A Scoping Study on:
Research into Changes in Sediment Dynamics Linked to Marine Renewable Energy Installations

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EXECUTIVE SUMMARY

This study scopes research into the impacts and benefits of large-scale coastal and offshore marine renewable energy projects in order to allow NERC to develop detailed plans for research activities in the 2009 Theme Action Plans. Specifically this study focuses on understanding changes in sediment dynamics due to renewable energy structures. Three overarching science ideas have emerged where NERC could provide a significant contribution to the knowledge base. Research into these key areas has the potential to help the UK with planning, regulation and monitoring of marine renewable installations in a sustainable way for both stakeholders and the environment.

A wide ranging consultation with stakeholders was carried out encompassing regulators, developers, researchers and other marine users with a relevance to marine renewable energy and/or sediment dynamics. Based on this consultation a review of the present state of knowledge has been produced, and a relevant selection of recent and current research projects underway within the UK identified to which future NERC funded research could add value. A great deal of research has already been done by other organisations in relation to the wind sector although significant gaps remain, particularly in long term and far-field effects. Research into the effects of wave and tidal schemes is still relatively sparse and presents an opportunity for NERC.

Taking into consideration all the viewpoints feeding into this study together with the known strengths within NERC and existing UK projects, the following key themes capture the essence of the future research.

1. Determine the far field effect of renewable energy installations that could alter the regional tides and wave climate in the UK and neighbouring countries and consequently impact on sediment transport and coastal morphodynamics.

2. Validate efficient methods of monitoring renewable energy installation impacts that can be accepted and adopted by stakeholders.

3. Increase predictive ability of models in the context of marine renewables by developing methodologies for connecting the different scales from small scale physical processes to device scale Computational Fluid Dynamics (CFD) and to regional numerical modelling.

Theme 1 should be the overarching scientific aim of NERC funded research. It focuses on far-field effects with the understanding that near-field effects would be more important in the two-way interaction between the renewable energy devices and the surrounding hydrodynamics and sediment dynamics and as such may be a better fit to funding or co-funding from engineering sources (e.g., EPSRC). Naturally, this overarching scientific topic should be addressed using both observational and modelling programmes, which respectively correspond to Theme 2 and Theme 3. Such prominence of monitoring and modelling results from the extent to which almost all possible future studies on the far-field impact of renewable energy installations ought to rely on a combination of both approaches.

A major issue that has been consistent across the academic, industry and regulator consultation is the need for long-term baseline datasets together with continued monitoring through installation lifetimes. This would help separate natural variability of sites from anthropogenic impacts and validate model predictions.

Significant added value could be gained through buy-in (largely but not exclusively of manpower) to a number of existing research projects that represent an already substantial investment, rather than by developing entirely new research programmes with all the overheads that entails. These linkages have been summarised in Section 5.2 and span projects involving a significant number of the UK's key coastal and sediments research groups. Other potential partners could include SMEs, device developers and regulators.

Most key stakeholders consulted expressed a willingness to be involved in future research projects, including developers and the Crown Estate. Some may also be willing to co-support projects that they feel are particularly applicable to their remit – notably the Crown Estate via the Research Advisory Group, SEAs Programme, EPSRC and possibly the Environment Agency. These organisations should be consulted in the planning stages to explore this possibility.

CONTENTS

1. INTRODUCTION

This study scopes the state of research into the impacts and benefits of large scale coastal and offshore marine renewable energy projects through changes in sediment dynamics linked to renewable energy structures. This will allow NERC to develop detailed plans for research activities in the 2009 Theme Action Plans (TAPs). The call for this study originates specifically from the existing TAP on Sustainable Use of Natural Resources. Other linkages to NERC themes include Natural Hazards and Climate System Research.

There are three main types of marine renewable energy device currently installed or planned for UK waters – Wind turbines, wave energy converters and tidal energy converters. An overview of their current state of development and implementation in the marine environment is presented in section 1.1. Note that environmental impacts & benefits of tidal barrages are out of scope for this study and will be addressed by NERC in a future study.

The way this scoping study was conducted is described in section 1.2 and can conveniently be divided into two sections:

- A review of the knowledge base and views of marine renewable device developers and regulators
- A review of the knowledge base and views of the research community

These two communities have somewhat different interests and priorities and so are treated separately, although very similar themes in responses are apparent.

The terminology used in the following sections is defined in Section 1.3 with reference to a conceptual model of coastal processes and the way in which the environmental impact severity of marine renewable energy devices is assessed is given in section 1.4. Impacts have differing severity depending on the stage of development of an installation, and these different stages are identified in section 1.5.

1.1 Overview of UK Marine Renewable Energy Developments

Energy extraction from the marine environment 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). The following section gives an overview of the potential for each source as well as current developments within the UK, and a map of current wind farms and potential areas for future development is shown in Figure 1, together with the sites of Wavehub, EMEC and the Scrobie Sands Wind Farm case study.

1.1.1 Wind

Offshore wind farms are a comparatively established technology within the renewable energy industry. They are essentially the same as the land based versions but mounted on marine monopiles, which are relatively straightforward static structures.

Five offshore wind farms are in operation as of March 2009 and licence applications from the Crown Estate have reached the third round with 10 exclusivity agreements announced in February 2009 (see Appendix 1). 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.

ABPmer (2002) determined that the major components of an offshore wind farm that could affect coastal processes are the turbine foundations, array spacing and seabed cable laying. All five operational wind farms (Burbo Banks, Barrow, Kentish Flats, Scroby Sands and North Hoyle) have monopile foundations, which are suited to shallow water with stable, sub-bottom sediments. However, other foundations are being investigated. Deep-offshore, floating turbines are being developed in the US (Blue-H, Principle Power), mainly due to the higher energy potential further out to sea compared to coastal sites along the US coast.

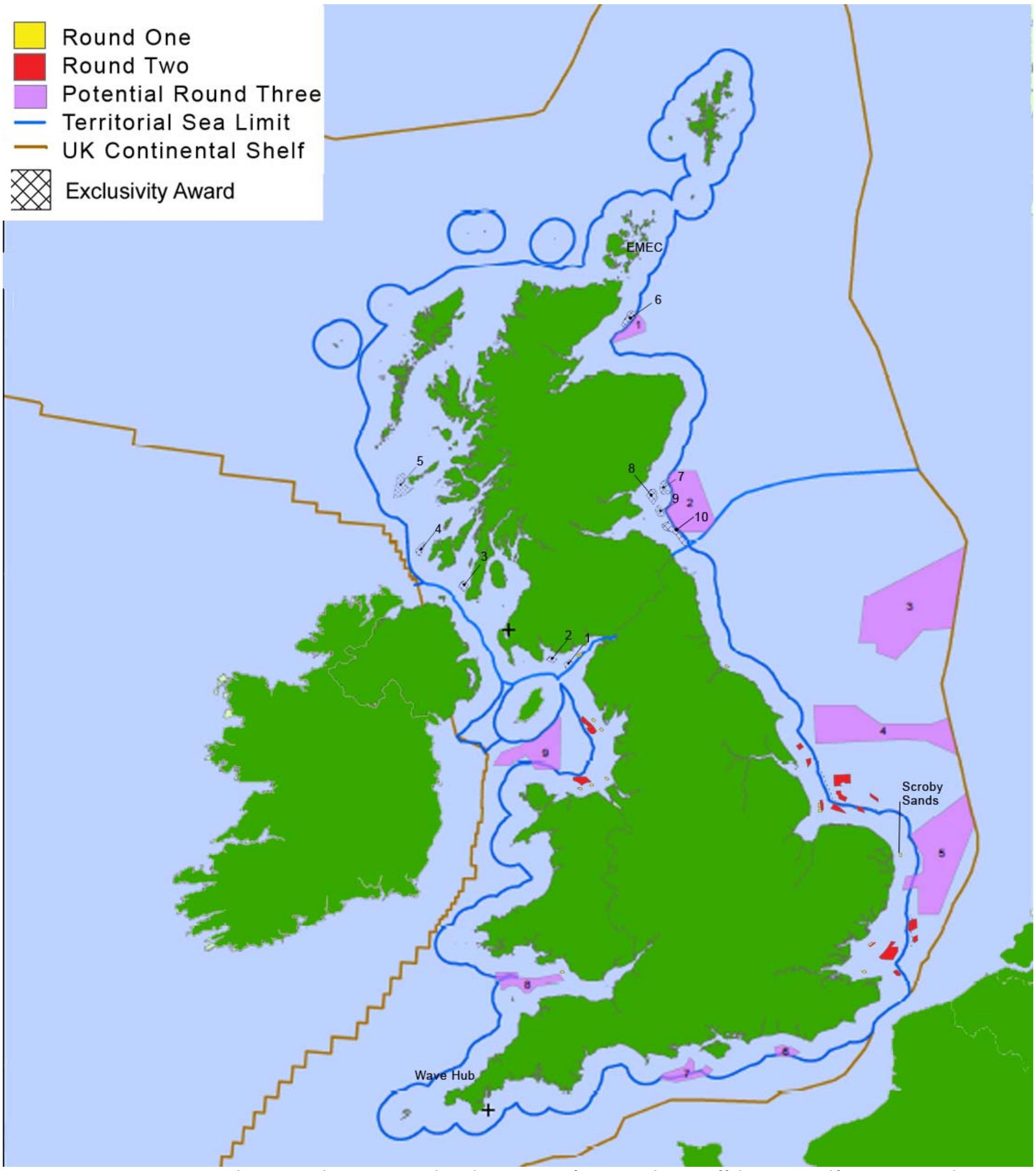


Figure 1. Map indicating the geographic location of R1 and R2 offshore windfarm sites, the Crown Estate R3 offshore wind areas, and Scottish inshore (territorial) waters exclusivity award areas (numbered). The location of the EMEC and Wave Hub technology demonstartion sites, and Scroby Sands (a case study site) are also indicated.

1.1.2 Wave

Wave energy converters are the least developed of marine renewable devices due to the relative inefficiency and unpredictability of the energy source. 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. The significant wave height doubles during the winter months in comparison to summer around the UK, but again corresponds to peak energy demand.

Wave energy development is thought 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. So far, only the oscillating water column type has proved to be successful (LIMPET, on Islay), although Pelamis, an attenuator device is undergoing long-term testing at EMEC and in Portugal (although financial problems with the major stakeholder has mothballed the testing here) and appears to be fairly successful. Other device types currently in development are listed and described in Appendix 1. Wave energy devices have the potential to have a secondary function of coastal protection (e.g. Siadar breakwater).

A survey conducted by Seaview Sensing and Wave Energy Today on the current wave energy market suggested that there are knowledge gaps in our understanding of waves as an energy source. There is a general agreement that the spatial coverage of data buoys is not extensive enough or of a standardised format.
http://social.waveenergytoday.com/content/making-sense-wave-energy

1.1.3 Tide

Tidal stream technology is potentially 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), they are highly predictable, and the supply is seasonally constant. The UK has a huge potential, having 15% of the worldwide resource. A report on the UK tidal energy potential suggests focus should be applied on deep water devices (> 40 m) in high-velocity sites, rather than shallow water devices which are comparatively uneconomical (Black and Veatch, 2005). 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.

Tidal barrage technology has been implemented in France (La Rance), Russia (Kislaya Guba experimental station) and in the Bay of Fundy (Canada); a potential development is being planned in the Severn Estuary. However, the environmental impacts and considerations of barrages are in a different league from other marine renewables and are out of scope for this study.

1.2 The Scoping Study

In order to gather together a synthesis with respect to the impacts of the major marine renewables (wind, wave, tide) on sediment transport and coastal processes a range of approaches has been adopted. First, development of a conceptual model of all coastal processes has formed an initial basis for deriving a number of key themes/categories (e.g. suspended sediment loading; seabed morphology; scour etc.) against which to frame impact assessment. A framework was then developed to permit a consistent assessment of impacts. An overview of the current status of the marine renewables across each sector (wind, wave, tide) was conducted.

Information on the impacts of the major marine renewables on sediment transport and coastal processes was collected in two ways:

- First, a thorough literature search highlighted the major existing areas of knowledge, together with providing information on the status and extent of actual datasets (which may of use to commissioned research programmes).

- Simultaneously, a consultation through a variety of means including telephone-based questionnaire, e-mails and face to face meetings was undertaken.

A gap analysis was then applied to objectively review the information and to establish genuine gaps in knowledge. Potential collaborators and partners were identified together with links to recent and current research being undertaken in the UK.

1.3 Conceptual Description of Interactions between Offshore Renewable Energy Devices and Sediment Transport and Coastal Processes

In order to assess the impacts on sediment transport and wider coastal processes of a single installation or an array, it is necessary to define the raft of potential interactions an offshore array may have on the range of coastal processes. Figure 2 highlights these in a schematic. Broadly speaking, impacts can be considered on a local (single structure) level or in terms of an array of structures (presently the case for many completed windfarms, and the future case for wave and tide stream developments).

The interactions of the structure[s] with coastal processes can be further divided into:

Localised or Device Scale – on the scale of individual devices.

Nearfield - within 10 times the diameter for a single structure or the entire areal extent of an array, plus 10 times the diameter of the outer array structures, for an array.

Far-field - to a distance of 1 tidal excursion from a single structure or to a distance of 1 tidal excursion from the centoid of an array.

The principal development-specific variables of relevance include number, spacing, size and geometry of structures, as well as cable connections and distance to shore.

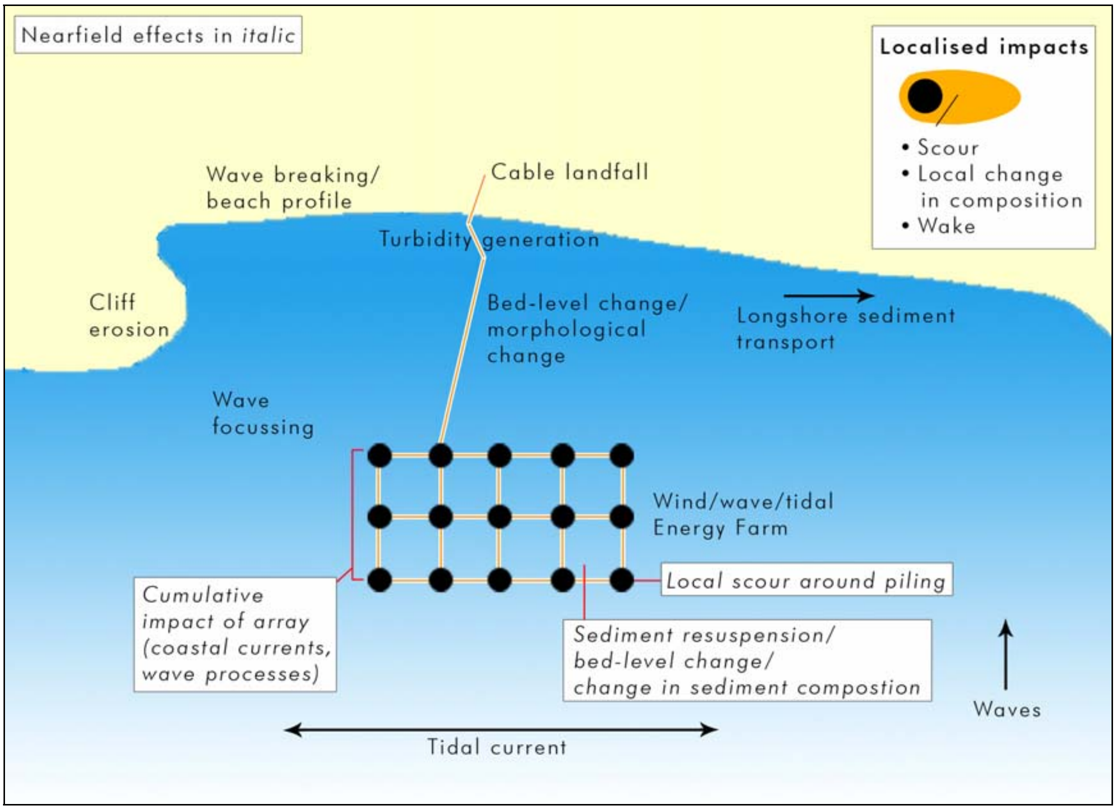


Figure 2 Conceptual model the interactions of an offshore array with coastal processes.

From the above framework, a number of discrete categories were defined against which an assessment of impact can be made. These are:

• Tide current speed/energy	• Longshore drift
• Suspension of sediments/turbidity	• Change in seabed composition
• Wave height/energy	• Turbulent wake generation
• Wave breaking	• Bedforms
• Water circulation /orthogonals/rip currents	• Seabed scour/deposition (nearfield)
• Cliff erosion	• Seabed channel morphology
• Beach erosion/deposition	• Seabed level (farfield)

1.4 Development of Impact Assessment Criteria

Assessment of the potential impacts of marine renewables on coastal processes requires a framework in order to assess the significance of impacts relative to the situation of an undeveloped coastal site. This framework must include all relevant information, including:

- severity (major, moderate), including no interaction and positive effects;
- persistence (momentary to years/decades);
- spatial extent (local, nearfield, far-field);
- areas of no knowledge or experience.

We have developed a systematic approach to impact assessment cognisant of each of these variables. It is important to remember that the review considers all impacts i.e. those which are judged positive as well as negative.

1.5 Impact Assessment through Project Timeframes

A holistic review of potential impacts of renewable projects on coastal processes must consider the different impacts through the *project development time-frame*. Offshore renewable projects typically develop over a period of 5-7 years. A typical project involves site selection and survey (oceanographic, geotechnical, geological), pre-installation of foundations, installation of structures and cables, and post-construction assessment. A typical installation will have a minimum design life of 25 years. The potential/known impacts in our specific area of review must consider the impacts through each of these stages, simply because they may change dramatically during the different phases.

2. SUMMARY OF THE EVIDENCE BASE OF IMPACTS ON COASTAL SYSTEMS FROM THE REGULATORS & DEVELOPERS

2.1 Where Is the Evidence Base?

A wide variety of data have been collected to date on the impact of offshore renewable developments on coastal processes and sediment transport, and in some areas e.g. sediment resuspension, the evidence base is strong. **Largely these data have been collected in relation to Rounds 1 and 2 of the present offshore wind sector**, both by industry for specific developments and by Defra/CEFAS on a summarisation basis. Much of this information, knowledge and actual data for wind are held by COWRIE. **Far less information exists in relation to wave and tidal energy**. Information is also available through various FEPA (1985) and Coast Protection Act (1949; and in Scotland, Section 36 of the Electricity Act) licenses issued to developers on a case-by-case basis. Monitoring of certain coastal process and sediment related variables is often a key component of license provision, and frequently the data is available from Environmental Statements derived from a formal Environmental Impact Assessment (EIA) process driven by the above licensing impositions (note some developers also undertake non-statutory monitoring). In addition, data is available within several recent syntheses commissioned directly by Defra and SNH (Rees, 2008; Whitehouse et al. 2008; CEFAS 2006; Cooper et al., 2008; Scott Wilson and Downie, 2003; Cooper and Beiboer, 2002; BMT, 2003; DBERR 2008);. Figure 3 summarises the range of potential data sources available to this review. Higher level, broad-scale data and information are in addition contained in two historic and three contemporary Strategic Environmental Assessments (SEAs). Appendix 2.4 includes a list of data sources were many of the reports cited here may be found and from there the holders of actual data may be identified. Finally, the academic sphere has given rise to a set of data and observations in this area and are reviewed separately in section 3.

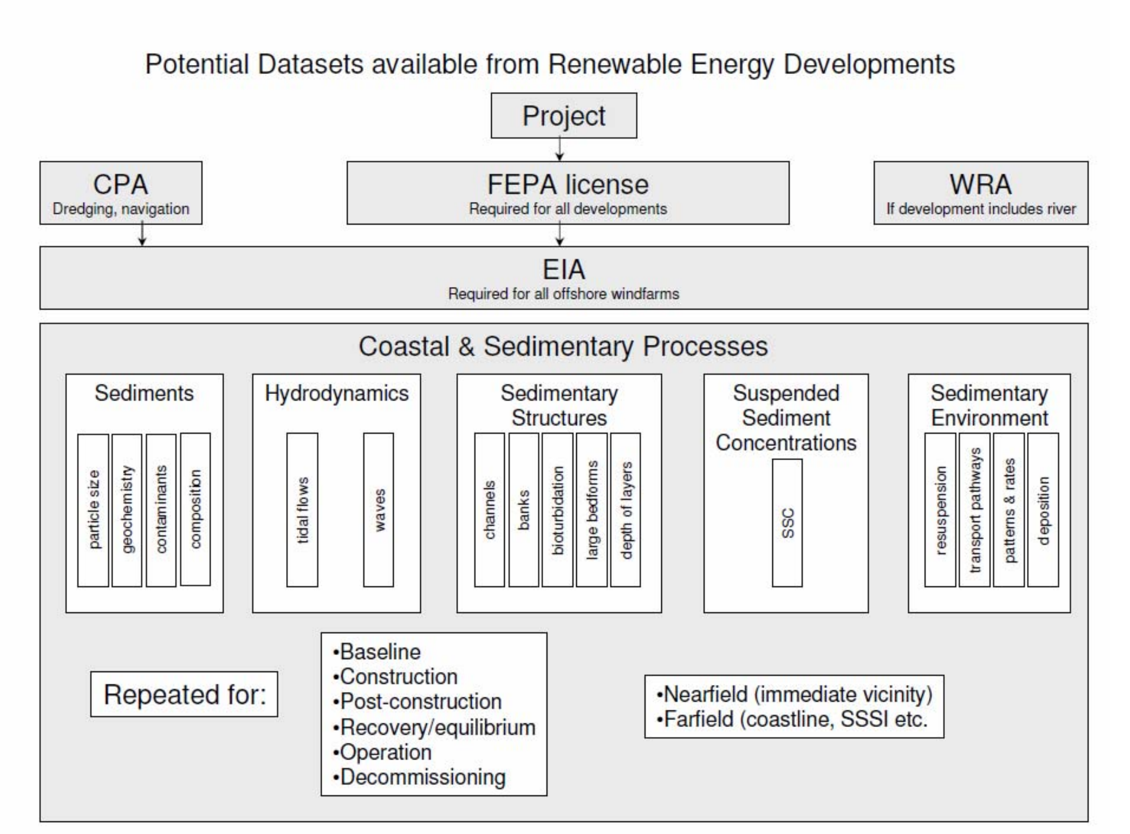


Figure 3 Potential datasets and information relevant to assessment of the evidence base, in conjunction with temporal and spatial considerations.

2.2 Categorisation

In Section 1.3 a conceptual model of the interaction of an offshore array of renewable energy devices with coastal processes is proposed (Fig. 1) and a number of discrete categories against which an assessment of impact can be made are proposed. This approach to impact assessment follows along the lines advocated by Cooper et al (2008) and is derived in part from the data areas given in Figure 3. These categories represent processes (e.g. sediment resuspension) or environmental attributes (e.g. bedforms) which may suffer impacts as a consequence of development of a site. These categories are relevant across the wave-tide-wind sectors. Table 1 presents these categories in greater detail than in Section 1.3 and summarises some of the principal issues with each. These categories provide a foundation for an objective review of the evidence base (e.g. SEAs, EIAs, academic studies etc.) regarding the impacts associated with the installation and presence of marine renewables structures in the coastal zone.

Table 1 Discrete sediment transport categories providing indices for impact assessment.

