UPTEC W08 034

Examensarbete 30 hp
April 2009

Possible impact on hydrography and sediment transport by wave power park – numerical modelling

Strömnings- och sedimentationsförändringar av vågkraftspark – numerisk modellering

---

Olof Persson

Abstract

Possible impact on hydrography and sediment transport by wave power park – numerical modelling

Olof Persson

Anthropogenic climate change is upon us and renewable energy sources are needed as one part of the solution. Humanity needs to take responsibility for its actions, to be able to hand on a sustainable society for future generations to come.

Wave power is one renewable energy source that today is unexploited, but is thought to possess global potential in same extent as hydro power. Several concepts of electric conversion from wave power are being developed, few are thought to reach commercial potential. One of the most promising techniques at the time were by point absorbers consisting of a linear generator, attached to a buoy at the surface with a rope, developed at Uppsala University. The technique of linear generators is being tested at the Swedish west coast. The test site is situated at the Bohuslän coastal area where marine geological surveys have been done for suitable locations for a possible future full scale commercial wave power park.

Possible impact on hydrography and sediment transport by linear generators standing on the bottom is investigated in this master thesis. Current and sediment changes can have effects on ecosystems, for example by sediment trapping and accumulation of pollutants attached that bind to the sediment. Simulations with the marine modelling package, MIKE 21 by Danish Hydraulic Institute (DHI), have been conducted. Modelling at a possible future location in the Bohuslän coastal area has been done. As no full scale park exists, a cluster of 60 generators have been modeled, which is the number of generators in a cluster sharing a low voltage substation. The results showed on low impact of local scale in current speed and sediment movement. Previous investigations of such impact by wave power devices are few and the main comparisons have been done to off shore wind power parks in Denmark and Sweden.

Key words: Hydrography, sediment transport, environmental impact, wave power, MIKE 21, numerical modelling

Department of Engineering Sciences, Electricity. Ångströmlaboratoriet,Uppsala University, Lägerhyddsvägen 1, SE-751 21 Uppsala.

ISSN 1401-5765

Referat

Strömnings- och sedimentationsförändringar av vågkraftspark – numerisk modellering

Olof Persson

Klimatförändring till följd av mänsklig aktivitet blir allt starkare och förnybara energislag behövs som en del av lösningen till problemet. Mänskligheten behöver ta ansvar för sin påverkan för att kunna lämna ett hållbart samhälle till framtida generationer.

Vågkraft är idag ett outnyttjat förnybart energislag som globalt har potential i samma storleksordning som vattenkraft. Flertalet tekniker för elektricitetsomvandling ur vågkraft är under utveckling men endast ett fåtal förväntas nå kommersiell nivå. En av de mest lovande teknikerna är linjärgeneratorer drivna av bojar på ytan, vilken utvecklas vid Uppsala universitet. Tekniken med linjära generatorer testas på den svenska västkusten. Testparken ligger i Bohusläns skärgård där också maringeologiska undersökningar av Sveriges Geologiska Undersökning (SGU) har utförts på lämpliga platser för vågkraft i uppdrag av Seabased; vilket är företaget som försöker kommersialisera tekniken.

I detta examensarbete undersöks linjärgeneratorers påverkan av vattenrörelser och sedimenttransport. Förändringar i havsströmmar och sediment kan påverka ekosystemen där förändringarna sker, exempelvis vid upplagring av sediment och medföljande föroreningar. Det världsledande modellpaketet för marin modellering MIKE 21 från DHI har använts. Simulering har gjorts för generatorer på en lämplig plats för framtida vågkraftspark utanför Kungshamn. Eftersom ingen fullskalig park finns idag har ett kluster om 60 generatorer modellerats, vilket är kapaciteten för det ställverk som är planerat att användas. Tidigare undersökningar av vågkraftsutvinnings påverkan av strömmar och sediment är få. Därför har jämförelser gjorts med havsbaserad vindkraft i Sverige och Danmark.

Nyckelord: Oceanografi, sedimenttransport, miljöpåverkan, vågkraft, MIKE 21, numerisk modellering

Institutionen för teknikvetenskaper, Elektricitetslära. Ångströmlaboratoriet, Uppsala universitet, Lägerhyddsvägen 1, SE-751 21 Uppsala.
ISSN 1401-5765

Preface

This master thesis, of 30 ECTS credits, has been done at the Swedish Centre of Renewable Electric Conversion at the Ångstrom laboratory in Uppsala. With this thesis I finished my M. Sc. Education in Aquatic and Environmental Engineering. The need for the investigation of a wave power parks impact on hydrography and sediment was brought to me by my supervisor Jan Sundberg at the Department of Engineering Sciences, Electricity at Uppsala University. My assisting supervisor has been Jens Engström at the same department. Thank you both for working with me, for help and support.

I wish to thank Stefan Ahlman at DHI for helping me find the model used and get the student license to the same. Without the license this master thesis would never have been done, the added level of environmentally friendliness of the linear wave power system would still have been kept in the dark. The founder of the wave power system and also subject reviewer of this work is Mats Leijon who I wish to thank for giving me the opportunity to work in such a dynamic and friendly place as this department.

I have a lot of people to thank for valuable help with e. g. data collecting: Anna-Lena Lind (SGU), Else-Marie Wingqvist (SMHI), Maria Aneljung (DHI), Maja Hemph (Seabased), Ole Petersen (DHI) and Philip Axe (SMHI).

I also want to thank all the people that have been working in room 5240, for giving me a smile in the everyday work in the "ex-jobbsrum" and truly nice coffee brakes.

Uppsala February 2009

Olof Persson

UPTEC W 08 034, ISSN 1401-5765
Printed at the Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala, 2009.

Populärvetenskaplig sammanfattning

Strömnings- och sedimentationsförändringar av vågkraftspark – numerisk modellering

Olof Persson

Med ökad kunskap och insikt av det moderna samhälles påverkan av klimatet blir behovet av förnybar energi allt tydligare för varje dag som går. Vågkraft kan ha potentialen att bli ett kostnadseffektivt och miljömässigt alternativen till fossila resurser. Vågkraft har många goda egenskaper som hög energitäthet, global potential, liten visuell störning och förväntad låg miljöpåverkan. Utredningar och preliminära resultat om miljökonsekvenserna antyder en låg påverkan jämfört med konventionella och andra förnybara källor. Flertalet tekniker för elektricitetsgenerering från vågkraft är under utveckling men endast ett fåtal förväntas nå kommersiell nivå. En av de mest lovande teknikerna är linjärgeneratorer som med linor sitter fast i bojar på ytan. Tekniken är framtagen och utvecklas av Uppsala universitet och avknoppningsföretaget Seabased i Uppsala försöker kommersialisera tekniken. En enhet består av en generator fäst till en boj (Figure 2), en framtida park kan komma att bestå utav tusentals enheter. Tekniken med linjära generatorer har testats på den svenska västkusten sedan 2006. Testanläggningen ligger i Bohusläns skärgård där det i närheten även finns lämpliga platser för en fullskalig vågkraftspark. Marin geologiska undersökningar av bottenförutsättningarna har utförts inom ramen av andra studier.

I detta examensarbete undersöks om vattenrörelser och sedimenttransport kan påverkas av att det står nio meter höga linjärgeneratorer på bottnen. Förändringar i vattenrörelser och sediment kan få platsspecifika följder, om sedimentupplagring sker kan övergödning eller halter av föroreningar öka då de kan vara bundna till det ackumulerade sedimentet. Undersökningen är gjord genom att simulera vattenflöden och sedimenttransport i en tvådimensionell oceanografisk modell. Ett världsledande modellpaketet för marin modellering, MIKE 21 från Danskt Hydrologiskt Institut (DHI) har använts. Modellering har gjorts för 60 generatorer på en plats lämplig för en framtida park utanför Kungshamn för teoretiska platser med helt platta bottenkartor om 20, 30 respektive 40 m djup. Det finns ingen installerad vågkraftspark med linjärgeneratorer på platsen för simuleringarna utan undersökningen är teoretisk. Bohuslänsimuleringarna kan ses som typfall för den svenska västkusten. Det ställverk som är planerat att användas i framtida parker har en kapacitet av 60 generatorer. Utformningen av en park kan varieras men ställverken ger att det kommer bestå av delar om 60 stycken. Där med har simuleringar gjorts för ett kluster om 60 generatorer.

Modellen delar upp det modellerade området i trianglar vilkas storlek kan varieras. Modellen använder sig av ett flexibelt nät, vilket innebär att olika storlek på beräkningsrutorna kan användas. Ekvationerna som bygger upp modellen löses för en punkt i mitten av varje ruta. Högre upplösning användes för den mer intressanta ytan med generatorer och den närmsta omgivningen. Modellkörningar kräver väldigt mycket beräkningar, men genom att ha ett varierat beräkningsnät kan simuleringstiderna hållas kortare. En stor del utav arbetet i detta examensarbete har varit databehandling och att göra beräkningskartor till modellen. Modellen är användarvänlig och det finns mycket bra exempel och manualer. Marin modellering tar lång tid och att lära sig ett nytt modellverktyg har varit en utmaning.

De platta bottenkartorna hade samma indata i form av varierande vattennivåer vid gränserna vilket gav olika flödeshastigheter för modelldomänerna. Flödeshastigheterna var i samma storleksordning som för en mätstation vid Läsö på västkusten. Simuleringen med 40 m djup karta hade högst flödeshastighet och den med 20 m kartan lägst. Genomsnittliga flödeshastigheten var 0,186 m/s för 40 m kartan, 0,165 m/s för 30 m och 0,132 m/s för 20 m. För de olika kartorna har simuleringar utförts med och utan generatorer för att eventuell påverkan ska bli synlig. Trots att den djupaste kartan hade högst flödeshastighet visade den lägst påverkan på strömmarna av generatorernas närvaro, i både absoluta tal och relativt referensscenariot.

Resultaten från simuleringarna analyserades som medelvärden av hastighetsförändring över simuleringstiden. För de helt platta bottnarna fanns det områden med följande förändringar i flödeshastighet: -2,93 % för 40 m, -3,77 % för 30 m och -5,41 % för 20 m. Strömningsförändringen var lokalt belägen inom eller i närheten av klustret av generatorer. Strömningspåverkan var likformad för de olika djupkartorna, men omfattningen av minskningen blev mindre om djupet var större. Detta kunde ses i det längsta avståndet till 1 % flödeshastighetsminskning: 940 m, 1050 m och 1300 m. Med minskande djup för de platta bottnarna (från 40 m till 20 m) tar generatorerna upp en större del av vattenkolumnen. Därmed orsakades en kraftigare blockerande effekt. För den mer naturtrogna simuleringen i det möjliga framtida parkområdet var djupet runt 50 m och flödeshastigheten lägre än för de platta kartorna. Detta gav lägre påverkan i simuleringarna, -1,80 %. Det längsta avståndet till 1 % hastighetsminskning var endast 160 m från kanten av generatorklustret.

Minskningen kan jämföras med blockering från andra havsbaserade konstruktioner, som Horns revs vindkrafts park med en 2 procentig minskning i flödeshastighet och Nysteds vindkraftspark med förändringar på 3-4 procent. Öresundsbron ger en mindre än 4 procentig minskning. Enklare simuleringar för ett varierat antal vågkraftstekniker, för testplatsen Wave Hub syd väst om England, visade påverkan av tidvattenströmmarnas hastighet av -0,8 till 0,6 m/s inom ett närområde om 15 km x 15 km.

Resultaten av simuleringarna tyder på att effekter av linjärgeneratorer på strömningshastigheter och sediment är små. Vid konstruktion av en framtida park rekommenderas ändå noggrannare undersökning och simuleringar, då platsspecifika förutsättningar som inte tagits i beaktande i den här undersökningen kan påverka.

Table of content

ABSTRACT .... **I**

REFERAT .... **II**

PREFACE .... **III**

POPULÄRVETENSKAPLIG SAMMANFATTNING .... **IV**

1. INTRODUCTION **1**

2. BACKGROUND **2**

2.1 POSSIBLE ENVIRONMENTAL EFFECTS BY HYDROGRAPHY AND SEDIMENT CHANGES 3
2.2 OFFSHORE WIND TURBINE FARMS 3
2.2.1 Horns Rev Havmöllepark *4*
2.2.2 Lillgrund offshore wind farm *4*
2.2.3 Nysteds offshore wind farm *4*
2.2.4 Induced mixing in the water column due to offshore windmills *6*
2.2.5 Construction phase *6*
2.3 WAVE POWER PARK 6
2.3.1 Previous investigations of wave power park impact on hydrography *6*
2.3.2 Linear generator *8*
2.3.3 Construction phase *10*
2.3.4 Operational phase *10*

3. METHOD **11**

3.1 MODEL 11
3.1.1 Solution technique and stability *12*
3.1.2 Wave power park represented in the model *13*
3.2 STUDY AREA 15
3.3 DATA 16
3.3.3 Bohuslän coastal area *17*
3.4 COMPUTATIONAL MESH 18
3.4.1 Mesh Generator *18*
3.4.2 Flat bathymetries *18*
3.4.3 Bohuslän coastal area *21*
3.5 MUD MODULE 22
3.5.1 Bottom substrate outside Kungshamn, area-A *23*
3.5.2 Bearing capacity of clays *23*
3.5.3 Seabed resistance and layer thickness map *24*
3.6 CALIBRATION 25
3.6.1 Hydrodynamic module *25*
3.6.2 Mud transport module *26*
3.7 VALIDATION 26

4. MODELLING RESULTS **27**

4.1 FLAT BATHYMETRY 27
4.1.1 40 meters depth *28*
4.1.2 30 meters depth *30*
4.1.3 20 meters depth *31*
4.1.4 Sediment movement *31*
4.2 BOHUSLÄN COASTAL AREA 33
Solution stability *35*
4.3 Sediment movement *37*

5. DISCUSSION 40

5.1 RESULTS HYDRODYNAMIC SIMULATIONS 40
5.2 RESULTS MUD TRANSPORT MODULE 40
5.3 COMPARISION OF HYDRODYNAMIC RESULTS WITH EARLIER WORK 41
5.3.1 Offshore wind farms and Wave Hub 41
5.3.1 Induced mixing by windmills 41
5.4 SEDIMENT CHANGE 41
5.5 GENERAL DISCUSSION HYDRODYNAMICS AND SEDIMENT MOVEMENT 42
5.6 RECOMMENDATIONS FOR FUTURE HYDRODYNAMIC SIMULATIONS 43
5.7 RECOMMENDATIONS FOR SEDIMENT INVESTIGATIONS 44

6. CONCLUSIONS 45

REFERENCES 46

TABLE OF FIGURES 49

APPENDIX 51

1. INTRODUCTION

As climate change proceeds, with increasing knowledge and recognition of the issue (IPCC, 2007), the need for renewable energy stands clearer for every day. The use of wave power is about to be borne as a clean and cost efficient alternative to fossil resources for electric generation. Wave power is a renewable energy source with a lot of good characters as such; high energy density, high utilization level, global potential, low on site visibility and expected low environmental impact (Seabased, 2007a). Investigations and preliminary sayings of the environmental impact are that it is low compared to conventional and other renewable sources.

There are several different techniques developing for converting wave power to electricity today (Boström et al., 2008). One of these is linear generators under development at the department where this master thesis has been made.

Several investigations of biological effects from the linear generators technique have been done (Langhamer, 2007). What has not been investigated before is the possible impact on hydrography, sedimentation and movement of bottom substrate that the can be caused by the presence of linear wave power generators standing on the seabed.

The aim for this thesis was to set up a numerical model and simulate if such processes would be affected by a park of linear wave power generators. As there are no wave power parks “up and running” today the modeling technique and reference were taken from offshore wind farms. As windmills standing in the water column affects current speeds and sediment transport. The main research done for offshore wind farms have been done in Denmark by the Danish Hydrological Institute (DHI). This is also the organization which has provided the model MIKE 21 and its application modules needed for this master thesis. The method for the investigation was to simulate the hydrodynamic situation and sediment transport with and without generators in a hypothetical park. Simulations were done for a constructed flat bottom domain and in a suitable location for a future wave power park in the Bohuslän area. The effects on hydrography and sedimentation, from linear wave power generators, are not thought to be large, or even significant, if the same processes are active as in the tested wind farm areas (Petersson, 2001).

2. BACKGROUND

Since the end of the second world war there have been wave power generators in use, for example in 300 nautical navigation buoys around Japan (Payne, 2006). Extensive research for wave power started in the early 70´s during the oil crisis. In the beginning focus was on large plants but as the oil price dropped focus was shifted towards smaller systems more suited for remote areas. At the time of progress of this thesis several projects were running with variety of techniques (Halcrow, 2006b & Boström et al., 2008). Wave power plants are to be operating under hard conditions due to the nature of its power source (Eriksson, 2007). The main problem is getting the system cost efficient enough. Too complicated systems can not compete with cheaper renewable sources such as wind power today.

Wave power has a great potential due to the energy density it possess, the "highest energy density among all renewable energy sources" (Eriksson, 2007 p.11). It is estimated that, on a global scale, wave power has the potential in order of hydro power whit range from 10 000 to 15 000 TWh per year according to different estimates (Seabased, 2008). The potential in Europe alone is on the order of 2000-2500 TWh which is about the electricity demand for western Europe. Naturally, countries that got long coasts with heavy wave climate have the greatest potential, such as Norway and Great Britain with estimated 500 TWh each (DN, 2008). This can be compared with the possibility of 10TWh in Sweden, which equals the production from a normal nuclear reactor (Clement et al., 2002).

Effects on ecosystems and biota are thought to be small but research is being done. For the development of linear generator wave power at Uppsala University, the ecosystem effects are of great interest, due to the profile of environmental friendly power supply in the form of a wave power parks. Effects such as growth on foundations and buoys called biofouling are being investigated (Langhamer and Wilhelmsson, 2007). Problem with biofouling is expected to be less for deeper areas as abundance of species decrease (Waters, 2008). With enhanced growth biological degradation of dead material on the seabed can cause local hypoxia. This growth can, in theory, cause higher nutrient concentrations in sediments in the park area and its closets surroundings. Stratified areas are especially sensitive for oxygen depletion. In the Belts, Kattegat and Skagerak there are occasionally hypoxia caused by high nutrient levels that are followed by high primary production and biomass degradation (Karlsson et al., 2002). Hypoxia is most common under the stratification layer therefore can stratified waters in general be said to be more sensitive to enhanced growth.

The effect from a wave power park on hydrography and sediment movement is thought to take form in three stages of the park's life; construction, operation and removal in line with offshore wind turbine farms (Petersson, 2001). To be able to predict the effects during the operational phase on sediment transport and water movement simulations of such processes in a park have been done and the effects have been interpreted. Earlier investigations of such have been done by the Halcrow Group in 2006 for the South West of England Regional Development Agency, where effects in tidal surface currents were simulated, as well as wave height reduction (Halcrow, 2006a). Changes in current speed and wave height were only small and limited to the area close to the devices.

2.1 POSSIBLE ENVIRONMENTAL EFFECTS BY HYDROGRAPHY AND SEDIMENT CHANGES

Environmental impacts from offshore wind farms can be in form of habitat changes due to changes in hydrography and thereby sediment movement (Petersson, 2001). Sediment particles in the water column reduce light permeability which has great impact on photosynthesizing organisms as the photic zone gets reduced leading to reduction in primary production. It is not only the amount of light that changes but also the light spectra. Sessile flora and fauna can be shadowed or buried in sediment. Mobile fauna can avoid murky waters but there can be art specific consequences and eggs and juvenile fish are more sensitive to this (Petersson, 2001). Effects on flora and fauna depend on the sediment volume, water movements and the tendency of the particles to stick together and flocculate. It also has a great deal to do with the organisms exposed to the sediment pollution (Petersson, 2001). Sediment can pollute by the nutrients and heavy metals that bind to it (Lumborg, 2004). Eutrophication can be caused by accumulated nutrients in sediment. Adsorption of pollutants depends on the surface of sediment particles, grain size. Finer grained sediment transport and accumulation is of high significance when estimating pollution of marine environments.

2.2 OFFSHORE WIND TURBINE FARMS

As there are no full scale wave power parks “up and running” to this day the most similar constructions are in form of offshore wind turbine farms. A wind farm area can have a potential impact on hydrography and geomorphology both in the construction phase and during the operational phase (Elsam Engineering, 2005). The towers and foundations change water flows and by this the transport of material and sedimentation. Local hydrography changes can also affect coastal morphology, especially in sandy areas in continuing change due to movements of currents and waves (Andersson et al., 2008). Hydrographic changes can in this way have an impact on animal and plant life in and outside the farm area (DHI, 2000). Sediment suspensions arise mainly during test drilling and anchoring of foundations but also when the cable is sluiced or dredged in the sea floor. These impacts are generally low and temporary (Holmes & Hansson, as cited in Petersson, 2001). Changes in currents are on the other hand in general not temporary and by such hydrographic changes wind power parks can form sediment traps. The extent of this is due to the size of construction and conditions in the area.

The effects from windmills on hydrography are expected to be small. Therefore they can only have a significant environmental effect if the park is located in a narrow sound and is not to be expected in open coastal and maritime areas. (Andersson et al., 2008). It also depends on the water depth and depth to halocline (stratification). The small changes that could occur are of local scale. There are no simulations of different types of foundations for comparison in investigations done, according to Andersson et al. Though what can be concluded is that the smaller diameter of foundation, the less is the effect.

The existing wind farms compared to in this thesis are Horns Rev outside the west coast of Denmark, Lillgrund in the Öresund area and Nysteds offshore wind farm south of Sweden. For the latter effects on hydrography, water quality and coastal morphology have been simulated with the numerical model MIKE 21 by DHI in 2000 (DHI, 2000).

2.2.1 Horns Rev Havmöllepark

Horns Rev Havmöllepark is one of the largest offshore wind farms in the world to this day. In the wind farm area the water depth varies from 6.5 m to 13.5 m (Tech-wise, 2002). Due to the shallow waters in the park area waves are breaking. Average annual wave height is about 1 m to1.5 m and the tide varies around 1.2 m. The impact on currents in the wind farm area was of local scale. Simple calculations of blocking effect of foundations on currents in the power plant area were done by DHI in 1999. DHI found that a maximum current reduction of 2 %.

2.2.2 Lillgrund offshore wind farm

In the environmental impact investigation needed for permit for the Öresund bridge, between Denmark and Sweden, DHI made simulations of blocking of deepwater flux to the Baltic Sea. Such flux is of great importance for the oxygen supply for the whole Baltic area and the blocking effect is not to be more than 0.5 % of the flux without the bridge. These simulations were conducted with MIKE 3 and showed a blocking effect of ±0.1 % which is less than the uncertainty of ±0.18 % in the calculations (Edelvang et al., 2001a p. 6-3). Not just the regional impact but also the local was investigated. In the park area current speeds were reduced less than 4 %, which was concluded not to affect current speed or sedimentation outside the park area. The impact on wave climate was also calculated. Wave climate depends on water depth, incoming frequency of waves, foundation: form, number and their placement. Significant changes in waves were found within 10 m of foundations and the energy reduction of waves in the park area was less then 5 % (Edelvang et al., 2001b).

2.2.3 Nysteds offshore wind farm

Depth varies between 5 m and 8.5 m in the Nysteds offshore wind farm area Rödsand (DHI, 2000 p.2-1), which is too shallow compared to a possible location for a wave power park. The effects on hydrography and sediment transport were expected to be limited. Close to the foundations the impact was rather high, within 5 m, the flow rate would be reduced by 15 %. The shape of currents around a circular object in size of a windmill can be seen in Figure 1.

