Cumulative impact of marine renewable energy

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Abstract

The development of sustainability in the UK has led us towards the implementation of marine renewable energy. The most widely available marine renewable energies are wind, wave and tidal energy. While they all hold immense potential for clean electrical energy generation, the development and the implementation of these devices raises several questions in terms of the negative impacts they have on their surrounding environment. This project focuses on the cumulative impacts that the installation and use of marine renewable energy farms have on the immediate areas. The presence of a single device has very low effect on its environment; however, the cumulative implementation of such devices in industrial farms may severely impact the area. Both the presence and significance of these cumulative impacts raises questions about the sustainability of these renewable energies. This could lead to a reconsideration of the mass implementation of renewable marine energy devices. The project focuses on the three main types of marine renewable energy devices: wind, wave and tidal. A wind model developed by a Danish national Laboratory and Mike 21 software from DHI was used to model and evaluate the cumulative impacts of the deployment for the three groups of devices. The simulations were run using existent active sites or planned projects, and real devices already deployed. The results show a major impact on the environment due to the cumulative impacts of marine renewable energies. Therefore it is recommended for future projects to assess these impacts prior to implementation. Similar methodology to that applied in this project using Mike 21 software, could be used for this purpose.

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List of Abbreviations

BW	Boussinesq wave
COWIE	Collaborative Offshore Wind Research into the Environment
HD	Hydrodynamic
MRE	marine renewable energy
ORED	Offshore Renewable Energy Device
ST	Sediment transport
SW	Spectral wave
WF	wind farm

I) Introduction

Our concern for the environment has become widespread. Our negative impact upon it has been noted as the effects of greenhouse gases have been publicised and have informed political debate; we are now familiar with issues surrounding global warming, the melting of polar ice caps and rising sea levels. Such negative effects raise pertinent questions regarding the environmental legacy we will leave to future generations. Several measures are being implemented in response to these concerns, in the hope that our impact on the environment will be reduced, and of particular interest here is the use of renewable energy. Solar power and onshore wind farms, whilst popular, aren't, however, the only solutions which offer us the opportunity to produce clean energy. On an island such as the UK, the use of marine renewable energy is becoming more popular. Amongst such energies, three are of particular interest today; offshore wind farms, wave energy and tidal energy. Although renewable energies have become a need for our modern society, a rush to introduce such devices on a mass scale could result in further environmental harm. By way of contrast, the cumulative implementation of such devices in industrial farms might severely impact the immediate environment. The presence and significance of these cumulative impacts is important because it concerns the sustainability and renewability – and therefore the very use of such energy farm installations. Such considerations may force people to reconsider the overall benefits of large industrial marine energy farms.

There is a need to assess the potential impact of the implementation of renewable marine energy farms. This paper presents and discusses results of the modelling realised with three models of the Mike 21 software (DHI Group 2011a) in addition to the calculation using a wind model. These simulations and calculations were conducted using devices of each type of energy in order to determine the cumulative impacts for each of them on the sediment transport processes, and on the wind, waves and tidal environments.

There are four main chapters in this paper. First, a background of marine renewable energy in the UK and the different technologies used in wind, wave and tidal devices are presented. This is followed by a description of the potential resources available and their characteristics along UK coastlines for each energy type. The potential effect of the implementation of such devices is then stated. The impacted populations, the likelihood and the significance of these effects are outlined and the cumulative impacts are explained. The aims of the project are listed in a short section which also describes the cumulative effects as assessed using Mike 21.

The second section chapter will look at the tools used to realise the aims mentioned. The first tool is a model used by the wind energy department of Risø National Laboratory of Denmark; this model will be used to assess the modification of the wave environment by wind farms. Then Mike 21 and the different models that will be run are presented. There are three of them: the Boussinesq wave module (BW) that will look at the impacts on wave environment, the Flow model (HD) that will look at the effect on tides and currents, and the non-cohesive sediment transport (ST) that will look at the sediment transport process modification. Finally the parameters used in the wind model and Mike 21 software will be briefly enumerated.

The third section chapter will look at the implementation of the tools. The criteria for the choice of renewable energy implementation sites that will support the simulation will be presented. The potential sites along the UK coastlines that meet these criteria will be stated. Then the final choice of the sites for the simulation will be described and explained. The devices that will be used for the simulation will be chosen in accordance with the sites. The Mike 21 simulations and the calculations using the wind model will be presented step by step.

The final section will present the results of the Mike 21 simulations and wind model calculations. The cumulative impacts on sediment transport process and wind, waves and tidal environments will be described for each type of energy. Then a discussion concerning the results and the approximation made will be given, together with suggestions for possible further work.

Overall, the project aim was to use Mike 21 software in addition to a wind model to look at some of the potential impacts created by the presence of marine energy farms. The three main types of marine renewable energies were assessed: wind, wave and tidal energy. Since the methodology used in Mike 21 was successful and the results promising, a user guide describing how to use Mike 21 to assess the cumulative impact of marine renewable energy was written and can be found in Appendix D).

II) Context and Impacts of Marine Renewable Energy in the UK

A) Background

Renewable energy is a new economic sector in the UK which is rapidly growing:

- "Between 1996 and 2003 the use of renewable sources of energy increased at a rate of 14.5% per year.
- From 2003 to 2005 the increase was 22% per year.
- In 2005, 17,000GWh were produced from renewable resources, the equivalent to more than 4m tonnes of oil." (Pugh 2008)

The UK has set itself several objectives in accordance with EU guidelines concerning the production of renewable energy. "By early 2011 the United Kingdom is forecast to reach 10% of its electricity consumption from renewables. The proportion is set to rise to around 30% by 2020, in line with EU 2020 targets and UK government plans on reducing carbon emissions" (Renewable UK 2010a).

The energy extraction from the marine environment plays a key role in this. "It is expected to contribute 20% of the total renewable energy production of the UK by 2020. This is approximately 3% of the overall UK electricity demand (Carbon Trust, 2005). The UK has a huge potential in terms of marine energy and is a world leader in terms of energy production from offshore wind and development of marine renewable devices (wave and tide)." (Pugh 2008)

The government supports the offshore component of this growth as a part of its policy to encourage the development of renewable sources of energy generation (Pugh 2008). It "committed £60 million to the development of the UK marine renewables industry" in 2009. (BWEA 2009)

B) Offshore Wind

1) Context

Offshore wind energy production is the main component of the development of renewable energy in the UK. It is a well-established technology within the renewable energy industry (Amoudry et al. 2009) because it shares the knowledge of the onshore wind farm (WF) industry implemented a few years earlier. It is strongly supported by the government, in particular with the three rounds of implementation shown in Figure 1.

The UK is currently number 1 in the world for offshore WF capacity (BWEA 2009). Rounds 1 and 2 and extensions total 9GW. Scottish Territorial Waters reach 6.5GW and Round 3 is expected to provide up to 25GW more. The UK is currently making plans to implement over 40GW of offshore WFs (BWEA 2009).

The technology of wind energy is described in Appendix A).

1) Resource assessment

The early development of wind renewable energy compared to wave and tidal energy can be explained by the fact that the UK has significant wind resources. "The potential for wind-generated electricity in winter is over 1500 W/m^2 (mean) over most of the UK, although this falls by approximately two thirds during the summer - a trend that supports the winter peak of electricity demand in the UK."(Amoudry et al. 2009)

The resource assessment for the wind energy in the UK is presented in Figure 2. The annual mean wind power density at 100 metres is illustrated. We may note that the North-West offers huge potentials for using wind energy.

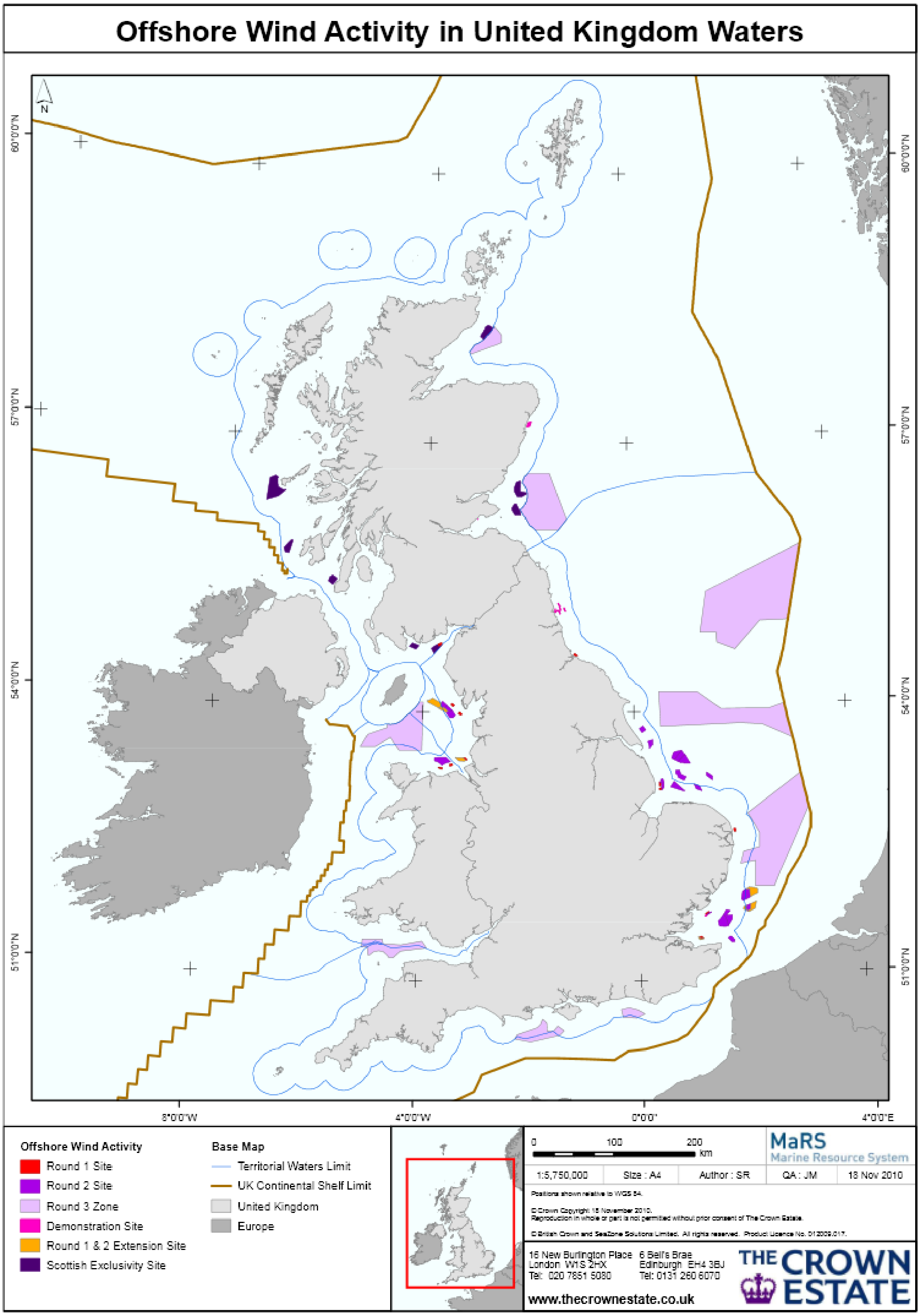

Figure 1: Offshore Wind Activity in UK Waters

Source (Marine Resource System 2008)

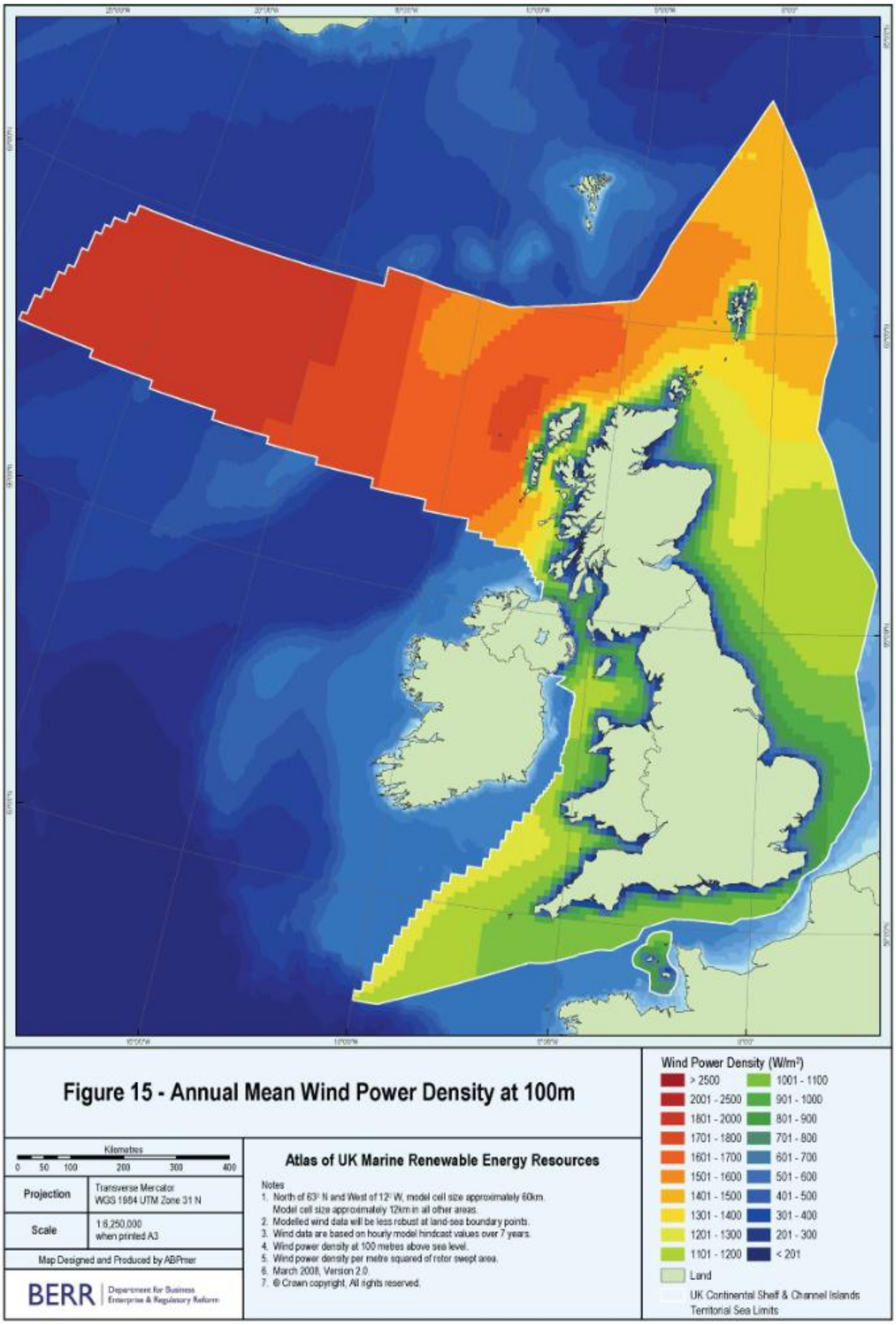

Figure 2: Annual Mean Wind Power Density at 100m

Source (ABPmer 2008a)

2) Characteristics

“The offshore wind energy is seasonal and unpredictable” (Simons 2011). The wind is stronger in winter than in summer (Amoudry et al. 2009). However this knowledge doesn’t help us to foresee the power available on a day-to-day basis. We can currently forecast wind speed a few days in advance but this isn’t sufficient to call it predictable for the industry of electricity demand over UK. The variability of the wind speed might affect the power production of the wind turbines and then affect the entire network with a consequent loss of power.

“An individual wind turbine will generate electricity for 70-85% of the time and its electricity output varies between zero and its full, “rated” output in accordance with the wind speed. However, the combined output of the UK’s entire wind power portfolio shows less variability, as there are always differences in wind speed across the country as a whole. Whilst the amount of wind power varies, it rarely (if ever) goes completely to zero.”(RenewableUK 2010) The different locations of WFs along the UK shoreline might therefore help decrease the impact of wind variability on the power available to the electricity network.

The question remaining is: will the network be able to deal with this variability even though it is small?

“Utilities first started looking at the issues surrounding variability about 30 years ago. Since then numerous studies have been published, and they all reach very similar conclusions. A comprehensive list of these studies is included in the DTI/Carbon Trust “Renewable Energy Network Impacts Study”. Another recent review identified over 150 references. Parliamentary Select Committees that have looked at the question in some detail have concluded that variability is unlikely to cause any significant problems. “The GB system operator, National Grid Transco, is confident that wind variations can be managed”. (RenewableUK 2010)

Despite its variability and the fact that the wind can only be forecast according to season, it remains an appropriate source of energy for the UK electricity network.

C) Wave Energy

1) Context

Wave energy didn't enjoy early development like wind energy. There are very few wave energy devices across the country. This technology is still in the testing phase of its development. The industrial application is still to start: "Wave energy development is thought to be at the stage wind power devices were during the 1980s (The Carbon Trust, 2005) in so much that most devices are currently still in the development stage with few that have progressed to full scale testing." (Amoudry et al. 2009)

"Wave energy converters are the least developed of marine renewable devices" (Amoudry et al. 2009). This can be seen in Figure 3. There are very few places with wave devices; moreover, sites shown are on lease, so it doesn't necessarily mean that devices are already active on it. For example in Pentland Firth and Orkney Waters there is no device active at present. The Scottish Government is waiting for the bidders of round 1 to start installing devices in their respective locations. Similarly the Wave hub isn't industrially active but is used as a test site.

"The Crown Estate expects to award leases for a minimum number of 700MW in the Pentland Firth and Orkney Archipelago strategic area. With 42 applicants, the Crown Estate was overwhelmed by the number of expressions of interest in the area. Preferred bidders have been notified and the finalisation of lease contracts is anticipated in early 2010."(BWEA 2009)

"The development of wave energy is well behind that of wind and because of the diversity of devices currently being progressed, the level of generic understanding applicable to the offshore wind sector is still a distant future goal in the wave industry. There are however already a variety of devices undergoing performance testing, and because of some similarities in the challenges, wave and tidal energy research can often transfer between sectors" (Linley et al. 2009)

Despite a late development compared to wind energy, wave energy seems to hold great potential for the UK. It is becoming more interesting for the renewable energy industry, particularly after the recent leases in Pentland Firth and Orkney waters, which also include the development of tidal energy.. Some devices have successfully passed tests and some projects are already being implemented across the UK.

The technology of wave energy is described in Appendix A).

1) Characteristics

“Wave energy converters are the least developed of marine renewable devices due to the relative inefficiency and unpredictability of the energy source” (Amoudry et al. 2009). The wave energy devices aren’t yet sufficiently cost efficient in order to overcome the issue of unpredictability. It seems that wave energy is facing the same issue as wind energy. The unpredictability of the power generated by wave devices makes its use by the UK electricity network difficult. However we can reach similar conclusions as those stated for wind energy. The fact that wave energy devices will be spread across the country will prevent a general loss in power if one part of the country is facing less powerful waves. Moreover we can easily assume that if the network can deal with the variability of wind energy, it will be able to cope when the sea is calmer. Wave energy seems to have a promising future since there is increasing interest among industry experts for this domain e.g. 42 bidders for Pentland and Orkney Waters have shown interest in this development (Amoudry et al. 2009).

2) Resource assessment

The UK has significant potential for the production of wave energy; this is shown in the Seasonal Mean Wave Power illustrated in Figure 4. “The UK has a large potential for powerful waves, around the southwest peninsular (to be utilised for the forthcoming wavehub experimental station), the Northern Isles (EMEC wave testing site), Pembrokeshire (Wavedragon testing site), and the Outer Hebrides, on which the first commercial wave energy converter was built in 2000” (Amoudry et al. 2009). The increasing interest in wave energy might come from the fact that there is a substantial resource which is available along the coastlines.

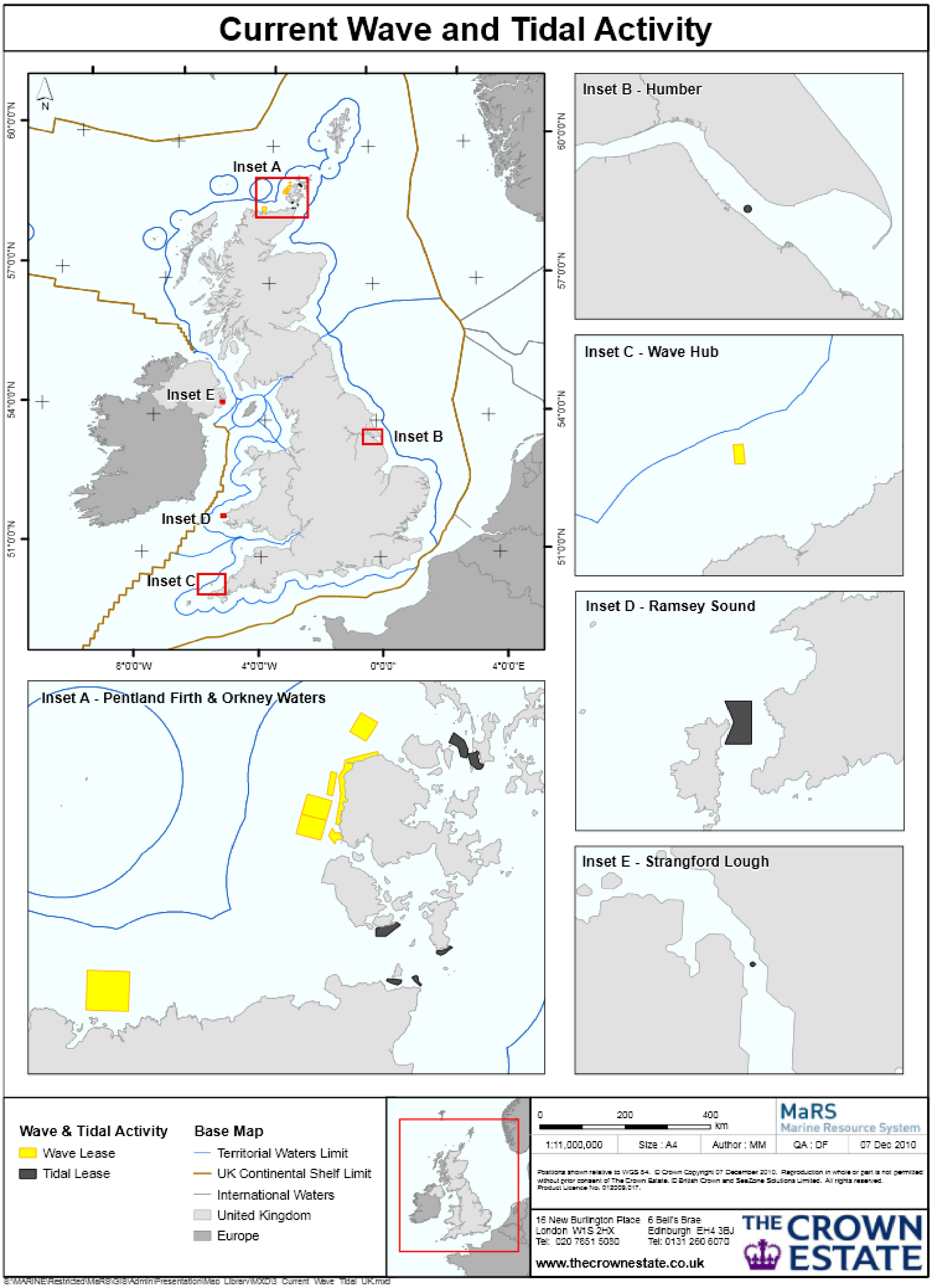

Figure 3: Current Wave and Tidal Activity

Source (Marine Resource System 2010)

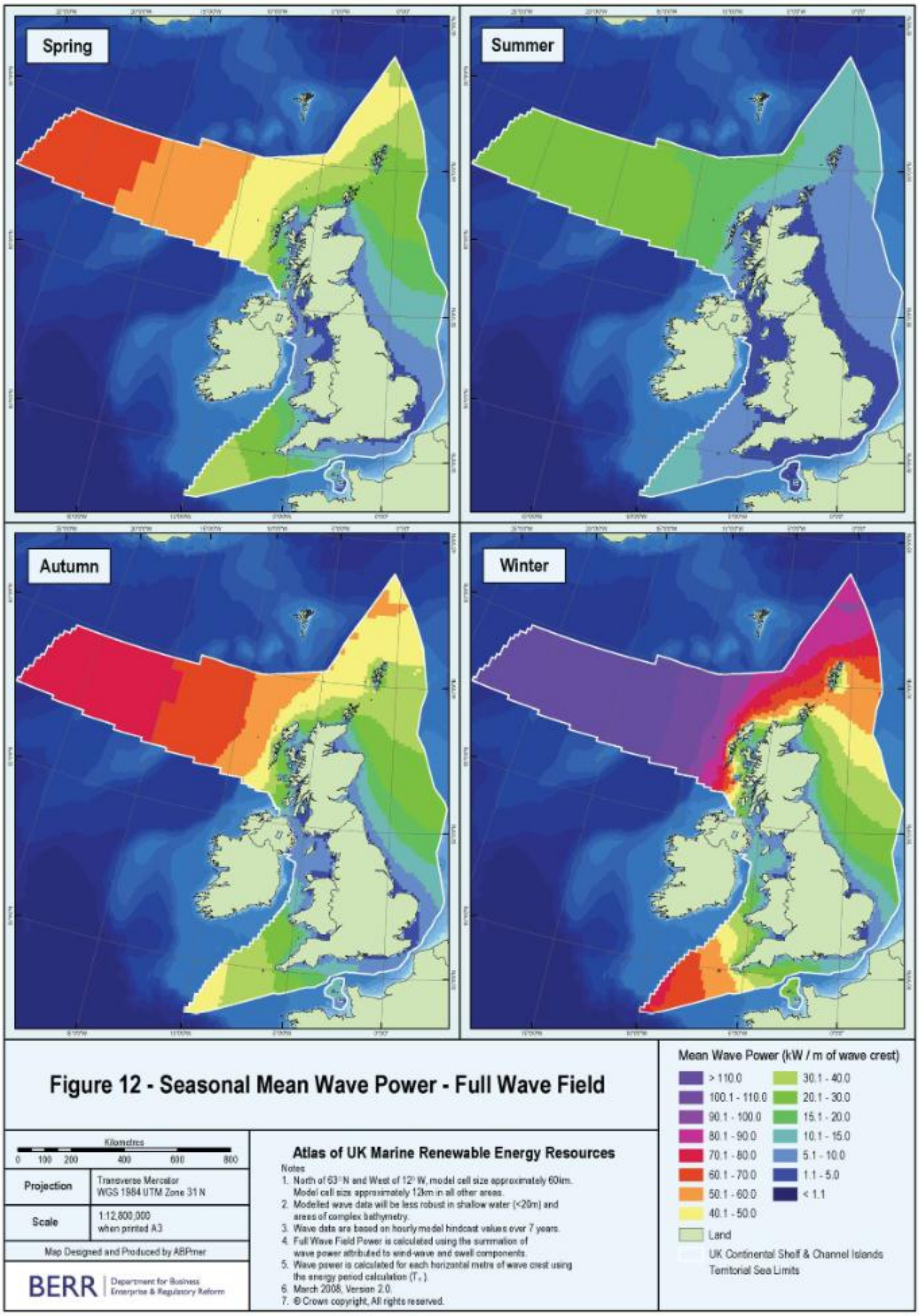

Figure 4: Seasonal Mean Wave Power

Source (ABPmer 2008a)

D) Tidal Energy

1) Context

"The development of the so called "wet renewables", tidal-stream and wave energy extraction is considerably behind the offshore wind industry which has benefited from the large experience of onshore developments. Thus taking wet renewables offshore has meant starting with a clean slate for almost all aspects; moorings, fundamentals of energy capture, specifics of energy capture, water column location and so on. With such strong political and economic drivers now in place, these two industries are now expanding extremely quickly." (Linley et al. 2009).
As previously stated, the development of tidal and wave energy is behind that of wind energy but both are expanding very quickly. Tidal energy is very similar to wave energy in that both are now at the same developmental stage. The only difference is that tidal energy was used early on for industrial purposes, for example in France, with "Le barrage de la Rance" in Brittany. Built in 1966, the barrage has an average power output from 24 turbines of 68MW (peak output 240MW) (Simons 2011). Alternative schemes have been proposed since the 1970s but all of these were rejected, with for example the project for a barrage in the Severn Estuary rejected due to environmental issues. However the government has a growing interest in this kind of renewable energy due to improved technological advances, making it more environmentally friendly. This is due to alternatives to the construction of barrages, which use rotating turbine blades mounted underwater and oriented into the oncoming tidal current. These have been recently proposed and are now being implemented in the UK. These projects are displayed in Figure 3.

