Nord Stream AG

# Offshore pipeline through the Baltic Sea

Memo 4.3A-1
Model setup for the Baltic Sea

September 2008

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## Table of contents

## List of abbreviations and definitions

| | |
|---|---|
| DHI | The former "Danish Hydraulic Institute" – now "DHI – Water & Environment" |
| EEZ | exclusive economic zone |
| EIA | environmental impact assessment |
| HELCOM | Helsinki Commission. Convention on the Protection of the Marine Environment of the Baltic Sea Area |
| ICES | International Council for the Exploration of the Sea |
| MIKE 3 | 3-diamentional modelling family developed by DHI |
| MIKE 3 HD | Hydrodynamic module of the MIKE 3 model |
| MIKE 3 PA | Transport module of the MIKE 3 model |
| NM | Nautical mile (1852 m) |
| NOVANA | Danish Environmental Monitoring Programme |
| PSU | Practical Salinity Unit. Used to describe the concentration of dissolved salts in water defining salinity in terms of a conductivity ratio, according to UNESCO Practical Salinity Scale of 1978 (PSS78). Salinity was formerly expressed in terms of parts per thousand by weight (ppt or o/oo). |
| TEN-E | Trans European Energy Network |

# 1. Introduction

## 1.1 The Nord Stream project

Nord Stream is a natural gas pipeline transmission system from Russia to Germany with connections to onshore transmission systems in these two countries. The system will consist of two almost parallel 48-inch steel pipelines and is to be built by Nord Stream AG. It will pass through the exclusive economic zones (EEZ) of five countries: Russia, Finland, Sweden, Denmark and Germany, and the territorial waters of Russia, Germany and Denmark. At full capacity it will provide 55 billion cubic metres (bcm) of natural gas per year to western European consumers. Nord Stream is a priority project within the Trans-European Network - Energy (TEN-E).

The shareholders of Nord Stream AG are: OAO Gazprom, Wintershall AG (a BASF subsidiary) and E.ON Ruhrgas AG (an E.ON subsidiary). Soon the company NV Nederlandse Gasunie will join the shareholder 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 pipelines and will be the operator of the gas transmission system.

## 1.2 Environmental impacts – Hydrographical aspects

The environmental impact of the construction and operation of the pipeline on the marine environment is foreseen to include modelling of spreading of various substances such as sediment, contaminants, pressure test water etc.

This memo is meant to establish and report a common basis for the modelling. This involves:

- Overall discretion of the Baltic Sea
- Description of model approach
- Description of key input
- Description of hydrodynamic basis
- Validation of hydrodynamic basis
- Definition of representative simulation periods

This memo is not intended to report model results for spreading of various substances. Specific results from calculation are found in dedicated memos on e.g. seabed intervention works.

# 2. Summary

The Baltic Sea is described with respect to hydrographical conditions. The Baltic Sea is highly influenced by the large river runoff of approximately 15,000 $m^3/s$ (mean of 1921 - 1975) and the inflow from the North Sea. The Belt Sea forms the narrow and shallow transition area between the North Sea and the Baltic Sea. The internal bathymetry divides the Baltic Sea into several sub-basins or deeps, which are connected through shallow areas or sills. The mean depth of the Baltic Sea is 56 m.

The Baltic Sea is a complex stratified system with surface salinities varying between 3 -10 psu and bottom salinities up to 20 psu following a major inflow from the North Sea.

In summer, well-developed thermoclines exist. During the winter, parts of the Baltic Sea, mainly in the Bothnian Sea and Gulf of Finland, are covered with ice.

The influence of tide is usually negligible in the Baltic Sea, but the occurrence of free seiches at times dominates the water-level variation in the Baltic Sea.

The permanent current system in the Baltic Sea is weak, except for the transition area, i.e., the Belt Sea. However, the dense bottom current following a major inflow of North Sea water may reach speeds up to 30 cm/s. Over the 70-year period up to 1977, 90 major inflows were reported.

A general transport model is set up. The MIKE 3 PA model is used to simulate the transport and possible fate of dissolved and suspended substances. The simulated substances may be pollutants of any kind, including suspended sediment, chemicals or nutrients. The model uses a Lagrangian-type approach, which involves no other discretisations than those associated with the description of the bathymetry current and water-level fields. The Langrangian approach allows the PA model to be set up in a finer horizontal resolution than specified in the hydrodynamic basis, which is ideal for describing narrow plumes.

The hydrodynamic basis for transport simulation is acquired from the hydrodynamic model for the Baltic Sea setup by DHI Water - Environment - Health in MIKE 3 HD. The data from the model has a spatial resolution of 3 nautical miles (nm) horizontal and 1 m vertical down to 210 m (surface layer ~2.5 m) and covers the entire Baltic Sea, including Danish waters.

Based on time series from six positions along the alignment of the pipeline, periods are identified representing:

- Calm conditions (weak currents)
- Normal conditions (average currents)
- Rough conditions (strong currents)

The net transport (the linear distance between the start and end of the trajectory) is chosen to be the measure for characterisation of the above-mentioned hydrographic scenarios. The timescale for calculation of the net transport is chosen as the time it takes a typical particle to settle. This gives an average timescale of four days for all six positions.

The scenarios require a duration of one month to ensure a simulation period long enough to complete the particle-transport simulations. Based on this, the following three periods have been identified:

| | |
|---|---|
| Calm conditions | 28 April 2005 – 28 May 2005 |
| Normal conditions | 26 September 2005 – 26 October 2005 |
| Rough conditions | 21 November 2005 – 21 December 2005 |

Table 1: Simulation periods

## 3. Description of the Baltic Sea

The Baltic Sea is a very large, brackish water body encompassing 415,000 square kilometres /1/. It is a semi-enclosed area connected to the North Sea through the Danish Belt Sea. The Baltic Sea comprises five main regions: the Belt Sea – Kattegat, the Baltic Proper, the Gulf of Riga, the Gulf of Finland and the Gulf of Bothnia, cf. Figure 1.


Figure 1: Regions and catchment area of the Baltic Sea according to HELCOM, /15/.

The Nord Stream project area only covers a slender corridor through the Baltic Proper and the Gulf of Finland, but major impacts in these areas may influence conditions in other parts of or throughout the Baltic Sea. The general bathymetrical, hydrological and hydrographical characteristics of the Baltic Sea are described below.

## 3.1 Hydrology

The Baltic Sea is highly sensitive to variations in hydrological conditions due to the constrained transition area to the North Sea. The drainage basin of the Baltic Sea is 1,720,000 km$^2$ , cf. Figure 1, /15/. The mean (1994 - 1998) river runoff is approximately 15,700 m$^3$/s, /15/. The greatest runoff in April and June (up to ~25,000 m$^3$/s) due to ice and snow melting. The lowest runoff is in January and February (down to 9000  m$^3$/s) /15/2/. The largest river is the Neva River, entering at St. Petersburg and contributing with 114 km$^3$/year, /15/ which is approx. 23% of the total river discharge /3/. The long-term annual mean of precipitation/evaporation is 2,000 m$^3$/s. The river runoff and the precipitation/evaporation are responsible for balancing the inflow of saline water from the Belt Sea.

## 3.2 Bathymetry

The Belt Sea, i.e., Little Belt, Great Belt and Øresund, forms the narrow and shallow transition area between the North Sea and the Baltic Sea. The Darss sill and Drogden sill constitute the shallowest part of the Belts and the Øresund flow and have typical depths of 17 - 18 m and 7 - 8 m respectively. Approximately 70% of the water flow is directed through the Great Belt and the remaining 30% through the Øresund /4/. The internal bathymetry divides the Baltic Sea into several sub-basins or deeps, which are separated by shallow areas or sills. The extent and key parameters of the sub-basins are shown in and
Table 2 /3/.

The mean depth of the Baltic Sea is approximately 56 m, and the total volume is approximately 20,900 km$^3$ /3/. The deepest parts, up to 459 m, are found in the Northern Central Basin, while the shallow area of the Bornholm Strait separating the Arkona Basin from the Bornholm Basin has maximum depths of 45 m. The Stolpe Channel sill separating the Bornholm Basin and the Gotland Deep reaches depths of approximately 60 m. /5/.

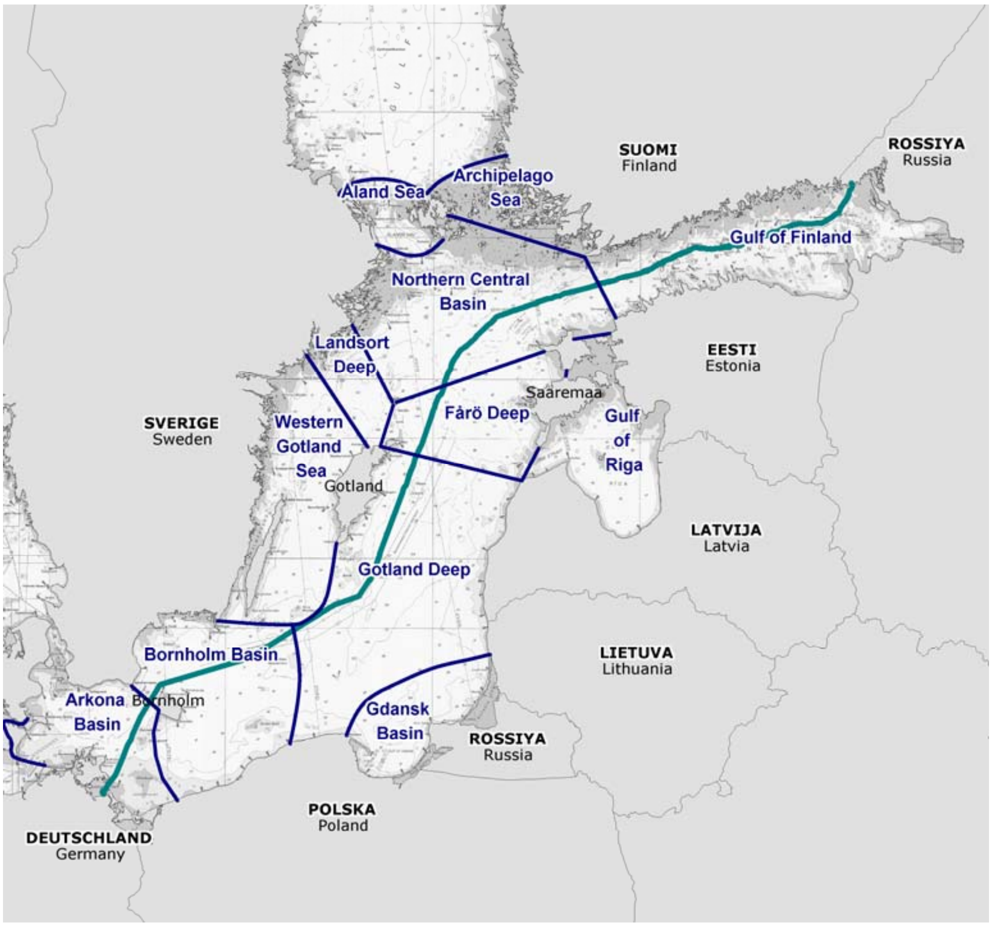


Figure 2: The region in the Baltic Sea illustrated on Figure 1 can be subdivided into basins/3/. The Nord Stream pipe line route is included on the map.

| Region | Area (Basin/Deep) | Maximum depth (m) | Volume ($km^3$) | Mean Depth (m) |
|---|---|---|---|---|
| Baltic Proper | Arkona Basin | 55 | 430 | 23 |
| | Bornholm Basin | 106 | 1780 | 46 |
| | Gdansk Basin | 116 | 1460 | 57 |
| | Gotland Deep | 249 | 3470 | 81 |
| | West Gotland Sea | 205 | 1640 | 61 |
| | Fårö Deep | 205 | 1270 | |
| | Lansort Deep | 459 | 780 | |
| | Northern Central Basin | 459 | 2090 | 72 |
| Gulf of Riga | Gulf of Riga | - | 410 | 23 |
| Gulf of Finland | Gulf of Finland | - | 1100 | 37 |
| Bothnian Sea | Archipelago Sea | 40 | 170 | 19 |
| | Åland Sea | 300 | 410 | 75 |
| Baltic Sea | (excl. transition area)[1] | 459 | 20900 | 56 |

1: Kattegat and the Belt Sea are forming the transition area between the Baltic Sea and the North Sea and are not considered as a part of the Baltic Sea.

Table 2: Bathymetric key parameters for the regions and sub-basins of the Baltic Sea /3/.

## 3.3 Salinity

The bathymetric and hydrological conditions in the Baltic Sea essentially create a complex stratified system as well as a horizontal salinity gradient due to the fresh-water inflow.

