Minimizing HSE Impacts During Design and Construction of a Major Gas Pipeline Through the Baltic Sea

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Summary

From 2010 to 2012, two parallel gas pipelines (the Nord Stream Project) were installed in the Baltic Sea between Vyborg in Russia and Greifswald in Germany. The pipeline system will enable an annual transport of 55 billion m^3 (bcm) of natural gas from the large Russian gas fields to the European gas grid.

Comprehensive environmental and safety studies were carried out in the design phase. The outcome of these studies was used in iterations with the pipeline-design process, ensuring that the final pipeline design has minimal impact on the environment as well as on human activities in the Baltic Sea. Also, due consideration has been given to ensuring the health and safety of construction personnel and minimizing the environmental impacts during construction.

Major changes to the design were made in order to minimize project impacts, including

- An originally planned intermediate service platform was "engineered out," eliminating the risk of ship collisions in the operation phase.
- The pipeline route was optimized to avoid sensitive natural areas and heavily used ship-traffic routes.
- Extensive geophysical surveys were carried out in order to identify and mitigate interaction with dumped chemical and conventional munitions and cultural-heritage objects.
- It was ensured by theoretical analysis verified by measurements that the pipeline with the chosen route did not have a negative impact on inflow and mixing of water in the Baltic Sea.
- Environmental monitoring and subsequent feedback to the construction vessels were carried out during seabed-intervention works near sensitive habitats.

Unique for this project are the major design changes that have taken place as a result of the health, safety, and environment (HSE) analysis. One outcome of this has been that all five affected countries have given permit to the project in a relatively short time period, even though it is the first major pipeline project in the Baltic Sea.

Introduction

According to present estimates, the European Union (EU) annual natural gas requirement of 550 bcm in 2006 will rise by approximately 130 bcm to approximately 680 bcm/a in 2020. At the same time, the production of gas in the EU is expected to decline to cover only 20% of its projected natural-gas requirement in 2020.

In order to meet future energy demands in the EU, the EU Commission (EC) has launched the Trans-European Energy Networks (TEN-E) program. The Commission particularly suggests expansion of the EU's supply relationship with Russia.

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The Nord Stream project, which consists of two gas pipelines at the bottom of the Baltic Sea connecting Russia with Germany, has been designated as an EU priority project within the TEN-E program.

Nord Stream consists of two 1224-km natural-gas pipelines through the Baltic Sea, directly linking the EU to some of the world's largest gas reserves in Russia. The Nord Stream pipeline will soon be ready to contribute to the EU's energy security and help it meet its greenhouse-gas-reduction goals. Nord Stream is on schedule to start transporting gas directly to the EU in late 2011. When fully operational in late 2012, the twin-pipeline system will supply 55 bcm/a of Russian gas to the EU for businesses and households for at least 50 years.

The pipeline project is constructed and operated by Nord Stream A.G., which is a joint venture established on 2 December 2005 with the purpose of carrying out a feasibility study and building the Nord Stream Pipeline. Gazprom holds a 51% stake in the joint venture. BASF SE/Wintershall Holding GmbH and E.ON Ruhrgas each hold 15.5%, and Gasunie and GDF SUEZ each have a 9% share.

In **Fig. 1,** the Nord Stream Pipeline route from Russia to Germany is shown. The transboundary nature of the pipeline makes the project quite unique. The pipeline passes through the territorial waters or Exclusive Economic Zones (EEZs) of Russia, Finland, Sweden, Denmark, and Germany. Permission from the authorities of these countries was required before construction could start. Extensive consultations therefore took place with these countries in order to ensure that the pipeline project was in full compliance with the national legislation. Because the pipeline project potentially could impact Estonia, Latvia, Lithuania, and Poland, these countries also were part of the consultation process.

Because of the transboundary character of the Nord Stream Pipeline project, requirements for safeguarding the environment are stipulated both in international regulations and in national regulations in the countries whose economic zones will be crossed by the pipelines.

The United Nations Convention on the Law of the Sea (UNCLOS) requires reasonable measures to be taken for

- The exploration of the continental shelf
- The exploitation of its natural resources
- The prevention, reduction, and control of pollution from pipelines

The coastal states may not impede the laying of pipelines. In accordance with UNCLOS, the permitting authorities of the coastal states may set conditions with the aim of controlling the aforementioned matters, to prevent, hinder, and control contamination from the pipeline.

All Baltic coastal states are signatories to the Convention on the Protection of the Marine Environment of the Baltic Sea Area, which is governed by the Helsinki Commission (HELCOM). Article 7 of the convention provides for an obligation for consultation concerning projects in territorial waters that may have significant detrimental effects on the marine environment.

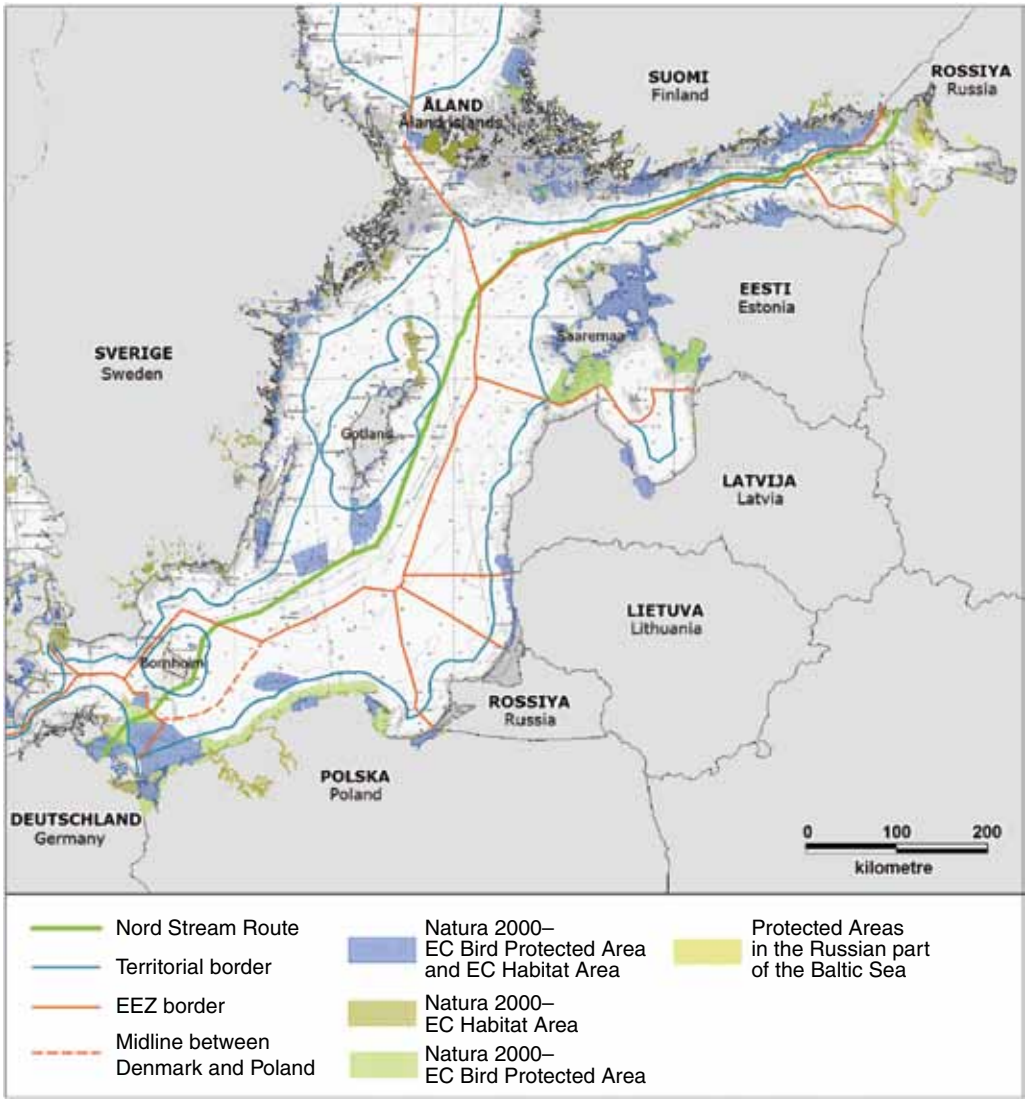

Fig. 1—Pipeline route through the Baltic Sea. The blue lines shows the 12-nautical-amile territorial waters limit, the orange lines show the limit of the EEZs of the Baltic Sea countries. Also protected nature areas in the region are shown.

The Convention on Environmental Impact Assessment in a Transboundary Context (the Espoo Convention) stipulates the obligations of parties to assess at an early stage of planning the environmental impact of certain activities that are likely to cause transboundary environmental impacts. It lays down the general obligation of states to notify and consult each other on all major projects that are likely to have a significant adverse transboundary environmental impact.