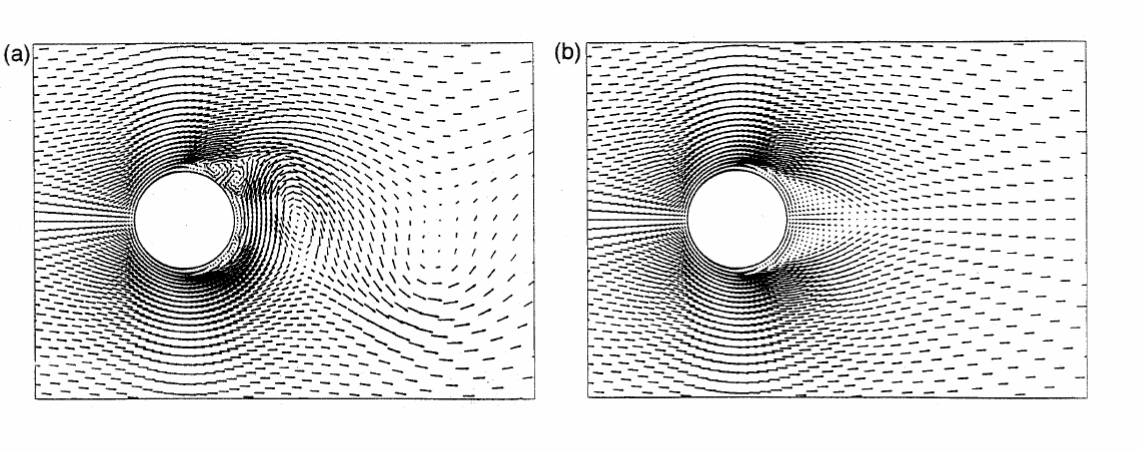


Figure 1 Wake behind one windmill foundation; a) snapshot, b) mean current speed. Each arrow represents the current speed in a particular mesh element (DHI, 2000 p.2-5)

The hydrographic changes from foundation could lead to “insignificant deposition/erosion (less than ± 2 cm) at distances greater than 10 m from the foundations” (DHI, 2000 p. 2-5). According to simulations of the wind farm in MIKE 21 done by DHI in 2000 the expected changes in current velocity and waves are small. Within the farm the maximum flow rate change was of 3-4 % (DHI, 2000). Wave height reduction will at its maximum be 4 % behind 9 wind turbines (the park consists of nine rows). Material movement simulations showed that the wind farm delays the natural coastal morphological development at Rödsand. The barrier reef moved some 3 m less (12 m instead of 15 m) per year due to the blocking caused by the wind farm. In a simulated 30-year period the wind farm is expected to make the reef move some 500 m instead of about 750 m, which was expected without the farm. The wind farm is situated in front of a lagoon. Water residence time in the lagoon decreased due to the natural morphological development of the reef during the 30 years. Water exchange in the lagoon during the period simulated differed with the wind farm present. As the wind farm causes lower current speeds influencing sand transport and the reef development, it is the reason for the weaker reduction in natural water exchange in the lagoon (DHI, 2000 p.2-7).

It was concluded that the effect on waves and currents by a single foundation as well as the complete farm is very small and the change to natural variations in the area is insignificant. There is no change in the present situation with or without offshore windmills. The only significant change due to the park is in the lagoon over a 30 year period and without magnitude that will have an environmental effect. There can not be found any significant environmental impacts due to the offshore windmill farm at Rödsand.

2.2.4 Induced mixing in the water column due to offshore windmills

According to laboratory experiments in flowing unstratified waters, eddies created from monopile windmills are to be expected of size not more than 2 object diameters orthogonal and 10 times the object diameter downstream (Carmer as cited in Lindow et al., 2007 p. 11). If eddies can be expected in the same way for the linear generator wave power converter (1.7 m in diameter) it would cause an affected area of about 3.4 m by 17 m. Linear wave power are to be aligned at least 20 m apart, the internal waves will not be able to superposition each other in a significant way.

Skottarevet offshore wind farm

If windmills stand in stratified waters the induced turbulence could increase mixing of surface and bottom water. The level of mixing is highly connected with the current speed. In planning of a wind farm outside Falkenberg, west coast of Sweden, SMHI have investigated if the foundations locally can have an effect on mixing and affect the stratification (Karlsson et al., 2006). In that area the stratification is located at depth of 10 m-15 m. Therefore windmills placed in shallow areas of less than 10 m can have no effect on the mixing of bottom and surface water. The calculations by Karlsson et al. were based on unstratified water mass and mixing in the horizontal plane. Mixing behind a foundation was enhanced by a factor 10. For the planned park with 30 monopiles in an area of 20 km^2 this would equal an increase in mixing of 1 % above the background level in the area. These calculations should be seen as the top limit of what is feasible in the real case. As there were no stratification included and mixing was only calculated in the horizontal plane, which needs less energy than vertical mixing. A mixing of 1 % is in the order of natural variations in Kattegatt and could therefore be said to be of small importance.

2.2.5 Construction phase

Excavating for foundations or sluicing for cables in the construction phase will lead to sediment spill with increased turbidity of the water as result (Elsam Engineering, 2005). The extent of such spill depends on the method used, precautionary activities as well as the hydrography in the area. Turbidity increase also depends on the amount of spill, the grain size of the spill and the hydrographic conditions at the time of the spill. Smaller grain size gives slower sedimentation and stronger turbidity increase.

2.3 WAVE POWER PARK

2.3.1 Previous investigations of wave power park impact on hydrography

In Cornwall, England, a test area for wave and under water power generation is planned, called Wave Hub. Wave Hub is aiming to be the first demonstration and test site in the UK for “wave energy generation devices” (Wave Hub, 2008). For this area simulations have been done for different types of devices and the reduction in wave height is modeled at the shore. Wave height is reduced some 5 % at the coast, for a certain storm with variety of directions and 13 % for waves coming from a single direction (Halcrow, 2006a). Wave climate simulations at the site were done by the University of Exeter. The blocking effect of 100 % of waves was simulated for power devices (Halcrow, 2006a). A wave reduction of 100 % is not realistic rather a reduction of less then 30 % was expected. It was found that Wave Hub can have a potential impact on the wave climate north of Cornwall. More detailed simulations were needed with more realistic boundary conditions and with units allowing some percentage of the wave power to pass through. More detailed simulations done by the Halcrow Group, for the same area with various wave power devices installed. For typical sea state with varying wave directions a 3 % reduction in wave height was found at the coast. A reduction of 7 % was found for uniform wave condition, with single direction. With various devices, among others power buoys, surface tidal currents were changed -0.8 m/s to 0.6 m/s in a 15 km by 15 km area, that did not extend into the coast. Sediment movement was simulated for 48 hours, showing no significant changes in sediment transport. The changes in current speed and wave height were only small and limited to the area close to the devices. Wave pattern changes were significant but cannot, during normal conditions, have an impact on sediment at the 50 m deep planed test site.

For the latter simulations, the floating power devices were simulated by applying different wave transmission factors, letting varying amount of wave energy pass by the wave energy converting device. For Wave Dragon this was set to 0.68 and for Power Buoy, Fred Olsen and Pelamis the transmission factor was set to 0 (Halcrow, 2006a p.26). This due to the transmission factor is very low after the solid structure. As the Pelamis is 150 m long, the transmitted wave immediately after the structure should also be low.

2.3.2 Linear generator

In a wave power generation device the mechanical energy of sea waves is converted to electrical energy. One unit consists of a linear generator placed on the seabed attached to a buoy at the surface with a line (Figure 2).

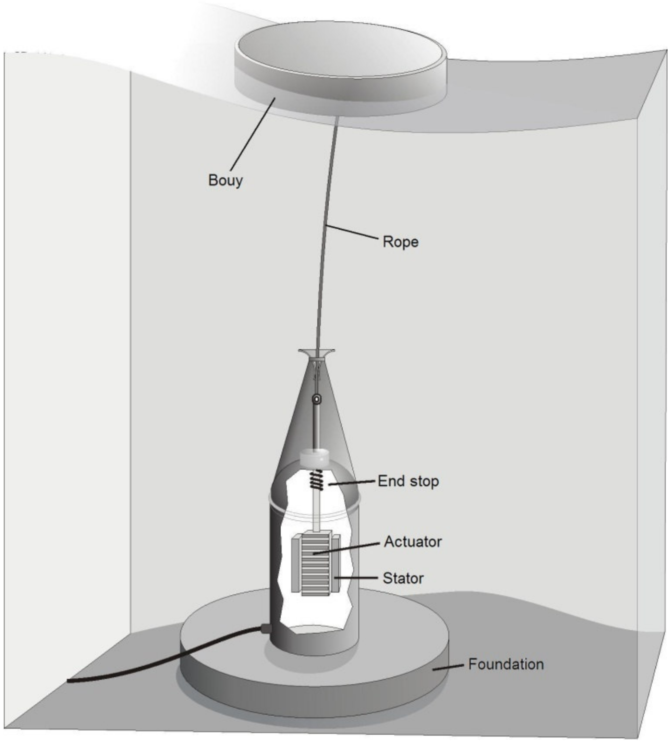


Figure 2 Wave energy converter with buoy, line, linear generator and foundation (Seabased).

The system is expected to be "cheap, sturdy, environmental benign and be able to cope with extreme conditions at sea" (UU, 2008). As the converter is directly driven with no energy conversion steps between the buoy and generator it does not use any gearbox or other complicated hydraulic mechanics (Waters, 2008). Directly driven generators do need more complicated electrical converting system as the generated electricity is varying in frequency, amplitude and phase order. Generators are planned to be arranged in rows in every 20 m, with rows 50 m apart (Seabased, 2007b). Thereby is the area demand is about 1km^2/1000 units. Generators are to be placed in clusters of 60 units due to the connecting capacity of the substation. Thereby great variety in the formation of parks in different areas is possible (Figure 3).

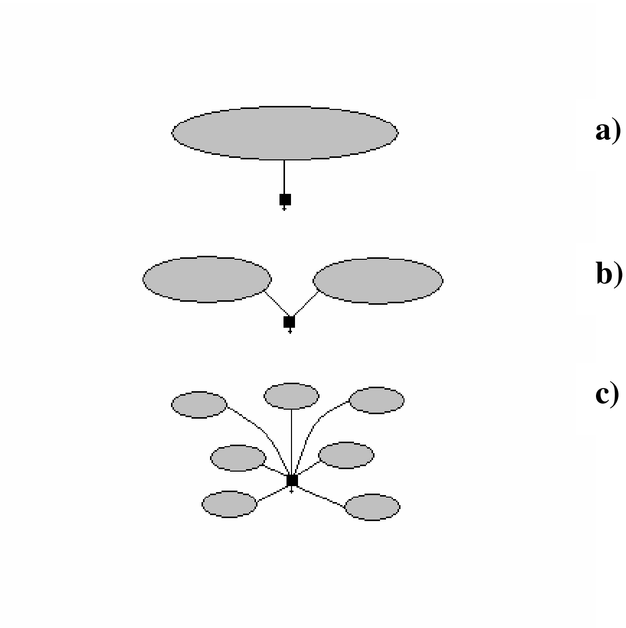


Figure 3 Three possible formations of wave power parks, a) single area, b) divided area and c) multiple cluster area (Bernhoff, 2007 p. 175).

Areas suitable for wave power parks should according to Seabased Industry AB which is the company trying to commercialize the technique, fulfill these following criteria (Lind & Nordgren, 2006b).

Depth:	30 m to 70 m
Slope:	A flat bottom is preferred as the generators are not to be tilted and it gives less risk for landslide.
Bearing capacity:	A firm seabed is preferred for its ability to support the generators. It is just an advantage if the foundations sink down a bit in the seabed as it will anchor the generators to the bottom.
Coherent area:	1 km^2 for 1000 units.

The technique is being tested, under realistic circumstances, at the Lysekil test site on the west coast of Sweden since 2004 (Seabased, 2007b and UU, 2008). The research area is situated about 2 km west of the Islandsberg peninsula. Water depth at the test site is ca 25 m. This test site will consist of maximum 10 wave power devices and 30 dummy buoys, the latter ones for biological studies. Islandsberg is to shallow and sheltered to be able to have a real full scale wave power park, therefore another test site will be constructed further out at sea in the region. The purpose of the test site is to test the technique and operation of the system, but it is also for marine biological and ecological investigations. Investigations concerning growth on structures are being done at the test site (UU, 2008). The operation period of the facility is until 2013 and after this all equipment will be removed.

2.3.3 Construction phase

Placing of foundations

With dredging may differences in sedimentation and turbidity occur, which can have an effect on the marine environment (Petersson, 2001). Foundations do not need to be anchored in the bottom substrate in the way needed for an offshore windmill. Thereby almost no sediment spill is to be expected for the placing of foundations. The effect on sediment transport during this phase is expected to be negligible and therefore not further investigated in this report.

Cable connection

When the “land base” cable is placed in the seafloor by sluicing or dredging, there can be turbidity changes due to sediment spill (Petersson, 2001). The accepted level of turbidity can be set by e.g. the environmental authority. The impact of water jetting the cable into the sediment at Horns Rev wind was local and temporary (Elsam Engineering, 2005 p.21). The bottom was visibly disturbed in the trench and an area of 10m width. The cable impact on sediments was not simulated in this work.

2.3.4 Operational phase

Generators possess only a small part of the water column but still they can, in theory, have a blocking effect on sea currents (Seabased, 2007b). Behind the park the wave height will be reduced. To some extent the waves will grow again but the reduction is thought to last some distance from the end of the park. Theoretically, the park can also effect water exchange and sediment movement. This effect is thought to be small in line with the offshore wind turbine farms effects investigated by DHI and Elsam Engineering among others. The operational phase is the focus for this thesis as this is the period of a future park life where a significant environmental impact is possible.

3. METHOD

To investigate possible impact on hydrography and sediment movement from a wave power park a proper simulation engine was needed. People contacted in the search for a suitable software package are named in appendix 1. DHI´s software MIKE 21 is a much used simulation engine for oceanographic simulations. A student license for the two dimensional model package Mike Marine was used.

Previous investigations of hydrography changes (blocking) due to circular constructions in the water column have been done but to a small extent (Hansen et al., 1997). For instance MIKE 3 (3D version) has been used for simulations of hydrographic changes due to the wind farm Lillgrund in Öresund (Edelvang et al., 2001). The model has predefined structures such as vertical piers, which were used to represent windmills in the simulations. The same approach was used in this thesis to simulate those effects of the wave power generators on hydrography and sediment movement.

The Swedish west coast situation was thought to be of interest and therefore the data collection was focused on that area. Data series of: water levels, wind speeds, bathymetry and bottom substrates, were obtained from SMHI, DHI and SGU (see appendix 2). Other useful data for good model set-up would have been current speeds and directions, bottom substrate properties as erosion coefficients and critical shear stress. The lack of data of current speeds inside the model domains, water levels and turbidity among others showed to be the main problem for the investigation. The water levels used, some modified, were good enough for hydrodynamic simulations situation within the ruff levels known. Calibration and validation are two crucial steps in modeling but with the data sets available neither of them could be done to a satisfactory level. The approach to investigate possible impact on hydrography and sediment movement was to construct a flat bottom domain and a more complex situation in the Bohuslän area. The Bohuslän domain was to simulate a more complex environment compared to the flat bathymetries, in terms of varying: bathymetry, bottom substrate and current speeds. Without calibration the model was not expected to reproduce the actual situation in the simulation period.

3.1 MODEL

The model used is MIKE 21 Flow Model FM by DHI, a two-dimensional water model with flexible mesh, flexible model grid. Small elements in the calculation grid can be used where more detail is needed, and larger elements used where not, to optimize information for a given simulation time. 2D modeling is preferred for water columns that are homogenous in salinity and temperature (DHI, 2008b).

The MIKE 21 FM series consists of several modules. The two modules used were:

1. Hydrodynamic, HD, which simulates the water level variations and currents
2. Mud Transport Module, MT, which simulats cohesive and non cohesive sediment transport

3.1.1 Solution technique and stability

The order of governing numerical schemes for numerical calculations could be set to low order (first order) or higher order schemes. The low order scheme demands shorter calculation times but generates less accurate results. The model were set to low order solution for time integration and space discretization as the most influencing processes were expected to be by diffusion and slow flowing water, in line with the manual for the hydrodynamic module (DHI, 2008a p.28). Computational time increases with a factor of 3-4 for higher order of equation solution in space and time. A finite volume method was used for the domain discretization and the time integration was by explicit scheme. As a low order solution technique, MIKE 21 is using a first order explicit Euler method (eq. 2). Stability of the produced numerical schemes is to be secured if CFL (Courant Friedrich Lewy) numbers are less then 1 (Weistein, 2008). The CFL number can be set in the model, but it can also be controlled by the maximum time step allowance as time is one of the parameters on which the CFL number is based on (eq. 3). In which the characteristic length scale is approximated with the minimum edge length of a mesh element and water depth and velocity components are estimated in element center.

General equation formulation:

$$\frac{\partial U}{\partial t} = G(U) \tag{1}$$

G	general function of U
U	general time dependent parameter

First order explicit Euler:

$$U_{n+1} = U_n + \Delta t G(U_n) \tag{2}$$

U_{n+1}	general parameter for example current speed at time step n+1
Δt	time step interval

Friedrich-Lévy number for shallow water equations:

$$CFL_{HD} = \left(\sqrt{gh} + |u|\right)\frac{\Delta t}{\Delta x} + \left(\sqrt{gh} + |v|\right)\frac{\Delta t}{\Delta y} \tag{3}$$

g	gravitational acceleration
h	total water depth
u	velocity component in x-direction
v	velocity component in y-direction
Δx	characteristic length scale in x-direction

Δy characteristic length scale in y-direction
Δt time step interval

Friedrich-Lévy number for transport equations: $$CFL_{AD} = |u|\frac{\Delta t}{\Delta x} + |v|\frac{\Delta t}{\Delta y} \qquad (4)$$

3.1.2 Wave power park represented in the model

In MIKE 21 five different structures can be included. As there are no wave power devices in the model today the generators are represented in the model by vertical sections of piers. The linear generators were represented by cylindrical pillars. Piers are modeled as sub-grid structures as they are of such small horizontal extent (DHI, 2008). The mesh size in the park area was chosen so that the piers in theory could be resolved as one structure per mesh-element. Due to the unstructured grid some of the piers came in the same mesh-element (Figure 9).

The locations of piers were specified in the model domain and the number of vertical pier sections. A stream line factor was specified, as a part of the total drag force. It takes into account the velocity increase due to the blocking effect by piers (eq. 5). A typical value for the stream line factor is 1.02 (DHI, 2008 p.58). Each pier could be divided in sections as in Figure 4 (DHI, 2008a p.59). The generator has a diameter of 1566 mm approximately 1.6 m and height in total of 9 m where the top 3.2 m is in the form of a cone. The foundation used is a square with 4 m sides and 1 m in height but it was not included in simulations as one pier section could not be circular in one section and square shaped in an other. As the model did not accept fraction numbers the generators were simulated as cylinders of 9 m height and 2 m in diameter, (one section).

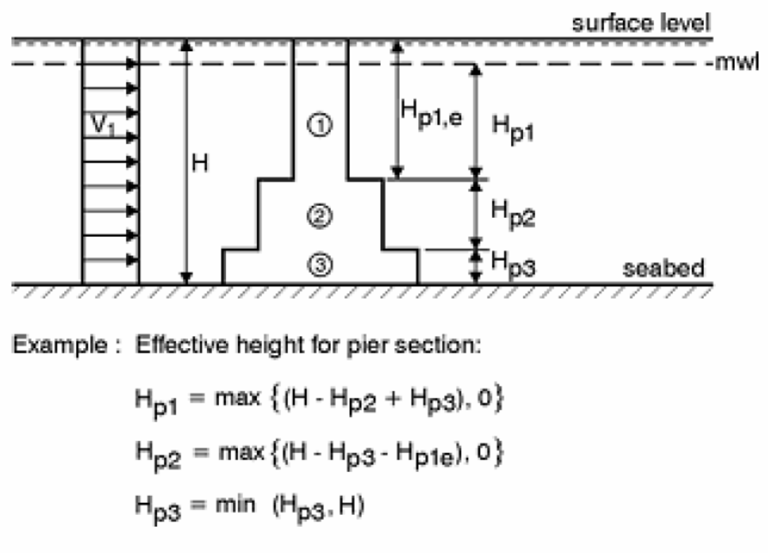


Figure 4 Definition of pier sections, number of sections could be defined and only one was used $H_{p3} = 9$ m.

The effects of piers were modeled by “calculating the current induced drag force on each individual pier” (DHI, 2008 p. 59).

The effective drag force was determined from (eq. 5).

$$F = \frac{1}{2} \cdot \rho_w \cdot \gamma \cdot C_D \cdot A_e \cdot V^2 \tag{5}$$

ρ_w	density of water
γ	streamline factor
C_D	drag coefficient
A_e	effective area of pier exposed to current
V	current speed

The drag force was equated as shear stress by (eq. 6).

$$\tau_p \cdot \Delta x \cdot \Delta y = n \cdot F \tag{6}$$

τ_p	equivalent shear stress
F	drag force on one pier
n	number of piers in one grid point (density of piers)
$\Delta x, \Delta y$	grid spacing

The additional shear stress, τ_p is added to the bottom shear stress, τ_o. The representations of the generators in form of elements with induced shear stress are marked with gray elements in Figure 9.

3.2 STUDY AREA

Three different flat bathymetries were created and used in simulations, with depths of 40 m, 30 m and 20 m. The square shaped model domain had 50 km sides (Figure 5). This is the approximate distance between Gothenburg and Ringhals, from where water level data was used as boundary conditions. The flat domain can be seen in
Figure 5, the same grid was used, the difference between the flat bathymetries was depth. Different depths were simulated to see if this affects the parks blocking effect of currents.

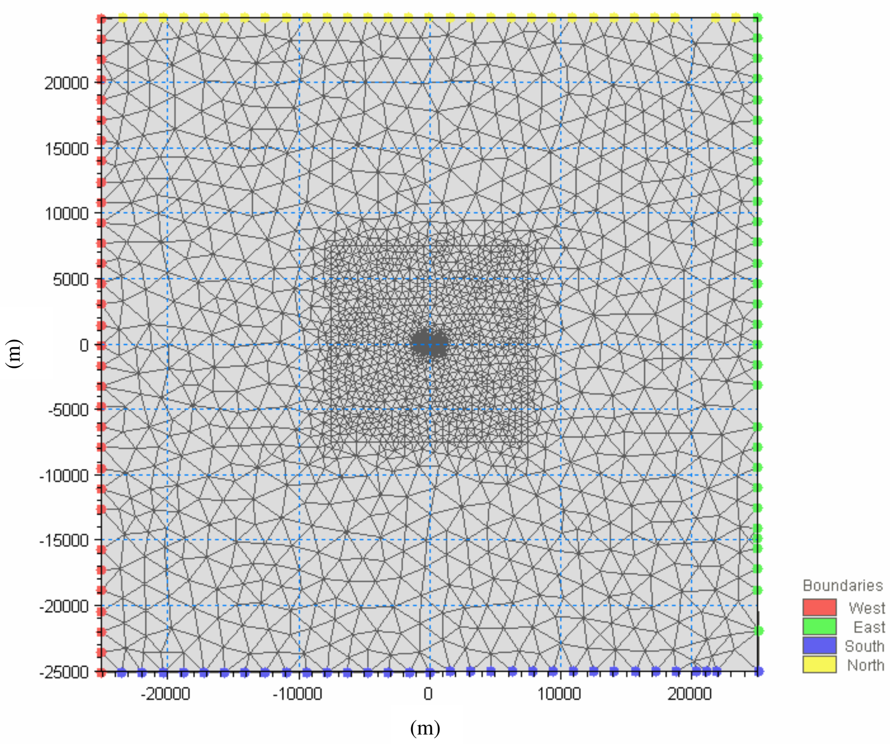


Figure 5 Model domain for flat batnymetry runs with four varying boundaries.

For the more realistic case the Bohuslän coastal area was chosen. There the Uppsala University test site is running outside Lysekil and investigated areas for possible future parks exist in the same region (Figure 10). Marine geology has been investigated in the region and one site was chosen to be modeled, due to the characteristics of the site and the suitable location within the bathymetry data received. The position chosen to possess the generator cluster is shown in Figure 10, it is called area-A in the SGU reports and in this work. Precise bathymetries were applied at area-A were detailed seabed charts were available (see Appendix 16) and less precise bathymetries further away from that area (Figure 10). Land boundaries and water depths were received form DHI.

3.3 DATA

Input data for the HD module is divided into the following groups (DHI, 2008b p.6)

- Domain and time parameters
  - computational mesh and bathymetry
  - simulation length and time step
- Calibration factors
  - bed resistance
  - momentum dispersion coefficients
  - wind friction factors
- Initial conditions
  - water surface level
  - velocity components
- Boundary conditions
  - closed
  - water level
  - discharge
- Other driving forces
  - wind speed and direction

Data was received from SMHI by a research license (Core Services Department - Information and Statistics). Data was ordered for all the stations available for the northwest coast of Sweden. The data came from the database SHARK (Svenskt HavsARKiv) and is quality checked by SMHI. Water level boundary conditions for the flat bathymetry were created in MIKE with the profile series. For the flat bathymetries, Gothenburg and Ringhals water level data was imported at the north and south points and the program interpolated values for the boundary points in between. For the Bohuslän coastal area bathymetry and land boundary data were received from DHI from MIKE C-map, in the form of xyz-files which is the format used in MIKE. MIKE C-map is collaboration between DHI and C-Map Norway. The sedimentological data was taken from work done by the Geological Survey of Sweden (SGU, Lind & Nordgren, 2006a-c).

