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Horns Rev Wind Power Plant

Environmental impact assessment of hydrography

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1 INTRODUCTION

1.1 Background

ELSAM is planning an offshore 150 MW wind power plant at Horns Rev, which is to be in operation by the end of 2003. The project is part of the Danish governmental environment and energy objective and is to act as a role model for future power plants at sea. The go-ahead for the project was obtained in the summer of 1999.

This report is written at the request of ELSAMPROJEKT, according to the proposal: 'Tilbud på VVM undersøgelse af hydrografi for havvindmøllepark ved Horns Rev' (Ref./1/) dated 8 April 1999.

Establishing a wind power plant at Horns Rev 15 km offshore Blåvands Huk has a potential impact on local hydrography and thus potentially on local and regional coastal morphology. In order to assess these topics, investigations of the impact of the foundations on currents and waves have been carried out locally in the area where the wind power plant is to be erected area as well as in the nearby region. Furthermore, in connection with establishing the single foundations, sediment spill may influence the water quality in sensitive areas and spill simulations have thus been carried out.

This investigation is to be part of an overall EIA of the setting up of the wind power plant at Horns Rev, describing the consequences of establishing and running the power plant. In order to meet the requirements of the statute concerning impact on the environment, the following aspects will be addressed in this document:

- hydrography
- coastal morphology
- sediment transport

1.2 Method

In the very early project phases, an initial environmental examination is required to establish a list of all potential environmental effects of importance leading to a proper environmental impact assessment. This resulting assessment should include environmental effects identified in the initial examination and the conclusions should be presented in the form of a report. Monitoring and observations from the operation phases may later be verified against the conclusions of the EIA statement and mitigating factors or a change of operations may be introduced if environmental effects are greater than assumed.

The impact assessment is based on a number of investigations carried out prior to this study. The most important are listed below:

- Baseline study of hydrography at Horns Rev: water level, currents, waves and bed morphology (Ref./2/).
- Type of foundations, design criteria, sea bed sediments, bathymetry, geo-technical investigation (Ref./2/, /3/).
- Morphology in the region, littorals transport (Ref./4/).

In this EIA, an overview of the geological conditions in the area at Horns Rev is given in order to emphasise the basis on which the related conclusions are drawn. In the same way the hydrography is described based on the conclusions in Refs./2/ and /3/. Spill simulations with MIKE 21 PA were carried out in order to assess a worst case scenario of spill when using gravity foundations. The local impact on hydrography and sediment transport is also addressed based on the earlier findings. Finally, a list is given addressing the possible impact, the mitigation measures and relevance for the Horns Rev area.

2 RESUMÉ AND CONCLUSION

2.1 In English

An Environmental Impact Assessment (EIA) of hydrography has been carried out concerning the erection of a 150 MW wind power plant at Horns Rev. The EIA has followed the "Guidelines for EIA of offshore power plants" given by the Danish Ministry of Energy and Environment in Ref. /5/. It is concluded that the impact on the hydrography and sediment transport at Horns Rev from erecting the power plant will be negligible.

Horns Rev is situated seaward of the westernmost point of Denmark, Blåvands Huk. Horns Rev is a shallow reef with water depths between 2 and 9 m consisting primarily of pebbles, gravel and sand. Geomorphologically it can be described as a terminal moraine ridge formed of glacio-fluvial material deposited in front of the icecap during a retreating state of the Saale glaciation. The glacier in an advancing state then pushed up the deposited material.

Horns Rev is considered a stable form, which has kept its present position since its formation. The area around Blåvands Huk is constantly adjusting to the changes in the adjacent coastline and to minor changes in hydrography and sea level. The wave climate in the North Sea is rough both during summer and winter. Based on a conservative assumption it is rendered probable that the wave height just leeward of the power plant area will be reduced by less than 3.5 %. The nearshore wave climate will be practically unaffected by the presence of the foundations. The reduction in currents downstream of the power plant area is insignificant and considered without importance for the environment.

It is therefore concluded that the erection of a wind power plant at Horns Rev will cause no measurable influence on the environment with respect to hydrography and sediment transport. The impact of the foundations on the water exchange in the area at Horns Rev is also considered insignificant, because the prevailing turbulent conditions do not favour stratified conditions or oxygen depletion. The sediment on the seabed in the planned power plant area consists of medium sand with a median particle diameter of about 0.3 mm. It is not expected to contain any contaminating substances and may therefore be recycled after dredging. This will call for permission from the authorities.

Simulations have been carried out concerning sediment spill from dredging for gravity foundations using the numerical model MIKE 21 PA. The total demand for dredging is estimated to 80,000 m^3 if gravity foundations are chosen. The simulations were carried out related to a worst case scenario. They document that spill from dredging has only a very small impact in the immediate vicinity of the dredger (up to 1/3 of the total mounting area). The estimated concentrations are well within the same order of magnitude as the normal variation in suspended matter concentrations in the area. It is therefore concluded that spill from dredging will have no effect in the area.

2.2 Resumé og konklusion

Denne VVM redegørelse for hydrografien ved Horns Rev er skrevet på grundlag af planerne om at opføre en 150 MW vindmøllepark med 80 vindmøller og en transformatorstation på denne lokalitet. "Retningslinier for udarbejdelse af VVM redegørelse for vindmølleparker på havet" fra Miljø & Energiministeriet (Ref./5/) er blevet fulgt. Det konkluderes, at hydrografi og sedimenttransport ved Horns Rev kun påvirkes i ubetydelig grad af opførslen af vindmølleparken.

Horns Rev ligger i forlængelse af Danmarks vestligste punkt, Blåvands Huk. Horns Rev består hovedsageligt af ral, grus og sand, vanddybden over revet varierer mellem 2 og 9 m. Geomorfologisk set er Horns Rev en terminalmoræne. Den sandsynlige dannelse af revet er, at glacio-fluvialt sediment aflejret foran isen under Saale glaciationen er blevet skubbet op på et tidspunkt, hvor isen avancerede. Revet består derfor ikke af det typiske blandede sediment fra en moræne (grus, sand, silt og ler), men af relativt velsorterede sedimenter i form af ral, grus og sand. Denne dannelseshypotese underbygges af at man flere steder på det jyske fastland f.eks. ved Kjelst beliggende kun ca. 12 km øst for Blåvands Huk finder mægtige (tykkelse) aflejringer af denne type. Dette vidner om, at området har været beliggende foran en afsmeltende isfront i en længere periode.

Horns Rev anses for en stabil landskabsform, der ikke har ændret placering siden den blev dannet. Blåvands Huk tilpasser sig løbende den overordnede kystudvikling i området samt de naturligt varierende strøm og bølgeforhold på lokaliteten. Bølgeklimaet i Nordsøen er barskt både sommer og vinter. Det vurderes på baggrund af konservative estimater, at bølgehøjden i læ af vindmølleparken vil blive reduceret med mindre end 3,5 %. De kystnære bølger vil derfor praktisk taget være upåvirkede af mølleparken. Reduceringen i strømhastigheden gennem mølleparken er ligeledes ubetydelig.

Det konkluderes derfor, at opførelsen af en vindmøllepark ved Horns Rev ikke vil have nogen målbar indflydelse på hydrografi og sedimenttransport. Der forventes ingen påvirkning på vandudskiftningen ved Horns Rev, da de fremherskende turbulente forhold ikke tillader udvikling af lagdeling af vandmassen og deraf følgende iltsvind. Området ved mølleparken er domineret af sand med en mediankornstørrelse på ca 0.3 mm. Dette sand er uden miljøfremmede stoffer og kan derfor uden problemer klappes eller genbruges efter udgravning. Det skal dog bemærkes, at klapning/genbrug kræver en klappetilladelse.

Simuleringer er blevet udført for at dokumentere effekten af sedimentspild ved udgravning til gravitationsfundamenter ved anvendelse af den numeriske model MIKE 21 PA. Vælges gravitationsfundamenter, skal der i alt afgraves 80,000 m^3. Simuleringerne er baseret på et worst case scenario. De dokumenterer, at spildet vil lokaliseres omkring den enkelte udgravning med en maksimal udbredelse på 1/3 af mølleparkens areal. De estimerede koncentrationer er i samme størrelsesorden som den naturlige variation i den suspenderede sedimentkoncentration i området. Det konkluderes derfor at spild fra gravearbejderne ikke vil have nogen indflydelse på miljøet.

3 INVESTIGATION AREA

3.1 Geographic setting

Blåvands Huk is the westernmost point in Denmark. Geomorphologically, Blåvands Huk is a cuspate foreland stabilised by the shallow reef, Horns Rev, situated to the west of Blåvands Huk and extending more than 40 km to the west into the North Sea (Figure 3.1). The width of the reef varies between 1 and 5 km, and water depths also vary with depths down to less than 5 m. Horns Rev can be characterised as a huge natural groin blocking part of the sand volume transported along the Jutland coast. The transport is mainly directed towards the south and southeast with a yearly magnitude of some 500.000 m^3 (Ref./4/).

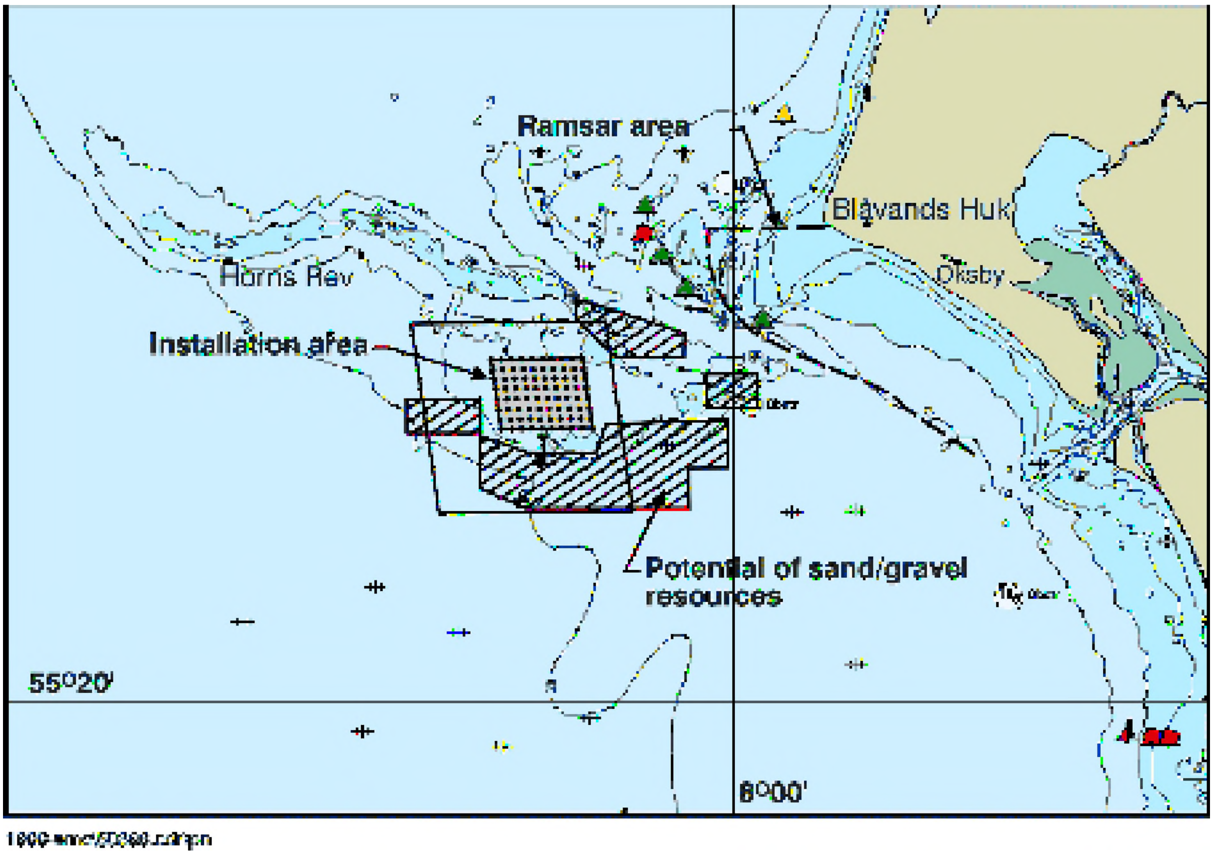

Fig 3.1. Overview of the installation area at Horns Rev (from C-MAP Norway A/S).

Blåvands Huk is also the northernmost point of the European Wadden Sea, which stretches from Den Helder in Holland to Blåvands Huk. The Wadden Sea comprises of a string of barrier islands protecting the lagoons and mainland behind it; starting at the barrier spit Skallingen and proceeding to the barrier islands Fanø, Mandø and Rømø in the Danish area of the sea (Figure 3.2).

