendicular to the pipeline the PNEC is exceeded up to about 10 km from the pipelines. The average duration of exceedance is typically ½ - 1 day (except 3 days for SUM16PAH in Sweden.

The areas and average durations of a concentration > PNEC for Cu and SUM16PAH are summarized in Table 10.1. For Cu the largest affected area is in Finland (~49 $km^2$ during averagely 12.2 hr) while for SUM16PAH the largest area is in Sweden (~117 $km^2$ during averagely 73.3 hr). This is due to different sediment bound concentration levels. The longest average durations are found in Sweden, which is mainly due to the deeper locations with weaker currents.

The results for the Kalbadagrund alternative in Finland are very similar to those of the main route. The difference in results is mostly an outcome of the different hydrographical influence since the overall change in rock placement volumes is small. The main distinction is that the affected areas are moved corresponding to the route location, see Appendix B: Atlas maps. For the east route in Finland the affected areas are smaller compared to the west route reflecting the smaller rock volumes.

Table 10.1 Area and average duration of a concentration > PNEC for Cu and SUM16PAH.

| | Suspended Cobber (Cu)[1] | | Suspended SUM16PAH[1] | |
|---|---|---|---|---|
| **Normal weather** | **Area of concentration > PNEC** | **Avg. duration of concentration > PNEC** | **Area of concentration > PNEC** | **Avg. duration of concentration > PNEC** |
| **ID** | **[$km^2$]** | **[hr]** | **[$km^2$]** | **[hr]** |
| ROC_SW | 17.5 | 24.4 | 116.7 | 73.3 |
| ROC_FI_W | 45.8 | 18.6 | 75.0 | 20.7 |
| ROC_FI_E | 28.2 | 13.1 | 42.0 | 16.6 |
| ROC_KAL_W | 49.0 | 12.2 | 82.5 | 13.6 |
| ROC_KAL_E | 28.1 | 13.5 | 43.4 | 16.6 |
| ROC_RU | 37.4 | 14.0 | 7.5 | 14.0 |
| **Average** | **-** | **16.0** | **-** | **25.8** |

- Not modelled.

[1] Average concentration 0 - 10 m above the seabed (including all suspended particles), cf. section 8.4.

## 10.4 Sensitivity of hydrographical conditions on contaminant spreading

The sensitivity of hydrographical conditions on contaminant spreading has been studied for the case of rock placement in Finland (covering most of the Gulf of Finland), by simulating the same scenario for 3 different periods representing calm, normal and rough conditions, cf. section 7.3. Finland has the largest amount of rock placement and the results may be seen as representative of the overall sensitivity of contaminant spreading modelling.

The results are shown in Table 10.2 for scenario ROC_FI_W and in Table 10.3 for scenario ROC_KAL_W. The results indicate some sensitivity with areas and durations of suspended concentrations > PNEC varying up to +/- 25% from average. The higher sensitivity of contaminants compared to sediment is a consequence of the contaminants being dissolved in the water thus lacking any settling velocity. This results in calm conditions causing longer exceedance durations in larger areas, i.e. being the worst overall case.

Table 10.2 Area and average duration of a concentration > PNEC for Cu and SUM16PAH for calm, normal and rough hydrographical periods in scenario ROC_FI_W.

| | Suspended Cobber (Cu)[1] | | Suspended SUM16PAH[1] | |
|---|---|---|---|---|
| **Scenario: ROC_FI_W** | **Area of concen-tration > PNEC** | **Avg. duration of concentration > PNEC** | **Area of concen-tration > PNEC** | **Avg. duration of concentration > PNEC** |
| **Weather** | **[km²]** | **[hr]** | **[km²]** | **[hr]** |
| Calm | 53.0 | 17.4 | 85.2 | 22.1 |
| Normal | 45.8 | 18.6 | 75.0 | 20.7 |
| Rough | 45.6 | 12.7 | 75.1 | 20.8 |
| **Average** | **48.1** | **16.2** | **78.4** | **21.2** |

Table 10.3 Area and average duration of a concentration > PNEC for Cu and SUM16PAH for calm, normal and rough hydrographical periods in scenario ROC_KAL_W.

| | Suspended Cobber (Cu)[1] | | Suspended SUM16PAH[1] | |
|---|---|---|---|---|
| **Scenario: ROC_KAL_W** | **Area of concen-tration > PNEC** | **Avg. duration of concentration > PNEC** | **Area of concen-tration > PNEC** | **Avg. duration of concentration > PNEC** |
| **Weather** | **[km²]** | **[hr]** | **[km²]** | **[hr]** |
| Calm | 55.3 | 16.7 | 81.1 | 21.2 |
| Normal | 49.0 | 12.2 | 82.5 | 13.6 |
| Rough | 44.8 | 11.0 | 77.7 | 12.8 |
| **Average** | **49.7** | **13.3** | **80.4** | **15.9** |

# 11. Conclusion

The spreading of sediments and contaminants in connection with works in the seabed related to the Nord Stream gas pipeline project, including rock placement, trenching and dredging has been evaluated.