The highest surface salinities (8 – 10 psu) are found in the Arkona Basin and the lowest (3 – 8 psu) are found in the Bothnian Bay and the Gulf of Finland. These magnitudes are dynamic, especially in the transition and river-outflow areas /7/, /8/.

The halocline is at about 50 – 70 m in the Baltic Proper and at about 40 m in the Bothnian Bay. In the deep part of the Arkona Basin the salinity may reach about 20 psu following a major saline inflow /7/, /3/.

## 3.4 Temperature

During summer well-developed thermoclines exist at about 20 m, but during autumn strong winds and cooling gradually deepen the surface layers until they reach the more permanent haloclines /9/.

## 3.5 Ice conditions

During winter, part of the Baltic Sea is frozen, which affects the wind-induced current pattern. The ice conditions show a high degree of variance in time and space, with higher probability of ice in the north and along the coast. The 50% probability contour crosses the open sea in the northern Baltic proper, while the 90% contour covers only the Finish and northern Swedish coasts. In the central and southern Baltic Sea, ice occurrence is less than 10% /6/.

## 3.6 Water level

The influence of tide is usually negligible in the Baltic Sea. Due to the narrow Danish straits acting as a filter, the amplitudes are usually less than 3 cm, some of which may be internally generated /3/, /9/.

The occurrence of free seiches at times dominates the water-level variation in the Baltic Sea. Typical amplitudes of the “western Baltic proper – Gulf of Finland” seiche are 10 – 20 cm in the Gulf of Finland, but they may reach amplitudes in the order of metres /9/.

The variations in air pressure and wind stress can force sea-level variations for days or weeks. The wind stress causes Ekman transports that shuffle water around but can also cause sea level slopes in the wind direction. The approximate contributions to the mean sea level slope are: density gradients (salinity and temperature), 55%; air pressure gradients, 30%; and wind stress, 15% /9/.

## 3.7 Currents

The permanent current system in the Baltic Sea is weak, except for the transition area, i.e. the Belt Sea. On average, the surface current may be described as cyclonal horizontal, with speed of a few cm/s. However, wind-driven currents of higher velocities appear in the upper layers. At deeper levels, small-scale vortices may appear due to the influence of bathymetric variations /4/, /8/.

The circulation pattern in the Gulf of Finland is complex, with meso-scale eddies and a cyclonic mean circulation. The inflow to the Gulf of Finland is mainly near the coasts of Finland and Estonia with a compensating outflow in the northern part of the open Gulf. The typical mean current velocities in the uppermost layers (< 7.5 m) range between 5 – 10 cm/s, with the highest velocities related to the in- and outflow pattern, /8/.

The currents in the Arkona Basin are influenced by the large-scale circulation created by dense bottom currents entering over the sills. The volume of the intruding saline water increases due to the entrainment during the downward flow through the Arkona Basin, Bornholm Strait and Bornholm Basin. The dense bottom current may reach speeds up to 30 cm/s /4/.

## 3.8 Major saline inflows

The stratification which is essential for the environment of the Baltic Sea is mainly caused by water exchange with the North Sea and freshwater river runoff. The major inflows (high salinity, long duration) account for about 30% of the total salt influx, while the remaining 70% is due to weaker inflow incidents /4/.

Over the 70-year period up to 1977, 90 major inflows were reported. The largest major saline inflows with salinity higher than 17 psu have water volumes between 40 and 235 km3 and is occurring over 5 – 30 days, /2/.The frequency of major inflows has decreased over the last decades. Significant inflows have only occurred 3 times in 1983, 1993 and 2003, /16/.

The major inflows of saline water through the Danish straits are usually associated with a long period of outflow from the Baltic Sea followed by the passing of a large low-pressure system with winds pushing the water through the Kattegat and east into the Baltic Sea. The amount of water exchange is governed by the following parameters:

- Water-level differences
- Wind and atmospheric pressure
- Surplus of fresh water
- Density differences between surface and bottom water
- Level differences of the halocline
- Shear stress on the surface, interface and/or bottom
- Entrainment at the halocline
- Geometry of the considered area

The bottom current of inflowing saline water is driven by gravity. As the saline water passes the narrow cross sections at the sills, the water flows down the sloping seabed towards the Bornholm Basin. Consequently the water exchange is highly sensitive to physical changes in the transition area and not very sensitive to the bathymetric conditions in the open basins. However, increased flow resistance or other obstacles may lead to increased entrainment.

# 4. Model approach

A general transport model is set up. The spreading of material is evaluated using the numerical particle-analysis model MIKE 3 PA developed by DHI Water – Environment - Health. A brief description of the model and setup with emphasis on the applicability in the Nord Stream project follows.

## 4.1 The MIKE 3 PA model

The MIKE 3 PA model is used to simulate the transport and fate of dissolved and suspended substances in three dimensions. The substances may be discharged or accidentally spilled in estuaries, coastal areas or 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 by means of a hydrodynamic model simulation.

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

The model uses a Lagrangian 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 model are:

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

Each particle is moved within a time step 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 Langrangian 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:

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

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

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

Where:

| | |
|---|---|
| $u, v, w$ | Current velocity along *x*-, *y*- and *z*-axis |
| $\|\vec{U}\| = \sqrt{u^2 + v^2}$ | 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 /10/.

### 4.1.1 Resolution

The Langrangian 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 spreading of materials in the vicinity of the pipeline, the horizontal resolution in a corridor of some kilometres around the pipeline is refined by, e.g., a factor 7, giving a horizontal resolution of approximately 250 m. The corresponding hydrodynamic parameters are interpolated to each sub-grid point in the PA model.

The vertical-layer thickness is 1 m, except for the top layer, which is approximately 2.5 m, equivalent to the hydrodynamic basis.

### 4.1.2 Specification of sources

The source of released material/substance is given as time series of coordinates (x,y,z) and spill rate is given as mass/time.

### 4.1.3 Background concentration

Modelling is intended to be focused on excess concentrations due to project activities. Consequently the background concentration is defined as zero. In this way the model result identifies/isolates the excess concentration due to project activities.

In case the absolute concentrations are needed for the impact assessment a back ground concentration can be added to the model result.

## 4.2 Hydrodynamic basis

The hydrodynamic basis for the MIKE 3 PA simulations is acquired from an existing model setup of the numerical model MIKE 3 by DHI Water - Environment – Health for the Danish National Environmental Research Institute under the Danish Environmental Monitoring Programme (NOVANA). A brief description of the model and setup with emphasis on the applicability in the Nord Stream project is given in Appendix A. For further documentation, please refer to /11/, /12/ and to www.havmodellen.dk (in Danish).

Hydrodynamic data are received as three-dimensional, gridded data. The data has a spatial resolution of 3 NM horizontally and 1 m vertically down to 210 m (surface layer ~2,5 m) and covers the entire Baltic Sea, including Danish waters. For the inner Danish waters and German waters, there is further data in 1 NM horizontal resolution, cf. Table 3. Current fields are delivered with a temporal resolution of one and six hours.

The following data are available for the project.

| Parameters | 1 hour time interval | 6 hour time interval | Constant in time |
|---|---|---|---|
| Three velocity components, Pressure | 3-dimensional | 3-dimensional | |
| Temperature, Salinity | 3-dimensional | 3-dimensional | |
| Water level | 2-dimensional | 2-dimensional | |
| Meteorology | 2-dimensional | | |
| Bathymetry | | | 2-dimensional |

Table 3: Model data for the entire Baltic Sea, including inner Danish waters in 3 NM. Data for the Danish and German waters also in 1 NM. Vertical resolution is 1 m down to 210 m (surface layer ~2,5 m)

## 4.3 Simulation periods and design conditions

The environmental modelling is carried out for actual hindcasted hydrographic scenarios. This means that the modelling is carried out for a real "design period" and not for an artificial situation. The challenge is to define a representative design period for this purpose. The representative design period should within a short period of time (~1 month) represent situations that that is normally seen and characterising long term data.

The definition of the design period should be based on analysis of a longer period of data. In order to identify the influence of the hydrographic conditions Design periods are defined for different conditions. On basis of current time series from the hydrodynamic model, periods are to be selected representing:

- Calm conditions (weak currents)
- Normal conditions (average currents)
- Rough conditions (strong currents)

The terms "Calm", "Normal" and "Rough" is defined below. The terms should be defined in relation to transport modelling. This reflects the fact that "calm" conditions result in spreading over a small area close to the point where a substance is released. "Rough" conditions will cause transport further away from the point of release under larger dilution. Meteorological events creating a transport that rapidly changes direction forwards and backwards and does not give a net transport should not influence the result.

When a particle (or a quantity of dissolved substance) is released, it is transported by the ambient water. The track of the particle is follows a trajectory. The particle is transported in this way to a position at a distance from the source within a given time period. The net transport (linear distance between start and end of the trajectory) is in the following chosen to be the measure for characterisation of the above mentioned hydrographical scenarios in relation to transport and spreading.

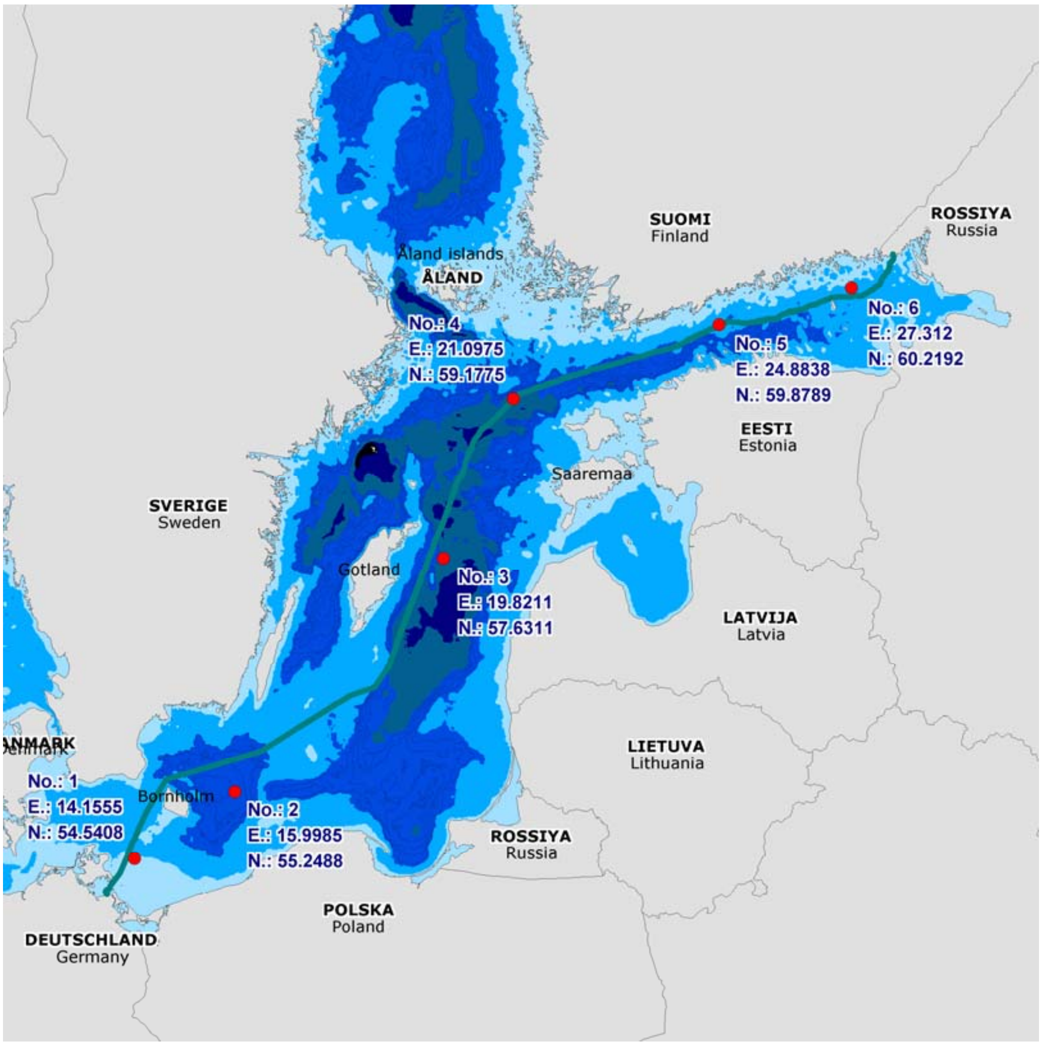

Figure 3: Positions of time series data from the MIKE 3 hydrodynamic.