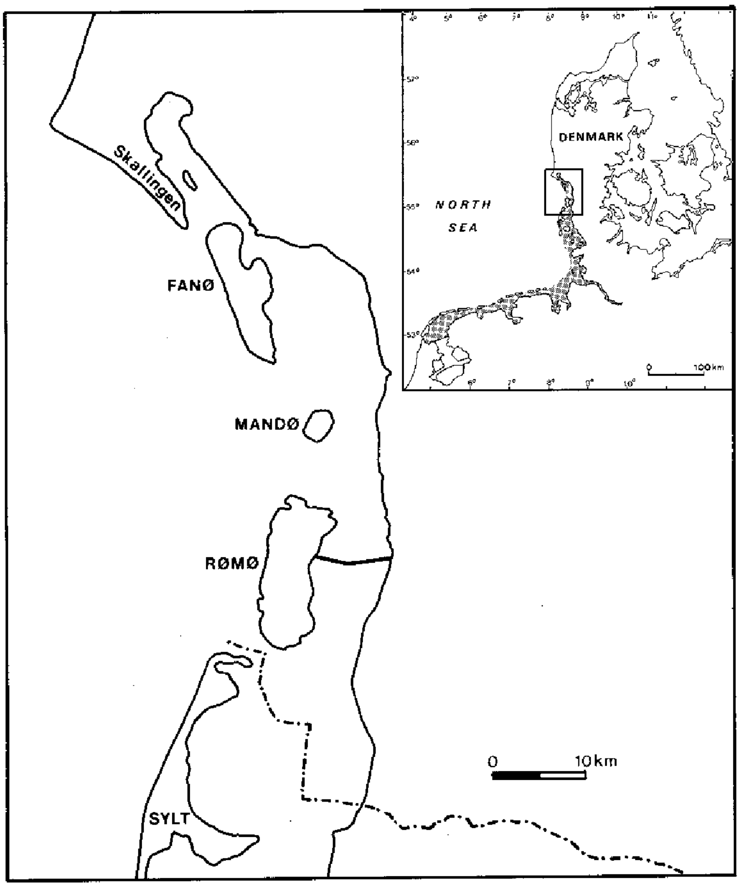

Fig. 3.2 The European Wadden Sea (from Ref./6/).

3.2 Tidal amphidromy

The North Sea is a complex resonant tidal system caused by the rectangular form of the basin. The Atlantic tides send a wave southward into the North Sea, which is reflected and which moves back northwards taking three tidal periods to return to the entrance (Figure 3.3).

Three amphidromic systems are present in the North Sea and the tidal range at the coast is partly due to the distance from the amphidromic centre point (Ref./7/). The tidal range has a great influence on the geomorphology of the coast. The tidal amphidromy along the Danish West Coast is anti-clockwise. The mean tidal range south of Horns Rev is 1.5 m compared to 0.5 m to the north. The hydrographic effect of Horns Rev is thus a dampening of the tidal wave north of the reef.

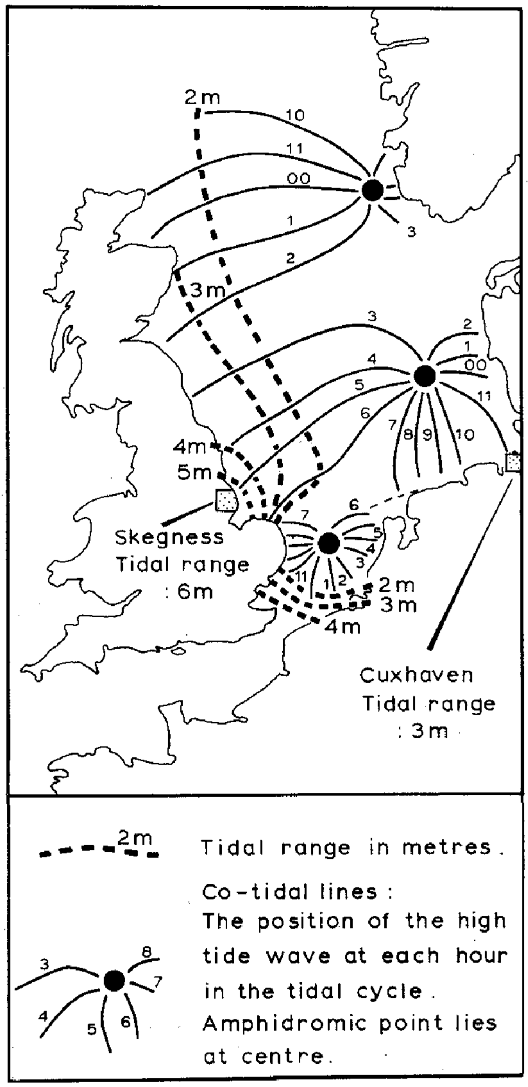

Fig.3.3 The tidal system of the North Sea (from Ref./7/).

3.3 Geomorphology and geology

Investigations have shown that the outcrop of Horns Rev consists of an accumulation of sand, gravel and stones covered by several meters of fine and medium marine sand. At the basis of Horns Rev, moraine is found at the deepest parts < -18 m dating back to the Saale or Elster ice ages (Ref./8/) (Figure 3.4).

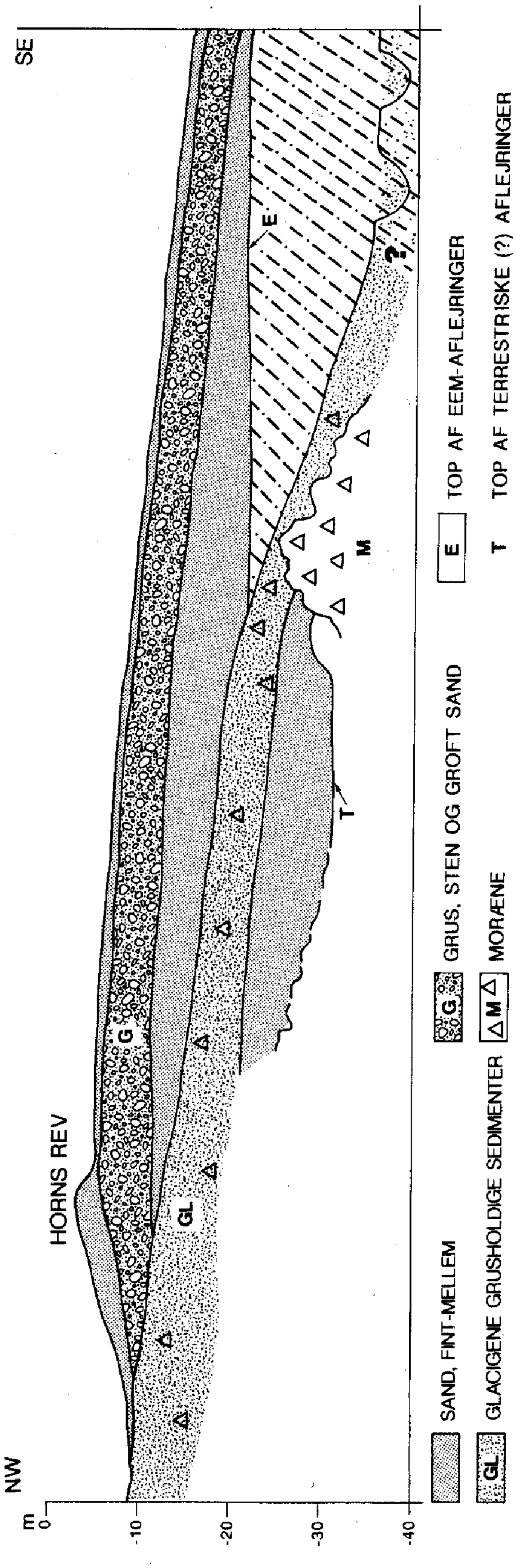

Fig. 3.4 Schematic model showing a cross section of the geological formation of Horns Rev (Ref./8/).

Geomorphologically, the Horns Rev formation can be described as a terminal moraine ridge. It is most likely formed from glacio-fluvial sediments deposited in front of the icecap during the Saale glaciation in a retreating state; the glacier in an advancing state then pushed up the deposited material. This is the explanation as to why Horns Rev does not primarily consist of till (gravel, sand silt and clay), but of relatively well-sorted sediments: mainly gravel and sand. This geomorphologic interpretation is additionally supported by the fact that deposits of this type are seen at several locations on the Jutland peninsula; e.g. at Kjelst, 12 km east of Blåvands Huk, where thick layers are exposed in gravel pits. These findings point to the conclusion that the area was situated in front of a retreating glacier for a longer period (Ref./9/).

The above discussion does not exclude the speculations that Horns Rev during the Eem interglacial period formed an island or peninsula in a transgressing Eem Sea (Ref./10/) as depicted in Figure 3.5.

When the latest glaciation (Weichsel) ended (12,000 BP), the sea level was significantly lower than today, allowing extensive out-wash plains to form in Southwest Jutland. Sand and gravel were transported by the melt-water from the ice-cover in a westward direction out to the sea on a very mild slope (~ 1 ‰) depositing its material at, for example, Horns Rev. During this period (Fastlandstiden), before the onset of the transgression, eolian sand, silt and gytje were deposited in the area south of Horns Rev. These deposits may also be found on the actual reef except for the north-western part, where glacigen deposits are seen on the seabed.

During the Holocene transgression, the formation at Horns Rev was subject to wave erosion forming a wave-cut platform extending to the east and south (Ref./8/). Investigations have pointed to the conclusion that the hydrography in the area changed, when the transgression reached level 11m; from then on the marine accumulations of fine sand began.

Today, Horns Rev appears as a reef with water depths between 2 and 9 m with a large lee-side formation (Tombolo) east of the area (Blåvands Huk). Although Blåvands Huk is constantly subject to changes adjusting to variations in hydrography and sea level changes, it is considered a quasi-stable formation that will continue to adjust to minor changes in the local conditions, including the possible influence from the planned wind power plant. Figure 3.6 shows the shoreline change from north of Blåvands Huk to the south spit of Skallingen, showing the westernmost point to have moved up to 500 m within 200 years. This local change in shoreline location is not considered to have any effect on the installation area.

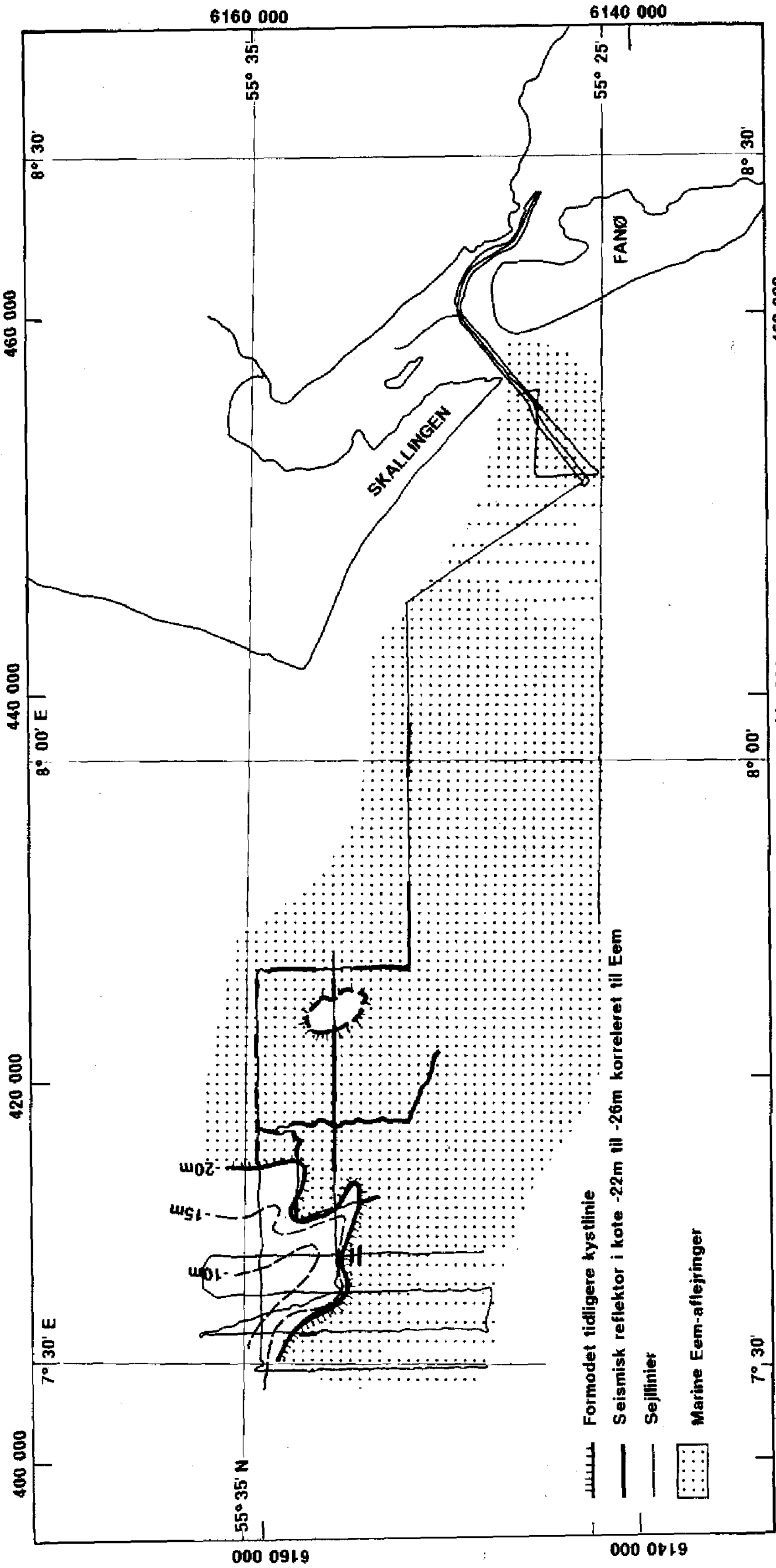

Fig. 3.5 *Conjecture of Horns Rev in Eem at a much lower sea level forming an island or peninsula (from Ref./8/).*