Category	Principal Issue
Tide current speed/strength	Changes to the current speed and direction; slowing/acceleration of currents
Wave height/energy	Reduction/increase in wave height locally
Wave breaking	Inducement of wave breaking locally
Water circulation/orthogonals/rips	Causes to focus (converge) or diverge waves; changes to refraction and diffraction patterns
Cliff erosion	Changes to cliff erosion at the shoreline
Beach erosion/deposition	Changes to beach erosion/deposition e.g. at cable landfall
Longshore drift	Interruption to the longshore drift
Change in seabed composition	Changes in seabed composition (grain size) due to sediment transport associated with structures
Suspension of sediments	Local increases in sediment resuspension (boat wakes, scour)
Bedforms	Interruption of seabed changing
Seabed channel morphology	Large-sale changes to seabed morphology
Seabed scour/deposition (nearfield)	Local scour around structures; scour of cable routes
Seabed level (farfield)	Changes to intra-turbine bed level generally

2.3 The SEA Evidence Base

Strategic Environmental Assessments arise through legislation deriving from the EU (SEA Directive 2001/42 EC). The objective of a SEA is "*to provide for a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programmes with a view to promoting sustainable development*". As such, the SEA reports provide a good overview of the issues of concern to regulators and a number of these are discussed in this section.

The SEAs consider a range of coastal processes (Table 1). Assessments of potential impacts are based largely upon a *qualitative* approach, although certain survey data are collected as part of this process and are routinely lodged with the DEAL data archive run by BGS.

The main DECC SEA website is at http://www.offshore-sea.org.uk/. This site has current SEA consultation information, SEA Reports available for download and other relevant information.

The British Geological Survey (BGS) were contracted by DECC to manage the data collected during the SEA process and a first phase of work was completed in 2008 making the then available data accessible via the UK DEAL website at http://www.ukdeal.co.uk/.

DEAL holds reports and data files for each SEA area and these can be searched for using forms to find data and documents by their SEA area, subject and type, or using the DEAL WebGIS (Map) to find data and documents graphically. The files available from DEAL are of many types, including short reports in PDF or Word format, photographs and maps in image format and very large data files in a variety of specialist formats. All the files are available to the public and many can be downloaded directly from DEAL. Those that are too large to download can be ordered via the DEAL website for delivery from BGS.

There are multibeam, sidescan and other geoscience data from various sites around the UK, augmented with some geological sample data and video and still photography of the seabed. There are summary geological reports and there are reports summarising the results of biological analysis of samples and sea bottom photography for each of the SEAS regions covering all UK offshore areas.

2.3.1 Round 2 Offshore Wind SEA

The report identified a range of coastal processes that may be affected by the operation of offshore wind farms, these are:

- sandbank mobility;
- sediment redistribution;
- changes to seabed morphology;
- scouring of sediments at the base of a turbine tower;
- changes to flow regime and wave climate; and
- changes to coastal sediment budgets.

In addition, it was identified that during the geotechnical investigation, installation and decommissioning phases local sediment plumes can be generated over relatively short-timescale's (.i.e. days to weeks).

The impacts that the report considered of medium significance or potential impacts were:

- sandbank mobility –medium, long-term;
- seabed morphology – large sites (>90 turbines) - unknown,
- coastal sediment budgets - large sites (>90 turbines) -unknown;
- flow regime and wave climate – far field effects – unknown.

In comparison to more recent SEA studies this initial Round 2 SEA was clearly based on less data and there have been many more windfarms built after the report was published which has provided a body of work that more recent SEAs have drawn upon.

2.3.2 SEA for Wave and Tidal Energy (Scotland)

The SEA for wave and tidal energy (Scotland) deals with the effects of tidal and wave energy separately.

Wave Energy Extraction:

The anticipated effects identified are the wave climate, sediment processes and coastal processes. The report highlights that there is little information on which to base the effects of wave energy extraction on the wave climate. However, it is considered that wave devices affect a zone of ~20 km around the device or device array. This is considered a conservative estimate for all but the largest conceivable developments, particularly in view of the assumption of 100% energy extraction and the lack of detail in diffraction or refraction effects. It is therefore likely that for most device arrays, effects would be felt over a smaller area, but this remains to be substantiated.

Sediment processes were considered for floating, bed-mounted and coastal-mounted systems. The primary effect considered from floating and bed mounted devices was scour, and it was referenced to the body of work that exists on scour influences at the seabed attachment point. The conclusion was that significant distortion to the sediment dynamics could be expected for a distance of up to ~50 m from the device. For coastal-mounted (breakwater) systems (e.g. the Siadar development) the report identified that the energy extraction using these devices would perhaps lead to a tendency for more local deposition. The medium or far-field effects would be dealt with during the timescale of the EPSRC SUPERGEN project.

Where wave energy extraction is based near soft-coastlines it is considered that the alteration in the wave-field pattern has the potential to affect the sediment dynamics, by altering the dynamic equilibrium between deposition and erosion of soft sediments. In some circumstances this may affect the pattern of longshore drift, possibly leading to erosion downstream of the development as the supply of sediment may be interrupted.

Tidal Energy Extraction:

The SEA considered that given the current width of commercial turbines a zone of hydrodynamic influence would be a distance of ~500 m downstream of the device. However, in more enclosed sites (straits, channels), substantial tidal energy extraction will modify flows and levels. In such sites the effects of locally modified sea levels would be to move the focus of wave erosion up or down the coastal height profile. The effect of a modified flow field would be to change erosion and deposition patterns. It would also have the secondary effect of refracting wave trajectories, thereby potentially altering the associated coastal wave erosion.

The modifications and general reductions to flow speed anticipated through tidal energy extraction will likely alter sediment suspension and deposition. Energy extraction also introduces turbulence into the flow which may have a local counter-influence on sediment, causing sediment resuspension in the region of the wakes. The most noticeable influences would be experienced in estuarine conditions, such as the Solway, rather than in energetic channels such as the North Channel and Pentland Firth. In such sites, sediment is dynamic and already strongly influenced by native waves as well as tidal currents.

Impacts on sediment processes depend on the size of the rotors compared to the water depth and height of the device above the seabed. These factors bear on the likelihood of seabed interactions. However, in cases where these effects reverse between the flood and ebb tide, the potential for net change in the deposition signature is small and the sediment regime would be expected to remain stable.

For tidal energy devices there is a dearth of necessary baseline data for understanding sediment behaviour in high tidal energy zones, particularly where unnatural turbulence would be introduced by moorings, piles and the operation of the devices. Such studies may be necessary in areas thought to be at particular risk from sediment redistribution.

2.3.3 Offshore Energy SEA

The Offshore Energy SEA differs from the above SEAs as it encompasses the whole of the United Kingdom waters across all offshore energy sources, including renewable sources. The document considered the environmental implications of a draft plan/programme for licensing offshore oil and gas and leasing for offshore wind. The report does not provide a detailed analysis of the potential impacts of offshore windfarms on sediment dynamics or coastal processes, but does identify some of the issues. This is primarily due to it being more focused on the biological and habitat issues as per the previous Oil and Gas SEAs (SEAs 1-8).

Activities associated with offshore windfarm development can lead to physical disturbance of seabed habitats with consequent effects on seabed features. The main activities which may result in disturbance are:

- piling of monopile foundations
- placement of gravity base foundations (inc. works to level the seabed)
- laying and trenching of export cables
- decommissioning of infrastructure

The potential impacts relevant to this project were:

- scour
- temporary disturbance (anchor scarring, anchor mounds, cable scrape and trenching) leading to re-mobilisation of sediments by current shear
- temporary increases in turbidity due to sediment plumes in the water column and settling to the seabed from construction and site investigation activities.

In particular, scour – a local erosion and lowering of the seabed around a fixed structure – was recognised at an early stage as a potential issue in relation to wind turbine foundations, and has been subject to considerable research and monitoring. The report references the extensive body of work that has been undertaken on scour at offshore windfarm sites, and concludes that scour effects are small in scale and local in extent.

The report discusses that temporary disturbance (anchor scarring, anchor mounds, cable scrape and trenching) leading to re-mobilisation of sediments by current shear is qualitatively similar to the effects of wave action from severe storms. The authors predict that the sand and gravel habitat recovery from these processes is likely to be relatively rapid (1-5 years) in most of the shallower parts of the UK continental shelf.

Temporary increases in turbidity due to sediment plumes in the water column and settling to the seabed were considered. The report considers that natural concentrations of suspended particulates in the coastal and southern North Sea areas and the Irish Sea are high and the effects of anthropogenic sediment plumes are unlikely to be significant or long-term.

2.4 The Evidence Base from Historic and Contemporary Site Developments (data sources: EIA, FEPA, CP studies; non-statutory monitoring)

Once a licence has been granted to a developer of a particular area of the sea bed, the developer must then carry out an Environmental Impact Assessment (EIA) at their own cost. EIAs are the formal, pre-construction means through which an initial investigation is made into potential impacts on a wide range of issues (including birds, archaeology etc.). EIAs usually include a Coastal Processes (CP) section, which examines in detail the range of hypothetical impacts on coastal processes and sediment transport. Acceptance of a comprehensive EIA by the regulators is required before a FEPA license is issued, without which the installation and construction phase of a development cannot begin.

These environmental impact assessments while evidently necessary are a considerable burden to developers and the sentiments that were conveyed by many of those contacted were that if NERC science is in any way able to streamline this process by providing a sound evidence base that they can draw upon then they will be happy to cooperate. Full guidance notes for developers regarding EIAs were produced by CEFAS (2004).

A good example of how research can reduce the regulatory burden on developers was the CEFAS led study into potential diffraction effects at the Scroby Sands wind farm. Report AE1227(2005) concluded that in relation to future monopile based wind farm developments, DEFRA's Marine Consents and Environmental Unit (MCEU) were advised "not to require developers at OWFs to monitor waves for diffraction/interference effects under a FEPA licence".

2.5 Assessment of Environmental Impacts through Site Development

A wide range of renewable energy developers and operators were contacted to determine what they perceived as the environmental issues surrounding their operations in the renewable energy arena, and were also asked about what happens to any data they collect and whether they would be interested in cooperating with future NERC research projects.

The responses from those consulted indicated that during the different stages of a marine renewable energy site development from initial leasing through to eventual decommissioning there are a range of environmental issues related to different marine operations. Most of the information in this section is biased towards the wind sector as that is where most of the industry experience lies, but many of the issues will be common to wave and tidal sectors as well.

Site development can be summarised under the following headings:

- Pre-construction
- Installation & construction
- Operation
- Decommissioning & Disposal

The most prominent issues and their perceived impacts at each of these particular stages are described below, and are summarised in Table 2. the criteria used for the impact assessments are described in detail in Appendix 3.

Table 2. Summary of impacts through project timescales.

Major			Underlined (far-field)
Moderate			**Bold (neafield)**
Minor		1	Short term (dd)
Negligible		2	Medium term (ww)
No interaction		3	Long term (MM to YY)
Positive		4	Lifetime of installation
			Unknown/NO IDEA
			Research gap

Beatrice Wind Power	Pelamis Wave Power	AWS (wave swing)	MCT tidal turbine		Physical Environment: Tide current speed/strength	Wave height/energy	Wave breaking	Water circulation/orthogonals/ri	Cliff erosion	Beach erosion/deposition	Longshore drift	Change in seabed composition	Suspension of sediments	Turbidity	Bedforms	Seabed channel morphology	Seabed scour/deposition (nearfield)	Seabed level (farfield)	Benthos	
				PRE-CONSTRUCTION																
				• Environmental monitoring/marine survey									1	1						Kit intrusion onto seabed (e.g. magnetometry); momentary increase in turbidity during deployment
				• Use of jackup, incl coring/drilling								2	1	2	2		2-3		2	Seabed erosion potential increased during jackup/down; scour=f(tides); impact on benthos/shellfish local and temporary
																				Deck-wash significant contribution to turbidity.
				CONSTRUCTION AT OFFSHORE SITE																
				• Deployment of vessel anchors								1	1	1	1		1		1	Scour only in strong tidal streams (scour potential f(tide))
				• Installation of Base Unit								2	2	2	1		2		1	Piling ops will generate localized sediment transport; scour=f(flow velocity). Benthos impact -ve during construction.
				• Installation of anchor points								1	1	1			1		1	
				• Installation of tower (wind)	3															Main effect is on localised flow field (turbulence, flow accleleration, wakes). Impact=f(tides, waves). Intallation vessel effects
				• Installation of turbine and blades (wave/tide)	3															Turbine/blade installation relevant to tidal/wave conversion only.
				• Trenching and installation of cable			1			1		2	2	1	1	1	1		1	Largely short-term localised effects; wave breaking=beachfall; sediment resuspoension potential moderate
				• Subsea work								1	1	1	1			1	1	
				• Placement of concrete mattresses	3															Disruption to sediments and benthic communities along route between WTG and Beatrice AP.
				• Use of jackup/ship as installation vessel	2							2	1	1	2		2-3		2	Disturbance proportional to length of time jackup in same position.
				• Installation of marker buoys									1				1			
				• Placement of anti-scour measures	3							3	3	3	3		3		1	Impact relative to anti-scour method used. Highly localised impact.
				Coastal/port infrastructure developments in support																
				OPERATION AT OFFSHORE SITE																
				• WAVE (FIXED TO SEABED) Physical presence of device in sea	4	4	4					4	4		4	4	4		4	
				• WAVE (FLOATING/MOORED) Physical presence of device in sea		4	4					4	4		4	4	4		4	Device specific impact.Scour risk function of tides. Site specificity important
				• TIDE Physical presence of device in sea	4	4							4	4			4			Device specific impact; site specificity important - resuspension dependant on sediment availability
				• WIND Physical presence of device in sea	4	4		4				4	4	4	4				4	Accumulative impacts not understood.
				• Presence of foundations	4			4				4	4		4		4			
				• Physical presence of buried cable to device						1	1	1	1	1			2			Cabling method may change impact. Rubble protection may interupt l/s drift. Exposure may have minor impact due to scour
				• Periodic maintenance/intervention by sea								1	1	1	1			1	1	Possible short-term inconvenience for commercial shipping and fishing operations.
				• Cumulative impacts																
				• In combination effects (multiple arrays/different device)																
				• In combination effects (multiple arrays/same device)																
				• Presence of anti-scour measures	4	4	4					4	1	1	4		4			Secondary scour can promote sediment impacts.
				DECOMMISSIONING AND DISPOSAL ONSHORE																
				• Cutting piles and removing base								1	1	1	1		1		1	Disruption to sediments and benthic communities.
				• Exposing and removing cables			1			1		2	1	1	1	1		2	2	Disruption to sediments and benthic communities.

2.5.1 Pre-Construction

Following leasing of the seabed region by the Crown Estate, the pre-construction phase involves:

- *Site survey* – sidescan and/or multibeam sonar & magnetometry mapping, together with meteorological & hydrodynamic spot measurements using bottom mounted frames.
- *Site Investigations* – sea bed coring & drilling to about 40m below the sea bed to assist the design of device foundations (wind). Such operations usually involve a jack-up barge. These are short-term but necessarily widespread.

The impacts of these are:

- *Site Survey* – minimal impact/short-term, very localised from deploying instrument frames using small ships, minimal increased turbidity from ship's propeller wash.
- *Site Investigations* – localised scour & footprints from jack-up barge legs. These have been shown to persist in some areas for an unexpectedly long time in clay substrate (>1 year Kentish Flats Wind Farm) (Cooper et al, 2008) and will disrupt the sea bed in the immediate locality of the legs. The sea bed could be expected to recover in the medium term. Drilling increases local turbidity from the washed out sediments & drill cuttings but is also a localised issue and should have little or no permanent impact.

2.5.2 Installation, Construction and Site Development

Once all regulatory criteria have been satisfied, and when all marine and foundation survey data have been collected, activities commence to construct the offshore structures and to connect outputs to the electricity grid. The activities associated with site development/construction include:

- *Monopile array installation*– drilling/piling using jack-up barge for monopiles and use of jack up barges for turbine installation (usually a separate barge deployment)
- *Gravity base installation* – large frames simply resting on the sea bed e.g. for wave converters e.g. Aquamarine's Oyster system.
- *Cabling Operations* – trenching by either ploughing or jetting followed in some cases by rock armouring to protect the cables.
- *Cable Landfall Operations*– Bringing the power cables ashore for grid connection via a substation.
- *Scour Protection Emplacement* – rock dumping and concrete/plastic mattressing (plastic seaweed) to protect vulnerable infrastructure such as monopiles & cable routes

The impacts from these are:

- *Monopiles* – localised scour and minimal to moderate impact in the long term
- *Gravity Bases* – little information but anticipated scour dependent on the bed and hydrodynamics of the particular site. Some knowledge from overseas (e.g. Danish Nysted OWF; see http://www.ens.dk/sw42531.asp) developments is relevant but these often are in low energy coastal waters and physical process data is sparse.
- *Cabling* – localised sediment disturbance, short term impact.
- *Cable Landfall* – ploughing in cables across beaches causing localised beach disturbance, dependent on duration and extent of operations.
- *Scour Protection* – this is a long term feature and impacts need to be viewed in that context. Secondary scour, particularly from poorly implemented rock dumping has caused problems at Scrobie Sands Wind Farm. Flow changes caused by rock dumping potentially constitutes a moderate impact in the long term. Matressing, on the other hand, works by reducing flows and encouraging sedimentation around the

foundation. The impacts consequently are judged to be less on sediment transport processes, or may be viewed as a positive effect. Matressing has been used at the Gwynt-y-mor met. mast, and at the Irish Arklow windfarm development, but no information was available to this study on its effectiveness.

Note regulators are able to impose compliance monitoring on the developers in response to specific issues at the developers cost, and this can minimise impacts on an ongoing basis. Table 3 provides example evidence of changes in suspended sediment concentration during site construction activities for various R1 OWF sites.

Table 3. Site-by-site evidence base of SSC monitoring for select offshore windfarms (comparing predictions in the Environmental Statement with observations).

Site	ES Prediction	Observed Impacts
North Hoyle	< 10% increase to SSCs.	< 5% detectable increase in SSCs as a result of construction works.
Kentish Flats	SSC levels could increase to double that of background levels. Final deposition side unknown.	Installation of the first cable saw no significant alterations to SSCs. Installation of the second and third indicated a 9% increase on background levels.
Scroby Sands	Impacts unlikely due to dynamic nature of the site.	SSC seen to increase 9 to 11% during construction works (may have been due to period of increased wave heights).
Barrow	No significant impact predicted as naturally high levels of SSCs at site.	Increases found to be small and relatively localised whilst remaining between 1 to 2m above the seabed.
Nysted	Small increases predicted.	Small increases observed but both temporary and localised.
Horns Rev	No significant impact due to naturally high SSC levels.	Impacts minimal.

2.5.3 Site Operation

Site operation relates to the situation where an offshore energy farm is built and operational. No further construction is necessary and the site is visited only for maintenance and repair by vessels. Evidence for this phase is limited to wind farms which are largely passive structures. No operational wave energy or current energy conversion systems have been in place long enough to provide evidence of impacts or lack thereof.
A selection of existing case studies from which evidence can be drawn are listed below and described in more detail in Appendix 4:

- Scroby Sands Windfarm
- North Hoyle Wind Farm
- Seagen Tidal Stream Turbine, tested in Strangford Lough
- Stingray Wave Energy Device, and Pelarmis Wave Energy Device

Active devices extracting energy from the water column are likely to have far more profound long term implications.

The impacts from these are:

- Local scour around turbine bases occurs in most OWF developments but is understood only in broad terms; whilst an approximate scour depth can be judged there is no knowledge on the temporal variability of scour around individual bases on a daily (tidal), fortnightly (Spring-Neap) and seasonal basis/

- **Local cumulative effects** of permanent arrays of structures to the local sea bed that can lead on to farfield effects. For wind turbine arrays there is no evidence of local scour around individual monopiles joining up with the scour footprint of other monopiles as their spacing is usually an order of magnitude larger than the scour/wake impact area of an individual device. However, the Scroby Sands development gave rise to 'unexpected' scour 'tails' comprising substantial current-aligned sediment bedform trails.
- **Farfield effects** at the coast due to long term changes in bathymetry and/or hydrodynamics at array sites. Potential issues are changes in wave propagation if the height of sandbanks change, and possible local diffraction effects. Again, no evidence demonstrating this to be an issue exists for monopile arrays, however, the longest monitoring post-installation has been at Scrobie Sands Wind Farm and provides 3.5 years of information to the present time, which is perhaps insufficient to be considered conclusive proof yet.
- **Localised increases in turbidity/sediment resuspension** – this is potentially a major issue for developers of wave/current devices since suspended sediments and moving parts are not a good combination for long term reliability of devices. Little information exists.

Operational Issues Specific to Device Type

Wind

- **Local impacts** - ABPmer determined that the major components of an offshore wind farm that could affect coastal processes are the turbine foundations, array spacing and seabed cable laying (ABPmer, 2002).
- **Breaking waves on shallow sandbanks** – cause increase in local turbulence and sediment resuspension, potentially leading to increased scour both around pilings and of pilings from sand blasting, potentially leading to accelerated corrosion.
- **Wave diffraction from monopile arrays** – Models suggested that this might be a problem close to the monopiles but studies with marine radar imagery commissioned by CEFAS shorewards of Scrobie Sands wind farm before and after monopile installation detected no measurable diffraction effects or superpositioning in the farfield at the shore. The conclusion from this was that no further studies into this particular effect are required for future monopile based wind farms – an example of how research can reduce the burden of regulatory process for developers.

Tidal Stream

- **Downstream turbulence** – modelling of the twin rotor Seagen device in Strangford Lough indicate that the turbulent wake can extend ~600m downstream of the device. This turbulence is sufficient to reduce data return from ADCPs, especially close to the device and could present increased scour and turbidity issues.
- **Flow acceleration** – modelling indicates flow acceleration either side of the Seagen device compensating for the increased drag it presents to the flow. This extends as far as the shore on either side (a distance of ~250m). The rock and coarse sand seabed are unlikely to be affected by scour issues, but possible effects on the shoreline have not been mentioned.

Wave

- **Wave height reduction** – a potential benefit for coastal protection. Modelling for the imminent Siadar breakwater project developed by Wavegen (developers of the LIMPET installation on Islay) & RWE shows that wave will be diffracted around the breakwater with little energy remaining in the lee of the structure. If this occurs for anchored very shallow water devices (<12 m depth) then the shadow effect can potentially give rise to changes in shoreline and surf-zone processes. This issue remain entirely unsubstantiated at present.

2.5.4 Decommissioning

The lifetime of turbines and internal cables is typically 20 to 25 years, while for transmission cables, transformer stations and cable transition stations the lifetime is 40 years. The issue of site decommissioning and the potential impacts this will generate is required as a consideration within FEPA licenses.

- Primary effects are the reverse of installation – marine traffic, localised sediment disturbance, turbidity generated as structures are either sawn off or wholly removed and pulled out of the water. Impacts are likely to local and short-term.
- Guidance notes and experience from other marine industries (e.g. oil and gas) are likely to be relevant and probably sufficient in this respect.

2.6 Summary of the Evidence Base from Regulators and Developers

Research and monitoring associated with the development of the offshore renewables industry have provided a wide range of data and information in relation to the impacts created by site developments. The majority of the quantitative evidence base stems from the offshore wind industry, on account of the progress of this sector relative to wave and tide. Most of the direct data and information also comes from industry (via licensing obligations) rather than from academia, although academic studies have made a contribution in some areas. This section provides a summary of the evidence base.