Time series of modelled current data have been acquired from the six positions shown in Figure 3. The periods representing the hydrographic scenarios are chosen on basis of analysis of the current for each of the six positions. However, the period of time (timescale) during which the particle is transported must be chosen depending on the physical properties of the released substance as well as the hydrographic properties.

### 4.3.1 Timescale for particle transport

The feature of interest when defining representative design periods for modelling of transport is how far a substance can transported away form the point of release. A substance is transported with the movements of the ambient water (advection). In case of suspended the substance (particles) will sink/settle. The substance is only subject to transport as long as it remains in suspension.

A timescale is defined as the period of time a particle is in suspension after release. The timescale is calculated as the average depth of the six positions shown in Figure 3 divided by the settling velocity of a typical particle. Since the analysis is used to compare transport conditions of the different periods it is applicable to use a common timescale for all six positions, even though the physical settings vary. The settling velocity is based on an estimate of the grain size of sediment particles spilled along the pipeline during trenching operations.

The sediment composition along the pipeline is primarily clay, but it varies from coarse sand sediments to silts and clay /13/. Only the fine fractions are considered because the larger particles settle rapidly. The geotechnical survey /13/ found that on average the fine fractions of the sediment are dominated by grain sizes in the interval 0.02 – 0.06 mm in areas where the bottom material is silt or sand, and by particles below 0.002 mm in areas where the bottom material is clay. However, the small cohesive particles in the fine fractions consist of larger aggregates when released in a dredging plume and have a slightly larger settling velocity than the primary particles in the sediment.

The typical particle size used to calculate the settling velocity is 0.02 mm. According to Stokes Law, the settling velocity of a particle with a diameter of 0.02 mm is 2 x $10^{-4}$ m/s.

A release 70 m above the seabed gives a four-day timescale for particle transport, cf. Table 4.

| | |
|---|---|
| Average depth of six positions | 70 m |
| Typical particle diameter | 0.02 mm |
| Typical settling velocity | 2 x $10^{-4}$ m/s |
| Timescale | 4 days |

Table 4: Timescale of particle transport.

### 4.3.2 Horizontal particle-transport distance

The horizontal net transport of a particle four days after a release is calculated. E.g. how far is a particle released 1st January 2004transported during 4 days. Time series of the horizontal transport distance for each of the six positions along the proposed alignment of the pipeline has been determined.

The trenching process at each of the trenching areas may take weeks to complete. To cover the trenching scenarios, the design periods, representing the three current conditions, need to have a duration of one month to ensure a simulation period long enough to complete the particle transport simulations.

To find periods representing the three conditions, curves of the moving average in percent of the total average are plotted for each position. The results are shown in Figure 4.

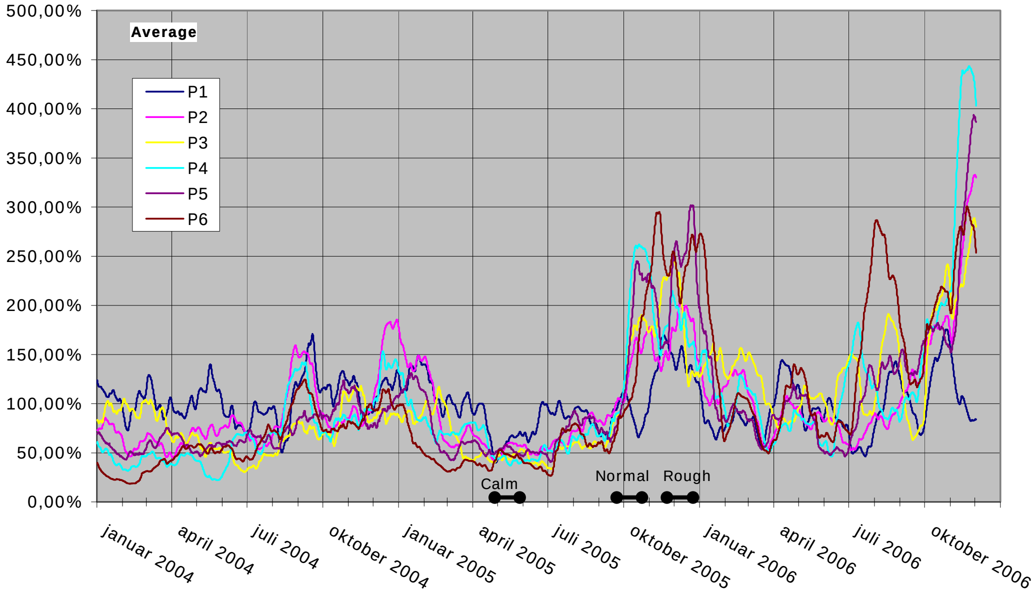


Figure 4. Relative net transport determined as one month moving average. The diagram indicates the relative "roughness" of the forthcoming month. For a one-month design period starting 28 September 2005 , for example, the net transport for all six stations (P1-P6) is approximately 100% of average for the period 2004-2006.

### 4.3.3 Choice of simulation periods

Based on the above data, analysis of the following three periods have been identified:

| | |
|---|---|
| Calm conditions | 28 April 2005 – 28 May 2005 |
| Normal conditions | 26 September 2005 – 26 October 2005 |
| Rough conditions | 21 November 2005 – 21 December 2005 |

Table 5: Simulation periods.

The accumulated frequency for the three design periods are estimated in order to demonstrate there validity. The accumulated frequency for the design periods are compared with the accumulated frequency diagram for the total period. The results are show in below figures 5-10.

- Normal conditions occur if the accumulated frequency diagram of a specific period is centred near the median (50% fractile) of the diagram for the total period (2004-2006).
- Calm conditions occur if the accumulated frequency diagram of a specific period is centred at a value in the upper part of the diagram for the total period (2004-2006).
- Rough conditions occur if the accumulated frequency diagram of a specific period is centred at a value in the lower part of the diagram for the total period (2004-2006).

The accumulated frequency diagram for the particle transport distance is plotted for the three design periods and a three-year period for all six positions in Figure 5-4.8

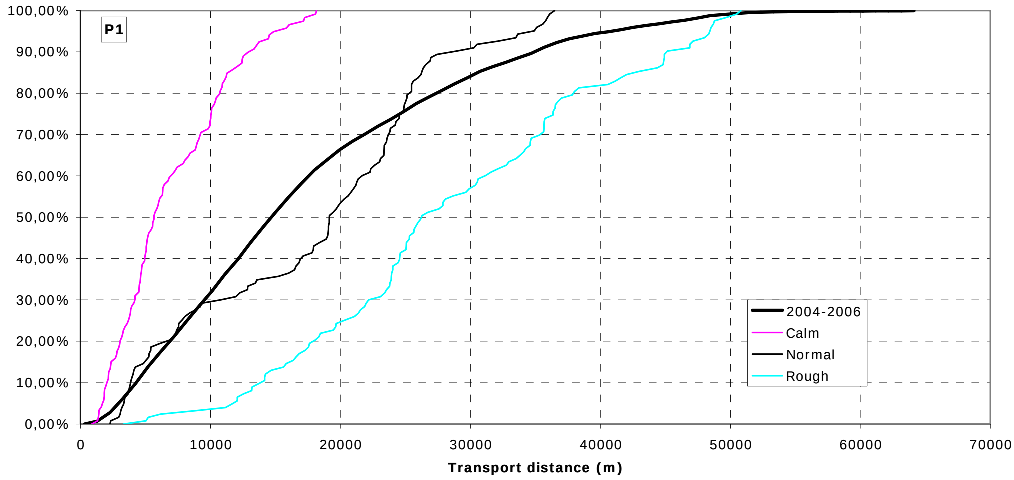


Figure 5. Accumulated frequencies of net transport distances at P1 during the design periods and the period 2004-2006.

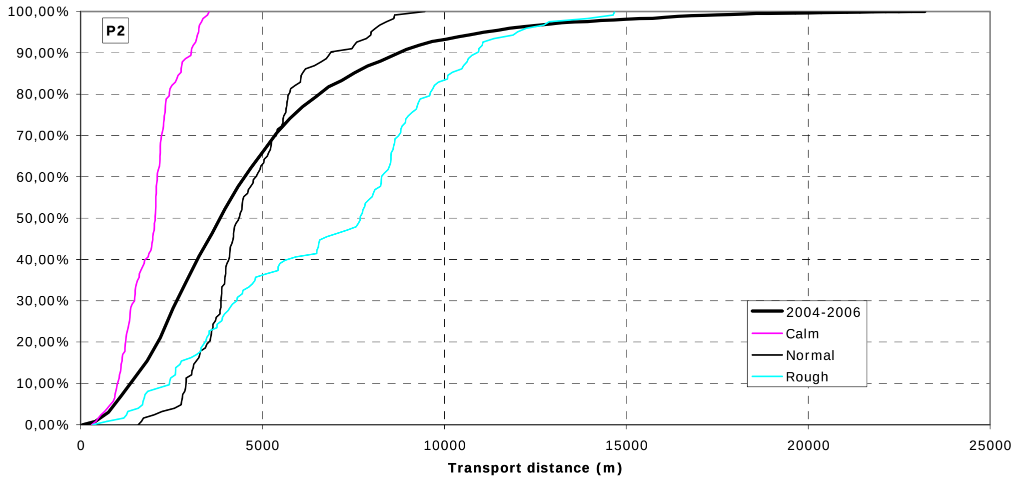


Figure 6. Accumulated frequencies of net transport distances at P2 during the design periods and the period 2004-2006.

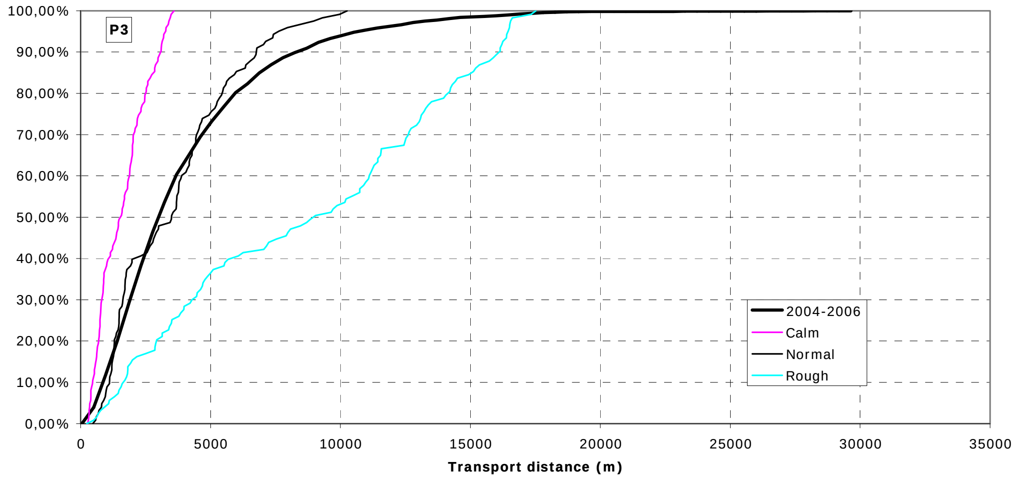


Figure 7: Accumulated frequencies of net transport distances at P3 during the design periods and the period 2004-2006.

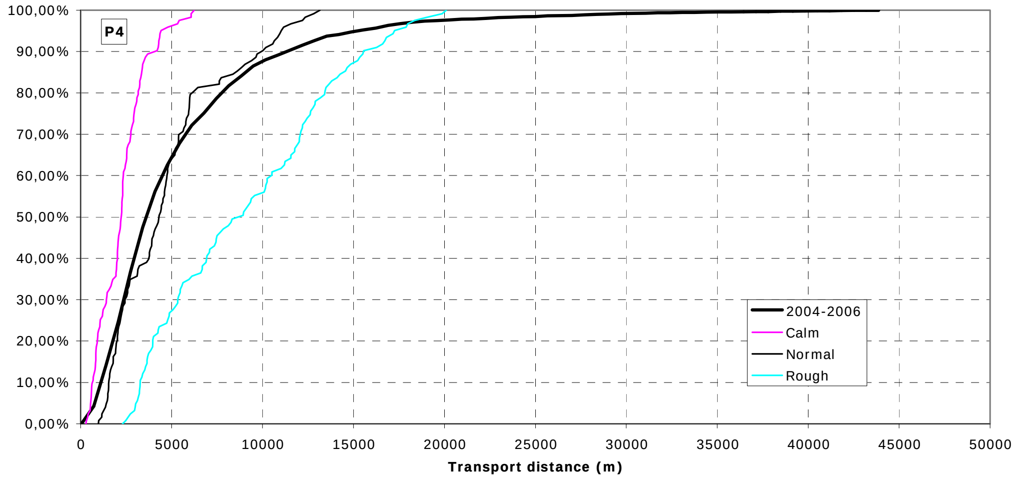


Figure 8: Accumulated frequencies of net transport distances at P4 during the design periods and the period 2004-2006.