The technology of tidal energy is described in Appendix A).

2) Characteristics

Tidal power is the only one of the three types of energy generation which is completely predictable. With astronomic considerations and the geography of the UK coastlines, a precise prediction of the tides can be made for several tens of years. "Tidal Power, which is highly predictable, is becoming increasingly of interest because of concerns about climate change and energy security. The UK is estimated to have a realisable resource of around 50TWh (13% of UK Electricity Demand)" (Burrows et Yates 2011)

The tidal resource has another advantage; it is regular with 2 tides per day on the UK's coast lines.

This makes the tidal resource very reliable for use as a renewable source of energy. There is therefore no issue concerning the connection to the electricity network in terms of the prediction of energy produced. For example the tidal prediction for Dover can be thus illustrated:

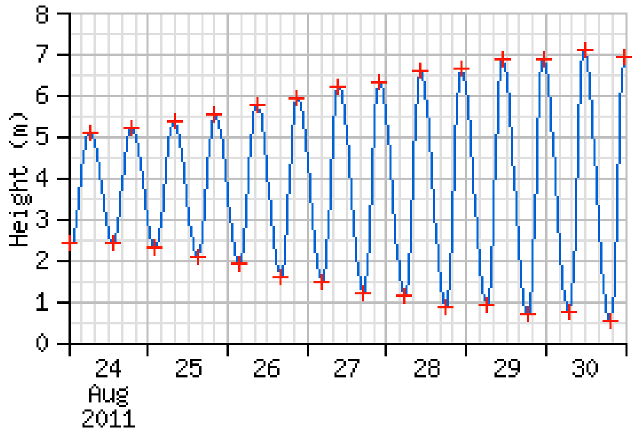

Figure 5: Tidal Prediction of one week for Dover

Source: (National Oceanography Centre 2011).

3) <u>Resource assessment</u>

The UK has an amazing tidal resource along its coastlines. "Drawing on a combination of previous resource studies and new calculations, B&V found that the UK tidal stream resource appears to be about half the entire European resource, and is probably 10 to 15% of the known world resource."(Black&Veatch 2005a).

Figure 6, below, presents the mean tidal power for a spring tide. "The UK potential for tidal stream technology is focussed in the Severn Estuary (2nd largest tidal range in the world), the Skerries (Anglesey), the South coast between the Isle of Wight and the Channel Islands, East Anglia, and the Pentland Firth."(Amoudry et al. 2009)

To conclude, the UK holds great potential for using tidal energy along its coastlines. Moreover, tidal resources are the most practical because they are regular and predictable; they are the “most efficient form of marine renewable energy extraction as tidal currents have a high energy intensity (approximately four times greater that of a good wind site)” (Amoudry et al. 2009).

The environmental impacts and considerations of barrages are in a different league from other marine renewables and won’t be considered in this study. This research will only consider arrays of tidal turbines.

The mass implementation of marine renewable energy devices may lead to unexpected consequences on the immediate environment if not carefully studied. Some effects and impacts are already known from past experiences or past studies. This section attempts to summarise all of the findings to date.

First, the difference between an effect and an impact needs to be highlighted. “When discussing stressors in environmental systems, an important semantic distinction should be made between an “effect” of a stressor on a receptor and an “impact”. The two terms are often used interchangeably, but “effect” doesn’t indicate a magnitude or significance, whereas “impact” implicitly deals with severity, intensity, or duration of the effect. Furthermore, impact also deals with direction of effect, which means that there can be positive or negative outcomes to the effect of the stressor. The distinction between effect and impact is of crucial importance when considering offshore renewable energy devices (ORED); a number of studies present findings that suggest or show an effect, but further work is usually required for it to be interpreted as an impact” (G. W. Boehlert et Gill 2010).

In the first part of this section, only the numerous effects will be presented. Further research would be required in order to assess the impacts of these effects. The second and third parts discuss information for some of the effects and manage to transform them into impacts. The last part describes the principles of cumulative effects and impacts.

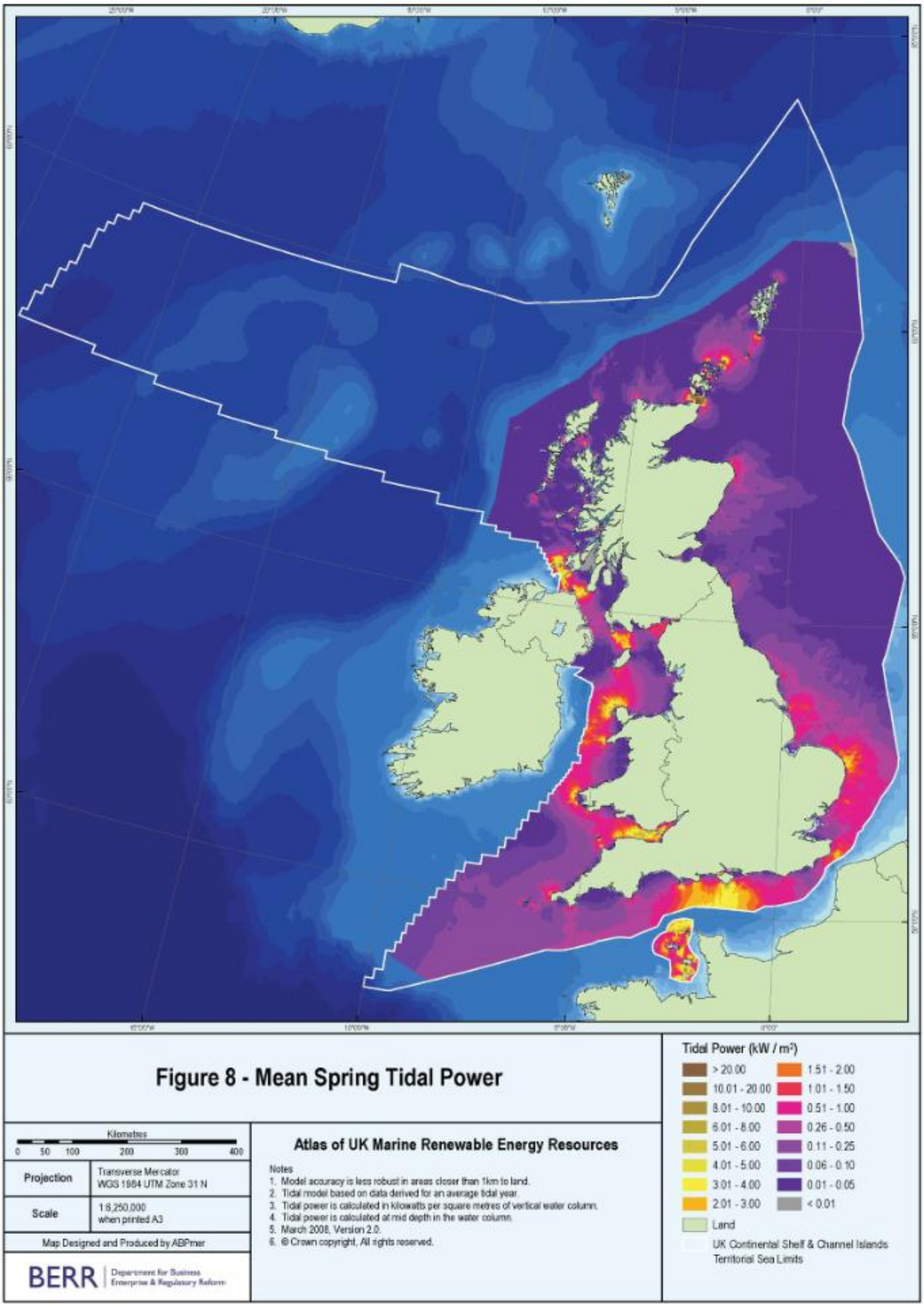

Figure 6: Mean Spring Tidal Power

Source (ABPmer 2008a)

E) Effects

Tables summarising all the references for the effects can be found in Appendix B). The first table presents the effect and associates reference numbers to each. In a second table the correspondence between the reference numbers and sources is given.
For clarity of expression, the effects have been sorted out into four categories, physical, environmental, social, and economic. However it must be noted that several effects could belong to different categories and are expressed here in specific ones in order to aid the reader.

1) Physical effects

The effects mentioned here are those which results in physical parameters around the device being modified or altered due to the installation, presence and operation of the energy generating devices.

- Wind alteration: as the wind goes through a wind turbine, the speed is modified and a wake effect appears.

- Wave alteration: as the waves go through the energy devices, their heights and periods are modified.

- Tide alteration: the implementation of tidal devices may locally affect the sea water level.

- Current alteration: the presence of the energy devices may affect the sea water currents in the local environment.

- Temperature alteration: the presence of the cable carrying the electricity generated might locally increase the sea temperature.

- Scouring: the presence of the devices and cables on the seabed may engender scouring effects around their bases.

- Sediment transport disruption: the presence of the devices and cables on the seabed may affect the sediment transport rate.

- Coastal protection/shoreline disturbance: the disruption caused by wind, wave and current sediment transport vehicles may have further consequences in terms of shoreline protection.

- Water quality renewal: through the disruption of the current or water turbidity, some devices may affect the water quality.

- Water contamination: the devices are covered with different chemicals such as paint and these may contaminate the water.

- Acoustic effect: mostly during the installation or decommissioning of devices there is a consequent level of noise produced. The device may also produce noise during operation.

- Vibration: vibrations may be produced during installation, decommissioning and operation.

- Electromagnetic effect: there are electromagnetic fields around the cables carrying the electricity.

- Air pollution/ greenhouse gas effects: the renewable energy devices don't require any fuel for their operation but all of the vessels and activities to set up the devices do and these produce greenhouse gases.

- Tidal resonance: this effect concerns only the implementation of barrages with tidal turbines. "The high tidal range required for the extraction of tidal energy by a barrage occurs within an estuary due to the shelving of the seabed, tidal resonance and funnelling of water. Tidal resonance occurs when the time taken for a large wave to travel from the mouth of the bay to the opposite end of the estuary, is then reflected and travels back to the mouth of the bay and coincidentally matches the time from one high tide to the next" (Finlay, Couch, et Ingram 2009).

2) <u>Environmental effects</u>

The effects mentioned here are those caused, by the installation, presence and operation of the energy generating devices, on the local flora and fauna.

- Habitat disruption above water: the habitat of some species above water may be affected.

- Habitat disruption below water: the habitat of some species below water may be affected.

- Species' behavioural disruption: the behaviour of some species living in the local environment may be affected.

- Collision: Some species may collide with the devices.

- Migration routes disruption: the presence of the devices may force some species to modify their migration routes.

- Destruction of some members of a population of species: some members of a population of species may be killed or injured.

- Intertidal areas loss: a modification of the tide in amplitude may result in a loss of intertidal areas.

- Waste/accidental spillage: accidental spillage and/or waste may harm species and their natural habitat.

- Lighting: some devices require lights for security and safety reasons. These may affect and disturb the behaviour and well-being of marine life.

- Greenhouse gases: the renewable energy devices produce electricity without releasing greenhouse gases in the atmosphere.

3) <u>Social effects</u>

The effects mentioned here are those caused, by the installation, presence and operation of the energy generating devices, to the local communities.

- Fish area disruption: some fish species may be disturbed and affect local fishing economies.

- Naval path disruption: well-established shipping lanes may need to be modified.

- Visual and landscape impact: the shoreline may be affected. Moreover the grid connection and electrical wires on land may affect the aesthetics of the local landscape.

- Communication systems interference: the presence of devices may interfere with communication systems.

- Recreational and professional users: the presence of the devices can create conflict with the professionals working in and around the local areas, and also recreational users who may not revisit the area. Some installations could be harmful for local tourist economies.

- Land and sea use: the grid connections on the shore line and the installation of electrical cables require land. Similarly, the installation of the devices requires large area capacity on the sea itself.

- Impact on marine archaeology: marine archaeological research as well as marine archaeological sites may be affected.

4) Economic effects

The effects mentioned here are those caused, by the installation, presence and operation of the energy generating devices, to the economy.

- Electricity production: the aim of the device is to produce electricity which will be sold via the national grid to household users. Moreover, devices represent investment opportunities and there is an overall cost and benefit.

- Overlap with other marine activities: the installation of marine renewable energy systems may disturb or prevent other sea professionals from working, for example fishermen who aren't allowed to enter the area of the devices anymore. Conflict with oil and gas industries could also occur.

Some effects can only be generated by some types of devices; Table 1 presents which type of devices can be responsible for which effect.

Effects	Wind	Tide	Wave
Physical effects			
Modification of the wind	yes		
Modification of the waves	yes	yes	yes
Modification of the tide		yes	
Modification of the current	yes	yes	yes
Modification of the temperature	yes	yes	yes
Scouring	yes	yes	yes
Sediment transport disruption	yes	yes	yes
Alteration of coastal defence/shoreline disturbance	yes	yes	yes
Water quality renewal	yes	yes	yes
Water contamination	yes	yes	yes
Accoustic effect	yes	yes	yes
Electromagnetic effect	yes	yes	yes
Vibration	yes	yes	yes
Air pollution/ green house gaz effect	yes	yes	yes
Creation of Tidal resonance		yes	
Environmental effects			
Disruption in the habitat above water	yes	yes	yes
Disruption in the habitat below water	yes	yes	yes
Disruption of a behaviours	yes	yes	yes
Collision	yes	yes	yes
Migration routes disruption	yes	yes	yes
Destruction of members of a species population	yes	yes	yes
Loss of intertidal areas		yes	
Waste/accidental spillage	Yes	Yes	Yes
Light	yes	yes	yes
Greenhouse gases	yes	yes	yes
Social effects			
Fish area disruption	yes	yes	yes
Naval path disruption	yes	yes	yes
Visual and landscape impact	yes	yes	yes
Interference with communication system	yes		
Recreational users	yes	yes	yes
Land/ sea use	yes	yes	yes
Impact on marine archeology	yes	yes	yes
Economic effects			
Electricity production	yes	yes	yes
Overlap with other marine activities	yes	yes	yes

Table 1: Effects and types of energy responsible

F) Population Impacted

In order to improve the details concerning the effects and turn them into impacts, we need to state which populations are impacted. This is summarised in Table 2. We must bear in mind that “population” is a broad term; it can represent human, animal populations or simply those pertaining to the natural environment at large.

Also, an inter-dependency exists between some populations:
-*“prey availability”:* if a fauna population is affected by an effect, the predators and the prey are also affected. This creates different links between the populations of fish and birds for instance.
-*fishermen:* the frequency of fishing is directly linked to the population of fish. Consequently, any effect on the fish will affect “other marine activities”.

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Effects	"Population" affected							
	Mammals	Birds	Fish	Benthos	hydraulics	natural environment	Communities	Other marine activities
Physical effects								
Modification of the wind		yes			yes	yes	yes	
Modification of the waves					yes	yes	yes	
Modification of the tide	yes	yes	yes	yes	yes	yes	yes	yes
Modification of the current	yes	yes	yes	yes	yes	yes	yes	yes
Modification of the temperature	yes	yes	yes	yes	yes	yes	yes	yes
Scouring				yes	yes	yes		
Sediment transport disruption				yes	yes	yes		
Alteration of coastal defence/shoreline disturbance						yes	yes	
Water quality renewal	yes	yes	yes	yes	yes	yes		yes
Water contamination	yes	yes	yes	yes			yes	yes
Accoustic effect	yes	yes	yes				yes	yes
Electromagnetic effect	yes		yes	yes				yes
Vibration	yes		yes	yes				yes
Air pollution/ green house gaz effect						yes	yes	
Creation of Tidal resonance					yes	yes	yes	yes
Environmental effects								
Disruption in the habitat above water	yes	yes				yes		yes
Disruption in the habitat below water	yes	yes	yes	yes		yes		yes
Disruption of a behaviours	yes	yes	yes	yes				yes
Collision	yes	yes	yes					yes
Migration routes disruption	yes	yes	yes					yes
Destruction of members of a species population	yes	yes	yes	yes				yes
Loss of intertidal areas	yes	yes	yes	yes		yes		yes
Waste/accidental spillage	yes	yes	yes	yes		yes	yes	yes
Light	yes	yes	yes	yes			yes	yes
Greenhouse gases		yes				yes	yes	

Effects	"Population" affected							
	Mammals	Birds	Fish	Benthos	hydraulics	natural environment	Communities	Other marine activities
Social effects								
Fish area disruption								yes
Naval path disruption							yes	yes
Visual and landscape impact						yes	yes	
Interference with communication system							yes	yes
Recreational users							yes	
Land/ sea use							yes	yes
Impact on marine archeology								yes
Economic effects								
Electricity production							yes	
Overlap with other marine activities							yes	yes

Table 2: "Populations" affected

G) Likelihood and Significance

In order to discuss impact, the likelihood, significance, duration and the nature of the effect (positive/negative) needs to be determined. Very few studies have been done on the impacts of marine renewable energy, however. A lot of work remains to be done in order for us to be able to assess all of the impacts that marine renewable energy devices have. The impacts that have already been surveyed are presented in Table 3 whilst Table 9 (Appendix A) provides the references for the numbers displayed in Table 3.

Effect positive/negative					
		Negative	positive	Unknown	
Likelihood		High	Medium	Low	Unknown
				0,5	0
Significance		Unknown	High	Medium	Low
Knowledge		1	0,5	0	
		High	Medium	Low	

Figure 7: Legend of Table 3

Classification of impacts	Effect	Positive/Negative	Likelihood	Significance	Knowledge	Reference
Hydrodynamics	Seabed Morphology					47
	Erosion and Scouring					47
	Sediment Transport and Deposition					47
Chemical impacts	Water Quality					45-47-64
	Corrosion					47
	Bio-fouling					45-47
	Anti-fouling and Anti-Corrosion Paints					45-47
	Physical/mechanical effects by coating organisms					45
	Cumulative effect					45
Environmental impacts during project stages	Pre-deployment Monitoring					47
	Deployment and Commissioning					47
	Operations					47
	Maintenance and Repair					47
	Decommissioning					47
Seabed/Intertidal habitats disturbance	Seabed disturbance					64
	Suspended sediment					64
	Potential contamination due to sediment disturbance					64
	Potential heating effects					64
	Cable coating effects					64
	Sediment mobilisation					64
	Settlement of material					64
	Turbidity					64
Alteration of Substrates and Sediment Transport and Deposition	Potential Near and Far Field Alteration of ST					45
	Scour and deposition of fine sediments					45
	Changes in longshore currents					45
	Water quality					45
Mammals	Injurious noise of pile diving					43-47-64-66
	Displacement of marine marmals					43
	Collisions					43-45-47-64
	Behavioural responses (attraction, avoidance etc)					43
	Chemical pollution					43
	Electromagnetic Fields					47
	Maintenance boat traffic					43
	Creation of reserve					45
	Migration issue					45
	Visual disturbance					64
	Entanglement					64

Classification of mpacts	Effect	positive/negative	Likelihood	Significance	Knowledge	Reference
Birds	Collision Risk			0	1	43-45
	Cumulative effect			0	0	43-48
	De facto Marine Protection Area designation				0,5	48
	Migration issue				1	45
	Disturbance of normal behaviour in the intertidal				1	64
	Disturbance of normal behaviour at sea				1	64
	Prey availability				0,5	64
	Disturbance			0	0,5	48
	Pollution				1	48
	Roosting				0,5	48
	Risk of entrapment				0,5	48
	Changes to oceanographic processes				1	48
	Changes in food availability				0,5	48
	Habitat enhancement				0,5	48
	Aggregation				1	48
	Indirect Habitat Loss			0,5	1	43
	Barrier Effects				1	43
	Population changes resulting from displacement				0	43
Fish	Construction				0	43
	Noise				0	43
	Vibration				0	43
	Operational disturbance: electromagnetic and noise				0	43
	No trawling zone				0	43
	Diversity				0	43
	Collision				0	43-45
	Pressure pulse				0	43
	Habitat for fish/refuges/areas for recovery				0,5	43
	Migration issue				1	45
Benthos	Destruction/disruption of the habitat			0,5	1	45-47
	Displacement of Benthic Organisms by Installation			0	1	45
	Introduction of new species				0,5	45
	Creation of reserve				1	45
Alteration of currents and waves	Potential Near and Far Field Hydrodynamic Alterations				1	45
	Alteration of water movement				1	45
	Alteration of wave height					45
	Reduction of the water exchanged				1	45
	Reduction of the tidal range landward of the turbines				1	45
	Reduction of the kinetic power density				1	45
	Alter wave heights and structures				1	45
	Reduce wind-wave interactions				1	45
	Alteration of water velocity			0		45

Table 3: Likelihood, Significance and knowledge of the effects

The empty cells in Table 3 highlight the fact that some information is missing and further research is required. Marine renewable energy is quite new and the knowledge that scientists have amassed is far from complete. There are lots of effects created by the energy devices but only a few of them are sufficiently known so as to be treated as impacts. In almost all of the references, the authors recommend further studies on the subject. It is very difficult to quantify and qualify (positively or negatively) several of the effects because of their nature. For example, the behaviour of the fauna and the reaction to the intrusion created by devices in their environment is a very complicated problem. Moreover, there are interdependencies between some effects and this makes the final positive or negative direction of the effect very difficult to determine. The effect of blade strikes on a bird's population would be one example of this. Birds stroked by wind turbine blades are usually killed. This reduces the population. However, "mortality resulting from WFs may reduce competition for resources, thus reducing the rate of natural mortality" (Linley et al. 2009). The final direction of this effect is unclear; it would be easy to classify it as a negative output (as in Table 3) but there is also an opposite effect, which is created consequently to the first one, giving a positive output. The final direction will be given by the result of the balance between the two opposite effects.

This phenomenon, in addition to the fact that the direction, likelihood and significance of the effects are site, population and time dependant, make the study of the impact of marine renewable energy very difficult to assess conclusively.

H) Cumulative Effects and Impacts

A cumulative effect or impact is an effect or impact which has different sources. These sources will each generate their own effect, which when taken together, will create a cumulative effect.

All the effects and impacts presented previously could act cumulatively as long as there is either a large number of devices or different marine activities, which create the same effect. The two principal causes of cumulative effects and impacts, which are dependent on the creation of the same effect and impact, are the mass implementation of devices and the presence of different marine activities located in the same area

COWRIE (Collaborative Offshore Wind Research into the Environment) evaluates the cumulative effect between the two categories in “Guidance for Assessment of Cumulative Impacts on the Historic Environment from Offshore Renewable Energy” (COWRIE 2008).

-‘internal’ cumulative effects which are affecting directly the environment of the devices.

-‘external’ cumulative effects, which could be described as collateral effects, for example “the positive cumulative effect of archaeological information generated by survey and other mitigation measures” (COWRIE 2008).

This introduces the fact that there can be an external cumulative effect. The presence of devices can create collateral effects, which can also act cumulatively.

The report “Developing guidance on ornithological cumulative impact assessment for offshore WF developers” (King et al. 2009) offers us a way of calculating cumulative effects for the impact related to a bird’s population: “Cumulative collision impact should be calculated as the sum of collisions from component projects unless evidence indicates that this approach would result in significant inaccuracy giving rise to a material difference in the assessment of the significance of the potential impact” (King et al. 2009). They also described several potential effects that may act cumulatively: “disturbance, displacement, barrier effects, mortality due to collisions and indirect effects on prey”.(King et al. 2009)

Recently, all the new projects taking place around the UK need to devote more attention to the cumulative effects. The two factors: a large number of devices or a large number of marine activities in the same area are found in more than one place. “In addition, we need to project our thinking to consider future climate change scenarios and cumulative effects of intensification of marine space use, before our coastal zone becomes cluttered with more arrays of devices than is sustainable when whole system environmental carrying capacity is considered” (Linley et al. 2009).
Further studies are required in these places to find out what the potential cumulative impacts generated by the implementation of marine renewable energy devices could be.

"Fundamental baseline data will be needed (mammal biology, presence/absence/species diversity, information on prey species) to understand projects' impacts and the cumulative effects as ORED reaches commercial scales" (G. W. Boehlert et Gill 2010).

The need for further research on the cumulative effects and impacts is all the more important given that they are very difficult to determine. "The cumulative impact of tidal energy device deployment, operation, maintenance, and decommissioning must be considered but will be extremely difficult to determine."(Polagye, Copping, et al. 2010)

I) Aim of the Project

In the previous section, the need for further studies concerning the cumulative impacts was highlighted. The aim of the project is therefore to contribute to fill the gap in terms of the lack of knowledge concerning these phenomena. Knowing that each effect or impact can act cumulatively, this project focused only on specific impacts.