The higher level SEA process covers environmental impacts in a very generic and qualitative fashion. It mainly considers impacts within a conceptual framework rather than demonstrates or records impacts from collected data since the data collected during some SEA studies are largely useless in terms of indicating impacts. Nonetheless, the evidence base from the SEA process is largely consistent. Perceived effects on sedimentary processes, such as physical effects of anchoring and infrastructure construction on seabed, sediments and features including scour, are concluded to be largely minimal, i.e. short-term and localised. Nevertheless, for some areas (e.g. far-field and large-scale effects, energy extraction devices) the reports acknowledge that many implications of development are unknown. The Scottish Marine Renewables SEA (Faber-Maunsell and Metoc, 2007) recognises the dearth of data and knowledge in the wave/tide area, and presents many suggestions for studies to fill these gaps.

A more quantitative evidence base exists for the offshore wind sector. Data associated with issuance by government of FEPA licenses for two development rounds has given rise to considerable data on impacts, which is stored mostly within the COWRIE/Geodata database and much of which can now be used to document impacts over the course of site developments. This data largely indicates minimal impacts, thus supporting the more speculative suppositions made within the SEA reports. Although a range of categories have been established as indices to judge in detail impacts, they can be summarized in more general index terms as suspended sediments, morphology, and seabed scour.

For many UK R1 and R2 OWF developments, rises in suspended sediment concentrations e.g. plume generation are relatively minor and not persistent over the medium to long term. Observations show they either remain within the range of natural variation through site development, or are mimimised through compliance monitoring obligations placed upon developers by the licensing process (this may occur where the seabed contains fine material).

l There is no evidence of permanently elevated suspended sediment concentrations within constructed wind farm arrays, nor in the area outside array footprints.

Scour is documented for all the R1 and R2 site developments. The evidence base chiefly consists of bathymetric data from consecutive surveys and thus the information is of high spatial quality (array-wide) but of low temporal quality. The data provides evidence of the scale of scouring around turbines and on bed-level changes in-between turbines. Scour is known to be reduced in areas of firmer seabed sediments e.g. sub-surface clay pavements, chalk horizons. The analysis by Whitehouse (2008) provides an examination of scour for the R1 and R2 windfarms, and develops an empirical predictive method for evaluating scour depth. Except for several non-UK cases, no research or monitoring has been done to describe the temporal variability of scour around individual bases on a daily (tidal), fortnightly (Spring-Neap) and seasonal timeframes.

The issue of morphology remains different for different geographic areas. High levels of morphological change are noted from areas of sand within exposed, high current coastal areas (e.g. Scroby Sands). Impacts due to the presences of offshore structures, such as scour around turbines and bed-level changes between turbines, are evident, but the environment is highly dynamic in any case. Lower levels of morphological change, and consequently less severe impacts due to structures, characterise areas where the oceanographic conditions are less aggressive. It must however be noted that the general changes in bed level at many coastal sites, i.e. the natural variation, is not known. The short time-base of observations (3.5 years) necessarily limits the ability in dynamic areas to separate large-scale and longer term morphological change that could be attributed to natural processes.

The issue of cumulative and far-field impacts, although frequently highlighted, has yet to be addressed. Evidence in the form of sediment wakes for the impact of multiple structures is available only from the Scroby Sands windfarm, which is the most energetic site developed to date. Elsewhere there is no indication of coupling of either sediment transport or hydrodynamic processes between turbines.

Developers rarely monitor conditions in the far-field, in spite of post-construction license obligations. It may be the case that data will arise from many R2 OWF site developments in due course. The body of modelling data and coastal radar data collected from the Scroby windfarm site suggest no measurable far-field effects or impacts on adjacent coastline.

The knowledge base regarding impacts of site developments on water column hydrodynamic processes comprises modelling on the effect of (OWF) arrays on wave propagation, and studies directed at the issue of wake generation for wave and tide energy conversion projects. For OWF development, as noted the research indicates indicates negligible nearfield and farfield impact; however, for some wave devices (e.g. Siadar) modelling indicates significant modification to the energy levels in the inshore region. The small body of wake modelling studies show wake generation in high energy tidal sites some 600 m downstream of structures, which is a large footprint in bi-directional current systems. However, no studies have been conducted to assess the consequences for sediment transport and coastline processes.

Decommissioning is currently a redundant issue for the offshore renewables sectors, but perceived geo-environmental impacts are generally considered to be the same as those for installation.

Table 4 summarises the knowledge gaps and issues identified by industry and regulators.

Table 4 Summary of knowledge gaps and issues in the evidence base for offshore wind, wave and tide derived from inspection of existing data sources, analysis and consultation with industry stakeholders.

	Issue	Notes
A	Generic data	1. Lack of site specific generic data (joined up observations with modelling) 2. Baseline data – need quality datasets on seabed level to judge change 3. Addressing specific data gaps e.g. Pentland Firth 4. Spatial coverage of data (esp. waves) 5. Data harmonisation/format (standardisation required) 6. Post-installation data and report
B	Scour	1. Temporal (days-weeks) scour variations around turbines 2. Importance of waves to scour 3. Scour on gravel beds and mixed/cohesive beds 4. Impact of energy extraction (tide) on scour potential
C	Foundations	1. Impact of different foundation types on scour potential
D	Anchorages	1. Matching anchoring/mooring systems to seabed type 2. Depth of sediment cover for secure anchorage
E	Hard bottom areas/hard coastlines	1. Impacts of whole device on sediment composition/dynamics in hard-bottom areas; 2. Effects of waves on coastal dynamics
F	Far-field effects	1. Far-field effects of tidal turbines on sediment processes (e.g. shoreline processes) 2. Interruption of sediment flux ⇔ downstream consequences 3. Quantification of maximum extractable energy before generation of significant consequences
G	Wake effects	1. Temporal evolution of the wake; 2. Simple classification scheme for wake types/structure
H	Route to data	1. Easy access to harmonised datasets (interoperability)
I	Inshore waves	1. *Measurements* of wave transformation into very shallow water (<12 m)
J	Use of models	1. Confirmation of far-field predictions of EIAs/ES with regard to shoreline sedimentary processes; 2. Inter-comparison of different numerical models 3. Use of real data for calibration 4. Advance modelling (integration of area models with CFD; 3D, linked hydrodynamic-sediment transport)
K	Seabed mobility	1. Generic descriptions of seabed mobility would be useful 2. Source-sink data at prospective sites
L	Coastal protection	1. Investigation into the use of wave energy devices for coast protection (e.g. Siadar)
M	Cumulative impacts	1. Impacts of multiple energy farms
N	Scale effect	1. Consideration of future very large scale arrays
O	Long-term effects	1. Long-term metocean/scour measurements to judge long-term CP impacts
P	Extreme events	1. Prediction of frequency-magnitude of extreme events at wave/tide sites

3. THE ACADEMIC PERSPECTIVE

While regulators and developers must by necessity take a very focussed view of marine renewable developments, the academic world is free to consider a broader view of the implications of installing devices in the marine environment. From the renewable developers point of view this can be perceived as a tendency to look for and highlight potential, still unknown or poorly understood, problems. Independently from this view, NERC can support the sustainable development of the marine renewables sector by fostering an evidence base of all impacts, not only negative but also neutral and positive. However, academic scientists may well have an adverse bias to conducting research likely to have a neutral outcome due to possible lack of perceived added value in their community, i.e. the 'I didn't find any effect' conclusion may not necessarily excite scientists, but is of potentially great significance to developers and regulators.

3.1 Review of Academic Views

It is widely considered that sediment transport is driven mainly by the flow hydrodynamics (e.g., bottom shear, turbulence) and waves. Therefore, the accuracy of sediment transport models largely depends on that of the hydrodynamic and wave models. For example, sediment transport rates are usually considered as proportional to the cube of the flow rate. In spite of advances from purely simple phenomenological description to sophisticated theories and numerical models, the understanding of sediment transport responses to unsteady and complex hydrodynamical forcings is still limited. This is further complicated by the two-way interaction between sediment dynamics and hydrodynamics, as well as interactions between sediments, hydrodynamics and bio-geo-chemical processes. While investigations into such interactions are necessary, the first step is traditionally to provide satisfactory descriptions of the hydrodynamic component.

3.1.1 Impacts on hydrodynamics

Passive Structure Impact (e.g. Wind Turbine Monopiles)

From the combination of consultation and review, the view of researchers depicts that impacts of monopile structures used by wind extracting energy devices are more or less well defined with regard to large scale impacts although this view is based in the limited datasets so far available and contrasts with the developer's concerns about more localised scour. Nevertheless, findings on the effects of an array of such structures are minimal and further research is required. Studies using both physical and numerical models suggest that the array might work like a single large obstruction generating large wakes behind them that will affect the far field dynamics and sediment transport (Ball et al, 1997). A very simple modelling strategy was employed by Ball et al, and the issue should be revisited using more advanced and sophisticated approaches. Additional complications also rise from these structures being located in areas of strong tidal flows. The interactions with the flow might then produce flow patterns similar to those produced by small islands and described in Simpson and Tett (1986). Such flow disturbances may impact nearby sand banks and coasts.

Impacts of Active Structures

Recently, some research interest has shifted towards tidal stream devices. Major reviews of the resource characteristics and the devices presently in development have been produced by the Energy Policy Research Institute (EPRI 2005, 2006), BC Hydro (2002) and the Carbon Trust (2005, 2006). Much of the resource appraisal work has been aimed at evaluating the environmental impact of extracting energy from natural tidal streams. Studies by Garrett & Cummins (2005) and Bryden & Couch (2006) show that the amount of energy that can be extracted without significantly altering the flow through a channel is dependent on the site bathymetry but that energy extraction of up to 20% of the kinetic energy of the free stream could be achieved at many sites. These environmental indicators and preliminary estimates of device performance indicate that up to 16.5TWh/yr (a mean output of 1.6GW) of electricity could be generated from sites in UK waters.

A wide range of tidal stream devices are presently in development. Although the design details vary between developers, most obviously in terms of the support mechanism and generator used, these can broadly be classified into three groups: vertical axis turbines and both open- and ducted-horizontal axis turbines. At the present time all three types of device are undergoing offshore testing (the ducted devices of Lunar Energy and OpenHydro at EMEC, the vertical axis devices Kobold in Italy and WPI in Norway amongst others) but perhaps the closest to commercial deployment are open-bladed horizontal axis turbines: Marine Current Turbines deployed in the Bristol Channel in 2000 (Seaflow) and Strangford Lough, Ireland in 2007 (Seagen), VerdantPower in New York and Hammerfest Stromm in Norway.

Despite progress, concerns remain on whether the basic hydrodynamics are indeed always fully understood and well modelled. Tidal energy devices are subjected to loading by tidal current, surface waves and turbulent structures within the flow. Whilst the mean flow velocities are reasonably well understood, both the influence of combined wave and tidal loads and the long-term effects of turbulence are not. This, in turn, has far reaching consequences on sediment transport dynamics.

Even though this is outside of the scope of the present study, effects on turbulence also have far-reaching impact in the near field and on the devices themselves. The need to understand and quantify turbulent loads was identified by the Hagerman *et al*. (2006) and noted in both the Carbon Trust (2005) report and during the development of the DTI performance protocol for tidal energy devices (Couch *et al*., 2006).

At many tidal energy sites, high flow velocities occur over a relatively small area so it is desirable to place devices in close proximity to maximise power output from the available resource. It is therefore useful to understand how the mean flow velocity and the turbulence characteristics within a turbine wake differ from the incident flow. To date, the device spacing assumed in deployment studies has generally drawn on data from the wind industry (Myers & Bahaj, 2005). Several numerical and experimental studies have also recently been completed and provide further insight into the matter. Myers & Bahaj (2005) presented measurements of the wake from a 400 mm diameter turbine and investigated how this deformed the free surface downstream. Sun *et al*. (2008) reported the depth variation of mean velocity at several sections within the wake of a porous disc and showed that the free surface caused the centreline of the wake to drop below the horizontal. A brief comparison was also made with a porous disc model in steady flow. Batten *et al*. (2006) presented findings from two-dimensional Computational Fluid Dynamics (CFD) simulations designed to investigate how the wake from an upstream device changes the turbulence incident on a downstream device. Rectilinear and staggered configurations were considered and, in some cases, the flow incident on a device located ten "diameters" downstream was found to have twice the turbulence intensity of that on the first device. Further experimental work has been conducted to assess device performance (e.g. Clarke *et al*., 2007; Batten *et al*., 2008) but these studies do not address the behaviour of the wake. Furthermore, the work reported to date regarding turbine wakes generally concerns behaviour in uniform or steady flow. A study of the influence of unsteady flow on wake formation and characteristics was carried out by Gant and Stallard (2008). The actual effect of large number of these devices (e.g. suggestions of several hundred devices in the Bristol Channel) on the turbulence and flow have not been studied in detail nor in how we should properly integrate these effects on regional sediment transport models.

So far, this has only been pursued via simple approaches. Litt (2008) used a 1-DV hydrodynamic model coupled to a sediment transport model to look at possible effects of including tidal stream devices in the Bristol Channel and used a momentum sink, proportional to the stress, to simulate the energy extraction. Her main conclusion was that it was evident that the presence of a tidal stream turbine farm would have a significant non-localised impact on the morphological balance of the seabed over the 30 year lifespan of a turbine. A more complex modelling study in the Minas Passage in the Bay of Fundy, used an enhanced bottom drag coefficient as way to represent the presence of a tidal stream farm, the results show changes on the tidal amplitude of more than 15 % in Massachusetts Bay some 600km away (McMillan et al, 2008), which will have important impacts on the tidal dynamics, the positioning of the tidal fronts and possibly the position of the Mud Patch south of Martha's Vineyard.

Impacts on Wave Climate and Coastlines

The sensitivity of the shoreline to the nature of the incoming waves was highlighted by Williams & Esteves (2005) who were able to reproduce most of the observed oscillations in shoreline position on a section of the Brazilian coast based on a simple continuity model driven by hindcast wave model data. Their simulation demonstrated that reversals from erosion to accretion or vice-versa could be explained at first order by subtle changes in the wave climate. Changes in coastal wave climate also have the potential to alter rock coast erosion (Stive, 2004), which could be beneficial in areas where such erosion is a risk to infrastructure or detrimental by reducing supply in sediment budgets.

Such effects stress the need to correctly assess the impact of Energy Conversion Devices on coastal wave climate. In particular, the interaction of water waves with "periodic cylinder arrays" has received significant attention. Hu and Chan (2005) studied analytically and numerically the refraction of waves of long wavelength by an array of vertical bottom-mounted cylinder and discussed the implication on focusing ocean water wave energy. Some other recent analytical work studied the diffraction of monochromatic waves by a two-dimensional array of vertical cylinders and obtained explicit analytical results for the resonance of scattered waves (Li and Mei, 2007). Projections of future wave climate suggest some redistribution of wave energy (to be reported in UKCP 09 - DEFRA, 2009; Wolf, pers. comm.). Changes in tides and storm surges are not expected to be substantial. However, these projections present significant uncertainty due to the large amount of natural variability.

Even though the study of the impacts of wave energy devices is at an even earlier stage, Millar et al. (2007) assessed the impact of a wave farm on the shoreline wave climate. They specifically investigated the impacts induced by the Wave Hub off the north coast of Cornwall and found that it "will potentially affect the wave climate", but that "it is likely that these effects will be small". Recently, Alexandre et al. (2009) demonstrated with flume and modelling experiments that wave energy converters optimised for a particular range of wave frequencies could potentially transform a unimodal wave spectrum to a bimodal wave spectrum by preferentially removing energy from particular wave frequencies. This could have knock on effects at the shore as the shape of the wave spectrum can influence the impact the waves have on the shore, affecting wave groupiness (surf beat) and hence long period oscillations in nearshore currents and hence longshore drift of sediment.

3.1.2 Future Academic Research Interest.

It is clear that we do not have a clear understanding of how the hydrodynamics and hence the sediment transport behaves when we have large arrays of Energy Conversion Devises (ECDs) especially in the case of tidal stream and tidal impoundment devices. The use of arrays of devices is completely unknown and we don't know what the large scale implications of this will be. There is a good chance that there will be a large number of farms in the UK and the adjacent NW European shelf, if enough tidal energy is extracted, this could change the way the tidal wave propagates and hence change the position of tidal mixing fronts and the location of sand banks. If we have farms of tidal stream devices at the mouth of estuaries or in Regions of Freshwater Influence (ROFIs), this could change the tidal straining behaviour and hence not only modify the tidal currents, but also the residual currents and the tidal turbulence, which would have big impacts on sediment transport.

Although, it is still unclear how wave farms will change the wave propagation towards the coast, these studies suggest routes by which a greater understanding may be developed. In the longer term this could include the ability to include coastal protection and management considerations into the design of arrays of wave energy converters.

Finally, the consultation with academic researchers helped identify the following knowledge gaps, needs and issues:

Table 5. Summary of research needs identified by the academic community

Principal Issue	Type of work
Lack of high quality field scale data	Field measurements, Monitoring.
Need for better mapping and monitoring of the sediment bed	Field measurements, Monitoring.
Need to better understand the hydrodynamic processes, in particular how they may be impacted by the presence of renewable energy structures	Field measurements, Monitoring, Laboratory experiments, Modelling.
Need to better understand the responses of different sediments to various hydrodynamic conditions.	Field measurements, Monitoring, Laboratory experiments, Modelling.
Ensure that all relevant scales can be reasonably modelled.	Modelling, Validation against field data

4. KEY RESEARCH QUESTIONS

Taking into consideration all the viewpoints feeding into this study together with the known strengths within NERC, the following key themes capture the essence of the future research.

1. Determine the far field effect of renewable energy installations that could alter the regional tides and wave climate in the UK and neighbouring countries and consequently impact on sediment and coastal morphodynamics.

2. Validate efficient methods of monitoring renewable energy installation impacts that can be accepted and adopted by stakeholders.

3. Increase predictive ability of models in the context of marine renewables by developing methodologies for connecting the different scales from small scale physical processes to device scale CFD and to regional numerical modelling.

Theme 1 should be the overarching scientific aim of NERC funded research. It focuses on far-field effects with the understanding that near-field effects would be more important in the two-way interaction between the renewable energy structure and the surrounding hydrodynamics and sediment dynamics and as such may be a better fit to funding or co-funding from engineering sources (e.g., EPSRC). Naturally, this overarching scientific topic should be addressed using both observational and modelling programmes, which respectively correspond to Theme 2 and Theme 3. Such prominence of monitoring and modelling really results from the extent to which almost all possible future studies on the far-field impact of marine renewables ought to rely on a combination of both approaches. Examples of scientific studies are included in the following section. Several potential case study sites are detailed in Appendix 7.

A major issue that has been consistent across the academic, industry and regulator consultation is the need for long-term baseline datasets together with continued monitoring through installation lifetimes. This would help separate natural variability of sites from anthropogenic impacts and validate model predictions.

Examples for detailed scientific considerations

Several smaller, more detailed issues can be specified within the main themes identified. Almost all points are relevant to the three themes in that they aim to address some far-field impact and should follow both observational and modelling approaches when adequate. Their relevance to existing projects (and as such to research organisations) and external potential collaborators are also highlighted.

Table 6. Summary of specific questions and linkages to existing projects and potential collaborators

General Scientific Aim	Specific questions	Relevance to existing projects / Collaborators
What will be the impact of ECDs on tidal characteristics and propagation?	How would the impact of tidal stream farms compare with that of tidal barrages?	Joule, Mersey Tidal Power Study
	How far away would that effect propagate in the context of UK and neighbouring countries?	
	How would changes in tidal propagation caused by tidal energy extraction impact coastal defences e.g. shore parallel breakwaters designed for specific tidal conditions?	
	How would tidal amphidomes be shifted by extracting energy from the tides, which would alter the tidal propagation with possible impact on changes in the frontal positions with further knock on impacts on biodiversity and natural resources, e.g. the location and evolution of sandbanks?	
How would ECDs change wave propagation behaviour and wave climate?	How would wave farms change the behaviour of wave propagation to the coast?	COFEE, MICORE, Manchester Bobber, PRIMaRE, CEFAS, Oceans 2025 Theme 3
	Could the effects be beneficial and used for coastal protection or could they change the wave characteristics so that certain wave frequencies will focus on parts of the coast and cause erosion?	
How will ECDs affect coastline evolution?	If wave farms protect part of the coast, how would that affect what happens downstream and the management of adjacent beaches, i.e. does the sediment transport diminish out of that cell?	PRIMaRE, COFEE, CEFAS, UEA, Lancaster U., Coastal Observatories, Wave device developers, SUPERGEN (tidal near-field wakes)
	How do wave farms affect the seasonal cycle of beach-berm interactions?	
	What are the impacts of ECDs on erosion/deposition hinge points? Could this be used to advantage?	
	How would very shallow water wave energy devices modify the energy arriving at the shoreline, potentially leading to changes in shoreline sediment processes?	
	What would be the effect of wakes on coastal hydrodynamics and sediment transport processes?	
How do arrays of ECDs affect benthic ecology in the far field?	Will a farm of tidal stream devices off Holyhead stop the semi-permanent cloud of sediments from being maintained in suspension, how will this affect the benthic ecology and the sediment transport in the area?	U. Bamgor Oceans2025 - Theme 3
What is the added effect of arrays-of-arrays of ECDs?	Separate case studies possible for wind, wave and tide	Manchester Bobber, PRIMaRE, Coastal Observatories Skerries
How is turbulence modified by renewable energy devices, and what is the importance of such changes (e.g., on stratification, mixing, primary production)?		FORMOST, Coastal Observatories, PRIMaRE, Oceans 2025 Theme 3

How can the small scale physical processes be represented in device scale CFD?		FORMOST, SUPERGEN, Manchester Bobber
How can the small scale physical processes be represented in regional scale modelling?		FORMOST, Oceans 2025 Theme 3 and Theme 9
How would results from device scale CFD be integrated into regional scale modelling?	How can the evidence base from wind farm be used for model validation at the device scale and at the far-field scale?	SUPERGEN, Manchester Bobber, Oceans2025 Theme 9
	What would be the sediment transport and scour impact on non-monopile geometry foundations?	SUPERGEN, WEC organisations.
What is the nature of site variability for potential development sites?		Site developers, PRIMaRE, EMEC

5. ADDRESSING THE KEY RESEARCH QUESTIONS

5.1 Introduction

Significant added value could be gained through buy-in (largely but not exclusively of manpower) to a number of existing research projects that represent an already substantial investment, rather than by developing entirely new research programmes with all the overheads that entails. These linkages have been summarised in Section 4 (full details of the relevant projects can be found in Appendix 5) and span projects involving a significant number of the UK's key coastal and sediment research groups. Collaboration with the renewables industry and the SMEs and Consultants they use for many of their environmental work will also be critical.

There are a number of consistent themes that need addressing in order to answer the key questions listed in section 3. Some of these are operational issues that have relatively straightforward answers. Others are more philosophical in nature, particularly where predictive capability is concerned.

Inherently the desire will be to try and predict future behaviour of hydrodynamics and sediments, and this implies the use of modelling. However, 'modelling' is a very broad term and there are many approaches in existence and many issues in applying them to practical problems. A discussion of some of these issues is presented later in this section, with a full, more technical review of currently available coastal and sediment models included in Appendix 6.

Monitoring is another major theme, and it is clear that the complexity of the problem will require emerging methods of monitoring to be validated and adopted both to provide real time data for developers and regulators but also to act as long term datasets for model validation and to separate natural variability from anthropogenic change. To this end a discussion of monitoring techniques, both established and emerging is also presented.

There exist a number of repositories/Data Archive Centres for marine data from different sources, e.g. BODC, DEAL, COWRIE, Channel Coastal Observatory. A clear data archiving strategy will need to be established at the outset to provide a long term resource for researchers, developer and stakeholders alike. The study of existing marine renewable installations is routinely hampered by the inability of researchers to access the data collected at particular sites. Even where projects nominally have the support of developers of a particular site this can still be an issue.