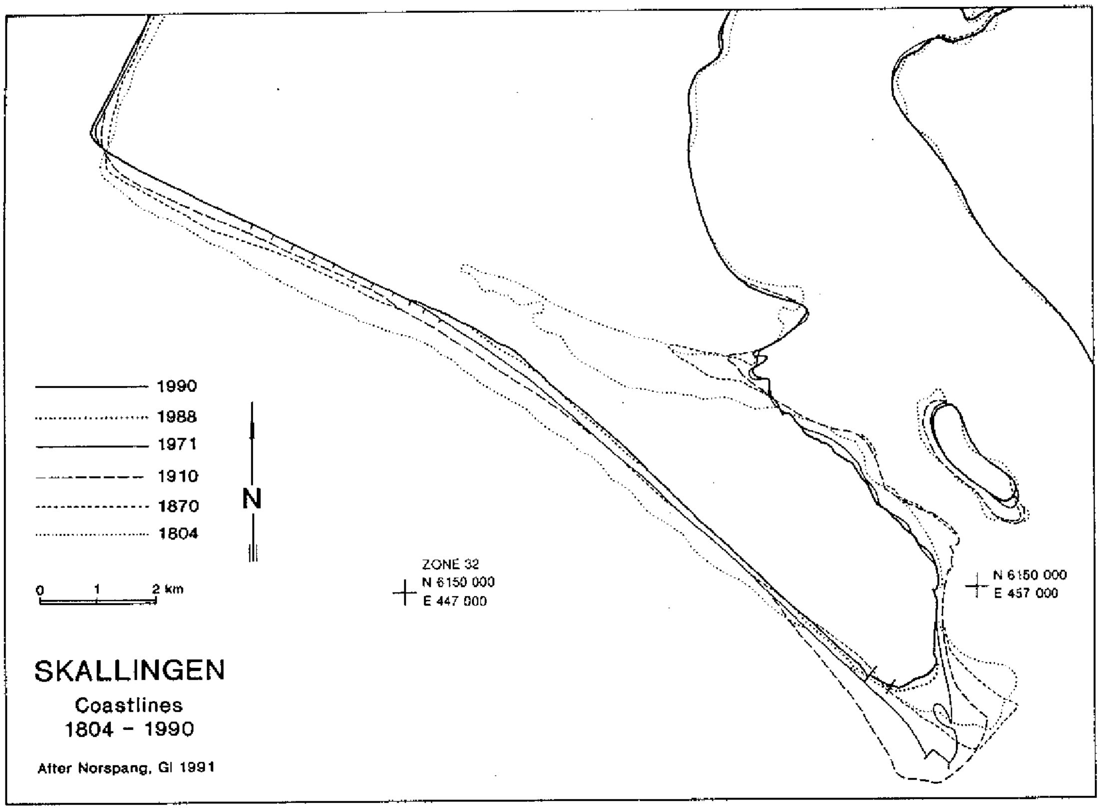

Fig. 3.6 Shoreline changes at Horns Rev and Skallingen 1804-1990 (Ref./4/).

3.4 Sea bed sediments

The seabed sediments at Horns Rev include Holocene beach ridges of coarse sand, gravel and stones from the area east of Vovov to the southeast. Coarse residual glacigene sediments are seen on the northwest and southwest part of Horns Rev, whereas finer material, post-glacial fine and medium sands and clayey and silty sands are seen east of the reef e.g. at Slugen (Ref./8/). Fine and medium sands dominate the rest of the area with magnitudes between a few decimetres up to more than 5 m (Ref./10/). In the erection area, medium to coarse sand is seen down to level –14.5 to 16.8 m. Fine to silty sand is found down to level –21.6 to –23.9 m (Ref./11/).

There are not many bed forms on the seabed, but small sand ribbles are seen all over the area caused by the wave impact on the bed. Waves from the northwest dominate north of Horns Rev; south of Horns Rev waves from south to west dominate.

Dunes and mega-ribbles are seen in the channels Normandsdyb and Slugen. Tidal currents create dunes and ribbles, showing evidence of transport directions both to the north and the south. Asymmetrical sand ridges are seen on the reef between Tuxen and Munk. All structures in the area apart from those in the tidal channels indicate a prevailing transport direction towards the south and southeast (see Figure 3.7).

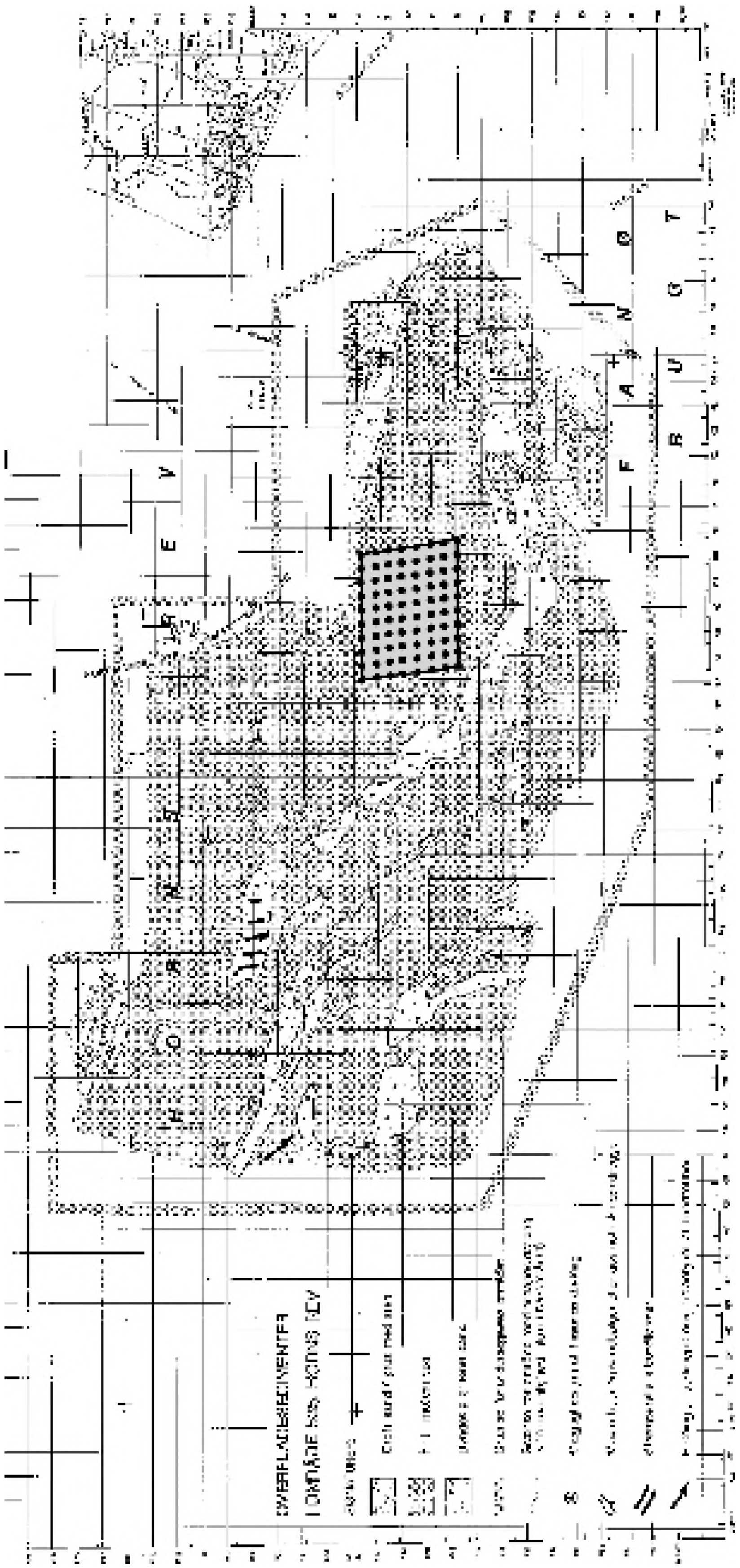

Fig. 3.7 Overview of surface sediments at Horns Rev (Ref./8/).

3.5 Fate of the dredged material

During the detailed planning of the dredging scenarios it is advisable to consider the fate of the dredged material. The dredged material at Horns Rev is expected to consist primarily of sand. This sediment is not expected to contain any contaminating substances or heavy metals, which normally adhere to fine cohesive sediments. Therefore, the dredged material may well be recycled to the seabed or utilised for beach nourishment at nearby works. However, under all circumstances, the deposit of dredged material requires a disposal permission (“klappetilladelse”), which will contain possible requirements for disposal location etc.

4 HYDROGRAPHY AT HORNS REV

4.1 Design of power plant

The wind power plant at Horns Rev will have the form of a parallelogram with 8 sets of 10 windmills erected at intervals of about 550 m. A transformer station is to be erected in the vicinity of the windmills. The present design is a square tower on three legs. Presently, the design of the foundations is a mono-pile with an assumed diameter of 3.5 m and a penetration depth of some 20-22 m. A prototype of this foundation is given in Drawings 1 and 2. The pile is driven about 20 m into the sea bottom. If local scour is likely to occur around the structure, then the pile must either be driven deeper into the seabed or be protected against scour (Ref./2/).

Another possible type of foundation is the gravity foundation, as given in Drawings 3 and 4 for example. This construction consists of a bottom plate made of concrete, on top of which is a steel tower filled with some kind of ballast in order to stabilise it. The wind turbine is then mounted on top of this construction. The mounting of the caisson requires a levelling of the sea floor. It is advisable that the bottom plate be dug into the seabed in order to stabilise it and to minimise the use of scour protection round its perimeter.

4.2 Erosion within the power plant area

Natural variation at the seabed as well as local scour is likely to occur within the power plant area as described in Ref./2/. Scour is deemed solely to have impact on the local area in the immediate vicinity of the foundations within the plant area. It is not likely that any regional scour or erosion will develop due to the placement if the foundations.

4.2.1 Natural changes in bathymetry in the area

The location of the planned wind power plant at Horns Rev is situated in a relatively stable area. The overall level in the area is relatively stable; seabed sediment is mainly sand, easily transported by currents and waves (see chapter 3.4). A comparison between the bathymetry from 1876-77 and present measurements (Ref./2/) shows that only changes within the order of 1.5 m occurred in the bottom level in this period. Changes caused by local dynamics of sand ripples, etc. are in the order of magnitude of 0.5 m (Ref./2/).

Thus, it is recommended that bed level changes up to 2 m be taken into account (Ref./2/) within the next 50-year period. This recommendation is based on the existing conditions at Horns Rev. The area around the planned power plant is subject to some mining of sediment resources. A continuation of the present level of activity is expected to have no measurable effect in the power plant area. A possible intensification of the mining may cause some impact in the erection area and may thus give rise to the need for further investigations.

4.3 Local scour around each foundation

Mono Pile
During a minor storm, local scour may take place within hours after the mounting of a mono pile structure at the erection area at Horns Rev. Calculations have established that the scour hole can be up to 6.7 m deep, equivalent to 1.9 times the foundation diameter of 3.5 m. A local change in the bottom level around a mono pile may be up to 8.7 m including the local changes in bathymetry of ± 2 m. The magnitude of the scour hole will have implications for the stability of the foundation. Therefore, it is recommended that the construction be protected against scour by establishing a protection layer around the foundation consisting of layers of gravel, pebbles and stones (Ref./2/).

Gravity foundation
A fully developed scour hole at an unprotected gravity foundation will also develop rapidly (within the first year after the installation). This may even lead to an undermining of the structure. Therefore, scour has to be prevented by placing a protection layer around the foundation, taking into account the maximum local change in bathymetry of up to 2 m (Ref./2/). The design of such scour protection has to be investigated further with regard to the gravity foundation at Horns Rev.

Sheet scour
The local scour near the individual foundations will not develop into a general scour (sheet scour) in the entire power plant area.