Because of the potential transboundary impacts of the project and because of international regulations, a number of working group meetings with representatives from the Baltic Sea coastal states have been held, and comments from authorities and other stakeholders have been received and included in the optimization of the environmental performance of the pipeline project.

The two pipelines will run almost parallel along the floor of the Baltic Sea, approximately 100 m apart. Each of the pipelines has a total offshore length of approximately 1224 km, and an internal diameter of 115.3 cm **(Fig. 2).** They will run from Portovaya Bay near Vyborg on Russia's Baltic coast through the Gulf of Finland and the Baltic Sea to Lubmin in the Greifswald area on the northern coast of Germany.

The environmental impact of the project was investigated thoroughly before construction. The gas pipelines will go through areas of the seabed in the economic zones of Russia, Finland, Sweden, Denmark, and Germany. Moreover, the countries of Estonia, Latvia, Lithuania, and Poland also have a vital interest in safeguarding the environment of the Baltic Sea.

The Baltic Sea is a unique aquatic ecosystem. It can be considered the world's largest estuary, forming the transition zone between the freshwater input from more than 200 large rivers (Frid et al. 2003) into the Baltic Sea, which has a surface area of 415 000 km^2 (HELCOM 2007), a catchment area of approximately 1.7 million km^2, and a volume of approximately 22 000 km^3. The population living in the catchment area is nearly 85 million. The population density varies from more than 500 inhabitants/km^2 in the urban areas of Poland, Germany, and Denmark to fewer than 10 inhabitants/km^2 in the northern areas of Finland and Sweden (HELCOM 2001).

No major pipelines existed in the Baltic Sea before construction of the Nord Stream Pipeline. Therefore, little experience with safety and environmental impacts of a pipeline project in this area exists. However, previous major dredging and reclamation projects [e.g, in Øresund between Denmark and Sweden (Lyngby and Valeur 1999) and in Singapore (Doorn-Groen 2007)] have shown that it is possible through a combination of thorough baseline investigations,

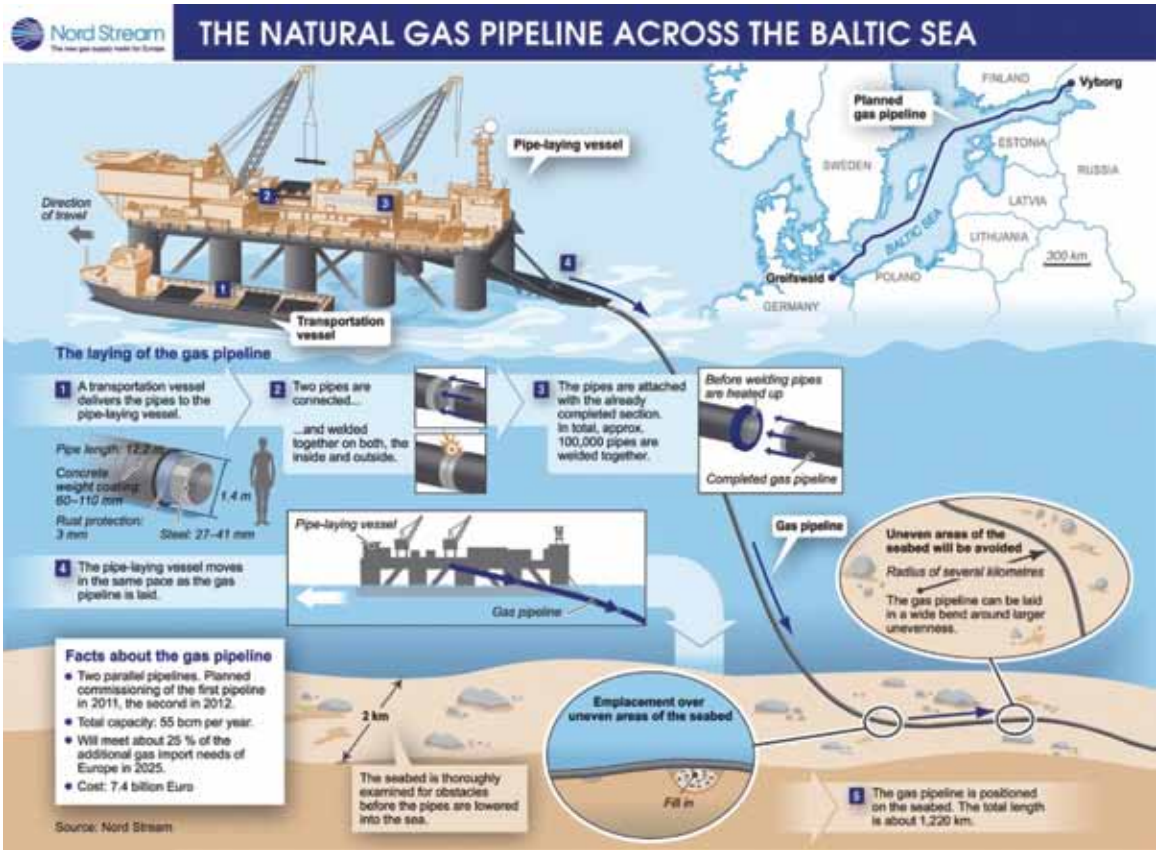

Fig. 2—The pipe-laying process for each of the two pipelines. Each pipeline is made up of appoximately 100,000 12-m pipe sections that are welded out at sea and lowered to the seabed by special pipe-lay vessels.

careful planning of the earthworks, and a suitable monitoring program to safeguard the surrounding environment.

Linden and Rust (2007) carried out a literature-review study on the North Sea experiences on the impacts of gas pipelines on the seabed. During construction of a pipeline, temporary effects in the form of destruction of the benthic environment at the site of the pipeline will occur. In addition, the water column will locally and temporarily be exposed to increased turbidity, or "cloudiness," caused by spill of sediments mobilized, and sedimentation of the released sediments will take place. Experience from other pipeline projects shows that the impact on benthic invertebrate communities and estuarine birds is limited in time and space (Lewis et al. 2003). After construction, the ecosystem will adapt to the new conditions during a recovery period. The pipeline on the seabed will be covered by benthic flora and fauna rapidly (it should be noted that this is valid for the North Sea, which does not have permanently anoxic deep areas as the Baltic Sea has). If the surrounding environment is made up of loose sediments, the new structure will contribute to increased biodiversity by introducing a new hard bottom substrate for the ecosystem (the "reef effect"). Linden and Rust (2007) note that a pipeline introduced on the seabed is likely to function as a shelter and an additional food source to organisms in the area.

Hyams et al. (2004) describe how it was possible to undertake successful installation of two offshore miniplatforms and associated pipelines with no adverse impacts, even though the construction took place in environmentally sensitive shallow tropical waters in the northwest shelf of western Australia. One important element was the introduction of a new barge-anchoring method that ensured that no significant damage took place to a total of 1,300 coral bomboras surveyed within the pipeline alignment.

Possible Service Platform and Associated Collision Risk

The originally planned design of the Nord Stream Project included an intermediate service platform to be located in the Swedish EEZ, northeast of the island Gotland. The service platform was planned to be a riser platform **(Fig. 3)** on the basis of the subsea pipeline between Vyborg in Russia and Greifswald in Germany. The advantage of having the service platform would be to gain increased flexibility when carrying out routine maintenance, and other functions.

The construction and presence of such a platform would introduce an additional risk to the project. The main hazards related to the service platform would be (Christensen 2007)

- Ship collision against platform
- Risks during construction of the platform
- Extreme weather conditions
- Helicopter transport
- Risks of terrorism against the platform

Comprehensive studies were carried out in order to calculate the risks associated with possible ship collisions against the platform. In Fig. 3, the ship-traffic intensity in the area around the proposed platform Locations A, B, and C21 is shown. The red color indicates high ship-traffic intensity, while the yellow areas indicate areas of lower ship-traffic intensity. The alternative, Platform Location C21, was analyzed after the analysis of Positions A and B showed that the platform-collapse risk caused by the ship traffic for Positions A and B was too high compared with the Det Norsk Veritas (DNV) acceptance criterion (*DNV-RD-F107* 2010).