All the data from SMHI (water levels, currents and wind) were formatted into MIKE time series files for the different data types used in the model. The time compability for the stations situated closest to area-A is shown in Figure 6.

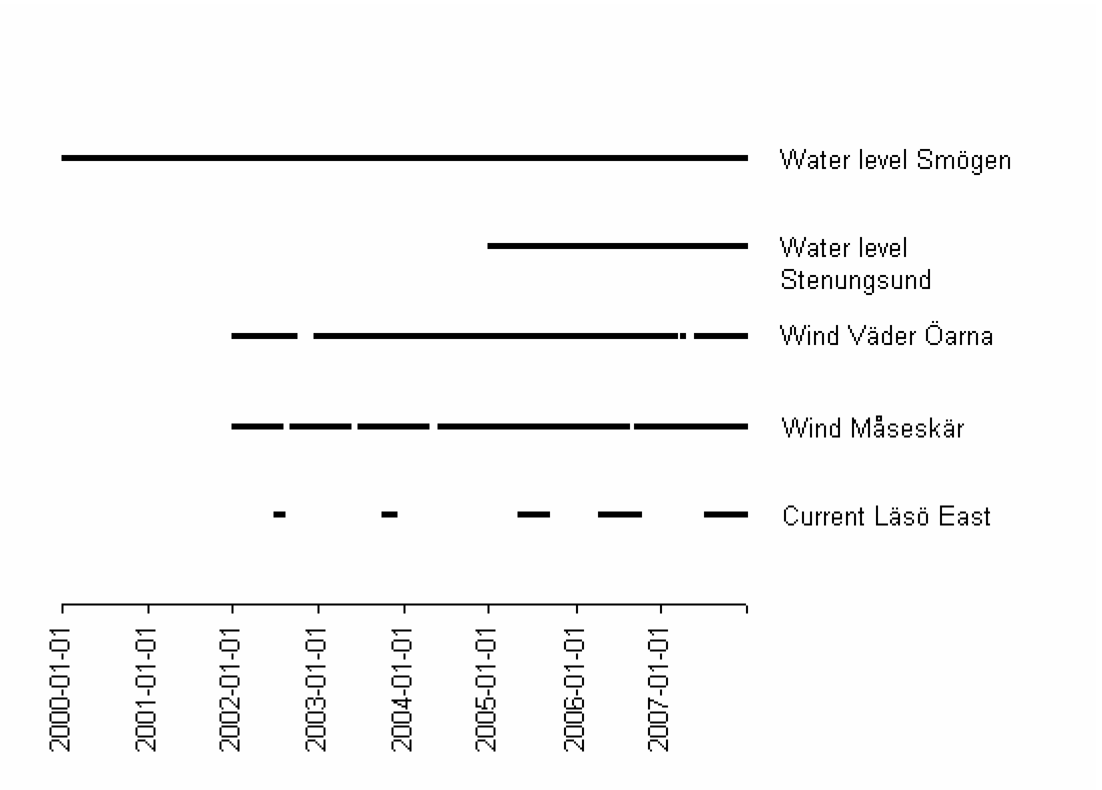


Figure 6 Time-compability of data points in Bohuslän coastal area.

3.3.3 Bohuslän coastal area

The time chosen for simulation started at 13/5 in 2005. The period was chosen due to the accessibility of data and the similarity of variations at the two water level stations. Higher water levels and stronger wave climate arise during winters and thereby could a winter period have been interesting to simulate, Appendix 3. The wind can be represented in the model in three different ways: constant in time and space, constant in space varying in time or varying in both time and space. There are no possibilities in the model for interpolating two points into a varying wind field over the model domain. For the Bohuslän area an average of two wind stations were calculated and applied as a varying time series equally distributed in the domain. The wind speed averaged was raised to the higher integer, for the model to rather overestimate than underestimate the wind driving force. The water levels at Smögen and Stenungsund can be seen in Appendix 11. Smögen was the north boundary and modified values from Stenungsund the south boundary, resulting in a flow northwards, in line with the Baltic current present in the area. Without modifications of Stenungsund water levels a south going current was present that can not be observed at the location. The reason for the simulated flow, based on measured water levels, to be in the opposite direction is that Stenungsund is situated sheltered from the open sea and therefore records lower water levels than what is present at the south boundary in reality. To correct the levels at Stenungsund into a realistic southern boundary for the domain the first approach was to apply the same procedure as was done for water level boundaries for the Gradyb tidal area, according to the Mike Mud transport Step-by-step training guide. There the water level changes from a sheltered measuring point were increased by some 10 percent, to compensate for energy loss from open to sheltered waters. This was not enough for the southern boundary for the Bohuslän area. The water levels simply needed to be higher for the flow to be in the right direction and therefore some modifications of the recorded water levels from Stenungsund were done. The average water level was increased to the same value as for the Smögen station. For most of the time steps where Smögen had higher water levels the difference was reversed. Finally the changes were raised with 50 percent to increase the current speeds in the model domain so it came up to about 0.5-1 m/s, in magnitude of the Baltic current. Thereby the main hydrographic situation of the region could be represented in the model.

3.4 COMPUTATIONAL MESH

The model version used for hydrodynamic and sediment simulations was Flexible Mesh, FM, with triangular mesh element parts. According to DHI, the unstructured grid provides “optimal degree of flexibility in the representation of complex geometries and enables smooth representation of boundaries” (DHI, 2008b p.1). The model calculations were done by finite volume method for each cell, with cell centered depth used.

3.4.1 Mesh Generator

The computational meshes used were all created in Mesh generator. Mesh generator is a work environment where unstructured calculation meshes can be created. Setting up a mesh includes selection of: area, bathymetry resolution, flow, wind and wave fields and definition codes for land and open boundaries (DHI, 2008d). The geographic resolution need to be selected to stability considerations. Meshes have been divided with polygons to create areas with different maximum element area as the need for high resolution is mainly close to the park. As the mesh is flexible and triangular the different triangular areas can take any sizes, up to the maximum level, depending on the number of nodes. An attempt to optimize the mesh size was done according to the method described by Jones et al. (2007), where current speed for a certain point is compared for the same simulation properties but for different mesh sizes (Appendix 5). In Mike 21 User Guides the general approach to maximum element size in the computational mesh is to have smaller elements in shallow areas and areas of interest. The optimization resulted in computational mesh sizes with computational time that was not too long, i.e. around 24h for each simulation for the flat bathymetries.

3.4.2 Flat bathymetries

For the flatbed bathymetries the size of the model domain was to represent an area from where boundary conditions of water levels had been taken. The stations picked was Gothenburg and Ringhals, 50 km apart, therefore a 50 km by 50 km large square was created as the model domain (Figure 5). In the Wave Hub investigation current changes was in a 15 km by 15 km large area (Halcrow, 2006a p.47). Therefore an area of that size was created with higher resolution than the main model domain with for more model equations to be solved in the interesting area (Figure 7). The park area in these flat meshes was of 2 km^2 as it is the dimension requested by Seabased for future park in the Bohuslän area (Figure 8). The park area had highest resolution as the most changes in currents are to be expected close to the generators.

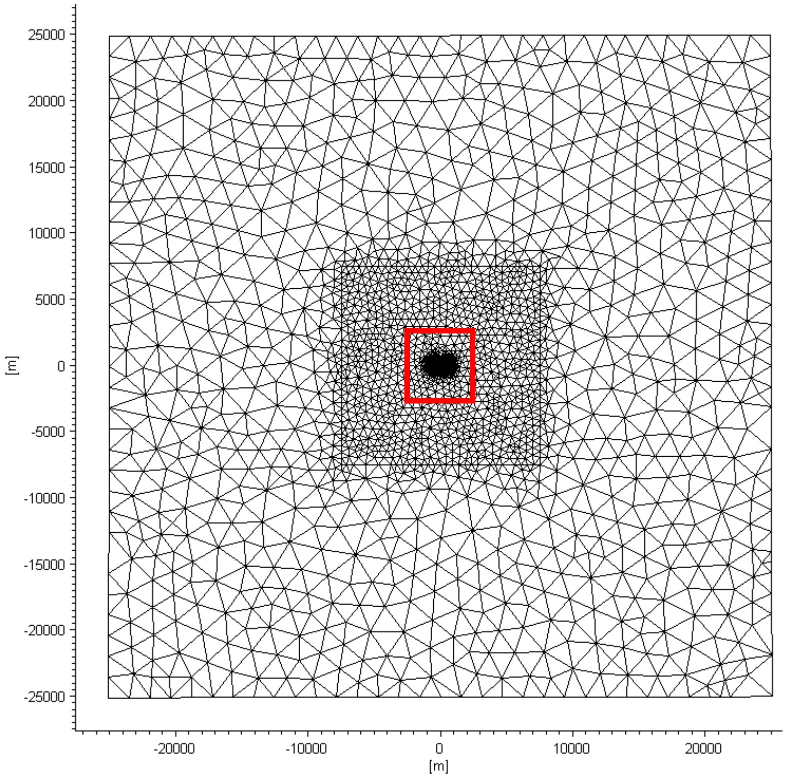


Figure 7 Model domain for flat bathymetries, with computational mesh. The mesh size is smaller closer to and within the park area where the cluster of generators were simulated. Close up of the red square with the power park area in the middle can be seen in Figure 8.

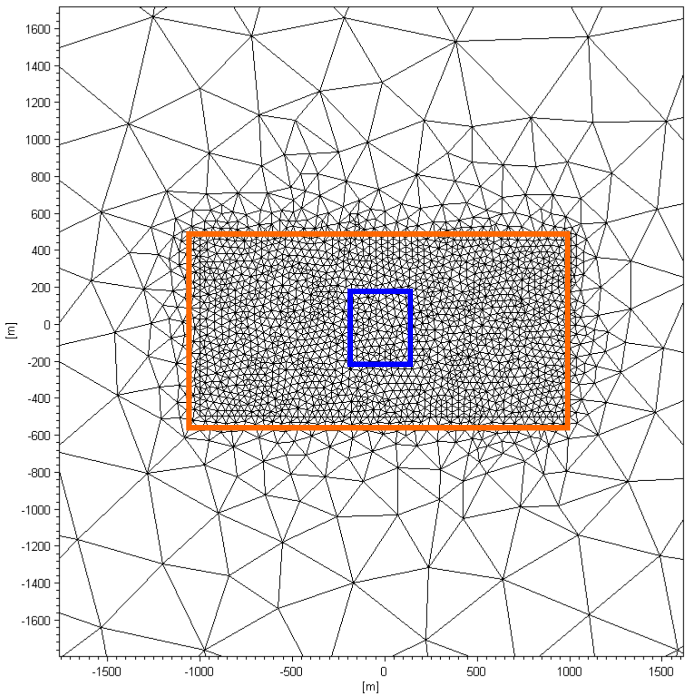


Figure 8 Calculation mesh with 2 km^2 park area marked with orange rectangle, close up of the blue square representing the cluster area with generators can be seen in Figure 9.

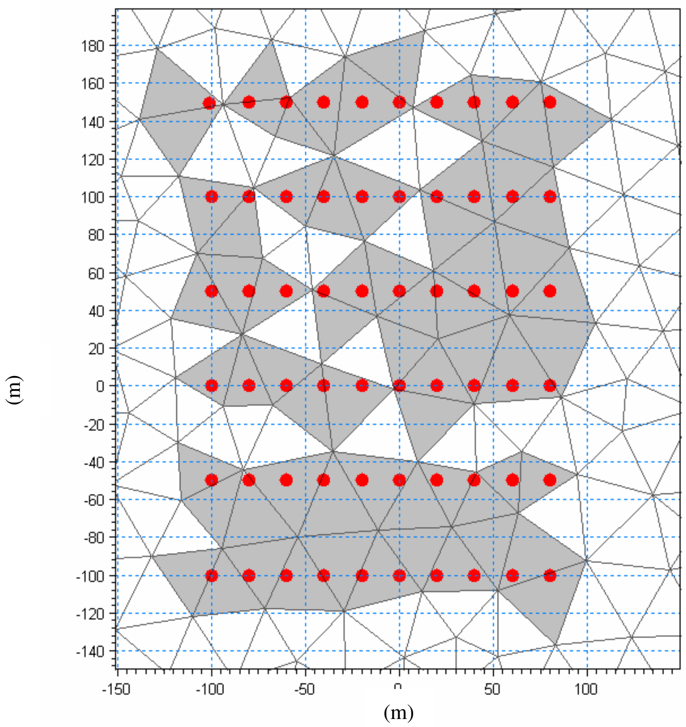


Figure 9 Cluster of 60 generators and the computational mesh. Each row consists of 10 generators 20 m apart and the rows are positioned 50 m apart. The triangular elements in the computational mesh are of sizes of maximum 1000 m^2.

3.4.3 Bohuslän coastal area

Land and depth data was received from DHI, which was used in the mesh generator with no further pre-processing of the file format only the extent of data. A computational mesh compliable with the computer properties in terms of simulation times was created by heavy reduction of the raw data. Manually editing was done by reduction of received boundaries of islands and coast by deleting island polygons and straight out (smooth) the land boundary. Finer parts of the net, with more calculation points, contribute heavily to the calculation time. Regions further from the park area got more scarce net, due to its lower significance for the park area hydrography. In the area close to the generators a resolution of 1000 m^2 was used to be able to resolute the cluster in the same way as for the flat bathymetry simulations (Figure 9). The cluster had the same formation of generators but it was directed from east to west instead of north to south as in Figure 9. For the area-A investigated by SGU by request of Seabased, sediment samples were collected. Depth data from the same have been added to complement the bottom bathymetry data received from DHI. The most interesting area situating generators in the simulations got in this way higher resolution. The size of the model domain was adapted to the data available, i.e. water levels and bathymetry. The nearest water level stations to the area-A was Smögen in the north and Stenungsund in the south. In the longitudinal extent it was the bathymetry that set the domain extent, the west boundary was put were the data point distribution started to get coarse (Figure 10).

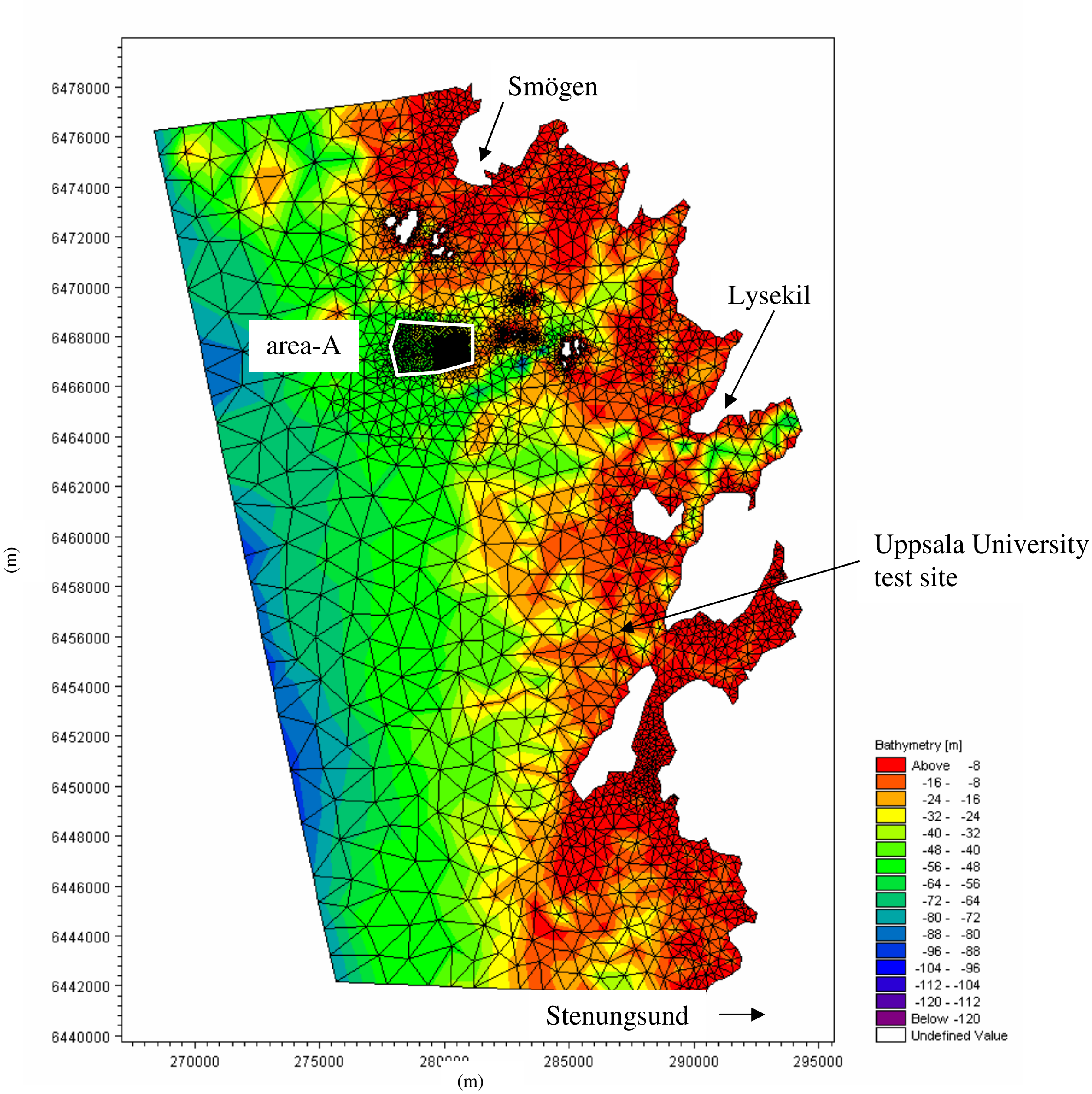


Figure 10 Bohuslän coastal area mesh and bathymetry with highly resolute grid at area-A marked with white border. Most shallow areas marked with red near the coastline and deepest parts further out at sea marked with blue.

3.5 MUD MODULE

The Mud Transport Module (MT) is an add-on module to the Mike 21 Flow Model FM. Use in this thesis was for cohesive as well as non-cohesive sediments transport. If bottom material erode or settle depends on the speed of flowing water passing by the surface and the critical speeds for different bottom material to erode. Up to 12 layers can be defined in the module at its most the Bohuslän simualtions had 3 layers. For each layer of bottom substrate a number of parameters were defined such as density and bed friction.

Of interest for this thesis was to investigate the impact on sediments by the precence of wave power park, i.e. sediment transport. The MT was run parallell to the HD but it can also be run in decoupled mode where results from previous HD simulations can be set to drive it. As the complex processes and the physics of sedimentation and sediment movements are not fully understood today, the model is empirical and needs field measurements to run properly. The advection dispersion equation is governing the MT-module, see flow chart in Appendix 6 where also the different parameters that call for measurements are shown. The need for field measurements was a problem for the set-up. Since none of these have been measured the set-up was done with assumed values from previously investigations with the MT for these parameters. The mud module needs initial conditions for sediment layer thickness, fraction distribution and sediment density. All of these have been created in data manager by using the bottom charts from the SGU survey as guide lines (Appendix 16-Appendix 19).

3.5.1 Bottom substrate outside Kungshamn, area-A

In the areas investigated by SGU the main bottom substrates were glacial and postglacial clays (Lind & Nordgren, 2006a). In the main part of the area there were thin layers of (<0.5 m) secondary sediments, consisting of material eroded by currents, waves and water flowing over land (Appendix 16). Often the sediments were coverered with millimeters to some centimeters of organic material, postglacial silt or fine sand. These thin covering layers are mobile and temporary and they are moved around and/or resuspendend during periods of ruff sea (Lind & Nordgren, 2006c).

Glacial clay mainly consists of clay but also portions of silt, sand and gravel. The glacial clays in the area has low organic content (<1%) (Lind & Nordgren, 2006a). Postglacial clay consists of more fine grained material than the glacial clay. The postglacial clays in the area investigted by SGU had a moderate amount of silt.

3.5.2 Bearing capacity of clays

In short the different clays found in the area were the following (Lind & Nordgren, 2006a):

Postgalcial clay	lose/soft
Transition clay	soft/firm
Real glacial clay	firm/hard

Glacial clays possess better bearing capacity than post glacial clays due the fact that they are older and have had more time to settle (Lind & Nordgren, 2006a). Galcial clay have in some parts been underlaying other sediment layers and been compacted by their weight. The glacial clay has lower organic content that contributes to the higher stability and bearing capacity. Of the glacial clays the real glacial clay has higher bearing capacity due to the higher content of friction materials such as sand, gravel and stones than the transition clay.

3.5.3 Seabed resistance and layer thickness map

Bed resistance in the model should vary with water depth and seabed type, higher resistance (lower Manning M number) for rougher and shallower areas (Appendix 7). The map was created in the Data Manager, by setting values to the triangular elements of the mesh-file of the Bohuslän coastal area, a close up of the seabed resistance map of area-A can be seen in Figure 11. The difference in seabed material and their distribution was taken from the SGU reports (Lind & Nordgren, 2006a-c). With help of a review report of bed roughness variability in MIKE FM, the map was set up with varying Manning M [$m^{1/3}s^{-1}$] numbers (Dix et al., in prep.). For the 2D model used depth integrated Manning numbers were needed. Seabed resistance depth dependence for the three different bottom material, rock, clay and sand is seen in Appendix 8. The main part of the resistance map covering the model domain in Figure 10 was set as Manning number of 32, as this is a farely good estimation for marine areas if no other information is available (DHI, 2008a). For the part of the map with more information available covering area-A and its near by surroundings, resistance numbers were applied with guidance from the Dix et. al report (Figure 11). The bottom chart maps from SGU (Appendix 16 -Appendix 17) were used to manually draw polygons and divide the area into different resistanceclasses due to depth and bottom substrate variety. The bottom substrate in area-A was set to five different types and two layers according to the SGU investiagtions.

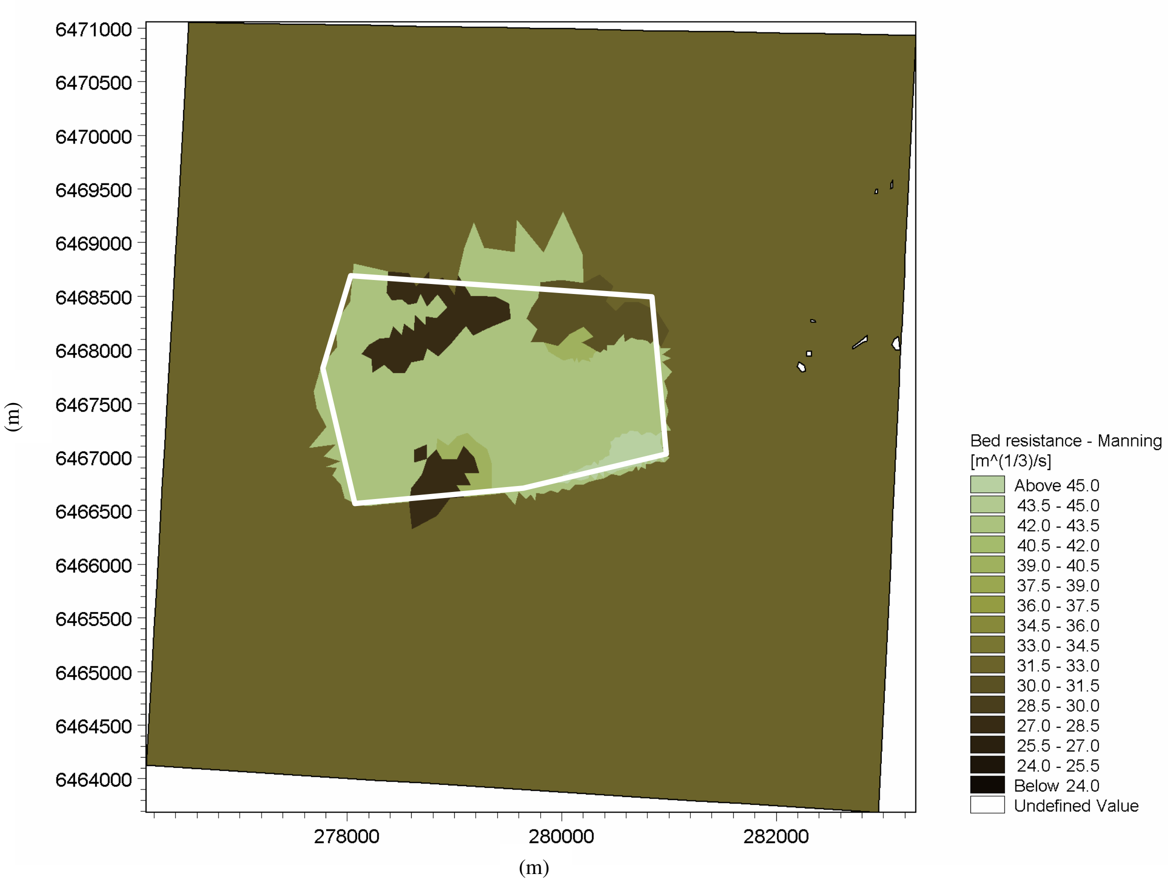


Figure 11 Seabed resistances map of area-A and surroundings, 7 km by 7 km sided square. Created in MIKE with guidance from Appendix 16. Varying Manning numbers in area-A marked with white border, highest resistance at bedrock areas (dark) and lowest friction in sandy and shallow area (bright).