4.4 Waves

4.4.1 Wave climate

The wave climate in the North Sea is rough, especially during the autumn and winter, but relatively high waves do also occur during the rest of the year. The design height of waves for Horns Rev has been analysed (Ref./3/). The results include design wave height depending on the direction based on 15 years of simulation of North Sea waves. Based on this data a maximum height, H_{max}, of the waves is given as 8.1 m in the south-west corner of the mounting area for all wind-directions. The significant design wave height, Hs, is about 5 to 5.4 m.

4.4.2 Interaction between incoming waves and foundations

Making a conservative assumption that all wave energy hitting a foundation is absorbed, it can be shown that the wave height will be reduced by less than 3.5 % immediately leeward of the power plant area. This small reduction in the wave height immediately leeward of the power plant area will be smoothed out before the waves reach the nearshore area. The nearshore wave climate will consequently be practically unaffected by the presence of the foundations. This is concluded based on the complicated bathymetry between the power plant area and the shoreline, as well as the presence of strong currents and the distance of about 15 km to the shoreline.

The flux of energy transported by a progressive linear wave $E_f\left(\frac{J}{sm}\right)$ is proportional to the wave height, H^2, and can be written as (see Ref./12/)

$$E_f \frac{1}{16}\rho g H^2 c\left[1+\frac{\frac{4\pi}{L}k\,depth}{\sinh\left(\frac{4\pi}{L}depth\right)}\right]$$

where L is the wavelength, c is the phase velocity and g is the gravity.

The integrated flux $\left(\frac{J}{s}\right)$ over a distance $dy = 550m$ hereby becomes

$$E_f\,dy = \frac{1}{16}\rho g H^2 c\left(1+\frac{\frac{4\pi}{L}k\,depth}{\sinh\left(\frac{4\pi}{L}depth\right)}\right)dy$$

If one assumes that all wave energy (conservative assumption) hitting the foundation with diameter D is reflected, the integrated reflected flux becomes

$$E^{ref}\left(\frac{J}{S}\right) = \frac{1}{16}\rho g H^2 c\left(1+\frac{\frac{4\pi}{L}k\,depth}{\sinh\left(\frac{4\pi}{L}depth\right)}\right)D$$

The ratio between the incoming wave height and the wave height after one windmill has been passed hereby becomes

$$\frac{E^{pass}D}{E_f D} = \frac{E_f D - E^{ref}}{E_f D} = \left(\frac{dy-D}{dy}\right)\left(\frac{H^{pass}}{H}\right)^2$$

Inserting D=4 m one finds a conservative estimate of the wave height reduction equal to 0.36%. With nine foundations (9 rows) after each other a conservative estimate of the wave height reduction is **3.3%.**

4.5 Water exchange in the power plant area

4.5.1 Local impact around foundation

Making a simple analogy with the channel flow it can be shown that there will be very little reduction in current speed around the foundations. This is based on the assumption that the flow in a stationary situation is a balance between the driving forces: the pressure gradient, and the restricting forces: the bed friction and the drag forces on the windmills (Ref./13/).

The drag on one windmill foundation can be written as

$$F_{drag} = \frac{1}{2}\rho D\,Depth\,C_D V|V|$$

where D is the diameter (taken to be D=4m), Cd is a drag coefficient typical equal one, and V is the depth-averaged velocity, ρ is the water density.

The bed friction in an area Dx time Dy is found from

$$F_{fric} = \rho Dx\,Dy\,U_f|U_f|$$

where the friction velocity Uf can be estimated from a

$$U_f = \frac{0.4V}{\ln\left(\frac{11 Depth}{k}\right)}$$

k is the bed roughness, for a plane bed taken to be 2.5 times the grain diameter. $k = 2.5 * d_{50}$. Inserting typical values in the windmill park area d_{50} = 0.3 mm and Depth=8m one finds:

$$U_f = 0.04 * V$$

Looking at a situation where the flow is stationary and driven by a constant pressure difference ∇P (water level difference), the flow in an area corresponding to one windmill Dx=500m and Dy=500m can found:

Situation without a windmill

$$Dx\,Dy 0.0016 V^{before}\left|V^{before}\right| = Dx * Depth\nabla P$$

Situation with a windmill

$$\frac{1}{2}\rho D\,Depth\,C_D V^{after}\left|V^{after}\right| + \rho Dx\,Dy 0.0016 V^{after}\left|V^{after}\right| = Dx * Depth\nabla P$$

Comparison

The velocity with a windmill compared with the situation without:

$$\frac{V^{after}}{V^{before}} = \sqrt{\frac{Dx\,Dy 0.0016}{Dx\,Dy 0.0016 + \frac{1}{2} D\,Depth\,C_D}}$$

Inserting the above numbers one find

$$V^{after} = 0.98 V^{before}$$

The above calculations show that the current velocity in the power plant area is reduced with 2% at a maximum. For non-stationary flow situations this reduction will be even smaller. This small and very local reduction in current velocities will have no influence on the current velocities and sediment transport outside of the erection area. It is in no way causing any blocking of the water transport along the Jutland coast and is therefore deemed insignificant with respect to the environment.

4.5.2 Regional impact at Horns Rev

Stratified flows do not develop along the North Sea coast. This is because the changing tidal currents and the rough wave environment favours homogeneous conditions along the shallow coastline. A strong thermocline is present in the centre of the North Sea. Horns Rev is situated in the transitional zone between the stratified zone and the well-mixed zone. However, this does not influence the area at Horns Rev, as stratified conditions will not develop at water depths <30 m (Ref./14/) The mixing of the water in the coastal zone by the turbulent dynamics also means that oxygen depletion is not likely to occur at Horns Rev.

It is considered that there will be no significant influence on the water exchange at Horns Rev after the erection of the power plant. This is based on the prevailing turbulent dynamic conditions at Horns Rev and the small impact of the foundations on currents and waves.

4.6 Impact on local and regional seabed morphology

On the basis of the calculated impact of the foundations on waves and currents it is evaluated that there will be only insignificant impact on the seabed morphology within the area of the power plant. This is apart from local scour around each individual foundation, which will be prevented by scour protection. Furthermore, there will be no impact outside the power plant area at the coast of Blåvands Huk or along the coastline of Skallingen.

4.7 Water levels

The water level fluctuations at Horns Rev are relatively small. The North Sea is a large basin with an area of some 900,000 km^2. The erection of 80 foundations at Horns Rev will have no impact on the water levels locally or regionally.

5 MIKE 21 SIMULATION OF SEDIMENT SPILL

5.1 Background and Objectives

The dispersion and sedimentation of spill from dredging activities in connection with the construction of the Horns Rev power plant has been modelled in order to evaluate the impact on the environment during the construction phase.

The type of foundation planned at Horns Rev at the present time is a mono-pile with a diameter of 3.5 m, which is driven into the sea bottom. This type of foundation will cause very little or no spill. The simulations presented in the following chapter are based on worst case scenario covering the possible impact on the environment from spill using gravity foundations. Thus the impact presented is the absolute maximum impact to be expected from spill under the known conditions.

5.2 MIKE 21 HD module

5.2.1 Procedure

At the moment no measurements of the current conditions at the area near Horns Rev are available. Due to this lack of measurements the current conditions in the erection area are evaluated using a numerical current model, DHI's MIKE 21 HD. Two wind periods have been modelled. The results of these simulations are the depth-integrated currents at the grid points. The Particle Model, MIKE 21 PA, models the subsequent spreading of spilled material.

5.2.2 Numerical modelling

The current conditions at the power plant area at Horns Rev are evaluated using DHI's hydrodynamic model, MIKE 21 HD. (See Appendix A for a short description). Figure 5.1 shows the complete model area.

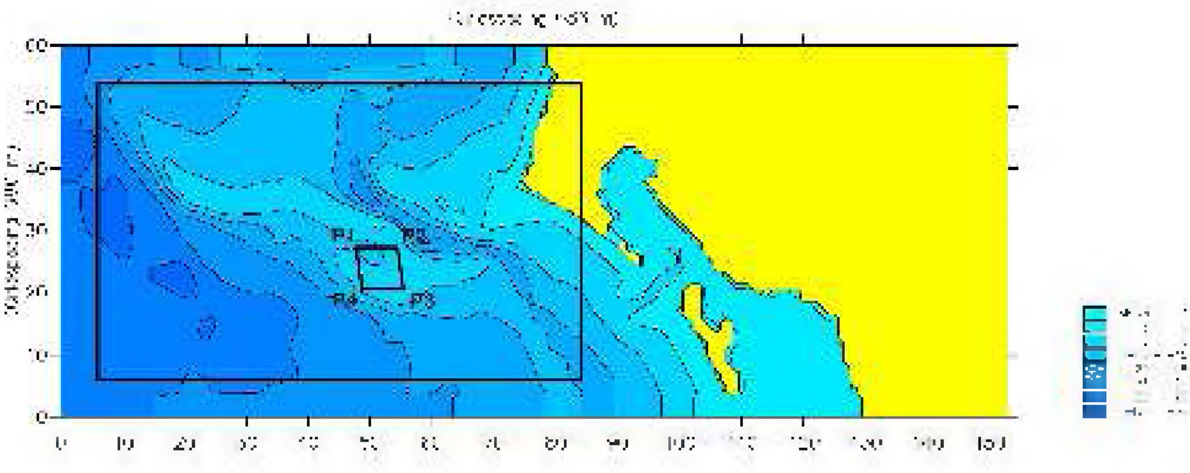

Fig. 5.1 Complete model area including location of power plant.

The calculation of the depth-integrated current is carried out in the grid points. For the present project we have been working with four different grid sizes. The three coarsest grids (grid spacing of 6173 m, 2058 m, and 686 m) constitute the nested model setup used in Ref./3/, where more detailed information about the model is given. The sediment spill simulations are based on hydrodynamic modelling in an even finer model with a grid spacing of 229 m (details given in Table 5.1).

Table 5.1 Definition of the fine grid

Grid spacing (m)	229
Time step (minutes)	30
Extension of grid (J, K)	(0…234, 0…144)
Latitude (°N)	$Lat = 55.37 + K / 486$
Longitude (°E)	$Long = 6 + \frac{(J + 369) / 486}{\cos(Lat)}$

The two periods chosen for the modelling of sediment spill are dominated by winds coming from a northwesterly and a southwesterly direction, respectively. The latter is the prevailing wind direction in the area of interest. The periods represent periods of mild wind with a duration of 14 days each chosen to represent periods when dredging is possible (wind must not exceed 10 m/s). The periods chosen are given below (see also Figure 5.2 and 5.3):

- 1998/09/08 00:00:00 – 1998/09/22 00:00:00
- 1999/03/17 00:00:00 – 1999/03/31 00:00:00

5.3 MIKE 21 PA for Sediment Spill Simulations

The MIKE 21 PA module describes the sediment transport by a Lagrangian model, where the particles are transported with the two-dimensional flow field calculated by the HD set up (advection). In addition to the advection, the particles are dispersed as a result of random processes in two dimensions allowing settling and resuspension of particles as well as random horizontal dispersion. After release from the dredging source, the dredged material is represented by single particles (See Appendix B for a short description).

The data used as parameters for the model are based on empirical relations describing settling velocities, deposition and erosion (see chapter 5.4.2).