Firstly the type of cumulative factor studied is the mass implementation of devices. The factor of effects/impacts generated from different marine activities won't be studied. This project will look at the implementation of three different types of devices:

- Wind devices: devices using wind energy to produce electricity
- Wave devices: devices using wave energy to produce electricity
- Tidal devices: devices using tidal energy to produce electricity

The cumulative impacts of each type of device will be studied separately. Using software simulations, a large number of devices will be installed on a site and some models (presented in section V) will be used to assess the consequences of such implementation on the site.

Since there is a very large range of potential effects/impacts and that the study of cumulative effects/impacts is extremely difficult to determine (Polagye, Van Cleve, et al. 2010), this project will be looking only at the impacts related the hydraulics stated below:

- Modification of the wind environment around the area of implementation
- Modification of the waves environment around the area of implementation
- Modification of the currents environment around the area of implementation
- Modification of the tides environment around the area of implementation
- Modification of the sediment transport process around the area of implementation

Using the tools described in section V, this project aims to describe these cumulative impacts resulting in the mass implementation of the wind, wave and tidal devices on a chosen area. This won't be a real assessment of these areas since no calibration of the model will be made. The project only aims to highlight the presence of cumulative impacts due to marine renewable energy and to show that Mike 21 software can be used to assess some of them. The final output is a user guide (Appendix D) of the three models of Mike 21 to assess some cumulative impacts using the methodology of this project.

III) Software and models used

The wind model is used to look at the cumulative impact of wind turbines on the wind and the consequences of it on the wave. Mike 21 is used to look at the impacts on waves due to the presence of the devices, water level, currents and sediment transport process.

A) Wind Model

In order to assess the modification of the wind due to the presence of the WF, the theory and model developed by the Wind Energy Department of Risø National Laboratory (Sten Frandsen et al. 2004) has been used.

The presence of the WF affects the wind environment in different ways. In particular, there is a creation of a wake behind a single turbine. Inside this wake the wind speed is reduced and there are turbulences. We will focus on the decrease of the wind speed inside this wake and the expansion of this wake around the turbine.

1) Wind velocity deficit

The calculations have been conducted in two steps. The first step was to calculate the attenuation of the wind behind a single turbine. The mathematical model used by the Wind Energy Department is the one developed by Jensen (1983). The value of the wind in the wake behind the turbine is given by:

$$U_{\text{wake}} = U_{\text{freestream}}\left[1 - (1 - \sqrt{1 - C_T})\left(\frac{D}{D + 2k_{\text{wake}}X}\right)^2\right],$$

(Barthelmie et al. 2006)

Where, U_{wake} represents the wind velocity value inside the wake,
$U_{freestream}$ represents the wind velocity value in front of the turbine,

D is the rotor diameter of the wind turbine,

k_{wake} is a wake decay constant (suggested value for offshore is 0.05),

X represents the downwind distance from the turbine,

C_T represents the thrust coefficient determined from the relation:

$$T = \frac{1}{2}\rho A_0 U_0^2 C_T, \quad A_0 = \frac{\pi}{4} D_0^2,$$

(Sten Frandsen et al. 2004)

Where, T is the thrust power of the turbine,

ρ is the air density (1.22521 Kg/m^3),

A_0 is the swept area behind the turbine,

U_0 is the wind velocity value in front of the turbine,

and D_0 is the rotor diameter.

Once the calculation for a single turbine is done, we do the second step: the calculation for a single row of wind turbines. The calculations are quite similar; the only change is in $U_{freestream}$. For the first turbine nothing changes, $U_{freestream}$ has the same value used previously; for the second turbine, the value of $U_{freestream}$ will be the value of U_{wake} of the first turbine at the distance X, which is the distance between the two turbines. We reiterate this process for all the turbines in the row in order to obtain the resulting wind velocity behind the WF.

Then by increasing the value of X behind the WF, we can find out how the wind velocity recovers once the WF is passed.

For this part of the calculation it was assumed that the wind direction was along the axis of the turbine rows.

Further calculations were made in order to look at the increase in the wake height and diameter. Since these calculations provided results that were too complicated to use with the Jonswap method (described below), a simplification was made concerning the area impacted. Further details about this simplification are given in section V.A. However the proper calculations are presented in Appendix B.

.

2) Wave effect

The wind is the source that creates waves. As the wind blows over the water surface, it transfers some of its energy to the water through friction. This transfer generates waves on the area where the wind is blowing. The height and period of the wave generated are dependent on the fetch length (area over which the wind is blows), the wind speed and the duration the wind blows on the area. Kamphuis in his book “Introduction to coastal engineering and management” presents the Jonswap parameters. Jonswap (joint north sea wave project) was a large experiment which took place in the north sea and aimed “to obtain wave spectral data of sufficient extent and density to determine the structure of the source function empirically” (Barnett et al. 1973).The research produced relationships linking the wave height and period to the fetch length, wind speed and duration the wind blows on the area.

The Jonswap method of wave hindcasting uses the following dimensionless expressions.

$$F^* = \frac{gF}{U^2}, \quad H^*_{mo} = \frac{gH_{mo}}{U^2}, \quad T^*_p = \frac{gT_p}{U}, \quad t^* = \frac{gt}{U}, \quad d^* = \frac{gd}{U^2}$$

The Jonswap relationships are

$$H^*_{mo} = 0.0016\,(F^*)^{1/2}$$

$$T^*_p = 0.286\,(F^*)^{1/3}$$

and

$$t^* = 68.8\,(F^*)^{2/3}$$

(Kamphuis 2000)

The wave attenuation due to the wind decrease can be calculated by using the Jonswap formulae together with results from previous calculations for the decrease in wind speed and the area covered by the wake. The impact of the wind turbines on the wave environment can therefore be deduced.

B) Mike 21

Mike 21 is used to look at the impacts regarding wave, tides, currents environments and ST.

1) Presentation of the software

Mike 21 is a software developed by DHI, a Danish group. It is a very powerful software that allows modelling in 2D of "physical, chemical or biological processes in coastal or marine areas" (DHI Group 2011b). Mike 21 is used by companies to look at different issues, such as:

- "Design data assessment for coastal and offshore structures
- Optimisation of port layout and coastal protection measures
- Cooling water, desalination and recirculation analysis
- Optimisation of coastal outfalls
- Environmental impact assessment of marine infrastructures
- Ecological modelling including optimisation of aquaculture systems
- Optimisation of renewable energy systems
- Water forecast for safe marine operations and navigation
- Coastal flooding and storm surge warnings
- Inland flooding and overland flow modelling" (DHI Group 2011b)

Mike 21 is composed of several modules that look each at a particular phenomenon. There are 15 modules in all. The ones used to model the impact on the "hydraulics" are presented in the sections below. These modules are:

- The Boussinesq Waves module (BW)
- The Hydrodynamics Module (HD)
- The non-cohesive Sediment Transport module (ST)

With the help of these three modules, the impacts of the implementation marine renewable energy devices can be modelled.

2) Presentation of the modules used

i. The BW module

The BW module can be used either in 1 or 2 dimensions. It is based “on the numerical solution of time domain formulations of Boussinesq type equations” (DHI Group 2011c). These equations were originally developed by Madsen in 1991, then Madsen and Sørensen in 1992). They allow the module to simulate “the combined effects of all important wave phenomena of interest in port, harbour and coastal engineering. These include:

- Shoaling
- Refraction
- Diffraction
- Wave breaking
- Bottom friction
- Moving shoreline
- Partial reflection and transmission
- Non-linear wave-wave interaction
- Frequency spreading
- Directional spreading” (DHI Group 2011c)

This module is highly appropriate for analysing the impacts, created by the implementation of devices, on the waves.

ii. The HD module

The HD module is one of the four parts of the Flow model. The flow model of Mike 21 is a “modelling system for 2D free-surface flows” (DHI Group 2011d). It simulates the hydraulics phenomena of water. “The hydrodynamic module simulates water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal regions. The effects and facilities include:

- bottom shear stress
- wind shear stress
- barometric pressure gradients
- Coriolis force
- momentum dispersion
- sources and sinks

- evaporation
- flooding and drying
- wave radiation stresses” (DHI Group 2011d)

This module can model all the impacts, generated by the implementation of devices, on the currents and tides.

iii. The ST module

“MIKE 21 ST is a module in the MIKE 21 application suite for calculating non-cohesive sediment (sand) transport rates. You can calculate sand transport based on pure current information, or you can take waves into consideration too.
In addition to sand transport rates, a simulation will give you the initial rates of bed level changes. This is sufficient to identify potential areas of erosion or deposition” (DHI Group 2010a).
This module provides information about erosion, sea bed alteration and transportation of sediment. It is suitable to assess the morphological impacts of implementing devices on the seabed.

3) Presentation of the expected outputs

i. Wind environment

The calculations based on the model of the Wind Energy Department of Risø National Laboratory provide all the information concerning the wind velocity decrease and the area where this phenomenon is happening.

ii. Wave environment

The Jonswap model describes the consequences of the wind decrease on the wave environment. In addition to this information, Mike 21 BW module will model the wave attenuation due to the presence of the device. Combining the two results, the final impact of the implementation of renewable energy devices on waves is deduced.

iii. Modifications of tides

Mike 21 HD module will model the modification of the water level due to the presence of the renewable energy devices. Two simulations will be carried out, one with the devices and one without. The comparison between the results will provide information about the impact on tides.

iv. Currents' environment

Mike 21 HD module will model the modification of the water velocity due to the presence of the renewable energy devices. Two simulations will be carried out, one with the devices and one without. The comparison between the results will provide information about the impact on currents' environment.

v. Modifications of sediment transport and erosion processes

Mike 21 ST module will model the modification of sediment transport and erosion process due to the presence of the renewable energy devices. Two simulations will be carried out, one with the devices and one without. The comparison between the results will provide information about the impact on sediment transport and the erosion processes.

C) Parameters Used

This section describes the inputs needed in order to run the calculations and models previously presented.

1) <u>Wind model</u>

In order to run the calculation for the wind model, the following parameters are needed:

- ❖ $U_{freestream}$ - the incoming wind speed to the WF: this parameter can be modified in order to analyse the different evolutions of the wind environment depending on the incoming wind velocity.

- D: Diameter of the turbine, which depends only on the type of turbine chosen
- Layout of the WF: the distance between rows and columns of the WF are needed. The number of rows and columns are also needed in order to know the extent of the WF area.
- Power capacity of the turbine: this is linked to the thrust and to the thrust coefficient which are both needed to run the simulation.

With the information about these 4 parameters, the calculations to determine the impact of wind environment modification can be carried out.

2) Mike 21

Mike 21 requires specific parameters to run simulations. These parameters are displayed in the left column of the setup file and are presented for each module in the appropriate sections in Figures 10-11-12.

i. BW model

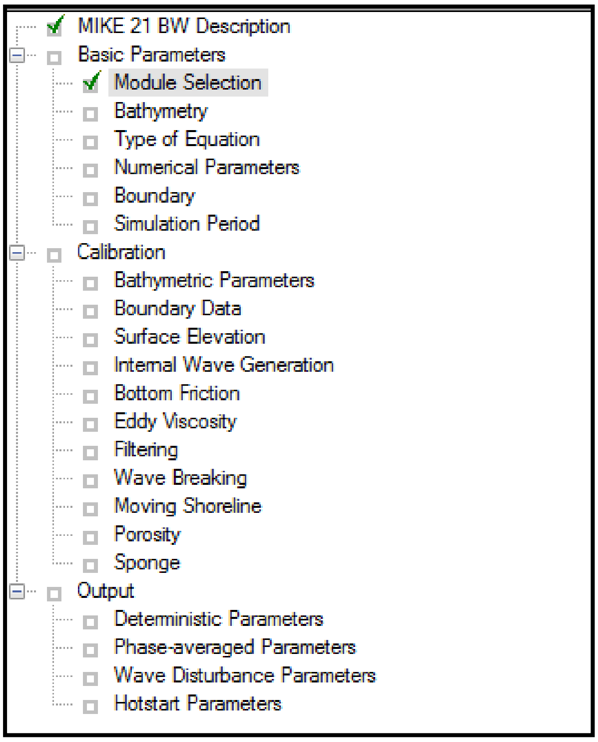


Figure 8: BW model parameters

Of the three models used, the BW model requires most information, as described below:

- The bathymetry is the most important parameter. In order to know how far the effect can go, a large area needs to be covered. So as to be sure to cover all the area affected, the bathymetry required will need to be known for an area of $250km^2$ around the devices. The devices are integrated in the bathymetry; therefore the details of the devices (dimensions, structure base dimensions, and need for scour protection) are also required.
- The porosity map is deduced from the bathymetry information. “Porosity values are used to model either partial reflection and/or transmission through structures.” (DHI Group 2010b). Mike 21 Toolbox can deduce the porosity map from the bathymetry, however the porosity values of the devices are unknown by the toolbox and need to be provided.
- The sponge map is deduced in the same way as the porosity map. “Sponge (or absorbing) layers can be used as numerical wave absorbers in Boussinesq wave simulations” (DHI Group 2010b)
- The mean sea level is needed to be added to the bathymetric values provided.
- The generation of waves is managed by the Mike 21 toolbox. The mean wave height, period and direction are parameters by the toolbox. The knowledge of the wave environment around the devices, allows the toolbox to provide a wave environment closer to reality.
- The other inputs of the model are used with the default values provided by DHI or are unused, if possible, in order to speed up the computation.

ii. Flow model

The flow model requires less information than the BW one:

- The bathymetry remains the main input of the model, using the same information provided for the BW model.
- Tides on the boundary of the bathymetry are needed to model the variation of water level and velocity through time.
- Wind conditions are needed as they can affect the water level.
- The resistance of the seabed and Eddy viscosity values are the same as the ones used in Mike 21 examples.

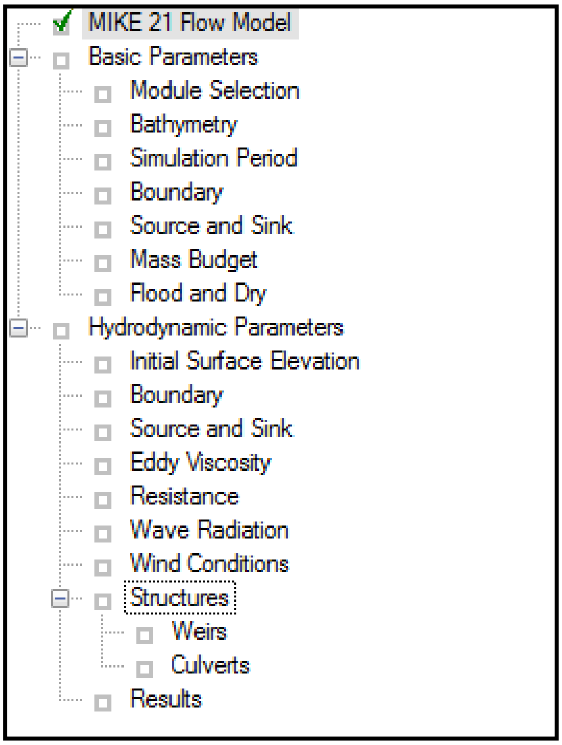


Figure 9: Flow model parameters

iii. ST model

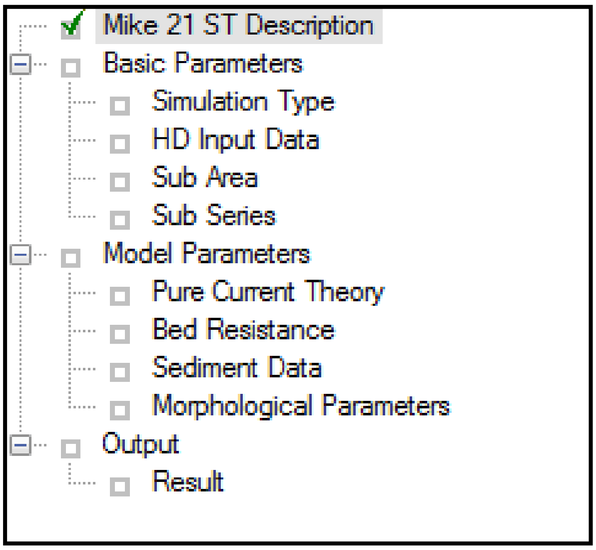


Figure 10: ST model parameters

The non-cohesive sediment transport model requires the least number of inputs of the three models:

- The main one being a result from a HD simulation

- The other parameters are used with the default values provided by DHI.

From the knowledge of all these parameters, the simulations of all the different models of Mike 21 and the calculations for the wind model can be processed.

IV) Implementation

In order to make this research more realistic, the simulation using Mike 21 needed to use a site where a marine energy farm was already implemented or one where plans for implementation were underway. A research concerning the potential site was made and the first step was to determine the criteria that define a suitable site for the implementation of marine renewable energy.

A) Potential Sites in the UK

1) High resource potential

The study of the resources of wind, wave and tidal energy have been presented in the resource assessment sections p4-9-13

The main conclusions were:

- The North-West of the country has a very strong potential in term of Wind energy
- “The UK has a large potential for powerful waves, around the southwest peninsular (to be utilised for the forthcoming wavehub experimental station), the Northern Isles (EMEC wave testing site), Pembrokeshire (Wavedragon testing site), and the Outer Hebrides, on which the first commercial wave energy converter was built in 2000 (Amoudry et al. 2009)”.
- “The UK potential for tidal stream technology is focussed in the Severn Estuary (2nd largest tidal range in the world), the Skerries (Anglesey), the South coast between the isle of Wight and the Channel Islands, East Anglia, and the Pentland Firth.”(Amoudry et al. 2009)

2) UK bathymetry

The UK bathymetry and territorial sea limits are presented in Figure 11. The UK has a number of suitable sites all along the coastline, and the only restrictions concerning territorial limits occur in the Channel and the Irish Sea.

From the bathymetry map and the information about the resource potential, three counties in the UK seem very attractive in terms of implementing marine renewable energy devices:

- North and West parts of Scotland where the wind and wave power resource are substantial.
- Norfolk where the bathymetry is very suitable for WFs.
- South and South West of England where tidal resources are major.

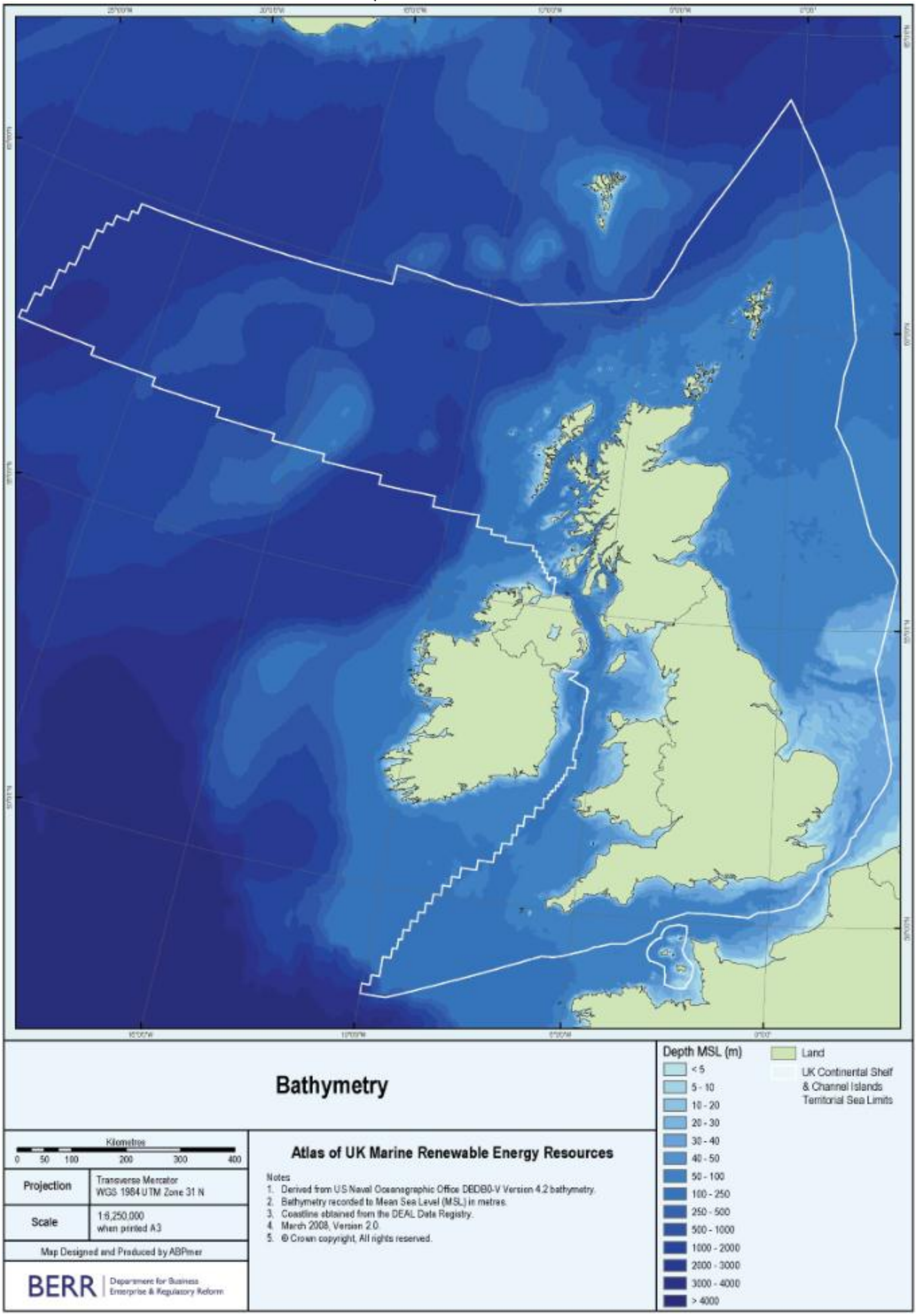


Figure 11: UK bathymetry

Source (ABPmer 2008b)

3) Accessibility

Access to marine renewable energy devices needs to be available and a sufficiently large area to harbour ships that install the devices must be present. Figure 12 shows a map of UK ports, represented by red circles. Almost all of the UK coastlines offer good access, with only the north and west part of Scotland being less accessible.

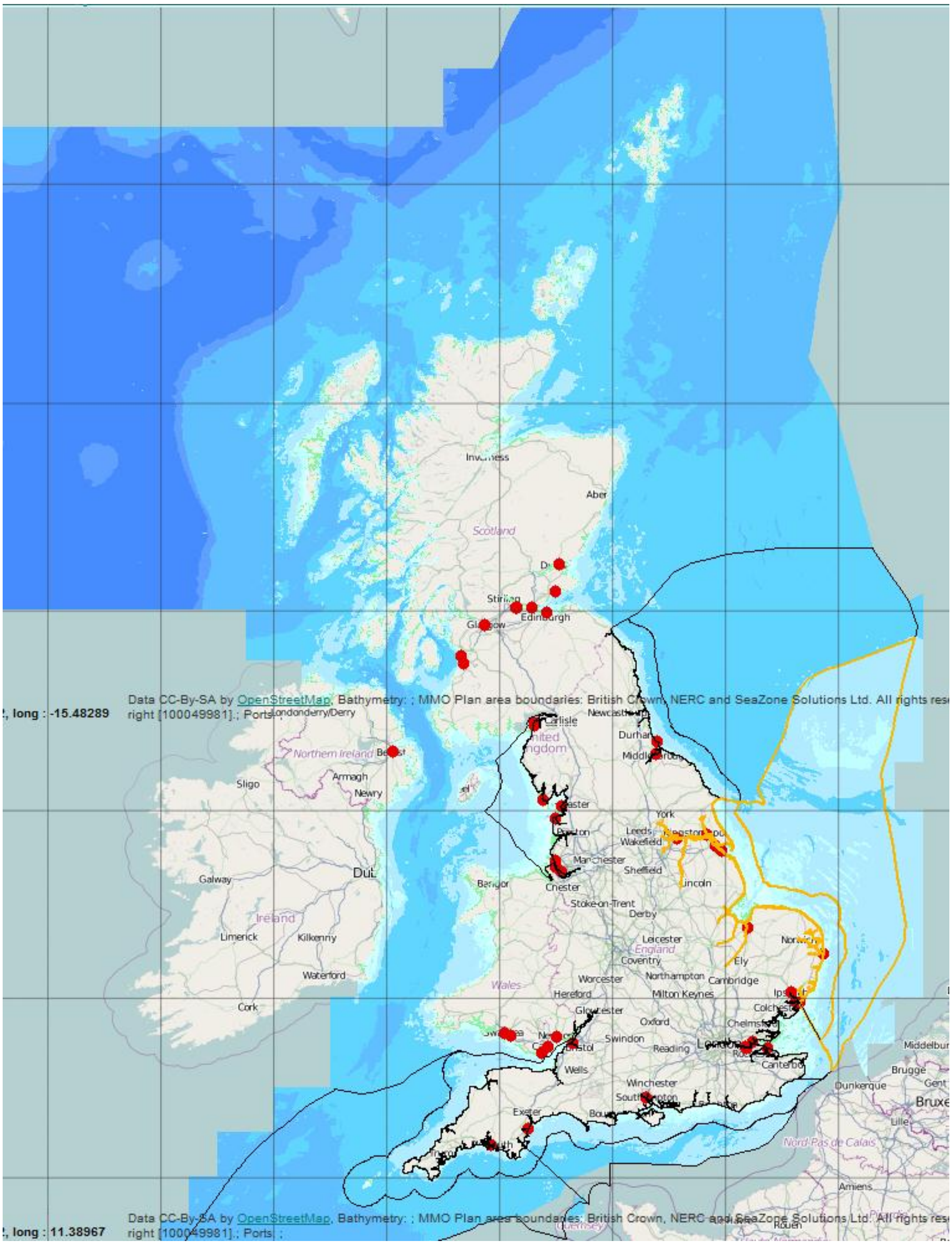


Figure 12: UK harbours

(Source: Marine Management Organisation)

B) Choice for the Sites

The choice for a site which would be the basis of the modelling on Mike 21 was guided by the criteria presented in Appendix C), taking into account the fact that I needed to have access to the information required to run the calculations and models (see section C) on page 38). For this reason, existing sites or sites in the process of being developed were targeted.

1) Wind energy site

There are a number of wind energy sites already active and more planned for round 3. In a previous assignment in a Coastal Engineering course I worked on Sheringham Shoal WF (Figure 13). Having already all the information required and knowledge of the site made this my site of choice.