3.6 CALIBRATION

To tune the model to reproduce measured situations in the model domain, simulations should be done with certain parameters changed, one at a time, and the changes saved in a log.

3.6.1 Hydrodynamic module

Seabed friction number in particular is suitable for calibration for the HD. This could not be done due to the lack of information of calibration data such as current speeds in the model domain. Seabed resistance was set as described in section 3.5.3, with guidance from previous work in MIKE 21 by Dix et al.

The timing of different scenarios was not possible to match as few where known only from the measuring buoy at Läsö Ost. Adjusting water levels at the southern boundary for the Bohuslän simulations was done to represent the Baltic current in the right direction and magnitude as mentioned before.

The default value for bed resistance is set to Manning value of 32 [$m^{1/3}/s$] as this is the equivalent of a seabed mean grain size of 0.1 m. Manning number of as much of 40 has successfully been used in the model, corresponding to a grain mean size of 1 m. Such large diameters are not representative for most natural environments and especially not for the Bohuslän coastal area. The reason for the recommendation of such high values is to represent the drag of bed forms of finer sediment (Dix et al. p.2).

3.6.2 Mud transport module

The preferable data for calibration would be turbidity. Since no time series of turbidity was available in the model domain, no calibration was possible. The physical processes of the sediment such as the settling and resuspension is to be resolved properly by changing the dispersion coefficients (Appendix 6).

3.7 VALIDATION

Validation is to be done by model simulations and comparison for a time series that the model has not been calibrated for. It can also be done for a similar area if the mode is thought to be of general type.

MIKE 21 is a well validated software package for hydrodynamic simulations, in both laboratory experiments as natural geophysical conditions (DHI, 2008f). The model set-ups used have not been properly validated due to the lack of data, such as current speeds in the model domain. The results from flat bathymetry of 30 m were checked against the few values known of current speed at the measuring buoy at Läsö and the Baltic current speed (Appendix 12).

4. MODELLING RESULTS

Impacts on hydrography and sediment transport have been found by comparison of simulations with sixty generators to a reference scenario without. Figures of current speed change and seabed thickness change caused by the generator presence are presented in percentage. Impact on current speeds and sediment movement was found for all the different model set-ups and compilation of the results area shown in Table 1 and Table 3. Changes in hydrography and sediment were small and very locally distributed such as less then 2 % current speed decrease within a distance of 200 m from the cluster of generators from the Bohuslän simulations.

4.1 FLAT BATHYMETRY

Hydrodynamic simulations were conducted in two steps -first without generators and then with 60 generators in a cluster previously described.

Table 1 Results from hydrodynamic simulations with flat bathymetries, current speeds and reductions due to generator presence

Bathymetry	*Average current speed in middle of park area [m/s]*	*Standard deviation current speed*	*Highest mean reduction [m/s]*	*Area average of the highest CFL for each element*	*Highest mean reduction [%]*	*Distance from cluster to 1 % decrease [m]*
40 m depth	0.186	0.0865	-0.00584	0.307	-2.93	940
30 m depth	0.165	0.0778	-0.00676	0.307	-3.77	1050
20 m depth	0.132	0.0677	-0.00793	0.307	-5.41	1300

Current speed differed for the different depth scenarios according to Table 1. Current speed reduction was found to be largest for the 20 m deep domain in terms of absolute numbers as well as percentage change compared to the reference scenarios, without generators. The generator size was constant and thereby it takes a larger part of the water column for the shallower simulations, causing a larger blocking in terms of current speed reduction. The area extent of current reduction was largest for the 20 m deep simulation. Decrease of current speed in the wake from the cluster extended furthest out for the 20 m domain, which can be seen in result figures and Table 1 giving the max distance for each simulation to 1 percentage decrease.

Table 2 Flow model set-ups, the main settings done for hydrodynamic simulations in MIKE

Parameter	***Value***
Mesh and Bathymetry	Flat bathymetries; 20, 30 and 40 m depth Figure 5)
Simulation Period	050401-050405
Time Step Interval	3600 s
No. of Time Steps	117
Solution Technique	Low order, fast algorithm Minimum time step 0.01 s Maximum time step 3600 s
Initial Surface Level	0
Wind	Varying in time, constant in domain. Data from Gothenburg (Appendix 4)
Wind Friction	Varying with wind speed: At 7 m/s $c_d = 0.001255$ At 25 m/s $c_d = 0.002425$
North Boundary	Water level at Gothenburg, constant along boundary (Appendix 3)
West Boundary	Interpolated between Gothenburg and Ringhals
East Boundary	Interpolated between Gothenburg and Ringhals
South Boundary	Water level at Ringhals, constant along boundary (Appendix 3)
Eddy Viscosity	Smagorinsky formulation, Constant 0.28
Resistance	Manning number. Constant value 32 $m^{1/3}/s$
CPU Simulation Time	3 h

The only parameter changed between the different simulations was depth, 40, 30 and 20 m, applied as constant depth in the model domain. The hydrodynamic situations in the middle of the power park area for the flat bathymetries are shown in Appendix 13. The depth is influencing the hydrographic situations in terms of current speed magnitude, as seen in current roses from (0, 0) middle of the wave power park area (Appendix 15). Increase of depth gave higher current speeds with the same water level changes at the boundaries.

4.1.1 40 meters depth

Solution stability

The CFL number must to be less than 1 for a given element in order to generate stable solutions. For the 40 m deep flat bottom the maximum CFL numbers in the wave power park area can be seen in Figure 12, with mean CFL of 0.307. CFL distributions were similar for the different flat bathymetry set-ups, shown in Appendix 13. Only two mesh elements showed values close to one, thereby the calculations were stable with the time steps set.

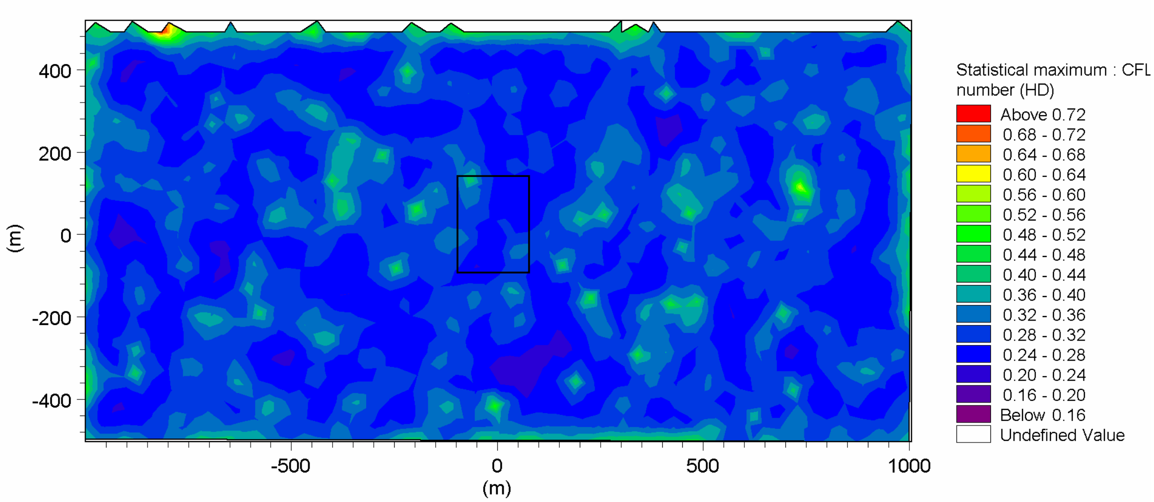


Figure 12 CFL numbers maximum in wave power park area that can be seen in Figure 8, 40 meters deep bathymetry. The location of the generator cluster is shown with the black rectangle.

Structures standing on the bottom can cause blocking of sea currents (Andersson et al., 2008). To detect such changes, reference scenarios without generators were simulated. The current speed change, due to the cluster, was obtained by extracting the current speeds in reference scenarios from simulations with generators. Result plots were created with the statistical tool in MIKE, and by the reusable procedure of simulation results. This was done with data manager in MIKE, where 2D unstructured files (.dfsu), result files, can be used in the calculations. The simple function for generating the data to Figure 13 was eq. 4.

$$\text{Current speed change percent} = \frac{\mathrm{Var2}-\mathrm{Var3}}{\mathrm{Var3}} \times 100 \qquad (4)$$

Var2 – Current speed from flat bathymetry of 40 m with generators
Var3 – Current speed from flat bathymetry of 40 m

The cluster is centered in the park area shown and the mean current is going from north to south (Appendix 15), the shape of the decrease in current speed is extended in the north-south direction in the wake of the cluster. The maximum decrease of less than 3 % was within and immediately behind the cluster area downstream the mean current direction. Areas with increased current speed up to 0.2 % were found in small areas at the side of the cluster. By the blocking of the generators water was pushed to the sides, increasing the current speed.

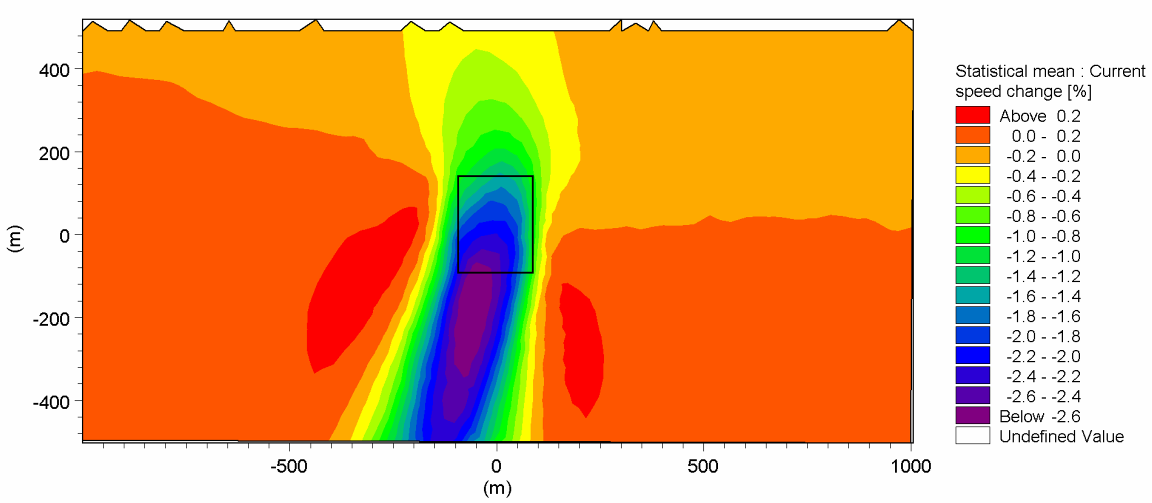


Figure 13 Mean current speed, 40 meters bathymetry in power park area marked with orange rectangle in Figure 8. 60 generators were placed in a cluster marked with the black rectangle. Current speed change is given in percent of the current speed from the reference scenario without generators.

4.1.2 30 meters depth

The mean blocking during the time simulated was of maximum 4 % in the cluster area (Figure 14). Current speeds were increased at the sides of the cluster due to the blocking and redirection of water, in local parts up to as much as 1 %.

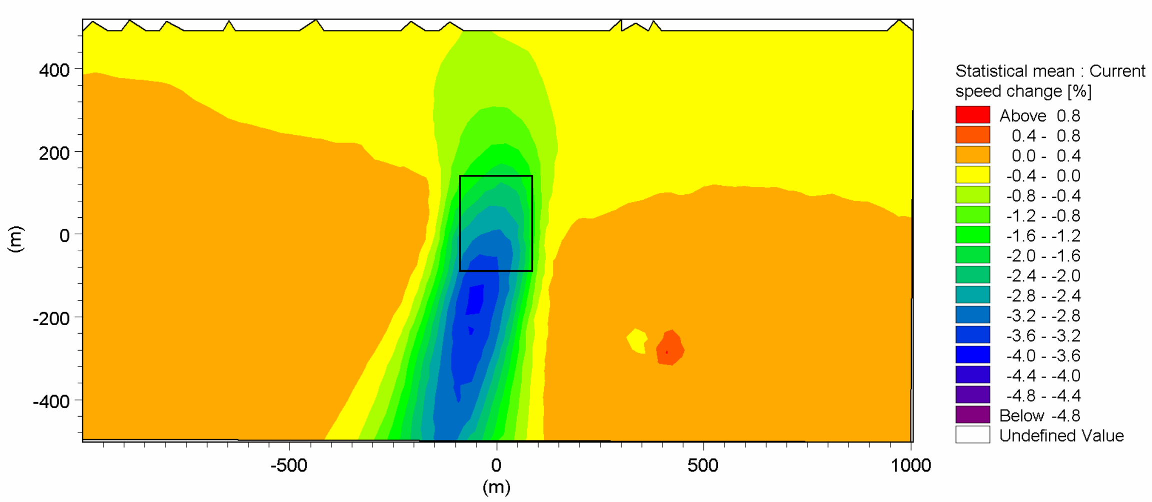


Figure 14 Mean current speed change with 60 generators, 30 meters bathymetry in Power Park area.

4.1.3 20 meters depth

Time average change in current speed in percent, cluster marked with black rectangle in Figure 15. The element with the most reduction in current speed showed value of about 5 %. In the same way as for the other flat simulations an increase in current speed was found at the sides of the cluster, element maximum of about 0.4 on the left side and 0.5 on the right side of the cluster.

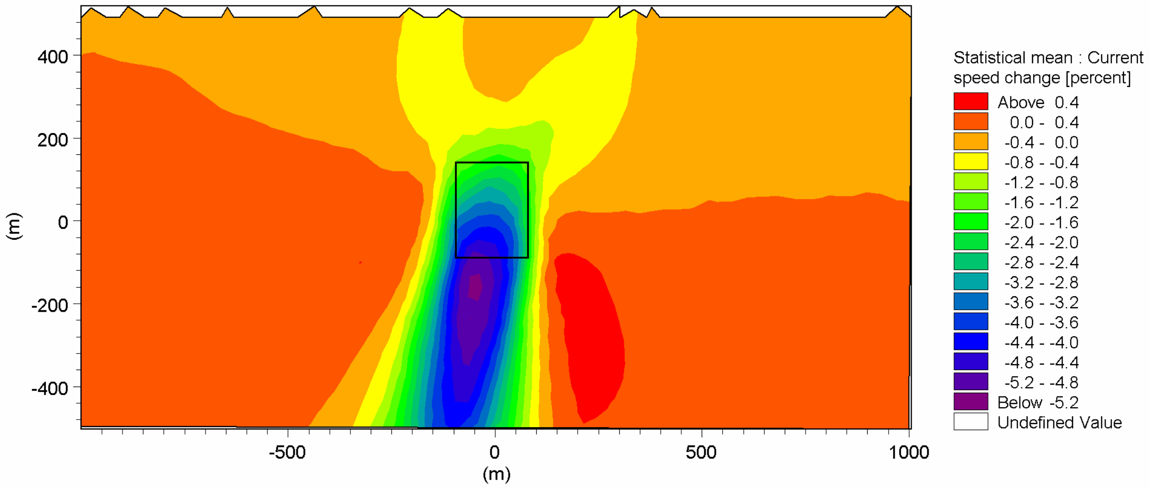


Figure 15 Mean current speed change with 60 generators, 20 meters bathymetry in Power Park area.

4.1.4 Sediment movement

The simulation with the MT module was forced with the hydrodynamic conditions (current speeds) that can be seen in Appendix 12. Figure 16 shows sediment thickness change caused by the generator cluster. The hydrodynamic situation used for forcing the mud transport module is similar but not the same as the hydrodynamic situations in Figure 14 used for analyzing generator influence on current speeds.

The sediment model was not properly calibrated or validated and therefore the results in absolute numbers were not seen as interesting. The differences in percentage with generators compared to without were thought to be of higher significance. For the 30 meters flat bathymetry with generators, the change in bed layer thickness change was calculated, (eq. 5). The current speed changes due to the generators on 30 m depth influenced total sediment thickness change (Figure 16).

$$\text{Change in bed layer thickness change in percent} = \frac{\mathrm{Var2} - \mathrm{Var3}}{|\mathrm{Var3}|} \times 100 \qquad (5)$$

Var2 – With generators flat bathymetry of 30 m change in bed layer thickness
Var3 – Without generators flat bathymetry of 30 m change in bed layer thickness

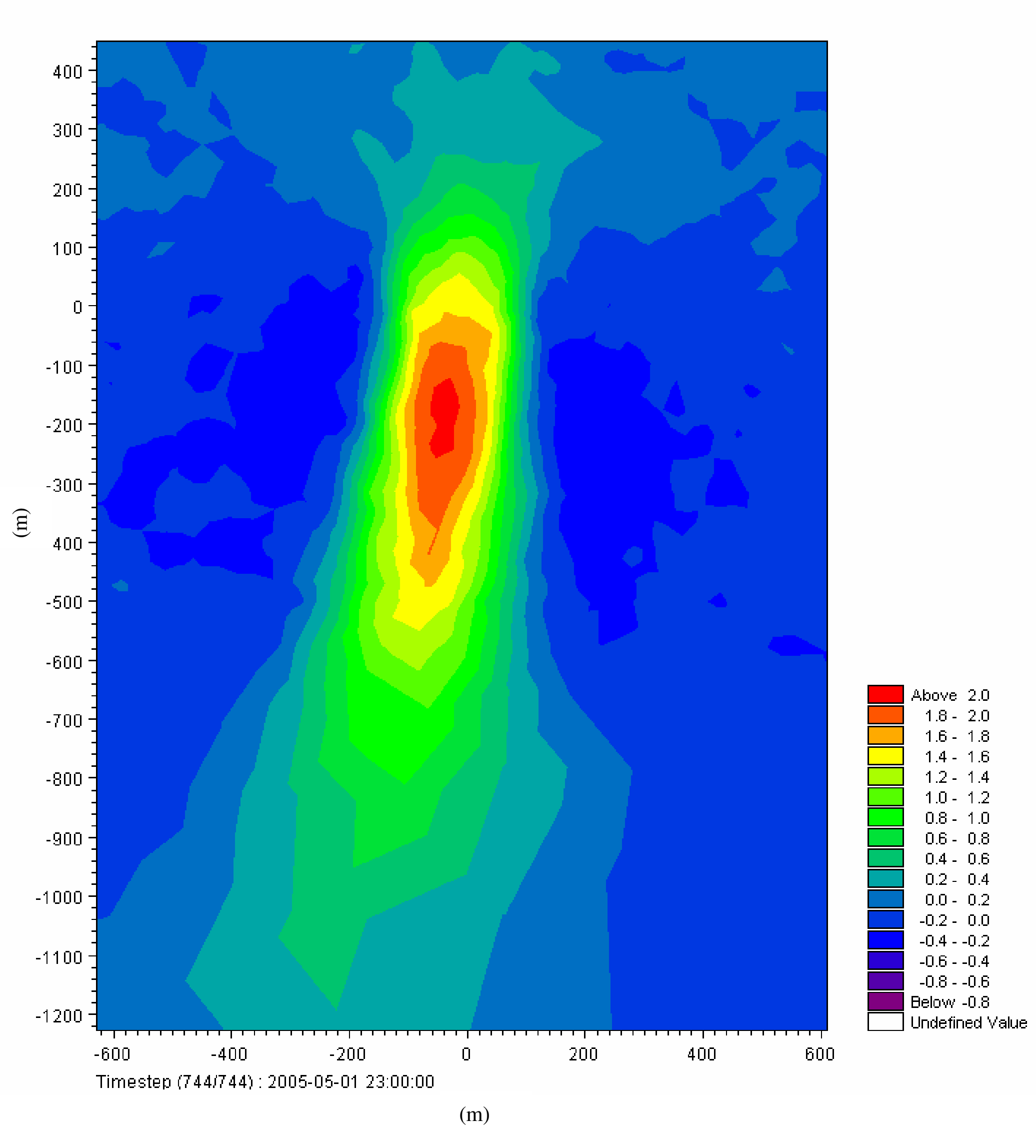


Figure 16 Total bed thickness change in [%] due to cluster of generators at 30 m depth 050410-050502.

The sediment change was strongly correlated with the current speed change. In the simulations done the total layer thickness decreased but 2 % less in the cluster area.

4.2 BOHUSLÄN COASTAL AREA

In this model set, intended to represent a real coastal area, manning number varied with depth and bottom substrate which resulted in a more complex hydrographic environment compared to the flat domains. With such domain, currents changed direction and magnitude in the park area. Current speed and direction from the middle of the cluster area can be seen in rose diagram in Appendix 9. Current speed presented as time series and other hydrographic information is given in Appendix 8.

Table 3 Results from hydrodynamic simulation within 15 km from the generator cluster. Current speeds and reductions due to generator presence

Bathymetry	***Average current speed in middle of park area [m/s]***	***Standard deviation current speed [m/s]***	***Highest mean reduction within 15 km [m/s]***	***CFL mean in cluster area***	***Speed decrease in park area, highest mean reduction [%]***	***Distance from cluster to 1 % decrease [m]***
Bohuslän	0.0465	0.0276	-0.0008	0.0665	-1.80	160

Current speed in the full model domain (Figure 10) was at its maximum in some areas in order of the Baltic current, 0.5 m/s -1.0 m/s. For the sheltered location of area-A the current speed was much lower with an average of about 0.047 m/s (Table 3). That is almost just a third of the current speeds present for the flat bathymetries. Current speed decrease of 1 % could only be found with in a couple of hundreds of meters from the generator cluster.

Table 4 Flow model set-up, the main settings done for hydrodynamic simulations in MIKE

Parameter	***Value***
Mesh and Bathymetry	Bohuslän coastal area (Figure 10)
Simulation Period	HD: 050514-050529 and MT: 050529-050605
Time Step Interval	3600 s
No. of Time Steps	529
Solution Technique	Low order, fast algorithm Minimum time step 0.01 s Maximum time step 3600 s CFL max 0.8
Initial Surface Level	0.032 m
Density	Barotropic (constant)
Wind	Varying in time constant in domain, mean from stations Måseskär and Väder Öarna (Appendix 10)
Wind Friction	Constant $c_d = 0.001255$
North Boundary	Water level Smögen (Appendix 11)
West Boundary	Land boundary, normal velocities
East Boundary	Land boundary, normal velocities
South Boundary	Modified Water level Stenungsund (Appendix 11)
Eddy Viscosity	Smagorinsky formulation, Constant 1
Bed resistance	Manning number, varying (Figure 11)
CPU Simulation Time	140 h

Solution stability

Mean CFL in cluster area (marked as black triangle) was 0.067 and max CFL was 0.17 (Figure 17). CFL numbers vary with depth and mesh size according to eq. 4. The variations in area-A (white border) and the area closest by the cluster (the green area) are seen in Figure 17.