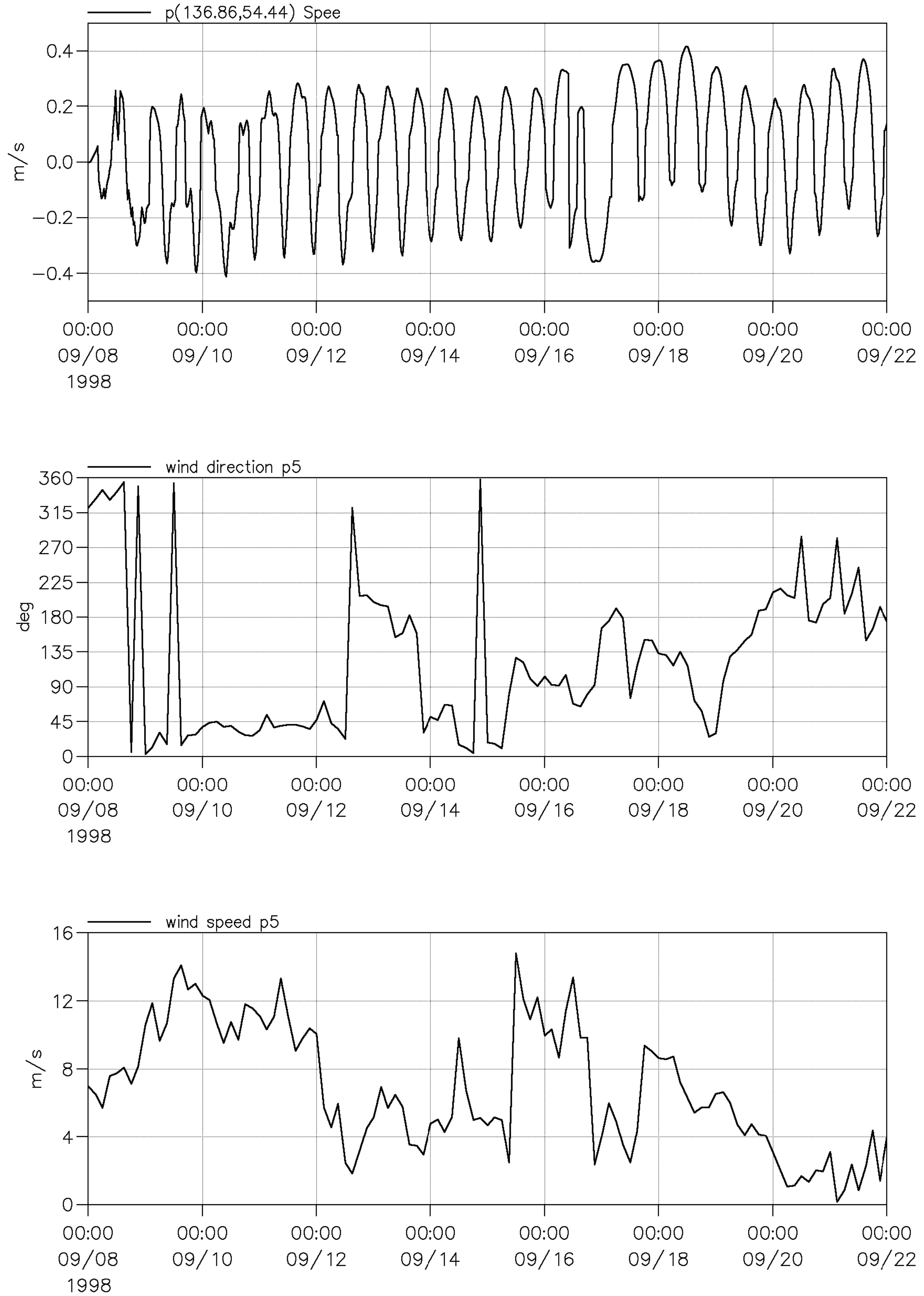

Fig. 5.2 Tidal currents, wind speed and direction from 14-days period September 1998.

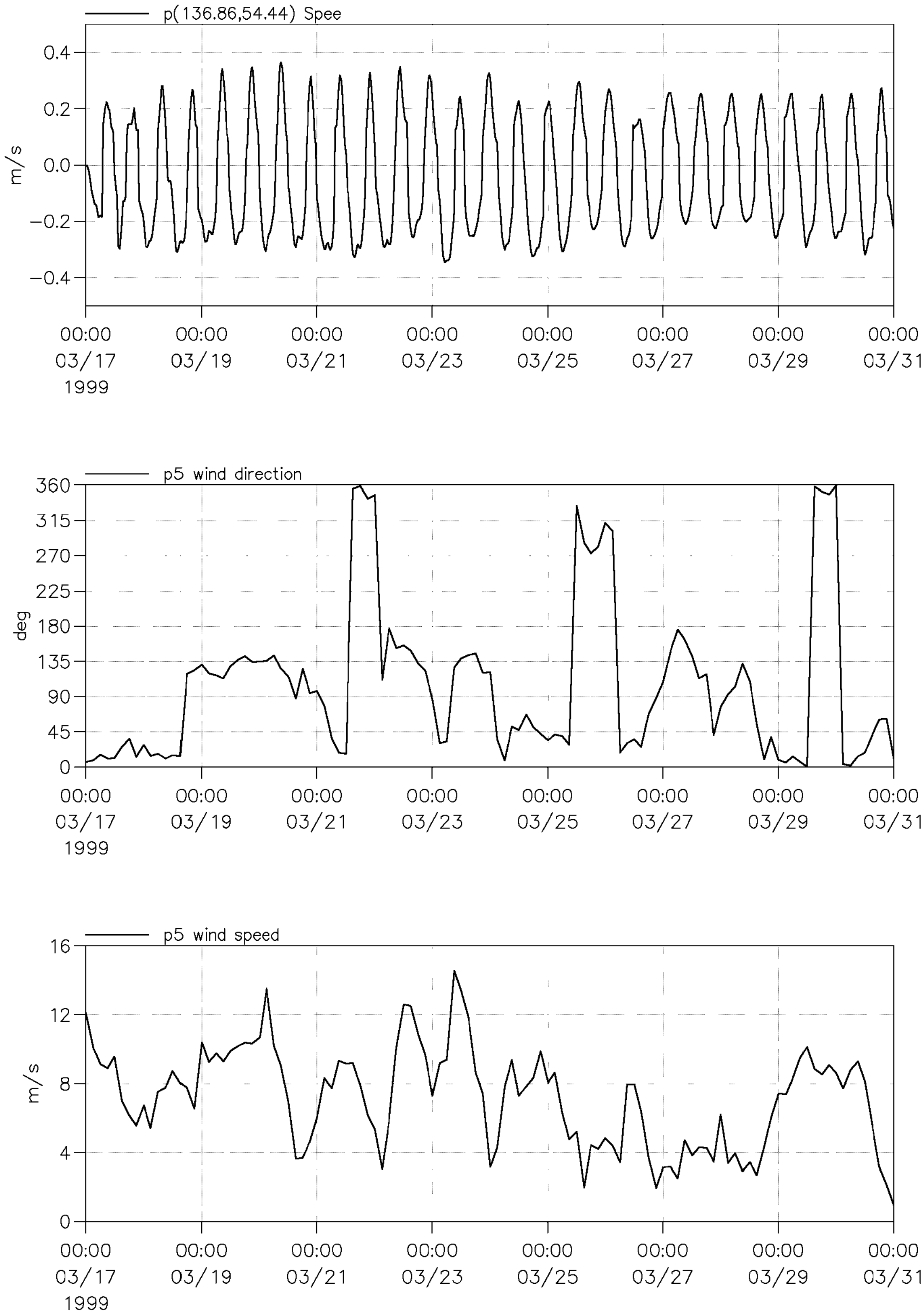

Fig. 5.3 Tidal currents, wind speed and direction from 14-days period March 1999.

5.4 Model set up

5.4.1 Design of dredging scenario

The dredging scenario planned for the windmill park area at Horns Rev is based on the following assumptions for a worst case scenario:

- that 80 foundations are to be placed in the dedicated area SW of Blåvands Huk
- that the type of foundation is the gravity type with a diameter of 12.5 m of each bottom plate
- that 1000 m^3 material has to be dredged at each foundation
- that the total minimum dredging volume is 80,000 m^3

The capacity of the dredger is set at 2600 m^3 per day, corresponding to a medium sized dredger. With the grain size spectra in the area SW of Blåvands Huk, a dredger of this type can fill up to maximum capacity in approximately one hour (Ref./15/).

For practical reasons, the spill source is placed centrally in the mounting area. This has no impact on the spill scenarios, where spill will not reach the Jutland coast no matter where dredging is carried out within the mounting area. The two 14-day dredging periods are taken as examples of periods with wind direction from the two dominating directions, which are expected to have a possible impact on the coastal areas. This is because these wind directions will lead to a possible transport of material from the dredging area to the coast. The periods are only to be considered as realistic scenarios of 14-day periods when dredging is possible. The limit for dredging activity in the area is set at wind speed of < 10 m/s. During periods of higher wind speeds the dredger as well as the working vessels will have problems operating due to waves.

5.4.2 Sediment parameters

The material at the mounting locations is mainly sand with a size 0.2 - 0.5mm. The amount of cohesive material is below 3% according to the results presented in Ref./16/. Based on this information, the median sediment grain size of the spilled material, which is mostly the finest part of the sediment, is estimated to be close to 0.1mm.

Two dredging scenarios are defined, to assess the impact of daily mean dredging activities and a maximum dredging rate respectively. The median sediment grain size is however 0.06 mm in the two simulations. This is because the model only includes one grain size and not a grain size distribution. A median grain size of 0.06mm is used to assess the area under impact of spill. This leads, however, to an overestimation of the amount of fine material whereby the time the sediment is in suspension is increased, leading to an overestimation of the sediment concentration and impact area. This is considered to be acceptable in the simulations presented as an overestimation favours the worst case scenario.

The general background concentration of suspended matter in the investigation area is some 2-10 mg/l (g/m^3) (Ref./17/), changing rapidly to much higher concentrations depending on tidal current velocities and wind. This is important to remember in relation to the given spill percentages and exceeding rates of suspended matter.

5.5 Scenario 1 (average dredging scenario)

In spill scenario 1 the estimated dredging per day is set at 2600 m^3, equivalent to 2.6 windmill foundations of the gravity type requiring 1000 m^3 dredging each. This dredging rate results in a total dredging period of a minimum of 32 days. A reference period of 14 days is used. The spill percentage is estimated to 3 %, equivalent to 180 tons per day. This is a qualified estimate based, for example, on the work in Øresund carried out by FBC (Ref./18/, /19/). Spill comes predominantly from the finest fraction of the dredged material; there is very little fine material < 0.006 mm in the mounting area. See table 5.1 for an overview of scenario data.

Table 5.1 Data concerning the dredging scenarios

	Scenario 1 average dredging activity	Scenario 2 maximum dredging activity
Loadings per day	1	4
Loading capacity (m^3)	2600	2600
Total amount dredged material per day (m^3)	2600	10400
Sediment density (kg/m^3)	2300	2300
Sediment mass dredged per day (tons)	5,980	23,920
Spill percentage	3%	5%
Dredging spill (tons)	180	1,196

Figure 5.4 shows the suspended matter concentrations exceeding 2 g/m^3 as percentages of the 14-day dredging period. 2 g/m^3 is the lowest visible concentration. Figure 5.5 shows the suspended matter concentrations exceeding 10 g/m^3 as a percentage of the dredging period. A concentration of 10 g/m^3 is the limit for fish migration (Ref./18). In the area that is influenced by a change in suspended sediment concentrations due to dredging, the sediment concentration will not exceed 2 g/m^3 in 90 % of the dredging period. Sediment concentrations exceeding 10 g/m^3 will only be located in the vicinity of the dredging area, where the concentration will be exceeded for less than 10% of the reference period.

5.5.1 March – northwesterly winds

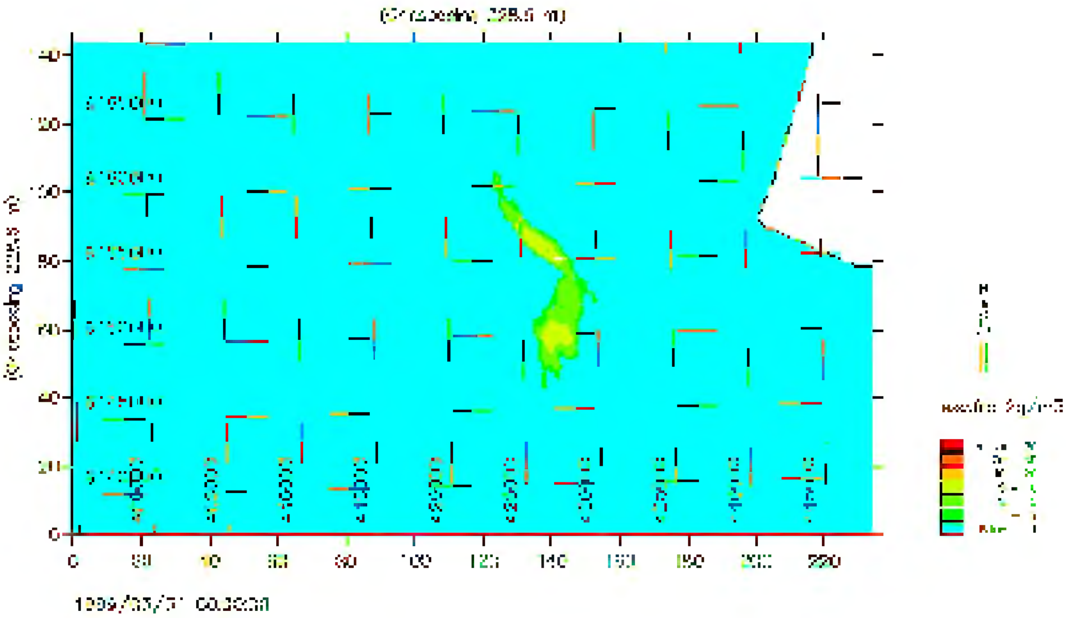

Fig. 5.4 Modelled distribution of exceedence frequency of 2 g/m^3 from March 17 to 31 as a result of average dredging activities.

The figures are based on depth-integrated values and the spill source is placed at the water surface so concentrations may be higher at the surface.