In the analysis, focus was on platform-collapse consequence, but there are also consequences related to human safety and the environment. Possible consequences include damage to the colliding ship, resulting in an oil spill; injuries and/or fatalities to personnel;

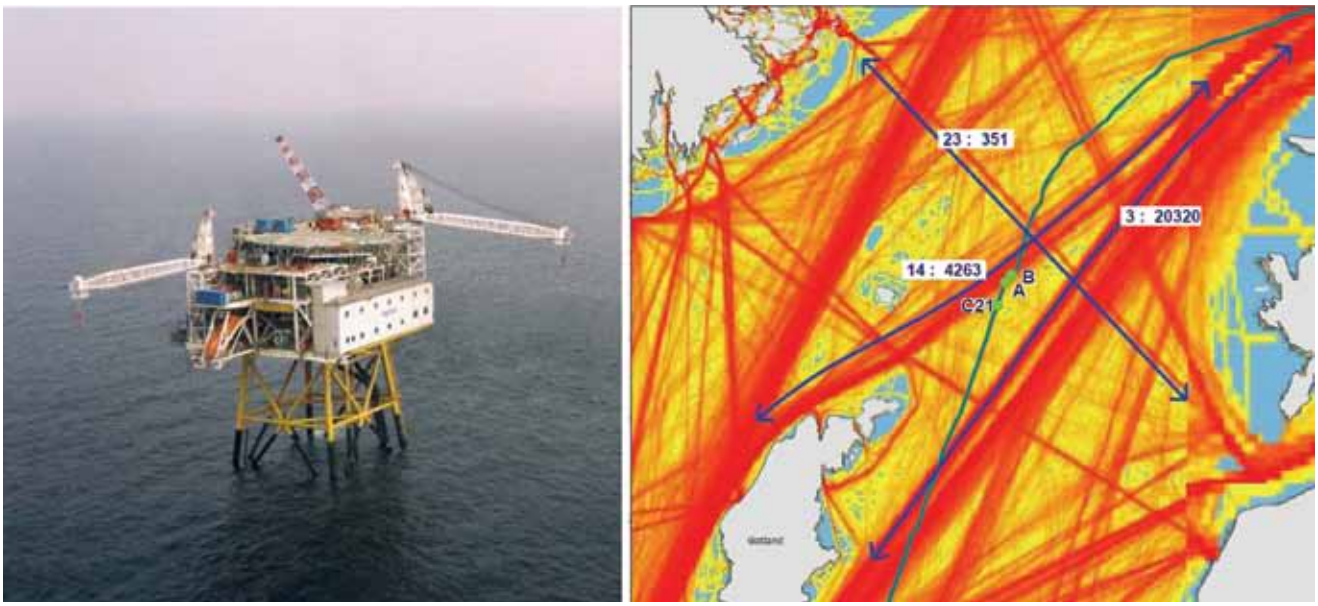

Fig. 3—Example of a riser platform (left) and ship-traffic-intensity plot with routes and Platform Locations A, B, and C21 (right) northeast of the island Gotland. The blue arrows indicate main regular routes (Christensen 2007).

and damage to the platform, resulting in a major gas release with consequences to personnel and environmental impacts.

After analyzing the risks associated with introducing the platform and engaging in a dialogue with the Swedish authorities and nongovernmental organizations, it was decided to design the pipelines without an intermediate service platform. Another large gas pipeline project—the Langeled gas-pipeline from Norway to the UK—was commissioned in 2009. Experience from this pipeline, which also has been constructed with no intermediate service platform, also was evaluated before the decision was made.

The preceding process is an example of how results of the quantitative risk assessment have been used proactively in order to design the pipeline project in the direction of improved environmental performance (in this case by reducing the risk of an unwanted environmental event), in close collaboration with the stakeholders in the area of the possible environmental impact.

Route Optimization With Respect to Safety and Environmental Concerns

When selecting the optimal route for the Nord Stream Pipeline, a number of factors were taken into account. The general goal when planning the route was to achieve the shortest route while respecting or avoiding certain areas such as bathymetrically disadvantageous regions, environmentally sensitive areas (see protected nature areas in Fig. 1), military exclusion zones, munitions dump sites, and major ship-traffic routes. Selection of the optimal route was a result of in-depth research, and alternatives were measured against three main criteria, with safety and environmental concern being an overarching objective. The first criterion was environmental and focused on avoiding protected and/or sensitive designated areas and other areas with ecologically sensitive species of animals or plants. Also taken into account was minimizing any seabed-intervention works that might cause local environmental impacts (Valeur et al. 2008). The second criterion looks at socioeconomic factors to minimize any interference with shipping, fishing, dredging, the military, tourism, and existing cables and wind turbines. Likewise, no impact to present and future raw extraction activities in the area should take place. In addition, avoiding areas with known discarded conventional and chemical munitions was also a top priority in the route-selection process. The third criterion covered technical considerations such as minimizing construction time and therefore any disruptions, as well as reducing the technical complexity of the operation to keep the use of resources low. These criteria were applied for five main routing choices. Following the route from Russia to Germany, these choices were between

- North or south of the island Gogland in Russian waters
- North or south of the island Kalbådagrund in Finnish waters
- East or west of the island Gotland and around the protected area Hoburgs bank in Swedish waters
- Northwest or southeast of the island Bornholm in Danish waters
- Bringing the pipeline ashore at Lübeck, Rostock, or Greifswald in Germany

In **Fig. 4,** the pipeline alignment options both northwest and southeast around Bornholm are shown (the green line). The arrows indicate major ship-traffic routes for the commercial ship traffic in the area, and the numbers show the vessel-traffic frequency. The dots show logistics bases to be used during construction, and the yellow lines show main work-vessel logistics routes during the construction period. The general ship-traffic information for each considered route is obtained from automatic identification system data, while the information for ship traffic associated with pipeline construction is based on planning logistics for the pipeline construction.

Analysis of the collision likelihood showed what also is clear from Fig. 4—that the pipeline route southeast of Bornholm includes a significantly lower likelihood of collision between work vessels participating in the construction of the Nord Stream Pipeline and the commercial ship traffic in the area (Christensen et al. 2009).

Therefore, the southeastern route was chosen around the island of Bornholm. In addition to this consideration, the southern route also requires less seabed-intervention work and crosses only three existing cables.

In Fig. 1, the protected natural areas in the Baltic Sea are shown. The Natura 2000 network of nature-protection areas across Europe was set up for the EC Habitats Directive in 1992 (EC 1992). The network also includes areas conserving bird species according to the EU Birds Directive of 1979 (EC 1979). Natura 2000 sites are not by strict definition nature reserves where all human activities are excluded. Rather, they are areas identified as important wildlife habitats and as such should be managed in a way that ensures that biodiversity is maintained. The purpose of the Natura 2000 network is to maintain habitats and species to favorable conservation status in their natural range.

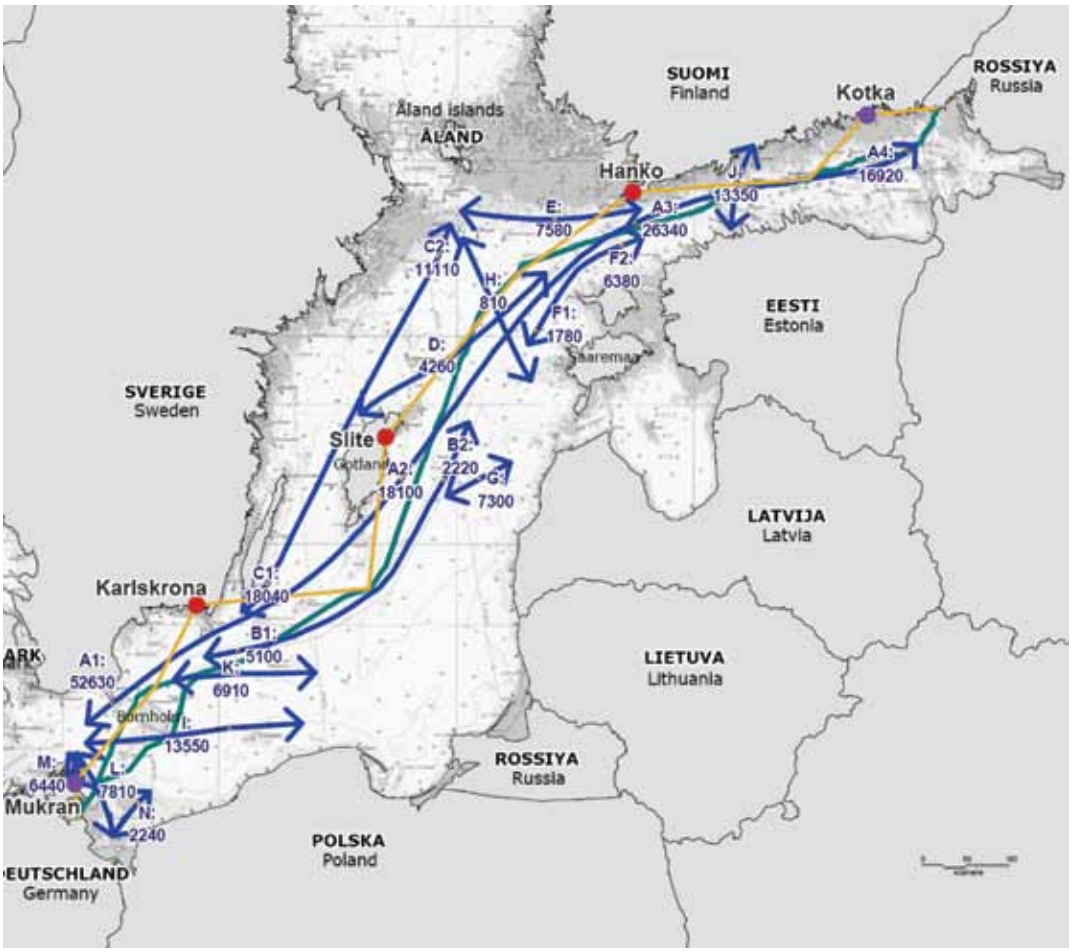

Fig. 4—Map of coating yards (purple dots), transshipment sites (red dots), and the major shipping routes (blue lines) (Christensen et al. 2009).