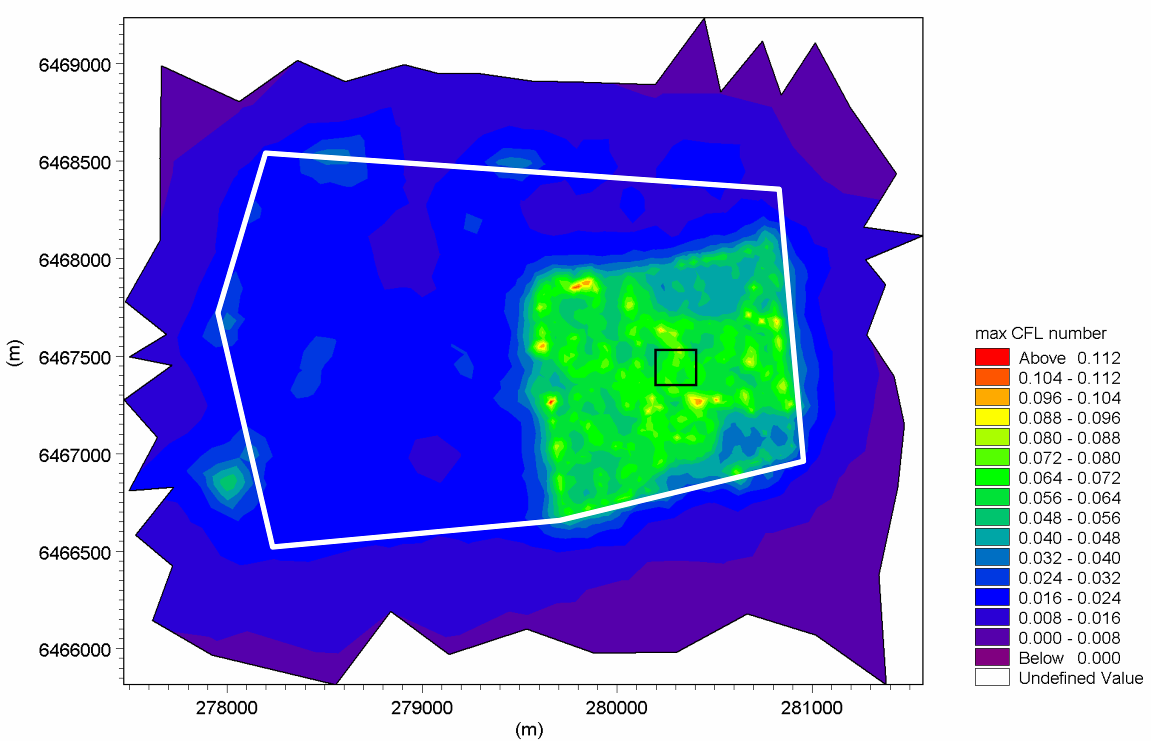


Figure 17 Courant Friedrich Lewy numbers in area-A marked with white border and its closest surroundings. Higher CFL where smaller element mesh and shallower water according to eq. 4.

The current speed reduction, due to the generator cluster, was of local scale with reduced current speeds by half a percentage within a kilometer from the cluster area. The current direction was northwest during the time simulated (Appendix 8). This gave a reduction plume towards northwest in the wake of the cluster (Figure 18).

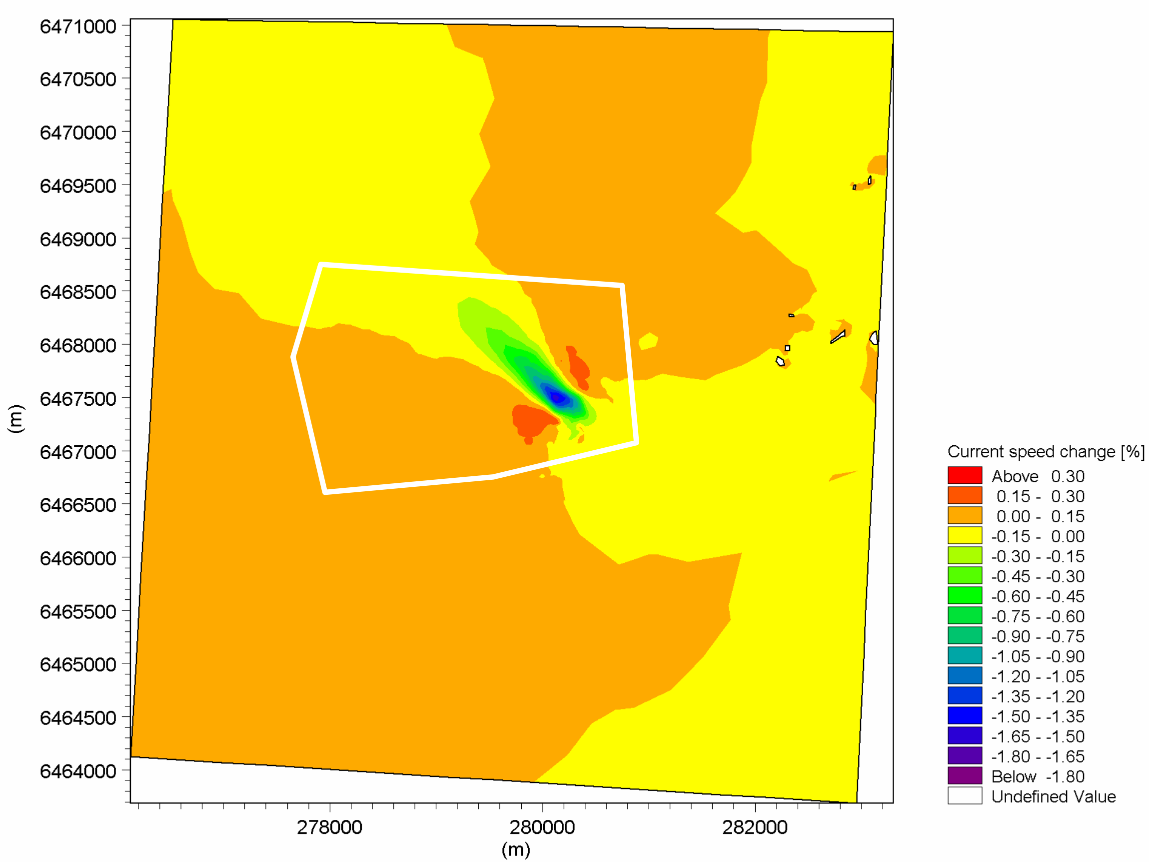


Figure 18 Current speed mean change in a 7 km by 7 km sided square. Area-A marked with white border.

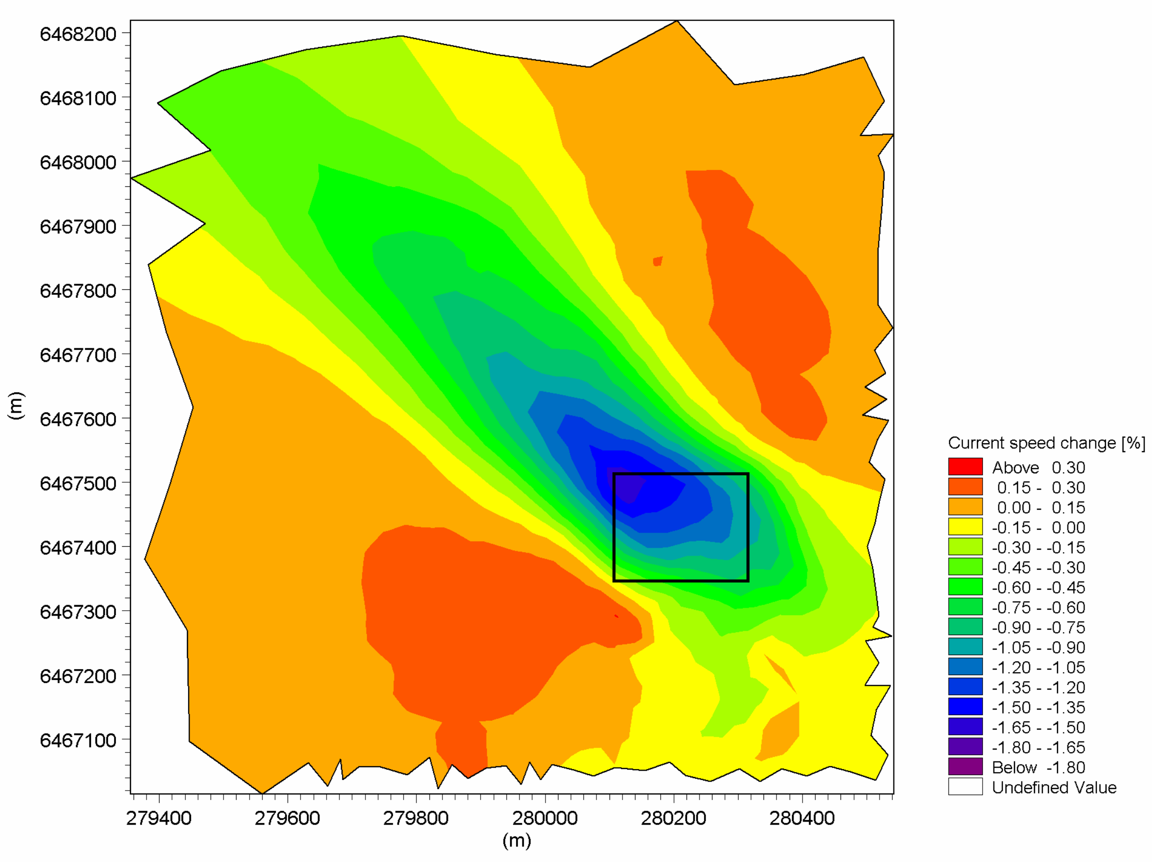


Figure 19 Current speed mean change in 1100 m by 1100 m sided square.

The area with generators marked with the black rectangle in Figure 19, enclosing an area of 180 m by 250 m. The reduction was 1.8 % in the north west corner of this rectangle. That position had the highest mean reduction during the simulation period. With the current direction most generators were in line with the current in the north west corner. The area average reduction in the cluster area was found to be about one percent (-0.996 %). Reduction was extended in the wake of the cluster, where 1 % of current reduction was found 160 m from the cluster and 0.5 % in 550 m. An increase of 0.3 % in current speed was found at the sides of the cluster. Due to the blocking effect, water was pushed to the sides increasing the current speeds.

4.3 Sediment movement

The driving HD run for the sediment simulations were not the same as in the Figure 18 used for hydrography changes, due to the need for finished simulation periods for decoupled files to be functional.

The cluster position is marked by the black triangle in Figure 20 and Figure 21. Equation 6 has been used, as for the flat bathymetry, to obtain the impact on bed thickness change by presence of generators. Results in absolute numbers were not seen as interesting in the same way as for the modelling with flat bathymetries (4.1.4). Changes in percent calculated according to eq. 5 are presented in overview in Figure 20 and zoomed in Figure 21.

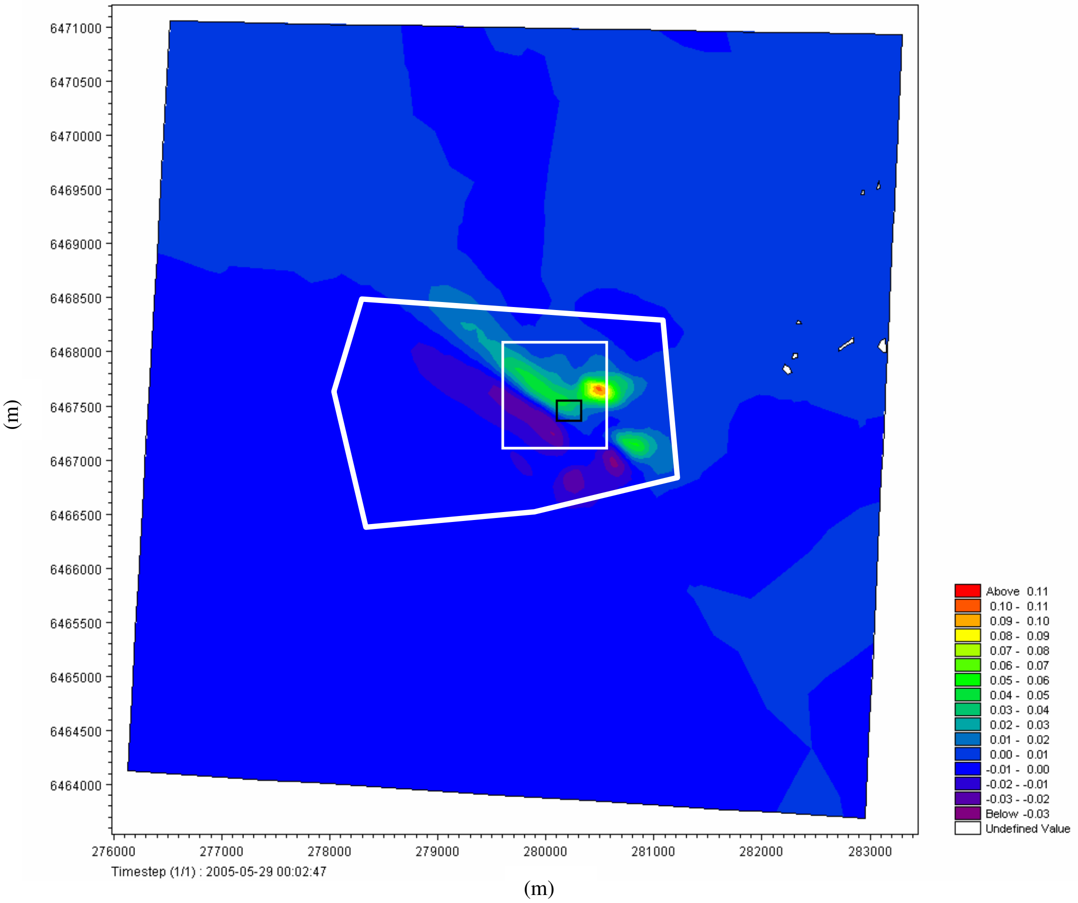


Figure 20 Change in total bed thickness change [%] in 7 km by 7 km sided square. Area-A marked with white border. The main part of the area (blue) is unaffected by the cluster represented by the black rectangle. The area within the thin white square is shown in close up in Figure 21.

The current speed change caused by the cluster causes the sediment change. The seabed layer change was in the same direction as the current speed change (Figure 18 and Figure 20). The area with change in sediment thickness is located in and around the cluster area (Figure 20). Sediment thickness increased by a maximum 0.1 % (red area) close by the cluster and decreased by a maximum 0.04 % (purple area). Comparison to the flat bathymetries the sediment change formation is more complex and not as similar to the current speed change formation. This could be due to the variations in bathymetry and sediment properties.

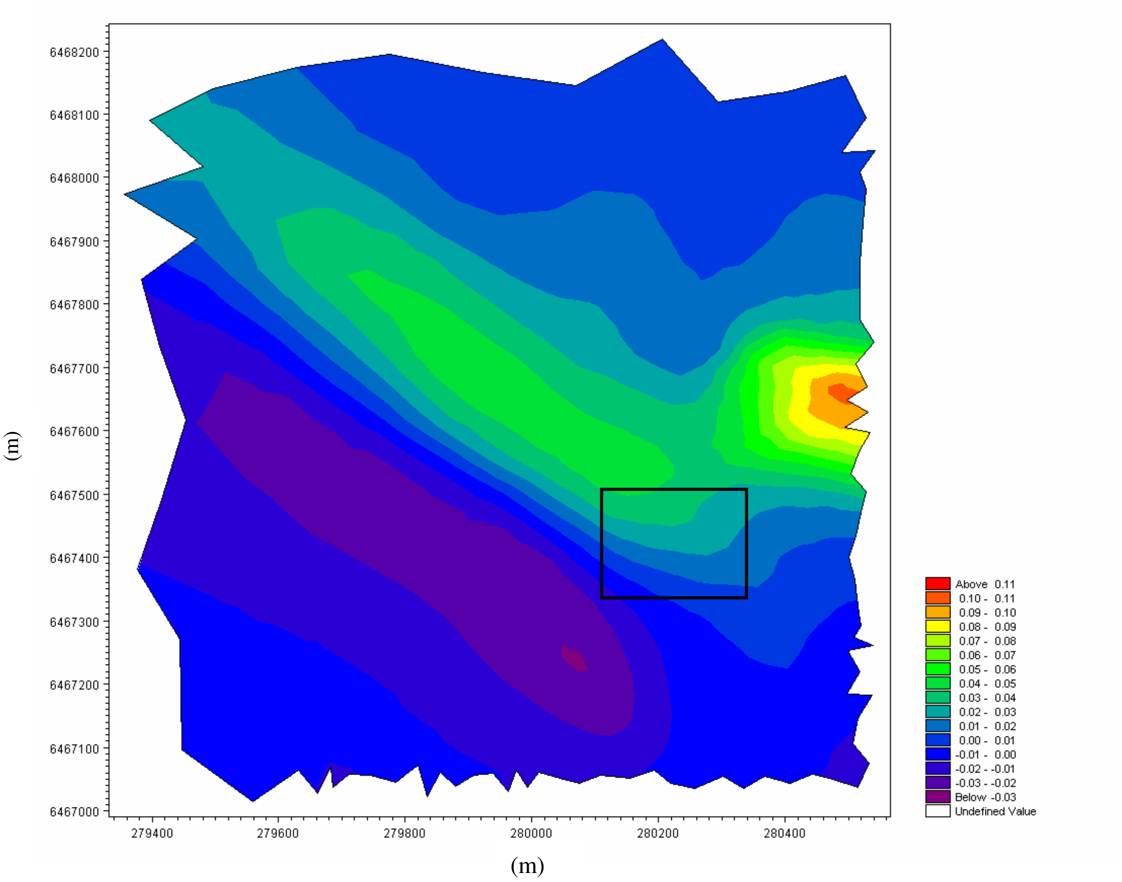


Figure 21 Change in total seabed thickness change [%] in 1100 m by 1100 m sided square surround the most affected area within and close to the cluster area situation generators, marked with the black rectangle.

5. DISCUSSION

5.1 RESULTS HYDRODYNAMIC SIMULATIONS

Generators showed to have some blocking effect in all the simulations with a decrease in current speed in the cluster area and in the wake of the cluster area.

The flat bathymetries had the same varying water level boundaries with different current speeds as result. Current speed increased with depth with average current speeds of 0.18 m/s for 40 m, 0.16 for 30 m and 0.13 m/s for 20 m bathymetry. Even though the deepest domain had the highest current speed it showed the lowest reduction in absolute numbers as well as relative reference scenario; -0.0058 m/s or -2.9 % for 40 m, -0.0068 m/s or -3.8 % for 30 m and -0.0079 m/s or -5.4 % for 20 m bathymetry. Current speed reductions were of local scale with maximums located within or near by the cluster of generators. The shape of the reduction was similar for the different depths tested but magnitude of reduction differed. That for example could be seen in the distance to1 % current speed reduction: 940 m, 1050 m and 1300 m. With decreasing depth for the flat bathymetries (from 40 to 20 m) generators possess larger part of the water column. Thereby more blocking of the bypassing waters was caused. The bottom friction got higher significance for current speed at shallower waters.

Simulations for the Bohuslän coastal area showed due to deepest bathymetry and lowest current speed the lowest current change. In the simulations for area-A the current average speed was 0.047 m/s and the current speed reduction was -0.0008 m/s or -1.80 % at its most. Calculation element with 1 % change was as its furthest only 160 m from the edge of the cluster. The results from the Bohuslän domain may represent possible impact by a cluster of linear generators in a suitable location. If the park would have been real and the results could be confirmed and the model validated. It would have been considered as very low impact compared to the off shore wind farms.

5.2 RESULTS MUD TRANSPORT MODULE

The water current speed was reduced by the presence of the 60 wave power generators, resulting in sediment accumulation in the park area. The hydrodynamic situation used in sediment simulation, was for 30 m flat bathymetry and, showed decrease of current speed in order of a few percent in the park area. Change in sediment transport was of the same magnitude and shaped as the current change. In comparison, in area-A the shape of sediment difference was not as congruent with the shape or magnitude of current speed change. The current was changing direction and magnitude in the park area for the more complex domain of Bohuslän. This could be a reason for the complex formation of sediment movement. As mentioned in 3.5 the sediment simulations done are to be seen as ruff estimations due to the lack of calibration data to the somewhat empirical model. As the generators call for hard bottom to stand on the change in sediment erosion/deposition is thought to be negligible for future parks but site specific situations are possible.

The magnitude of sediment thickness change is not thought to be reflecting actual influence that would occur at the location of area-A. Of greater interest was the formation of the sediment differences due to the park presence.

5.3 COMPARISION OF HYDRODYNAMIC RESULTS WITH EARLIER WORK

5.3.1 Offshore wind farms and Wave Hub

The reduction in current speed by linear generators can be compared to the blocking at the offshore wind farms as Horns Rev with 2 % reduction in current speed. Nysted wind farm with small changes in current and wave climate, change of 3-4 % in flow rate. From simulations of Lillgrund windmill farm in MIKE 21 done by DHI showed current speed reduction of 4 %.

From simulations of Wave Hub, tidal current speed changes of at most -0.8 m/s to 0.6 m/s in a 15 km by 15 km square that did not extend into the coast. For the Wave Hub location tidal current speeds could go up as high as 1.6 m/s and 1.0 m/s to 1.2 m/s in average (Halcrow, 2006). Current speeds of such magnitude have not been present in the simulations done for linear generators.

5.3.1 Induced mixing by windmills

Windmill foundations can have local effect, by standing through the water column, on stratification by induced mixing of deep water and surface water according to SMHI. For windmills that stands through the water column and pass the halocline or thermocline this is a risk. For linear generators, of less than nine meters height, this would just be applicable for very site specific conditions. Stratification due to halocline or thermocline is not expected to be found in the bottom 10 m in deeper areas suitable for wave power. Mixing has not been simulated as the model was 2D.

5.4 SEDIMENT CHANGE

For the Nystedt wind farm insignificant deposition/erosion was found at distance more than 10 m from foundations. No sediment was affected outside the park area. Sediment change from Wave Hub was simulated for 48 hours and no significant sediment change was found. Only small and limited changes close to devices far below levels of natural variations. The Wave Hub site was 50 m deep, so if any, only low sediment impact can be expected according to the investigation done by Halcrow.

5.5 GENERAL DISCUSSION HYDRODYNAMICS AND SEDIMENT MOVEMENT

Offshore wind farms can have impact on coastal morphology, by affecting current speeds and wave heights, but it is highly depending on site specific conditions (Andersson et al., 2008). In the same way there are risks for future wave power parks to affect natural coastal morphologic development. Effects on wave climate have not been included in this work but for parks near sandy coasts as for Wave Hub, effects are possible. According to the Halcrow group the decrease was just about 10 % of natural variations. Larger plants in sensitive areas can potentially have coastal morphological effects direct or indirect as for the Nysted offshore wind farm. For areas with anoxic sediment the possible ecological effects will be limited to water column possible increase in nutrients and pollutants. Offshore wind farms are built in shallower waters compared to future wave power parks. The influence on coastal and seabed morphology by wave power parks are thereby thought to be less. In terms of sand movement in the coastal zone, sediment trapping as well as erosion in the seabed in the closest surroundings to structures. At deeper locations current speeds are lower and thereby the seabed erosion is expected to be less. In the simulations the generators were represented as added friction in the mesh element placed in. The model is not applicable for close up result of area around single generator foundation. For more close up results a model with higher resolution possibilities is needed but in the scale of cluster (about 200 m by 300 m) it has the resolution needed.

The cluster of generators in the flat bathymetry simulations should be directed so the rows of generators are perpendicular to the wave direction. In the way that they would be in a future power park. The cluster was placed in line with the mean flow direction and thereby caused as much blocking possible. The simulated hydrodynamic situation for the flat bathymetries showed a mean current from north to south. The direction should be in the opposite direction for better representation of the Baltic current. With only two water level stations and simple model construction this could not be obtained. In the simulations for area-A the cluster was directed in east-west direction to absorb as much of the waves as possible, with almost exclusively direction from east at the real location.

The investigation was limited to 2D, in the actual case with stratified waters and currents that might differ significant with depth a more complex interaction of generators with current speed and sediment transport can be expected. With more comprehensive data sets the 3D version could have been used. The lack of data was the major limiting factor in this work in terms of calibration and validation possibilities. Simulations performed within this work were very time consuming and comparison of longer time series and from the same period are to be recommended in future work. The HD runs used for current speed results could not be used for MT simulations as preferred for best comparison of hydrodynamic and sediment change. As the simulations did not run to the end of the simulation period and thereby did not create functional decoupled MT files. With the data and model set used the different simulations periods were not thought to not make a significant difference for the results of this work. Better comparison between simulation runs of the hydrodynamic changes and the sediment are of course possible if the same design periods are used for both module results

5.6 RECOMMENDATIONS FOR FUTURE HYDRODYNAMIC SIMULATIONS

To make thorough simulations it is important to have access to quality data. As there are no data of currents in the model domain of the Bohuslän coastal area the model could neither be properly validated nor calibrated. This makes the results of this investigation mainly theoretic and further measurement and latter simulations are needed for more realistic results to be obtained. For example are measurements in the model domain necessary for this possibility.

Hydrographic changes might be more interesting during storms or other time specific scenarios with higher current speeds. Therefore a different design period could have been used or even several. The results could by that been based on more interesting events and better understanding could have been gained of a wave power park impact on hydrography and sediment. The mean effects over the time periods simulated were investigated as the simulations were not thought to reproduce the actual case. As sediment movement is dependent on the bottom substrate and the friction force of bypassing water it is mostly moved around and/or resuspended during strong current events. Wave power parks will most likely be placed in fairly deep waters. Thereby the weather (wave) induced currents are not to be expected to go as deep down as the bottom area situating linear generators. For investigations in shallow waters the HD model is recommended to be coupled with the module Spectral Wave so wave-current interactions can be included. To simulate as much of the wave power park influence on hydrography wave reduction should be included in simulations, due to the energy takeout by the wave power converter.