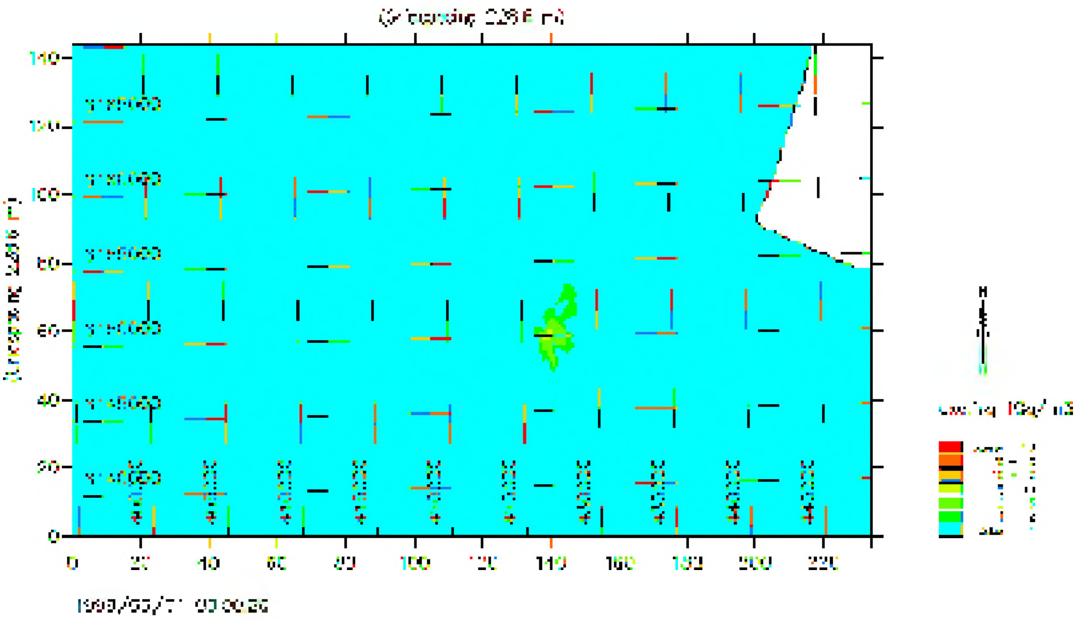

Fig.5.5 Modelled distribution of exceedence frequency of 10g/m^3 from March 17 to 31 as a result of average dredging activities.

Figure 5.6 gives the net accumulation of sediment in kg/m^2 after the 14-day simulation period with daily dredging of 2600 m^3, giving a total of 36,400 m^3. The spilled sediment accumulates in an area north of the dredging area during this period; the net accumulation does not exceed 2 kg/m^2 (under 1 mm of accumulation) anywhere in the area.

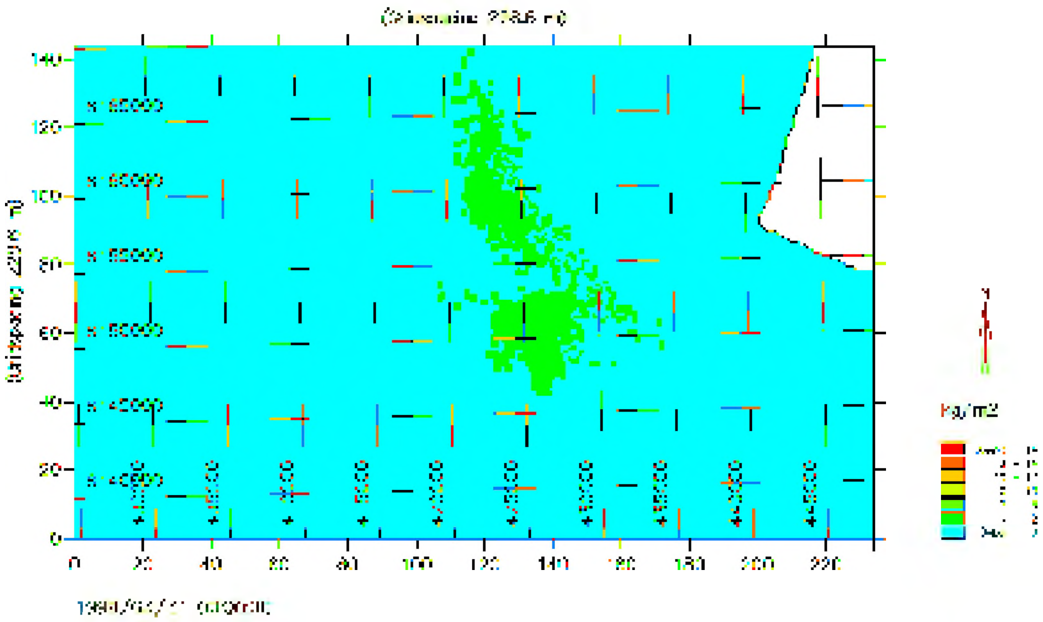

Fig. 5.6 Modelled distribution of accumulated net sedimentation from March 17 to 31 as a result of average dredging activities.

5.5.2 September – southwesterly winds

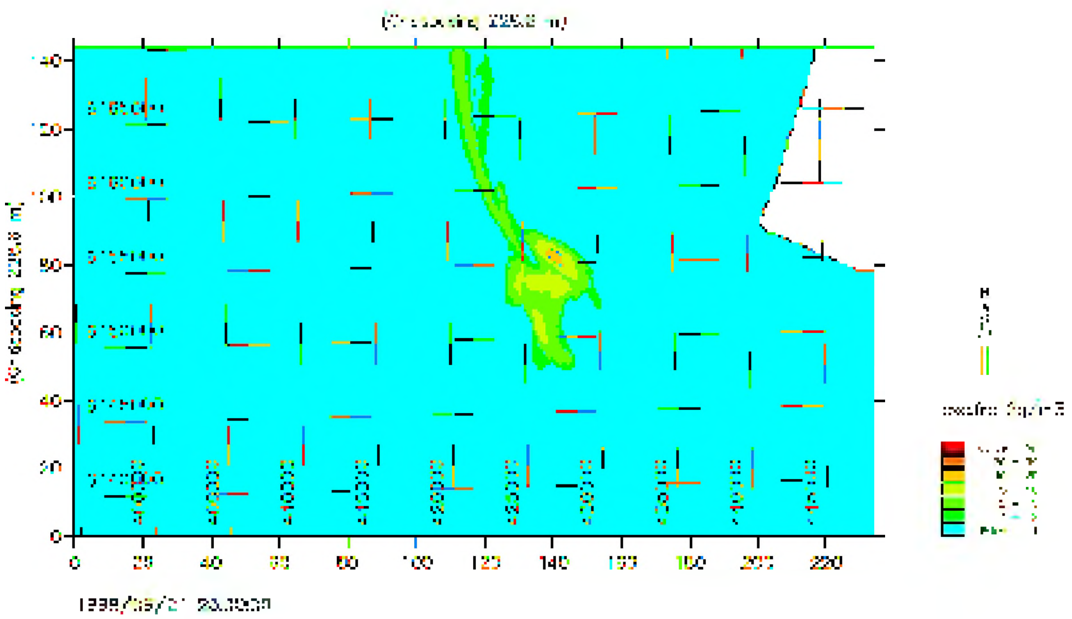

Fig. 5.7 Modelled distribution of exceedence frequency of 2g/m^3 from September 8 to 21 as a result of average dredging activities.

Figures 5.7 and 5.8 show the exceedence percentage of the suspended matter concentrations exceeding 2 g/m^3 and 10 g/m^3 respectively as percentages of the reference-dredging period in a period with southwesterly winds.

The results are very similar to those achieved for scenario 1 in March, with the exception that the spill spreads in a plume north of the spill site. The sediment concentration does not exceed a concentration of 2 g/m^3 more than 10 percent of the time, except for a very limited area north-east of the dredging site.

As in March, there is only a very limited area, where concentrations exceed 10 g/m^3 , and this only happens up to 5% of the time.

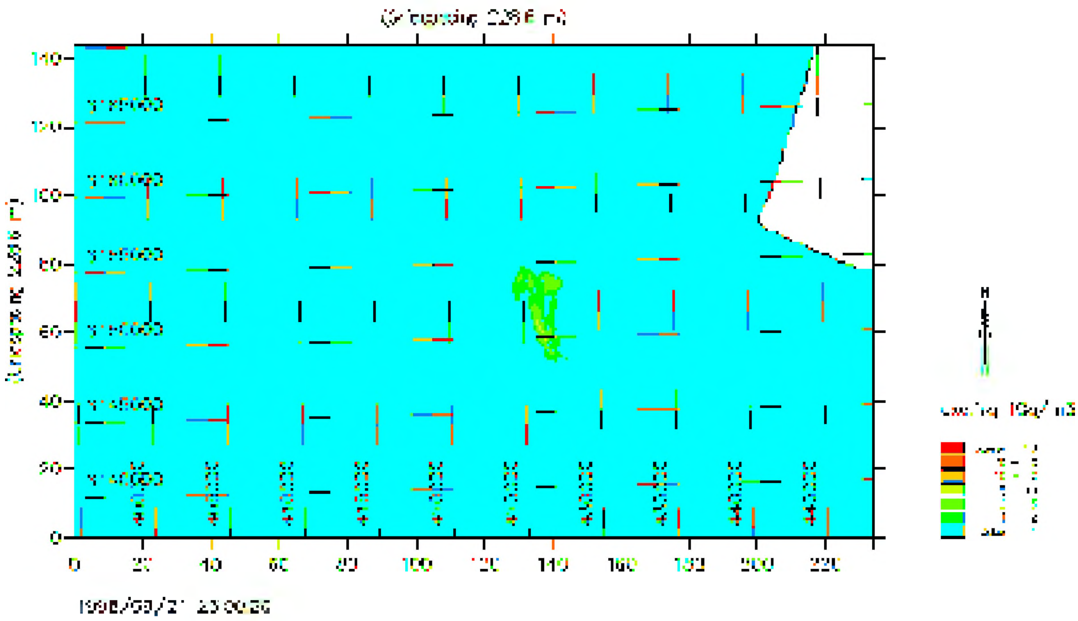

Fig. 5.8 Modelled distribution of exceedence frequency of 10 g/m^3 from September 8 to 21 as a result of average dredging activities.

The pattern of accumulated net sedimentation (Figure 5.9) is also similar to the simulation in March.

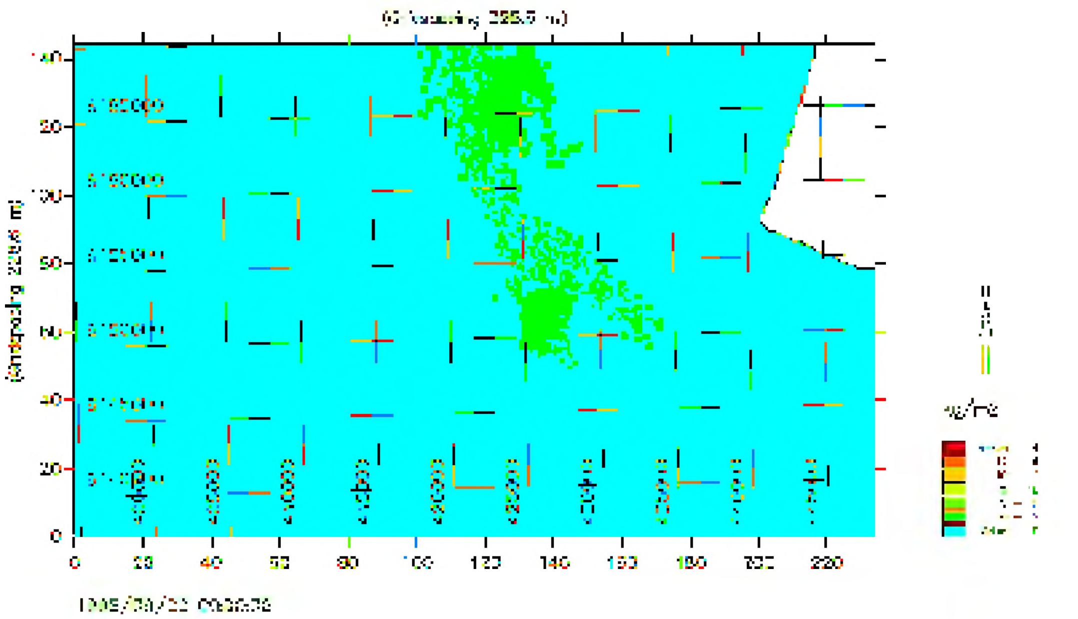

Fig. 5.9 Modelled distribution of accumulated net sedimentation from September 8 to 21 as a result of average dredging activities.

5.6 Scenario 2 (maximum dredging scenario)

In spill scenario 2 the maximum dredging activity level with a maximum spill is simulated. The dredging period is set at 6 hours, which includes dredging, unloading, transportation and standby periods allowing for changes of barges, minor corrections on the dredger, etc. Under these circumstances dredging of 10,400 m^3 material per day is possible, which corresponds to 10 foundations per day and a total dredging period of 8 days. The spill percentage is estimated at 5 %, equivalent to 1,196 tons per day. This is a very conservative assumption for Horns Rev, because median grain sizes are 0.3 mm and the background concentrations here vary from 2-10 mg/l up to several hundred mg/l (see also chapter 5.4.2). The spill percentage estimated is based on increased overflow from the dredger (Ref./18/).