The Nord Stream pipeline route is located in the vicinity of and also crosses sites within the Natura 2000 network. Therefore, these areas and the habitats and species they protect have been a key element in the surveys and research carried out by Nord Stream during the design of the pipeline route. Nord Stream's vision is to build and operate its pipeline safely and with no significant effects on biodiversity and nature conservation (i.e., no irreversible losses or damage to either species or habitats).

Of special concern in the Baltic Sea are areas, also along the planned pipeline route, where conventional and chemical munitions were dumped during and subsequent to both World War I and World War II. In particular, the Baltic Sea was used as a dumping ground for chemical munitions left over from World War II, and it has been estimated that approximately 40 000 t of chemical munitions were dumped in the Baltic Sea (HELCOM 1995). Of these, approximately 32 000 t of chemical weapons containing approximately 11 000 t of highly toxic agents was dumped in the Bornholm basin, east of the island of Bornholm in the southern Baltic Sea (Sanderson et al. 2010).

In 2005, a geophysical survey was conducted, covering a 2-km-wide research corridor. The result of the survey was used for planning further surveys. In 2006, a detailed geophysical survey of a 180-m-wide corridor was performed along the preferred route to provide engineering data and identify munitions.

Subsequent detailed surveys were carried out from 2007 to 2010 using combined geophysical and magnetic survey with remotely-operated-vehicle (ROV) inspections and a sampling program where sediment samples were analyzed for traces of chemical-warfare agents (Hjorth 2011). Traditional marine geophysical survey (comprising measurements with multibeam echosounder, side-scan sonar, single magnetometer, and seismic equipment) was combined with a newly developed instrument—a gradiometer array—that made it possible to detect ferrous objects on the seabed. The magnetic data were correlated with multibeam and side-scan sonar data, and this formed the basis of objects that were visually inspected with a ROV. The underwater footage of the objects made it possible to distinguish munitions from other objects on the seabed and to determine the type of munitions.

Geochemical methods were used to identify traces of chemical-warfare agents from dumped chemical munitions. Sampling of sediment cores and pore water was conducted along the Nord Stream route through the Danish part of the pipeline route, which extends near the primary dumping areas for chemical munitions in the southern Baltic Sea. Subsequently, the samples were analyzed in a laboratory. The results from the analysis showed that only very few stations had evidence of traces from warfare agents (Hjorth 2011).

Munitions, mainly in the form of contact mines, were identified along the Nord Stream alignment. The highest density was found in the Gulf of Finland, but also in Sweden sea mines were found. In Denmark, mustard-gas bombs of the type KC250 were identified.

In total, approximately 110 conventional munitions objects along the pipeline route were cleared in the end of 2009 and first half of 2010. Approximately 50 munitions objects in Russian waters were cleared by the Russian Baltic Fleet. Approximately 50 munitions

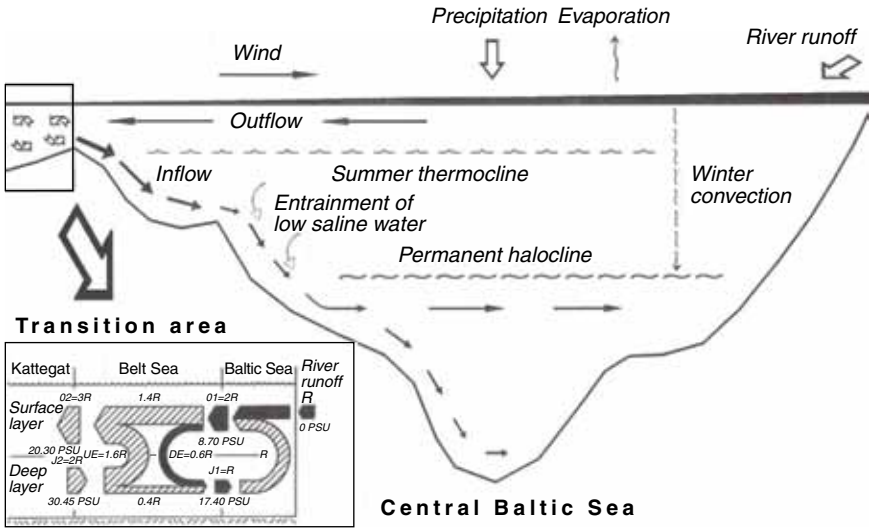

Fig. 5—Schematic of the water balance of the Baltic Sea, the water exchange with the North Sea, and the transformation of water masses in the Belt Sea (bottom left; in river-runoff units) (Matthäus 2006).

objects were cleared in the Finnish EEZ (by the company Bactec), seven in the Swedish EEZ (by the company Bactec), and four in German waters (by the company SeaTerra). Chemical-munitions objects are, in agreement with the Danish authorities, not cleared because it is generally accepted that attempts to clear or retrieve the chemical munitions will pose far higher risks to personnel and to the environment than leaving the objects in place. Therefore, identified chemical-munitions objects are instead avoided when designing the pipeline route and when carrying out the construction work.

Also, the potential risk of submarine slides was investigated. For another large pipeline project, the pipeline from the Ormen Lange gas field to the Norwegian coast (the gas that is subsequently transported to UK by the Langeled gas pipeline), comprehensive risk analysis was carried out for landslide potential (Lund et al. 2004). The reason is that the Ormen Lange project is situated within a scar of a large prehistoric landslide (the Storegga slide that took place approximately 8,200 years ago).

The knowledge of occurrences of landslides in the Baltic Sea is very limited. However, two submarine landslides were found during marine geological mapping by the Geological Survey of Sweden in the southwestern Baltic proper (Klingberg 2008). Therefore, detailed hydroacoustic surveys and seabed sampling were carried out in order to establish the mechanisms that have created the slides. The analysis showed that the slides were developed in glacial clay and in clay till, respectively. Below the sediment strata, glaciofluvial sediments occurred in both cases. The seabed in most places is almost flat with a slight slope of less than 10 m in 500 to 1000 m, indicating that the slides have occurred in slopes that are built by glaciofluvial sediments (Klingberg 2008). The analysis of the slides indicated that they most likely have occurred at the end of the latest glaciation and that there is no slide risk existing in the present environmental conditions.

Analysis With Respect to Influence on Water Inflow to the Baltic Sea

The Baltic proper is characterized by an extensive freshwater excess that produces a strong stratification. In the upper layer, the salinity is rather constant whereas large variations are found in the deeper parts. These are because of the sporadic inflows of more-saline water. The deepwater flows along the bottom as a gravity-forced dense bottom current that mixes with resident Baltic surface water. The salinity of the inflowing deepwater therefore decreases as the flow proceeds into the basin. At the same time, the volume flow increases (Borenaes and Stigebrandt 2009).

In **Fig. 5,** the water balance of the Baltic Sea, the water exchange with the North Sea, and the transformation of water masses in the Belt Sea are shown. The Baltic Sea is connected to the surrounding oceans through the shallow-water and narrow (0.8, 16, and 4 km wide, respectively) Danish straits Little Belt, Great Belt, and Oresund, which connect the brackish water of the Baltic Sea with the oceanic water of the North Sea. Two sills in this transition zone (the Dars sill, with a water depth of 18 m, and the Drogden sill, with a water depth of 8 m) effectively limit the inflow of saline, oxygen-rich water to the Baltic Sea to rare occurrences of storms from the west. The average water depth of the Baltic Sea is approximately 52 m and the maximum depth is 459 m. The water column in the Baltic Sea is stratified by an abrupt halocline, hampering the vertical mixing of water and the vertical diffusion of oxygen. The topography of the seabed is characterized by basins separated by sills at different depths (Frid et al. 2003).

Dense bottom currents flowing into the Baltic Sea through the Sound and Fehmarn belt replenish a deepwater pool in the Arkona Sea that loses water by the dense bottom current carrying water through the Bornholm Strait and into the Bornholm basin **(Fig. 6).** A deepwater pool is built up in the Bornholm basin that is drained through the Stolpe Channel. This water sustains the deepwater in the large basins in the interior of the Baltic proper.

Most of the Nord Stream Pipeline will be laid directly on the seabed. The presence of the pipelines, each with a diameter of approximately 1.4 m, will change the near-bottom current pattern near the pipelines. The Swedish Meteorological and Hydrological Institute carried out an analysis of the impacts on the hydrography and the water quality caused by the presence of the Nord Stream Pipelines. The pipelines may influence the deep water of the Baltic proper in three ways (Borenaes and Stigebrandt 2009):

- First, pipeline-generated turbulence might be more efficient than turbulence generated by bottom and interfacial friction. This may increase the mixing between the new deep water and ambient water.
- Second, the pipelines may increase the sill height and thereby dam the dense deep water if they are placed in a section of hydraulic control.
- Third, the pipelines may steer the dense water downslope if the current encounters the pipelines when flowing along a sloping bottom.