Flat bathymetries could have been created in a deeper interval for better comparison to the Bohuslän simulations. Current speeds for such runs could also have been chosen in the same magnitude as present in the Bohuslän simulations for better comparison. Thereby conclusions based on more comparable simulations, of wave power park impact on hydrography and sediment movement would have been possible. Sensitivity analysis for the generator impact is highly recommended. Simulate parks with a couple of thousands of units, in several clusters in different park outlays, would be of interest as it has not been included in this work. More aspects that can influence a wave power parks possible impact on hydrography can be investigated. Sensitivity analysis can also be done with wind induced currents and other current scenarios with different return periods. In the way it was done for the mixing calculations for future off shore wind mills at Skottarevet by SMHI (Karlsson et al., 2006).

According to DHI, best practice for simulations of stratified areas is to use 3D modeling. With more quality data available this could also have been used. For a full scale wave power park an environmental impact assessment is needed. For such a thorough investigation, measurements and possibilities of gathering enough samples of data is possible. Boundary conditions can be formed, calibration and validation be done to a satisfactory level. The 3D version is recommended if, and most likely, the park is to be in deep and stratified waters. This report only covers simulations of a small part of a future wave power park. The combined effect of (a couple of) thousands generators might be different than the local effect found in simulations. What should be kept in mind is that offshore windmill farms take up much more of the water column and have been proven cause very little impact on hydrography and sediments.

5.7 RECOMMENDATIONS FOR SEDIMENT INVESTIGATIONS

Estimations of a future wave power parks environmental impact would need to address issues with sediments during all stages of the parks life: construction, operation and removal phase. Possible sediment spill and accumulations are of interest. Sediment type, amount and distribution can affect levels of nutrients and pollutants in the marine environment and are therefore of interest for investigation (Lumborg, 2004). Physics do not cover the processes governing sediment distribution in marine areas in detail today. Empirical models call for measurements of parameters, as can be seen in Appendix 6. The main recommendation for future investigation on sediment impact by wave power is to collect the data needed for the MT module to run properly and produce as good results as possible.

The bottom charts from SGU can, in the full version of MIKE 21, be added directly to the grid generator by the ArcGis application and modified into formats usable in simulations. Seabed charts have been done manually by drawing polygons and can by no mean be said to reach full potential of resolution possible for the measurements available. The GIS application is of great interest for future and more accurate simulations of sediment impact by marine structures as the bottom maps can be much more precise.

Sandeels are sensitive to bottom substrate and are good indicators for changes in sedimentation fluxes (references within Elsam Engineering, 2005). They are also an important food source for marine mammals, fish and sea birds. Therefore IAPEME recommended sampling of sandells in the environmental impact assessment of Horns Rev. If sandeels are present in future wave power park areas such sampling can be used to monitor possible changes in seabed properties. In the Bohuslän area this is not applicable as there are no sandeel populations.

The MT module can be decoupled from the HD and simulations times can be kept much lower than for runs forced with HD results created for each simulation in coupled mode. Sensitivity analysis can by decoupling be done without being too time consuming.

6. CONCLUSIONS

According to the results from simulations done in MIKE 21 wave power park can have some impact on hydrography and sediment movement. The scale of impact was shown to be local within kilometers from the generator cluster simulated. With the properties used the cluster influence on hydrography and sediment is not expected to have impact on the marine environment, if any within the park area. Uncertainties in assumptions and parameter settings in the empirical mud transport module makes the values of sediment transport hard to interpret. Sediment transport is dependent on hydrography. Impact by generators on such will be followed by changes in sediment accumulation, movement and resuspention. Impact by future full scale wave power parks with linear generator technique can be investigated with the method used. The wave power technology developed at Uppsala University is not to be expected to have significant environmental effect on hydrography or sediment movement, if the hydrodynamic and sediment conditions at the site are similar as here investigated.

REFERENCES

Andersson, S., Hammar, L. and Rosenberg, R., (2008). *Miljömässig optimering av fundament för havsbaserad vindkraft*. Naturvårdsverket, ISBN 978-91-620-5828-9

Bernhoff. H., (2007). *Wave power compendium – technology, environment and system, 4th edition*. Division of Electricity Research, Department of Engineering Sciences, Uppsala University, Sweden.

Boström, C., Danielsson, O., Gustafsson, S., Haikonen, K., Langhamer, O., Leijon, M., Strömstedt, E., Stålberg, M., Sundberg, J., Svensson, O., Tyrberg, S., and Waters, R., (2008). *Wave Energy from the North Sea: Experiences from the Lysekil Research Site*. Surveys in Geophysics 10.1007/s10712-008-9047-x

Clement, A., Mc Cullen, P., Falcao, A., Fiorentino, A., Gardner, F., Hammarlund, K., Lemonis, G., Lewis, T., Nielsen, K., Petroncini, S., Pontes, M., Schild, P., Sjöström, B., Sorensen, H. and Thorpe, T., (2002). *Wave energy in Europe: current status and perspectives*. Renewable and Sustainable Energy Reviews 6 405-431

Danish Hydrological Institute, (1999). *EIA of wind power plant at Horns Rev*. Project number 50396-01

DHI Institut for Vand og Miljø, (2000). *Rødsand – VVM-redegørelse for havmøllepark. Vurdering af virkningen på hydrografi, vandkvalitet og Morfologi*. [20080625] Available at: http://www.nystedhavmoellepark.dk/frames.asp?Page_ID=18&Page_Ref=15&Templates_ID=1

DHI, (2008a). Mike 21 Flow Model FM – Hydrodynamic module, User Guide

DHI, (2008b). Mike 21& Mike3 Flow Model FM – Hydrodynamic Module, Short Description

DHI, (2008c). Mike 21 Flow Model FM - Spectral Wave Module, User Guide

DHI, (2008d). Mike Zero – Generic editors and viewers, User guide

DHI, (2008e). Mike 21& Mike 3 Flow Model FM – Mud Transport Module, Short Description

DHI, (2008g). Mike 21& Mike 3 Flow Model FM – Hydrodynamic Module, Scientific Documentation

DHI Institut for Vand og Miljø, (2000). *Rödsand VVM -redegörelse. Undersögelse af hydrografi og vandkvalitet for havmöllepark*. April 2000

Dix, J.K., Lambkin, D.O. and Cazenave, P.W., (In preparation). *Development of a Regional Sediment Mobility Model for Submerged Archaeological Sites*. University of Southampton, English Heritage ALSF Project No. 5224

DN, (2008). Vågkraft ska ge 20 villor el. [2008-06-24] Available at: http://www.dn.se/DNet/jsp/polopoly.jsp?d=147&a=796984

Edelvang K., Møller A. L. and Hansen E. A., (2001a). DHI. *Lillgrund Vindkraftpark, Assessment of effects to the zero solution in Öresund*. Final Report. Project number 51388

Edelvang K., Møller A.L. and Hansen E.A., (2001b). DHI. *Lillgrund Vindkraftpark, Environmental impact assessment of hydrography and sediment spill*. Final Report. Project number 51388

Elsam Engineering and ENERGI E2, (2005). *Review Report 2004, The Danish Offshore Wind Farm Demonstration Project: Horns Rev and Nysted Offshore Wind Farm Environmental impact assessment and monitoring*.

Eriksson, M., (2007). *Modelling and Experimental Verification of Direct Drive Wave Energy Conversion. Buoy –Generator Dynamics.* Acta Universitatis Upsaliensis. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 287. 76pp. Uppsala. ISBN 978-91-554-6850-7

Halcrow Group, (2006a). *Wave Hub Development and Design Phase Coastal Processes Study Report*, South West of England Regional Development Agency.

Halcrow Group, (2006b). *Wave-Hub Non Technical Summary, South West of England Regional Development Agency*, Available online: 2008-06-24, Available at: http://www.wavehub.co.uk/

Hansen, E. A. and Arneborg, L., (1997). *The use of discrete Vortex model for shallow water flow around islands and coastal structures*. Coastal Engineering 32 (223-246).

IPCC, (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Jones, O.P., Petersen, O.S. and Koefod-Hansen, H., (2007). *Modelling of complex coastal environments: Some considerations for best practice*. Coastal Engineering 54 (717-733).

Karlson K., Rosenberg R. and Bonsdorff E., (2002). *Temporal and spatial large-scale effects of eutrophication and oxygen deficiency on benthic fauna in Scandinavian and Baltic Waters – a review*. Oceanography and Marine Biology 40 (427-489).

Karlsson, A., Liungman, O. and Lindow H., (2006). *Överslagsberäkning av vertikal blandning vid Skottarevet vindkraftpark*. SMHI Rapport nr 2006-52. Dnr 2005/854/204

Langhamer, O. and Wilhelmsson, D., (2007). Referee checked conference paper (conference paper, referee checked). *Wave power devices as artificial reefs*

Lind, A. L. and Nordgren, P., (2006a). *Maringeologisk beskrivning, för vågkraft, av tre områden utanför Kungshamn – delprojektanalys 1*. SGU-rapport 2006, Dnr: 08-1653/2006

Lind, A. L. and Nordgren, P., (2006b). *Maringeologisk beskrivning, för vågkraft, av tre områden utanför Kungshamn – delprojektanalys 2*. SGU-rapport 2007, Dnr: 08-1653/2006

Lind, A. L. and Nordgren, P., (2006c). *Maringeologisk undersökning för vågkraft i havet utanför Bohuskusten*. SGU-rapport 2007, Dnr: 08-900/2007

Lindow, H., Lindahl, S., Kriezi, E., Nerheim, S., Nordblom, O. and Wickström, K., (2007). *Pilotstudie Kriegers flak*, SMHI Rapport 2007-22. Dnr. 2006/1059/204

Lumborg, U., (2004). *Modelling the deposition, erosion, and flux of cohesive sediment through Oresund.* Journal of Marine systems 56, 2005, (179-193).

OSPAR Commission, (2004). *Problems and Benefits Associated with the Development of Offshore Wind-Farms*. ISBN 1-904426-48-4

Payne, G. S., (2006). *Numerical modeling of a sloped wave energy device*. The University of Edinburgh.

Petersson, M., (2001). *Vindkraft till havs – en litteratursammanställning av inverkan på djur och växter*, Rapport 5139, Naturvårdsverkets förlag. ISBN 91-620-5139-3

Seabased, (2007a). *Komponenttest vågkraft i Sotenäs*. Seabased Industry AB Uppsala

Seabased, (2007b). *Underlag för samråd juni 2007, Ansökan gällande demoanläggning för vågkraft utanför Bohuskusten.*

Seabased, (2008). Seabased Group, Available online: 2008-11-21, Available at: http://www.seabased.com/docs/20061103Seabased.pdf

Tech-wise, (2002). *Elsam. Offshore Wind Farm. Horns Rev Annual Status Report for the Environmental Monitoring Programme 2001*. Report no.: D- 158037

UU, (2008). Wave Power Project – Islandsberg, Available online: 2008-09-17, Available at: http://www.el.angstrom.uu.se/meny/eng/index_E.html

Waters, R., (2008). *Energy from Ocean Waves – Full Scale Experimental Verification of a Wave Energy Converter*. ISBN 978-91-554-7354-9

Wave hub, (2008). *Wave Hub Project*, Available online: 2008-08-08, Available at: http://www.wavehub.co.uk/

Weisstein, E., Math World "Courant Friedrichs Lewy Condition", Available online: 2008-12-15, Available at: http://mathworld.wolfram.com/Courant-Friedrich-LewyCondition.html

Table of figures

Figure 1 Wake behind one windmill foundation; a) snapshot, b) mean current speed. Each arrow represents the current speed in a particular mesh element (DHI, 2000 p.2-5) . 5
Figure 2 Wave energy converter with buoy, line, linear generator and foundation (Seabased). 8
Figure 3 Three possible formations of wave power parks, a) single area, b) divided area and c) multiple cluster area (Bernhoff, 2007 p. 175). 9
Figure 4 Definition of pier sections, number of sections could be defined and only one was used H_{p3} = 9 m. 13
Figure 5 Model domain for flat bathymetry runs with four varying boundaries. 15
Figure 6 Time-compability of data points in Bohuslän coastal area. 17
Figure 7 Model domain for flat bathymetries, with computational mesh. The mesh size is smaller closer to and within the park area where the cluster of generators were simulated. Close up of the red square with the power park area in the middle can be seen in Figure 8. 19
Figure 8 Calculation mesh with 2 km^2 park area marked with orange rectangle, close up of the blue square representing the cluster area with generators can be seen in Figure 9. 20
Figure 9 Cluster of 60 generators and the computational mesh. Each row consists of 10 generators 20 m apart and the rows are positioned 50 m apart. The triangular elements in the computational mesh are of sizes of maximum 1000 m^2. 20
Figure 10 Bohuslän coastal area mesh and bathymetry with highly resolute grid at area-A marked with white border. Most shallow areas marked with red near the coastline and deepest parts further out at sea marked with blue. 22
Figure 11 Seabed resistances map of area-A and surroundings, 7 km by 7 km sided square. Created in MIKE with guidance from Appendix 16. Varying Manning numbers in area-A marked with white border, highest resistance at bedrock areas (dark) and lowest friction in sandy and shallow area (bright). 25
Figure 12 CFL numbers maximum in wave power park area that can be seen in Figure 8, 40 meters deep bathymetry. The location of the generator cluster is shown with the black rectangle. 29
Figure 13 Mean current speed, 40 meters bathymetry in power park area marked with orange rectangle in Figure 8. 60 generators were placed in a cluster marked with the

black rectangle. Current speed change is given in percent of the current speed from the reference scenario without generators.. 30
Figure 14 Mean current speed change with 60 generators, 30 meters bathymetry in Power Park area.. 30
Figure 15 Mean current speed change with 60 generators, 20 meters bathymetry in Power Park area.. 31
Figure 16 Total bed thickness change in [%] due to cluster of generators at 30 m depth 050410-050502. 32
Figure 17 Courant Friedrich Lewy numbers in area-A marked with white border and its closest surroundings. Higher CFL where smaller element mesh and shallower water according to eq. 4.. 35
Figure 18 Current speed mean change in a 7 km by 7 km sided square. Area-A marked with white border. 36
Figure 19 Current speed mean change in 1100 m by 1100 m sided square..................... 37
Figure 20 Change in total bed thickness change [%] in 7 km by 7 km sided square. Area-A marked with white border. The main part of the area (blue) is unaffected by the cluster represented by the black rectangle. The area within the thin white square is shown in close up in Figure 21. 38
Figure 21 Change in total seabed thickness change [%] in 1100 m by 1100 m sided square surround the most affected area within and close to the cluster area situation generators, marked with the black rectangle.. 39

APPENDIX

Appendix 1 People contacted during research for method and simulation engine.

Hans Bergström, Uppsala University, scientist in meteorology – wind energy. Personal communication: 2008 05 08

Lars Bergdahl, Aquatic and environmental technique, Chalmers University of Technology, Personal communication by email and phone: 2008 05 08 - 09

Marine monitoring, Linus Hammar, email: 2008 05 08

Sara Hallert, Vind forsk, Coordinator, phone: 2008 05 09

Peder Hjort, Aquatic and environmental technique, Faculty of engineering LTH

Stefan Ahlman, DHI, contacted in the end of May and decision of license on the June 3 2008

Appendix 2 Data collection.

<u>Bathymetry</u>

Maja Hemp, Seabased

Gustav Kågesten, marin.se

Marin Miljöteknik AB

Björn Bergman, SGU

Anders Elhammer, SGU

Ole Svenstrup Petersen, Department of Coastal Engineering, DHI Water, Environment and Health

corel.com

<u>Data</u>

Maja Hemp, Seabased

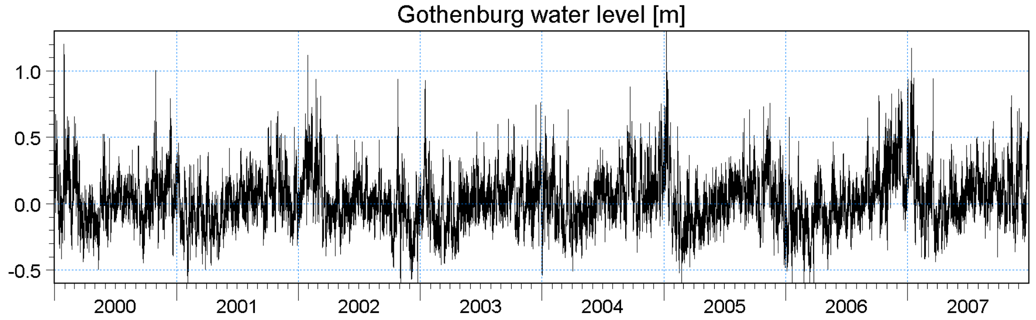
Emilia Lalander, Uppsala University, Department of Engineering Sciences, Electricity

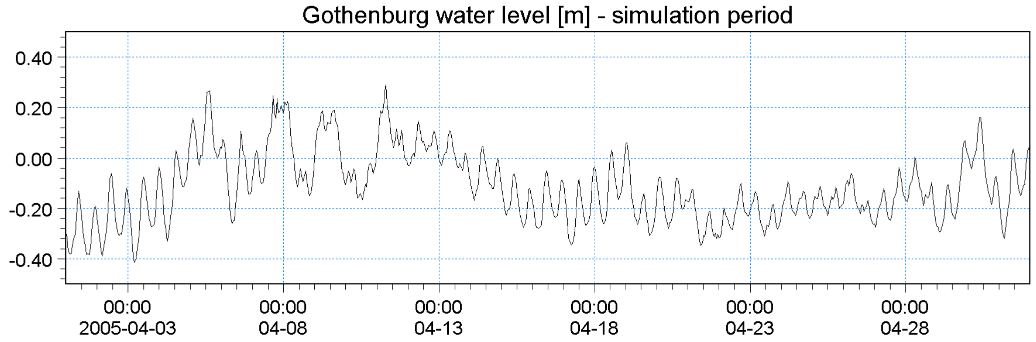
Dr. Philip Axe
Environmental & Safety Services / Oceanography
Swedish Meteorological & Hydrological Institute

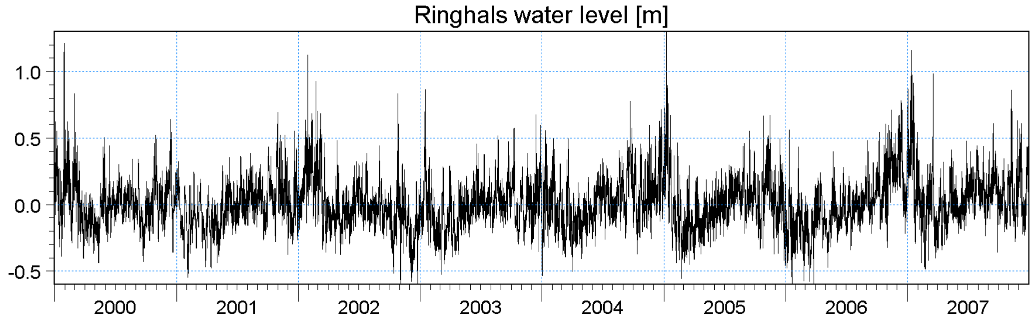
Else-Marie Wingqvist, Swedish Meteorological & Hydrological Institute
Core Services Department - Information and statistics

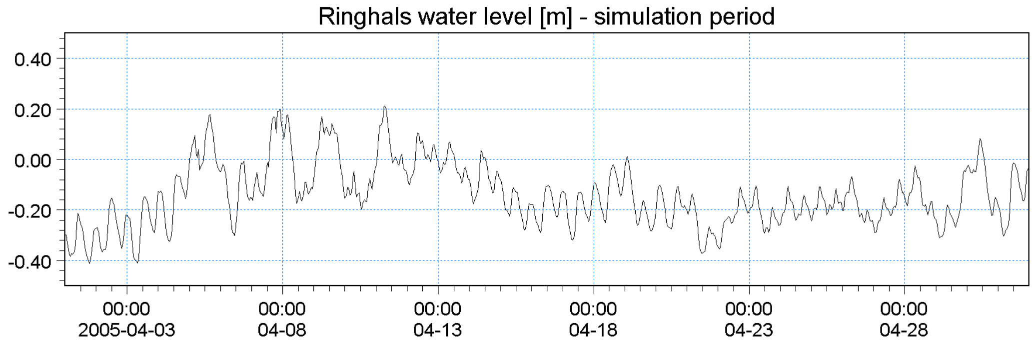
Vandvakt.dhi.dk

Appendix 3 Water levels at Gothenburg and Ringhals.

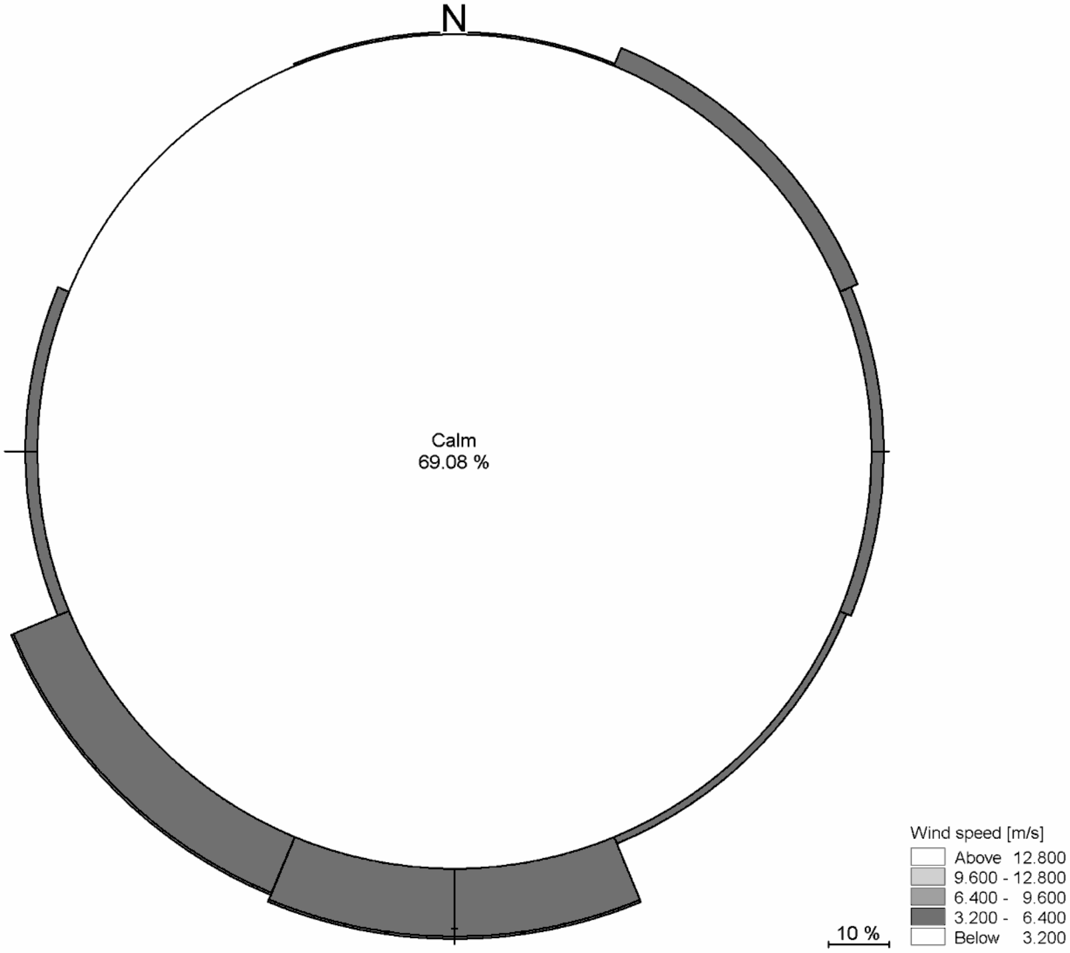

Gothenburg water level [m]


Gothenburg water level [m] - simulation period


Ringhals water level [m]


Ringhals water level [m] - simulation period

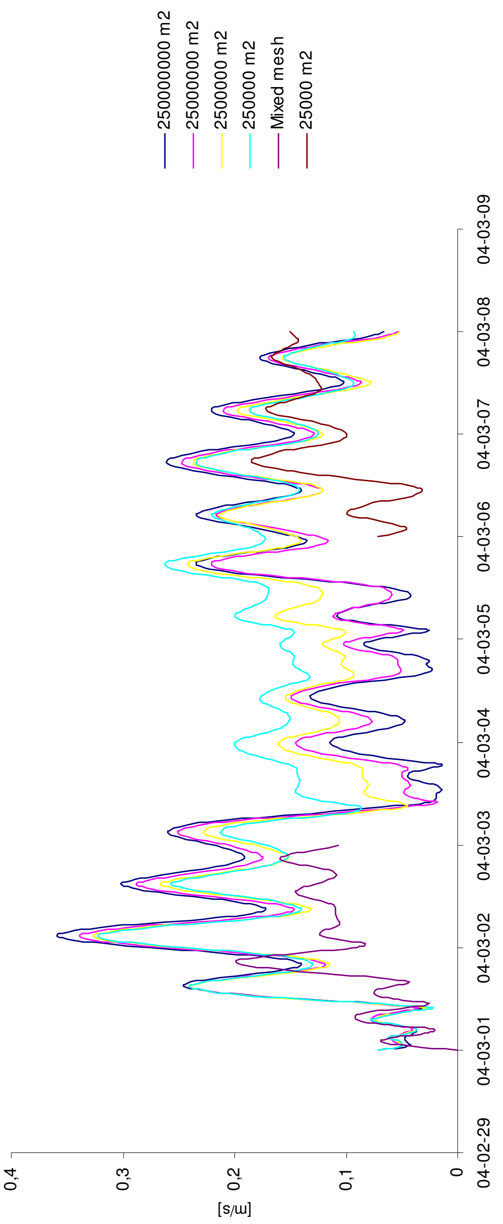
Appendix 4 Wind rose for Gothenburg.