Sheringham Shoal site meets the criteria previously described: "The Sheringham Shoal Offshore WF site is located in the Greater Wash, between 17 and 22 kilometres off the Norfolk coast, north of the seaside town of Sheringham. The site was chosen because it:

- lies within a government approved area for development
- enjoys high wind speeds
- has favourable water depths
- has relatively low levels of fishing activity
- affords good access
- has grid connection options
- is outside protected and scientifically designated areas." (Scira Offshore Energy 2011)

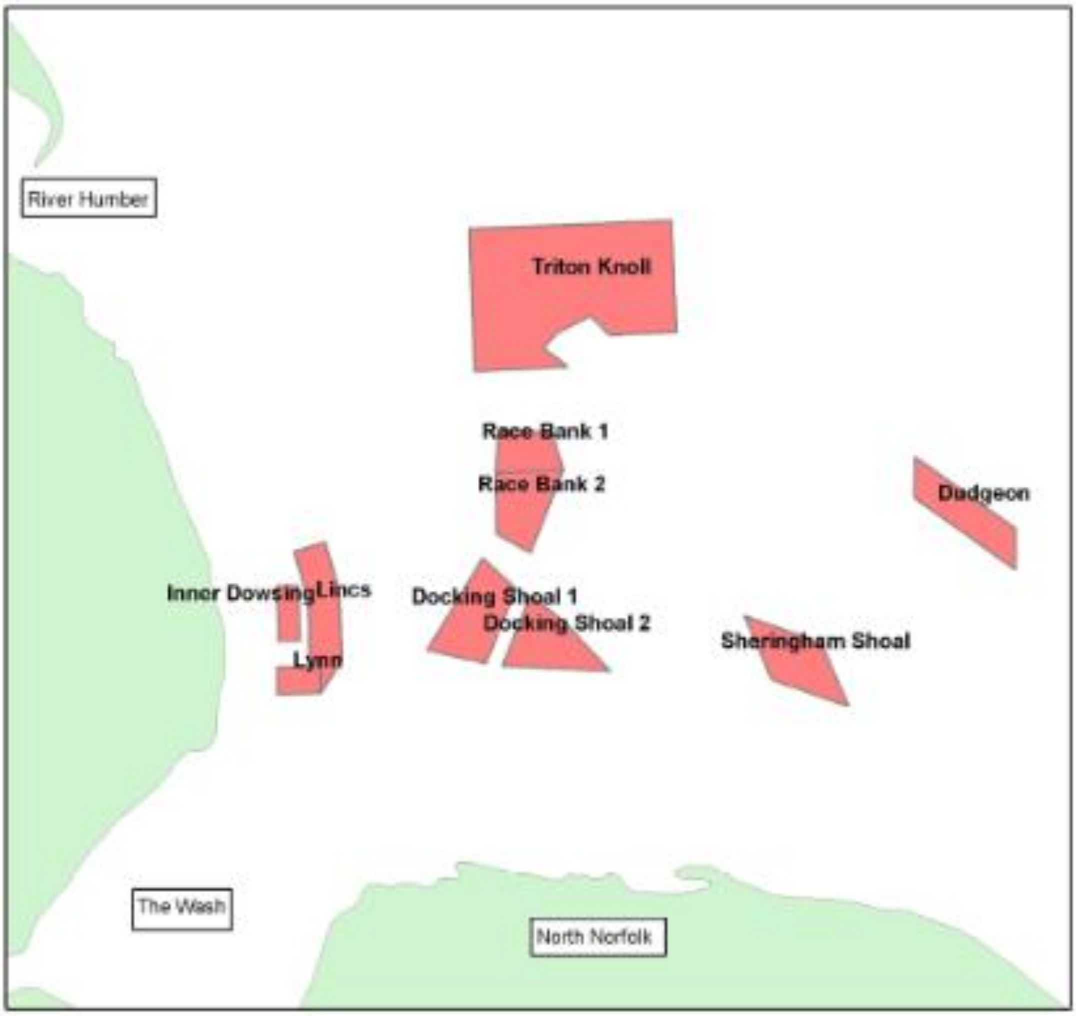


Figure 13: Potential and existing WFs in the vicinity of Sheringham Shoal

Source: (Statoil 2010)

2) <u>Wave energy site</u>

The choice for the wave energy site was less obvious. There is no active site to date. The only site which is in operation is the wave hub site (Figure 3), which is used only for testing purposes. It can be seen in Figure 3 that there is another large place where wave devices are about to be implemented: Pentland Firth and Orkney Waters. It is situated in Scotland where the wave potential resource is significant. There is also a large place which allows the implementation of a large number of devices. This makes the modelling of cumulative impacts easier.

From all the sites for wave devices in Pentland Firth and Orkney Water, the site of Costa Head was chosen (Figure 14). This site has been acquired by SSE Renewables Developments, which project to implement 200 MW of wave devices.

This site was answering the main criteria expressed in section VIII).C) on page 107:

- High potential resource: “This is a significant opportunity area for wave energy development, both nearshore and offshore. Exploitable wave energy levels of 20-25 kW/m are available immediately adjacent to the coast.” (Scottish Government 2010)
- Bathymetry: “The rapid shelving to 50m means that it may be possible for moored offshore devices and shoreline devices to be proposed within short distances of each other, and potential cumulative effects will have to be considered. Seabed surface geology varies between sands and gravels” (Scottish Government 2010)
- Accessibility: “The Orkney Islands have a number of ports and harbours capable of supporting development in this area.” (Scottish Government 2010)

Moreover this site avoids the principal shipping roads, and other marine activities in the region.

3) Tidal energy site

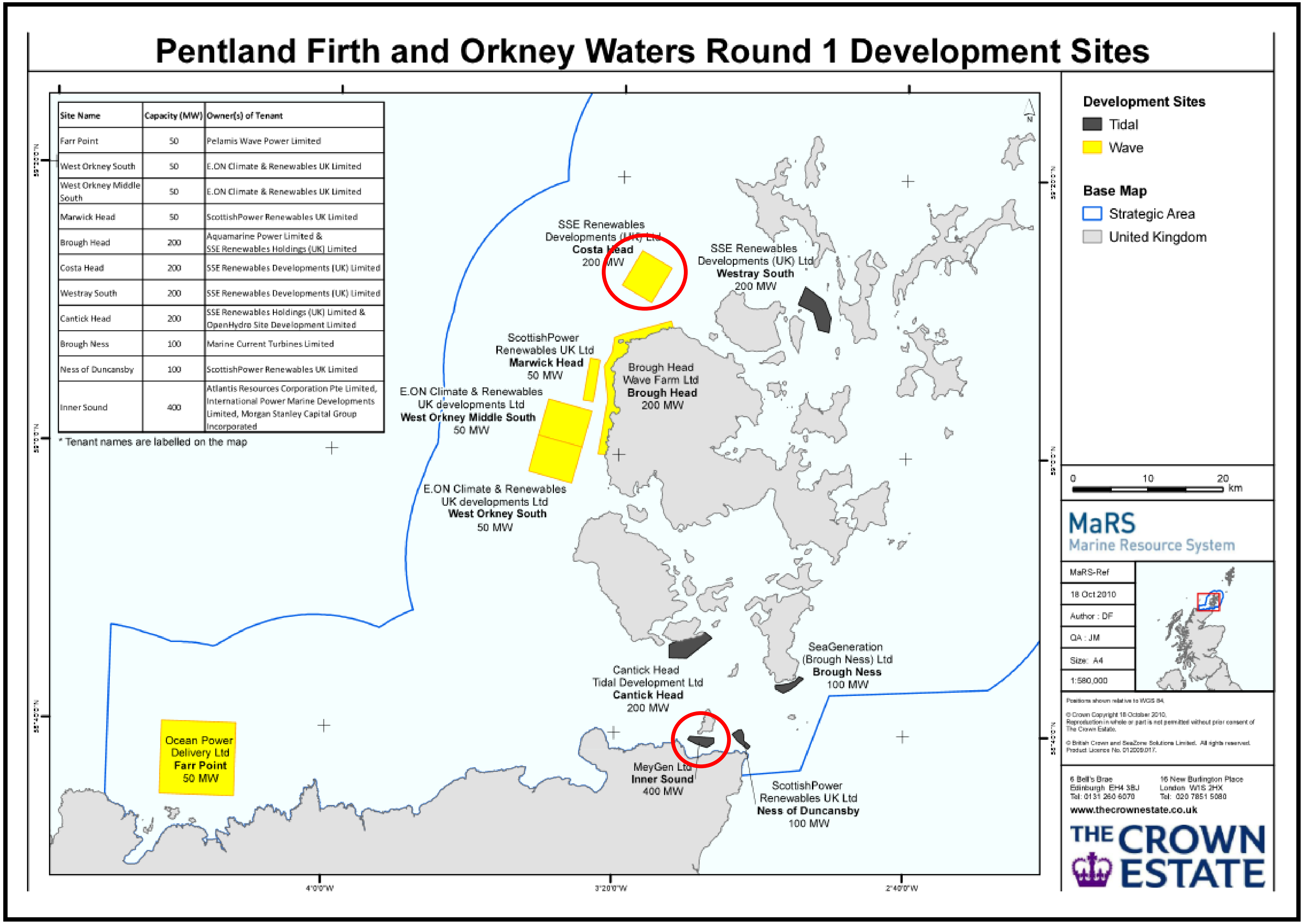
The choice of the tidal energy site was helped by the previous choice of the wave energy site. Both tidal energy and wave energy are at the same stage of development. Although, there are a few more active tidal places than wave ones, active sites have only implemented a small number of tidal devices and couldn’t be used for the purpose of analysing the cumulative effects. A larger number of tidal devices could be implemented in Pentland Firth and Orkney Waters and therefore the choice was directed towards Inner Sound, (Figure 14), which has a project for an implementation of 400 MW.

The three main criteria are respected:

- High potential resource: “The potential resource in this area is considerable. Peak spring rates of 4ms-1 are also typical of the channel between the Pentland Skerries and Duncansby Head on the mainland, although close in to the Pentland Skerries flows as high as 6ms-1are reported.”(Scottish Government 2010)
- Bathymetry: a rocky bed of 30 meters depth (Scottish Government 2010)

- Accessibility: “There are two small harbours on the coast of Caithness adjacent to this area.” (Scottish Government 2010)

Moreover since the choice of the two sites for wave and tidal models are in close proximity of each other, research on the parameters needed to run calculations and models was made easier.



Site Name	Capacity (MW)	Owner(s) of Tenant
Farr Point	50	Pelamis Wave Power Limited
West Orkney South	50	E.ON Climate & Renewables UK Limited
West Orkney Middle South	50	E.ON Climate & Renewables UK Limited
Marwick Head	50	ScottishPower Renewables UK Limited
Brough Head	200	Aquamarine Power Limited & SSE Renewables Holdings (UK) Limited
Costa Head	200	SSE Renewables Developments (UK) Limited
Westray South	200	SSE Renewables Developments (UK) Limited
Cantick Head	200	SSE Renewables Holdings (UK) Limited & OpenHydro Site Development Limited
Brough Ness	100	Marine Current Turbines Limited
Ness of Duncansby	100	ScottishPower Renewables UK Limited
Inner Sound	400	Atlantis Resources Corporation Pte Limited, International Power Marine Developments Limited, Morgan Stanley Capital Group Incorporated

Figure 14: Pentland Firth and Orkney Waters site

Source (Marine Resource System 2010a)

C) The Devices Types

1) Wind turbine

Sheringham Shoal offshore WF site is currently under development, therefore the different layouts and models of turbines were studied. Table 4 presents the different options that could be implemented at the site.

Layout Options	45 x 7MW	63 x5MW	70x4.5MW	88X 3.6MW	108x3MW
Indicative number of turbines	45	63	70	88	108
Turbine rated capacity (MW)	7	5	4.5	3.6	3
Rotor diameter of turbine (m)	150	126	120	107	90
Hub height (m)[3]	97	85	82	75.5	67
Anticipated number of columns	9	9	10	11	12
Anticipated number of rows	5	7	7	8	9
Wind farm capacity (MW)	315	315	315	315[4]	315[5]
Distances between rows and columns					
Perpendicular distance between rows[6] (by number of rotor diameters)	7.4	5.9	6.2	6.1	6.2
Perpendicular distance between rows (m)	1108	738	738	633	554
Distance between rows (m)[7] (turbine to turbine)	1120	780	750	650	570
Perpendicular distance between columns (by number of rotor diameters)[8]	4.4	5.3	4.9	5.1	5.3
Perpendicular distance between columns (m)	661	661	588	529	481
Distance between columns (m) (turbine to turbine)[9]	900	900	800	720	660

Table 4: Indicative layouts options for Sheringham Shoal

Source: (Scira Offshore Energy Ltd 2006)

Since the objective was to model cumulative impacts, there was a need for having a large number of devices. The choice was therefore oriented towards the two left columns of Table 4. The models of 3MW and 3.6MW have respectively a tower base diameter of 4.5 and 5m. In order to facilitate the modelling on Mike 21, a large turbine was needed.

The final choice for the wind turbine model was a 3.6MW turbine with a layout consisting of 88 turbines.

The water depth in the area is between 14 and 21 meters. A gravity base was chosen in addition to a scour protection. These two structures were chosen as they require a very large space, making the model in Mike 21 more significant due to the larger impact.

The layout chosen in Mike 21 has a similar shape to the layout that may be used in the Sheringham Shoal site (Figure 15).

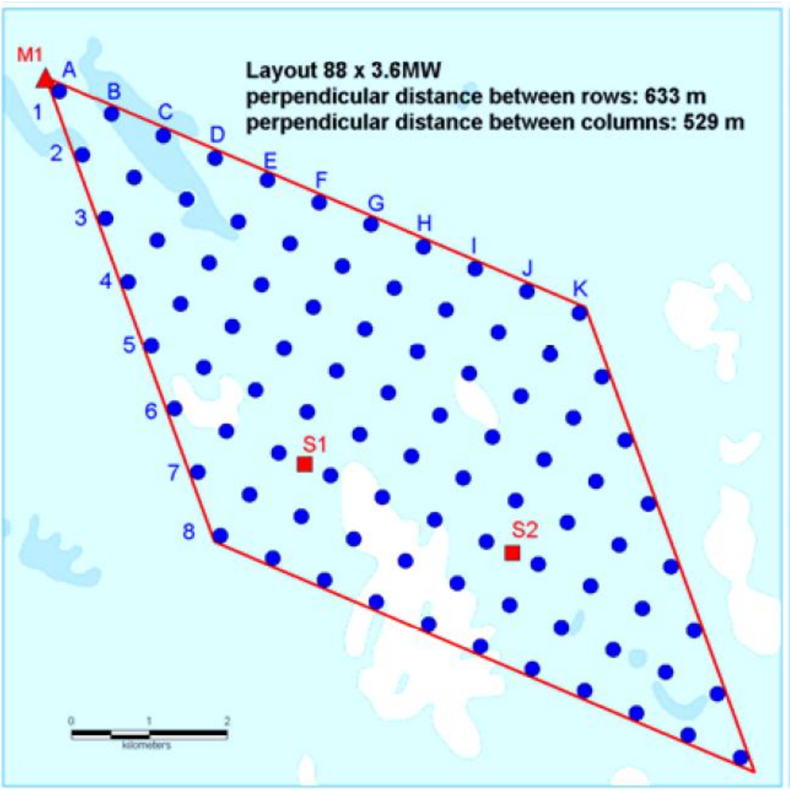


Figure 15: Possible layout for the 3.6MW model in Sheringham Shoal

Source: (Scira Offshore Energy Ltd 2006)

2) <u>Wave device</u>

Since the wave energy site hasn't been developed yet, it was impossible to use a potential device already recommended by the company. Research was therefore made into the existing site, in order to find a suitable device.

Since the depth is 60 meters and more, a device with a mooring system was needed and the site has a potential capacity of producing 200MW.

The PB150 PowerBuoy (Figure 16) is a device that has already been implemented in Scotland. It is only a single device deployment. However 14 units have been deployed on the West coast of the United States (Oregon) and this number could evolve to 200 if the previous deployment is satisfactory.(McMurray 2007)

The dimensions of the PB150 are:

- Float Diameter: 11m
- Float Height: 2m
- Height Above Water: 8m
- Draft: 36m
- Number of Anchors: 2 per buoy (buoys share 1 anchor)

(Oregon Solutions 2007)

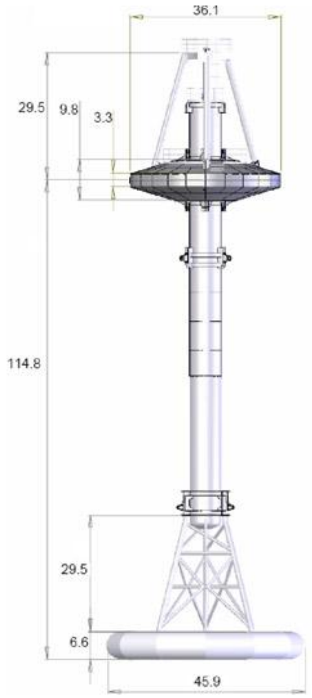


Figure 16: PowerBuoy dimensions in feet

Source : (OPT 2011)

Following upon the project in Oregon, a decision was made to consider the deployment of 200 units. The output power would be, as in Oregon, around 50MW (McMurray 2007). The layout of the 200 devices is "four rows of 50, parallel to shore" (McMurray 2007). With the knowledge that the footprint of the installation would be "about ½ mile by 3 miles" (McMurray 2007), the distance between the rows was calculated to be 257m and the distance between two devices in the same row 88.5m.

3) <u>Tidal device</u>

Once again the basis of the choice of the tidal energy device was similar to the wave energy one. Since the tidal energy site hasn't been developed yet, it wasn't possible to use a device recommended by the bidding company. Research was therefore made into the existing site in order to find a suitable device. In the case of tidal energy, there are some devices already deployed on the UK coastline. Sound of Islay is a site where 10 devices of 1MW will be deployed in 2013. ScottishPower Renewable received the consent of the Scottish government in 2011 for the installation of tidal devices (ScottishPower Renewable UK Ltd 2011). This site is quite similar to Inner Sound, and is also the only site where layouts for rows of turbines are presented. Indeed the state of development of tidal energy on the UK coastline is such that there is no other place where more than 3 devices are deployed. The devices and layout of this site was therefore chosen.

The Sound of Islay project will use Hammerfest Strøm tidal device HS1000 (Figure 17).

"The base of the device is about 22 metres high to the hub and the blades are about 11.5 metres long. The total height from the seabed to the top of the blade tip is approximately 33.5 metres."(ScottishPower Renewable UK Ltd 2011)

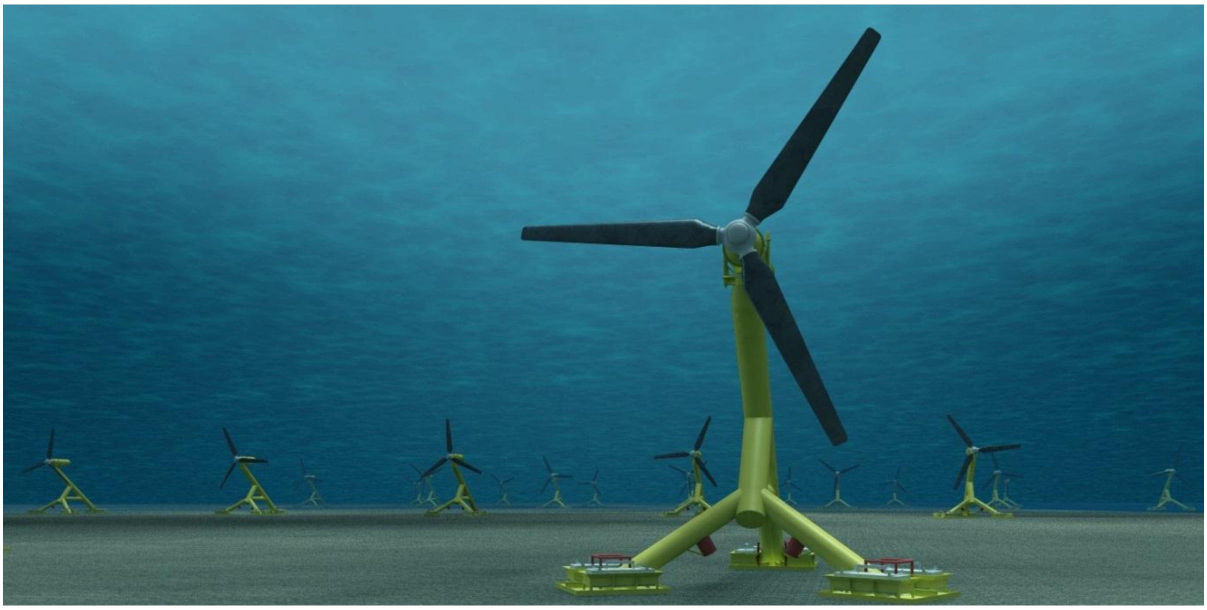


Figure 17: Hammerfest Strom HS1000 Tidal Turbines

Source (Islay Energy Trust 2011)

The devices don't need any additional anchors or gravity base as their own weight keeps them on the sea bed. The layout in Sound of Islay is composed of 4 rows with a distance of 483m between rows. The distance between two devices in the same row is approximately 50m (Figure 18).

Considering the bathymetry of Inner Sound and the potential of tidal energy at the site, 140 devices will be virtually deployed on Mike 21. The layout will be constituted of 8 rows of 18,16,16,16,14,16,16 and 28 devices respectively. The distance between two adjacent turbines in a row is 50m and the distance between two rows will be extended to 800m in order to allow ship traffic between the devices.

Following the choice and layout of the devices, the modelling on Mike 21 was carried out.

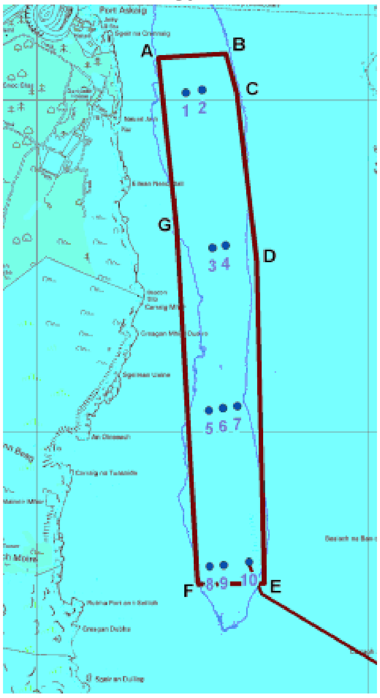


Figure 18: Layout of Sound of Islay

Source: (Royal Haskoning et ScottishPower Renewable UK Ltd 2010)

D) Implementation in Mike 21

The implementation in Mike 21 will be presented for each model separately, as the parameters and information needed for each is different. This section will focus on the milestones of the process and the issues encountered. The detailed process with all the steps carried out is described in Appendix B p98.

1) <u>BW model</u>

a. Bathymetry

This section describes the modelling used for the different devices implemented. Since, renewable energy devices aren't given as an option in Mike 21, their modelling was done during the process of bathymetry. The bathymetry of Mike 21 is represented by a grid of squares. These squares were given a size of 10m x 10m to compromise between the size of the devices and the area that could be studied, given computational memory restrictions. The Wind turbine has a diameter of 5m and a height of 70m; nevertheless, due to computer memory limitations, it was modelled by one square (10x10m) of 70m height. The gravity base in addition to the scour protection is a circle of 50m diameter centred on the turbine which is 2.5m higher than the seabed. These were represented by a rhombus of diagonal length 60m, 2.5m higher than the sea bed around the turbine (Figure 19).

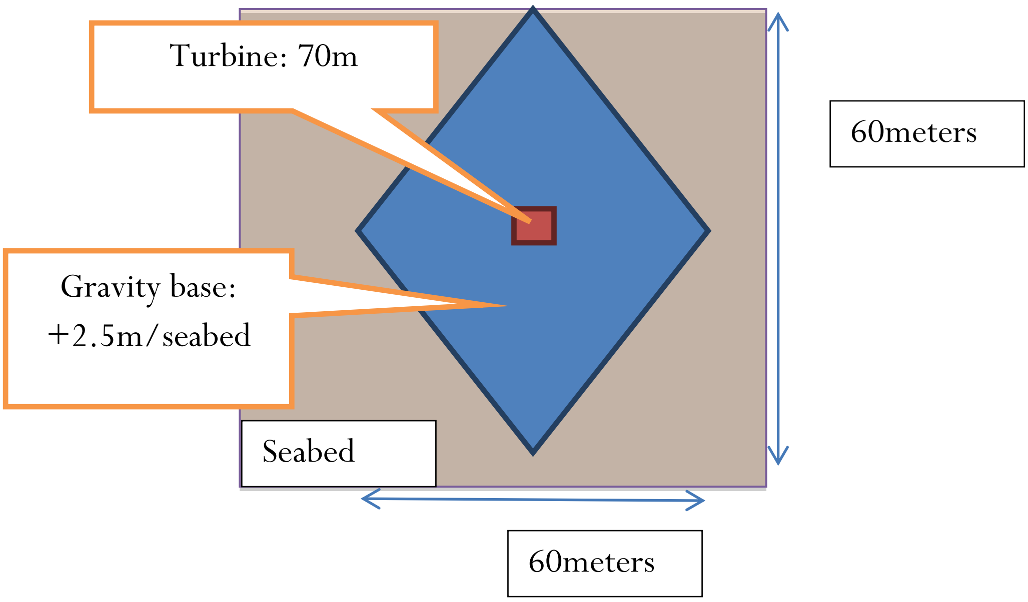


Figure 19: Wind turbine modelling on Mike 21

The wave device is a buoy and therefore its modelling is impossible unless an approximation is done. V.Venugopal and G.H.Smith in their paper "Wave climate investigation for an array of wave power devices" have experienced the same issue. They did the approximation that the wave device could be considered as bottom fixed and modelled the wave devices by land. "This procedure can be very well applied to bottom mounted fixed type wave devices but should be used with great caution to model floating type devices. Since it cannot model the dynamic interaction between the wave and floating device or between the devices within the array and therefore the application of this wave model to rapidly moving floating devices is questionable. However, for deep draught floating structures with restricted or limited motions, the authors believe that this wave model would still produce acceptable results if the main interest is only on the wave climate around the devices." (Venugopal et Smith 2007)

The buoy is 44m high, has a diameter of 10.7m and weighs 60 tons; it meets the requirements of the approximation made by Venugopal and Smith. The wave devices were consequently modelled by a square of land which was 3.5m high.