5.6.1 March – northwesterly winds

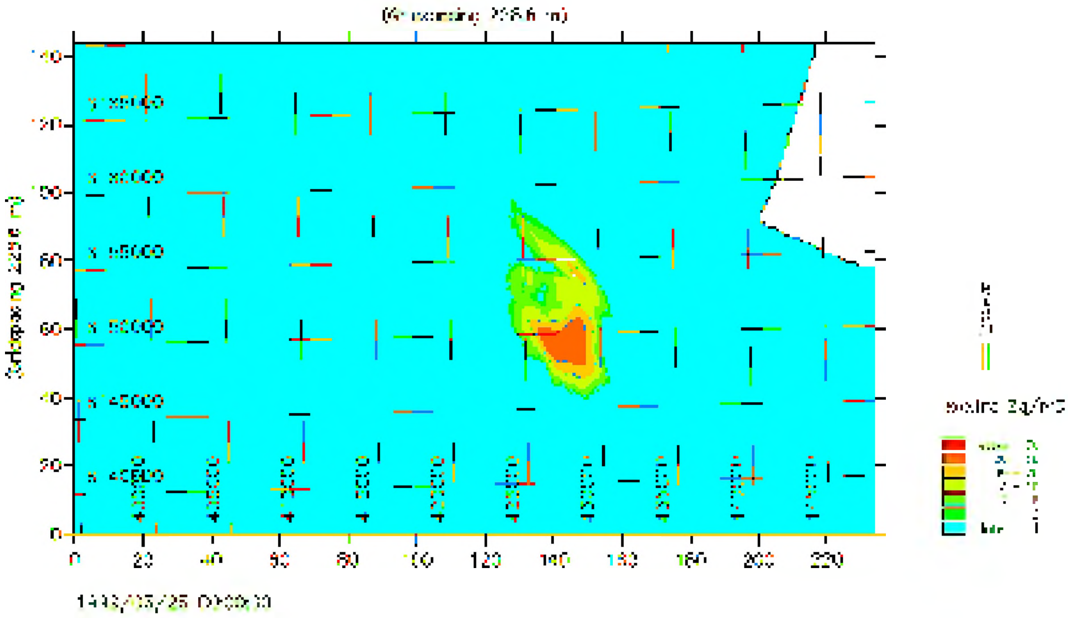

Fig. 5.10 Modelled distribution of exceedence frequency of 2g/m^3 from March 17 to 25 as a result of maximum dredging activities.

Figure 5.10 shows the exceedence percentage of suspended matter concentrations exceeding 2 g/m^3 as a percentage of the dredging period. Concentrations will be above 2 g/m^3, up to 50 % of the time, in an area of approximately 7 km^2 near the dredging area. This is about 1/3 of the total power plant area of some 20 km^2. Figure 5.11 shows the exceedence frequency of suspended matter concentrations exceeding 10 g/m^3 as a percentage of the dredging period. In the vicinity of the dredging area concentrations will exceed 10 g/m^3 up to 50 % of the time during the dredging period.

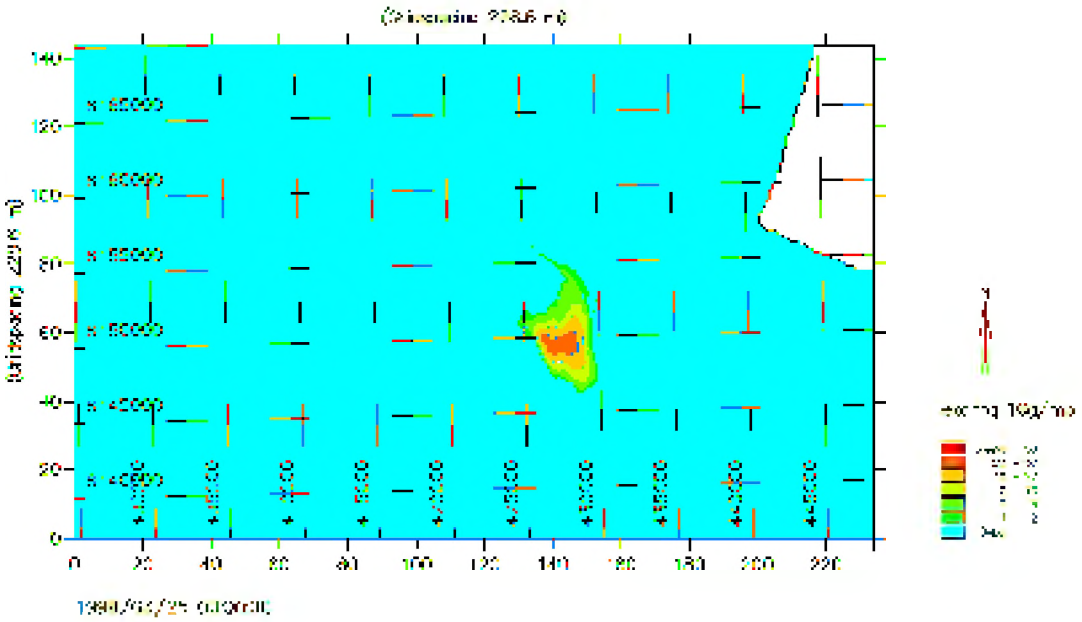

Fig. 5.11 *Modelled distribution of exceedence frequency of 10g/m^3 from March 17 to 25 as a result of maximum dredging activities.*

Figure 5.12 gives the net accumulation of sediment in kg/m^2 after the dredging period with daily dredging of 10,400 m^3. The net sediment accumulation does not exceed 2 kg/m^2 and the area of distribution is limited.

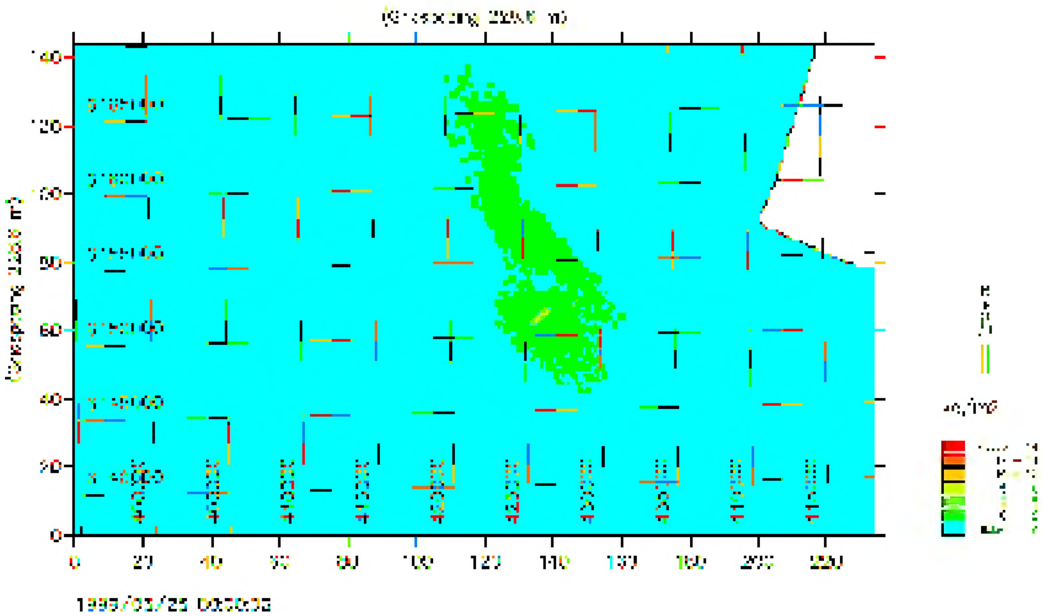

Fig. 5.12 Modelled distribution of accumulated net sedimentation from March 17 to 25 as a result of maximum dredging activities.

5.6.2 September – southwesterly winds

Figures 5.13 and 5.14 show the suspended matter concentrations exceeding 2 g/m^3 and 10 g/m^3 respectively as a percentage of the 8-day dredging period in a period with southwesterly winds.

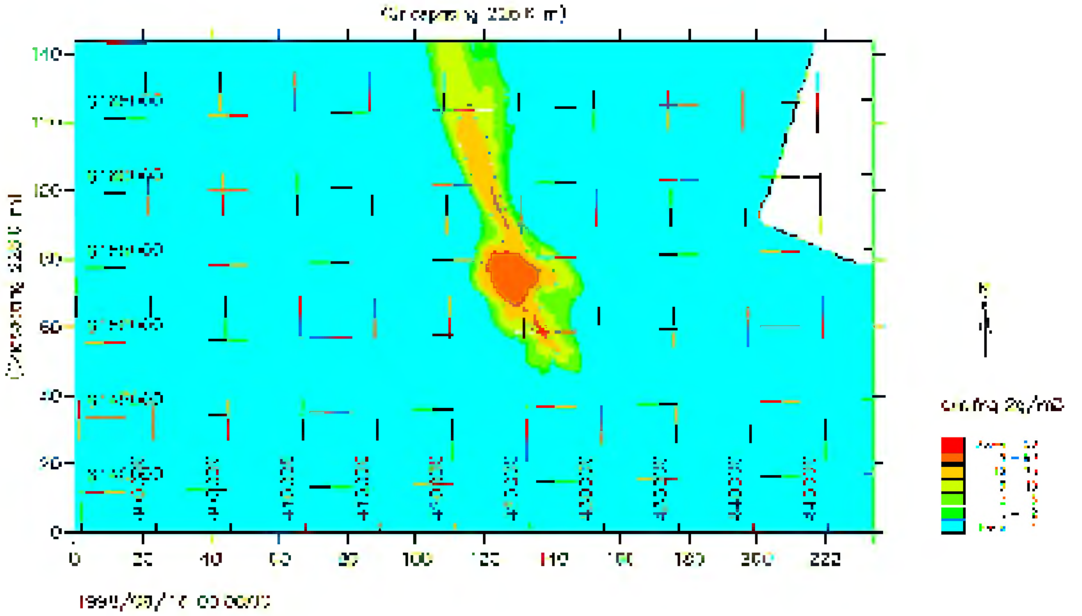

Fig. 5.13 Modelled distribution of exceedence frequency of 2g/m^3 from September 8 to 16 as a result of maximum dredging activities.

As in the situation with northwesterly winds, an area of approximately 7 km^2 near the dredging area (1/3 of the mounting area) experiences concentrations exceeding 2g/m^3 up to 50% of the dredging period. In the area north of the park area concentrations exceed 2g/m^3 up to 20% of the time.

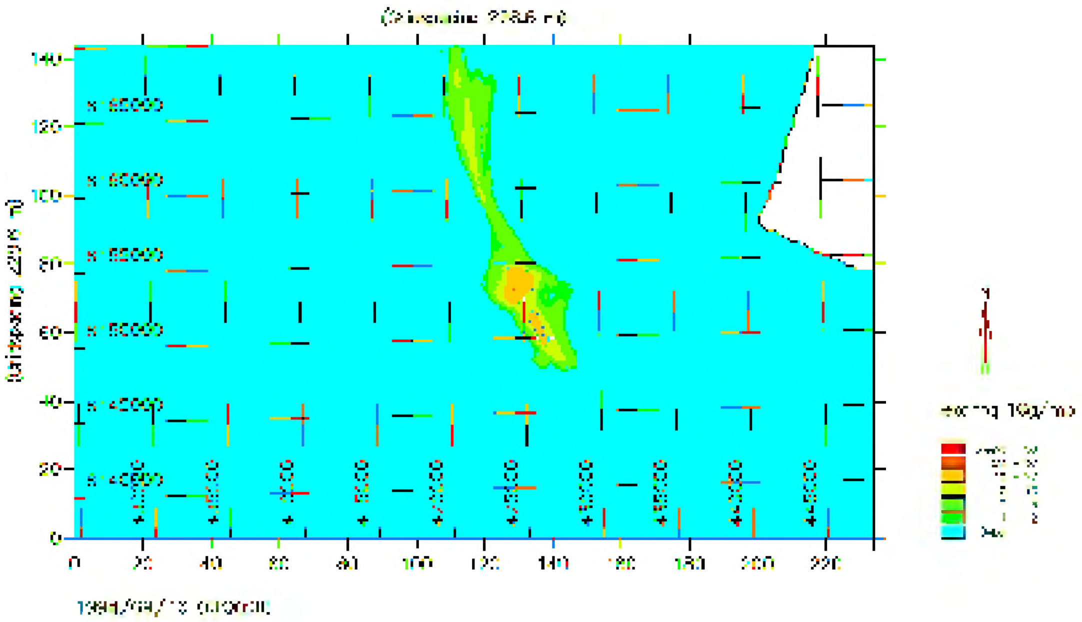

Fig. 5.14 Modelled distribution of exceedence frequency of 10g/m^3 from September 8 to 16 as a result of maximum dredging activities.