5.2 Partnerships and Collaborative Opportunities

NERC envisages a potential net gain in value where collaborations with external bodies and organisations can be forged, and within the framed research questions key collaboration partners have been identified. During consultation with industry in particular almost all people engaged expressed a general desire to work with NERC to achieve the research objectives. The form of the contribution ranges widely but may include:

- Jointly funded research programmes, e.g. Crown Estate, DECC SEAs Programme, EMEC
- Use of infrastructure already in the sea e.g. fixing of sensors to assess temporal variability of scour.
- Use of demonstration facilities where they exist (e.g. at EMEC) or where they are currently under development (e.g. WaveHub);
- Use of existing and future datasets (where appropriate);
- Provision of industry experience (e.g. via the BWEA, SRF);
- Provision of expert technical knowledge (e.g. the mechanical engineering consultants);

<u>SMEs</u>: there is considerable expertise across the UK within small and medium sized enterprise (SME) business sector, (which include ECD developers). Although NERC does not routinely engage with these organisations, in this instance it is recommended that ways might be explored by NERC of involving those SMEs with experience and the willingness to co-operate (for example MCT, OWEL, Shoreline Management Partnership, IECS, SeaStar Survey). The SME involved in this scoping study, Partrac would be willing to assist NERC in finding relevant SMEs.

Table 7. Summary of existing/recent research projects with relevance to the impacts of marine renewables.

	Project	Relevance/Linkage to Key Questions
A	Tapping Tidal Power Potential of the Eastern Irish Sea (Joule)	Existing wide area tidal models Already studying impacts of tidal energy extraction
B	Oceans2025 Theme 3	Expertise in marine radar remote mapping of waves, currents and bathymetry Could be applied to EMEC test sites in particular due to proximity to the coast. Marine radar will be used to observe an erosion/deposition hinge point at Sefton in Liverpool Bay where arrays of arrays of wind farms are present and Mersey tidal energy schemes are under consideration Development & implementation of sediment transport modules in area models
C	Oceans2025 Theme 9 Modelling Development	3D Hydrodynamic modelling development & implementation including wave and turbulence modelling
D	POL Irish Sea Observatory	Long time series of monitoring data in an area with arrays of arrays of wind turbines and possible future Mersey tidal energy scheme In particular a WERA HF radar as planned in EMEC and Wavehub has been in operation since before installation of Rhyl Flats wind farm and will continue to operate as the much larger Gwynt y Mor wind farm is installed. Potential to determine impacts or lack thereof of arrays of arrays of wind farms on hydrodynamics and applicability of this type of measurement for this purpose.

E	WHISSP & DREEM	Extensive background data on coastline from beach surveys and video WERA HF radar planned for 2 years (Lease) but no funding in place to continue through to Wavehub installation and installation of arrays of wave devices in the Wavehub (Capital investment needed to ensure continuation of measurements) Potential to study impacts of arrays of wave energy devices with extensive background data to separate natural variability from anthropogenic changes Long term baseline monitoring here would also provide extensive data to study farfield impacts of any future Severn tidal power scheme
F	SUPERGEN	Ongoing studies into nearfield effects around energy devices, e.g. scour, wakes etc Potential for NERC to collaborate/contribute with transitioning from device scale studies to parameterisation in area models
G	Manchester Bobber	Ongoing studies into wave transformation at device and arrays of wave energy device scales Potential for NERC to collaborate/contribute with transitioning from device/array scale studies to parameterisation in area models
H	UKCIP	Studies have shown climate change impacts on wave climate around the UK that should be considered in any predictive work
I	Mersey Tidal Power Study	Any Mersey Tidal Scheme will take place in the context of the Irish Sea Observatory. POL are planning marine radar trials to study sand bank/bedform evolution in the Mersey Estuary that could, if successful, provide valuable baseline data should a tidal power scheme go ahead
J	FORMOST	Ongoing studies aiming to use increased observational capabilities to validate local modelling concepts and improve parameterisations into coastal area modelling systems. Potential for NERC to further advance the linkage between process studies and area models. Case studies in Liverpool Bay
K	Blinks	Investigated links between offshore sand banks and beach morphology Follow up work to study the link between sand banks, a ness, and sediment exchange in the area between them was not funded by NERC, although could have relevance if device arrays are shown to have cumulative impacts on sandbank morphology. This proposal should perhaps be re-examined. Case study – East Coast of UK
L	COFEE	Links to understanding changes in wave climate due to climate change and impacts on the coast, but could equally be applied to changes in wave climate due to arrays of renewable energy devices. Studies are focussed in Liverpool Bay where arrays of arrays of wind farms are present and under construction.
M	MICORE	See COFEE
N	BGS MARINE GEOSCIENCE PROGRAMME	Ongoing studies of the sea bed (multibeam, seismic etc.)

5.3 Modelling

One of the most important characteristic of sediment transport modelling is the wide range of scales it needs to cover both lengthwise, from the grain diameter scale to regional coastline changes, and timewise, from intrawave processes to decadal evolutions. Models reflect such scale diversity. "Coastline models" integrate over all small-scales and only describe the largest scale long-shore behaviour. "Coastal profile models" ignore this long shore variation and concentrate on the cross-shore evolution by only considering the vertical and cross-shore dimensions. “Coastal area models" include both horizontal dimensions and may resolve vertical variations but do not resolve the scales of the smallest physical processes. Finally, “local models” focus on small-scale processes (e.g., bottom boundary layer, intra-wave processes, ripples) and ignore the larger scales.

In area modelling systems, flow turbulence, near-bed dynamics and wave-processes are often resolved neither lengthwise nor time wise and appropriate parameterisation of the smaller scale processes is crucial to the representation of coastal and estuarine sediment dynamics. This is the real challenge in such models and represents most of the effort associated with sediment transport modelling. Poor near-bed and small scale parameterisations are still commonly blamed for the performance of coastal regional models due to the large variability resulting from the different approaches, and further process studies will thus be pivotal to improving our predictive abilities.

5.3.1 Hydrodynamic and turbulence modelling

Historically, the investigations leading to the various conceptual and mathematical models describing the small scale processes have focused first on the hydrodynamic components and then on the response of sediment to given flow, turbulence and wave conditions. While the flow-sediment interaction is two way, such an approach builds on the main linkage being from the hydrodynamics to sediment and will still be relevant when dealing with the impacts of renewable energy devices on sediment dynamics.

An important part of correctly determining the hydrodynamic component lies in the turbulence closure. So far, Coastal Ocean Models use Reynolds Averaged Navier-Stokes (RANS) turbulence models. While RANS models have been extensively studied and can usually be applied to a wide range of turbulent flows, they inherently involve some empiricism and a loss of information from the averaging. In contrast, both Direct Numerical Simulation (DNS) and Large-Eddy Simulation (LES) solve equations for time dependent variables for one realization of the turbulent flow. More information on RANS, DNS and LES approaches can be found in the appendices within the sediment modelling review. Where it can be applied, DNS provides an unmatched level of description and accuracy and has been valuable in procuring information on turbulence that is impossible to obtain experimentally. However, the computational cost of DNS still makes geophysical applications prohibitively expensive. LES aims to avoid such expensive calculations while maintaining a high level of description. Compared with RANS models, LES closures will describe more accurately problems where large-scale unsteadiness is significant but are also significantly more expensive. Furthermore, near-wall resolution in wall bounded flows still remains infeasible due to the incurred computational cost and simulations rely on some near-wall modelling usually similar to that used in RANS models. Overall, new developments in computer resource will allow more realistic and detailed solutions of flows, and even though this is still probably limited to device scale CFD and local models, it will potentially lead to better models for sediment transport at the larger scale.

5.3.2 Empiricism of sediment modelling

Historically, sediment transport modelling has also heavily relied on empirical and semi-empirical work. For example, near-bed hydrodynamics and sediment dynamics depend on empirical roughness predictors and empirical near-bed (bed load) sediment transport rates.

This often results in formulations that only account for a partial description of the sediment and near-bed dynamics and that exhibit limited range of applicability in real world scenarios. In particular, most formulations are still unable to fully describe natural conditions. They also often need to be calibrated by experimental means, which always involve some degree of specificity respect to the underlying conditions. For example, Davies et al. (2002) highlights the need for knowledge of on site conditions for reasonable predictions.

In the general context of regional modelling, a solution is already far from being cheap and simple. Two principal directions are to pursue extensive model-data comparisons for hindcast and using theoretical and numerical work to reduce the degree of empiricism and extend the range of applicability of the studies. This in turn raises the issue of the mismatch between:

(i) three dimensional sediment transport and two dimensional morphological modelling and
(ii) the experimental data available.

Experimental techniques used in coastal oceans only give a partial description of the fully three-dimensional problem. Techniques commonly used range from point-measurements obtained through Acoustic Doppler Velocimeter (ADV) to vertical profiles at a specific location with instruments such as Acoustic Backscatter Systems (ABS) for sediment concentration and particle size profiles, Acoustic Doppler Current Profilers (ADCP) and Coherent Doppler Velocity Profilers (CDVP) for current and velocity profiles. Spatial variations (in the "horizontal" plane) can be obtained for surface currents (from HF radar). In general, experimental data then do not include both vertical structures and horizontal variations and necessary model-data comparisons with three-dimensional sediment transport proves to be difficult. The situation is slightly different for two dimensional morphological modelling as bathymetric changes can be inferred from a depth inversion technique on X-band radar data (Bell et al., 2004). Furthermore, while recent advances in experimental techniques also provide better descriptions of the small-scale processes, a mismatch between quantities measured and quantities to be parameterised, such as erosion and roughness, often remains. This currently represents an important gap of knowledge, which may be overcome by using recent advanced small scale process models to represent the appropriate physical processes and to model the quantities necessary at the large scale. For example, the model by Amoudry et al. (2008) was shown to provide promising new estimations of the bed load transport rate and of the roughness.

5.3.3 Small scale process studies

This general mismatch between measurements and model hindcast only stresses the need for another approach, i.e. theoretical and numerical work to improve our fundamental understanding of sediment responses to hydrodynamic conditions. Sediment transport modelling has so far mainly been addressed without much scale interconnectivity. Some effort has been and is being devoted to development of models able to accurately describe the small-scale hydrodynamics and sediment dynamics, but the link to larger scales are still seldom made. Not only is a significant effort to further improve the understanding of the small scale processes still required, but research should also focus on integrating the acquired knowledge into the larger scale models. For example, our present understanding and representations of many essential small-scale processes are far from being satisfactory due to a mixture of high uncertainty, lack of sufficient description and insufficient range of applicability, when accounted for. Future efforts should address this problem concerning the following parameterisations (Table 8).

Table 8. Model parameterisations of sediment processes requiring further research

Parameterisation	Modelling context issue.	Note
Erosion rate	Uncertainty, description, range of applicability	
Ripple predictor	Uncertainty, description, range of applicability	This has a direct implication on determining the roughness and the bed shear stress.
Bed load transport rate	Uncertainty, description, range of applicability	It still exhibits unreasonable variability in spite of apparent consensus.
Sediment turbulent diffusivity	Uncertainty, description, range of applicability	
Cohesive sediment processes	Neglected	e.g., flocculation and consolidation
Mixed sediment	Neglected	Mixed cohesive (mud) and non-cohesive (sand) sediment beds have been found to behave differently than either singular case, but our understanding is still too limited.

5.3.4 Relevance to studying the impact of marine renewable energy devices

In the context of the impact of marine renewable energy devices, the same issues are relevant. In addition, the lack of pre-existing datasets seriously hinders the ability to appropriately hindcast models. In turn, this further emphasizes the need to better parameterise both the hydrodynamic component and the response of sediment to flow conditions (range of applicability, cost and ease of use, accuracy and level of description) using bottom-up methodologies. Some appropriate range of applicability of sediment responses will be particularly crucial given the a priori unknown effect on the hydrodynamic component. Scale interconnectivity will also be more important, as the far-field impact shall require information from the near-field impacts which in turn shall require information from the localised impacts.

5.4 Monitoring

The need for comprehensive datasets spanning periods before and after device installation cannot be emphasised strongly enough. Without high quality long time series of data at high spatial and temporal resolution any attempt to separate natural variability of the marine system from changes induced by renewable energy devices will be difficult, in the same way that demonstrating sea level rise from only a few measurements of water levels is unrealistic. Marine renewable sites are inherently going to be high energy environments and deploying any form or instrumentation is going to be a challenge. Because of the large spatial extent and the fact that these devices are designed to alter the hydrodynamics of the area by removing energy, systems that are capable of monitoring spatial changes in hydrodynamics, with the knock on effects on sediment response, will become increasingly valuable. Such techniques may also help developers both to monitor their installations and satisfy regulators that device impacts are being monitored as efficiently as possible.

Such data can serve multiple purposes:

- Provide data needed to define the extent of natural variability of an area
- Provide validation data for coastal area models
- Demonstrate the impacts or lack thereof of renewable energy structures
- Assist in optimal planning of arrays of renewable energy structures

The complexity of these sites and the potential effects of the devices planned for them will necessitate the use of a range of emerging technologies, particularly in the remote sensing arena. To date, the preferred option for shallow-ocean monitoring has been the use of a variety of in-situ point measurement systems that require regular servicing and data recovery (some can be equipped with telemetry for real-time data recovery):

- Acoustic Doppler Current Profilers (ADCPs) mounted on frames on the sea bed, One of the advantages of ADCPs is that not only can current profiles (including turbulence characteristics) and wave spectra be determined but recent work has shown that sediment concentrations may also be estimated based on the acoustic backscatter information, and hence sediment flux measurements are possible. These systems are widely available to researchers and consultancy companies alike, and are becoming viewed as standard instruments.
- Wave buoys – a variety of directional wave buoys are available to produce 2D wave spectra at a point – considered standard instruments for several decades now, but can be difficult to maintain and equipment losses can be high depending on the area due to mooring failure/tampering.
- Particle Tracking – is a method which uses uniquely identifiable sediment analogues to visualise and map sediment transport pathways in estuaries and the sea. (Black et al., 2007)
- Benthic Flumes – are a marine instrument that imposes a controlled flow stream at the sediment-water interface in order to measure sea bed erodability. They can provide in-situ estimates of bottom boundary condition variables (e.g. critical entrainment stress, erosion rate, settling velocity).
- Acoustic Backscatter Systems (ABS) – have been pioneered at POL and can be used to measure detailed suspended sediment profiles close to the sea bed where most sediment is moved by currents.
- Optical backscatter systems – most appropriate for turbidity measurements – well established technology. Starting to appear in multifrequency form to assist in identifying sediment type (organic/inorganic/mineralogy etc)

Remote sensing methods on the other hand are usually based out of harms way and so the large up-front investment needed to buy such systems pays off in the minimal risk of losing it. The trade off with remote sensing methods is that the measurements taken may not be as precise as in-situ measurements, but provide a map of sea state parameters over a large area of the sea, which can place point measurements taken by conventional instruments into a broader context, allowing relative changes over a large area to be observed.

The following systems are particularly appropriate for this application and were identified at the recent "Adoption of New Technologies for Coastal Defense Monitoring" workshop organized by Sefton Council in February 2009 as of particular interest:

- Satellite observations – Good for observing very large areas, although optical wavelengths used to infer suspended sediment concentrations require in situ calibration data and are limited by cloud cover. Synthetic Aperture Radar (SAR) imagery has been used in combination with high resolution tidal modelling to infer changes to large intertidal areas such as Morecambe Bay (Mason et al), and techniques coupling high resolution flow models with surface roughness measurements based on SAR data have been used to derive wide area maps of large scale bedforms (Gagliardini et al., 2005), a technique that has potential to be extended to marine radar observations at higher resolution (Hennings & Herbers, 2005). Dopplerised SAR imagery is showing potential for monitoring currents with high resolution over very large areas, with potential application to monitoring changes in hydrodynamics around arrays of structures and arrays of arrays.
- High Frequency (HF) Radar – Transmit in the low 10s of MHz, have ranges of 50-100km and work on the Doppler principle. They provide maps of surface currents and wave spectra at approximately km scale intervals (Wyatt et al., 1999). Both Wavehub & EMEC are investing in such measurements, but Wavehub at least does not have the funds to maintain the measurements at this time.
- Marine X-Band Radar – Standard ships radars that produce image sequences of the sea surface. Maps of wave spectra, currents and bathymetry may be derived by analysis of these image sequences over ranges of ~4km and with intervals of 50-100m (Bell, 2006). Recent work at POL has shown that sand waves/dunes of wavelength 50-100m and peak-trough heights of ~1m are resolvable both using wave inversions for bathymetry estimation and also using other imaging mechanisms based on convergence and divergence of flow over bedforms.
- Video - High resolution video cameras produce oblique images of the sea surface that can be rectified to provide plan views of areas up to a few hundred metres from the camera. These are particularly useful for short range applications where high spatial resolution is required such as monitoring ridge-runnel patterns on beaches and the location of rip channels through sand bars (Lippmann & Holman,1990)

The use of remote sensing techniques can overcome the issue of monitoring particularly shallow areas where vessels are unable to operate due to the risk of grounding, but where sediments are likely to be most dynamic.

6. SUMMARY

A wide ranging consultation was conducted with stakeholders in the marine renewable industry, regulators, marine users and academic researchers together with a literature review of available knowledge regarding the impacts of renewable energy structure on sediment dynamics and coastal morphology.

The majority of the industry evidence base is associated with wind farm developments that are arrays of static monopiles driven into the sea bed. Some knowledge exists from active structures that harvest energy from waves and tidal currents, but the majority of these devices are still under developments and the developers are quite naturally focussed on engineering issues surrounding the hostile effect of the marine environment on the operation of large devices with moving parts rather than the other way around.

Many of the research gaps identified by industry stakeholders surround the issues of scour around structures and from wake effects. Some of these more localised effects are more suited to research by the engineering community via EPSRC funding, and are already listed under the work packages for SUPERGEN 2. However there is no distinct border between applicability to a particular research council and some of these issues may be most appropriately dealt with by either council individually or through cross-council cooperation.

Taking into consideration all the viewpoints feeding into this study together with the known strengths within NERC, the following key themes capture the essence of the future research requirements:

1. Determine the far field effect of renewable energy installations that could alter the regional tides and wave climate in the UK and neighbouring countries and consequently impact on sediment and coastal morphodynamics.

2. Validate efficient methods of monitoring renewable energy installation impacts that can be accepted and adopted by stakeholders.

3. Increase predictive ability of models in the context of marine renewables by developing methodologies for connecting the different scales from small scale physical processes to device scale CFD and to regional numerical modelling.

Theme 1 should be the overarching scientific aim of NERC funded research. It focuses on far-field effects with the understanding that near-field effects would be more important in the two-way interaction between the renewable energy structure and the surrounding hydrodynamics and sediment dynamics and as such may be a better fit to funding or co-funding from engineering sources (e.g., EPSRC). Naturally, this overarching scientific topic should be addressed using both observational and modelling programmes, which respectively correspond to Theme 2 and Theme 3. Such prominence of monitoring and modelling really results from the extent to which almost all possible future studies on the far-field impact of marine renewables ought to rely on a combination of both approaches. A list of smaller, more focussed research questions have been identified that can be categorised under the different themes and may be addressed in most cases by adding value to existing research projects.

A major issue that has been consistent across the academic, industry and regulator consultation is the need for long-term baseline datasets together with continued monitoring through installation lifetimes. This would help separate natural variability of sites from anthropogenic impacts and validate model predictions.

In particular, the need for detailed bathymetric maps and maps of sea bed sediment type and availability have been repeatedly flagged by consultees as an issue with regard to investigating both the suitability of sites and the long term effects of marine renewable installations. This is an issue that BGS are ideally placed to address with existing capability in this area.

7. APPENDICES

7.1 Appendix 1 – Overview of UK Marine Renewable Energy Developments

Energy extraction from the marine environment 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). The following section gives an overview of the potential for each source as well as current developments within the UK.

7.1.1 Wind

Offshore wind farms are a comparatively established technology within the renewable energy industry. Five offshore wind farms are in operation as of March 2009 and licence applications from the Crown Estate have reached the third round with 10 exclusivity agreements announced in February 2009 (see Table). 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, which corresponds to peak energy demand in the UK.

ABPmer determined that the major components of an offshore wind farm that could affect coastal processes are the turbine foundations, array spacing and seabed cable laying (ABPmer, 2002). All five operational wind farms (Burbo Banks, Barrow, Kentish Flats, Scroby Sands and North Hoyle) have monopile foundations, which are suited to shallow water with stable, sub-bottom sediments. However, other foundations are being investigated. Deep-offshore, floating turbines are being developed by the US (Blue-H, Principle Power), mainly due to the higher energy potential further out to sea compared to coastal site along the US coast.

	Location	Status	Capacity MW (turbines)	Developer/Turbines
Round 1	North Hoyle	Operating (12/03)	60 (30)	npower renewables (Vestas 2 MW)
	Scroby Sands	Operating (12/04)	60 (30)	E.ON UK Renewables (Vestas 2
	Kentish Flats	Operating (09/05)	90 (30)	Vattenfall
	Barrow	Operating (09/06)	90 (30)	Centrica/DONG Energy(Vestas 3
	Gunfleet Sands	Construction	108 (30)	DONG Energy
	Lynn/Inner Dowsing	Installed (07/09)	90 (27)	Centrica
	Scarweather Sands	Consented	108 (30)	E.ON UK Renewables/DONG
	Rhyl Flats	Construction	100 (25)	npower renewables
	Burbo Bank	Operating 10/07)	90 (25)	DONG Energy (Siemens)
	Robin Rigg	Construction	216 (60)	E.ON UK Renewables
	Teesside	Consented	90 (30)	EDF
Round 2	Docking Shoal		500 (100)	Centrica
	Race Bank		500 (100)	Centrica
	Sheringham	Consented	315 (108)	Ecoventures/Hydro/SLP
	Humber		300 (70)	E.on
	Triton Knoll		1,200 (286)	npower renewables

	Lincs	Consented	250 (120)	Centrica
	Westermost Rough		240 (80)	DONG
	Dudgeon East		300 (60)	Warwick Energy
	Greater Gabbard	Consented	500 (140)	Airtricity/Fluor
	Gunfleet Sands II	Consented	64 (20)	DONG Energy
	London Array	Consented	1,000 (271)	DONG Energy-Farm Energy/Shell/
	Thanet	Consented	300 (60)	Warwick Energy
	Walney	Consented	450 (102)	DONG Energy
	Gwynt y Mor	Consented	750 (250)	npower renewables
	West Duddon	Consented	500 (140)	ScottishPower / Eurus / DONG
Scottish territorial Waters	Solway Firth		300	E.ON Climate & Renewables UK
	Wigtown Bay		280	Dong Wind (UK)
	Kintyre		378	Airtricity Holdings (UK)
	Islay		680	Airtricity Holdings (UK)
	Argyll Array		1500	Scottish Power Renewables
	Beatrice		920	Airtricity Holdings UK, SeaEnergy
	Inch Cape		905	NPower Renewables, SeaEnergy
	Bell Rock		700	Airtricity Holdings UK , Fluor
	Neart na Gaoithe		360	Mainstream Renewable Power
	Forth Array		415	Fred Olsen Renewables

7.1.2 Wave

Wave energy converters are the least developed of marine renewable devices due to the relative inefficiency and unpredictability of the energy source. 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. Whilst wave energy extraction during the summer months may not be feasible around most of the UK, the significant wave height and power doubles during the winter months.