A tidal device is a very big prop mounted on a structure which allows the water to go through it. Once again, it wasn't possible to model this characteristic in Mike 21. The tidal devices were therefore modelled by four squares 33.5m higher than the seabed. An example of bathymetry used for tidal modelling is shown in Figure 20.

b. Generation of porosity layer

The generation of the porosity layer was made by the Mike 21Toolbox. It was based on the bathymetry map. The only correction that was needed was the friction value for the devices. For the wind turbine, a minimum value of 0.2 was chosen since it is completely reflective. A value of 1 was chosen for places with no attenuation at all. For wave devices several tests with different values were run. A similar process was used by Venugopal and Smith (Venugopal et Smith 2007). For the tidal devices several values were also tested.

c. Internal wave generation

The use of an internal wave generation was used to represent the incoming waves. The information concerning the main wave directions, height and period were taken from Wavenet for the wind turbines and two websites (Metcentral Ltd 2011; Meteo365 2011) for the tidal and wave devices since there was no Wavenet buoy recording this information close to the sites selected.

d. Simulation period

The simulation period was chosen in order to reach a rather stable state where no more evolutions were taking place. The length of the simulation was mainly depending on the size of the bathymetry. The starting date was the default value 01/01/1990.

e. Encountered issues

Several issues have been encountered during the simulations with Mike 21 BW model.

-The first areas which were assessed were too big or had too high a precision to get result within a viable timeframe. The size had to be reduced and a precision of a10 meter grid was finally chosen. The need to analyse a larger area in order to measure the impact made this choice necessary. However, this compromise of 10 meter grid resolution wasn't sufficient for the wind model. Some impacts were also outside the area supported by the simulation.

- Whenever some spaces were unused, they were replaced by artificial land to be excluded from the analysis in Mike 21 and decrease computational time required.
- Generation of a sponge layer map was necessary to avoid blow-up of simulation (crash of the simulation) due to unexpected high waves. The water level was too low for the wave height found. Some low values of the sponge layer were needed around the devices to avoid this phenomenon. The values were chosen as low as possible to maintain the running of the simulation without altering the results.

The BW model wasn't easy to run; it was very unstable with frequent stops of the simulations due to blow-up. A long process of setting the calibration parameters was necessary before getting any useful results.

2) Flow model

a. Bathymetry

The bathymetry used for the flow model was the same as for the BW model except at the boundaries. The boundaries were kept open in order to model the flux of water through them. An example of bathymetry is displayed in Figure 20.

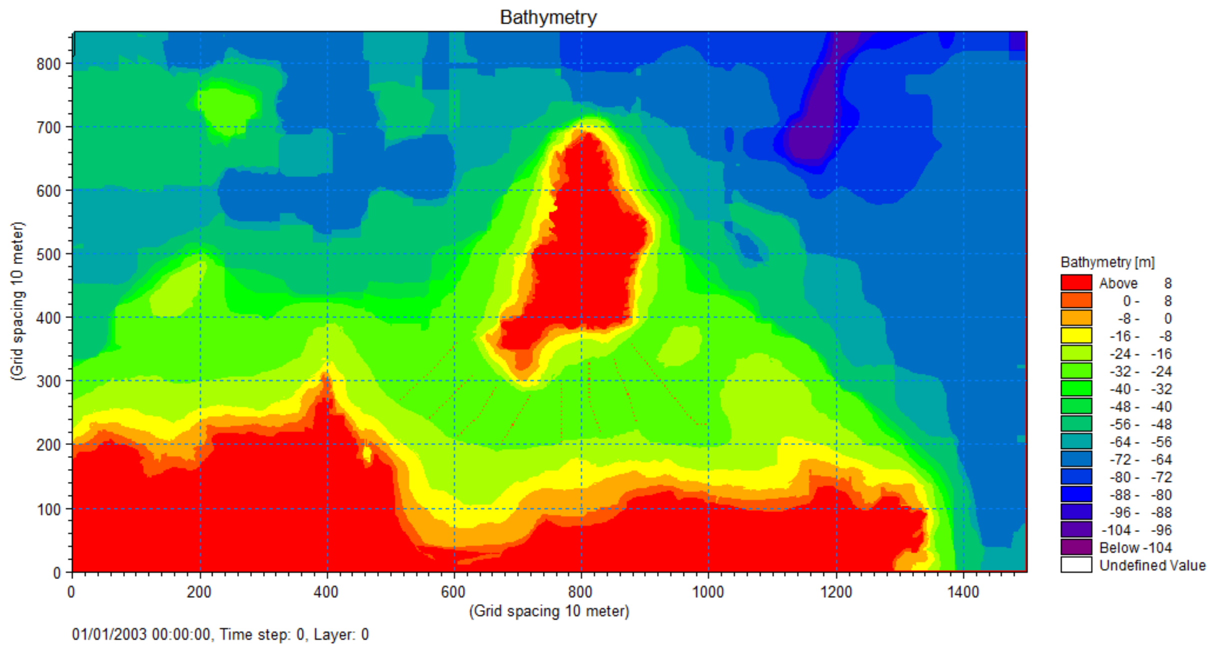


Figure 20: Bathymetry created for tidal energy using Mike 21 software

b. Initial surface elevation

The initial surface elevation corresponds to the main sea water level. The tides and tidal ranges of the area were needed. The information was taken from the environmental statement of the energy farm for the wind sites (Scira Offshore Energy Ltd 2006) and from websites giving local tides for wave and tidal sites: (Aquatera Ltd 2011; Tides4fishing 2011).

c. Boundaries

The boundaries were supporting the information about tidal range period and mean sea level. The parameters of the sinusoid representing the tidal function were specified for each open boundary.

d. Eddy Viscosity and Resistance

The values for these two parameters weren't the default ones but the value used in Mike 21 examples (DHI Group 2011d) for similar simulations.

e. Wind conditions

The wind conditions were found in the environmental statement of the farm for the wind sites (Scira Offshore Energy Ltd 2006) and from websites giving local forecast and statistic for wave and tidal sites (Meteo365 2011; Metcentral Ltd 2011).

f. Encountered issues

The main issue encountered concerned irrelevant values of flow found along the boundaries. This issue requested the use of tilting: "Tilting of a boundary is a facility that generates a setup along the open boundary so that the slope of the surface elevation is in equilibrium with the wind stress and Coriolis force." (DHI Group 2011d). The tilting method smoothed the value found along the boundaries.

3) <u>ST model</u>

The ST model is a simple model to run as long as the correct output of a HD simulation is available.

a. Flow model output

The main input for a ST model is an H, P, Q file. This file is the result obtained after a HD simulation. If a HD simulation was run successfully, you have the correct input for the ST simulation.

b. Pure current theory

The ST model allows the use of several theories for the current effect on ST and it can also model the effect of the waves. In order to simplify the simulation and since the wave data needed is substantial (a 2D file for each time step of the simulation) and cannot be generated by Mike 21, a pure current theory was chosen to run the ST model. Default values were kept for all other parameters.

c. Encountered issues

The only issue encountered was the difficulty to obtain the wave data for this model. In order to do this the wave effects on sediment transport were excluded.

The result obtained after having implementing the three models following the steps described above are found in section 0.

E) Implementation of the Wind Model Calculations

The wind calculations were realised using Microsoft Excel software.

The calculations steps have been presented in detail in section IV.A). Since the implementation consisted on following these steps, it wasn't deemed useful to repeat everything. Refer to page 32 to see the detail of the methodology used.

The choice of the parameters were $U_{freestream}$=12m.s^{-1}, D=107m, Power=3.6MW and the layout is as displayed in Figure 21.

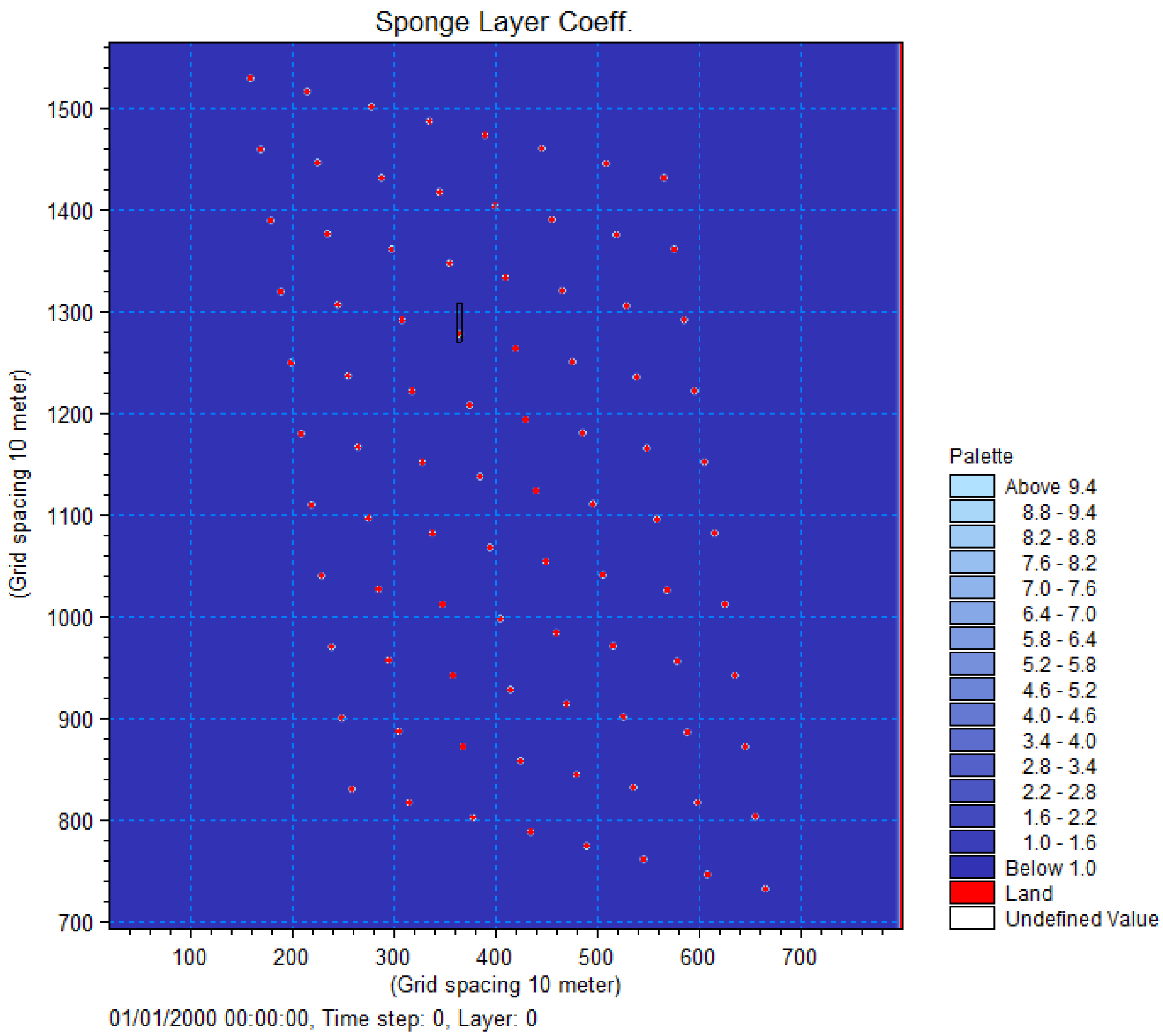


Figure 21: Layout WF for Mike 21

It was assumed that the wind was coming from the top in the direction similar to the axis of the rows. Similar calculations could be made for different directions, however this direction was chosen in order to maximize the impact on wind and facilitate the calculations.

V) Discussion

A) Results for WF Model

The results of the simulations and calculations of cumulative impacts concerning the WF are described in this section.

1) Impact on wind environment

The impacts on the wind environment are drawn from the calculations made with Excel. The wind velocity is shown in Figure 22.

The location where the wind turbines are situated can be easily seen in Figure 22 by look at the net decrease in the wind velocity. The percentage of decrease of the wind velocity reaches 68.8% of the initial speed at the last turbine. The wind recovers 90% of its initial speed at 2km from the last turbine, 95% of the initial speed at 3km, and 99% at 8.5km.

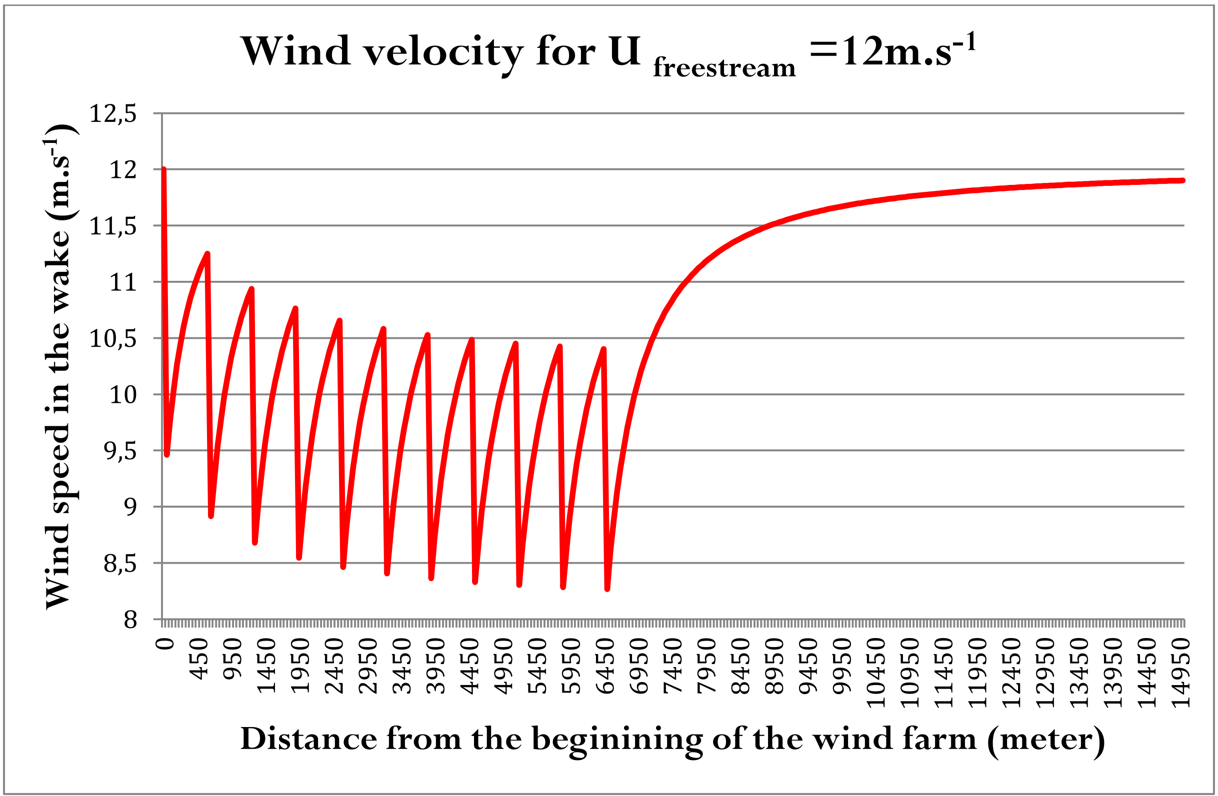


Figure 22: Wind velocity calculated for the WF

More calculations were made for different $U_{freestream}$, with similar results being found. The distances needed to recover 95% and 99% of the initial velocity are therefore independent of the initial $U_{freestream}$. The curves drawn for different initial speeds are shown in Figure 23.

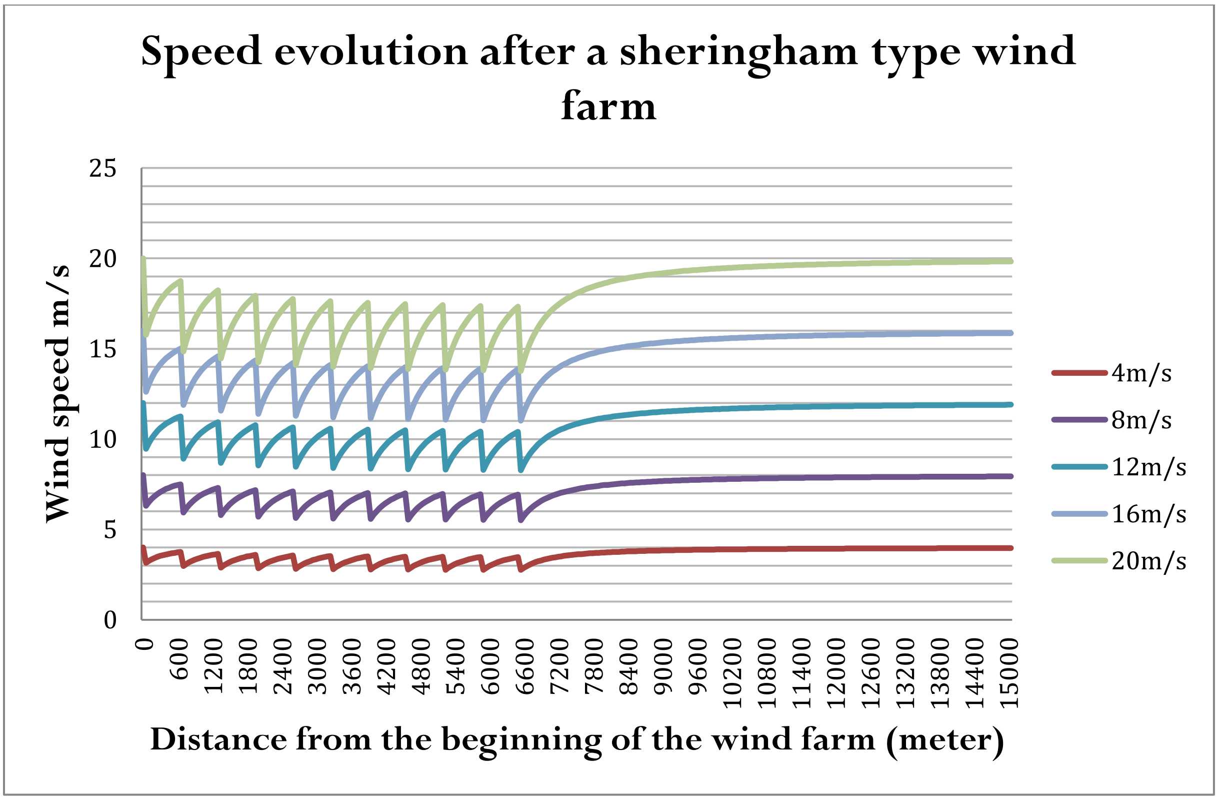


Figure 23: Speed evolution for different initial speed

The cumulative impact of implementing wind devices is a decrease in the wind speed over an area represented by the wake. The areas over which there is a decrease of more than 90%, 95% and 99% of the initial wind speed are 31.6, 32.4 and 33.7km^2 respectively. The information regarding the area was determined from the calculation of the wake diameter presented in Appendix B).

2) Impact on wave environment

There are two ways by which the wind devices alter the wave environment. The first is by decreasing the wind speed, which also decreases the power of wave generation. The second is by the presence of the devices which act as breakwaters. The first alteration of the wave environment was calculated using Excel and the Jonswap method, the second was assessed using Mike 21 BW model.

i. Jonswap Method

The mean wave height for Sheringham shoal is around 1meter high. However, since high wind speeds of $12m.s^{-1}$ were used in order to make the turbine deliver 3.6MW, the modelled wave height included 2m high waves in addition to the 1m high ones.

In order to use the Jonswap method, the expression of wind speed in the wake was simplified. The presence of turbines creates steep variations of the wind speed value and it isn't possible to use Jonswap method with an irregular wind. The wind speed was thus approximated constant equal to $10m.s^{-1}$ on the first 9km and $12m.s^{-1}$ on the remaining 6km. Note that the simulations were run over a distance of 15km, which is the distance from the beginning of the wave farm to the point where wind speed is recovered to 99% of the initial velocity.
The calculations results are: wave heights of 0.58m for a wind blowing at 12m.s-1 over a 9km fetch and wave heights of 0.48m for a wind blowing at $10m.s^{-1}$ over a 9km fetch. The presence of the wind turbines influenced the wind speed and therefore decreased the wave height by 0.10m.

Defining the exact area where this phenomenon is taking place is quite complicated. In order to facilitate further assessment of the impact, an approximation was made. The wave height decrease is assumed to take place in a rectangular area of the WF width, starting from the end of it and continuing downwind. It is assumed that this area doesn't end by neglecting all the processes that might attenuate or supress the initial difference in the wave height.

ii. Mike 21 BW

Several simulations have been run using the implementation described in section IV). The results of the simulation with incoming wave heights of 1m and 2m are displayed in Figures

24-25. It can be seen that the presence of the devices has a strong effect on the waves' environment.

A part of the wave height decrease is due to the wave shoaling process. This diminution is presented in Table 5 and these values were used to calculate the wave height decrease at the different positions.

position	beginning of the wind farm	end of the wind farm	7 km downwind from wind farm
depth	14.5m	21m	19m
wave height	1m	0.97m	0.85m
wave height	2m	1.98m	1.69m

Table 5: Wave height decrease due to shoaling effect

For the simulation of 1m high waves, wave height decreases of 64% to 59% are observed behind the devices and decreases of 59% to 41.2% are still observed 7km behind the WF. The wave height decrease has a tendency to be attenuated behind the WF. The final extent of the impact couldn't be determined successfully using the BW model since the extent was too large. This issue will be discussed in section D) on page 82.

For the simulation of 2m high waves, wave height decreases of 64.5% to 24.8% are observed behind the devices and decreases of 58% to 0% are still observed 7km behind the WF. Higher waves seem to recover quickly from the attenuation due to the presence of the wind turbines.

The combination of the attenuation due to the wind speed decrease and the physical presence of the devices result in decreases in a range of between 63.4% and 33.4% for the 1m high waves, and between 55.7% and 4.4% for the 2m high waves. This impact affects the wave environment until at least 7km behind the WF.

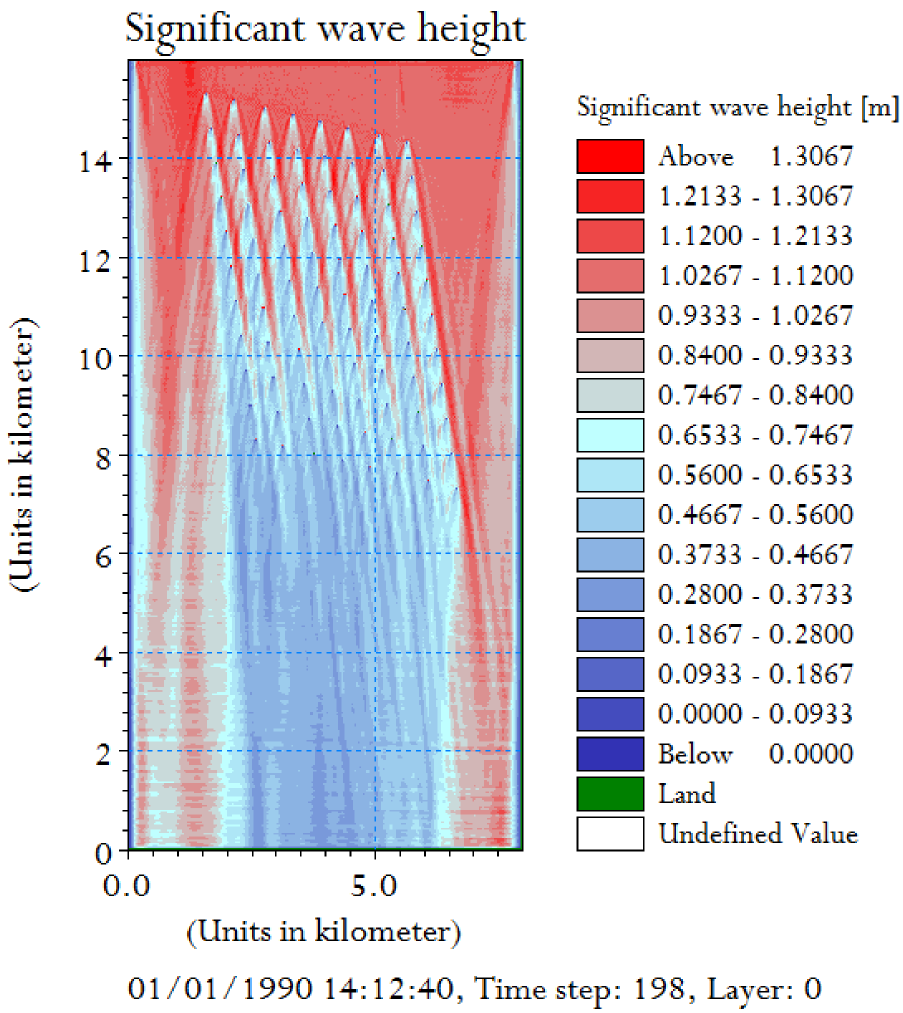


Figure 25: Results for the simulation of 1m high waves on WF

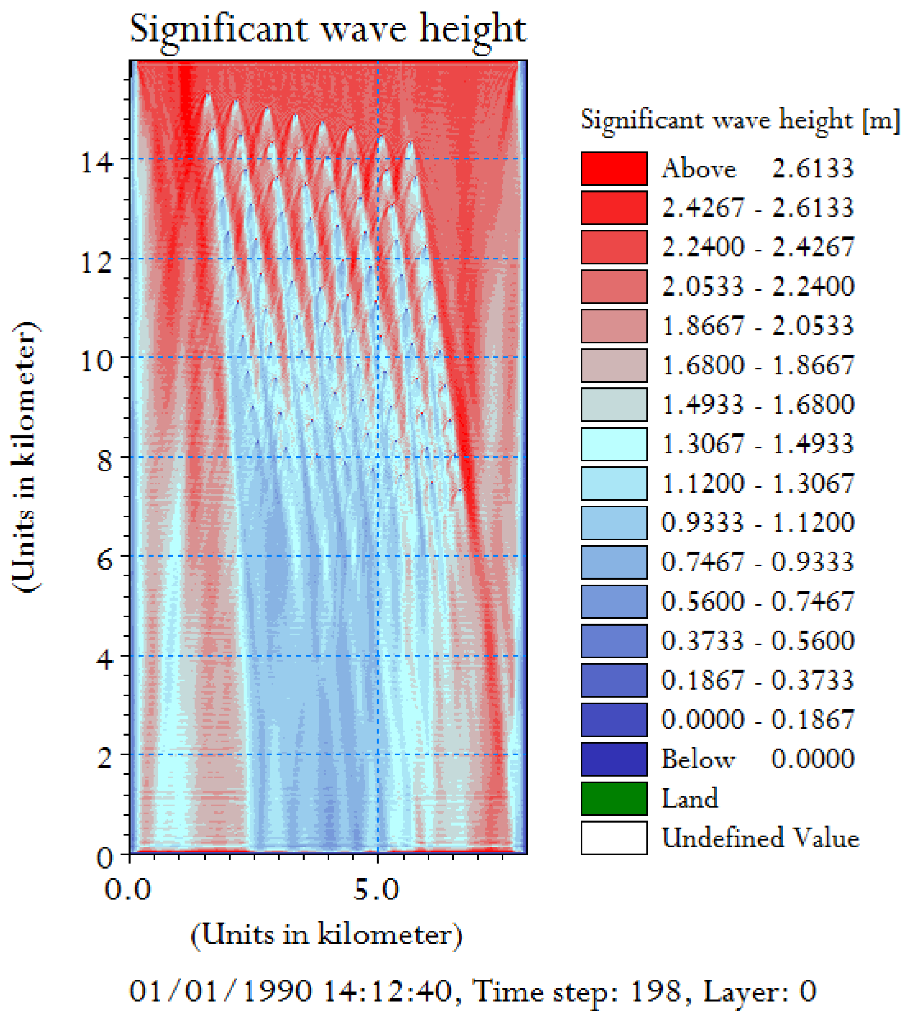


Figure 24: Results for the simulation of 2m high waves on the WF

3) Impact on water level

The impact of the presence of wind turbines on the water level is very low; a difference of a few millimetres can be noted at the WF location between the simulation with and that without the devices. This difference of a few millimetres between the two simulations is negligible, particularly since this is a numerical simulation which therefore contains a natural small error. The natural error and the differences observed are of the same order. It can be concluded that the WF does not have any impact on the water level.