Information regarding the planned seabed works was obtained from Snamprogetti, while hydrodynamic data from 2005 was acquired from a numerical 3D model of the Baltic Sea, run by DHI, Denmark. Properties of seabed sediment and contaminants were adopted from PeterGaz Ltd reports, existing databases, literature and new sediment samples along the pipeline corridor. The spreading of sediment and contaminants were assessed through simulations using the 3D numerical particle analysis model MIKE 3 PA.

The spreading was quantified in terms of net sedimentation and concentrations of suspended sediment and contaminants (see Appendix B: Atlas maps). It is noted that the model results are an outcome of specific hydrographical conditions and should be seen as examples of a representative events and not as an exact result of what will actually occur.

The spill rate of sediment related to the seabed works was estimated at app. 20 kg/s for trenching, 1 kg/s for rock placement and 7 kg/s for dredging. It was found that the most critical chemical compounds are Cobber (Cu) and PAH's (SUM16PAH).

The following main results are found:

<u>Rock placement (fall-pipe):</u>

- A total area for all countries of about 2 $km^2$ (within a few 100 m of the pipelines) may experience a suspended sediment concentration > 10 mg/l with an average duration of 5 – 8 hrs.

- Any significant net sedimentation (> 1 mm) is expected only in very minor areas beyond the close vicinity of the pipelines (> 100 m away).

- A total area of 100 – 200 $km^2$ (typically within about 5 km from the pipelines) may experience an exceedance of the PNEC value of Cu and PAH for typically ½ - 1 day on average and up to ~3 days at certain locations.

- For contaminants the total areas and average duration of concentrations > PNEC may vary up to +/-25% from average due to different hydrographical conditions. During rough weather exceedance is seen up to about 10 km from the pipelines in few locations, but the overall exceedance is highest during calm conditions.

Trenching (plough):

- A total area for all countries of about 100 $km^2$ (generally within ~1 km of the pipelines) may experience a suspended sediment concentration > 10 mg/l with an average duration of 2 – 5 hrs.

- The durations of suspended sediment concentrations is shorter compared to rock placement which is mainly due to the more exposed locations (higher current velocities) where trenching is performed.

- Any significant net sedimentation (> 1 mm) is expected only in very minor areas beyond the close vicinity of the pipelines (> 100 m away).

- For sediment the areas and durations of suspended concentrations vary less than +/- 20% from average due to different hydrographical conditions. The trend is that calm conditions cause longer exceedance durations that covers smaller areas.

Dredging (scoop/excavator) (excluding German landfall):

- A total area of about 6 $km^2$ (generally within a few km of the pipelines) may experience a suspended sediment concentration > 10 mg/l with an average duration of about 12 hrs.

- A total area of 1 - 2 $km^2$ (generally within 1 km of the pipelines) may experience a net sedimentation > 1 mm.

It is concluded that the applied methods for trenching (plough) and rock placement (fall-pipe) mainly causes a disturbance in the close vicinity (within the order of 100 m) of the pipelines.

The suspension of sediment is generally far too minor to produce a visible sediment concentration (> 1 mg/l) in the water more than a few hundred meters away and only primarily in the lower part of the water column. The resulting net sedimentation is therefore also very minor (< 1 mm) when more than a few 100 m from the pipelines.

Since conservative assumptions have been applied for assessing the governing input parameter, the sediment spill rate (1-20 kg/s), the results are considered to be on the safe side and only weakly sensitive to other parameters.

Dredging (only Russian landfall) is expected to cause some visible sediment concentrations and net sedimentation in excess of 1 mm as quantified above.

Only the release of Cu and PAH’s causes any significant exceedance of the PNEC values (typically within 5 km of the major rock placement sites). However, the release of contaminants is based on rather conservative assumptions including:

- $90^{th}$% fractile of the measured sediment bound concentrations
- High values for desorbtion and bioactivity in the water body
- No decay, settling or biodegradation after release
- Fast average discharge (i.e. little non-productive working time)

The actual observed concentrations in nature are therefore expected to be less. Further it is noted that the main ecotoxicological impact potential of the pipeline project is not caused by an emission of chemicals, but by a redistribution of depositions of chemical compounds already present in the Baltic Sea. Re-distribution in large scale occurs due to natural processes under storm events see /46/.

Some uncertainty lies in the assessment of sediment suspension (spill rate), especially from rock placement, all though comparison with reported observations of fall velocity indicates that the applied rates are conservative. In order to further validate the applied rates, a laboratory study is on-going to quantify the sediment release during rock placement.

# 12. Appendix A: Model basis

See attachment in the back of the document.

## 13. Appendix B: Atlas maps

See attachment in the back of the document.

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