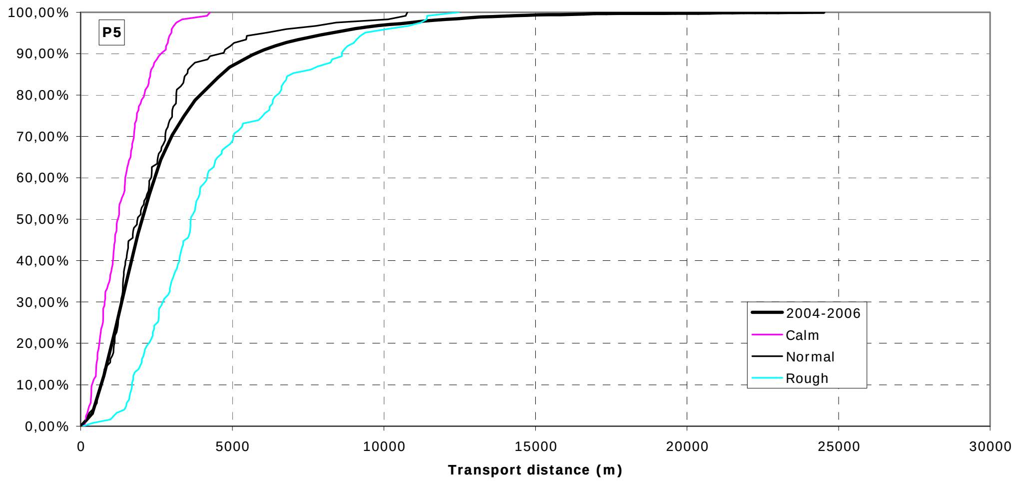


Figure 9: Accumulated frequencies of net transport distances at P5 during the design periods and the period 2004-2006.

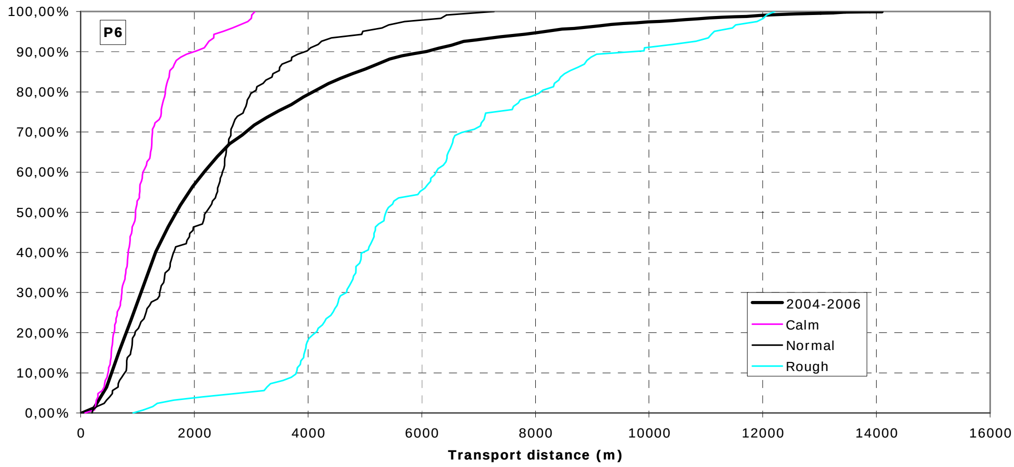


Figure 10: Accumulated frequencies of net transport distances at P6 during the design periods and the period 2004-2006.

# 5. Conclusion

The transport and fate of dissolved and suspended substances is to be simulated using the particle-tracking module MIKE 3 PA from DHI Water - Environment – Health.

The hydrodynamic basis for the transport simulations is acquired from the hydrodynamic model for the Baltic Sea setup by DHI Water - Environment – Health in MIKE 3 HD under the Danish Environmental Monitoring Programme (NOVANA).

Three simulation periods have been identified covering respectively

- Calm conditions (28 April 2005 – 28 May 2005)
- Normal conditions (26 September 2005 – 26 October 2005)
- Rough conditions (21 November 2005 – 21 December 2005)

This data is evaluated as being applicable to the Nord Stream EIA study.

# 6. References


/1/ HELCOM Homepage: http://www.helcom.fi.

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/3/ Jacobsen, F., 1991, “The Bornholm Basin – Estuarine Dynamics”, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark.

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# 7. Appendices

## 7.1 Appendix A: Hydrodynamic model setup

The hydrodynamic data for the Nord Stream project is acquired from an existing model setup of the numerical model MIKE 3 by DHI Water – Environment - Health. A brief description of the model and setup with emphasis on the applicability in the Nord Stream project follows.

### 7.1.1 The MIKE 3 HD model

MIKE 3 is three-dimensional, baroclinic non-hydrostatic numerical model system developed by DHI Water – Environment - Health. The model application areas include oceans, coastal regions, estuaries and lakes.

The MIKE 3 hydrodynamic (HD) module simulates unsteady three-dimensional flows, taking into account density variations, bathymetry and external forcing, such as meteorological, tidal and hydrographical conditions.

The MIKE 3 HD module solves the mass conservation equation; the Reynolds-averaged Navier-Stokes equations, including the effects of turbulence and variable density; and the conservation equations for salinity and temperature in three dimensions together with the equation of state of sea water relating the local density to salinity, temperature and pressure. The module features include:

- Bed resistance
- Density variations
- Transport of salinity and temperature
- Turbulence modelling
- Wind friction
- Sources and sinks
- Heat exchange with atmosphere including evaporation/precipitation

The hydrodynamic module is applicable to hydraulic studies where three-dimensional flow phenomenon, such as stratified flows, oceanographic circulation or heat and salt recirculation, are important.

A detailed technical description of the MIKE 3 hydrodynamic module is given in /10/.

## 7.2 The model setup

The MIKE 3 HD model is set up in an equidistant grid covering the area of the North Sea, Danish waters and the Baltic Sea with a horizontal resolution of 9, 1 NM and 3 NM respectively. The relevant model area and bathymetry of the setup is shown in Figure 11. The vertical layers have a constant thickness of 1 m to a depth of 210 m, except for the surface layer, which is 2.5 m. The maximum depth is in the model truncated at 210 m in order to reduce the number of layers.

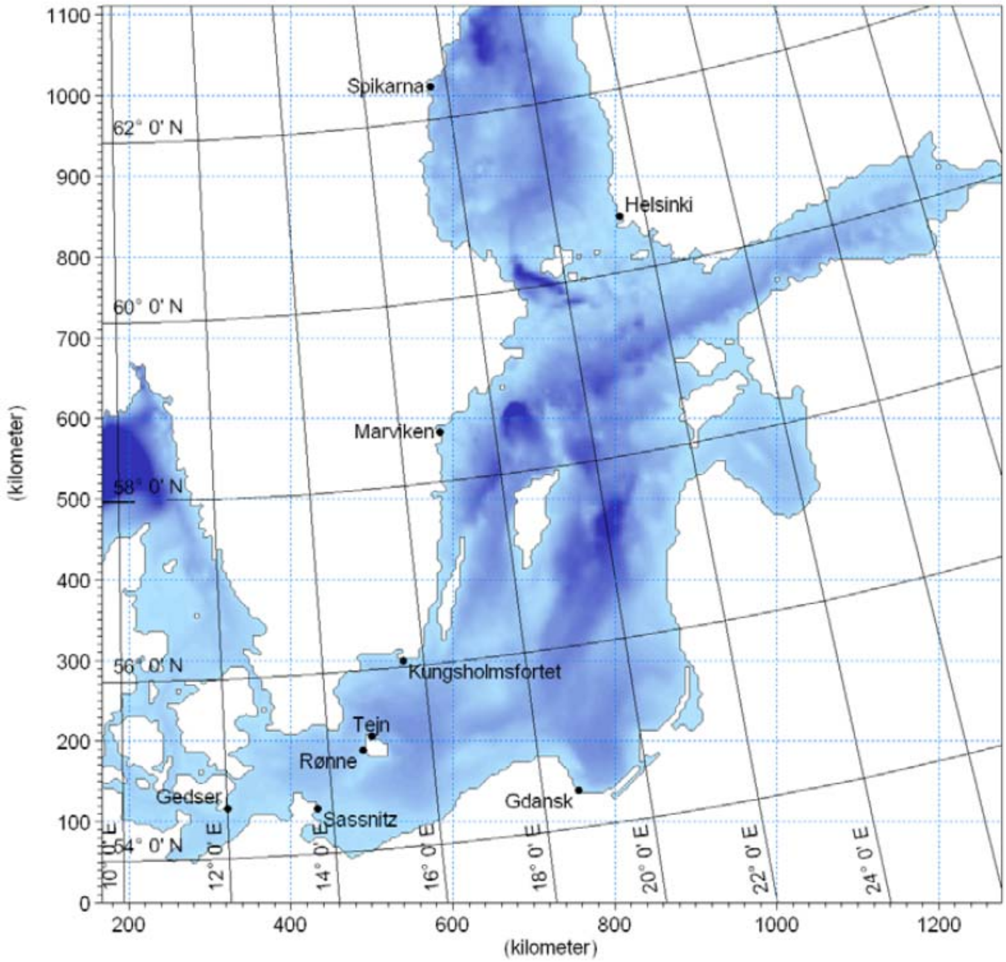



Figure 11: Model area and bathymetry of the MIKE 3 setup (excluding the North Sea).

The model is forced by meteorological and hydrographical conditions including wind, atmospheric pressure, air temperature and river outflow. At the North Atlantic boundary, the model is forced by water-level variations originating from tide and surge. The parameters of the MIKE 3 model setup are summarized in

| **MIKE 3 Model Setup** | |
|---|---|
| Grid type (Hor./Ver.) | equidistant / constant |
| Geographical coverage | North Sea / Danish Waters / Baltic Sea |
| Horizontal resolution | 9 NM / 1 NM / 3 NM |
| Vertical resolution | 1 m down to 210 m depth (surface layer is 2.5 m) |
| External forcing | wind, atmospheric pressure, temperature, river outflow |
| Boundary conditions (North Sea) | tide, surge correction |

Table 6.

| MIKE 3 Model Setup | |
|---|---|
| Grid type (Hor./Ver.) | equidistant / constant |
| Geographical coverage | North Sea / Danish Waters / Baltic Sea |
| Horizontal resolution | 9 NM / 1 NM / 3 NM |
| Vertical resolution | 1 m down to 210 m depth (surface layer is 2.5 m) |
| External forcing | wind, atmospheric pressure, temperature, river outflow |
| Boundary conditions (North Sea) | tide, surge correction |

Table 6: Parameters of the MIKE 3 model setup.

## 7.3 Data availability

Model data is stored with a temporal resolution of one and six hours for the period of 1 January 2004 – 31 December 2006. The parameters stored in each grid point include:

| 2D: | 3D: |
|---|---|
| Water level | Current |
| Wind | Salinity |
| Atmospheric pressure | Temperature |

## 7.4 Validation

Time series of model data at six locations along the pipeline route have been extracted for quality assessment and selection of simulation periods for three-dimensional studies. Observational data has been obtained from station 212 in the Bornholm Basin and the EGB mooring position in the Gotland Basin. The locations are shown in
Figure 12 and Table 7.