Wave energy development is thought 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. So far, only the oscillating water column type has proved to be successful (LIMPET, on Islay), although Pelamis, an attenuator device is undergoing long-term testing at EMEC and in Portugal (although financial problems with the major stakeholder has mothballed the testing here) and appears to be fairly successful. Other device types currently in development are listed in Table XX. Wave energy devices have the potential to have a secondary function of coastal protection.

Wavegen, the developers of the LIMPET (Land Installed Marine Powered Energy Transformer) is currently in the planning stages with RWE npower for a wave breakwater system at Siadar. Power rating 250 kW.

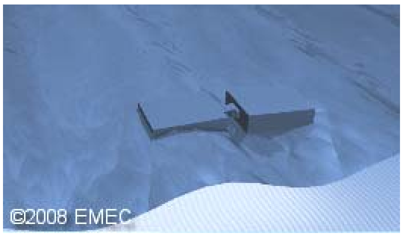
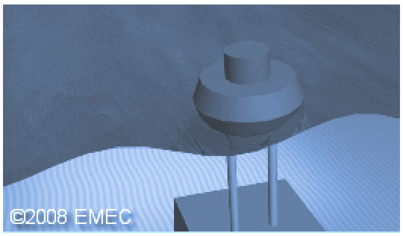
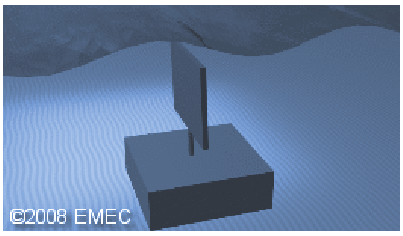
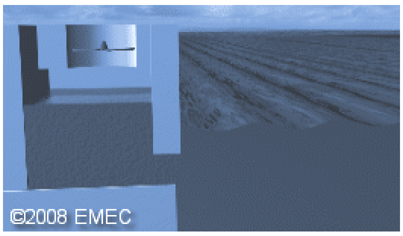
Pelamis Wave Power until recently, were running three Pelamis wave energy convertors in Portugal after successfully trailing the technology at EMEC, and are planning to deploy a further four machines at EMEC to create the worlds largest wave farm. Power rating 750 kW.

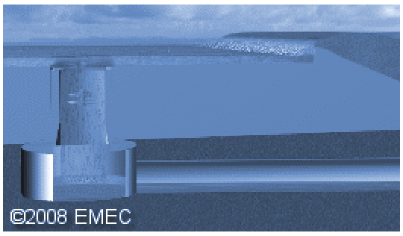
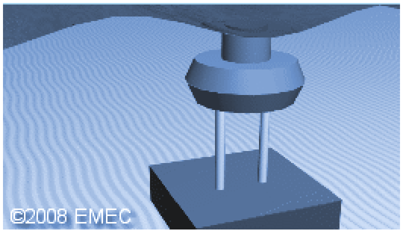
AWS have a test device of their Archimedes wave swing (point absorber) deployed in Portugal and are planning to deploy an array of 20 devices in Scotland by 2010. This device is fully submerged (and thus relatively protected from storms) and purported to have minimal environmental impact for a high power density. Power output 13 kW.

Aquamarine Power, which also specialises in tidal energy, has developed a oscillating wave energy device, the Oyster, which will be deployed at EMEC in the latter half of 2009. It has been designed to be efficient with a high power output but able to shed the power from the largest waves to be robust in extreme weather. Power rating 500 kW.

A survey conducted by Seaview Sensing and Wave Energy Today on the current wave energy market suggested that there are knowledge gaps in our understanding of waves as an energy source. There is a general agreement that the spatial coverage of data buoys is not extensive enough or of a standardised format. http://social.waveenergytoday.com/content/making-sense-wave-energy

EMEC has identified six main types of wave energy device:

Wave Energy Device	Description	UK Device (companies)
	Attenuator – a floating device lying perpendicular to the wave direction. Its movement as it straddles each wave converts the energy.	• Ocean Treader WEC (Ocean Energy) • Pelamis (Pelamis Wave Power) • Salter Duck Sloped IBS (Wave Power Group).
	Point absorber – a floating device which extracts energy from all directions from its movements at the sea surface.	• Sperboy (Embley Energy) • Manchester Bobber.
	Oscillating wave surge converter – extracts energy from paddle movement due to the oscilating water particles.	• Oyster (Aquamarine Power)
	Oscillating water column – built onto the shore so is semi-submerged. Is a hollow device through which waves affect the internal water level. Changes in air pressure drive a turbine.	• Limpet (Wavegen)

	Overtopping device – water is captured through overflow of waves, and is allowed to return to the sea after passing through a turbine which generates power.	• Wave Dragon
	Submerged pressure differential – located nearshore on the seabed, passing waves cause changes in water pressure which moves the device inducing a pressure differential within that generates energy.	• Archimedes Wave Swing (AWS Ocean Energy)

7.1.3 Tide

Tidal stream technology is potentially 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), they are highly predictable, and the supply is seasonally constant. The UK has a huge potential, having 15% of the worldwide resource. A report on the UK tidal energy potential suggests focus should be applied on deep water devices (> 40 m) in high-velocity sites, rather than shallow water devices which are comparatively uneconomical (Black and Veatch, 2005). 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.

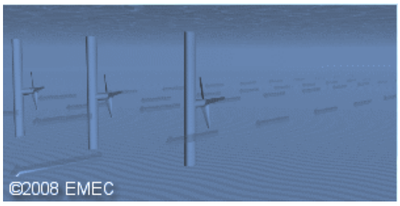
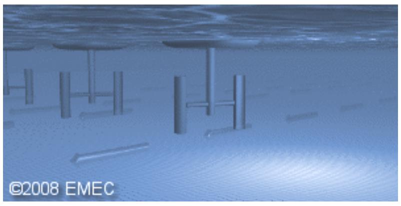
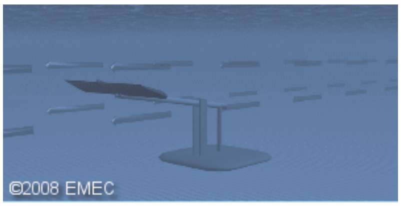
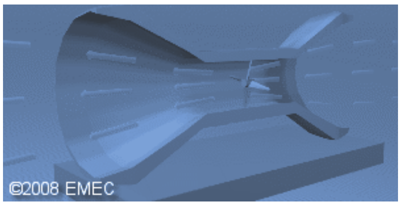
OpenHydro are expected to be the first to connect a tidal stream device to the UK grid having tested their open-centred, tidal turbine at EMEC in 2006. The device is completely submerged but has a fairly large footprint with a tripod foundation.

Hammerfest Strøm have been testing their tidal turbine (similar to a wind turbine) in Norway for four years, which currently supplies electricity to Hammerfest town. They plan to deploy a second test device in EMEC, followed by installation of an array of such devices along the Scottish west coast.

The TidEl turbine (contra-rotating dual turbines) from SMD Hydrovision is a self-orientating device (being a floating device anchored to the seabed), which is installed 30 m below the surface to avoid pressure differentials and biofouling. A 1/10 scale prototype has undergone seven successful weeks testing at NaREC and a full scale device is scheduled to be installed in EMEC.

Stingray (the Engineering Business) is a hydrofoil device, has been tested in the Shetland Islands for three years. It is connected to the seabed by four points; the hydrofoil oscillates with the tide moving internal hydraulic cylinders. A short, three-month test showed no environmental impact from the device itself, although anchors from construction barges did scar the seabed.

MCT have installed the Seagen tidal turbine in Stranford Lough and have been able to connect to the grid. It has two pitch-regulated, axial flow rotors so energy can be extracted during the whole tidal phase. This follows the highly successful test of the experimental Seaflow design off the Devon coast in 2003.

Tide Energy Device	Description	UK Device (companies)
	Horizontal axis turbine – similar mechanism to wind turbines.	• Seagen (MCT) • Neptune (Aquamarine Power) • Sea Snail (Robert Gordon University)
	Vertical axis turbine – similar to above but mounted vertically.	• Proteus (Neptune Renewable Energy Ltd)
	Oscillating hydrofoil – hydrofoil attached to an oscillating arm moved by tidal currents drives hydraulic fluid to generate electricity.	• Stingray (The Engineering Business) • Pulse Generator (Pulse Generation)
	Venturi effect – tidal flow is concentrated in a funnel-like device to drive a turbine.	• Rochester Venturi (Hydroventuri)

7.2 Appendix 2 - Data Sources

The wide variety of data have been collected to date on the impact of offshore renewable developments on coastal processes and sediment transport, and in some areas e.g. sediment resuspension, the evidence base is strong. Largely these data have been collected in relation to Rounds 1 and 2 of the present offshore wind sector, both by industry for specific developments and by Defra/CEFAS on a summarisation basis. Much of this information, knowledge and actual data for wind are held by COWRIE. Far less information exists in relation to wave and tidal energy. Higher level, broad-scale data and information are contained in two historic and three contemporary Strategic Environmental Assessments.

Information is also available through various FEPA (1985) and Coast Protection Act (1949; and in Scotland, Section 36 of the Electricity Act) licenses issued to developers on a case-by-case basis. Monitoring of certain coastal process and sediment related variables is often a key component of license provision, and frequently the data is available from Environmental Statements derived from a formal Environmental Impact Assessment process driven by the above licensing impositions. In addition, some developers undertake non-statutory monitoring. Alongside these, monitoring data exists within several European offshore windfarms, notably the developments in Danish waters.

7.2.1 Generic Data Sources

There is a considerable body of data across a range of organisations which exists and which is useful to assessment of baseline conditions around the UK coastline generally and which would be useful to any future NERC-directed research. The table below summarises the data types and their respective storage locations.

	Data	Data type	Source of Data	Link
Waves	Wave conditions and directions	grid data	BERR/ABPmer	Renewables Atlas
	Wave buoy locations	vector	BODC	BODC
	Wave data series	web	BODC	BODC
	WaveNet realtime and time series data	time series	CEFAS	CEFAS
	Channel Coastal Observatory (south coast only)	locations and time series	CCO	CCO
Wind	Wind Speed (at different heights)	grid data	BERR/ABPmer	Renewables Atlas
Tide	Tidal current speeds and directions	grid data	BERR/ABPmer	Renewables Atlas
	Surge (depth averaged extreme surge currents (cm/s), with a return period of 50)	paper	Kenyon and Cooper, 2004)	
	Current Meter series		BODC	BODC
Coastal Process	Seabed sediments (DIGSBS250): based on sea-bed grab samples of the top 0.1m, combined with cores and dredge samples as available.	Vector	SeaZone	SeaZone Hydrospatial
	Suspended Sediments	archive	CEFAS	Suspended Sediment
	UKSeaMap (to be updated) integrated habitat and physical data for landscapes and water column	Vector	JNCC	JNCC
	Sea cover (areas of sea displaying a common property, e.g. sandwaves)	vector	SeaZone	SeaZone Hydrospatial
	Seabed habitats (mapping of EU seabed habitats according to European EUNIS habitat classification system and the EC Habitats Directive types	Vector/webGIS	MESH	MESH
Related Interest	Water Column (for spring, summer, autumn, winter)	vector	JNCC UKSeaMap	JNCC
	Marine Aggregates (licensed)	Charts	BMAPA	BMAPA
	Offshore Installations	Vector	SeaZone	SeaZone Hydrospatial
	Bathymetry (DigBath250) Vector attributed digital bathymetry of UK and adjacent European waters: regional scale digital bathymetry	Vector	BGS	BGS
	GEBCO Bathymetry	Raster	GEBCO	GEBCO
	Wind farm rounds	Various	Crown Estate	Crown Estate

	Data	Data type	Source of Data	Link
	MARLIN - online seabed species records and sensitivity assessments (Marine Life Information Network)	Online DB	MARLINE/MBA	MARLIN
	Environment Agency environmental indicators	Various	Various	Environment Indicators
Licensing divisons	FEPA Licence Areas		Marine and Fisheries Agency	Current MFA Licence's
	SEA Boundaries	pdf image	BERR	SEA areas
	SEA Rnd 2 areas	pdf image	BERR	SEA areas
	ICES Rectangles	vector	Danish Institute for fisheries Research (DIFRES)	ICES
	ICES Divisions	vector	ICES	ICES
	JNCC Regional Seas	web	JNCC	JNCC
	BODC sea areas	web	BODC	BODC

7.2.2 Government Information Sources (Defra, WAG, SE)

A wide variety of data have been collected to date on the impact of offshore renewable developments on coastal processes and sediment transport CEFAS (2001), particularly from the offshore wind Rounds 1 and 2 experience. Several government-led studies have resulted in a number of important syntheses that are useful to the current analysis. These include:

Rees, J., SED01 (2008) Morphological changes around Round 1 offshore wind farms. A report for the Research Advisory Group (RAG), on behalf of DECC. 26pp.
Whitehouse et al. (2008) SED02 Dynamics of scour pits and scour protection – synthesis report and recommendations A report for the Research Advisory Group (RAG), on behalf of DECC. 98pp.

CEFAS 2006 Scroby Sands Offshore Wind Farm – Coastal Processes Monitoring. Final Report for MED, the Department of Trade and Industry and Defra. Contract AE0262. 51pp.
Cooper et al., (2008) Review of Round 1 Sediment process monitoring data – lessons learnt (2008) A report for the Research Advisory Group (RAG), on behalf of DECC. 142pp.

Scott Wilson and Downie, A.J. (2003) A review of possible marine renewable energy development projects and their natural heritage impacts from a Scottish perspective. Scottish Natural Heritage Commissioned Report F02AA414. 98pp.

Cooper, B, and Beiboer, F. (2002) Potential effects of offshore wind developments on coastal processes. Report W/35/00596/00/REP to ETSU. 127pp.

BMT (2003) Offshore Wind Energy Generation: Phase 1 Proposals and Environmental Report. Report 009.04.01/2003 for the DTI.

DBERR 2008 Review of cabling techniques and environmental effects applicable to the offshore wind farm industry Technical Report.164pp. Report to DBERR.

In addition, concurrent with the inception of the first round of offshore wind leasing CEFAS on behalf of Defra/MCEU issued EIA guidance to the developer community:
CEFAS (2004) Offshore Wind farms. Guidance note for Environmental Impact Assessment in respect of FEPA and CPA requirements. Report to Defra/MCEU June 2004. 48pp.

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The primary aim was to provide the scientific guidance to those involved with the gathering, interpretation and presentation of data within an EIA as part of the consents application process. It does not necessarily indicate the impacts but highlights the baseline data that it would be useful to collect, or consider collecting. This report is also relevant to the present study.

Strategic Environmental Assessments (SEA)

Strategic Environmental Assessments arise through legislation deriving from the EU (SEA Directive 2001/42 EC). The objective of the SEA Directive "to provide for a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programmes with a view to promoting sustainable development". SEA is an iterative process of gathering data and evidence, *assessing potential effects*, developing mitigation measures and making recommendations to refine the plan in view of the predicted environmental effects. The temporal range for effects to be considered is the expected life-time of a scheme, allowing for identification of key issues that may emerge over construction, operation and decommissioning. The Directive requires environmental assessments to be carried out for a range of plans and programmes likely to have significant effects on the environment, including offshore tide, wind and wave energy proposals. The SEAs which have been carried out to date therefore contain information relevant to the assessment of impacts of renewable energy developments on the physical environment.

The structure of SEA (under the Directive) is based on the following phases:
"Screening", investigation of whether the plan or programme falls under the SEA legislation,
"Scoping", defining the boundaries of investigation, assessment and assumptions required,
"Documentation of the state of the environment", effectively a *baseline* on which to base judgments,
"Determination of the likely (non-marginal) environmental impacts", usually in terms of Direction of Change rather than firm figures,
Informing and consulting the public,
Influencing "Decision taking" based on the assessment and,
Monitoring of the effects of plans and programmes after their implementation.
Table XX summarises the SEAs conducted to date, but includes future relevant planned SEAs.

Table 1: Marine Renewable SEAs Commissioned

No.	SEA	Commissioning Organisation	Stage	Reference
1.	UK Offshore Windfarms Round 2 SEA	DECC	Published 1 May 2003	http://www.offshore-sea.org.uk/consultations/Wind_R2/index.php
2.	Strategic Environmental Assessment for Wave and Tidal Energy (Scotland)	Scottish Government	Post Adoption Statement was published in July 2008.	http://www.seaenergyscotland.co.uk/
3.	Offshore Energy SEA	Department of Energy and Climate Change (DECC)	Public consultation closes 22nd April 2009	http://www.offshore-sea.org.uk/site/scripts/book_info.php?consultationID=16&bookID=11
4.	Severn Tidal Barrage SEA	DECC	Public consultation closes 23rd April 2009	http://severntidalpowerconsultation.decc.gov.uk/
5.	Strategic Environmental Assessment (SEA) of offshore wind and marine renewables in Northern Ireland waters.	Northern Ireland Executive	Started January 2009. To be completed 2010	http://www.northernireland.gov.uk/news/news-deti/news-deti-december-2008/news-deti-021208-northern-ireland_s-offshore.htm

7.2.3 Baseline Surveys

Baseline surveys are frequently commissioned during the pre-consenting period in order to describe the fundamental aspects of a site, and to provide a foundation on which to make informed assessments of 'presumed' effects attributable to the particular project. Baseline investigations identify processes maintaining the system, reasons for any past changes, and sensitivity of the system to changes in the controlling processes. Below are examples of data areas often uder consideration:

- Identification and quantification of the relative importance of high-energy, low frequency ("episodic" events), versus low-energy, high frequency processes.
- Identification of the processes controlling temporal and spatial morphological change (e.g. longevity and stability of bedforms), which may require review ofhydrographic records and admiralty charts.
- Identification of sediment sources, pathways and sinks, and quantification of transport fluxes.
- Identification of the inherited geological, geophysical, geotechnical and geochemical properties of the sediments at the site, and the depth of any sediment strata.

Consenting (FEPA, CPA, Section 36 licensing) Background

Government consent is required in order to develop an offshore site. The statutory authority for this is the Marine Environment Team of Defra, through the Marine and Fisheries Agency (MFA). MFA is responsible for the administration of a range of applications for statutory licenses and consents to undertake works in waters around England and Wales, including offshore renewable developments. The primary legislation to offshore wind, wave and tidal energy developments is the Coast Protection Act (1949) and the Food and Environment Protection Act(1985) (FEPA). The unit also administers certain applications on behalf of the Welsh Assembly Government (for which it is the licensing authority in Welsh Territorial Waters. In Scotland, Section 36 of the Electricity Act is used by the Scottish Executive as the tool to cover offshore licensing for wind, wave and tidal energy applications. These legislation collectively provide the means of instructing a developer with relevant consent conditions, including coastal process monitoring. The CEFAS (2004) guidelines are usually a component part of any FEPA license aiding developers select appropriate assessment approaches.

Environmental Impact Assessments

Environmental impact assessments (EIAs) are the formal, pre-construction means through which an initial investigation is made into potential impacts on a range of issues (including birds, archaeology etc.). EIAs usually include a Coastal Processes (CP) section, which examines in detail the range of hypothetical impacts on coastal processes and sediment transport. Most frequently, this examines the magnitude and significance of potential changes due to the development to the hydrodynamic regime (waves, tidal currents, water levels) and to the sediment regime (composition of seabed sediments, bedform features, transport pathways including disruptions of sediment supply, patterns of erosion and accretion including scour potential, suspended sediment concentrations). Sometimes, though not always, limited field data is collected to inform this process. These investigations combine existing data, numerical modelling and scenario testing approaches with expert judgement. The findings of the CP are summarised in an Environmental Statement.

Non-statutory Monitoring

In some instances, developers undertake to collect additional data which is not specified as part of the license condition. This can, for example, be a result of highly specific interests on the art of a developer e.g. to find a suitable scour risk mitigation approach.

7.2.4 Project Specific Data Sources

A literature search within a selection of tidal, wave energy, and offshore wind developments has revealed the scale and scope of data that has been collected. Boxes have been infilled only if the specific dataset has been referred to in the public domain; therefore this list is not exhaustive and is not indicative of data available to be utilized by NERC. Generally, unless the data is commercially sensitive, data referring to an offshore wind development should be available on COWRIE (until this unit ceases to be supported in the near future), or can be requested from the developer as part of licensing/lease agreements. The development stage of the wave and tidal devices is such that no data bank currently exists and so data release is at the disgresion of the developer. However, during the consultation phase of this report, the majority of developers supported a data-sharing agreement/database as long as no commercial/economical disadvantages arose.

Beatrice Windfarm

Environmental Statement http://www.beatricewind.co.uk/environmental_statement.pdf
Scoping Study http://www.beatricewind.co.uk/Uploads/Downloads/Scoping_doc.pdf

Pelamis

Environmental impact (not yet done) http://www.pelamiswave.com/content.php?id=154
Scoping study http://www.pelamiswave.com/media/opdeia.pdf

MCT SeaGen

Env Statement http://www.seageneration.co.uk/downloads/EIS%20Non%20Technical%20Summary.pdf

Wavehub

FEPA http://www.mfa.gov.uk/environment/energy/documents/Wave-Hub-FEPA.pdf
ES http://download.southwestrda.org.uk/file.asp?File=/projects/general/Environmental%20Statement.pdf
Geophysical & Bathymetric data report
http://download.southwestrda.org.uk/projects/general/geotechnicalandgeophysicalinterpretative.pdf
Wave & metoc data
http://download.southwestrda.org.uk/file.asp?File=/projects/general/Halcrow%20Group%20June%202006%20-%20Comparison%20of%20recorded%20wave%20data%20and%20Met%20Office%20data.pdf
Wave power
http://download.southwestrda.org.uk/file.asp?File=/projects/general/Halcrow%20Group%20July%202006%20-%20Analysis%20of%20wave%20power%20at%20Wave%20Hub%20site.pdf
Wave measurement technology
http://download.southwestrda.org.uk/file.asp?File=/projects/general/Technology%20Review%2024%20Nov%2006.pdf
Wave power climate
http://download.southwestrda.org.uk/file.asp?File=/projects/general/Applied%20Wave%20Research%20Review%20of%20Wave%20Power%20Climate%20-%20November%2006.pdf
Shoreline impacts http://download.southwestrda.org.uk/file.asp?File=/projects/general/Review-of-Wave-Hub-Technical-Studies-Apr-07.pdf

Trident

FEPA http://www.mfa.gov.uk/environment/energy/documents/tridentwave-FEPA-licence-14-Feb-08.pdf

Not really relevant but I'm struggling to find anything for trident!
Comparative Study Of Linear Generators And Hydraulic Systems For Wave Energy Conversion
http://www.tridentenergy.co.uk/pdf/DTI%20Report.pdf

Pulse Generation (Tidal)

FEPA http://www.mfa.gov.uk/environment/energy/documents/licence33837-08-1-2-May-08.pdf
ES http://www.pulsegeneration.co.uk/files/environmentstatement.pdf
University of Hull has done research for Pulse Tidal http://www.hull.ac.uk/geog/research/JH01.htm

Only 3 FEPA licenses have been issued for Wave/Tidal in England & Wales – WaveHub, Trident & Pulse.

AWS (wave swing)

No proposed site yet. Still at development stage "The power-absorption concept has been proven at full-scale in 2004 via a pilot plant that was installed off the coast of Portugal. Detailed engineering for a 250kW optimised pre-commercial demonstrator is now ongoing."