4) Impact on currents

Results for the HD simulations concerning the sea water current are shown in Figure 26. Two simulations were run; one without devices (left) and one with (right).These simulations were run using open boundaries at the top and bottom of the bathymetry to model the real tidal current through the WF. The flow is vertical and directed towards the bottom. It can be seen that the presence of the devices affects the current. The decreases observed are 67% just behind the turbine and 25% 100m behind. However this alteration is local compared to the alteration to the waves. After 2km until 12km the flow was seen to have a decrease of 4% compared to the simulation with no device implemented.

The cumulative impact of wind energy devices on flow model is a decrease of 67% maximum of the value. This modification of the current is spread over an area of 2km.

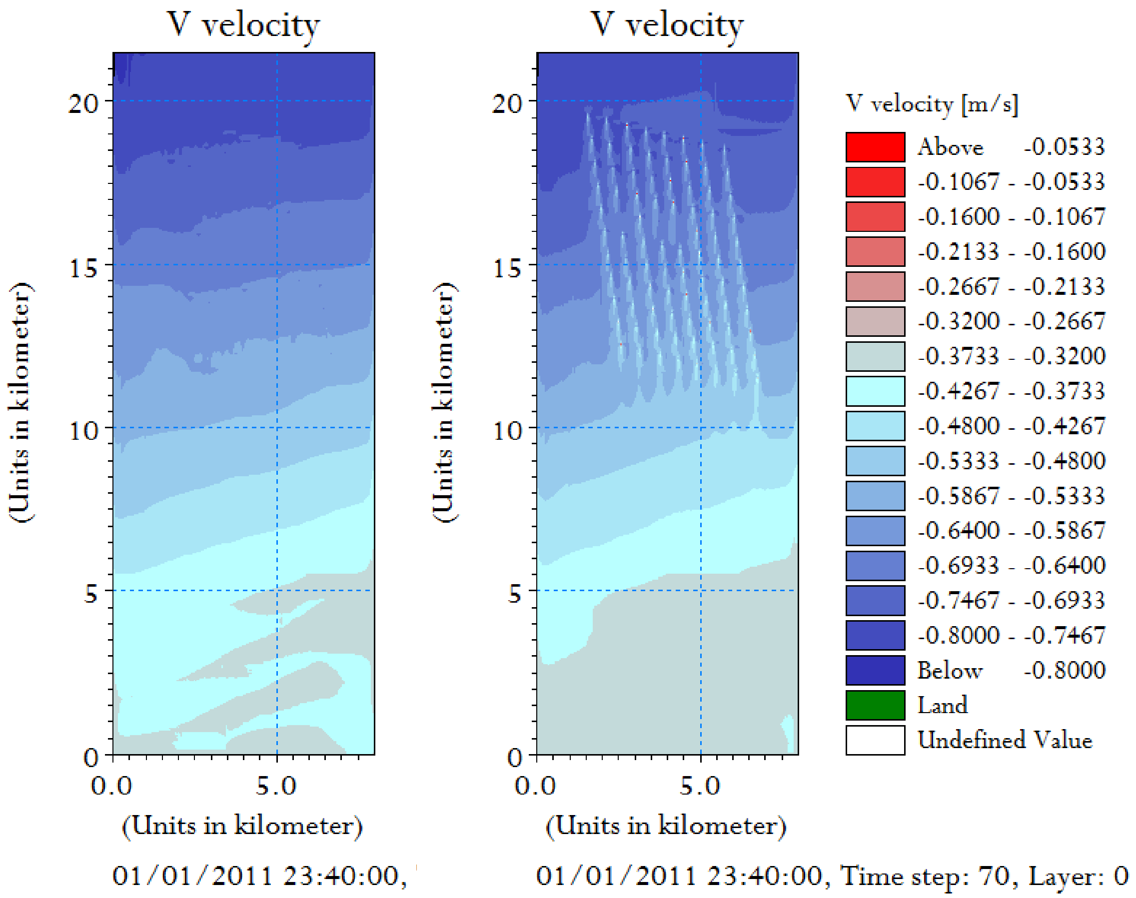


Figure 26: Results for the simulation of Flow model for WF

5) <u>Impact on ST process</u>

The modification to the currents at the WF location consequentially modifies the ST transport rate in the area. The decrease of ST process speed is total (100%) just behind the turbine; 85% after 100m; 24.4% after 2km. The average speed remains decreased by 12% 12km behind the farm.

The cumulative impact of WF on sediment transport process is a decrease varying from total (100%) behind the farm to 15% 12km after the farm.

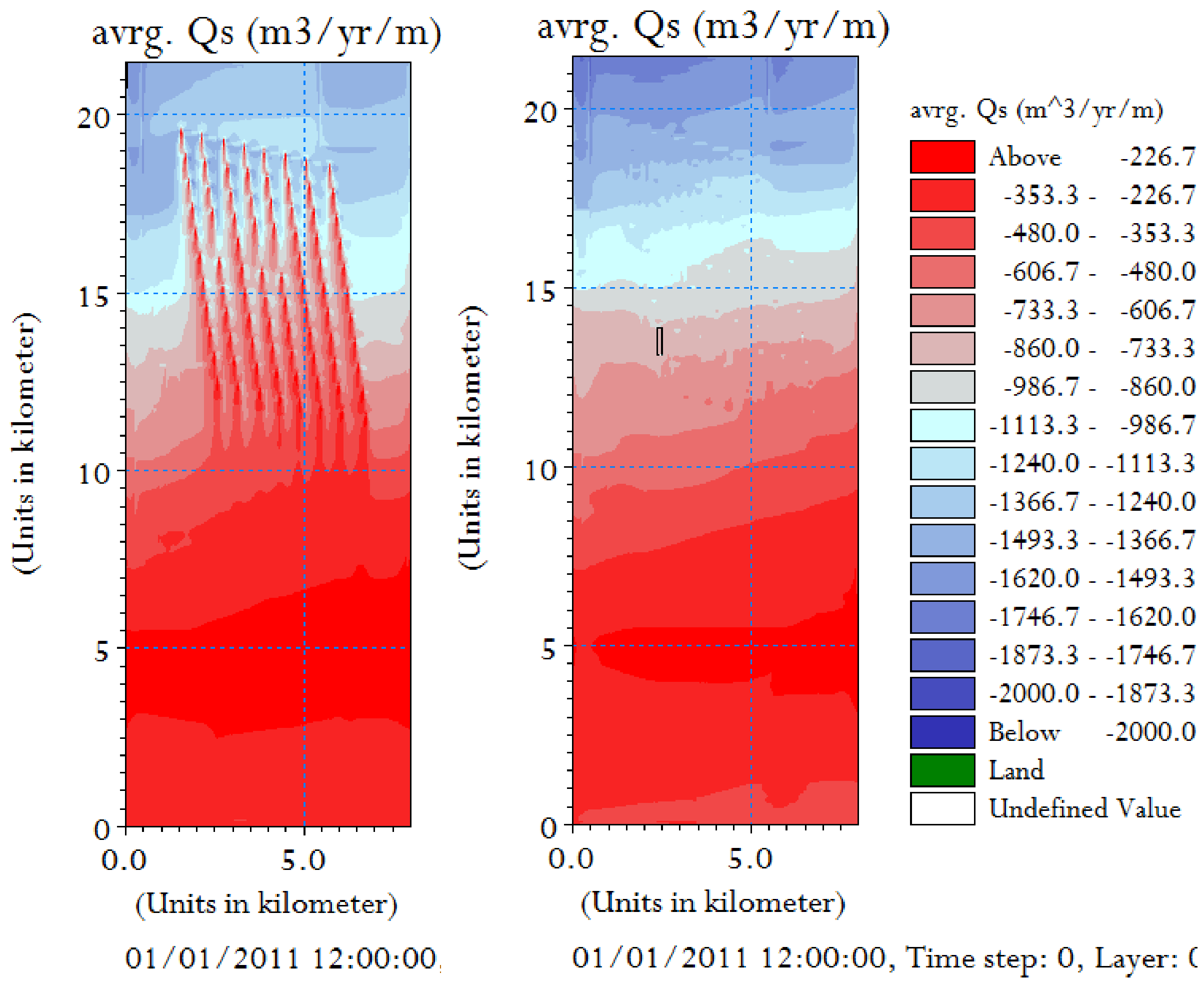


Figure 27: Results for the ST Model on the WF

6) <u>Conclusion</u>

To conclude, the cumulative impacts of the WF are easily notable concerning the sediment transport process and the wind, waves and current environments. There is no remarkable impact on the water level.

B) Results for Wave Farm

The results of the simulations/calculations of cumulative impacts concerning the wave devices are described in this section.

1) Impact on wind environment

The wave devices are 9m height above the water, are relatively thin and don't have any prop. Their effect on the wind environment is therefore negligible.

2) Impact on wave environment

Several simulations were run using different porosity values. Regardless of the value used, results were similar. The wave heights are strongly attenuated. The results of this simulation for a porosity value of 0.9 can be seen in Figure 28: Results of the 2.5m high waves' simulation on wave farm. There are four rows of devices, and between each one there is a significant decrease. The three first rows decrease the wave height by 50% and the last one decreases it by 40%. The total decrease of wave height is higher than 90% even by taking into account wave shoaling. This impressive result could be the reason of the approximation made to model the wave devices. It will be discussed in section D) Further Work.

The BW simulations are very difficult to run as a blow-up issue can happen at the boundaries as was the case here. Nevertheless, interesting results were drawn from the first few time steps. There is no recovery of the wave height before the waves reach the floor. On this site the bathymetry prevents it. The wave devices act as very efficient breakwaters.

The cumulative impact of wave devices on the wave environment is significant. The wave height is decreased by more than 90% and there is no recovery for more than 8km behind the rows.

3) Impact on water level

The impact of the presence of wave devices on the water level is very low; a difference of a few millimetres can be noted at the wave farm location between the simulation with and that without the devices. This difference is of a few millimetres between the two simulations and is negligible, particularly since this is a numerical simulation which therefore contains a natural small error. The natural error and the difference observed are of the same order. It can be concluded that the wave farm doesn't have any impact on the water level.

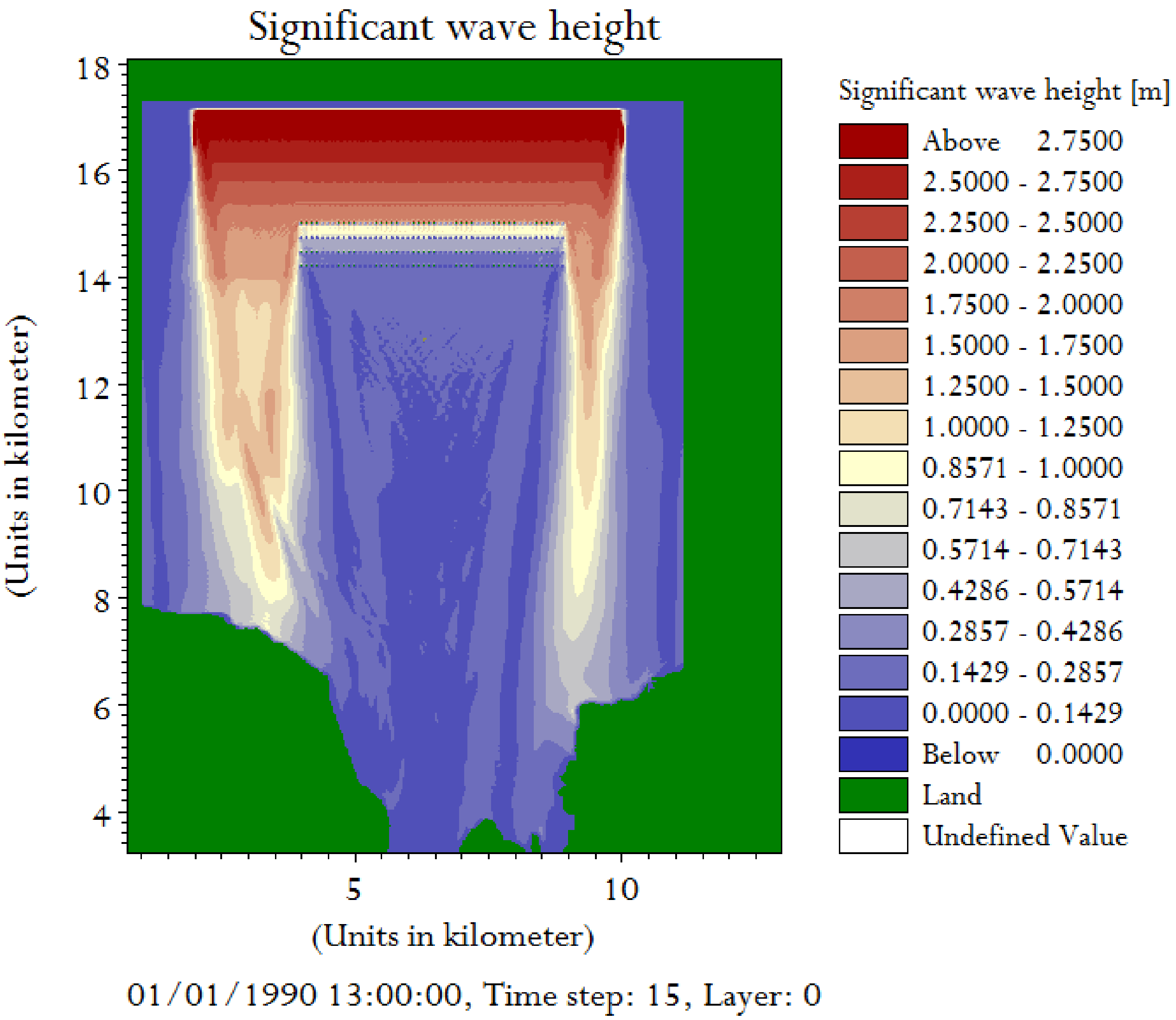


Figure 28: Results of the 2.5m high waves' simulation on wave farm

4) <u>Impact on currents</u>

Results of the HD with (right) and without (left) wave devices are presented in Figure 29.

The presence of the wave device affects clearly the current velocity; the decreases observed reach 84.7% between the rows. Nevertheless the impact was quite local. Only 50% decrease was observed 4km behind the wave farm and after 7km, the initial current velocity had recovered.

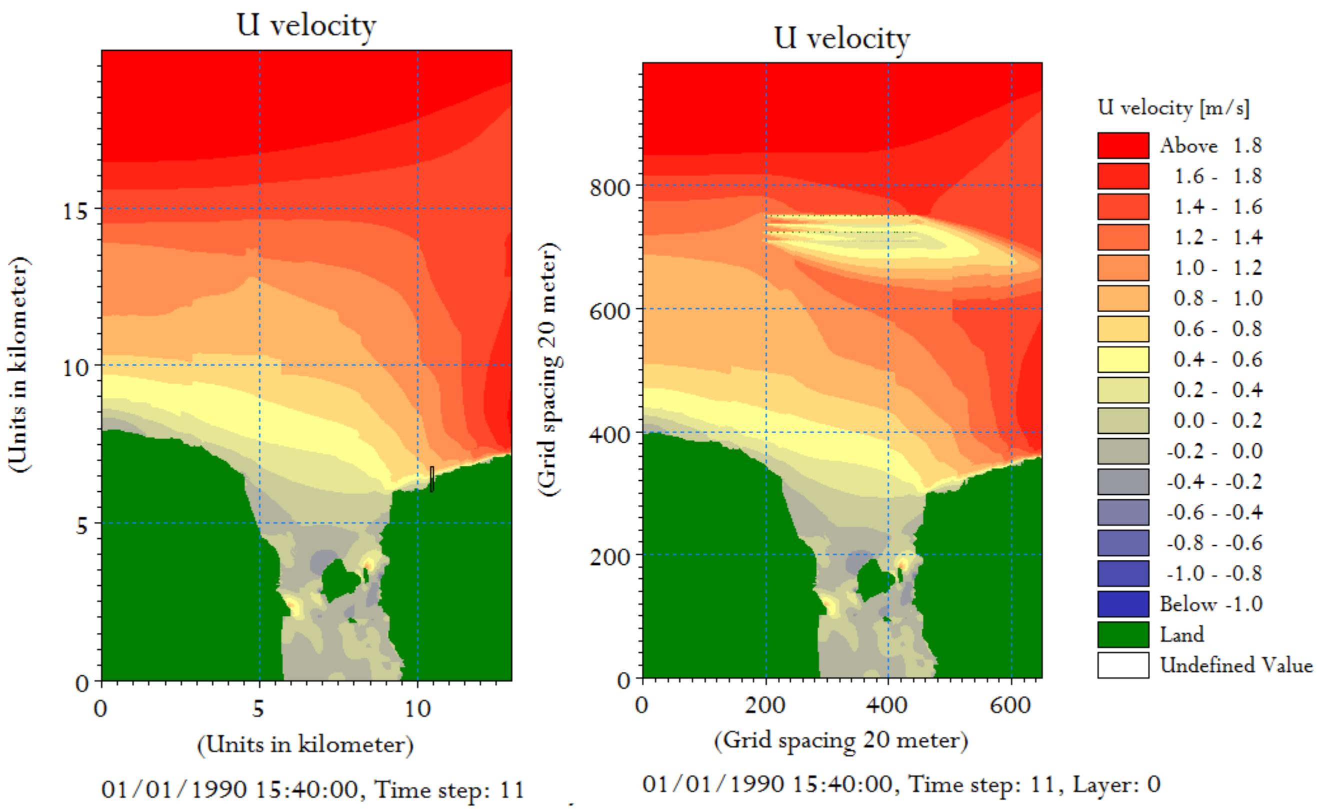


Figure 29: Results of flow model on the wave farm

The cumulative impact of wave devices on the current velocity is a decrease of 84.3% maximum; the initial velocity is fully recovered 7km from the wave farm.

5) Impact on ST process

Since there is a strong impact of wave devices on the current velocity, the same significance is expected on the sediment transport. A complete attenuation of the ST process was observed on the immediate environment of the devices, 95% of decrease 2km behind, 70% of decrease 3km after. The initial process velocity was fully recovered 4km from the wave farm.

The cumulative impact of wave devices on the ST transport process is a decrease within the 2km behind the farm varying between 100% and 95%. The impact was inexistent 4km from the WF.

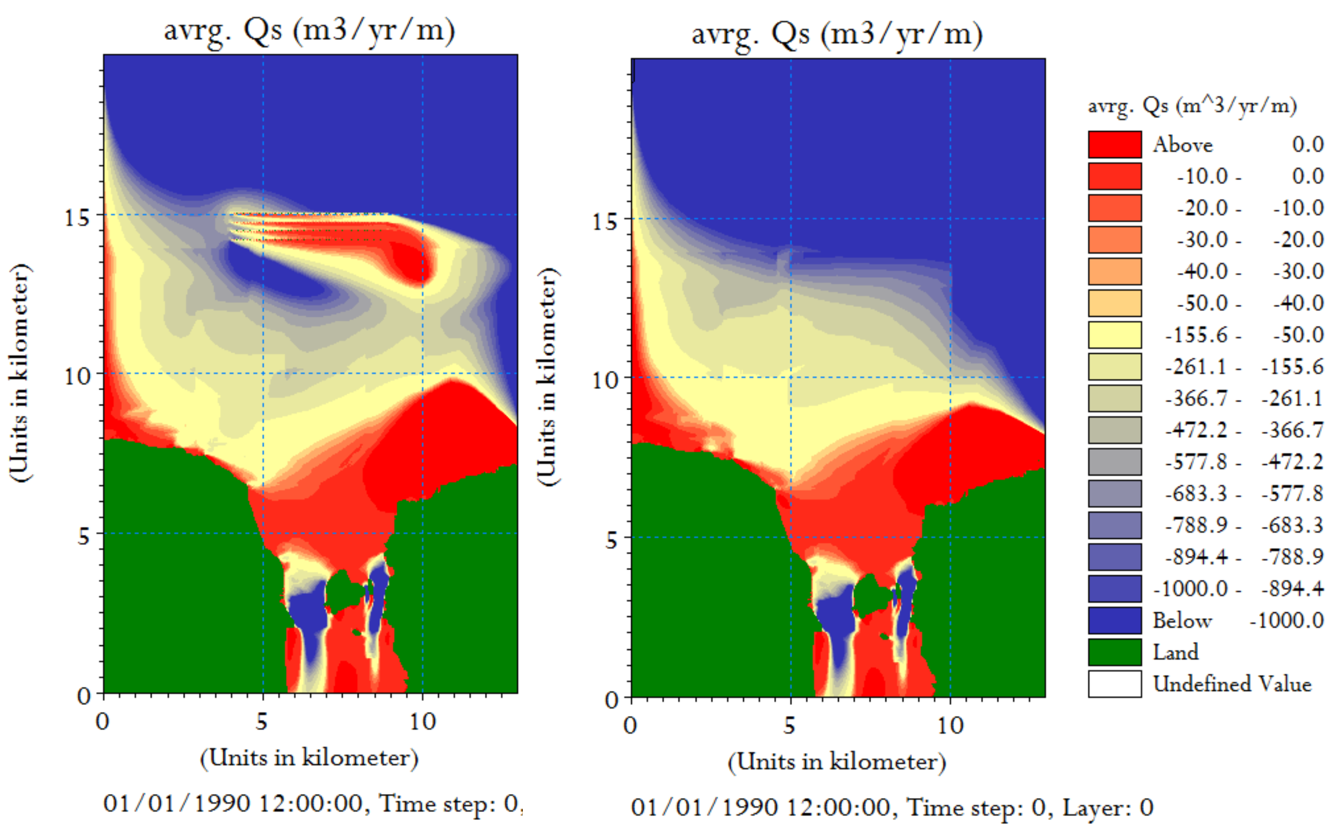


Figure 30: Results ST model on wave farm

6) Conclusion

To conclude, the cumulative impacts of the wave farm are easily notable concerning the sediment transport process, the waves and current environments. There is no remarkable impact on the water level and on the wind environment.

C) Results for Tidal Farm

The results of the simulations/calculations of cumulative impacts concerning the tidal devices are described in this section.

1) Impact on wind environment

Tidal devices are located underwater and their effect on the wind environment is therefore negligible. Even if the devices installed can at times be out of the water, depending on the tides, this effect wasn't considered for the same reasons expressed in the case of wave devices.

2) Impact on wave environment

Because of the bathymetry of the tidal site (Figure 20) simulations with waves coming from both sides were run. Several simulations were also run to look at the impact of porosity values; the results were similar for each of them. The results of the simulation run with a porosity value of 0.95 are displayed in Figure 31. These simulations were difficult to run because of the blow-up issues. As the line generating the wave was close to the coastlines, the depth of the sea was varying rapidly, leading to a crash in the simulation. The results presented are the results obtained until the time point when the blow-up occurred.

Decreases of wave heights were observed after each row of devices:

- West side (bottom part of Figure 31): decrease of 17-25% depending on the row. The total decrease when the waves reached the shore was 41%.
- East side (top part of Figure 31): decrease of 16-29% depending on the row. The total decrease when the waves reached the shore was 57%.

The cumulative impact of tidal devices on the wave environment was a decrease of 41-57% of the wave height when the waves reach the shoreline.