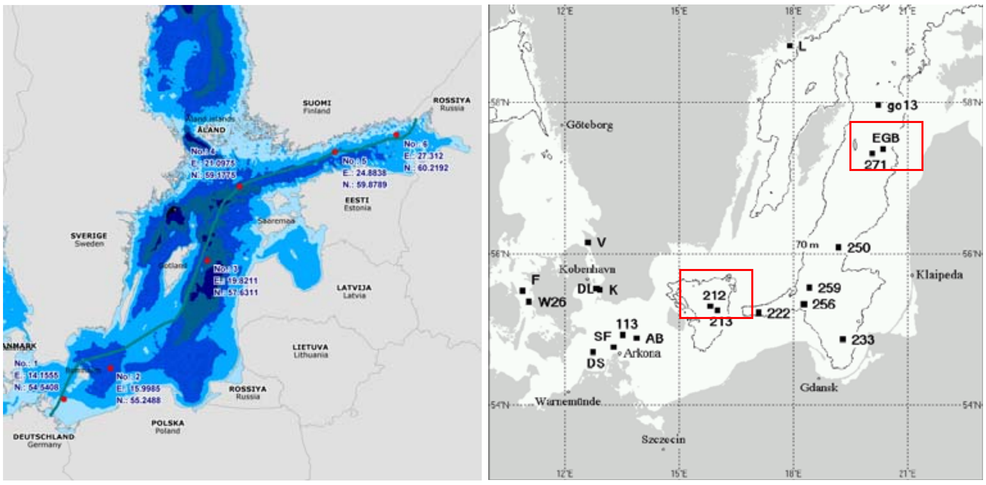



Figure 12: Positions of time series data from the MIKE 3 hydrodynamic model setup and observational data.

| Name | Location | Latitude (°N) | Longitude (°E) | Depth (m) |
|---|---|---|---|---|
| Position 1 | Landfall Germany | 54.5408 | 14.1555 | 18 |
| Position 2 | Bornholm Basin | 55.2488 | 15.9985 | 89 |
| Position 3 | Gotland Basin | 57.6311 | 19.8211 | 105 |
| Position 4 | Northern Baltic Proper | 59.1775 | 21.0975 | 113 |
| Position 5 | Gulf of Finland | 59.8789 | 24.8838 | 53 |
| Position 6 | Landfall Russia | 60.2192 | 27.3120 | 44 |
| 212 | Bornholm Basin | | | 95 |
| EGB | Gotland Basin | | | 245 |

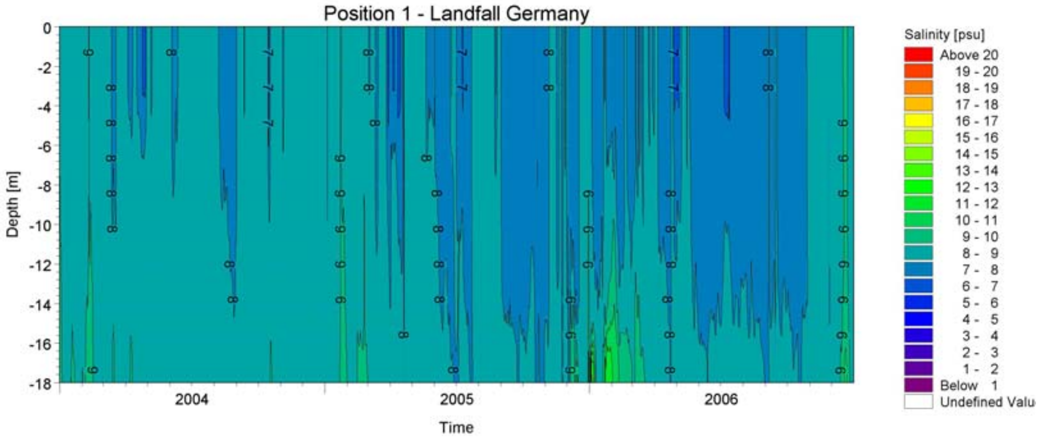
Table 7: Positions and depths of time series data from the MIKE 3 hydrodynamic model setup and observational data.

Data for validation is taken from open sources. It has not been possible to find data that coincide in time.

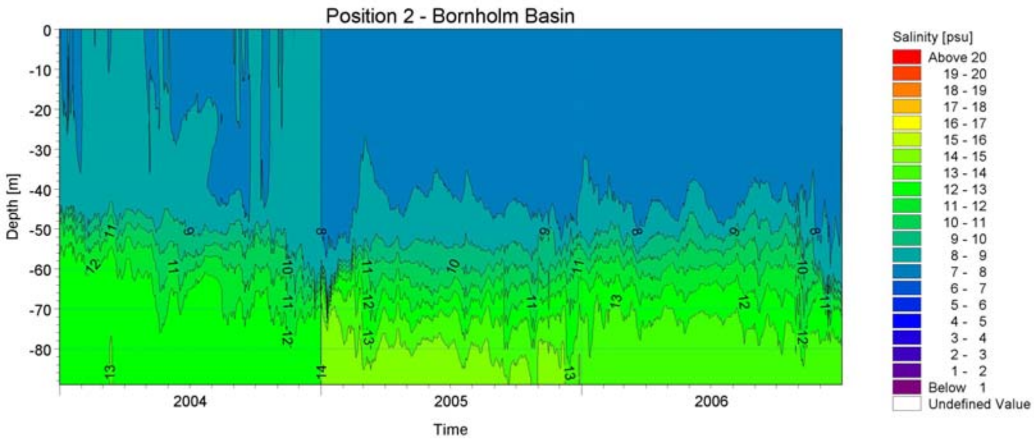
### 7.4.1 Salinity

The modelled salinity in each position is illustrated as isopleths plots for the 2004 - 2006 time period in Figure 13. There is a discrepancy on 1 January 2005 due to re-initialization of the model.

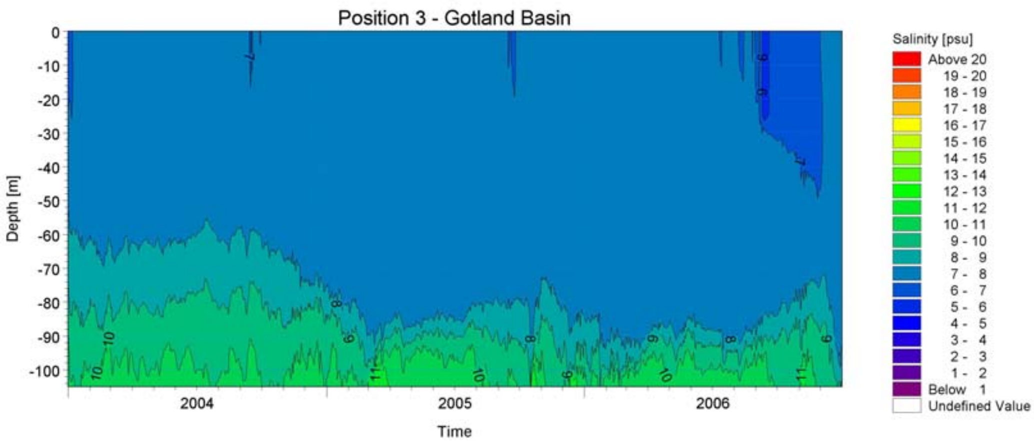
In Figure 14 and Figure 15 the observed salinity in the Central Bornholm Basin (vicinity of Position 2) and Gotland Basin (vicinity of Position 3) are shown for 2002 and 2003 during which time a major saline inflow occurred /7/.



Position 1 - Landfall Germany
Depth [m]
Time
2004
2005
2006
Salinity [psu]
Above 20
19 - 20
18 - 19
17 - 18
16 - 17
15 - 16
14 - 15
13 - 14
12 - 13
11 - 12
10 - 11
9 - 10
8 - 9
7 - 8
6 - 7
5 - 6
4 - 5
3 - 4
2 - 3
1 - 2
Below 1
Undefined Valu

Position 2 - Bornholm Basin
Depth [m]
Time
2004
2005
2006
Salinity [psu]
Above 20
19 - 20
18 - 19
17 - 18
16 - 17
15 - 16
14 - 15
13 - 14
12 - 13
11 - 12
10 - 11
9 - 10
8 - 9
7 - 8
6 - 7
5 - 6
4 - 5
3 - 4
2 - 3
1 - 2
Below 1
Undefined Value

Position 3 - Gotland Basin
Depth [m]
Time
2004
2005
2006
Salinity [psu]
Above 20
19 - 20
18 - 19
17 - 18
16 - 17
15 - 16
14 - 15
13 - 14
12 - 13
11 - 12
10 - 11
9 - 10
8 - 9
7 - 8
6 - 7
5 - 6
4 - 5
3 - 4
2 - 3
1 - 2
Below 1
Undefined Value

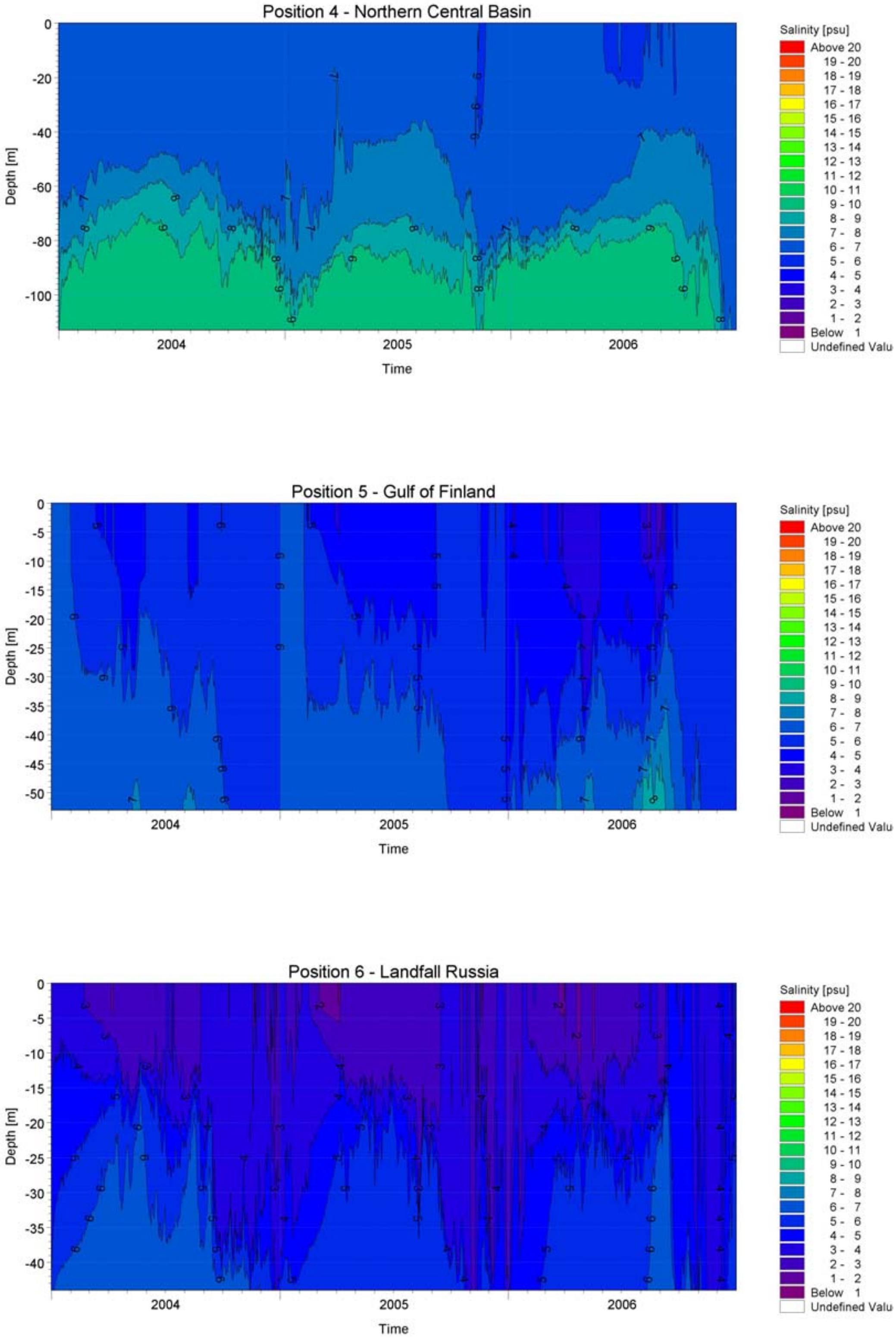



Figure 13: Modelled salinity during 2004 – 2006 at P1 - P6.

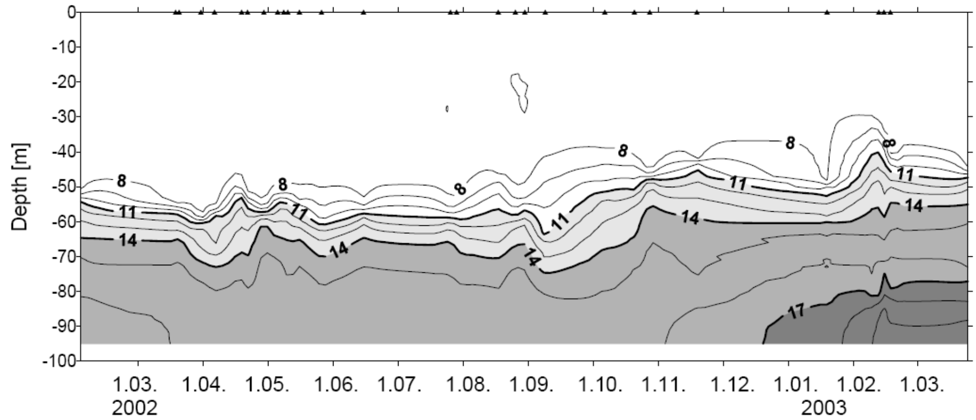



Figure 14: Observed salinity in the Central Bornholm Basin (station 212) from February 2002 – March 2003 /7/.