The analysis shows that the mixing new deep water flowing into the Baltic Sea might increase by at most 2%. Increased mixing of new deep water means lower salinity, increased flow rate, and increased transport of oxygen, which would tend to improve the ox-

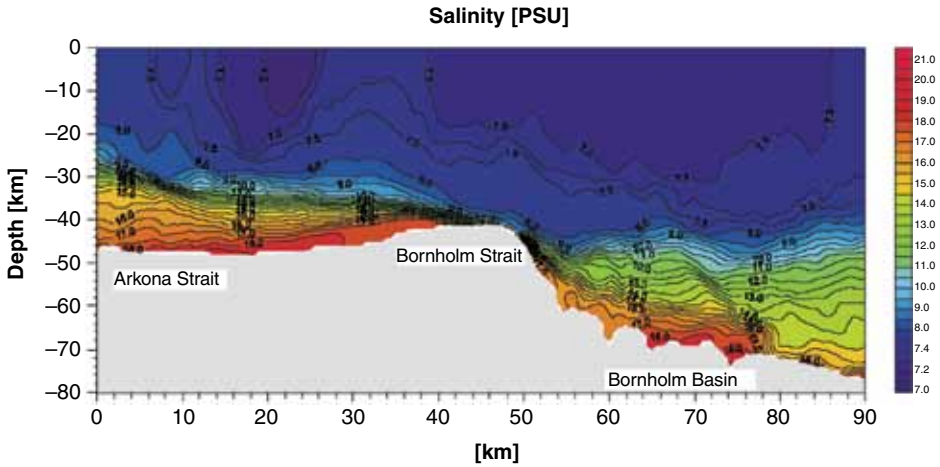

Fig. 6—Salinity along a section from the Arkona basin to the Bornholm basin, passing the Bornholm Strait in February 2003, shown in pracgtical salinity units (PSU) (Piechura and Beszczynska-Möller 2003).

ygen conditions in and below the halocline and thereby increase the deposition of phosphorus in the deep water. Although the effect is very small, the pipelines may thus tend to decrease the effects of eutrophication in the Baltic Sea (Borenaes and Stigebrandt 2009).

For ensuring that the assumptions for the preceding analysis are correct, a monitoring station that measured the current profile and profiles of salinity and water temperature was installed in the Bornholm basin from January 2010 to January 2011. Monitoring was performed with an acoustic doppler current profiler and with a conductivity, temperature, and depth recorder, both with special emphasis on the lowermost part of the water column. The measurements aim at describing bottom currents, interfacial friction, and dissipation of inflow waters.

The analysis suggests that the presence of the pipeline at the seabed does not have any negative impact on the environment of the Baltic Sea. A very small theoretical impact causing additional mixing of new deep water flowing into the Baltic Sea will tend to have a very small theoretical positive impact in increasing the removal of phosphorus from the uppermost part of the water column, but this possible impact is so small that it is negligible compared to the natural variations.

Environmental Monitoring and Feedback During Construction

In the Swedish EEZ, the pipeline route extends relatively close to the two protected Natura 2000 areas Hoburgs Bank and Norra Midsjöbanken (Fig. 1). Therefore, special precautions were taken for ensuring that the construction works for the Nord Stream Pipeline in this area had no negative impact on the two areas.

Norra Midsjöbanken is a vast bank, partly consisting of a moraine ridge on bedrock. The water is clear and clean, as indicated by attached large algae at a depth of 25 m. The bank is a spawning area for turbot (*Psetta maxima*) and herring (*Clupea harengus*). A large population of blue mussels (*Mytilus edulis*) makes the area important for birds. It is of global interest for black guillemot (*Cepphus grylle*) and is an important wintering area for long-tailed duck (*Clangula hyemalis*) (Lindblad and Grip 2006; Lindblad and Nikolopoulos 2010).

Hoburgs Bank is a shallow sea area, with large parts of the area at depths of approximately 35 m. The bank consists partly of bedrock, but there are also large areas comprising sublittoral sandbanks and reefs. Hoburgs Bank has a unique substrate composition, with wave-induced glaciofluvial deposits that are very rarely found on Earth. The seafloor at this wave-exposed site is characterized by stones, rocks, and extensive areas with sand on bedrock. Large algaes can be found down to a depth of 25 m. The most widely distributed animal is the blue mussel (*M. edulis*). Foraging of the long-tailed duck (*C. hyemalis*) seems to have a major effect on the blue mussel population. Two red-listed bird species can be found at Hoburgs Bank—long-tailed duck and velvet scoter (*Melanitta fusca*) (Stockholm University Marine Research Centre 2000).

The very clear water in the area is key to the unique characteristics of the of the two Natura 2000 areas because algae usually cannot grow at this greater water depth. Therefore, the Swedish authorities included the following condition in the construction permit for the Nord Stream Pipeline in the Swedish EEZ:

"Turbidity caused by seabed operations connected with the laying of each pipeline should, as a guideline, amount to a maximum of 15 mg/L at the boundaries of the Natura 2000 areas Hoburgs Bank and Norra Midsjöbank (in accordance with the classification of these areas as Natura 2000 areas). The measurement technique and procedure shall be governed by the environmental monitoring programme that the Company is to produce pursuant to section 7. If monitoring of the turbidity shows that this value has been exceeded, additional precautionary measures shall be taken during seabed operations, such as cutting back on or temporarily ceasing seabed operations so that the value can be maintained. Thereafter, the Company shall, in so far as possible, ensure that any breach of the limit is not repeated."

Seabed interventions (post-lay trenching) were planned for the stretches indicated in **Fig. 7.** The areas to be trenched closest to the Natura 2000 borders are approximately 4 km away. As part of the environmental-assessment studies, numerical modeling of the spreading of sediments from seabed interventions was carried out. The MIKE 3 PA model (DHI 2007) was used, assuming a sediment spill rate of 2% of the materials trenched, on the basis of experience from other projects. To study the variability, three different periods (with weak, average, and strong currents) selected on the basis of current statistics from 2004 to 2006 were used in the modeling. The modeling results have shown that it is unlikely that the seabed-intervention works would cause measurable increase of suspended matter or sedimentation at any point within the two Natura 2000 areas. The modeling shows that 97 to 99% of the sediment released because of seabed-intervention works settles less than 2.5 to 3 km away from the point of release (Nielsen 2010).

Because of the uncertainty always present in numerical modeling, both with the assumptions for the modeling and with respect to the modeling algorithms, a monitoring program was designed in consultancy with the Swedish authorities for ensuring compliance with the 15-mg/L permit condition. The monitoring program includes:

• Four long-term (LT) monitoring stations at the border of the Natura 2000 areas, two at each bank (Fig. 7), where turbidity, salinity, and water temperature are measured at 1, 5, and 15 m above