EMEC - Orcadian Wave Project (Pelamis)

Scoping study – Aquatera

FEPA http://www.scotland.gov.uk/198269 http://www.scotland.gov.uk/198265 There are only two wave/tidal applications with "consent granted" status in Scotland. The other three are "Scoping".
Pre-EMEC - Tidal energy, seabed survey etc – Aquatera

Siadar Wave Energy

FEPA http://www.scotland.gov.uk/257392 http://www.scotland.gov.uk/257461

SeaFlow

Project summary http://www.berr.gov.uk/files/file29969.pdf
Development, installation And testing of a large scale Tidal current turbine
http://www.berr.gov.uk/files/file18130.pdf

SeaGen

Preliminary Works http://www.berr.gov.uk/files/file33162.pdf
Limpet (Islay) – shoreline

Various papers: http://www.wavegen.co.uk/research_papers.htm

http://www.wavegen.co.uk/pdf/LIMPET%20publishable%20report.pdf (pp42-49)

OPT PowerBuoy – EMEC Orkney

EIA & Resource Assessment – Aquatera

Barrow Offshore Wind
Construction info http://www.bowind.co.uk/construction.shtml

Constuction Monitoring Report – p14 (table)
http://www.bowind.co.uk/pdf/CMR%20BOW/BOW_Construction_Monitroing_Report_All_v2.pdf

Post Construction Monitoring Report – p8 (table)
http://www.bowind.co.uk/pdf/MPCR%20BOW/BOW_PCMR_december%202007_15012008_v2.pdf

FEPA license http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/Barrow_letter2.pdf

Scroby Sands

Scroby Sands *Offshore* Wind Farm – Coastal Processes Monitoring
http://www.cefas.co.uk/media/21503/ae0262-final-report-scroby-owf.pdf

FEPA licence http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/Scrobyconsent2.pdf

ODE involvement (engineering) - http://www.ode-ltd.co.uk/whatwedo/projectdata/eon.html

North Hoyle

Post construction monitoring report
http://www.mfa.gov.uk/environment/energy/documents/Monitoring/NHoyle_EXECUTIVE-SUMMARY.pdf

FEPA license http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/NHoyle-new_letter.pdf

Annual monitoring (marine sediments p12 – 30) year

Annual monitoring (marine sediments p14 – 27) 2003-04
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2690

Annual monitoring (marine sediments 11-23) 2005-06
http://data.offshorewind.co.uk/catalogue/result.php?id=2440

Baseline monitoring http://data.offshorewind.co.uk/catalogue/getReport.php?report=173

Construction Summary http://data.offshorewind.co.uk/catalogue/getReport.php?report=174

Kentish Flats

FEPA license
http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/KFlats_letter2.pdf

OBS deployment (turbidity monitoring) http://data.offshorewind.co.uk/catalogue/getData.php?data=2528

Environmental Statement
http://data.offshorewind.co.uk/catalogue/getReport.php?report=165

Post construction bathymetric survey http://data.offshorewind.co.uk/catalogue/getReport.php?report=2523

Bathymetric plot drawings – turbines http://data.offshorewind.co.uk/catalogue/getReport.php?report=2522

Bathymetric Chart
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2502

Pre-construstruction debris
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2501

Bathymetry – seabed features
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2503

Kentish Flats Pos-Construction Scour Survey
Kentish Flats Monitoring Programme (oceanography)
Both carried out by EMU http://www.emulimited.com/clients/projectexperience.htm

Burbo Bank

FEPA licence http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/Burbo_letter2.pdf

Environmental Statement http://www.dongenergy.com/NR/rdonlyres/4309DE08-502E-4D99-BF53-5D4E2DD275F3/0/BurboVol_2_0Contents.pdf

Construction phase – benthic grabs http://data.offshorewind.co.uk/catalogue/getReport.php?report=2542

Seabed Scour & cable burial report http://data.offshorewind.co.uk/catalogue/getReport.php?report=2533

Construction – Env Monitoring report
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2535

Suspended sediment monitoring 2008
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2541

Suspended sediment monitoring 2006
http://data.offshorewind.co.uk/catalogue/getReport.php?report=2540

Other

A scoping study for an environmental impact field programme in tidal current energy
http://www.berr.gov.uk/files/file15348.pdf

Cromer FEPA license http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NEWSITEMS/Cromer_letter.pdf

Lynn FEPA license http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/Lynn_letter2.pdf

Rhyl FEPA license http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NewsItems/Rhyl_letter2.pdf

Gunfleet FEPA license http://www.mceu.gov.uk/MCEU_LOCAL/fepa/NEWSITEMS/Gunfleet_letter.pdf

7.3 Appendix 3 - Criteria Used to Assess Impacts on Sediment Dynamics

Assessment of the potential impacts of marine renewables on coastal processes requires a framework in order to assess the significance of impacts relative to the situation of an undeveloped coastal site. This framework must include all relevant information, including:

- severity (major, moderate), including no interaction;
- persistence (momentary to years);
- spatial extent (nearfield, far-field);
- areas of no knowledge or experience.

Table X summarises the terminology and coding that has been developed and applied to impact assessment in this study. The significance of impacts is judged from informed sources (e.g. historic, contemporary studies, data, reports etc.) and from expert judgement, to range from major through no interaction to positive impact. The definitions associated with these terms are given below:

Table 2 Terminology for classifying and defining geo-environmental impacts.

Impact	Adverse/beneficial	Definition
Major	adverse	The impact gives rise to serious concern; potentially it should be considered as unacceptable.
Moderate	adverse	The impact gives rise to some concern but it is likely tolerable (given its scale and duration).
Minor	adverse	The impact is undesirable but of limited concern.
Negligible	---	The impact is not of concern.
No interaction	---	
Positive	beneficial	The impact provides some gain to the environment.

Each of these qualitative descriptors is assigned a colour (Table XX).

The persistence (in time) of each impact is then given a number ranging from 1 (short term i.e. days) to timescales on project development (from site selection to decommissioning). An indication of whether the impact is limited to the nearfield or extends to the farfield is required. The following definitions have been used to define these terms, respectively:

Localised or Device Scale – on the scale of individual devices.

Nearfield - within 10 times the diameter for a single structure or the entire areal extent of an array, plus 10 times the diameter of the outer array structures, for an array.

Far-field - to a distance of 1 tidal excursion from a single structure or to a distance of 1 tidal excursion from the centoid of an array.

In tabulated information, nearfield and far-field information is conveyed through the use of **bold** and normal text fonts, respectively. For issues where the impacts on coastal processes are entirely unknown grey shading is used. Where the assessment is that impacts are not known or are only poorly known/understood (but nonetheless are considered worthy of attention in terms of future research), a bold outline box is used.

Table 3 Summary of assessment criterion used to establish the significance of geo-environental impacts.

Qualitative Descriptor	Numerical Temporal Descriptor			
	1	2	3	4
	Short term (days)	Medium term (weeks)	Long-term (months)	Life-span of development (years – decades)
Major				
Moderate				
Minor				
Negligible				
No interaction				
Positive				
Nearfield impact only	Bold text			
Farfield impact	Underlined			
Unknown				
Research gap				

Impact assessment has largely been conducted at a generic level, and yet it is apparent there are site specific differences even within the same sector due to a range of factors (e.g. proximity to the shore; wave climate), and certainly between sectors (wind-wave-tide). An attempt has been made where appropriate to consider and integrate these differences in the information presented to highlight and separate differing impacts. For example, different impacts are expected to arise from wave energy conversion devices which are floating and anchored (e.g. OPDs Pelamis system) in comparison to where these are mounted on the seabed (e.g. the Oyster device of Aquamarinepower). The tabulated information reflects worst case scenarios.

Perceived impacts have not been expressed in terms of *risk* (where risk=likelihood times consequence) mainly as this is outside the project scope. Some previous reports e.g. BMT (2002) which was an SEA, have taken this approach. It can be relevant where sediments are contaminated, for example.

7.4 Appendix 4 – Case Studies Illustrating the Industry Evidence Base

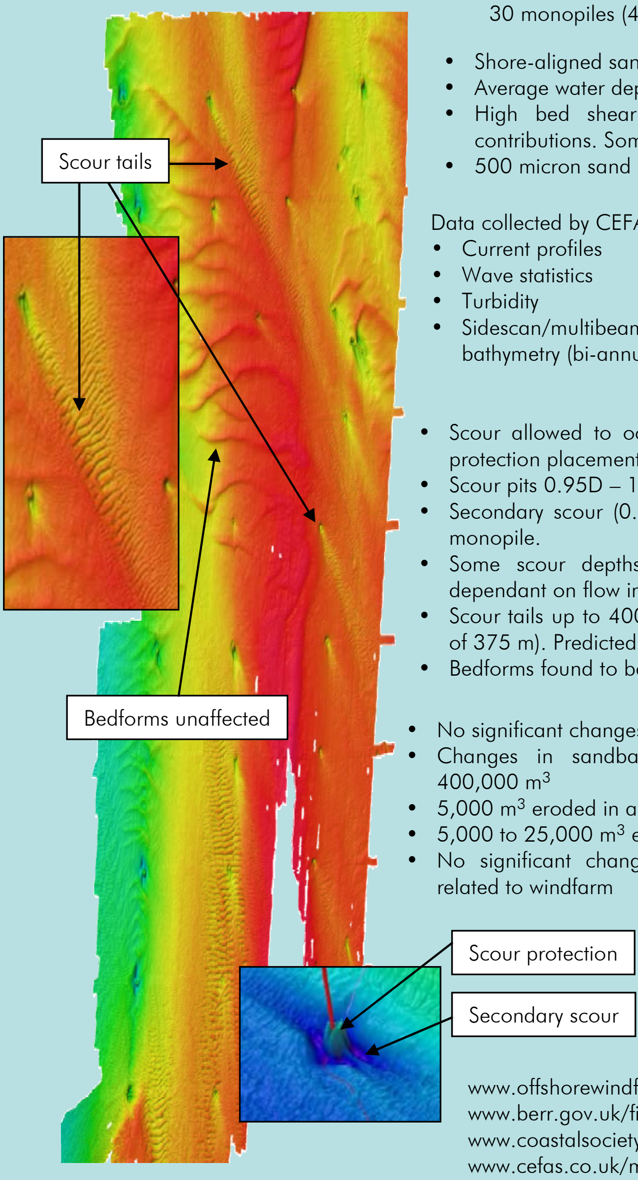
7.4.1 Wind – Scroby Sands

WIND:Scroby Sands

Developed by E-on – June 2005
30 monopiles (4.2m Ø) driven 30 m into seabed

- Shore-aligned sandbank 12 km long.
- Average water depth of 6-12 m; tidal currents 1 m s^{-1}
- High bed shear stress with equal tidal and wave contributions. Some exposure at low tide
- 500 micron sand in transport 95% of time during winter.

Data collected by CEFAS:
- Current profiles
- Wave statistics
- Turbidity
- Sidescan/multibeam bathymetry (bi-annual)



- Scour allowed to occur over a few tidal cycles prior to scour protection placement
- Scour pits 0.95D – 1.38D deep (D=monopile diameter; 4.2 m)
- Secondary scour (0.21D – 1.66D) but not present adjacent to monopile.
- Some scour depths greater with scour protection in place dependant on flow interaction.
- Scour tails up to 400 m in length (exceeding inter-turbine space of 375 m). Predicted to be 40-60 m
- Bedforms found to be unaffected by piles and scour pits.

- No significant changes in sandbank morphology
- Changes in sandbank volume between 100,000 and 400,000 m^3
- 5,000 m^3 eroded in a typical 5 m scour pit
- 5,000 to 25,000 m^3 eroded in the scour 'tails'
- No significant change to sediment regime of sandbank related to windfarm

www.offshorewindfarms.co.uk
www.berr.gov.uk/files/file50448.pdf
www.coastalsociety.org.nz/back/NZCS31.pdf
www.cefas.co.uk/media/21503/ae0262-final-report-scroby-owf.pdf

7.4.2 Wind – NorthHoyle

WIND: North Hoyle

Located four to five miles from the north Wales coast, it was the first major offshore wind farm to be built in Round one.

As part of its FEPA licensing, environmental monitoring has been undertaken prior to construction, during to construction and post-construction, following recommendations set out by CEFAS.

The seabed of North Hoyle is generally fine to medium sand with coarser material found to the west and further offshore. Some boulder clay is present, which in most places in buried by overlying sand/gravel. Sediment is generally coarser and poorly sorted within many of the sites sampled within the wind farm.

Comparison of samples taken in 2002 and 2003 show little synchronicity of variation; mean grain sizes remained comparable or changed fairly significantly by increasing or decreasing.

www.npower-renewables.com/northhoyle

Surveys	Sediment samples at 17 sites (nearfield and farfield)	Sediment samples at three sites near an installed monopile	TSS: nearfield, control (north), and in the Dee estuary (farfield).
Baseline (Aug 2001)	X		X
Pre-construction (Sep 2002)	X		X
Construction (Oct 2003)	X	X	X

•The Environmental Statement predicted minor impacts from construction related increases in suspended sediment concentration (SSC). 38 days of monitoring immediately following the baseline survey were conducted in order to incorporate changes in SSC during pilling and drilling activities of three monopiles (installed consecutively).

•The baseline survey determined that SSC was highest in the farfield site near to the Dee estuary, and progressively fell towards the offshore control site.

• Concentrations were dependant on the tidal phase, mobilising during flood and ebb currents, although increased wave energy also facilitated an increase in the volume of sediment in suspension in the shallower sites. As the farfield estuarine site and the nearfield wind-farm site both suffered from significant changes in suspended sediment concentration during spring tides, something not seen significantly in the offshore control, it was deduced that neap tides provided the best opportunity for construction-related peak identification.

• There appeared to be little affect on the concentration of sediment in suspension in the nearfield site; maximum SSC actually decreased by approximately 50 mg l^{-1} between the baseline and construction surveys. The control site saw an increase in maximum SSC, but a decreased mean. No reasons were given for this; however, the relatively coarse grain size may have reduced the potential for the piling plume to travel even as far as the nearfield monitoring site..

•Modelling carried out for the Environmental Statement predicted a maximum 12,000 m^3 of sediment to be released with minimal impact (within 10 mg l^{-1} of baseline concentrations) seen only in the nearfield site. In reality, only about 6,000 m^3 of sediment was released and no impact was seen in the nearfield or farfield.

7.4.3 Tidal Stream – MCT Seagen in Strangford Lough

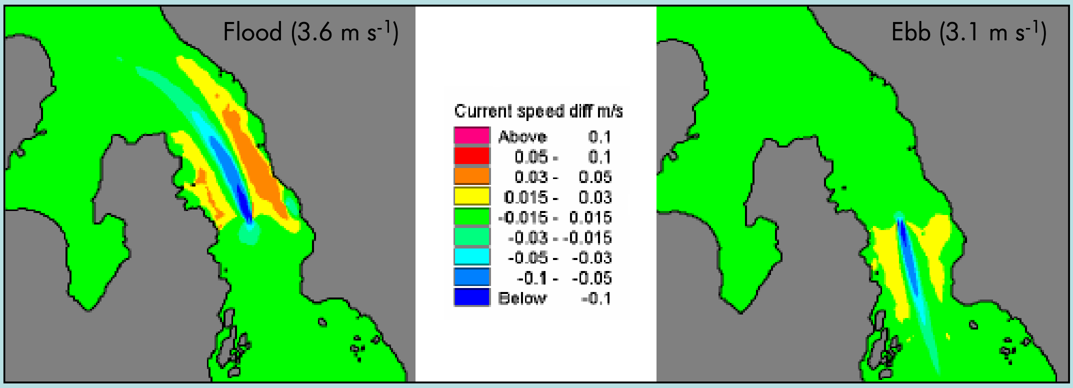
TIDAL: MCT Seagen

Installed in Stranford Lough April 2008

Two years baseline monitoring:
- Flood dominant
- 1.5 to 4 m s-1 (neap & spring flow speeds)
- Coarse sediment/bedrock

- EIA:
- Localised scour with little influence of coastal processes
- Drill residue distributed thinly over most of Strangford narrows (< 0.01 mm).
- Most deposition onto sand banks either side of narrows.
- Total energy extracted: 0.56%
- Flow speed reduced up to 600 m away from turbine.
- No farfield effects/impacts predicted.

Wake effects:
- Longer wake durign flood (3.6 m s-1)
- Current speed increases eitherside of turbine
- Velocity difference of 0.1 m s-1 within 200 m of turbine (between baseline & operational)



www.seageneration.co.uk/downloads/recent/EIA/Appendix%2012%20-%20KMM%20MIKE21%20Hydraulic%20Model%20Report.pdf

7.4.4 Wave – Pelarmis & Stingray

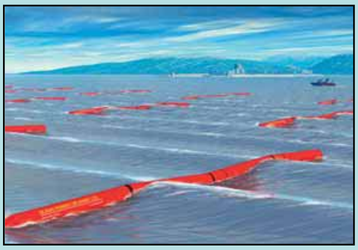
WAVE: Pelamis Wave

Level of energy removal of a wave energy converter is a function of:
- Scale of energy intercepted
- Relative position of device in water column
- Local environment (restricted channel/open water)
- Single device//farm

- Pelamis are floating, deep water converters (> 50m).
- World's first commercial scale machine/farms.
- Extracts energy through hydrostatic forces in smaller waves, avoiding hydrodynamic forces.
- Impact of using seven Pelamis devices at Wavehub produces little impact at the surf zone (see table).
- Average wave height reduction would be ~0.7 cm reduction in wave height in the surf zone.
- Wave heights: Pelamis presentation

	Wave Period (s)						
Wave Height (m)	7	8	9	10	11	12	14
1	0.46%	0.45%	0.35%	0.26%	0.18%	0.11%	0.06%
2	0.44%	0.41%	0.33%	0.23%	0.18%	0.12%	0.07%
3	0.41%	0.36%	0.29%	0.22%	0.16%	0.12%	0.07%
4	0.41%	0.32%	0.25%	0.20%	0.15%	0.11%	0.07%
5		0.24%	0.21%	0.17%	0.12%	0.09%	0.06%
6			0.15%	0.14%	0.12%	0.09%	0.06%

Table shows percentage loss of wave height



A 30 MW wave farm would consist of 40 machines interconnected with 1 km^2

Few data available on impact of device on coastal processes, except for what can be implied from changes in wave heights.Risk identified in EIA and mitigated by design (absorbs minimal energy in storm waves when peak sediment transport occurs).

Mooring spreads have been designed to have aminimal footprint (3 m^2), with local disturbance of sediment when mooring is removed durign decommissioning.

www.pelamiswave.com
Further data provided by A. Scott (Pelamis)

WAVE: Stingray

The Engineering Business tested Stingray in the Shetlands between July and September 2003

Post decommisioning environmental surveys:
- Virtually identical data to original seabed surveys
- Seabed scar visible (62 m) thought to be construction barge anchor related

www.engb.com/downloads/Stingray%20 Phase%203r.pdf

7.5 Appendix 5 - Recent/Current Relevant Research Projects

A range of recent and current research projects are aimed at developing the knowledge needed to understand and ultimately predict the behaviour of coastal hydrodynamics and sediments. These are summarised below and provide an overview of UK academic and research centre capability.

Tapping the Tidal Power Potential of the Eastern Irish Sea
(Joule Centre Project JIRP106/03)
U. Liverpool (Richard Burrows) & Proudman Oceanographic Lab (Judith Wolf)
The Joule Centre, supported by the North West Regional Development Agency has funded a range of projects related primarily to developing renewable energy technologies, but this project includes a substantial component related to assessing the impacts of tidal energy schemes in the North West of England.
Principal study objectives:

- To evaluate the tidal energy potential of the coasts of the North West of England – by the installation of estuary barrages, tidal
- fence structures or tidal stream rotor arrays.
- To establish the potential daily generation window from optimal conjunctive operation taking account of the different possible modes of operation. – ebb, flood or two-way [dual mode] generation in the case of barrages.
- To evaluate any impact of this energy extraction on the overall tidal dynamics of the Irish Sea.
- To assess any implications to biophysical coupling in the external marine ecosystem – manifesting water quality or ecological consequences.
- To ascertain the flood protection benefit from proactive operation of barrages. – fully accounting for the worsening effects of sea level rise (SLR) and climate change.

Oceans 2025: Theme 3, work packages 3.3, 3.4, 3.5
Coastal Morphodynamics and Bathymetric Evolution &
Bottom Boundary, Optics and Suspended Sediment (BoBOSS)
Proudman Oceanographic Laboratory
www.pol.ac.uk/home/research/theme3/
A study aimed at using a combination of modelling and monitoring to develop an understanding of bathymetric evolution in dynamic coastal areas. Field sites include the Dee Estuary and Sea Palling in East Anglia. Marine radar remote observation techniques have been developed under this project with the intention of generating long time series of wave, current and bathymetry maps. These data will help identify the relative contributions of the driving forces to coastal evolution and sand bank migration, and will provide validation data for modelling studies aimed at hindcasting the observed behaviour and ultimately predicting future scenarios.
Specific applications of this work could include high resolution monitoring of the spatial changes introduced into wave and current fields around wave and current devices, together with the ability to monitor shallow (<20m) bathymetry remotely and over long time scales. Capital outlay for such a commercially made system would be of the order of £100k, and staff effort would need to be made available to support the radar (minimal once it is installed) and work with the data.

Oceans 2025: Theme 9, Modelling

www.pol.ac.uk/home/research/theme9/

Theme 9 will deliver the state-of-the-art models needed for the next decade of UK marine science.

The work at POL for theme 9 focuses on the development, integration and analysis of shelf sea modelling systems. We are primarily involved in the physics (hydrodynamics, waves and turbulence) but also working with coupled ecosystem and sediment models.

POL has been developing numerical models of shelf-seas for over three decades. Early work focused on the development of 2D models for storm surge predication (Flather and Davies, 1977) and simple models of the dynamics of shelf sea fronts (James, 1986). This baroclinic B-grid model (POL3DB) has been developed into a fully three-dimensional s- coordinate model, which can utilise realistic forcing from atmospheric and deep ocean models. This forms the basis for the POLCOMS modelling system: the primary shelf sea model for operational and research use in the UK today.

The aims of Theme 9 at POL are:

- To identify, quantify and reduce uncertainties in coastal-ocean modelling systems through the inter- comparison of a range of models, model data-synthesis and data assimilation techniques.
- To develop the unstructured and structured grid shelf sea modelling capability available to ourselves and the stakeholders.
- To conduct and validate key model experiments in conjunction with other Themes.

Irish Sea Coastal Observatory

Proudman Oceanographic Laboratory

cobs.pol.ac.uk

Research objectives

- To understand, through effective continuous measurement and modelling, a coastal sea's response to natural and anthropogenic forcing and demonstrate the value of an integrated approach to marine environmental management.
- Underpinning science for Ecosystem based approach to marine management Integrated coastal zone management
- Data include a WERA HF radar that has been operating since August 2005 and may have potential to determine whether there are any cumulative effects of wind turbine arrays and arrays of arrays on currents and waves, and indeed the applicability of using HF radar for investigating such effects – a potentially important question since both Wavehub and EMEC are investing in such technology.

Specific relevance includes a long time series of hydrodynamic measurements that extend before and after the installation of the Rhyl Flats wind farm. (North Hoyle was already in place when radar measurements started, Burbo is outside the field of view). The planned Gwyn-Ty-Mor wind farm will be a much larger offshore array but will also be within the field of view of the radar so a substantial pre-installation dataset exists to study any discernable impacts on waves and currents. A NERC funded PhD is nearing completion at Sheffield University studying the impacts of wind farms on radar measurements, but no work is currently planned to investigate the impact of the wind farms on the environment using this data. Funding to support a researcher would have to be made available for such a study to proceed.