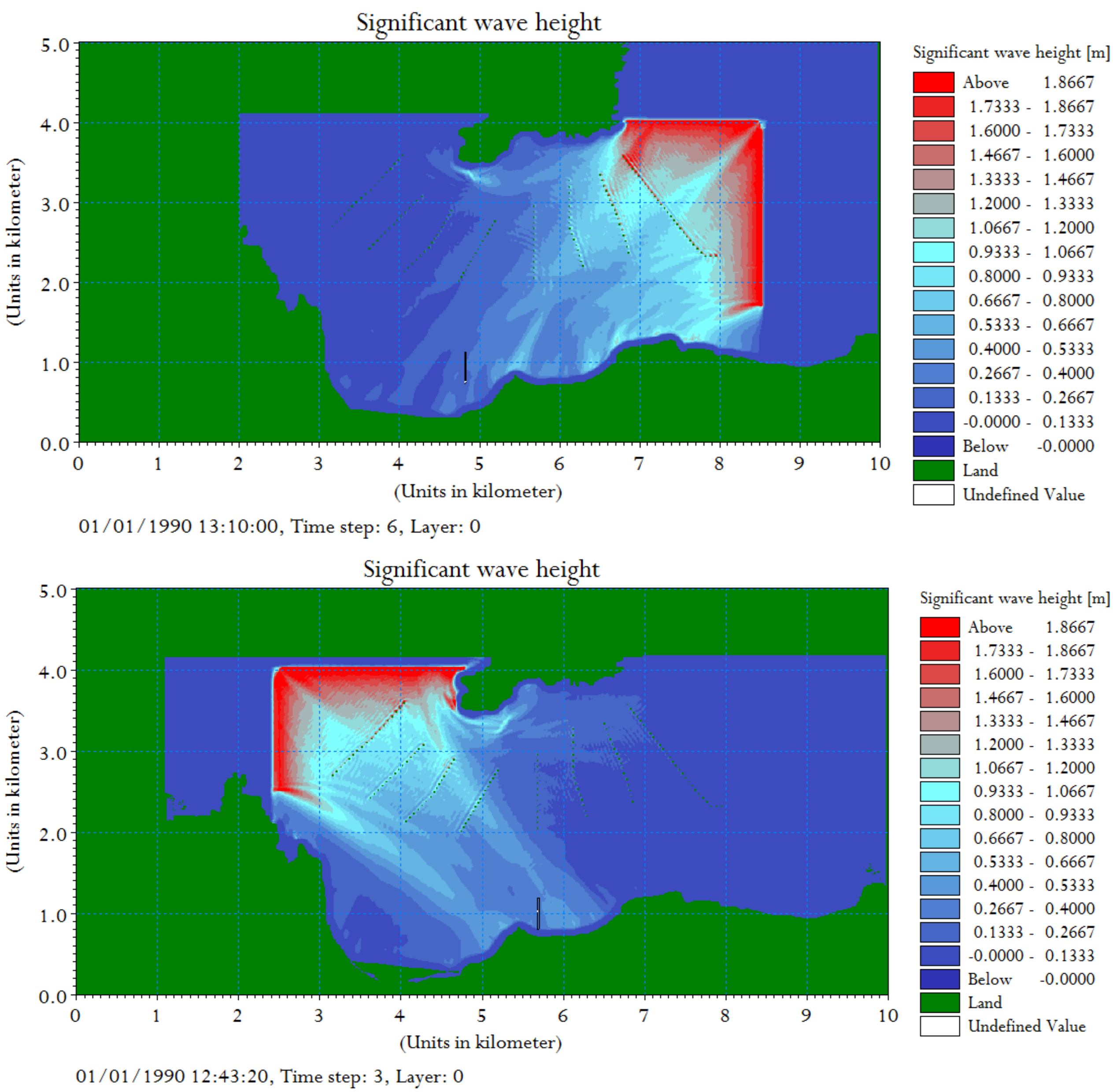


Figure 31: Results of the simulation with 2m high waves on tidal farm

3) <u>Impact on water level</u>

The tidal devices are the only one which had a visible impact on water level. The difference in water level without and with the devices is presented in Figure 32. The presence of the devices decreases the water level by 0.6m maximum next to the device and reaching 0.54m at some parts of the shoreline. This might decrease the tidal range by a height of 1.08m.

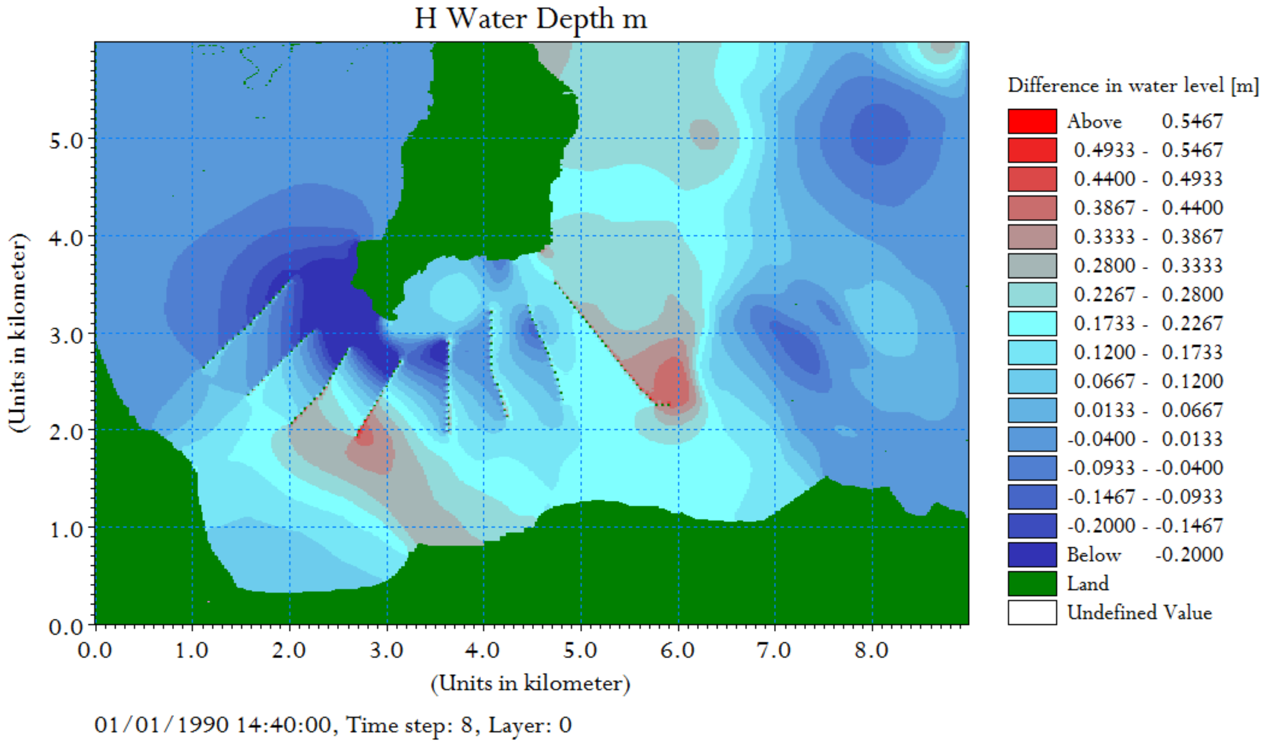


Figure 32: Impact of tidal farm on water level

The cumulative impact of tidal devices on the water level is a decrease in the tidal range reaching 1.08m at the shoreline next to the farm. This impact is present at 5km maximum away from the farm.

4) Impact on currents

The results of the HD simulation on the currents with (top) and without (bottom) the tidal farm is presented in Figure 33. The maximum decreases observed vary, 100% just behind some devices, 62% between rows, 70% after the farm and 68.6% after 4km. The bathymetry was too small to look at the distance where the impact stopped. This was due at the apparition of a new boundary and tilting issue associated if the bathymetry was extended. The cumulative impact of tidal devices on the current velocity is a decrease varying from 62% between rows to 70% behind the farm. Concerning the extent, a decrease of 68.6% was still observed 4km after the farm.

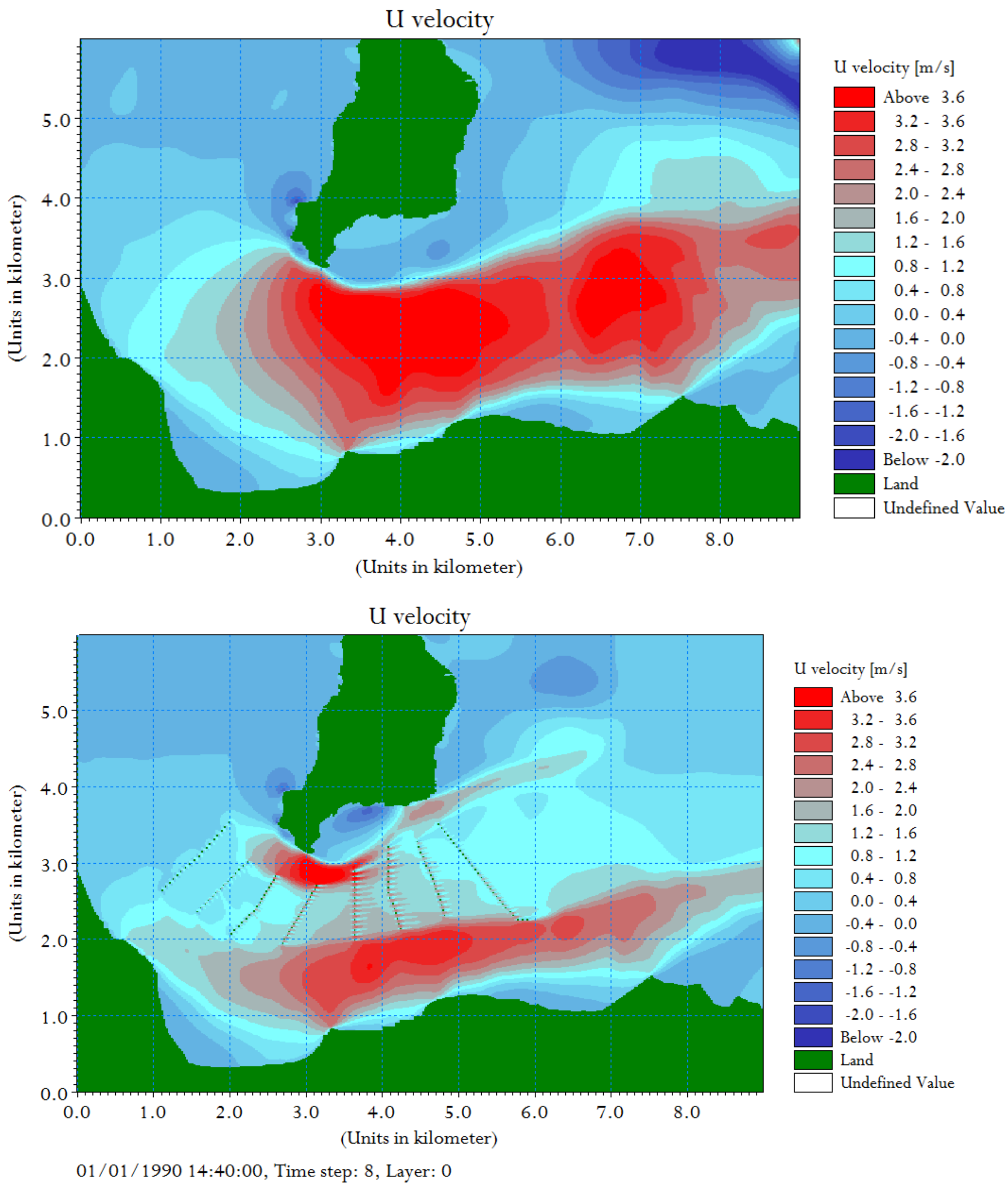


Figure 33: Result of Flow model for tidal farm

5) Impact on ST process

The results of the simulation on the ST model for the tidal farm are presented in Figure 34. This simulation supposed that the sea bed is composed of non-cohesive sediment. This isn't the case as the sea bed in this area is rocky. This simulation has been run in order to give an idea of what could have happened if there was a sandy seabed at this location. The values are unrealistic since in a place with such a strong current the sediment transport would be huge. No conclusions were drawn from this simulation except that in the hypothesis of a sandy seabed, it can be easily seen that a strong decrease in the ST process happened due to the presence of the tidal devices.

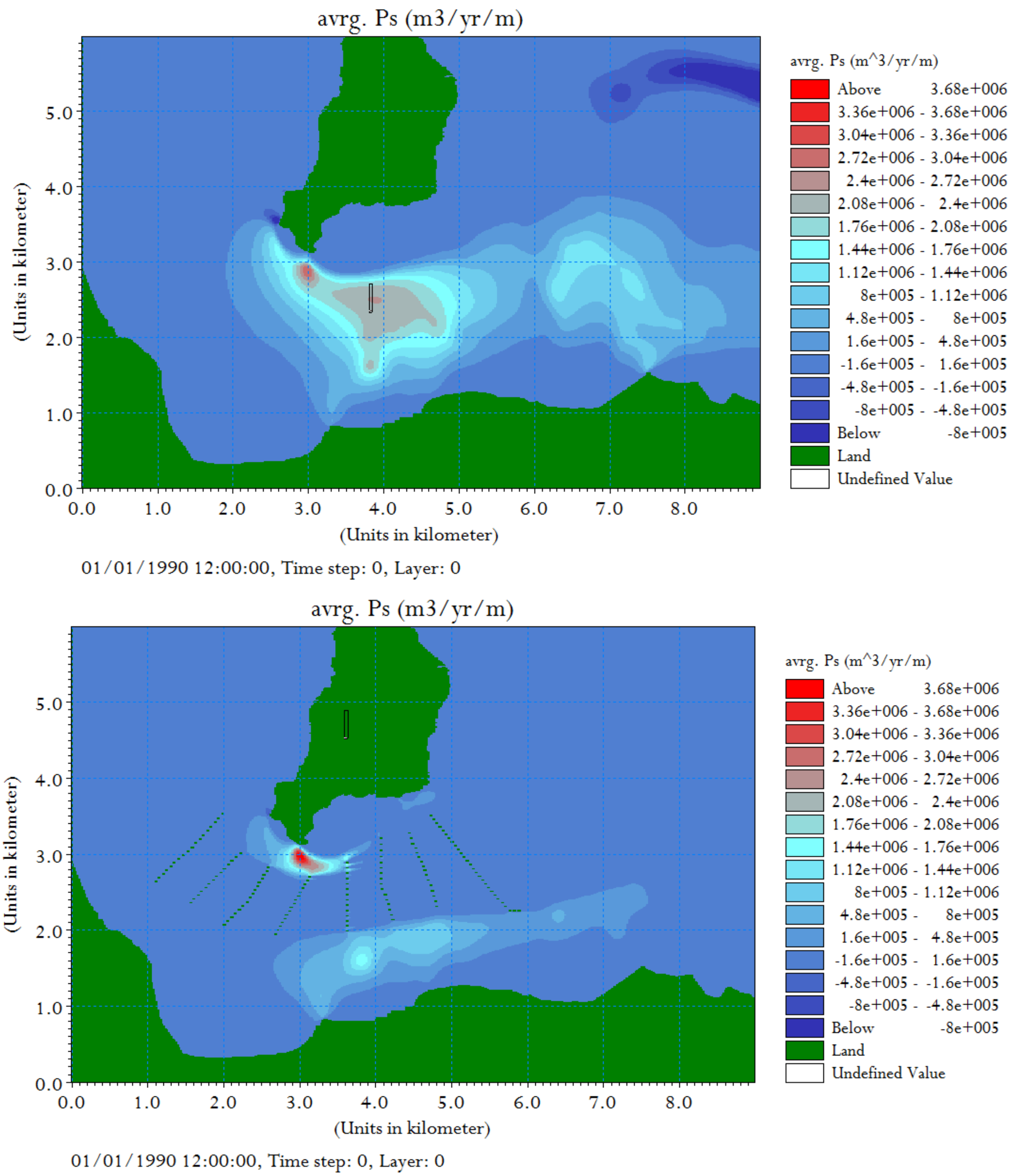


Figure 34: Results of ST simulation for tidal farm

6) Conclusion

To conclude, the cumulative impacts of the tidal farm are easily notable concerning the sediment transport process, the water level, the waves and current environments. There is no remarkable impact on the wind environment.

D) Further Work

This section will explain some limitations previously made and describe further work.

1) Model used

The wind model used with the approximations made gives a rough idea of the impact on the wind speed. The influence of height hasn't been taken into account for the fetch in the Jonswap calculation. The merging of the waves inside the WF will have an influence on the wake height since the expansion is only vertical inside the farm. The wake expansion behind the WF was also simplified since no useable equations were found to model how the wake will resorb. These approximations could be reconsidered in a more advanced analysis.

The approximation during Jonswap method for the area where waves are affected is very simple. The simple formulas used don't allow pushing the model further; a real and complete study is required to find out where and how this effect takes place.

The modelling used for the devices for each type of energy was compromised as Mike 21 doesn't have this type of structure integrated in the software. This issue concerns the bathymetry, porosity values and the use of sponge layer to avoid blow-up (crash of the simulation). The bathymetry values also needed to be filtered at times in order to avoid blow-up during the simulations. This may have affected the results.

Some issues were specific to a type of energy or a model:

- The grid resolution and the compromise between resolution and size of the bathymetry for the wind energy
- The absence of wave data to be used in ST
- The BW model is very difficult to run and is a very sensitive model. Some simulations didn't finish successfully and some compromises had to be made on the quality of the results.

The approximations and hypothesis made during the project were done in order to be able to provide simple results. The time allocated to the project and the data possessed didn't allow for the production of a more detailed output and results. Results need to be considered carefully as no calibration with the real world was conducted. A real assessment will require further work to produce improved results.

2) Further work

i. BW model

The issues concerning the BW model were time-consuming; it is a very powerful tool to look at local wave effects. The SW model of Mike 21 could be used in addition to the BW model. A first analysis could look at the waves around the devices and the SW model could look at the interaction and the evolution of the wave environment alterations.

ii. Test of the model

No calibration with the real world was done since the aim of the project wasn't to assess the cumulative impact on the chosen area, but rather the possible use of Mike 21 to assess them. The calibration of the results will be needed in a real assessment. The model needs to be tested before the results can be used to provide suitable mitigation measures and restrictions.

The possible error of numerical modelling should be taken into account in the resulting analysis.

iii. Other cumulative impacts

Other cumulative impacts could be assessed using Mike 21. Three models of the software were used, but there are others that could be used to assess marine renewable energy.

VI) Conclusion

The need for environmental protection isn't a novel idea. However, the implementation of marine renewable energy on the UK coastline to participate in the sustainable production of electricity is much more recent. For every project that may happen, an environmental assessment is required. The apparition of cumulative impact assessments appeared when the devices producing electricity from the wind, wave and tidal energy became more and more present. A third round of WFs is currently about to be installed, which means that thousands of devices will be implemented in some offshore areas. All these factors highlight the need for cumulative impacts assessment for marine renewable energy.

This dissertation was constituted in four main chapters. The first one gave a summary of UK context concerning marine renewable energy and presented the three main types of marine energy used: wind, wave and tidal energy. The implementation of these energies leads to the apparition of potential effects. They were presented as impacts and therefore described with their significance and likelihood. The origin of the cumulative effects was pointed to present the main subject of this project. The transition to the second chapter was made by presenting the project aims.

This chapter gave a short presentation of the tools used to reach the target fixed. These tools are the software Mike 21 from DHI Group, a Danish company, and a wind model developed by a national Danish laboratory. Three modules of the software were used to assess some cumulative impacts of marine renewable energy. The impacts on the sediment transport process, the wind, waves, currents and tidal environment were studied.

The third chapter concerns the implementation of the tools. The implementation required sites to be the support of the simulation and a specific type of device each. The choices made and the criteria for them were presented in this chapter. Eventually the implementation of the three models of Mike 21 and the calculation with the wind model were described step-by-step.

The final chapter included the results from the simulations and calculations. An analysis of these was done and some further work was suggested.

Along this project many approximations were made in order to obtain the results presented. The idea of the project was to show the presence, significance and likelihood of the cumulative impact of marine renewable energy, rather than a real assessment of the specific sites. The models weren't calibrated with real data and many approximations were made, however the results clearly show that there are significant cumulative impacts. There is a real need to assess them in the coming future, particularly with the intensification of the deployment of offshore devices. This project showed that Mike 21 is a powerful software tool that can be used in order to realize these required assessments. Together with the results presented, the project gives a methodology for the use of Mike 21 in order to realize this assessment. A similar methodology complemented with a calibration using real data could be used for real, active and future project deployment.

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VIII) Appendixes

A) Appendix A: Technology of Marine Renewable Energy

1) Technology of wind energy

Wind turbines produce electricity by using the natural power of the wind to drive a generator (BWEA 2005a). “Generating electricity from the wind is simple: Wind passes over the blades exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotation speed for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700 Volts (V) to the right voltage for the distribution system” (BWEA 2005a). Then a grid connection will pass the electricity onto the national network so as to power homes.

Turbines require a minimum wind speed to start generating electricity, generally around 3-4 m/s. They reach their maximum rated power at around 15m/s and shut down if the wind speed reaches 25m/s in order to prevent damages. (BWEA 2005a)

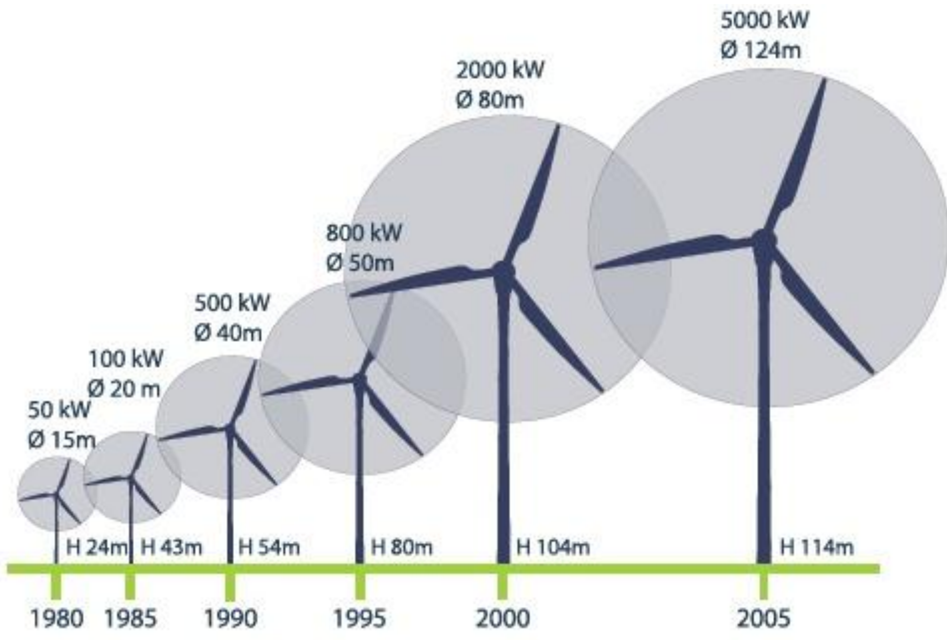

Figure 35: Trend in increasing wind turbine size

Source: (EWEA 2007)

The evolution of wind turbine technology is shown by the increase of the rotor diameter and the power delivered. The average size of an onshore wind turbine installed in 2005 was approximately 2 MW. Wind turbines have an average working life of 20-25 years, after which time they can either be replaced with new ones or decommissioned. (BWEA 2005a)

The offshore technology is essentially similar to the land based version (Amoudry et al. 2009).

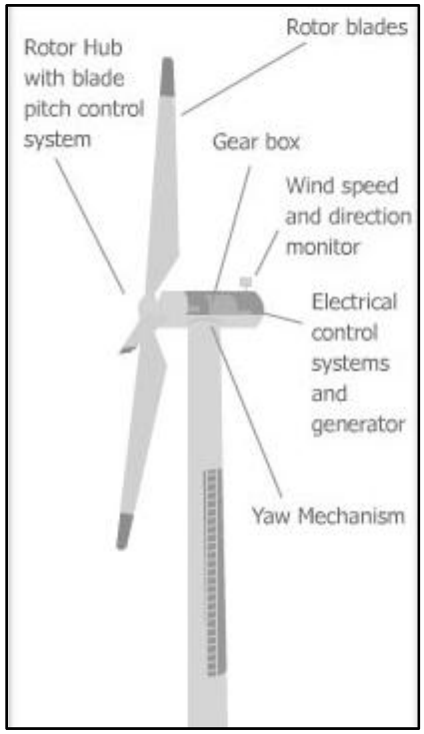

Figure 36: Components of a typical wind turbine

Source (BWEA 2005a)

2) <u>Technology of wave energy</u>

Wave energy generates electricity from the power contained in the waves in different ways. A classification of the basic methodologies can be divided in seven groups (Simons 2011):

- "Point absorbers, where a floating device uses the vertical motion of the waves to absorb power;
- Attenuators, where the articulation of a device following the changing water surface is used to operate hydraulic rams thereby generating power;
- Oscillating wave surge converters, where an arm is moved like a pendulum by the wave motion under the surface;

- Overtopping devices, where the wave crest overtops a wall, trapping water which is then discharged through a turbine;
- Oscillating water columns, where the water surface inside a tube with an open bottom displaces the air above through a turbine;
- Submerged pressure differential devices, where the pressure fluctuations induced by the waves pumps fluid through the device to generate power;
- Rotor devices, where the turbine is turned directly by wave-induced flow."

3) Technology of tidal energy

Tidal energy harnesses energy from the tidal current in the same manner that wind turbines harvest energy from the wind. Tidal turbines produce electricity by using the natural power of the tide to drive a generator. The tidal current passes over the blades exerting a turning force. The rotating blades then turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotation speed for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. Then a grid connection passes the electricity onto the national network to power homes.

The general devices used to harness tidal energy can be divided in four categories:

- Horizontal axis: the blades are fixed on a horizontal axis
- Vertical axis: the blades are fixed on a vertical axis
- Oscillating hydrofoil: a hydrofoil is attached to an oscillating arm and the tidal current causes an upwards and downwards motion. This can then drive fluid in a hydraulic system in order to be converted into electricity.
- Venturi tube: it is used to amplify the tidal current through a horizontal axis turbine (this is the system used for the Rance barrage: 24 tubes with turbines for the entire width of the river).

B) Appendix B: Wake diameter and height

1) Implementation of Calculations

i. Wake diameter

The calculation of the wake diameter gives information about the wake expansion. This expansion depends on different conditions: before or after the wakes of different rows merge, inside or outside the farm.

The calculation of the wake diameter is carried out directly considering the complete WF. Then there are three different evolutions of the wake diameter:

- The first evolution, inside the WF before the merge, is given by:

$$D(x) = \left(\beta^{n/2} + \alpha \cdot s\right)^{1/n} D_0, \quad s = x / D_0,$$ (

Where D(x) is the wake diameter at the distance x behind the turbine,

D_0 is the rotor diameter which is also the initial wake diameter,

$$\beta = \frac{1}{2}\frac{1 + \sqrt{1 - C_T}}{\sqrt{1 - C_T}},$$

(Barthelmie et al. 2006)

$$\alpha = \beta^{n/2} \cdot \left[\left(1 + 2\alpha_{(noj)} s\right)^n - 1\right] \cdot s^{-1}$$

(Sten Frandsen et al. 2004)

n and $\alpha_{(noj)}$ are constants chosen to be equal to 2 and 0.1 by the Wind Energy Department model for D and α formulas.

- The second evolution happens when the wakes of neighbouring rows merge. The horizontal expansion of the wakes stops inside the WF. In the case of the wakes of rows located on the boundaries, a horizontal expansion continues outside the WF.

- The last part of the evolution happens at the end of the WF. The wind will gradually return to its starting state, i.e. the state it was in before encountering the WF. It was assumed that the wake resorbs, such that the wake diameter is reduced, as the wind velocity recovers. Indeed, the wake is just an area where the wind velocity is lower than the freestream velocity and where there is turbulence. Once the wind speed is recovered in a section of the wake, this section is no longer part of the wake; as it went back to its initial state. In order to determine how the recovery happens, the previous calculation operated for the wind velocity was used. It was assumed that the wake diameter decreases at the same rate that the wind speed increases behind the WF. This means that if we plot the wake diameter and wind velocity functions on a graph, a similar contour for both will be seen.

ii. Wake height

The calculation of the wake height is similar to that for the wake diameter, but with only two steps as there is no merging of the wake in this case. Consequently the first step is to calculate the increase in wake height as the wind goes over the WF. The Wind Energy Department explained that the model developed by Elliot (1958) needs correction.