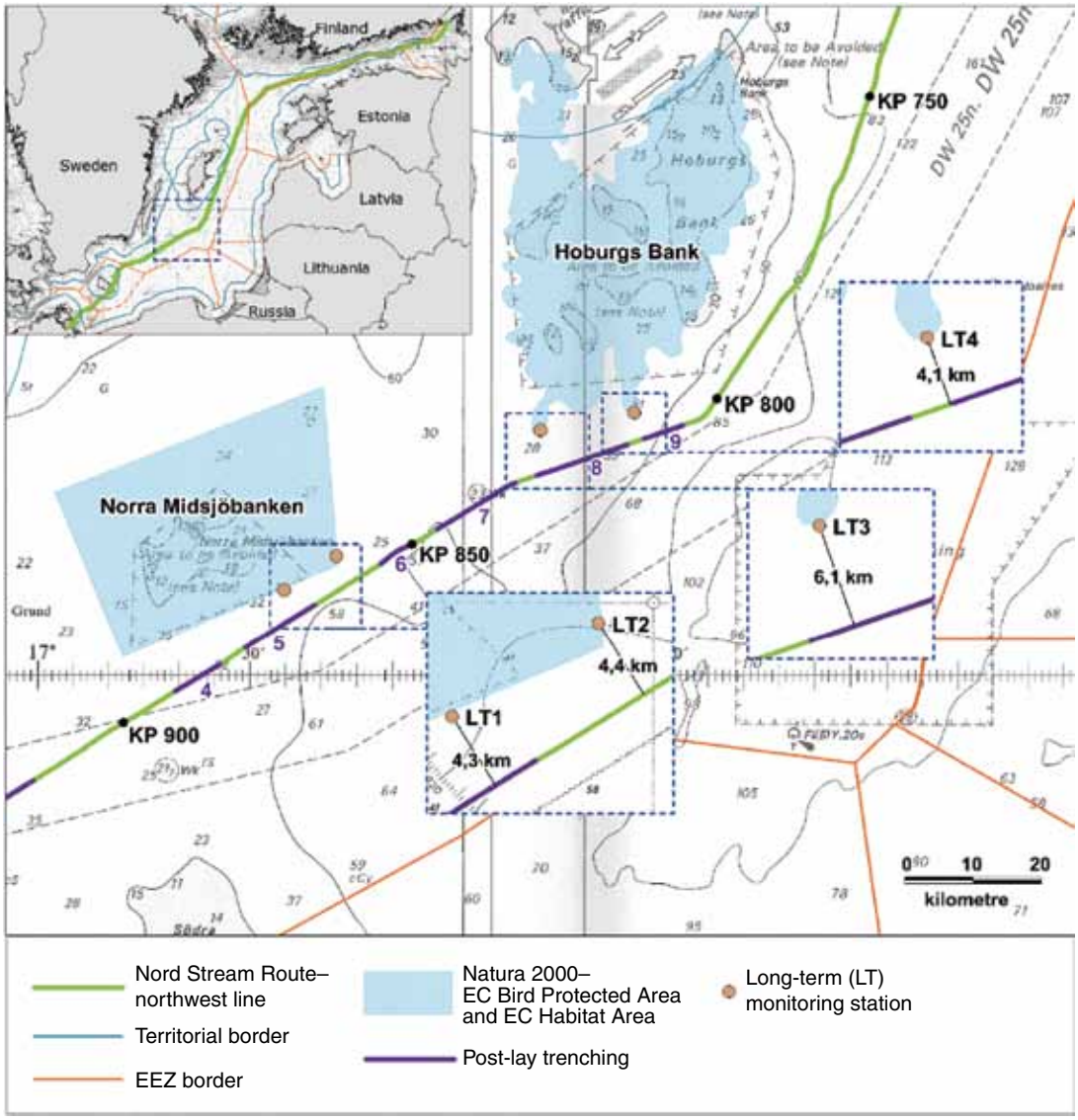

Fig. 7—Location of Natura 2000 areas in the vicinity of the pipeline route in the Swedish EEZ, with trenching areas shown (see also overview map in Fig. 1). At the four long-term (LT) monitoring stations, turbidity, temperature and salinity are measured 1, 5 and 15 m above the seabed, and currents are measured through the entire water column. The water depths for the stations are LT1: 40 m, LT2: 43 m, LT3: 28 m, LT4: 35 m. KP (Kilometre Point) indicates the distance from the landfall in Russia.

the seabed. In addition, currents were measured through the entire water column. The stations are situated where it is most likely that sediments mobilized by the seabed-intervention works may reach the Natura 2000 areas. The measurements included online data transmission and an alarm procedure to ensure that mitigation action could take place in case the turbidity increased because of the construction work.

• A vessel-based monitoring program for measuring the sediment plume close to the trenching areas during the periods of trenching for ensuring that mitigation measures could be initiated at a very early time, and for validating the assumptions for the modeling with respect to sediment spill rate, sediment concentrations, and other factors.

Sediment concentrations are measured in an arbitrary unit called nephelometer turbidity units (NTU). Calibration toward water samples collected at the site showed a good correlation between NTU and suspended-sediment concentration in the unit mg/L, such that 1 NTU = 1.9 mg/L, meaning that a turbidity of 8 NTU above the natural turbidity corresponds to the authority limit of 15 mg/L.

Although trenching in the Swedish EEZ did not begin until 19 February 2011, the four LT-stations were established on 6 to 7 November 2010. This was in order to measure the natural sediment dynamics in the area in advance so separation between the natural sediment concentrations and the contribution to the sediment concentrations caused by construction work could take place when trenching started.

The baseline measurements showed in general very low turbidity values for both stations, most of the time below 1 mg/L. During stormy periods, the level increased, at LT1 only up to approximately 3 mg/L, at LT2 up to approximately 10 mg/L, at LT3 up to approximately 3 mg/L, and at LT4 up to approximately 80 mg/L. The seabed in the area consists mainly of coarse sand and gravel; therefore, even under stormy conditions, the seabed is not resuspended at this water depth. Northeast of LT4 are areas of more-fine-grained seabed sediments; this is why the natural turbidity gets higher at this station.

Trenching took place in the Swedish EEZ from 19 February to 19 March 2011. No increase of turbidity was measured at the four

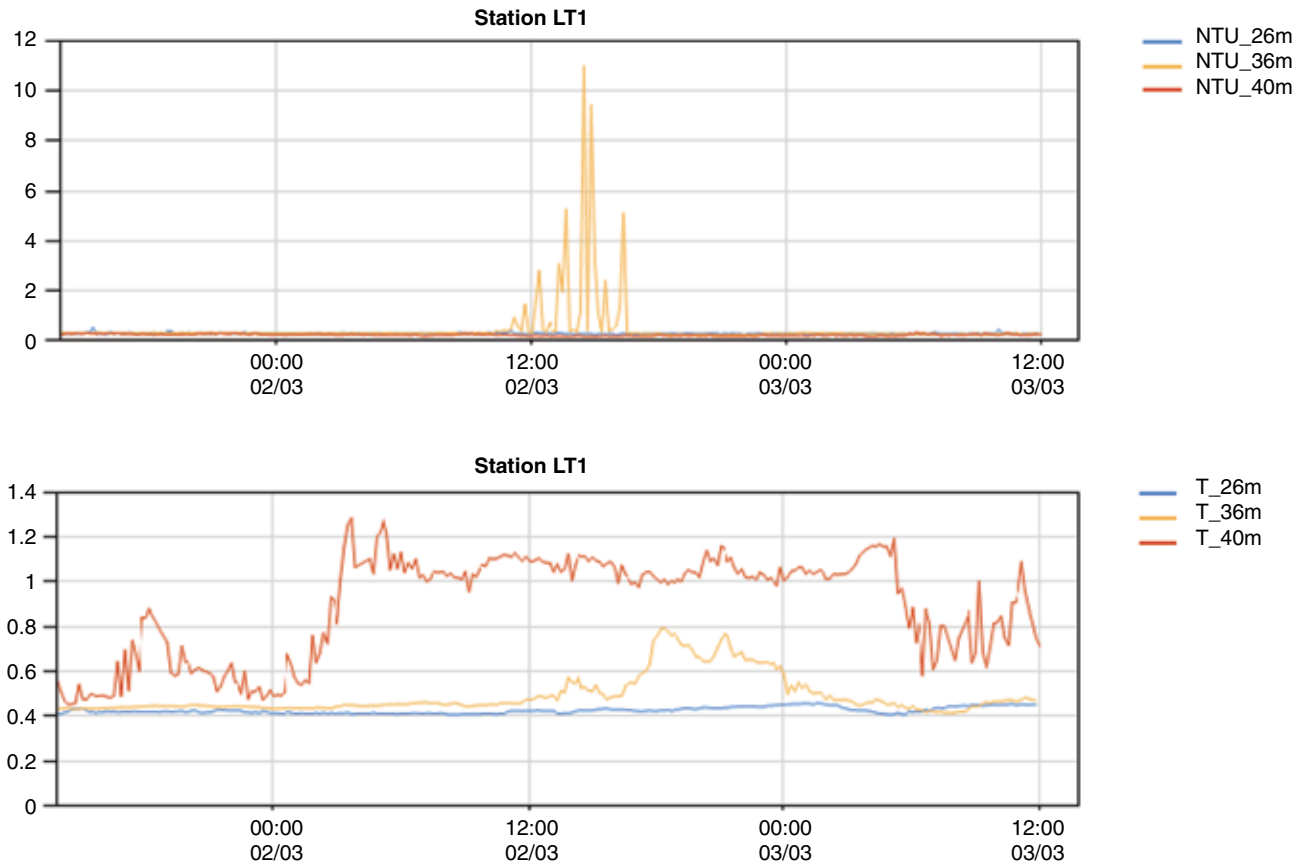

Fig. 8—Measured turbidity at LT1 (uppermost figure) shown together with water temperature (lowermost figure) on 1 March 14.00 UTC to 3 March 12.00 UTC (Universal Time, Coordinated). Levels are shown below water surface; 26m~15m above seabed, 36m~5m above seabed, 40m~1m above seabed. The measurements were carried out by DHI.

LT-stations because of the construction work in that period. An increase in turbidity at LT2 on 2 March 2011 **(Fig. 8)** did, however, cause some concern. Trenching ceased on 27 February 2011 and was planned to commence again on 2 March 2011 at 2100 hours. The turbidity peaks occurred during the afternoon of 2 March 2011.

In Fig. 8, the turbidity measured at LT1 during the period 1 March 14.00 UTC to 3 March 12.00 UTC is shown, together with the measured water temperatures.