In a very limited area near the dredging site, concentrations exceed 10g/m^3 up to 20 % of the dredging period. This means that the impact of the estimated spill is well within the natural variation of suspended matter concentrations in the area; thus it is not likely to cause any environmental problems.

The pattern of accumulated net sedimentation is similar to the simulation carried out in March (Figure 5.15).

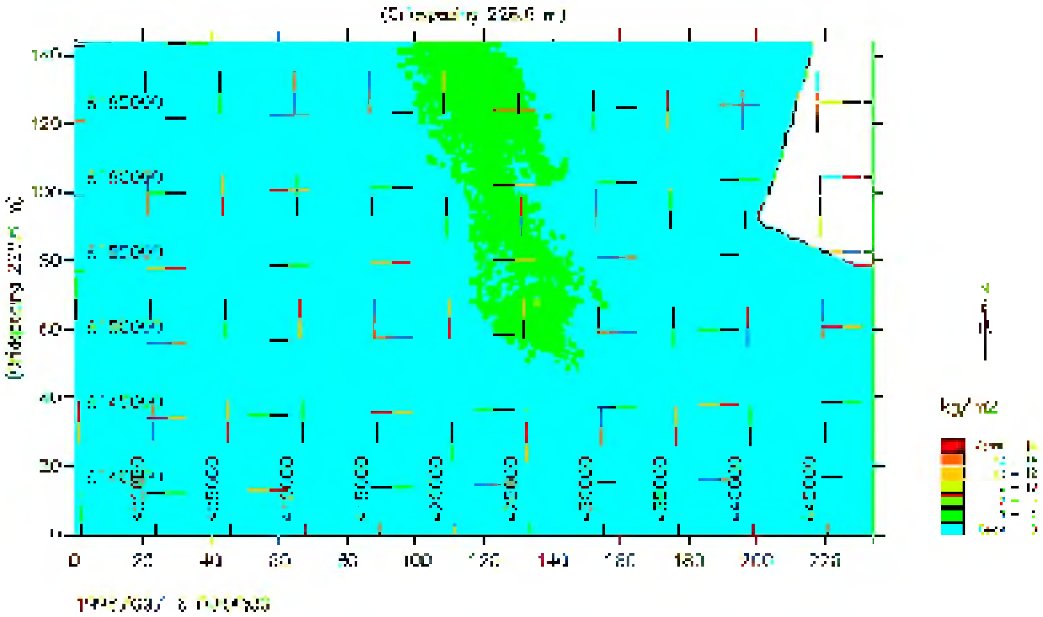

Fig. 5.15 Modelled distribution of accumulated net sedimentation from September 8 to 16 as a result of maximum dredging activities.

6 LOCAL IMPACT ON HYDROGRAPHY AND SEDIMENT TRANSPORT

In the previous chapters, the geographic setting, geology and sediments are described. An overall revue of the main hydrographic parameters is carried out as are simulations referring to a worst case scenario concerning sediment spill during dredging for gravity foundations. In the following, overviews of the local impact in the power plant area as well as the regional area of Blåvands Huk and Skallingen are given.

6.1 Overview of environmental impact

It is anticipated that the most likely questions to be raised concerning a possible environmental impact on hydrography due to the construction and the operation phase of a wind power plant at Horns Rev are listed in Table 6.1.

Table 6.1 Possible hydrographic environmental impact, mitigation and relevance for construction of wind power plant at Horns Rev.

Potential Negative Impact	Mitigating Measure	Relevance at Horns Rev
Sediment dispersion	Minimise dredging	No relevance
Water exchange	Compensation dredging	No relevance
Waves and currents	Optimise construction form	No relevance
Resuspension of toxic sediments	Change location. Change construction method	No relevance
Degradation of coastal morphology	Optimise construction method. Make careful restoration	No relevance

6.2 Construction phase

During the construction phase, the erection of 80 foundations and one transformer station is likely to have an influence on the local sediments transport in the area at the power station. The impact is expected to be intermittent and primarily related to the dredging for the gravity foundations.

Dredging
In the worst case scenario described in chapter 5, local concentrations of suspended matter may exceed 10 g/m^3 (mg/l) 20 % of the time in the immediate vicinity of the area in which the power plant is to be erected. In a 7 km^2 area near the dredging lo-

cation (equivalent to 1/3 of the total mounting area), concentrations may exceed 2 g/m^3 (mg/l) for up to 50 % of the dredging period.

The model simulations of spill show that the distance from the Jutland coast means that no sediment is transported from the dredging site to the coast. This means that there is no influence along the coastline near Blåvands Huk or Skallingen during the construction phase. The influence is solely in the immediate vicinity or the power plant area. The dredged sediment consists of sand with a median grain size of about 0.3 mm. The sediment is not contaminated; thus it may easily be recycled.

Furthermore, the results of the spill simulations can be compared with the natural background concentration of suspended matter in the area which is 2-10 mg/l during calm weather situations (Ref./17/). This concentration may rise to several hundreds mg/l during storm events. Thus, the influence on the environment from spill during dredging is negligible and no environmental criteria are deemed necessary.

6.3 Operation phase

During the operation phase, no further influence on sediment transport is to be expected. There may be a minor influence on current and waves in the immediate vicinity of the foundations as described in chapter 4.

Currents
The influence of the foundations on the current in the power plant area is deemed insignificant based on simple calculations of the blocking effect of the individual foundations. The reduction in the current downstream of the foundation is only a local phenomenon, which has no impact whatsoever on regional currents or sediment transport along the Jutland coast at Blåvands Huk and Skallingen.

Waves
In a similar way, the influence of the foundations of the waves is restricted to the power plant area in the vicinity of the foundations. It is anticipated that a reduction of about 3 % in wave height is likely to occur downstream of the foundations. No influence is expected to occur on the Jutland coast.

Seabed and coastal morphology
In the local area around each foundation, sediment transported by currents and waves may be slightly influenced by the reductions in current velocities and wave height locally. However, the impact is deemed so small that it is negligible and of no importance to the regional sediment transport along the Jutland coast.

7 SUGGESTIONS FOR MONITORING THE ENVIRONMENT

In the Guidelines for the environmental impact assessment of an offshore power plant (Ref./5/) it is required that a measuring and surveillance programme be suggested to monitor the possible impact on the environment (Ref/5/).

7.1 Hydrography

In relation to the suggested power plant at Horns Rev, there is only a very small impact on the hydrography in the immediate vicinity of the foundations; there is no regional impact whatsoever. It is therefore not deemed necessary to design a measuring programme with respect to monitoring changes in currents, waves and water levels.

7.2 Sediment spill

During the construction phase of the wind power plant at Horns Rev, spill will occur if gravity foundations are chosen. However, it has been evaluated that this spill will have no effect on the environment. A monitoring programme is therefore not recommended in connection with the dredging activities. However, if required by the authorities, a monitoring programme may be established in order to demonstrate that there will be no impact on the environment. A strategy for environmental monitoring during the construction of the power plant at Horns Rev is given below. The programme is only relevant if gravity foundations are chosen and should only be initiated if required by the authorities.

7.3 Suggestions for monitoring programme

It is concluded that no measurable influence from spill will occur outside the mounting area. The suggested monitoring programme is therefore only designed to demonstrate that this conclusion is correct. The suggested programme is ONLY relevant in connection with gravity foundations.

Experience from earlier studies of sediment spill from constructions in the marine environments suggests that a combination of model simulations of sediment spill and field surveys of actual spill ensure an optimal monitoring of the environment. This is done with only a small time delay. Model simulations have generally been documented to comply with actual spill quantities and spatial distribution.

Monitoring programme

A monitoring programme is to include the following activities:

1. The model used for spill simulations in the present EIA report can be used for spill monitoring during the construction phase
2. A field survey is carried out to document magnitude and spreading of spill during dredging
3. A spill scenario is carried out based on 1+2
4. Evaluation of the spill scenario is carried out

Time schedule
It is estimated that the total time for dredging 80,000 m^3 equivalent to 184,000 tons of material is about two months with a dredging efficiency of 2,600 ton/day. However, as weather conditions at Horns Rev are rough, it is likely that dredging will take several months more including times when dredging cannot be performed due to weather down time and time adjustment caused by the installation schedule. It should be noted that dredging for the individual foundations should preferably be performed immediately prior to the installation, otherwise the dredged area will be exposed to back filling before the installation is implemented.

The field survey should coincide with the maximum dredging activity. After the simulations have been carried out, there will be an evaluation. This means that, on the basis of present knowledge, it is estimated that a Monitoring Programme for the Horns Rev power plant will be active only for a short period.

8 CABLE ALIGNMENT CONSIDERATIONS FOR THE LANDFALL

8.1 Introduction and requirements of EIA

The EIA of an offshore wind power plant shall, according to the Guidelines in Ref. /5/ also include the cable connection to land. However, as this is not included in the present contract between ELSAMPROJEKT and DHI, the subject will only be summarised briefly in this report. Environmental Impact Assessment (EIA) is, as mentioned above, a mandatory requirement in relation to the cable connection for an offshore wind power plant. The descriptions and the methodology in this chapter have been adopted from Ref. /20/.

Projects in relation to cable landfalls are only associated with potentially mild adverse environmental effects. Despite the fact that only mild adverse impacts are expected they should be taken into consideration in the planning, design, construction, operation and monitoring of the project. The cable route selection is one important element influencing the environmental impact. The initial environmental examination is thus an important instrument in the first screening of possible pipeline routes.

8.2 Discussion of cable alignments at Horns Rev

ELSAMPROJEKT is operating with several alternative alignments. However, the preferred alignment has yet not been selected. In a letter sent to DHI dated 12 July 1999, ELSAMPROJEKT mentioned two alternative alignments as follows:

1. Oksby on the SW coast of Skallingen approximately 5 km SE of Blåvands Huk
2. Blåvands Huk, immediately north of the headland

However, other alternatives are being considered, among these are the following:

1. Near Kærgård, approximately 15 km north of Blåvands Huk immediately south of the already existing dual oil and gas pipeline landings
2. Between Blåvands Huk and Kærgård immediately north of the military shooting range, approximately 8.5 km north of Blåvands Huk
3. On the west coast of Fanø

One very important aspect of the cable landing is the stability of the coastline at the landing site. According to historical information, as shown in Figure 3.6, the coastline north of Blåvands Huk is stable or advancing, whereas the Skallingen coastline south-east of Blåvands Huk is under recession. From this it follows that the area around Blåvands Huk is a fairly complicated area with respect to stability, as the headland is the connection point between a receding and an advancing coastline. As a consequence of this (from a coastal morphological point of view) the coastline from 1 – 2 km north of Blåvands Huk and further northward is by far better for the cable landing than the Skallingen coastline. This is not to say that it is impossible to make the landing at the Skallingen coastline, but it just requires additional burial depth.

The West Coast of Fanø is also stable or advancing, for which reason this coast could also be considered. The suitability of this coastline for cable landing is demonstrated by the fact that several cables are already installed across this coast, which can be seen at the Sea Chart No. DK 94. The morphological conditions are, of course, only one of several issues, which are to be included in the evaluation of the alternative cable landing sites.

8.3 Landfall concepts

The possible landfall concepts, construction methods and equipment have not yet been described. The final selection of the landfall solution and the construction method depends on a large number of parameters, which are site specific but also dependent on the availability of equipment. However, normally two basic concepts of landfalls are used today:

1. Installation in pre dredged trench: The cable is placed in a trench crossing the beach and nearshore zone. The placing of the cable is done by bottom pull either pulling it ashore from a cable barge or the opposite, pulling it offshore. Details of the two methods may vary a great deal depending on the specific equipment available at the moment of construction and the hydrographic and geotechnical conditions at the landfall location.

2. Installation on the seabed followed by trenching: This method is normally used on sections of the seabed off the very movable nearshore zone, whereas the required trenching depth on an exposed sandy and possibly unstable coastline is sometimes higher than what can be produced by traditional trenching.

   In case excavation in the fragile dune area is not allowed:

3. The cable can be placed in a tunnel crossing the nearshore zone, the beach and /or the dunes. The tunnel may be drilled using horizontal directional drilling or excavated using traditional tunnelling techniques dependent on length, soil conditions, costs and other considerations

8.4 EIA considerations

The more detailed EIA performed during the feasibility studies often reveals that more than one solution may have an acceptable environmental impact. Therefore, the final solution for the landfall concept is often decided as part of the bidding process when the feasibility and cost of various solutions will be known. This is beyond the scope of this summary.

The cable landfall consists of a marine section and a land section. The construction does not distinguish between the marine section and the land section of the landfall. However, when it comes to EIA it is often practical to include the marine part of the landfall in the EIA for the overall marine cable and similarly for the land part of the landfall.

9 REFERENCES

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D R A W I N G S

D R A W I N G S

1 & 2 Prototype of mono pile foundation

D R A W I N G S

3 & 4 Prototype of gravity foundation

A P P E N D I C E S

A P P E N D I X A

A MIKE 21 HD – A Short Description

A P P E N D I X B

B MIKE 21 PA – A Short Description