"The Elliott model estimates the internal boundary approx. 3 times higher than the proposed model. However, the basic Elliot and Panofsky (1973) models are based on ratios of surface stress at the upstream and downwind conditions. For velocity conditions, the proper IBL height is one third of the basic height, see Sempreviva et al.(1990)."(Sten Frandsen et al. 2004). Therefore the formula of Elliot (1958) multiplied by the coefficient 1/3 is used in the calculations.

Elliott's (1958) empirical formula may be written in its most familiar form as:

$$\delta' = A(x')^{0.8}$$ (Walmsley 1989)

The formula is used with A=0.75 (Walmsley 1989).

This gives the final formula: $h(x) = \frac{1}{3} \times \frac{3}{4} \times (x)^{\frac{4}{5}}$

At the end of the WF, the wake height follows the same phenomenon as its diameter: it decreases as the wind velocity recovers. For this step, the same process as the one for used the wake diameter is applied. The wake height, diameter and the wind velocity follow the same laws when leaving the WF area.

The calculations of the wake height and diameter give us the information about the area of disturbance of the wind. It is considered that inside the wake, the wind velocity is the one calculated; outside the wind velocity is $U_{freestream.}$

2) Results

The wake diameter and height have been plotted of Figure 37 and Figure 38. The graphs give the information about the area where the wind speed is attenuated. Figure 37 shows a point, situated 3743m from the beginning of the WF, at which the wake diameter inside the WF stops evolving. This is due to the merging of neighbouring wakes inside the WF, which happens when the diameters of the wakes are greater than the distance between two consecutive rows. It can also be seen that the shapes of the wake diameter and height after the WF are similar to the wind velocity one. The distances for the attenuation are therefore identical.

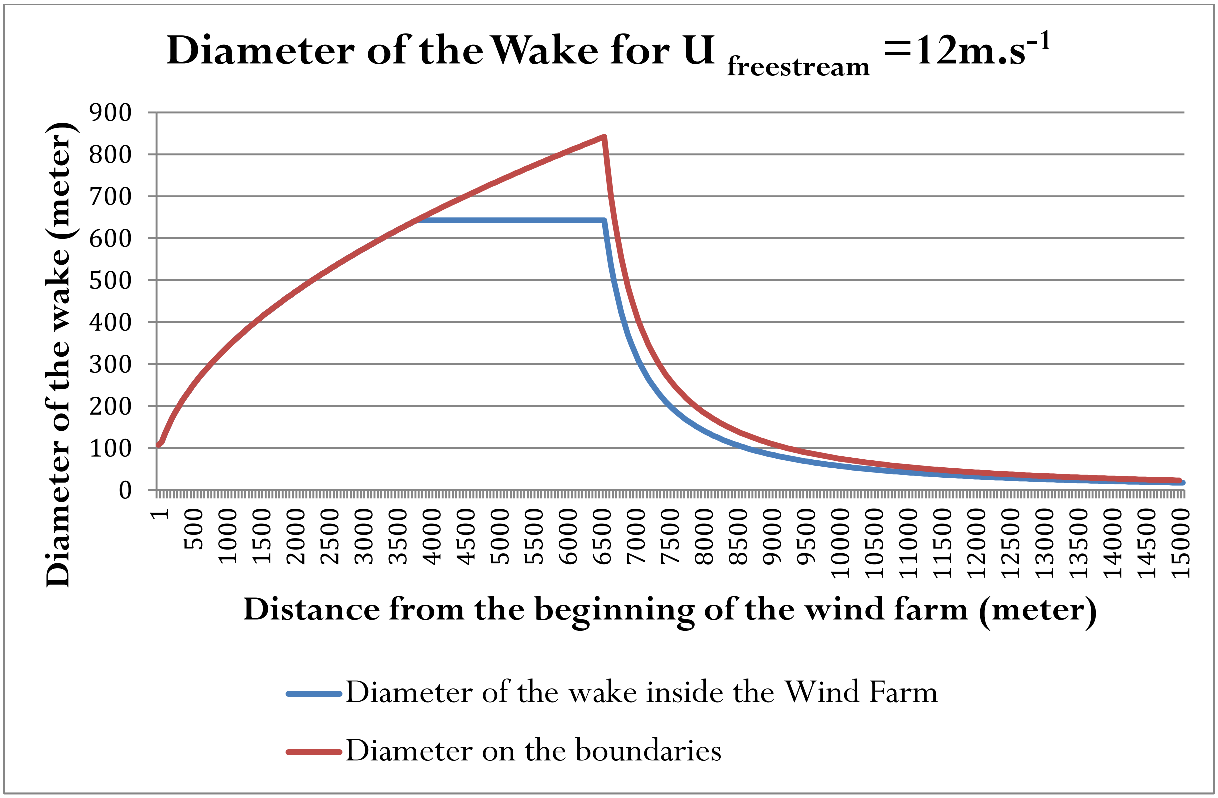

Figure 37: Wake diameter for the WF

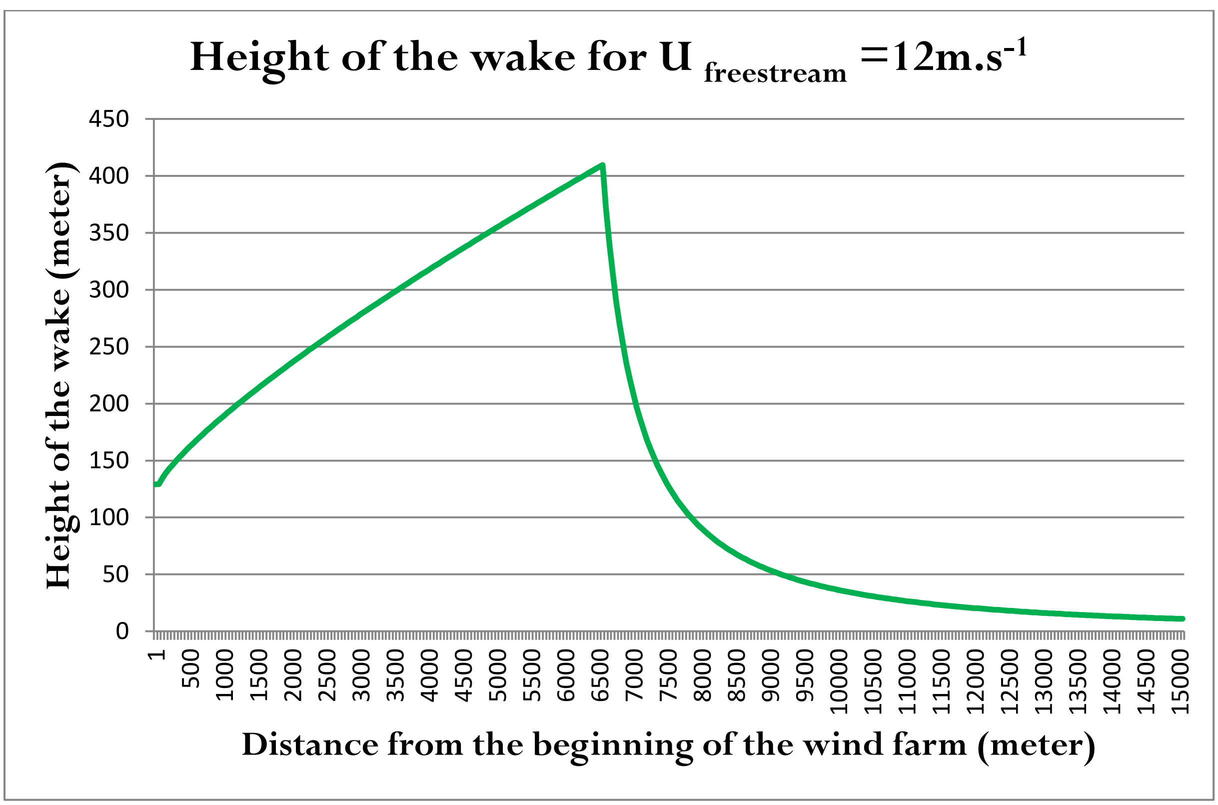

Figure 38: Wake height for the WF

It is assumed that the wake height is decreasing, following the same relationship as that for the wind speed. However this hypothesis doesn't take into account the fact that wind has boundaries with two different fluids: air and water. The attenuation of the wind speed may be modified due to the boundary with water. This issue was solved by assuming that the area covered by the wake expansion horizontally represented the fetch for the Jonswap method.

C) Appendix C: Criteria for the Choice of a Suitable Site

Research for the criteria of good sites within the UK territory was conducted by going through existing sites and seeing the reasons that pushed companies to invest into renewable energy in these locations. This was done by looking at the websites of the companies building renewable energy devices, and going through the sites where projects existed. In order to facilitate the reading, the different criteria are displayed in Table 6.

The criteria have been sorted out according to the different groups:

1. Available/allowed area
2. Feasibility of the construction
3. Economic/efficiency issue
4. Social issue
5. Other

Among these 32 criteria, the group with the criteria that were decisive was the feasibility of the construction. If one of the requirements in this group wasn't meet, the project of implementing renewable devices in the site was seriously compromised. The top '6' criteria that companies look at in order to find a suitable site to implement marine renewable energy devices, in order, were:

1. High potential resource
2. Suitable bathymetry
3. affords good access
4. Geology
5. Large unoccupied space
6. Suitable marine condition

.

This table was created from the information provided in:

(DONG Energy 2009; E.ON UK 2011; Vattenfall UK 2010; Mainstream Renewable Power 2011; EDF Energy Renewables 2009; RWE npower renewables 2010; Sea Energy Renewables; Scira Offshore Energy 2011; 4COffshore 2011; EDF Energy 2004; Aquamarien Power 2011; SeaGeneration (Kyle Rhea) Ltd 2010; SeaGeneration (Wales) Ltd 2008; Davison et Mallows 2005; Atkins Consultant Ltd 2004; Baker, Walbancke, et Leach 2006)

In order to find suitable site for the project, the places where there was a high resource potential, a suitable bathymetry and a correct access were looked at. These are the criteria from the 'top 6' that guided my research.

Number	Criteria		Wind	Wave	Tidal
1	Within a government approved area	1	✓	✓	✓
2	Low levels of fishing activity	1	✓	✓	✓
3	Outside protected and scientifically designated areas.	1	✓	✓	✓
4	No perceived environmental issues (EIA)	1	✓	✓	✓
5	Within Port Authority jurisdiction (for safety reasons)	1	✓	✓	✓
6	Outside shipping lanes	1	✓	✓	✓
7	Minimize impacts on physical/biological/human environn	1	✓	✓	✓
8	No known active oil, gas or aggregate interests in the area	1	✓	✓	✓
9	Areas of existing tourism;	1	✓	✓	✓
10	Regions of known surfing activity;	1	✓	✓	✓
11	Proximity to military rifle ranges.	1	✓	✓	✓
12	archaelogical surveys	1	✓	✓	✓
13	High resource potential	2	✓	✓	✓
14	Suitable bathymetry	2	✓	✓	✓
15	Good access	2	✓	✓	✓
16	Good seabed conditions for foundations.	2	✓	✓	✓
17	Suitable and safe marine conditions (tides and waves)	2	✓	✓	✓
18	Unoccupied space	2	✓	✓	✓
19	Suitability of onshore topography;	2	✓	✓	✓
20	Safety regarding flooding	2	✗	✗	✓
21	Grid connection options	3	✓	✓	✓
22	Long life expectancy	3	✓	✓	✓
23	Cost	3	✓	✓	✓
24	Efficiency	3	✓	✓	✓
25	Low visual amenity	4	✓	✓	✓
26	Low noise impact for the onshore environment	4	✓	✓	✓
27	Job created	4	✓	✓	✓
28	Positive feedback from local stakeholders;	4	✓	✓	✓
29	Decommissioning	4	✓	✓	✓
30	Benefit to the local communities and businesses	4	✓	✓	✓
31	Local familiarity with wind power	5	✓	✗	✗
32	Road access with the potential to be upgraded	5	✓	✓	✓

Table 6: Criteria for a good site to implement marine renewable energy devices

Appendix D: Tables of References for Effects

Effects	References
Physical effects	
Modification of the wind	5;7;12;19;84;85;86;93;
Modification of the waves	5;19;20;42;44;45;82;83;84;85;86;92;93;
Modification of the tide	4;5;18;38;40;41;42;44;84;85;86;92;93;
Modification of the current	5;34;38;40;41;42;44;45;82;83;84;85;86;92;93;
Modification of the temperature	5;41;82;
Scouring	5;19;34;41;42;44;45;59;83;86;92;
Sediment transport disruption	5;18;19;34;38;41;42;44;45;59;79;82;83;86;92;
Alteration of coastal defence/shoreline disturbance	5;38;41;44.82;86;
Water quality renewal	2;37;42;82;84;86;90;92;93;
Water contamination	5;34;37;42;43;44;79;82;89;90;92;93;
Accoustic effect	5;27;34;36;39;41;42;43;44;45;77;79;81;82;85;89;90;92;93;
Electromagnetic effect	5;41;42;43;44;45;79;82;85;89;90;92;93;
Vibration	27;34;41;82;84;89;90;93;
Air pollution/ green house gaz effect	27;
Creation of Tidal resonance	38;
Environmental effects	
Disruption in the habitat above water	5;18;20;36;41;44;45;79;80;81;82;89;90;93;
Disruption in the habitat below water	5;18;20;34;35;36;37;41;42;43;44;45;78;79;80;81;82;85;86;89;90;92;93;
Disruption of a behaviours	5;20;35;36;37;39;42;43.44;78;79;80;81;82;89;90;92;93;
Collision	5;34;35;36;39;41;42;43;44;45;78;79;80;81;82;89;90;93;
Migration routes disruption	5;35;39;41;42;43;44;45;79;82;89;90;93;
Destruction of members of a species population	20;42;43;89;90;92;93;
Loss of intertidal areas	37;38;82;
Waste/accidental spillage	27;34;43.44;45;82;85;89;90;92;93;
Light	27;41;43;44;84;90;91;
Greenhouse gases	57;
Social effects	
Fish area disruption	5;34;43;44;90;91;92;
Naval path disruption	5;13;26;34;78;90;91;92;
Visual and landscape impact	27;34;91; 46;47;57;54;64;90;92;93;
Interference with communication system	26;27;91;93;
Recreational users	34;41;90;91;92;93;
Land/ sea use	47;90;91;92;93;
Impact on marine archeology	26;34;93;
Economic effects	
Electricity production	1; 91;
Overlap with other marine activities	46;47;

Table 7: Effects and References associated

Number	Source		Source
1	(Burrows et Yates 2011)	46	(Victorian Government Department of Sustainability and Environment 2010)
2	(Koutikas 2011)	47	(AWATEA 2008)
4	(Black&Veatch 2005a)	57	(Renewable UK 2010b)
5	(G. W. Boehlert et Gill 2010)	59	(BWEA 2005b)
13	(Salter 2009)	63	(COWRIE 2008)
18	(Black&Veatch 2005b)	64	(Vize et al. 2008)
19	(YCSE 2011)	77	(Anon. 2008)
20	(Beharie 2009)	78	(Dolman, Green, et Simmonds 2007)
26	(Boehme et al. 2006)	79	(Gill 2005)
27	(EMEC 2008)	80	(Exo, Hüppop, et Garthe 2003)
34	(Norris 2009)	81	(J. C. Wilson et al. 2010)
35	(T. H. E. Smith et Scott 2009)	82	(Polagye, Van Cleve, et al. 2010)
36	(Andersen et al. 2009)	83	(Andersson 2011)
37	(Kawase et Thyng 2009)	84	(Lambkin et al. 2009)
38	(Finlay, Couch, et Ingram 2009)	85	(Kramer et al. 2010)
39	(Patrício, Moura, et Simas 2009)	86	(Amoudry et al. 2009)
40	(Draper et al. 2009)	89	(B. Wilson et al. 2007)
41	(J. Norris et Mueller 2005)	90	(Faber Maunsell et METOC PLC 2007a)
42	(Polagye, Copping, et al. 2010)	91	(Faber Maunsell et METOC PLC 2007b)
43	(Linley et al. 2009)	92	(Michel et al. 2007)
44	(G. W. Boehlert, McMurray, et Tortorici 2008)	93	(Devine Tarbell & Associates, Inc. 2006)
45	(U.S. Department of Energy 2009)		

Table 8: Numbers and references associated

Number	Source
43	(Linley et al. 2009)
45	(U.S. Department of Energy 2009)
47	(AWATEA 2008)
48	(Grecian et al. 2010)
64	(Vize et al. 2008)
66	(Department of Energy and Climate Change 2009)

Table 9: References for Table 3

D) Appendix E: User Guide to assess cumulative impacts of marine renewable energy devices using Mike 21 BW, Flow HD and ST models

This user guide provides a step-by-step description of the implementation carried out in this project to assess the cumulative impacts of marine renewable energy using Mike 21. The user guide is composed of three parts presenting each model used:

- BW model
- Flow Model HD
- ST model

Mike 21 is a software which has formidable potential. I didn't use all this potential because some parts weren't relevant to my project. Often, in order to make the simulations simpler, some values of parameters were left as default values. There are plenty of possibilities by modifying them. This user guide is a simple version that aimed only to show that Mike 21 could be used to assess cumulative impacts of marine renewable energy. The sections below describe only the steps I did when I used Mike 21. Any user is free to go over these simple steps and use a greater potential of Mike 21. If any functionality of the model is left without any explanation, it means that it was kept with the default value for the project.

This user guide isn't intended to give the basic knowledge concerning Mike 21. If a word is unknown or a parameter not understood, please refer to Mike 21 manuals.

1) BW model

a. Module selection

The first step in the BW model is the choice of the module that is needed. For this project the 2D Boussinesq Wave Module was chosen.

b. Bathymetry

The bathymetry is the milestone of the simulation; a lot of parameters are dependent and/or related to it. In order to create it a Bathymetries file is needed. Create a new one inside the Mike Zero product types.

i. Empty Grid Document

The first step to create the bathymetry is to provide the information about the map projection, the geographical coordinates and the spatial extent of the bathymetry which is expected. Once these parameters are given a blank bathymetry file is created.

ii. Marine map for background

Since the integration of data in Mike 21 requires a precise format, I used the bathymetry tools to create my bathymetry. The Work Area menu has a function Background management which allows integrating a picture in the background on the bathymetry file. A marine map was chosen.

iii. Draw depth line and interpolation

Using the Bathymetry tools, contours and land polygons can be added. They have to be added following the isobaths lines of the marine map in the background. Select a contour and polygons and click right on it, then on the edit contour level function to specify the depth of it. Then in the work area menu, choose bathymetry management, create a new bathymetry area, enter the information about the place, size and resolution you want for your area. Then click on interpolate in order for Mike to acquire the bathymetry data of your area. There are several types of interpolations. I ran tests to see if there was any difference depending on the interpolation. None were found on my maps. Further explanations of the different interpolations can be found in Mike manuals.

iv. Exportation and second interpolation

The next step is to export the bathymetry interpolated. Click on Export and specify the address the save the file. Open the file, all the isobaths will be drawn on it. Select everything using the grid editor tools and click on interpolation. Several types of interpolations are once again available. I ran tests to see if there was any difference depending on the interpolation. None were found on my maps. As previously further explanations about the different interpolations can be found in Mike manuals. The interpolation will determine the value between the isobaths drawn.

v. Boundaries

The BW model proposed different types of boundaries, refer to the manual for further information on them. I chose to use closed boundaries with sponge and porosity layers to avoid the reflexions and the flows across the boundaries. Therefore a value representing the land must be set in each cell of the boundary. If you wish to use open boundaries some additional information about the wave environment on them is needed. Further details are given on this in the section f. Internal Wave generation below.

vi. Devices

The devices can now be integrated inside the bathymetry. The grid editor tools and the Tools menu are really useful for their integration. It allows the change the value (setting, adding or multiplying) of a large number of cells in the meantime. Microsoft Excel can also be used to work on the bathymetry using copy and paste.

At this point you have created a bathymetry file, save it and continue.

c. Generation of porosity layer

From the bathymetry, you can generate many things using Mike 21 Toolbox. One of them is the porosity layer. The porosity layer generation is made in two steps. The first step consists in finding the parameter used in the porosity generator. This parameter is found by using Mike 21 Toolbox again. Open a new Toolbox, go in the section Waves and select Calculation of the reflection Coefficient. Enter the information required concerning the waves, water depth, layer, range, location for saving. Then execute and click on finish. A graph will be saved at the location you specified. Using this graph and the table p40 in BW module Step-by-Step training guide you will determine the parameter. In your toolbox click on generate sponge and porosity layer maps. Select the bathymetry file, the porosity/friction Layer Generation, enter the value found before, specify the saving location, execute and finish. The porosity map will be found at the location entered. You can now specify/correct the value for the devices if needed using the grid editor Tools. Save and continue.

d. Generation of sponge layer

The generation of the sponge layer is very similar to the porosity layer. In your toolbox click on generate sponge and porosity layer maps. Select the bathymetry file, the number of values of the sponge layer, specify the saving location, execute and finish. The sponge layer map will be found at the location entered. You can now specify/correct the value for the devices if needed using the grid editor Tools. Save and continue.

e. Surface elevation

The surface elevation represents the main sea level of the water for the area studied.

f. Internal wave generation

If the information about the wave environment on the boundaries is known, you can use open boundaries instead of the internal wave generation. Consequently the step concerning the closure of the boundary shouldn't be done. In the boundary menu you will enter the wave environment for each open boundary.

In the case that these data are unknown, the internal wave generation line can be used to model the wave environment. The starting and ending points need to be specified in the setup file. You can select the type of wave that will be generated. For this project unidirectional waves were chosen. The Mike 21 Toolbox will create the input for the internal wave generation. Select in Waves menu the random wave generation function. Several frequencies spectrums are available, in this project, Jonswap, the default one was kept. Specify the wave height and period, then select unidirectional, give the coordinates of the internal wave generation line extremities and the grid spacing, specify time series information and saving location. Execute and finish, you will then find the generated wave fine at the location specified and integrate it in the setup file.

g. Setup file and Simulation period

The other sub-sections of the setup files were left unchanged for most of the simulation but they can be modified to have more calibrated results or add some additional effects. You also need to specify the simulation period details, trying to keep the Maximum Courant No under 1.

h. Results

The results of the simulation are selected in the Output sections of the setup file. In this project, there was a preference for using 2D results in the Phase averaged parameter section.

Once all these steps are passed, save everything including the setup and run the simulation if there is no validation error. The result will be found in a folder created by Mike 21 named with the setup file name. If there is an abnormal completion of the simulation the result are still available until the crash of the simulation. Have a look at it to see how the model reaches this stage and look at the information given by the software that might help you to find the origin of the crash. Patience and perseverance will be needed to make the software run successfully and obtain a result in agreement with common sense.

2) Flow model

a. Module selection

The first step for the flow model is to choose the module for the simulation. The HD module was chosen for this project.

b. Bathymetry

These steps are very similar to the BW model.

i. Empty Grid Document

See BW model

ii. Marine map for background

See BW model

iii. Raw depth line and interpolation

See BW model

iv. Exportation and second interpolation

See BW model

v. Boundaries

This step is a bit different since this time the flows need to be able to go through the boundaries. If you want to prevent the flow to go through, follow the steps described in BW model, if not you don't have to do anything for now. The boundary will be open by default and you will have to precise in the Hydrodynamic parameters section the value for it. This will be developed in section e. Boundaries below.

vi. Devices

See BW model

At this point you have your bathymetry for the flow model ready, save and continue.

c. Source and Sink

Since the aim of the flow model was to assess the effect on water level and current, the tides were the only inputs, there was no source and sink. If there is a river mouth or other, this parameter can be used.

d. Initial surface elevation

The initial surface elevation represents the mean sea level of the water; it can be determined by averaging the mean sea levels of the boundaries.

e. Boundaries

The open boundaries need some additional information. You need to specify either the level on this boundary or the flux through it. If you have the water level or flux input you can integrate them directly. However you can also use a sine series, you need to precise the tidal range, mean sea level, period (set to 12hours=43200seconds by default) and the phase. This was the mean used to simulate the tides in the project. The FAB was left at the default value after checking the examples provided by DHI of the use of this model. The different values and their signification are explained in the manuals. The tilting function was used to smooth some irrelevant values found along some boundaries. The non-linear tilting method can be used when "a large inflow together with a large outflow at the same boundary, especially in a steady state situation, as the water level should actually be tilted" (DHI Group 2011d). The solution is often to activate the non-linear tilting and enter the deepest grid point of the boundary. Numerous tries might be necessary before reaching result that makes sense.

f. Eddy Viscosity and Resistance

The value for Eddy Viscosity and resistance sections used weren't the default ones. They were drawn from the examples provided by DHI for this model that was similar to the simulations run. The default values can be kept or if you found an example of a simulation which is relevant to you, use the same values. More information about these values can be found inside the manuals.

g. Wind conditions

A constant wind in time and space was included in the project simulations. You can go as far as you want in the detail of the parameters if you have the data required.

h. Results

The result files provided are selected inside the output section. The simulations for the project were providing two result files: one giving H,P,Q and the other one giving U and V. Don't forget to save everything before running the simulation and check that there is no validation error.

The result will be found in a folder created by Mike 21 named with the setup file name. If there is an abnormal completion of the simulation the result are still available until the crash of the simulation. Have a look at it to see how the model reaches this stage and look at the information given by the software that might help you to find the origin of the crash.

The Flow model met less errors and crashes than the BW one during the project. It gives you a wider manoeuvre margin.

3) ST model

The ST model requires a flow model result as main input.

a. Flow model output

The ST model requires a H,P,Q file as input. This file is obtained as a result of a HD simulation. This was the only input used for simulations using ST model during the project.

b. Pure current theory

There are plenty of different current theories, waves theory can be added to model the effect of waves on the ST. The project used only the default values or the choice that didn't require any additional input. Once again, you can play with all these parameters to sharpen your simulation. Further information about the theories can be found in the manuals.

c. Results

There are only two types of results than can be provided by the ST model: The output file including Ps,Qs and dz/dt and the transport time series including PS and Qs for each step of the HD model.

The ST model is very easy to run as long as you have the right H,P,Q file from the flow model. The difficulty will be to calibrate it using the good theory.

Once again, this user guide provides simple information to assess some cumulative impacts using Mike 21 BW, flow HD and ST models. Further information and details on specific issues can be found in Mike 21 manuals. The part of the work presented in this user guide is the visible part of the iceberg. Filling all the setup files and clicking on run simulation are easy actions. The real challenge is to make the simulation run successfully and get calibrated results or at least in accordance with common sense.