The turbidity levels indirectly represent measurements of the suspended-sediment concentrations (SSCs). For sediments in this area, a factor of proportionality between measured turbidity (in the unit NTU) and SSC (in the unit mg/L) has been found to be approximately conversion factor=1.9 (mg/L)/NTU. This means that a measured turbidity of 10 NTU corresponds to an SSC of approximately 19 mg/L.

The turbidity level measured at LT1 was low and very constant at 0.2 to 0.3 NTU at all three levels (1, 5, and 15 m above seabed) until 2 March 2011 at 11.00 UTC (Fig. 8). Thereafter, turbidity at 5 m above seabed fluctuates strongly with peak values of up to 11 NTU until 17.00 UTC, where after the level is again low, constant, and close to the turbidity measured at 1 and 15 m above seabed (again 0.2 to 0.3 NTU).

The natural turbidity measured at LT1 during winter of 2010–11 varied in the range of 0 to 1.5 NTU, corresponding to approximately 0 to 3 mg/L. Therefore the levels measured 5 m above the seabed on 2 March 2011 are quite unusual.

When looking at the water temperature in Fig. 8, the temperature measurements during the period are fluctuating, starting with a rather constant water temperature at all three levels on 1 March 2011. On 2 March 2011 the water temperature 1 m above the seabed increases rapidly during early morning, and at 5 m above seabed the temperature increases, but less abruptly, during the morning, and in particular after noon. The water temperature decreases again, first at 5 m above seabed (from the evening of 2 March 2011), and later at 1 m above seabed (in the morning of 3 March 2011). The salinity is slightly increased at 1 m above seabed for the same period. It should be noted that, with the level of salinity measured during the period, the temperature where the seawater has the maximum density is approximately 3°C. This means that the measured temperature increase from 0.4 to 1.2°C causes the density of the water to increase.

This information reveals that a pycnocline [a layer of maximum vertical density gradient caused by differences in water temperature (thermocline) and/or salinity (halocline)] is present in the area between 1 and 15 m above seabed during this period. Such density gradient layers are known to be able to accumulate turbidity (i.e., particles of a density close to that of seawater being trapped). For instance, this could be fish eggs, where some of the fish species (e.g., cod) have eggs with the ability to float in between water mass of different densities. It should be noted that with respect to cod, there are significant interannual variations in spawning time. Also there are spatial differences; the spawning of the western Baltic cod takes place from January to April (Nord Stream A.G. and Ramboll 2008).

Also, organic materials of other origins could be the explanation. The neutral density of the particles causing the turbidity layer suggests that the particles are of organic composition (because minerogene particles usually have a density of approximately 2650 kg/m^3). In addition to fish eggs, fish larvae or algae could be the cause of the increased turbidity. Also, air bubbles present at the front of an introduced water body could contribute to increased turbidity.

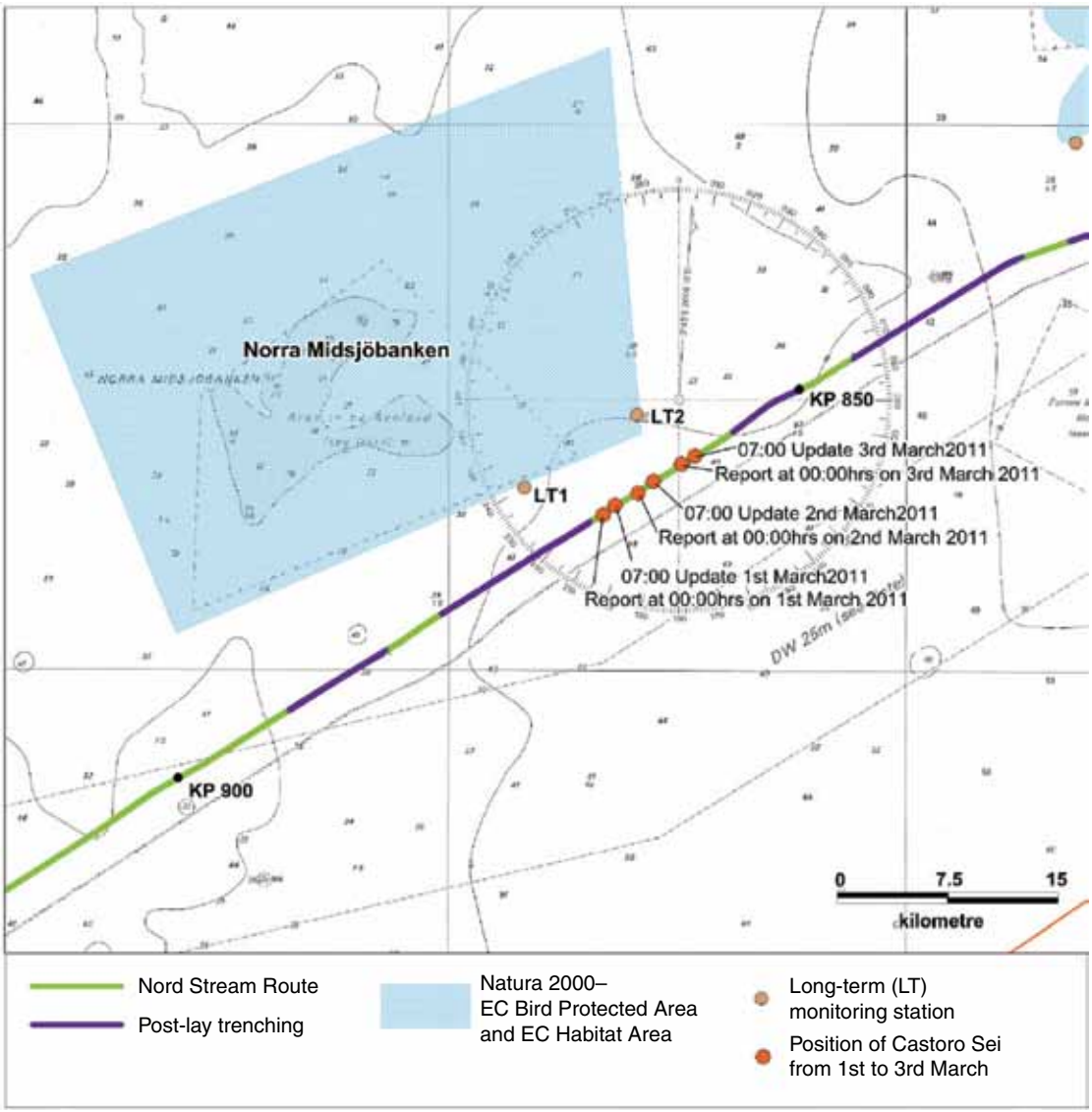

Fig. 9—Location of C6 on 1–3 March 2011.

The fact that the turbidity is measured at 5 m above seabed only (not 1 m above seabed and not 15 m above seabed) suggests that the turbidity is connected to particles with a neutral buoyancy in the level of the pycnocline because normal sediment particles sinking through the water column would also be measured 1 m above seabed (in particular because the current velocities are so low). The abrupt changes in turbidity could be caused by vertical movements of the layer caused by internal waves/seiches (standing waves in an enclosed or partially enclosed body of water), or by patchiness of the layer of particles causing the increased turbidity.

It is not expected that the activities of the pipe-lay vessel *Castoro Sei* (C6) could cause any turbidity increase at the border of the Natura 2000 areas. However, because of the unusual turbidity measurements on LT1 on 2 March 2011, the possibility that the activities of C6 could have anything to do with the measurements has been evaluated. The positions of C6 from 1 to 3 March 2011 are shown in **Fig. 9.** From the figure, it is clear that a possible origin of the turbidity measured at LT1 from C6 would require currents toward the west.

Analysis of the currents measured at LT1 the period before and during the time of the turbidity peaks has shown that it is not possible for sediments mobilized by the pipe-lay vessel to reach LT1. Even in a theoretical scenario that sediments spilled several days before the high-turbidity event could (through a number of settling-resuspension events) reach the position of LT1, it would show highest turbidity 1 m above the seabed, not 5 m above the seabed, because of the sediment concentration profile in the water column (Valeur et al. 1995). On the basis of this, it can be concluded that it is not possible that the turbidity peaks measured at 5 m above seabed at LT1 on 2 March 2011 have anything to do with the activities of C6.

It should be noted also that when pipe lay took place adjacent to LT3 and LT4, no increase in turbidity was measured at these stations.

This high-turbidity event is an example of the value of the comprehensive monitoring set up before and during the period of seabed-intervention work. Without detailed measurements of turbidity as well as salinity, water temperature, and currents it, would have been very difficult to exclude the possibility that either trenching in the days before the event or pipe lay before or during the event has something to do with the increased turbidity at the border of the Natura 2000 area. In that case, both the owner of the project and the authorities would have been in the situation where it would have been impossible to definitively say whether the turbidity peaks would have been in conflict with the 15-mg/L condition in the construction permit.