For the time period 050401-050502 that was used for hydrodynamic simulations for flat bathymetries.

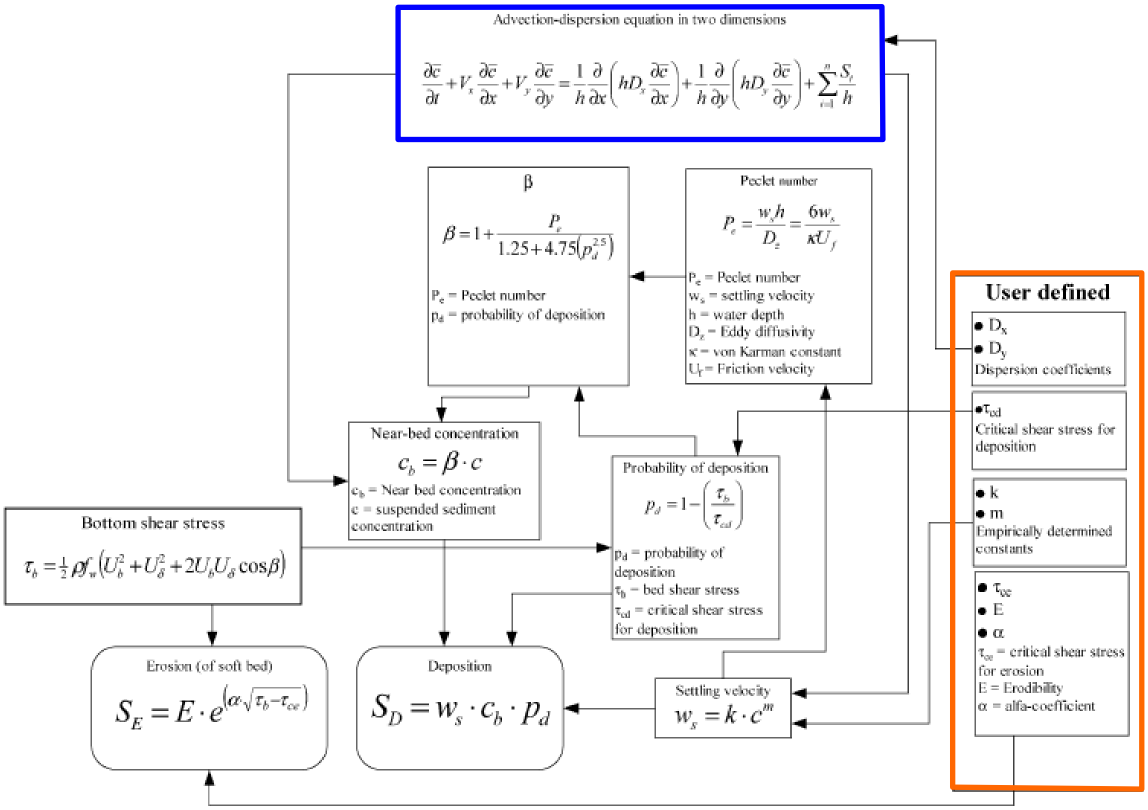
Wind direction was most of the time from south west.

Appendix 5 Current speed in middle of wave power park Figure 8. 40 meters flat bathymetry with different mesh size.



The computational mesh needs to have a surten maximum mesh size to generate as accurate results as possible. At a surten level, decrease in mesh element size do not generate more precise results. In the 15 km by 15 km square in Figure 7 the calculation mesh was varied to find the mesh size needed.

Appendix 6 Flow chart for the MT variables.

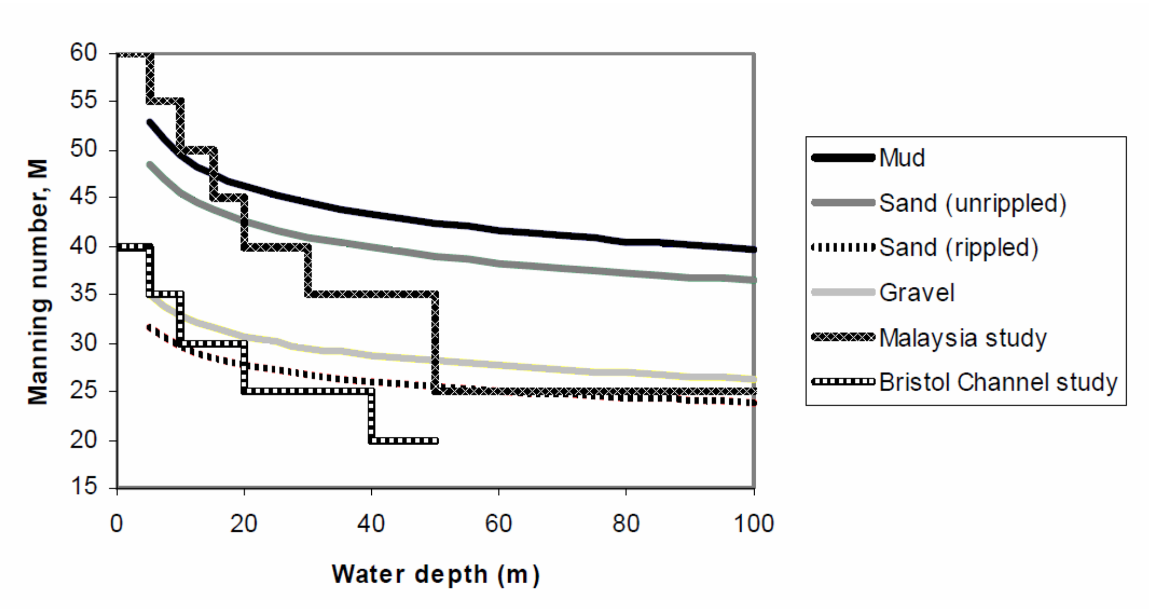


The advection-dispersion equation is governing the MT module seen in the blue rectangle. The user defined parameters are shown in the orange rectangle.

Figure 2, page 291 from:

Lumborg, U., Windelin, A., 2002. *Hydrography and sediment modeling: application to the Romo Dyb tidal area.* Journal of Marine systems 38, 2003, (287-303).

Appendix 7 Depth integrated Manning numbers, depth and seabed dependence.



Manning numbers depth and seabed dependence, also calibrated values from previous studies with MIKE 21.

The bottom types used is: Mud for the clay, Sand (unrippled) for the fine sands and Gravel for the bare rock surfaces.

The figure is taken from p. 4 in:

Dix, J.K., Lambkin, D.O. and Cazenave, P.W. (In preparation) *Development of a Regional Sediment Mobility Model for Submerged Archaeological Sites*. University of Southampton, English Heritage ALSF Project No. 5224

Available from:
http://faq.dhigroup.com/images/FAQ164/Bottom_roughness_parameter_study.pdf at: [081023]

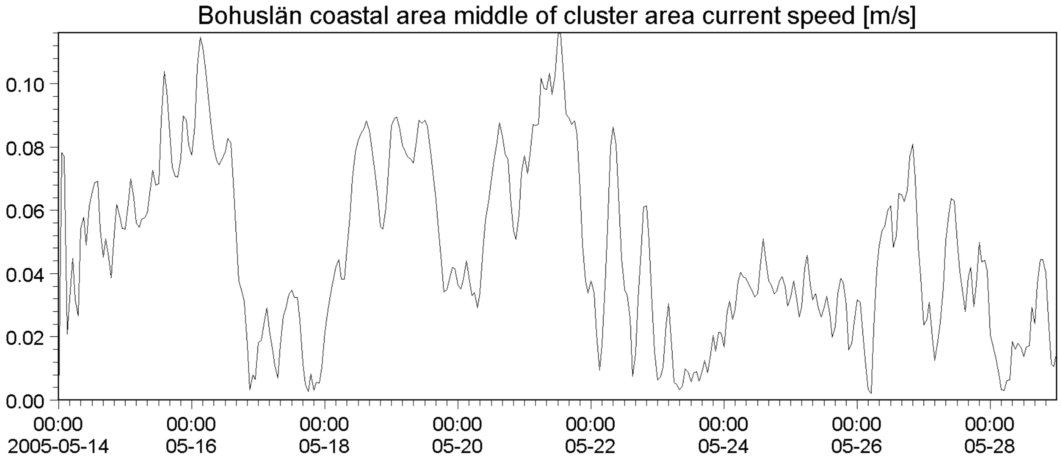
Appendix 8 Hydrographic conditions from simulation for Bohuslän coastal area.

Hydrographic situation in the middle of the generator cluster area marked in Figure 10. It was 49 m deep in middle of the cluster area. Simulation without generators for the time period 050514-050529.

HD results

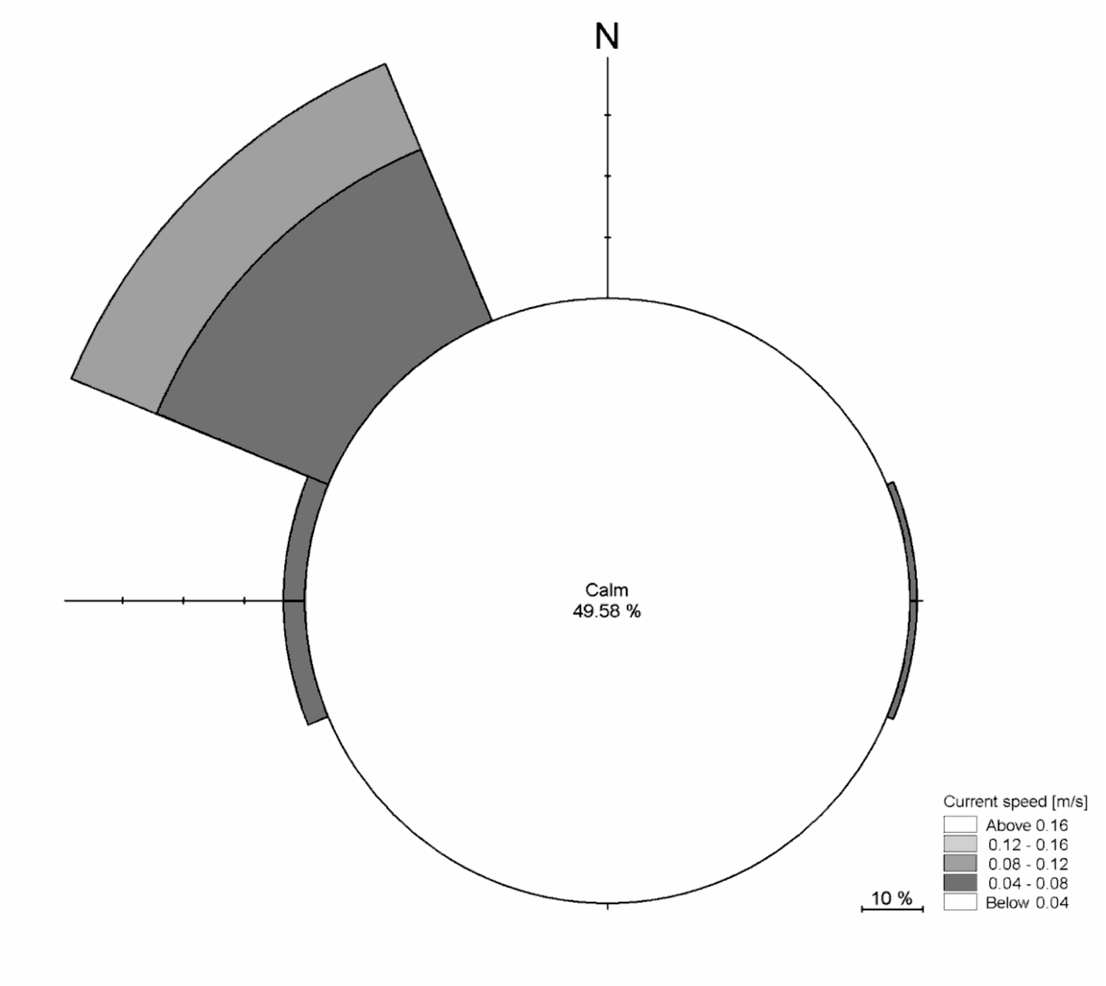
Name	*Min*	*Max*	*Mean*	*Std*
Surface elevation [m]	-0.3937029	0.316523	-0.02814177	0.127551
Current speed [m/s]	0	0.1160833	0.04649022	0.02756721
Current direction [degree]	6.186383	356.8512	281.5916	68.33528
Drag coefficient [undefined]	0	0.002648212	0.002634453	0.0001390586
Eddy viscosity [m2/s]	0	0.2131431	0.07846026	0.03733225
CFL number (HD) [undefined]	0.05123425	0.06580206	0.06247006	0.001388273

The figure shows the current speed in the middle of the cluster area.



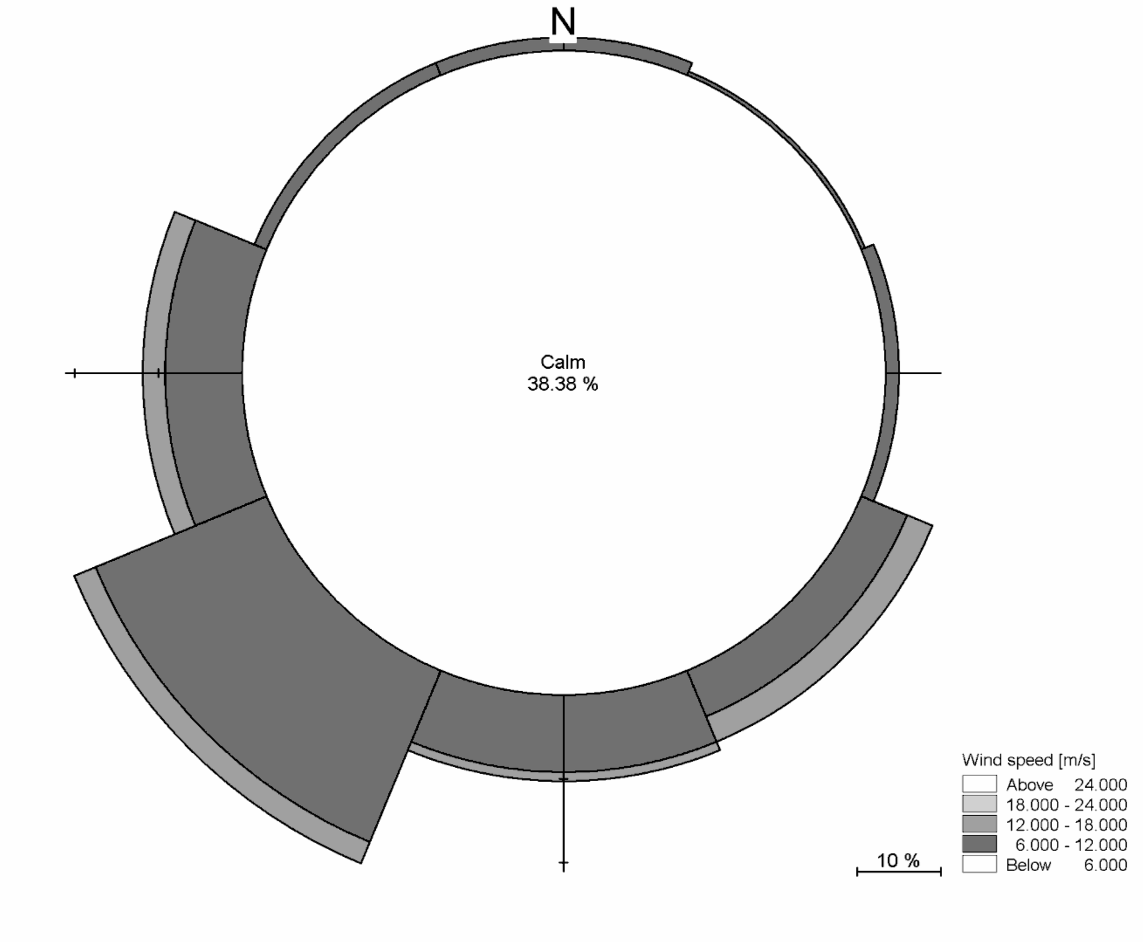
Appendix 9 Bohuslän coastal area, current rose for middle of cluster area.

Area-A, middle of cluster area, 49 m depth, without generators 050514-050529



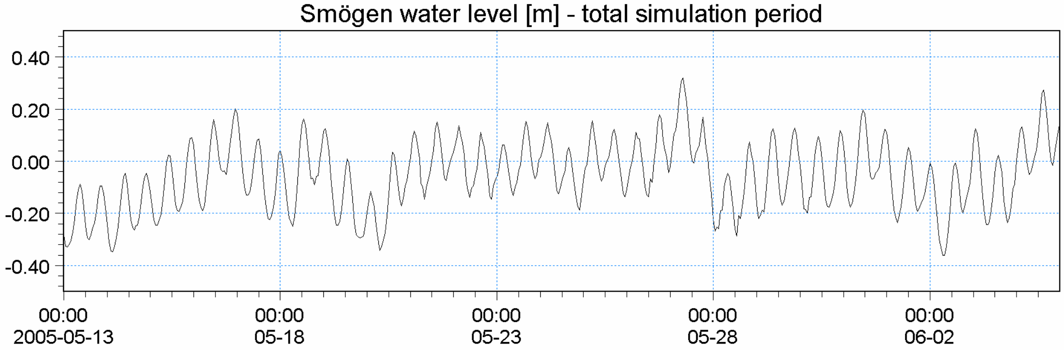
Current direction was most of the time towards north west.

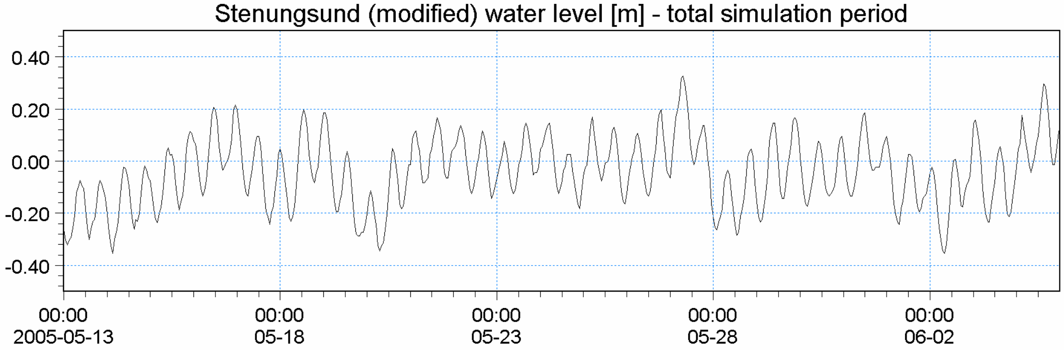
Appendix 10 Wind rose for mean wind from Måseskär and Väderöarna for total simulation time with the Bohuslän area, 050513-050605.

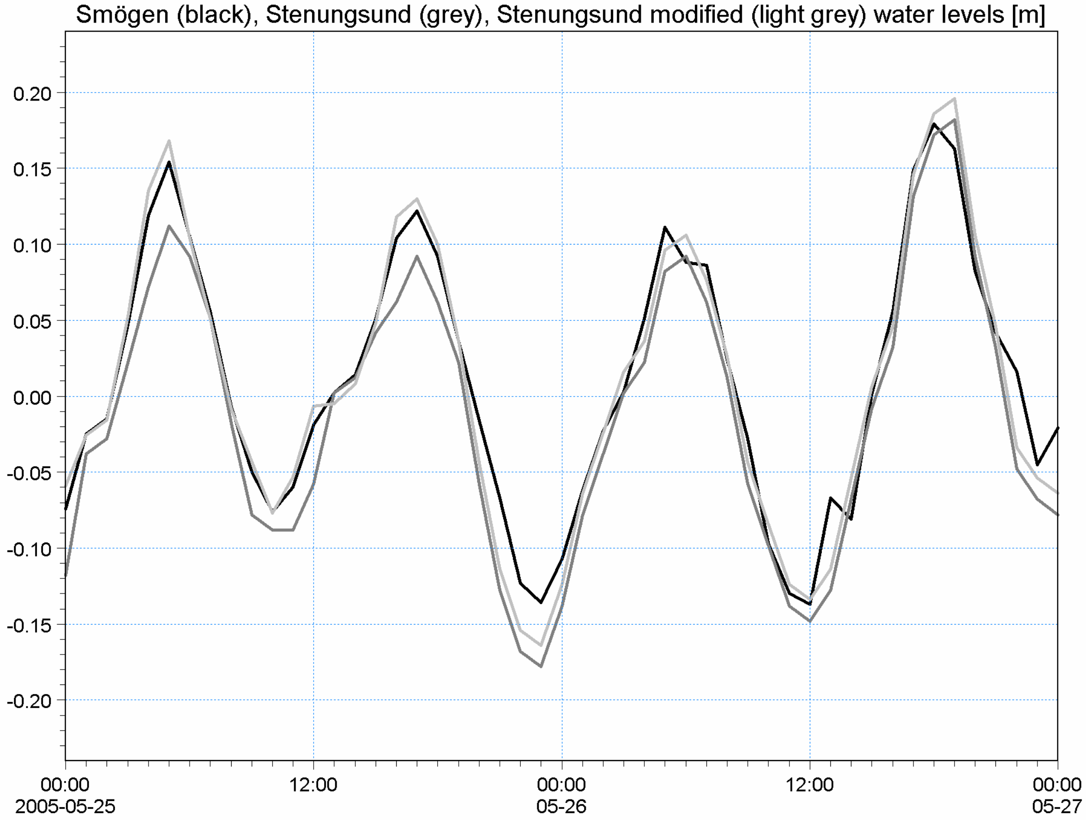


Current direction was most of the time towards south west.

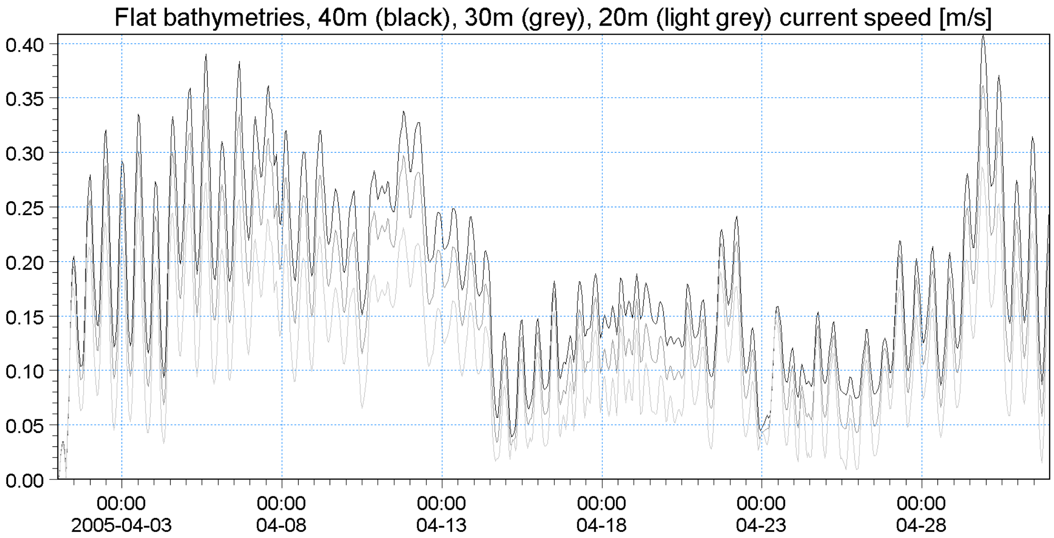
Appendix 11 Water levels at Smögen and Stenungsund.