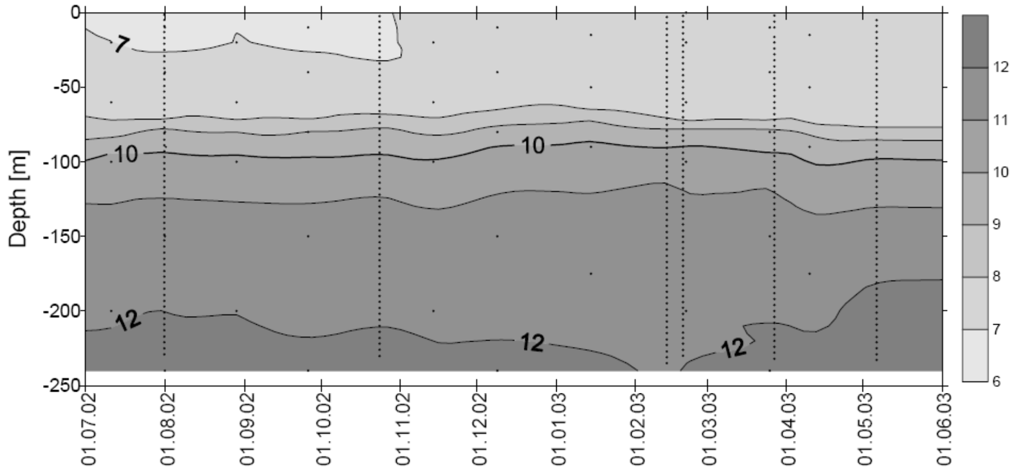



Figure 15: Observed salinity in the Gotland Basin (EGB mooring position) from July 2002 – May 2003 /7/.

For each of the six positions, the mean modelled salinity over the three-year period is compared with mean observed salinity from 1960 to 1980. In Table 8 the left-hand table shows mean model salinity at a number of depths and the table on the right shows the observed salinity at corresponding depths. The observed data is obtained from the ICES Oceanographic Data Centre, which divides the Baltic Sea region into 19 sub-regions /14/. The observed data is selected from the sub-region in which the data position is located.

| Position | Sub-region | Depth in model (m) | Depth of observa-tions (m) | Modelled mean sa-linity 2004-2006 (PSU) | Observed mean sa-linity 1960-1980 (PSU) |
|---|---|---|---|---|---|
| Position 1 | Southern Baltic Proper | 2 | 0 | 8.0 | 7.7 |
| | | 18 | 20 | 8.6 | 7.8 |
| Position 2 | Southern Baltic Proper | 2 | 0 | 7.9 | 7.7 |
| | | 20 | 20 | 7.9 | 7.8 |
| | | 50 | 50 | 8.8 | 8.9 |
| | | 70 | 70 | 12.5 | 12.5 |
| Position 3 | Eastern Got-land Basin | 2 | 0 | 7.2 | 7.3 |
| | | 20 | 20 | 7.2 | 7.4 |
| | | 50 | 50 | 7.5 | 7.7 |
| | | 70 | 70 | 7.9 | 9.2 |
| | | 100 | 100 | 9.9 | 11.1 |
| Position 4 | Northern Baltic Proper | 2 | 0 | 6.5 | 6.8 |
| | | 20 | 20 | 6.5 | 7.0 |
| | | 50 | 50 | 6.8 | 7.6 |
| | | 70 | 70 | 7.5 | 8.9 |
| | | 100 | 100 | 9.3 | 10.3 |
| Position 5 | Gulf of Finland | 2 | 0 | 4.9 | 5.5 |
| | | 20 | 20 | 5.2 | 6.0 |
| | | 50 | 50 | 6.3 | 7.5 |
| Position 6 | Gulf of Finland | 2 | 0 | 2.9 | 5.5 |
| | | 20 | 20 | 4.1 | 6.0 |
| | | 44 | 50 | 5.7 | 7.5 |

Table 8: Modelled and observed mean salinity at positions 1 – 6 (modelled data) and sub-regions of the Baltic Sea (observed data).

The level of the halocline is well represented in the model data, although slightly more mixed, in both the Bornholm Basin and the Gotland Basin. In the Bornholm Basin the salinities are in good agreement with observations above the halocline but slightly lower than observed during the saline inflow in 2003. In the Gotland Basin the salinities are in good agreement with observations throughout the water column.

The comparison of average model data and observed ICES data (1960-80) shows that in general there is a good agreement with differences less than 1 psu. However the model underestimates the salinities with 1.8-2.6 psu in the inner Gulf of Finland at position 6. Similarly the model seam to underestimates the salinities with approx 1 psu in the deep areas deep then 100 m in the Baltic Proper.

### 7.4.2 **Water level**

Time series of the modelled water levels at P1 - P6 are shown in Figure 16. The water level is seen to be highest during winter and has a larger annual variation in the Gulf of Finland than in the Baltic proper.

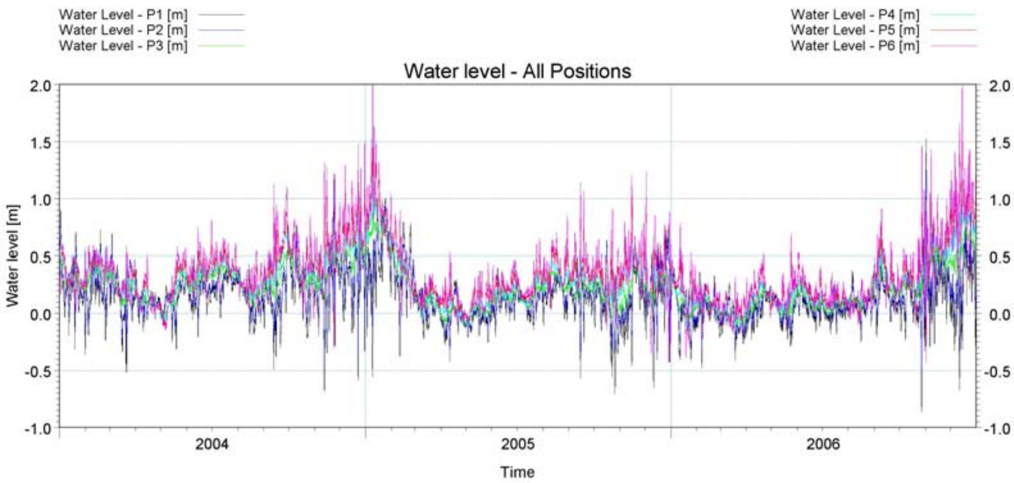



Figure 16: Time series of modelled water level at P1 - P6.

No water level data is available for the six positions shown on fig 3.

Table 9 shows analyses of the differences between modelled and observed data (observed- modelled) As measure for the quality of the model resultes the table shows the bias and standard deviation (STD) for "observed water level – modelled water level" in 2005 for a number of stations throughout the Baltic Sea, cf./14/. Statistics are also shown for the instantaneous values and for the 25-hour, time-averaged water level. According to Table 9 the STD of the water level is between 1 – 13 cm.

| **Station** | **Instantaneous data** | | |
|---|---|---|---|
| | **Bias[m]** | **Std [m]** | **Number** |
| Gdansk | -0.06 | 0.09 | 1391 |
| Gedser | -0.01 | 0.13 | 17281 |
| Helsinki | -0.29 | 0.11 | 7550 |
| Kungsholmsfortet | -0.16 | 0.10 | 8156 |
| Marviken | -0.20 | 0.09 | 8341 |
| Rønne | -0.14 | 0.11 | 16510 |
| Sassnitz | -0.04 | 0.10 | 8495 |
| Spikarna | -0.25 | 0.09 | 8430 |
| Tejn | -0.13 | 0.10 | 17176 |

Table 9: Comparison of modelled and observed water level.

The basis estimates how well the model is to determine the absolute mean sea level at the station. The differences are 1-29 cm for all the stations. The highest differences are at Helsinki in Gulf of Finland and the smallest at Gdansk in the southern part of the Baltic Sea. However How ever Tejn and Rønne on Bornholm show differences of 13-14 cm and consequently it can not be concluded that the predicted water levels are better in the southern part of the Baltic then in the northern. the differences can to some extend be caused by the model bathymetry since bathymetric data are compiled from different sources typically based on different datum. This can introduce an uncertainty on the datum at a given point in the model. in the order of a few cm.

The Standard deviation how well the model is to predict the dynamics of the model. The standard deviation is 9-13 cm. Standard deviation is found from the sum of the squared differences the value 0 cm can only be obtained far a perfect match between modelled and observed water levels.

### 7.4.3 Currents

The availability of current measurements in the Baltic Sea is very limited for validation purpose. According to Section 3.7, typical mean current velocities in the uppermost layers (< 7.5 m) range between 5 – 10 cm/s in the Gulf of Finland.

In Table 10 it is seen that the modelled mean surface current speeds (0 - 7.5 m) at P5 - P6 are 7 cm and 5 cm respectively.

| | Modelled surface current speeds (0 – 7.5 m) [m/s] | | | |
|---|---|---|---|---|
| **Location** | **Min** | **Max** | **Mean** | **Std** |
| Position 1 | 0.00 | 0.55 | 0.10 | 0.07 |
| Position 2 | 0.00 | 0.43 | 0.08 | 0.05 |
| Position 3 | 0.00 | 0.50 | 0.08 | 0.06 |
| Position 4 | 0.00 | 0.44 | 0.07 | 0.05 |
| Position 5 | 0.00 | 0.49 | 0.07 | 0.06 |
| Position 6 | 0.00 | 0.36 | 0.05 | 0.04 |

Table 10: Modelled surface current speeds (0 - 7.5 m) at P1 - P6.

Figure 17 shows a time series of observed near bed along slope current speed (average of depth levels 174 m, 204 m and 219 m) in the Gotland Basin from October 2002 - March 2003. The observed current speed varies between 0 - 9 cm/s with a mean value of approximately 3.5 cm/s.

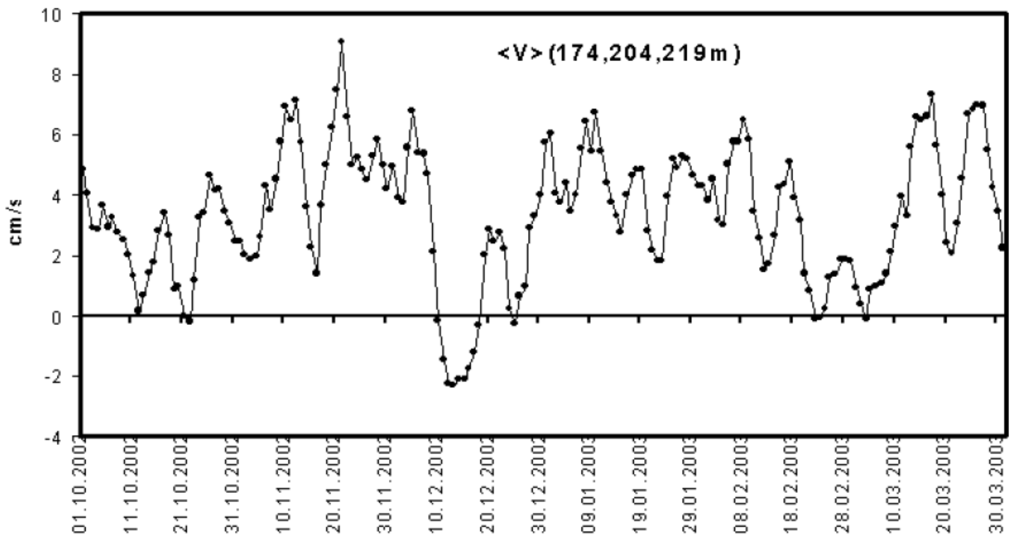



Figure 17: Time series of observed near bed along slope current speed (average of depth levels 174 m, 204 m and 219 m) in the Gotland Basin (EGB mooring position) from October 2002 - March 2003 /7/.