Also the extensive baseline monitoring carried out during the months before construction started proved to be valuable as a basis for interpretation of the measurements during the construction period. The interdisciplinary approach, considering both the physical and the biological factor when interpreting the monitoring results, was key in understanding the natural turbidity dynamics in the area.

Conclusion

Comprehensive analysis and extensive stakeholder dialogue before construction of the Nord Stream Pipeline have contributed significantly to ensuring optimal solutions with respect to safeguarding people, the environment, and socioeconomic activities. The pipeline route has been selected in order to minimize risks to the vessel traffic and to minimize the environmental impact during construction. Also it has been ensured that the presence of the pipeline does not have a negative impact on the inflow to the Baltic Sea. Mitigation actions have been taken in order to avoid interference with chemical and conventional munitions at the seabed.

Where construction close to protected Natura 2000 areas could not be avoided, extensive monitoring of the sediment spreading with feedback mechanism to the construction vessels was initiated. Detailed knowledge of the natural sediment dynamics proved to be key for being able to distinguish between the possible contribution of suspended sediments from the construction work and the natural suspended sediments in the areas.

The process from permitting started to construction permit given in the five countries through whose EEZs the pipeline traversed lasted 3 years and 3 months. This is a relatively short time for a project of this size and complexity; a permitting process of 5 to 10 years is quite normal for such a project. Reasons for the relatively quick process are that the authorities were both constructive and effective and that Nord Stream was flexible and willing to change elements of the project where required. This approach has also ensured a process of continual improvements with respect to minimizing the safety risks and the environmental impacts of the project.

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References

Borenaes, K. and Stigebrandt, A. 2009. Possible effects upon inflowing deep water of a pipeline crossing the flow route in the Arkona and Bornholm Basins. SMHI Report No. 2007-61 (Rev. 3.0), Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

Christensen, L.E.A. 2007. Risk assessment of ship collision with the service platform. Nord Stream AG Report, Ramboll, Zug, Switzerland (November 2007).

Christensen, L.E.A., Møller, S.S., and Lindholdt, A. 2009. Ship collisions during construction phase. Report, Nord Stream AG/Ramboll, Zug, Switzerland (January 2009).

DHI. 2007. MIKE 21 and MIKE 3 Flow Model FM—Particle Tracking Module, scientific documentation. http://www.mikebydhi.com/.

DNV-RP-F107, Risk Assessment of Pipeline Protection. 2010. Høvik, Norway: Det Norske Veritas. http://exchange.dnv.com/publishing/Codes/CurrentPDF.asp?file=rp-f107.pdf.

European Commission (EC). 1979. Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds. Official Journal L 103 (24/04/1979): 0001–0018. EUR-Lex Doc. No. 31979L0409. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31979L0409:EN:HTML.

European Commission (EC). 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal L 206 (22/07/1992): 0007–0050. EUR-Lex Doc. No. 31992L0043. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31992L0043:EN:HTML.

Frid, C., Hammer, C., Law, R. et al. 2003. *Environmental status of the European Seas*. International Council for the Exploration of the Seas (ICES), http://archimer.ifremer.fr/doc/00040/15135/.

HELCOM. 1995. Final Report of the *ad hoc* Working Group on Dumped Chemical Munition (HELCOM CHEMU) to the 16th Meeting of the Helsinki Commission. Final Report, Working Group on Chemical Munition, Helsinki, Finland (March 1995). http://www.helcom.fi/stc/files/Publications/OtherPublications/CHEMUFinalReport1995.pdf.

HELCOM. 2001. Environment of the Baltic Sea area 1994–1998. Baltic Sea Environment Proceedings No. 82A, Helsinki Commission/ Baltic Marine Environmental Protection Commission, Helsinki, Finland (April 2001). http://www.helcom.fi/stc/files/Publications/Proceedings/bsep82a.pdf.

HELCOM. 2007. Climate Change in the Baltic Sea Area: HELCOM Thematic Assessment in 2007. Baltic Sea Environment Proceedings No. 111, Helsinki Commission/ Baltic Marine Environmental Protection Commission, Helsinki, Finland (June 2007). http://www.helcom.fi/stc/files/Publications/Proceedings/bsep111.pdf.

Hjorth, H. 2011. Geophysical and Geochemical Methods Used for Safeguarding HSE When Constructing a Major Pipeline in the Baltic Sea. Paper SPE 140716 presented at the SPE European Health, Safety and Environmental Conference in Oil and Gas Exploration and Production, Vienna, Austria, 22–24 February. http://dx.doi.org/10.2118/140716-MS.

Hyams, M., Gorham, R., Howitt, L., and Dixon, K. 2004. Best Practice Methods for Offshore Pipeline Installation in Sensitive Shallow Water Marine Environments. Paper SPE 86581 presented at the SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Calgary, 29–31 March. http://dx.doi.org/10.2118/86581-MS.

Klingberg, F. 2008. Submarine slides in south-west Baltic Proper. SGU Report 2008:5, Geological Survey of Sweden, Uppsala, Sweden.

Lewis, L.J., Davenport, J., and Kelly, T.C. 2003. A study of the impact of a pipeline construction on estuarine benthic invertebrate communities: Part 2. Recolonization by benthic invertebrates after 1 year and response of estuarine birds. *Estuarine Coastal Shelf Sci.* **57** (1–2): 201–208. http://dx.doi.org/10.1016/S0272-7714(02)00345-1.

Lindblad, C. and Grip, K. 2006. Inventering av marina naturtyper på utsjöbankar (Inventory of marine habitats at offshore banks). Rapport 5576, Naturvårdsverket (Swedish Environmental Protection Agency), Stockholm, Sweden (June 2006), http://www.naturvardsverket.se/Documents/publikationer/620-5576-3.pdf.

Lindblad, C. and Nikolopoulos, A. 2010. Undersökning av utsjöbankar: Inventering, modellering och naturvärdesbedömning (Investigations of offshore banks: Inventory, modelling and environmental assessments). Rapport 6385, Naturvårdsverket (Swedish Environmental Protection Agency), Stockholm, Sweden (December 2010), http://www.naturvardsverket.se/Documents/publikationer/978-91-620-6385-6.pdf.

Linden, O. and Rust, M. 2007. Literature review of the North Sea experiences of the impacts of gas pipelines on the seabed. Report, University of Kalmar, Kalmar, Sweden (1 December 2007).

Lund, J.K., Olsen, J., Bryn, P. et al. 2004. Slide Risk Assessment in the Ormen Lange Field Development Area. Paper SPE 86703 presented at the SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Calgary, 29–31 March. http://dx.doi.org/10.2118/86703-MS.

Lyngby, J.E. and Valeur, J.R. 1999. Environmental Research Prior to Construction. Establishing Base-Line Conditions as Basis for Environmental Impact Assessments and Design of Monitoring Programmes. *Proc.,* Øresund Link Dredging & Reclamation Conference, Copenhagen, Denmark, 325–335.

Matthäus, W. 2006. The history of investigation of salt water inflows into the Baltic Sea - from the early beginning to recent results. Meereswissenschaftliche Berichte (Marine Science Reports) No. 65, Institut für Ostseeforschung, Warnemünde, Germany. http://www.io-warnemuende.de/tl_files/forschung/meereswissenschaftliche-berichte/mebe65_2006.pdf.

Nielsen, H.S. 2010. Long term modelling—Evaluation of potential impacts on Natura 2000 areas. Nord Stream AG Report, Ramboll Group A/S, Copenhagen, Denmark (March 2010).

Nord Stream AG. 2008. Nord Stream Pipelines in the Swedish EEZ. Environmental Study, Doc. No. G-PE-PER-EIA-48000000, Ramboll Group A/S, Copenhagen, Denmark (1 October 2008).

Piechura, J. and Beszczynska-Möller, A. 2003. Inflow waters in the deep regions of the southern Baltic Sea—transport and transformations. *Oceanologia* **45** (4): 593–621.

Sanderson, H., Fauser, P., Thomsen, M. et al. 2010. Environmental Hazards of Sea-Dumped Chemical Weapons - Does the post-WWII burial at sea of chemical weapons still pose a human and environmental risk? *Environ. Sci. Technol.* **44**: 4389–4394.

Stéphanie M. Doorn-Groen. 2007. Environmental monitoring and management of reclamation works close to sensitive habitats. *Terra et Aqua* **108** (September 2007): 3–18. http://www.terra-et-aqua.com/dmdocuments/nr108_1.pdf.

Valeur, J.R., Jensen, A., and Pejrup, M. 1995. Turbidity, Particle Fluxes and Mineralization of Carbon and Nitrogen in a Shallow Coastal Area. *Mar. Freshwater Res.* **46** (1): 409–418.

Valeur, J.R., Larsen, J.B., and Stroebaek, N. 2008. Environmental Study for Two Gas Pipelines Through the Baltic Sea. Paper SPE 117587 presented at the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE, 3–6 November. http://dx.doi.org/10.2118/117587-MS.

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