Wave Hub Impact on Seabed and Shoreline Processes (WHISSP) & Dynamic Response to Energy Extraction and Mixing (DREEM)

Peninsula Research Institute in Marine Renewable Energy (PRIMaRE)
Plymouth University and Exeter University.
www.primare.org
These projects aim to study the physical processes influenced by the installation of wave energy devices. These studies will aim to meet the immediate needs of the emerging marine renewable energy sector in the Peninsula and to address the wider considerations for renewable energy globally. Pump-priming funds over a period of three years have been provided by the South West RDA, this includes £1.4 million revenue to invest in staff and £6 million capital to invest in research infrastructure and equipment. The capital includes the 2 year lease of a WERA HF radar capable of mapping surface currents and wave spectra to ranges of 50-100km, which if continued through to wave device deployment would be capable of observing any changes in wave and current climate caused by the Wavehub. However, the funding will not take these projects beyond the baseline study and further funding will be needed to take them through to installation of the Wave Hub (approx 2010) and installation of the devices (approx 2011).

SUPERGEN 2

Universities of Edinburgh, Heriot Watt, Queens (Belfast), Strathclyde, Lancaster
www.supergen-marine.org.uk
EPSRC funded work aimed primarily at developing the knowledge base needed to assist renewable energy device development. Also includes some aspects of research into the effects of renewable energy devices on the environment:

WS3: Combined wave and tidal effects

Experience with devices at sea has now confirmed the need to be able to predict and mitigate the effects of tidal currents on wave devices and waves on tidal current devices. This work stream aims to develop an understanding of the effects of waves on tidal currents and energy conversion devices and the effect of tidal currents on waves and wave devices and how to formulate an integrated design methodology that mitigates counter productive effects. The identification of design practices necessary for mixed environments will considerably extend the exploitation of resources.

WS4: Arrays, wakes and near field effects

This work stream will explore how array interaction affects the design optimisation and performance of both multiple tidal current and wave energy converters and will enable more accurate quantification of the environmental consequences of large scale energy extraction. It will generate an enhanced understanding of how the presence of multiple wave or tidal current energy extraction systems will result in localised perturbations to the energy and momentum fluxes.

Manchester Bobber

University of Manchester (Peter Stansby)
www.manchesterbobber.com
Development of a wave energy device, together with a variety of experimental and modelling research into the impacts of such devices and arrays of devices.

UK Climate Impacts Programme (UKCIP)

http://www.ukcip.org.uk/index.php?option=com_content&task=view&id=163.

The UK Climate Impacts Programme (UKCIP) aims to help organisations to adapt to inevitable climate change. Since 1997 it has been drawing together the latest information on the future scenarios for future climate in the UK, based on state of the art scientific research. DEFRA will launch the next package of climate change projections for the UK, to be called UKCP09, probably in June 2009.

The Met Office/Hadley Centre has done the climate modelling and are responsible for writing the science reports. POL has had input into chapters on surges, waves and circulation modelling. Judith Wolf and James Leake wrote the chapter on wave projections based on work done for the Tyndall Centre Coastal Simulator project (Leake et al., 2008). Another paper is in preparation.

The results for projected changes in wave climate show a slight redistribution of wave energy with a reduction in wave height to the north of Scotland and an increase to the SW of UK which seems to be related to a southerly movement of storm tracks but there is a large amount of natural variability and hence uncertainty in the projections. Projected changes for the tidal regime around the UK sue to increased sea level are relatively small (Flather et al., 2001).

Mersey Tidal Power Study 2007

www.merseytidalpower.co.uk

A project looking at a range of options for generating power from the large tidal range present in the Mersey. This study includes aspects assessing the impacts and benefits of the possible schemes.

Key conservation areas in the region include the Mersey Estuary Special Protection Area (SPA)/Ramsar site; the North Wirral Foreshore, Mersey Narrows and Liverpool Bay proposed SPAs;and the Mersey Estuary, New Ferry, Wirral Foreshore and Mersey Narrows Sites of Special Scientific Interest (SSSI). Birds, intertidal invertebrates, fish, and marine mammals were also considered in the assessment. Potential impacts on the physical environment, including impacts on exposure of mudflats from changes in tidal heights, on water quality and on sediment quality and movements have been identified. All options have the potential for protection as well as ecological enhancement.

Field observation and modelling of the sediment triad (FORMOST)

www.pol.ac.uk/home/research/formost/

The NERC FORMOST project is a collaborative venture between Proudman Oceanographic Laboratory and Bangor University.

It brings together modellers and process scientists, with the aim of exploiting recent advances in observational capabilities to validate key local modelling concepts. The improved models will be parameterised to provide robust process-scale formulations for use within larger coastal area modelling systems.

Sediment transport can be thought of as arising from three interacting components, namely the mobile sediment itself, the bedforms and the forcing hydrodynamics. For example, vortex generation due to flow over ripples on the sea-bed can have a significant influence on the suspension of sediment. Further, the shape of the ripples contributes to the overall flow resistance, and hence to the flow structure in the boundary layer. Yet the ripples themselves are a product of the local sediment transport. This triad of interactions and feedbacks has to be measured simultaneously, both temporally and spatially, in order to understand the fundamental processes of sediment transport. The objectives of the project are:

- To address gaps in process knowledge that inhibit the development of reliable coastal area sand transport models (for example the effect of local variations in the mobile bed roughness).

- To validate local modelling concepts using existing and new large-scale laboratory and field data obtained using the new rig STABLE III (Sediment Transport And Boundary Layer Equipment).
- To critically assess, based on the of field data from Sea Palling (EPSRC funded LEACOAST2) and the outer Dee, the extent to which our sand transport predictive capabilities remain valid in a mixed sediment environment.
- To parameterise, over a wide range of coastal conditions (i.e. a seabed comprising sand or mixed sediments, in combined wave and tidal conditions), the results of a local transport model.
- To implement parameterised model within POLCOMS and TELEMAC, delivering a robust code for use in other area models. These models will be used to compute the annual sediment budgets in the outer Dee Estuary.

Impacts of Near-shore Sandbank Mobility on Beaches (Blinks)
University of East Anglia & CEFAS
Chris Vincent(UEA) & Jon Rees(CEFAS)
www.uea.ac.uk/env/blinks/
Blinks (Beach LINKs to Sandbanks) is the short title for the NERC funded project titled Impacts of Near-shore Sandbank Mobility on Beaches. The overall aim of the project is to improve our understanding of the linkages between beach condition (e.g., beach width) and the position and shape of nearshore sandbanks. Links between beaches and sandbanks have been qualitatively observed in the past, but an understanding of the response times, spatial scales and mechanisms that link the two, is lacking. Existing datasets are from studies of beaches OR sandbanks, but as yet not from both. Consequently there is not a good temporal match in the combined beach/bank records. Simultaneous measurements of sandbanks and adjacent beach condition, combined with numerical modelling are required.
Field measurements of the width, volume, shape and position of both beaches and sandbanks will be made from photographs collected by High Speed Digital Cameras (HSDCs) positioned on the roof of the CEFAS laboratory at the Pakefield Cliffs. The HSDC's are the photographic component of the Camera coastal monitoring system which was developed at the National Institute of Water and Atmospheric Research (NIWA) in New Zealand. NIWA are a research partner in the Blinks project.
Cam-era data are supplemented by monthly RTK-GPS beach surveys of the entire 6-km frontage between Claremont Pier and Benacre Ness. Bathymetric surveys of Newcombe Sands are also intended. Wave/tide measurements are being made at South Beach and will be supplemented by water level data from the Port of Lowestoft tide gauge and wave data from the West Gabbard wave buoy
This project has now completed and a follow-up proposal including the use of marine radar to monitor a ness, sandbank and the region between them (Nesslink) was turned down for funding by NERC in 2007.

Coastal Flooding by Extreme Events (CoFEE)

Universities of Plymouth, Liverpool, Edge Hill, Sefton Council, POL, BODC

www.geog.plymouth.ac.uk/cofee/index.html

The broad project aim is to improve our understanding of how the coast will respond to changes in climate, sea-level, storm and wave frequency in the future such that we can make informed decisions as to how to manage the consequences of these changes. The key elements that are being focussed upon are changes in coastal flood risk and changes in shorelines, beach profiles and coastal habitats. The detailed outputs of the project will be defined in collaboration with the end-users of this information. The project will use the Sefton Coast as a case study but the outputs will include the presentation of results in a generic format so that the knowledge gained can be applied elsewhere.

Morphological Impacts and Coastal Risks Induced By Extreme Storm Events (MICORE)

University of Ferrara, Italy; ARPA-SIM, Italy; Geological, Seismic and Soil Survey, Italy (SGSS); University of Algarve, CIACOMAR-CIMA, Portugal; University of Lisbon; University of Cadiz; BRGM-French Geological Survey; International Marine Dredging Consultants, Belgium (IMDC); University of Plymouth; University of Szczecin INoM, Poland; Institute of Oceanology, Bulgaria; Stichting Deltares, The Netherlands; Technical University of Delft; The Netherlands; POL; University Pablo de Olavide, Spain; Consorzio Ferrara Ricerche, Italy.

www.micore.eu

Both the EU and The United Nations are now taking seriously the predicted climate change scenarios of the IPCC. Of particular relevance to Integrated Coastal Zone Management is the predicted increase in the intensity and frequency of powerful storm events characterised by larger peak wind speeds and consequently larger waves.

The MICORE project will provide the knowledge necessary to assess the present day risks and to study the economic and social impact of future severe storm events. The project will also develop operational predictive tools in support of emergency response to storm events. Together, these elements will have an important strategic impact on the safety of the people living in coastal areas. The project will also investigate with stakeholders and end-users the possibilities of producing EU-wide guidelines for a viable and reliable risk mitigation strategy.

MICORE will produce an up-to-date data base for each partner country that will include: an historical review of storms; an inventory of data related to the forcing signals; quantification of the morphological response of coastal systems to storms and to sequences of storms; an assessment of socio-economic impact; a description of existing civil protection schemes and interventions.

BGS Marine Geoscience Programme

www.bgs.ac.uk/research/marineAndCoastal.html

The marine geoscience theme provides an integrated geological research programme to meet the challenges of the marine environment across the entire United Kingdom designated area. Current research focuses on

- detailed seabed mapping
- reconnaissance surveys
- basin analysis on the Atlantic Margin

7.6 Appendix 6 – Detailed Review of Sediment Transport Modelling Practice

7.6 Appendix 6 Detailed Review of Sediment Transport Modelling Practice

The use of appropriate models has been one approach employed to study the impact of marine renewable energy devices on sediment dynamics. Once again it is important to highlight the importance of the different scales involved as a preamble. Near field and far field impact studies will usually not rely on the same models. So called CFD models are targeted on the near field impact and may resolve the structures. For example, *Whitehouse et al.* (2005) presented modelling results for flow interaction with foundation stuctures using the ANSYS CFX system. In contrast, far field impacts are modelled using so-called regional models that operate at a larger scale and may not resolve the structures.

In spite of such difference between the models used for the near field and for the far field, both approaches do not resolve the small scale, near-bed phenomena crucial to sediment transport (e.g., wave current boundary layer, ripples). Instead, these processes have to be parameterised in some manner. We first review in this appendix the different approaches commonly used to that end in (often both) CFD and regional models. A crucial aspect is the focus on the approaches presently implemented, and biological effects on sediment dynamics in general have not yet been commonly implemented in either CFD or regional models, which is a significant shortcoming. We then review in more details several specific regional models, and specify some that have already been used in modelling studies on the impact of marine renewable energy devices on the sediment dynamics. Finally, we summarize the key shortcomings remaining in the current state-of-the-art sediment modelling.

7.6.1 Modelling sediment transport processes in regional ocean models

7.6.1.1 Governing equations of large scale sediment transport and morphological change.

Two major issues in coastal sediment transport models are to calculate suspended sediment concentration and to be able to track morphological changes, both of which are based on sediment mass balances. In the fluid flow, sediment mass conservation leads to a governing equation for the sediment concentration c, which typically reduces to an advection-diffusion equation of the following type:

$$\frac{Dc}{Dt} = \frac{\partial W_s c}{\partial z} + \nabla.\left(K_c \nabla c\right) + S_c \tag{7.1}$$

where D/Dt is the material derivative and thus includes the convective terms. W_s is the settling velocity of sediment and z the vertical coordinate. The diffusion term commonly uses the gradient diffusion hypothesis and K_c is the sediment turbulent diffusivity. Finally, S_c is a possible source/sink term. Appropriate boundary conditions and expressions for the settling velocity and sediment diffusivity are needed to solve this equation and are thus crucial issues in suspended sediment transport modelling.

The sediment mass balance between the bed and the flow results in a governing equation for the bed location which is often referred to as the Exner equation. A general form can be mathematically derived by considering the sediment balance in an arbitrary layer (*Paola and Voller*, 2005) but simplified formulations are usually employed in coastal models. The mass balance of sediment applied to the entire water column results in the following formulation (e.g., *Zhang et al.*, 1999; *Wu et al.*, 2000; *Harris and Wiberg*, 2001)

$$\frac{\partial}{\partial t} \int_{\eta_b}^{MWL} \rho_s c dz + \rho_s c_b \frac{\partial \eta_b}{\partial t} + \nabla_H \cdot \vec{Q} = 0 \tag{7.2}$$

where ρ_s is the sediment dry density, η_b the location of the sediment bed and c_b the bed concentration. Q is the total sediment transport rate and MWL stands for the mean water level. The operator ∇_H is the two-dimensional, horizontal gradient. Another approach considers the balance of sediment mass applied to a near-bed layer

$$\rho_s(1 - p_c)\frac{\partial \eta_b}{\partial t} + \nabla_H \cdot \vec{Q}_B + E - D = 0 \tag{7.3}$$

where E is the sediment erosion flux, D the deposition flux, $\vec{Q}_B$ the bed load transport rate vector and p_c the bed porosity (e.g., *Gessler et al.*, 1999).

The two governing equations (7.1 and 7.2 or 7.1 and 7.3) are coupled rather obviously in the first case. In the second case, the coupling occurs through the sum of the erosion and deposition fluxes, which are explicitly present in equation 7.3 and which will appear in the advection-diffusion equation either as a bottom boundary condition or as a source/sink term for the bottommost grids.

Boundary conditions

Appropriate boundary conditions are necessary for the lateral, top and bottom boundaries to solve the suspended sediment problem (equation 7.1). Lateral boundary conditions are commonly split between closed boundaries, for which a free-slip or no flux condition is used, and open boundaries, for which several options such as water level, normal velocity, discharge exist. Large-scale coastal models commonly do not resolve the surf and swash zones, which have been discussed in *Elfrink and Baldock* (2002), *Brocchini* (2006) and *Brocchini and Baldock* (2008). The shoreline boundary is thus usually taken to be of the closed type (e.g., *Lesser et al.*, 2004; *Blaas et al.*, 2007). At the top boundary (free surface), a flux condition is commonly used and is implemented in mainly two ways: either the total sediment flux (e.g., *Zhang et al.*, 1999; *Harris and Wiberg*, 2001), or only the vertical diffusive flux (e.g., *Lesser et al.*, 2000), is set to vanish. At the bottom boundary, the condition can either specify the concentration value or the sediment vertical flux.

The concentration boundary condition, also called reference concentration, usually provides a formula for the concentration at some reference level, i.e. C_{ref} at z_{ref}, where both C_{ref} and z_{ref} are functions of flow and sediment parameters such as the Shields parameter(non dimensional bed shear stress), the sediment specific gravity and the sediment diameter. An issue with this approach is that the bottom grid location may not coincide with the reference level, and the concentration at the bottom grid location then needs to be extrapolated from the reference concentration, usually by means of a Rouse profile, (*Lesser et al.*, 2000). Many reference concentration relationships have been introduced, eight of which were assessed in *Garcia and Parker* (1991), and the most commonly used formulae in large scale models remain that of *Smith and McLean* (1977) and that of *van Rijn* (1984c). An important difference between these two relationships is the absence of maximum concentration in the later. It has since become popular to enforce an upper limit on the reference concentration values for large Shields parameters, that is less than the maximum possible concentration ($c = 0.65$) (e.g., *Garcia and Parker*, 1991; *Zyserman and Fredsoe*, 1994; *van Rijn*, 2007).

Flux boundary conditions aim to provide some kind of information on the vertical sediment flux at the bottom boundary. Either the net sediment flux at the bottom boundary is specified directly (e.g., *Harris and Wiberg*, 2001; *Wai et al.*, 2004), or erosion and deposition act as source and sink in the advection-diffusion equation and diffusive (and advective) flux of sediment are set to zero at the bottom boundary (e.g., *Lesser et al.*, 2000; *Warner et al.*, 2008). Whichever method is used, both erosion and deposition need to be expressed in terms of flow and sediment parameters and will be discussed in more details in a following section.

Sediment diffusivity

Sediment diffusivity specifications are typically split between horizontal diffusion K_h and vertical diffusion K_v. Horizontal diffusion is commonly either neglected or taken to be constant. In contrast, a more advanced closure is used for the vertical diffusivity which is closely linked to the flow turbulence closure. K_v is related to the eddy viscosity ν_t through a Schmidt/Prandtl number σ_s

$$K_v = \frac{\nu_t}{\sigma_s} \tag{7.4}$$

Since the turbulent diffusivity is usually larger than the eddy viscosity because of centrifugal forces in turbulent eddies ejecting particles to the outside of the eddies, Schmidt numbers are typically less than 1. Relatively few studies have investigated flow and sediment dependent Schmidt numbers, and many models use a constant value.

Still, *van Rijn* (1984c) related the sediment turbulent diffusivity to the turbulent eddy viscosity through two parameters. The first, called β, is a function of the settling velocity and the friction velocity and as such can be seen as expressing the relative importance of the particles' gravitational inertia respect to the flow turbulence. The other is a function of the concentration and represents the effect that the presence of particles has on the sediment diffusivity. More recently, *Rose and Thorne* (2001) only considered the β parameter and introduced a different formula relating it to the velocity ratio. *Amoudry et al.* (2005) simply considered a concentration dependence for suspended sediment in sheet flows and provided an expression by an empirical fit of the numerical results to laboratory experimental data. *Thorne et al.* (2009) obtained vertical profiles of the sediment diffusivity for two different sands from flume experimental data.

Settling velocity

The sediment settling velocity, W_s, is an important parameter both in the determination of the suspended concentration profile and in the near bed conditions and depends naturally on the sediment and flow parameters. Some common approaches in coastal area models are to set it either as a user-specified, sediment specific parameter, or to employ formulae relating either the drag coefficient or W_s directly to sediment and flow parameters. It has also been observed that the settling of sediment depends on the local concentration. Such relationship is traditionally taken to follow the experimental results of *Richardson and Zaki* (1954) for non-cohesive sediments and *Mehta* (1986) for cohesive sediments. The *Mehta* (1986) expressions only relate the settling velocity of cohesive sediments to the suspended sediment concentration and thus do not really account for the influence of flocculation on W_s. Following recent work on turbulence-induced flocculation, *Winterwerp* (2002) introduced a formula expressing hindered settling of suspended cohesive sediments as a function of both the suspended sediment concentration and the concentration of flocs and *Winterwerp et al.* (2006) expressed the settling velocity as function of the suspended sediment concentration and the local shear stress.

7.6.1.2 Erosion and deposition of suspended sediment

The net bottom boundary sediment flux is commonly divided in an upward part (erosion E) that represents the exchange of sediment from the bed to the flow and a downward part due to gravitational settling (deposition, D). Several methods have been used to express erosion in terms of flow and sediment parameters and the two most common approaches have also been closely linked to the sediment cohesiveness. For non cohesive sediment, the most widely used method has been to assume that the disequilibrium introduced by the unsteadiness remains mild, and to consider the erosion flux to be equal to the entrainment rate under equilibrium condition (*Garcia and Parker*, 1991) and thus to relate it to the reference concentration value through the settling velocity, i.e. $E = c_{ref}W_s$ (e.g., *Harris and Wiberg*, 2001; *Wai et al.*, 2004; *Lesser et al.*, 2004). To ensure that the net vertical flux is not constantly zero the deposition is then calculated using the non-equilibrium concentration $D = c_bW_s$, where c_b is the actual bottom concentration. For cohesive sediments, the approach of choice has been to provide a formula relating directly the erosion flux to the flow and sediment parameters (*Hydroqual*, 2002; *Lumborg and Windelin*, 2003). This second approach has also recently been extended to study non cohesive sediment (*Warner et al.*, 2008).

Such a direct parametrization has been one of the most studied issue in fine sediment transport and theoretical, laboratory studies and field observations have been used to investigate the erosion rate. The general consensus is that bottom shear stresses are the dominant forces causing erosion while the sediment bed characteristics control the resistance to erosion. Mathematically, two formulations (a power law and an exponential law) have been introduced to relate the erosion to the bed shear stress τ_b. Usually, the excess shear stress $(\tau_b - \tau_{ce})$ is employed, where τ_{ce} represents the critical stress for erosion which is not necessarily equal to the critical stress for initiation of motion, first calculated by *Shields* (1936). The power law is often reduced to a linear expression (e.g., *Ariathurai and Krone*, 1976; *Mehta et al.*, 1989; *Sanford and Halka*, 1993; *Mei et al.*, 1997) and has been used for unlimited erosion. The exponential form has instead mostly been used for depth-limited erosion with $\tau_{ce} = \tau_{ce}(z)$. However, *Sanford and Maa* (2001) recently showed that a linear erosion formula may be used to represent both depth-limited and unlimited erosion, provided that both the critical bottom shear stress and the constant of proportionality increase with depth

$$E = E_0(z)\left(\frac{\tau_b}{\tau_{ce}(z)} - 1\right) \tag{7.5}$$

Such dependences, for the critical erosion stress in particular, are an important singularity of cohesive sediments respect to non-cohesive sediments and are often one conceptual limitation in models.

For fine particles, deposition has commonly followed the parametrization of *Krone* (1962) which enforces that no deposition occurs for bed shear stresses higher than a critical shear stress for deposition τ_{cd}. Since τ_{ce} is typically taken to be greater than τ_{cd}, this implies that erosion and deposition are mutually exclusive and defines three states (e.g., *Li and Amos*, 2001) depending on the value of the bottom shear stress: (i) when $\tau_b < \tau_{cd}$, there is no erosion and only deposition, which is the depositional state; (ii) when $\tau_{cd} < \tau_b < \tau_{ce}$, there is neither erosion nor deposition, which is a stable state; (iii) when $\tau_{ce} < \tau_b$, there is no deposition and only erosion, which is the erosional state. As mentioned previously, no critical stress for deposition has usually been used for non-cohesive sediment, and erosion and deposition are not mutually exclusive. This discontinuous representation of the deposition for fine particles has since been challenged. *Sanford and Halka* (1993) observed a decrease of the suspended sediment concentration in phase with the deceleration of the flow, which can not be modelled with the *Krone* (1962) formula since it would predict a continuous increase of the suspended sediment concentration until the bed shear stress decreases below its critical value for deposition. Instead, they were able to reproduce the observed concentrations by taking a continuous deposition. Additionally, *Winterwerp and van Kesteren* (2004) argue that mutually exclusive deposition and erosion is not supported by a sound explanation of the physical processes involved, and also assume that the deposition is continuous, thus allowing simultaneous erosion and deposition.