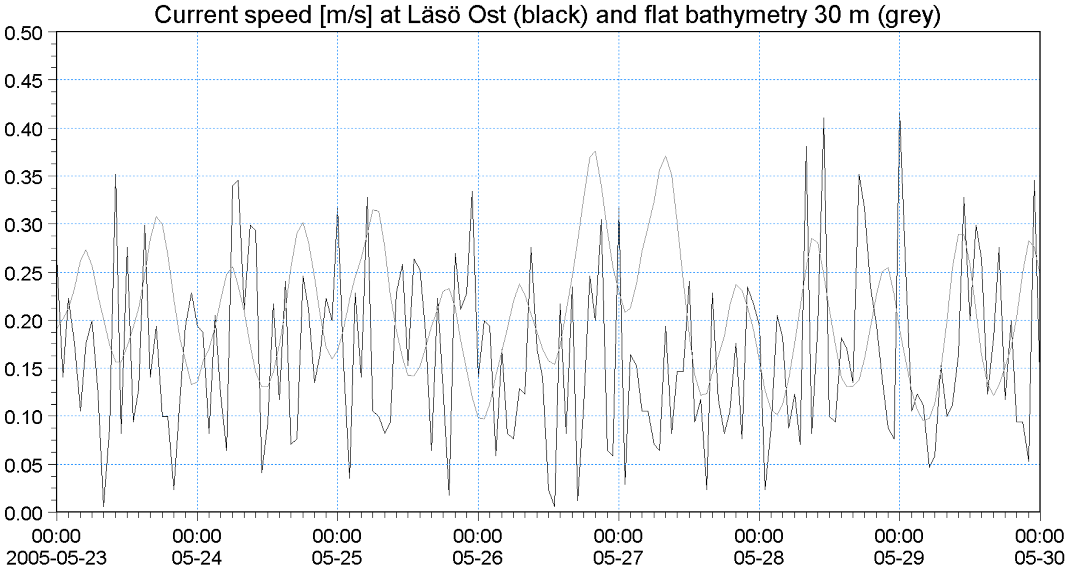






Appendix 12 Variation in current speed with varying depth in flat bathymetries and "validation" against measuring buoy Läsö Ost.





Appendix 13 HD results from flat bathymetries for point (0, 0) without generators.

	Name	***Min***	***Max***	***Mean***	***Std***
Flat bathymetry 40 m					
	Surface elevation [m]	-0.3953744	0.07400985	-0.2245051	0.1036895
	Current speed [m/s]	0	0.33545	0.1858076	0.08652177
	Current direction [degree]	182.9114	359.6071	202.5736	38.93782
	Drag coefficient [undefined]	0	0.002831003	0.002794966	0.0003013781
	Eddy viscosity [m2/s]	0	0.002849682	0.001551919	0.0006171254
	CFL number (HD) [undefined]	0.2632442	0.2647667	0.2646378	0.0001886011
Flat bathymetry 30 m					
	Surface elevation [m]	-0.5943353	0.08115501	-0.2292262	0.1216175
	Current speed [m/s]	0	0.297158	0.1653725	0.07788017
	Current direction [degree]	182.6629	359.2321	201.5926	38.63878
	Drag coefficient [undefined]	0	0.00312054	0.003076326	0.0003139861
	Eddy viscosity [m2/s]	0	0.002288243	0.00135035	0.0004684476
	CFL number (HD) [undefined]	0.2589042	0.2647793	0.2644837	0.0006513589
Flat bathymetry 20 m					
	Surface elevation [m]	-0.6704897	0.2339974	-0.1779683	0.1646116
	Current speed [m/s]	0	0.2610229	0.1319428	0.06767818
	Current direction [degree]	81.13018	357.9827	195.1905	33.08011
	Drag coefficient [undefined]	0	0.003581636	0.003521875	0.0003285458
	Eddy viscosity [m2/s]	0	0.009990171	0.005188662	0.002516427
	CFL number (HD) [undefined]	0.2610623	0.2647668	0.2644363	0.0004611977

Appendix 14 HD results for wave power park area, flat bathymetries.

Current speed change is the change when compared to reference scenario without generators.

40 m deep flat bathymetry

CFL (hd) max	average	0,30708
	median	0,298288
	max	0,99999
	std	0,061176
current speed change [%] mean values	min	-2,92895
current speed change [m/s] mean values	min	-0,00584

30 m deep flat bathymetry

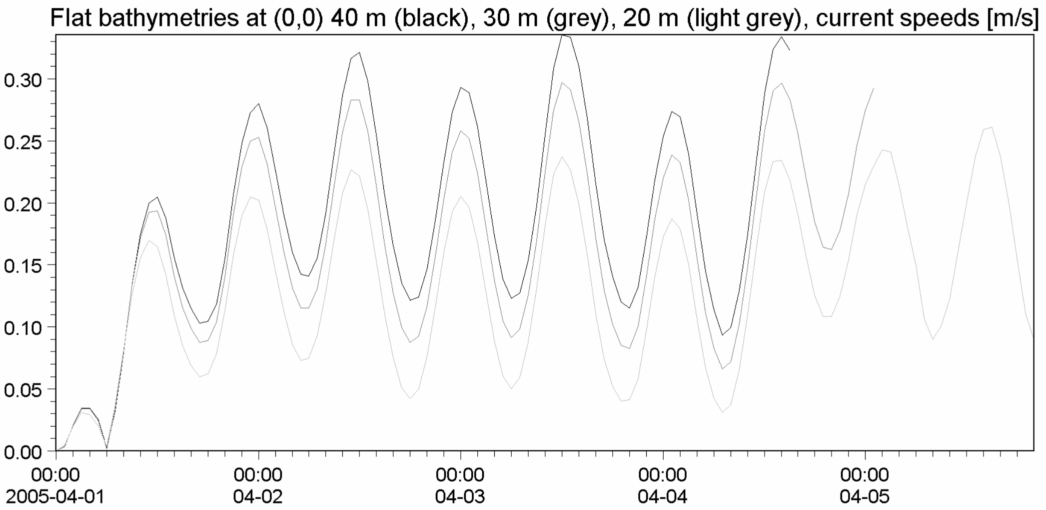
CFL (hd) max	average	0,307093
	median	0,298299
	max	0,999999
	std	0,061178
current speed change [%] mean values	min	-3,768
current speed change [m/s] mean values	min	-0,00676

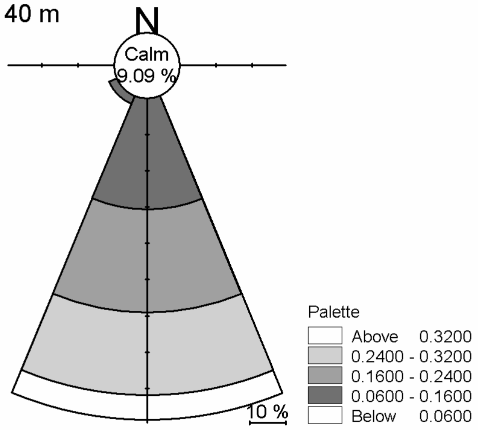
20 m deep flat bathymetry

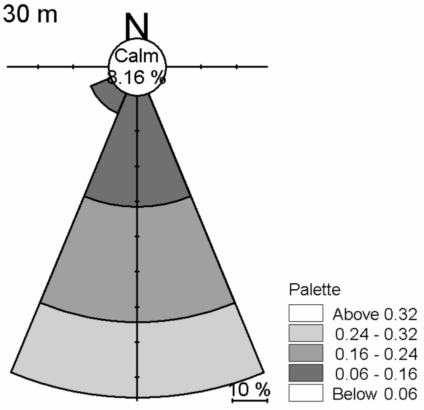
CFL (hd) max	average	0,307086
	median	0,298289
	max	0,999996
	std	0,061177
current speed change [%] mean values	min	-5,40984
current speed change [m/s] mean values	min	-0,00793

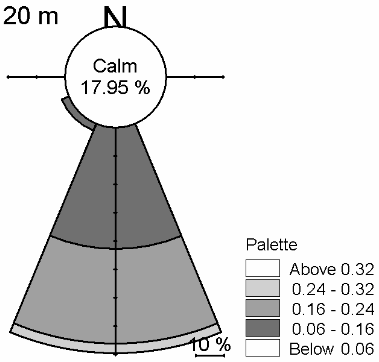
Appendix 15 Current speeds at (0, 0) from flat bathymetry simulations.

Time series and rose diagrams of current speed situations for different domain depth over the same simulation period.

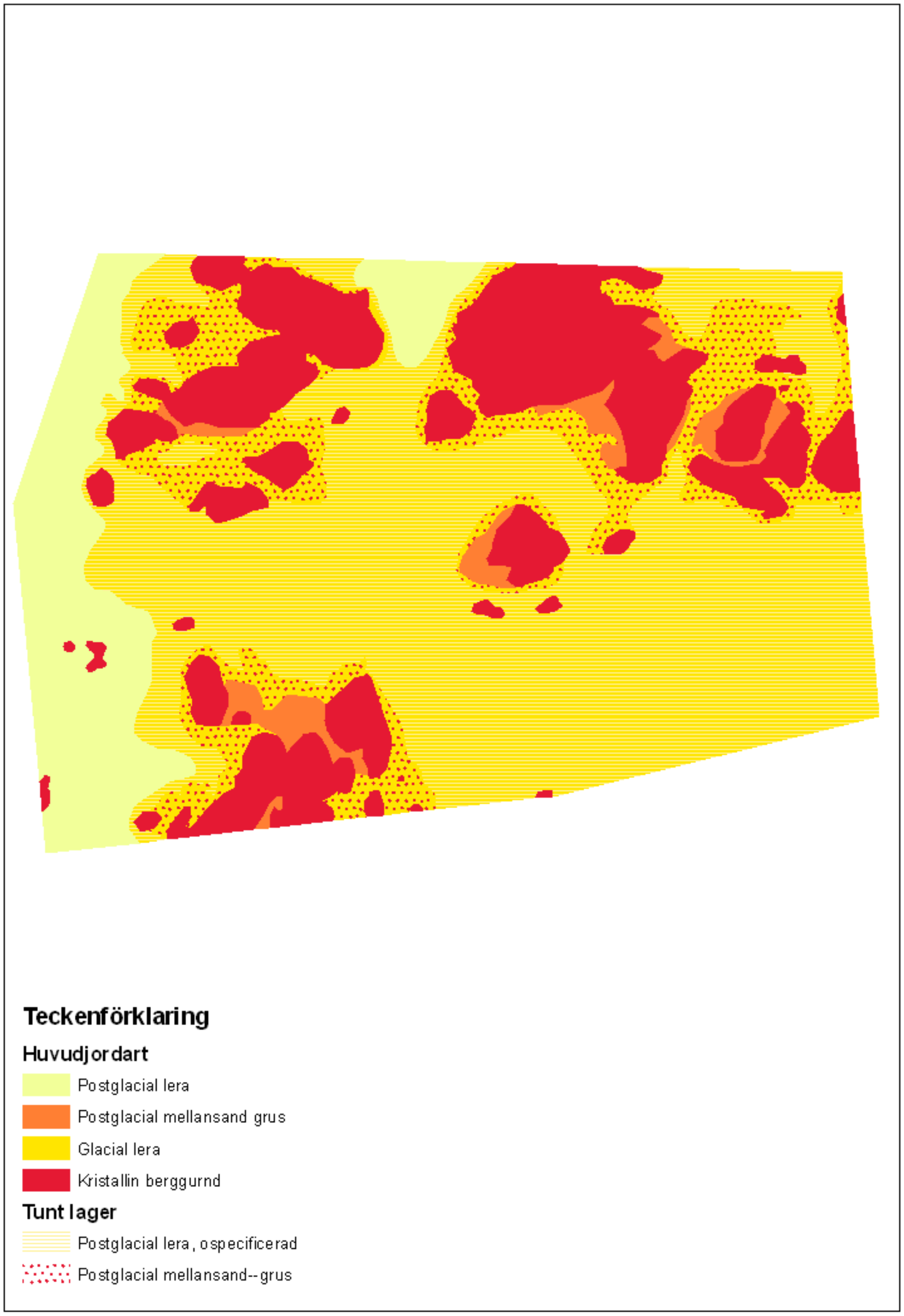






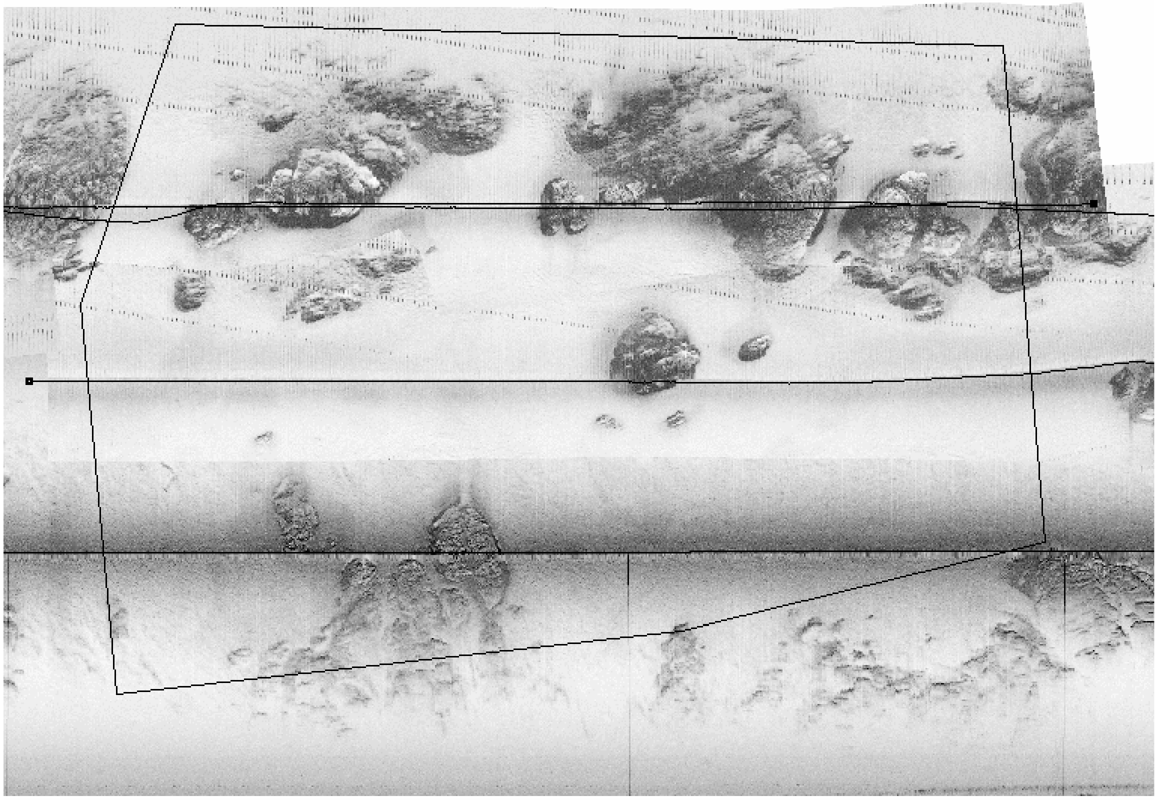


Appendix 16 Sediment types of area-A.



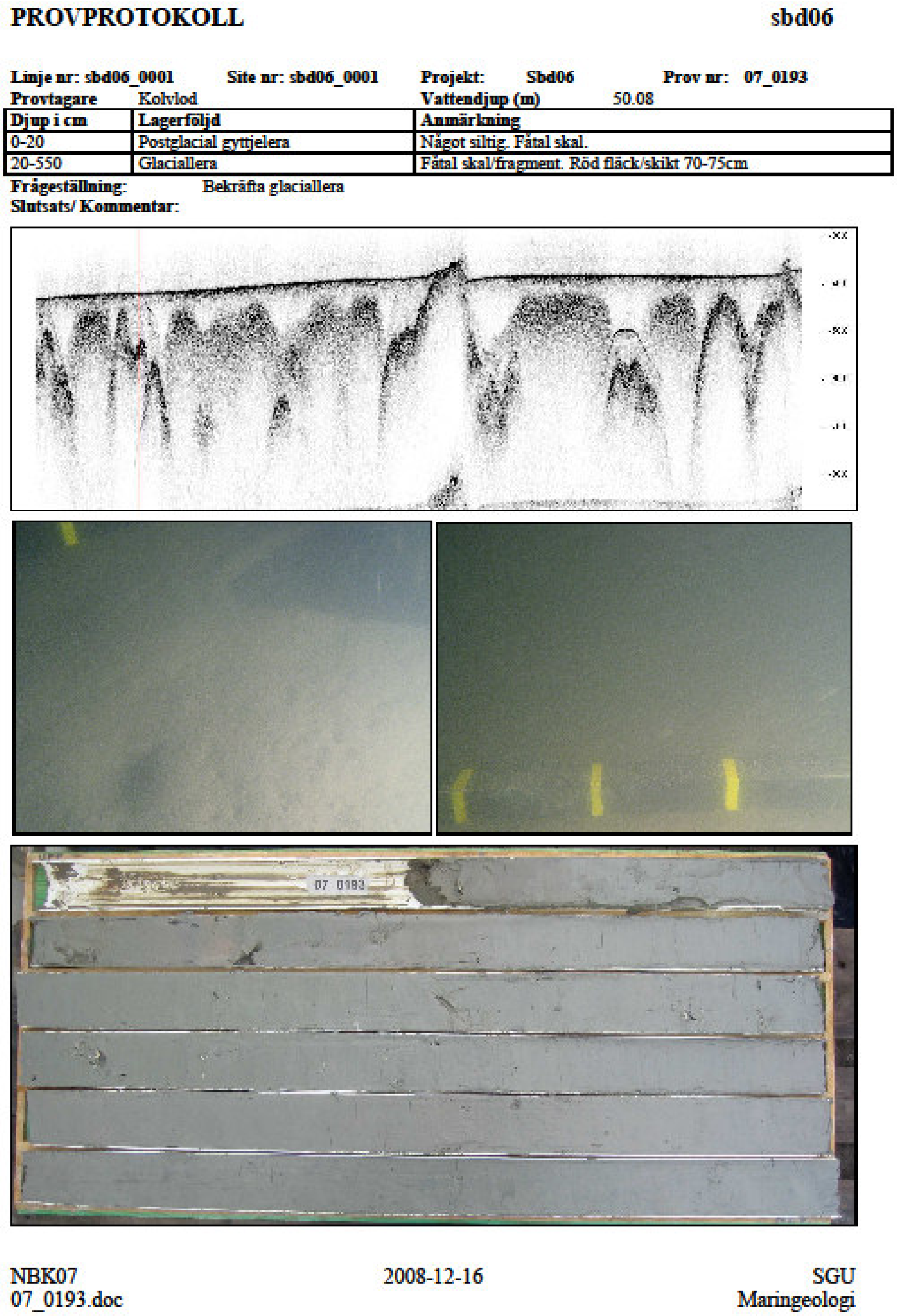
The figure is taken from Lind & Nordgren 2006c

Appendix 17 Sonar mosaic over area-A.



The figure is taken from Lind & Nordgren 2006c

Appendix 18 Sediment profile of area-A.



PROVPROTOKOLL **sbd06**

Linje nr: sbd06_0001 **Site nr: sbd06_0001** **Projekt:** **Sbd06** **Prov nr: 07_0193**
Provtagare Kolvlod **Vattendjup (m)** 50.08

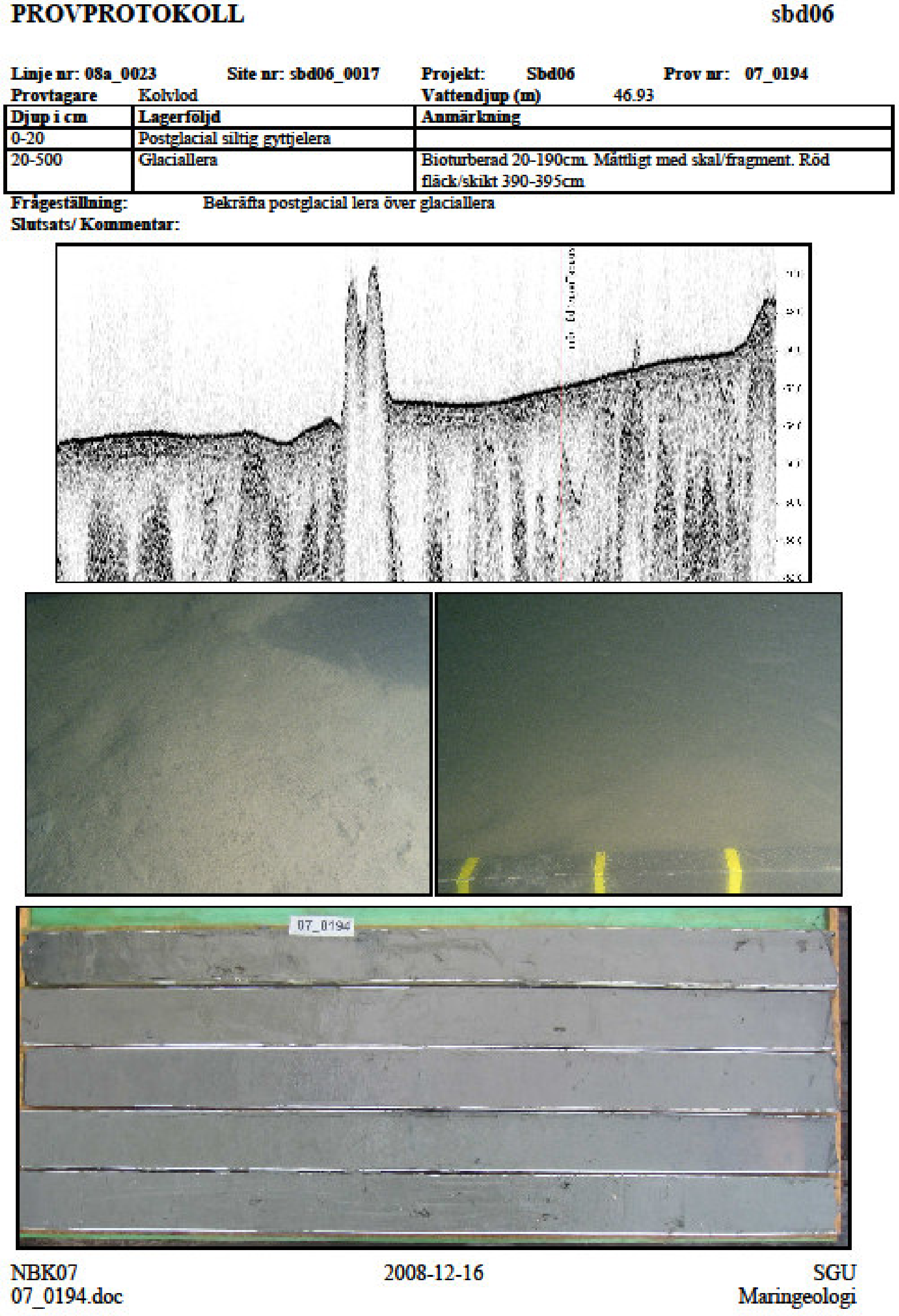
Djup i cm	**Lagerföljd**	**Anmärkning**
0-20	Postglacial gyttjelera	Något siltig. Fåtal skal.
20-550	Glaciallera	Fåtal skal/fragment. Röd fläck/skikt 70-75cm

Frågeställning: Bekräfta glaciallera
Slutsats/ Kommentar:

NBK07 2008-12-16 SGU
07_0193.doc Maringeologi

The figure is taken from Lind & Nordgren 2006c

Appendix 19 Sediment profile of area-A.



PROVPROTOKOLL **sbd06**

Linje nr: 08a_0023 **Site nr: sbd06_0017** **Projekt: Sbd06** **Prov nr: 07_0194**

Provtagare Kolvlod **Vattendjup (m)** 46.93

Djup i cm	**Lagerföljd**	**Anmärkning**
0-20	Postglacial siltig gyttjelera	
20-500	Glaciallera	Bioturberad 20-190cm. Måttligt med skal/fragment. Röd fläck/skikt 390-395cm

Frågeställning: Bekräfta postglacial lera över glaciallera

Slutsats/ Kommentar:

NBK07 2008-12-16 SGU
07_0194.doc Maringeologi

The figure is taken from Lind & Nordgren 2006c