Table 11 is showing the modelled mean bottom-current speed (deepest 10 m of the water column) at 6 positions in the Baltic Sea.

| | Modelled bottom current speeds (deepest 10 m) [m/s] | | | |
|---|---|---|---|---|
| **Location** | **Min** | **Max** | **Mean** | **Std** |
| Position 1 | 0.00 | 0.32 | 0.06 | 0.04 |
| Position 2 | 0.00 | 0.25 | 0.03 | 0.02 |
| Position 3 | 0.00 | 0.29 | 0.03 | 0.03 |
| Position 4 | 0.00 | 0.14 | 0.01 | 0.01 |
| Position 5 | 0.00 | 0.18 | 0.02 | 0.02 |
| Position 6 | 0.00 | 0.09 | 0.01 | 0.01 |

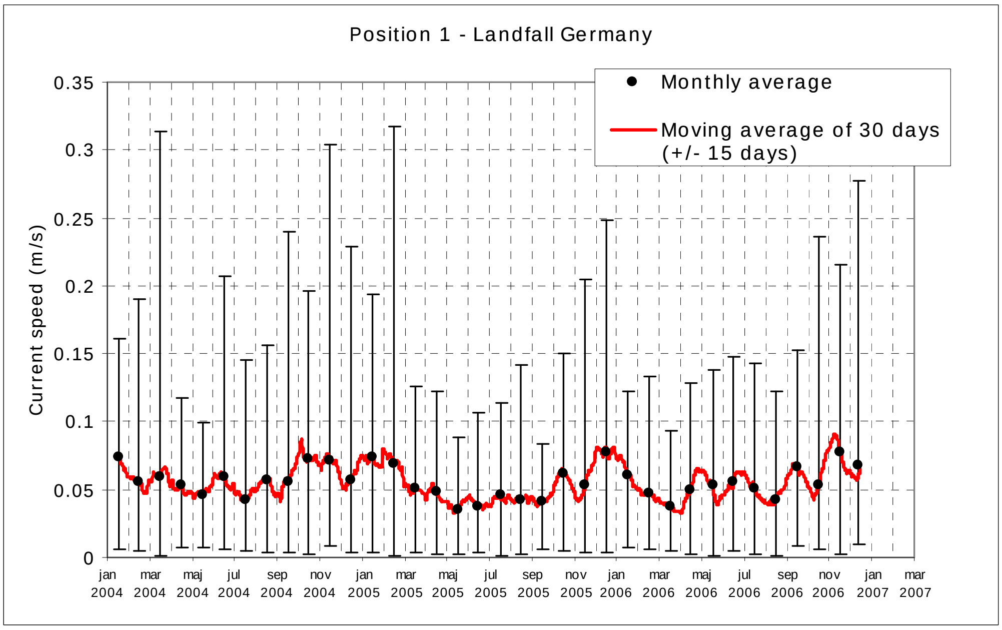
Table 11: Modelled bottom-current speeds (deepest 10 m) at P1 - P6.

It is seen the modelled mean velocity is 3 cm/s at P3 (Gotland Basin). The modelled mean current speeds are thus evaluated as being of fairly the same order of size as observations shown on figure 17. The modelled velocities are showing velocity range of 0-29 cm/s at position 3. This range is larger than observations in the Gotland Basin. However it is assessed that the reason for that is the resolution in time, which is much fine in the model data than in the observation data. The range for the model data defined as mean velocity +/- standard deviation is 0-6 cm, which is comparable to the observed bottom velocities at position 3.

Figure 18 - 23 show current data in more details for six positions. The data shown is monthly average and rose plots for the modelled current 0 - 10 m above the seabed during 2004 - 2006. Data is as preciously mentioned not available.

For further documentation to verification and validation, refer to /11/, /12/ and to www.havmodellen.dk (in Danish).

A) Monthly and 30-day moving average of modelled bottom currents (deepest 10 m)




B) Rose plots of modelled bottom currents (deepest 10 m)

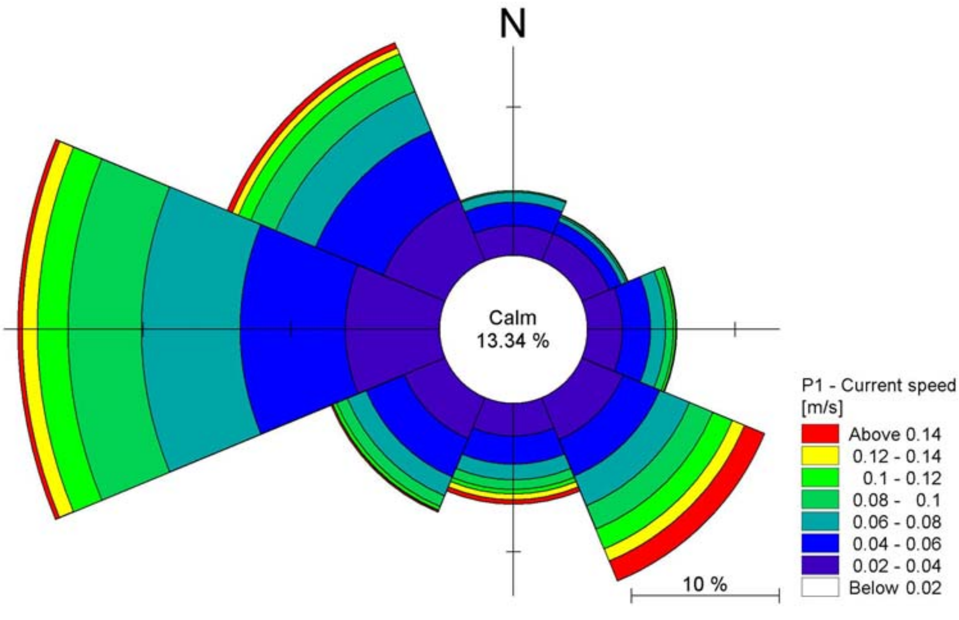
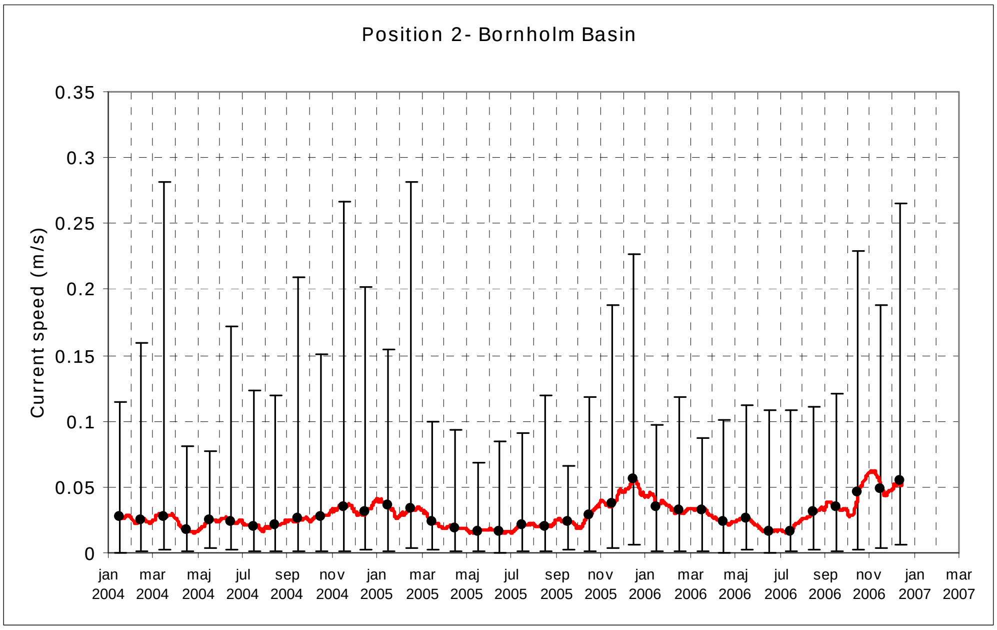



Figure 18: Bottom currents (deepest 10 m) at P1.

A) Monthly and 30-day moving average of modelled bottom currents (deepest 10 m)




B) Rose plots of modelled bottom currents (deepest 10 m)

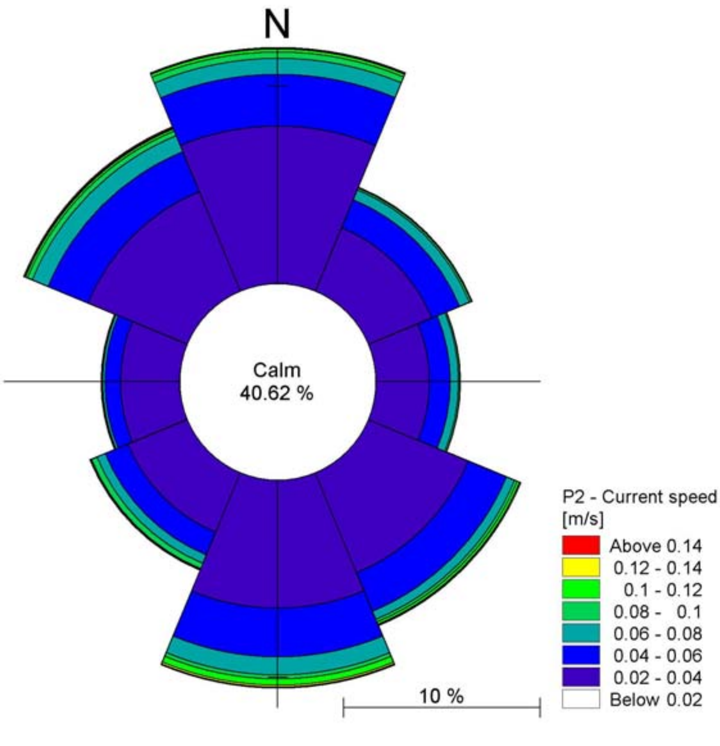
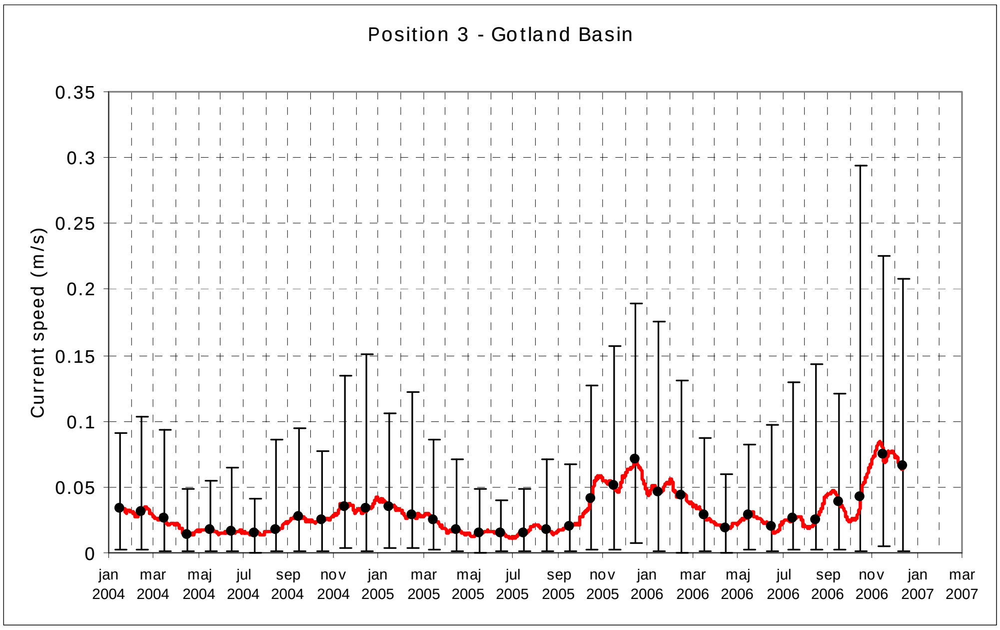



Figure 19: Bottom currents (deepest 10 m) at P2.

A) Monthly and 30-day moving average of modelled bottom currents (deepest 10 m)




B) Rose plots of modelled bottom currents (deepest 10 m)

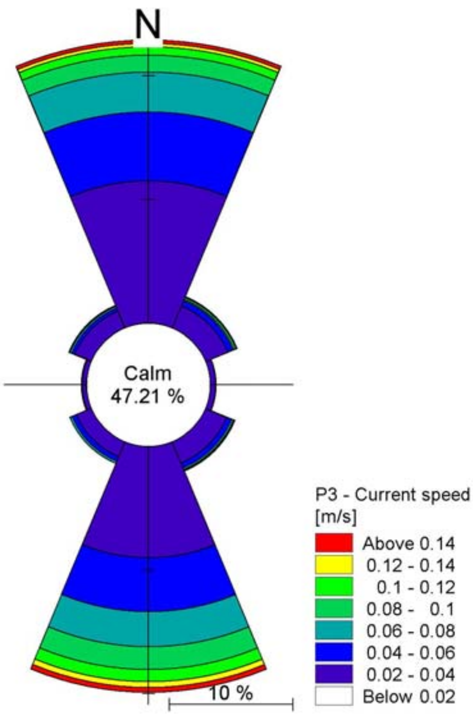
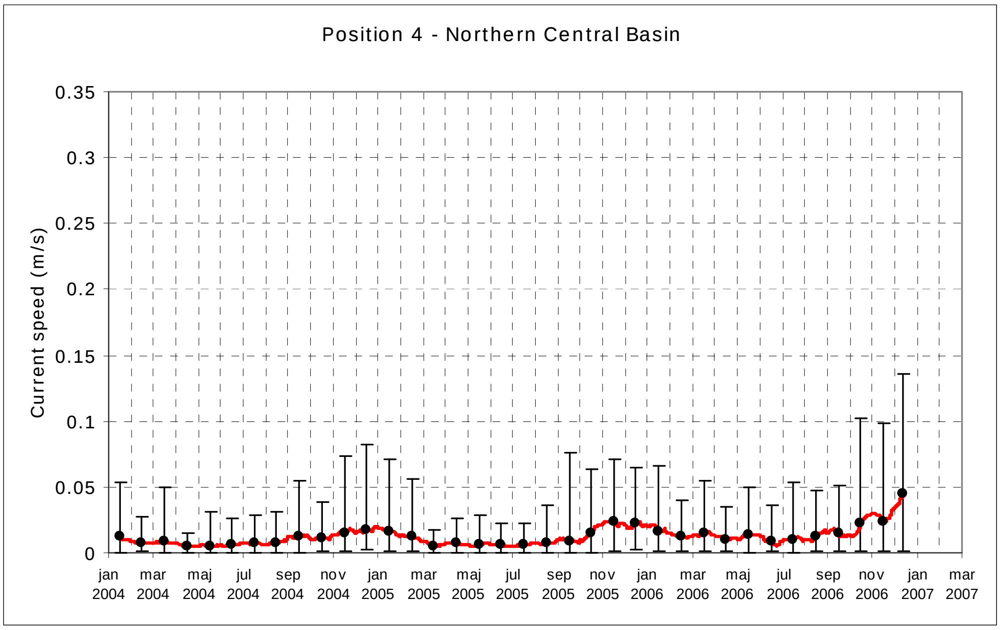



Figure 20: Bottom currents (deepest 10 m) at P3.

A) Monthly and 30-day moving average of modelled bottom currents (deepest 10 m)




B) Rose plots of modelled bottom currents (deepest 10 m)

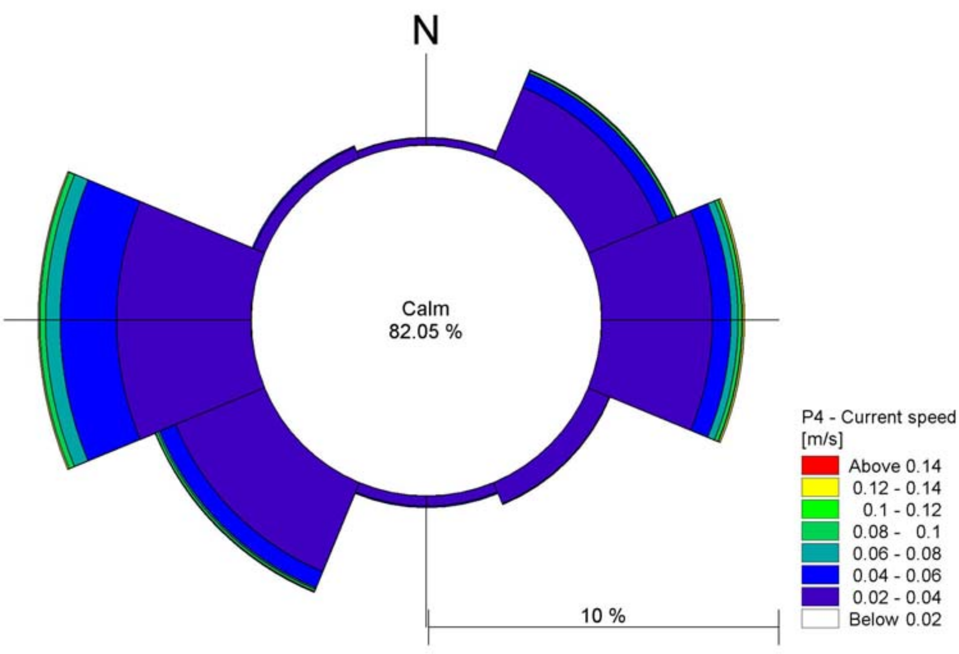
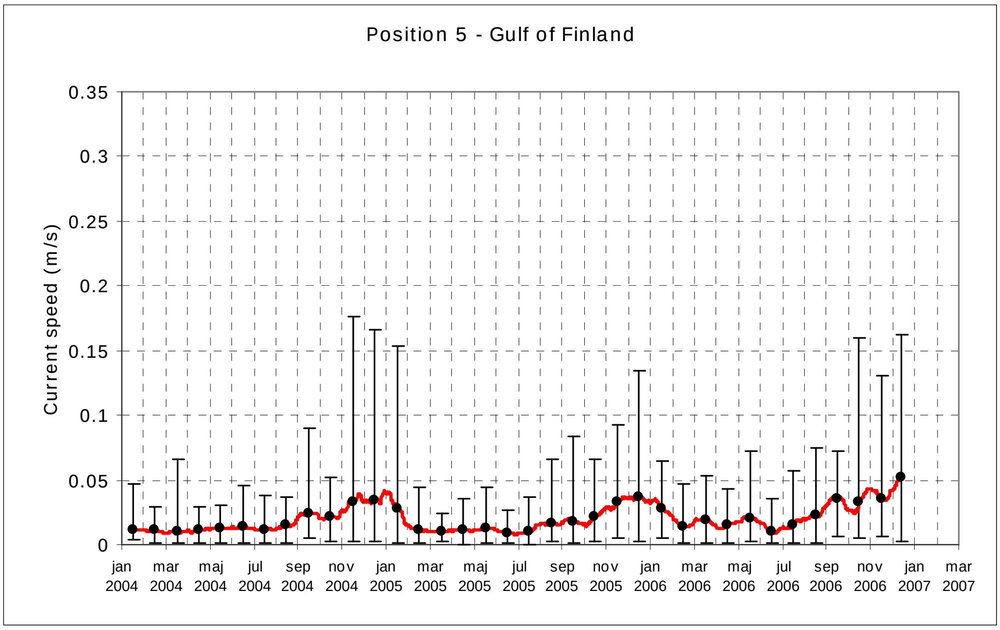



Figure 21: Bottom currents (deepest 10 m) at P4.

A) Monthly and 30-day moving average of modelled bottom currents (deepest 10 m)




B) Rose plots of modelled bottom currents (deepest 10 m)

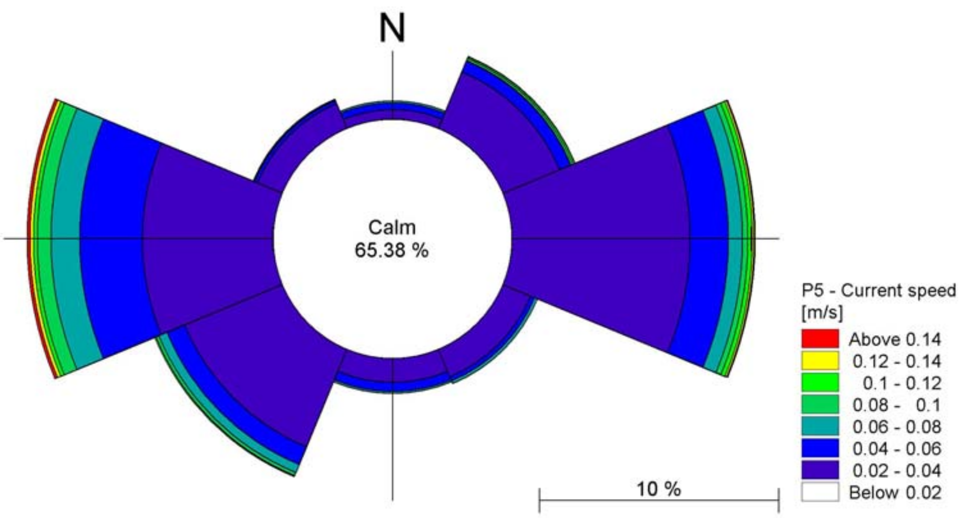
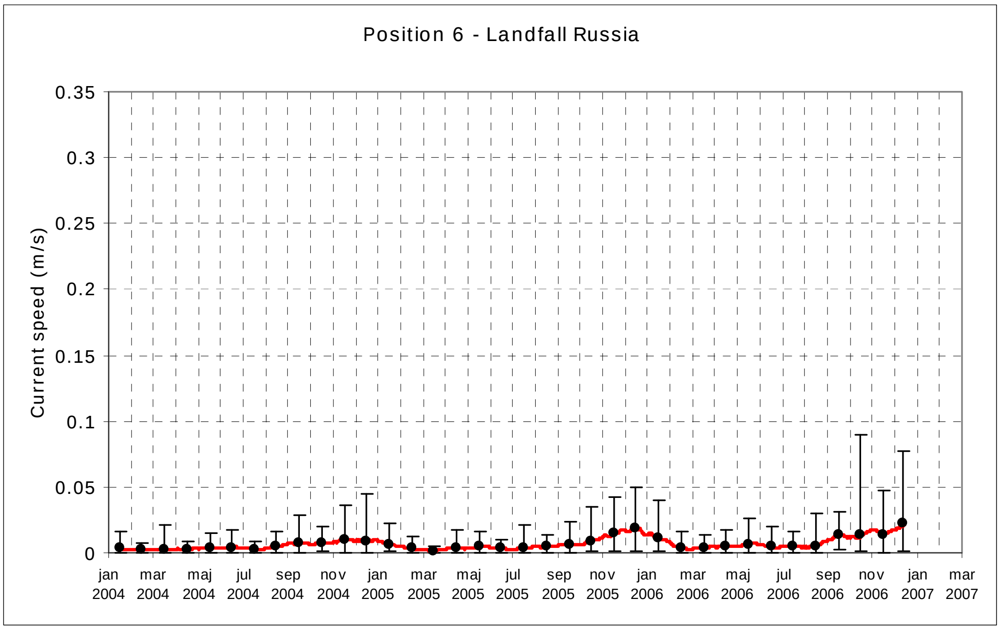
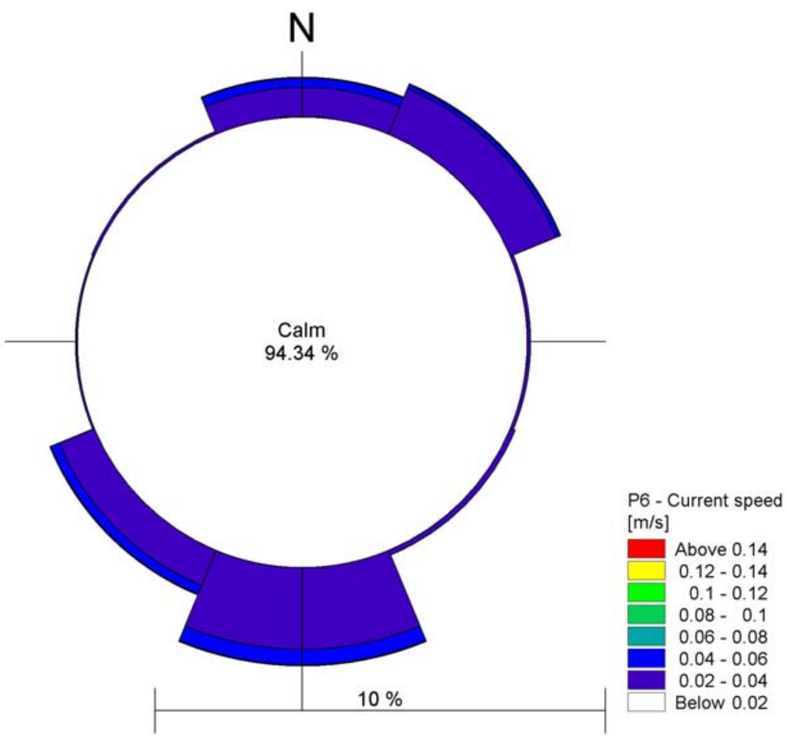



Figure 22: Bottom currents (deepest 10 m) at P5.

A) Monthly and 30-day moving average of modelled bottom currents (deepest 10 m)




B) Rose plots of modelled bottom currents (deepest 10 m)




7.5 **Figure 23: Bottom currents (deepest 10 m) at P6.**

## Conclusion

Based on the above analysis and /11/, /12/, it is concluded that the model data is applicable as the hydrodynamic basis for a general transport model.