7.6.1.3 Bed load sediment transport

Bed load is the part of sediment transport that is due to interparticle interactions and which occurs in a thin near-bed region of high sediment concentration. As such, it can typically not be resolved by coastal multidimensional models for which sediment is implicitly assumed to be dilute, and it is instead described by relating the bed load transport rate to the bottom shear stress. Such relationships have now been investigated both empirically and theoretically for several decades and a number of different formulations exist. The bed load transport rate has been measured directly in many experimental studies using bed load traps, leading to empirical formulae for steady uniform flow (e.g., *Meyer-Peter and Mueller*, 1948; *Wilson*, 1966) and more recently for wave-current flows (e.g., *Ribberink*, 1998). Most of these formulae relate the transport rate to a power of the excess bed shear stress (stress in excess of the critical stress for initiation of motion)

$$\Phi_B = m\theta^n(\theta - \theta_{cr})^p \tag{7.6}$$

where m, n, and p are constants such that $n + p \approx 1.5$ and θ_{cr} is the critical Shields parameter for initiation of motion. Recently, *Soulsby and Damgaard* (2005) provided relationships for the net bedload transport in wave-current combinations by numerical integration of a power law for the time-dependent transport rate and expressed the results in terms of the bed shear stress amplitude, mean and asymmetry.

Several studies also proceeded to provide theoretical and semi-empirical relationships for the bed load transport rate. *Einstein* (1950) used a statistical description of the near-bed sediment motions and related the bed load transport rate to the probability of a particle being eroded from the bed, itself related to the flow intensity. *Bagnold* (1966) introduced equations giving the bed load, suspended load and total load transport rates as functions of the stream power for steady flows using considerations of energy balance and mechanical equilibrium. An extension of this approach was pursued later by *Bailard* (1981) for unsteady flows and gave the transport rates as functions of powers of the time-dependent free stream velocity. *Engelund and Fredsøe* (1976) assumed that bed load corresponds to the "transport of a certain fraction of the particles in a single layer", and obtained a semi-empirical law by considering the motion of individual particles and the most important forces of relevance. *van Rijn* (1984a) computationally solved equations of motion of individual saltating particles and calculated saltation characteristics, then used these results to deduce a semi-empirical bed load transport rate formula.

7.6.1.4 Bottom boundary layer

The vertical resolution of regional scale models is not sufficient to resolve the fluid flow gradients and algorithms that parametrize the bottom boundary layer processes are thus required. For sediment transport, which strongly depends on the computation of the bottom shear stress, an appropriate bottom boundary layer modelisation is crucial. In coastal models, the wave oscillations are usually not resolved and the boundary layer model thus aims at providing some information on the bed shear stress τ_b without fully considering the intrawave result.

Current boundary layer

The bottom shear stress in the case of a pure current is commonly calculated using simple drag coefficient expressions that in turn rely on linear bottom drag, quadratic bottom drag, or a logarithmic velocity profile. The linear and quadratic drag-coefficient approaches relate the bottom shear stress to the near-bed velocity (usually the velocity in the bottom grid) via a a drag coefficient that has the dimensions of a velocity for the linear approach and that is non-dimensional for the quadratic case. The logarithmic approach assumes that the flow velocity follows the classic rough wall log-law vertical profile close to the bed, for which the velocity at a given elevation is given by

$$u(z) = \frac{u_\star}{\kappa} \ln\left(\frac{z}{K_s}\right) \tag{7.7}$$

where $u_\star = \sqrt{\tau_b/\rho_f}$ is the friction velocity, K_s is the bed roughness and κ the von Karman constant. This approach can also be rewritten in a quadratic form. An important advantage of the log-law approach respect to the other methods lies in its elevation dependence: because of morphological changes the elevation of the bottom numerical grid may change, thus impacting the bed shear stress calculations. An appropriate value for

κ has to be specified, and the clear fluid value of 0.41 is usually implemented, even though it has been observed that this value should be lowered in presence of sediments (see for example *Vanoni* (1975)) and values as low as 0.3 have been reported both from experiments (e.g., *Vanoni*, 1975; *Bennett et al.*, 1998) and numerical results (e.g., *Longo*, 2005; *Amoudry et al.*, 2008). The specification of the roughness will be discussed in more details in a following section.

Wave and wave-current boundary layer

Most of the bottom boundary layer models use the concept of a friction factor f_w to describe the wave bottom shear stress through a quadratic friction law, both for pure wave and wave-current cases:

$$\tau_{bw} = \frac{1}{2}\rho_f f_w u_b^2 \tag{7.8}$$

where u_b is the wave orbital velocity and τ_{bw} is the maximum wave bed shear stress. The wave friction factor f_w usually depends on the wave Reynolds number $A^2\omega/\nu$ with A the wave orbital amplitude and on the relative bed roughness (A/K_s) (*Jonsson*, 1966). Many different expressions have been introduced both explicit (e.g., *Swart*, 1974; *Kamphuis*, 1975; *Nielsen*, 1992; *Madsen*, 1994) and implicit (e.g., *Jonsson*, 1966; *Grant and Madsen*, 1979, 1986; *Styles and Glenn*, 2000). In the case of wave-current interactions, both the mean and the maximum combined bed shear stresses need to be determined. A common approach has been to consider the mean current to follow a rough wall log-law for which the roughness is enhanced by the presence of the wave boundary layer (e.g., *Grant and Madsen*, 1979; *Fredsøe*, 1984; *Madsen*, 1994). The enhanced roughness is in turn a function of the maximum combined shear stress and of the mean shear stress, which results in the need of iterative solutions to fully determine both the mean and maximum bed shear stresses. An issue for morphological coastal area models is then the computational cost of the wave current bed shear stress calculations and *Soulsby* (1995) and *Soulsby and Clarke* (2005) provided more efficient algorithms by using explicit formulas for both the friction factor and the wave-current stresses.

Another approach to the parametrization of the wave-current interactions has been provided by *Mellor* (2002) and is based on the approximating the results of an intra-wave model that uses a two-equation turbulence model (*Mellor and Yamada*, 1982) in combination with the law of the wall. The wave effects on the mean flow are then accounted through an increase of the turbulent kinetic energy production by an additional apparent production due to waves that is a function of the orbital wave velocity, the wave period, the angle between the current and wave directions, and the bed roughness.

Bottom roughness

Whether for currents, waves or combinations of the two, the bottom shear stress determination always depends on the the bed roughness, which is commonly associated with the grain roughness, bed load sediment transport and with the presence of ripples. Roughness lengths are generally considered to be additive and the total bed roughness has traditionally been the sum of the three roughnesses just introduced (e.g., *Grant and Madsen*, 1982; *Xu and Wright*, 1995; *Li and Amos*, 2001). Still, *Harris and Wiberg* (2001) argued that the total roughness should only be the larger of the bed load and bed form roughnesses. The grain roughness is taken to be proportional to the sediment grain diameter, and $K_{sg} = 2.5D_{50}$ is commonly used. The bed load roughness is related to the value of the excess Shields parameter and several expressions have been introduced (e.g., *Grant and Madsen*, 1982; *Wiberg and Rubin*, 1989; *Xu and Wright*, 1995; *Li and Amos*, 2001).

The bed form roughness is typically estimated as a function of the geometric characteristics of the bed forms (e.g., *Grant and Madsen*, 1982; *Nielsen*, 1992), which are in turn prescribed empirically using ripple predictors. *Nielsen* (1981) argued that the ripple length depends on the mobility number $\Psi = (a\omega)^2/(s-1)gD_{50}$, while the ripple steepness depends on the Shields parameter. He also introduced different formulae for laboratory and field data. *Wiberg and Harris* (1994) differentiated orbital, suborbital and anorbital ripples based on increasing values of the wave orbital diameter. For anorbital ripples, the ripple length is approximated by a constant and the ripple steepness is function of the ripple height and the diameter of the orbital motions. However, both roughness predictors presented were developed for wave dominated cases and might not be appropriate in all wave-current situations. Based on observations on the Scotian shelf *Li and Amos* (1998) distinguish between five categories: no transport, ripples in weak transport, ripple in equilibrium range, ripples in break-off range and plane bed (sheet flow). These five regimes are defined based on the values of the skin-friction shear velocity ($u_{\star s}$ found by only considering the grain roughness) and of the bed load shear velocity ($u_{\star b}$ found by considering the grain roughness and the bed load roughness). Specific relationships for the ripple height and steepness were then introduced for each regime. In the no transport regime, pre-existing ripples will increase the bed shear stress at the crests, which determines sediment transport, and a ripple-enhanced shear velocity $u_{\star e}$ is calculated. If the enhanced shear stress is still less than the critical shear stress for motion $u_{\star cr}$, the ripple geometry remains unchanged. In the case for which $u_{\star s} < u_{\star cr} < u_{\star e}$, weak localized transport occurs. The equilibrium regime happens for $u_{\star s} > u_{\star cr}$ and $u_{\star b} < u_{\star bf}$ where $u_{\star bf}$ is a break-off criterion.

7.6.1.5 Cohesive sediments

Suspended cohesive sediment concentration is determined by a combination of processes more complicated than those accounted for so far, such as flocculation, consolidation and liquefaction. Flocculation is the formation and break-up of flocs of cohesive sediment and is a key process in differentiating cohesive and non-cohesive sediments. Consolidation and liquefaction are processes by which the bed is either strengthened or weakened. In addition, settling, deposition, the interaction between particles and flow turbulence, erosion and entrainment are typically modelled differently for cohesive and non-cohesive sediments. However, these processes are not specific to cohesive sediments and have been discussed in previous sections. Presently, most cohesive sediment models that do account for processes such as flocculation and consolidation are implemented in one-dimension (e.g., *Winterwerp*, 2002; *Neumeier et al.*, 2008; *Sanford*, 2008). In most multidimensional models, cohesive sediments are modelled in simpler ways and in general, only cohesive specific formulations for settling, deposition and erosion are considered while both flocculation and consolidation are neglected.

In flocculation models, mud flocs are commonly treated as self-similar fractal entities (*Kranenburg*, 1994; *Winterwerp and van Kesteren*, 2004) and fractal theory is employed to derive equations for the floc's properties (size, settling velocity, density). *Winterwerp* (2002) derived balance equations for both the floc size and for the number of mud flocs in the turbulent fluid, which can be viewed as advection diffusion equations with an extra non-linear term due to the aggregation and floc break-up processes (*Winterwerp and van Kesteren*, 2004). However, the main issue for multidimensional models is really how to parametrize the effect of flocculation on the particle size, floc density, floc settling velocity without resolving the flocculation processes per se. For example, *Neumeier et al.* (2008) use a set of equations directly relating the floc length-scale, effective diameter and median settling velocity to the suspended sediment concentration following *Whitehouse et al.* (2000). This issue is similar to that encountered in bedload modelling and the importance of empirical studies should be relatively evident. These usually seek to relate the floc's properties to some parametrization of the turbulent cohesive suspension and common quantities used are the suspended sediment concentration and the shear rate at the smallest turbulence length scale, $G \equiv \sqrt{\varepsilon/\nu}$ which is the inverse of the Kolmogorov time scale (e.g., *Lick et al.*, 1993; *Dyer and Manning*, 1999; *Manning and Dyer*, 1999). The derived empirical expressions usually relate the floc diameter to both the concentration and G, and the floc settling velocity to the floc size. *Winterwerp et al.* (2006) derived from the *Winterwerp* (2002) model semi-empirical expressions for the floc size and settling velocity that are calibrated by field experiments. Unfortunately, such expressions are generally not non-dimensional and involve determination of empirical dimensional constants.

Self-weight consolidation is the consolidation of cohesive sediment deposits under the influence of their own weight. When flocs settle and accumulate on the bed, they are squeezed by the flocs settling on top of them. Pore water is then driven out of the intra-floc and inter-floc spaces. This process can result in large vertical deformations of the bed. Consolidation is commonly described by the Gibson equation (*Gibson et al.*, 1967), which is a one-dimensional equation for the void ratio.

7.6.1.6 Implementation in regional ocean models

The approaches described so far are then usually implemented within systems that combine hydrodynamic models, turbulence models and wave models. The turbulence models are briefly discussed next, and an increasingly popular option seems to be to couple the hydrodynamic model to some external advanced turbulence model, such as the General Ocean Turbulence Model (see www.gotm.net). Similary, waves are often modelled by coupling to an "external" model, such as Simulating Waves in the Nearshore (SWAN, *Booij et al.* (1999)) or WAM (*Komen et al.*, 1994). In the overarching systems, the interconnected hydrodynamics, turbulence and wave models provide the necessary inputs to sediment modelling. The bottom boundary layer methods are then implemented to obtain the bed shear stress. In turn, τ_b is used to calculate the sediment exchange between the bed and the flow (erosion and deposition) and the bed load transport rate. Finally, the suspended sediment and bed module solve the governing equations and may incorporate cohesive processes.

So far, Coastal Ocean Models have used Reynolds Averaged Navier-Stokes (RANS) turbulence models which usually provide some description of the velocity-velocity and velocity-scalar covariances by introducing the eddy viscosity and scalar diffusivities. Diffusivities K_a (including the eddy viscosity which the momentum diffusivity) are in turn calculated from a velocity scale $k^{1/2}$ and a length scale l as

$$K_a = c_\mu^a k^{1/2} l. \tag{7.9}$$

The quantities c_μ^a are typically referred to as the stability functions. Turbulence models in coastal area models can obtain the velocity scale and the length scale either (i) both from algebraic relations corresponding to the level 2 model of *Mellor and Yamada* (1982), or (ii) from a transport equation for the energy (square of the velocity) and an alebraic relation for the length scale, or (iii) from two transport equations such as in the level 2.5 model of *Mellor and Yamada* (1982), the $k-\varepsilon$ model (Rodi, 1987), the $k-\omega$ model (Wilcox, 1993; Umlauf et al., 2003). The stability functions can also be specified either (i) as constants, or (ii) as empirical algebraic functions, or (iii) from simplified forms of Reynolds-stress models (e.g., Canuto et al., 2001). Even though these models all involve some empiricism, they can usually be applied to a wide range of turbulent flow and their accuracy has been studied and compared in several studies (e.g., Umlauf and Burchard, 2003; Warner et al., 2005; Holt and Umlauf, 2008). The main drawback lies in the loss of information from the averaging and is thus inherent to the RANS approach. In contrast, both Direct Numerical Simulation (DNS) and Large-Eddy Simulation (LES) solve equations for time dependent variables for one realization of the turbulent flow. DNS consists in solving the equations of motions, resolving all scales, with appropriate initial and boundary conditions. Where it can be applied, DNS provides an unmatched level of description and accuracy and has been valuable in procuring information on turbulence that is impossible to obtain experimentally. However, the computational cost of DNS increases rapidly with the Reynolds number (Pope, 2000) making geophysical applications prohibitively expensive. In DNS, almost all the cost is due to resolving the dissipation range (Pope, 2000). LES aims to avoid such expensive calculations while maintaining a high level of description. Thus in LES, the dynamics of the larger-scale three-dimensional unsteady turbulent motions are explicitely computed, whereas the small-scale effects are modelled. Compared with RANS models, LES closures will describe more accurately problems where large-scale unsteadiness is significant but are also significantly more expensive. For wall bounded flows, near-wall resolution still remains infeasible due to the computational cost incurred. Instead, near-wall modelling is employed for which the near-wall energy containing scale is not resolved. The effects of the unresolved motions are then usually modelled through the use of boundary conditions similar to those used in RANS models.

7.6.2 Coastal sediment transport numerical models

Numerous models of varying complexity aim to describe sediment processes in coastal regions following the approaches presented in the previous sections. For concern of relevance to studying the far-field impacts of marine renewable energy devices on sediment dynamics, we will only review in details five of the most used area models that (i) use an advection-diffusion equation to calculate the suspended sediment concentration and (ii) track two-dimensional bed changes. Both two-dimensional horizontal (2DH) models, that solve depth-averaged equations, and fully three-dimensional models will satisfy both conditions. We conspicuously exclude two-dimensional vertical (2DV) models based on the approaches already discussed, but that only calculate one-dimensional bathymetric evolutions (e.g., *Rakha et al.*, 1997; *Zhang et al.*, 1999; *Harris and Wiberg*, 2001; *Hsu et al.*, 2006), and as such are not fit for assessing regional sediment transport issues. Other three-dimensional models predict sediment suspension but are also excluded because they lack morphodynamic changes (e.g., *Holt and James*, 1999; *Buchard et al.*, 2004; *Pandoe and Edge*, 2004; *Souza et al.*, 2007). It should however be noted that appropriate approaches are also currently being implemented into POLCOMS, and some basic validation of morphological tracking has been performed (*Amoudry and Souza*, 2009).

The five models discussed hereafter are the community sediment transport model embedded in the Regional Ocean Model System (ROMS) (*Warner et al.*, 2008), the DELFT3D modelling system (*Lesser et al.*, 2004), the ECOMSED model *Hydroqual* (2002), the sediment transport model (SISYPHE) coupled with TELEMAC (*Villaret*, 2004) and the MIKE modelling system (*DHI*, 2006, 2004, 2007b,a). In addition of all computing the suspended sediment concentration and two-dimensional morphology, all these models are coupled to a wave model and obtain the bed shear stress using a method accounting for wave-current interactions. A summary of the characteristics of the models is given in table 7.1 and further details on each model are presented in the following sections. As mentioned previously, some models have already been used to asses the far-field impact of wind farms. Commercial models are usually preferred: ABPMer used MIKE 21 and DELFT3D (D. Lambkin, pers. somm.) while HR Wallingford used TELEMAC (R. Whitehouse, pers.comm.).

Table 7.1: Summary of coastal morphological sediment transport models.

Model	Model type	Mesh [a]	Sediment mixtures	Cohesive sediment	Bed Load	Source [c]
ROMS	3D	FD	Yes	No	Yes	OS, LD
DELFT3D	3D	FD	Yes	Yes	Yes	C
ECOMSED	3D	FD	No	Yes	Yes [b]	OS, LD
TELEMAC	2DH	FE	Yes	Yes	Yes [b]	C
MIKE	3D	FV	No	Yes	Yes [b]	C

[a] FD: Finite Difference, FE: Finite Element, FV: Finite Volume
[b] Not necessarily separated from total load depending on formulation used.
[c] OS: Open-Source, LD: Limited Distribution, C: Commercial

7.6.2.1 ROMS

This three-dimensional model (*Warner et al.*, 2008) implements sediment algorithms for an unlimited number of non-cohesive sediment classes and for the evolution of the bed morphology within the finite-difference coastal circulation model ROMS (*Haidvogel et al.*, 2008). The model also provides two-way coupling between ROMS and the wave model SWAN. Radiation stresses have been added to the momentum equations. Suspended sediment concentration is computed with the same advection-diffusion algorithms as for other tracers, and vertical settling is not constrained by CFL criterion. The sediment bed is represented by a multi-layer structure that allows tracking of layer porosity, mass and thickness. The exchange between the flow region and the bed is prescribed using flux formulations for erosion and deposition between the flow and the top layer of the bed. In particular, the erosion depends linearly on the bed shear stress, and is limited by the amount of sediment in the active layer. Bed load transport is included and can be calculated following the *Meyer-Peter and Mueller* (1948) formula for unidirectional flow or following the *Soulsby and Damgaard* (2005) formulation for combined waves and currents, both of which are modified to account for bed slope effects. Bottom boundary parametrizations range from simple drag coefficient expressions (linear, quadratic, logarithmic profile) to formulations representing waves-currents interactions (e.g., *Madsen*, 1994; *Soulsby*, 1995; *Styles and Glenn*, 2000, 2002).

7.6.2.2 DELFT3D

The sediment module in DELFT3D (*Lesser et al.*, 2000, 2004) implements algorithms for up to five different classes within a three dimensional hydrostatic free surface flow solver. Suspended sediment concentration is obtained from an advection-diffusion equation and exchange between the bed and the flow depends on the sediment type (mud or sand). For muds, the exchange term is always added to the bottom grids and is computed using a linear equation for erosion and the Krone deposition formula (*Krone*, 1962). For sands, the reference concentration approach is employed following which (i) a reference height and the corresponding reference concentration are calculated (*van Rijn*, 1984c), (ii) sediment exchange is located in the first cell entirely above the reference elevation (reference cell) and calculated assuming a linear gradient between the reference concentration and the concentration in the reference cell. The bed load transport rate is calculated following expressions that are based on the *van Rijn* (1984a) and *van Rijn* (1993) formulas and the effects of the bed slope are included. The bed shear stress is given by the formulation of *van Rijn* (1993). Morphological changes account for a correction for the suspended load transport under the reference level and use morphological factor that allows to accelerate morphological changes.

7.6.2.3 ECOMSED

ECOM-SED (*Hydroqual*, 2002) only implements two sediment classes, one non-cohesive and one cohesive, in a three-dimensional, time dependent coastal ocean circulation model (*Blumberg and Mellor*, 1987). The suspended sediment concentration is calculated by solving the advection diffusion equation. For cohesive sediments, the erosion is modelled as a power of the excess bed shear stress and the deposition is modelled following the formula of *Krone* (1962). The settling velocity is taken to be a function of concentration and water column shear following *Burban et al.* (1990). For non-cohesive sediments, the erosion is modelled following a reference concentration approach (*van Rijn*, 1984c) to which a coefficient representing bed armouring is applied, while deposition is due to the self weight of the grains. The sediment bed is segmented into seven layers, the thickness of which are calculated from mass conservation. Erosion and deposition only occur for the topmost layer and bed load is not considered. Instead, the suspended load transport is calculated from the reference concentration following the procedure from *van Rijn* (1984c). The bottom shear stress is calculated using a logarithmic profile approach for currents and using the *Grant and Madsen* (1979) wave-current model otherwise.

7.6.2.4 TELEMAC

Coastal sediment transport under the TELEMAC system is only two-dimensional and couples a two-dimensional sediment transport module (SISYPHE, *Villaret* (2004)) with a hydrodynamic module (TELEMAC) and a wave module (TOMAWAC). TELEMAC is a finite-element model that interacts with SISYPHE through depth averaged velocities. Sand transport is computed for up to ten different sediment classes and several options are available at most stages. Sand transport is calculated from a choice of formulations such as *Meyer-Peter and Mueller* (1948); *Einstein* (1950); *Engelund and Hansen* (1967) for currents only and *Bijker* (1968), Soulsby - van Rijn (*Soulsby*, 1997), *Bailard* (1981); *Dibajnia and Wanatabe* (1992), which do not always separate bed load and suspended load. Bed slope effects and a hiding exposure factor are also considered. The suspended sediment concentration is obtained from a depth averaged advection-diffusion equation, and the exchange between the bed and the suspended load (erosion and deposition) is modelled using either a linear erosion and deposition following *Krone* (1962), or the net upward flux following *Celik and Rodi* (1988) with the *Zyserman and Fredsoe* (1994) reference concentration. The bed shear stress is related quadratically to the depth averaged current in the absence of waves with a choice between using the Chezy coefficient, the Stickler coefficient, the Manning coefficient or a log-law. For pure waves, the *Swart* (1974) friction factor is used and a wave-current friction factor is calculated from the current only stress, the wave only stress, the depth averaged current and the wave orbital velocity (*Villaret*, 2004).

7.6.2.5 MIKE 21 and MIKE3

MIKE 21 and MIKE3 are respectively two-dimensional (2DH) and three-dimensional systems developed by DHI and most of the modelling approaches are common to both. MIKE3-FM is a cell-centred finite volume with an unstructured mesh in the horizontal and a structure one in the vertical systems that contains several modules. The hydrodynamic module (*DHI*, 2006) solves the incompressible Reynolds Averaged Navier-Stokes equation under the Boussinesq and hydrostatic assumptions. A spectral wave module (*DHI*, 2004) account for the waves interactions. A sand transport module (*DHI*, 2007b) deals with non-cohesive sediments while a mud transport module (*DHI*, 2007a) does so for cohesive sediments. The sand transport module under combined waves and currents interpolates sediment transport from results of a quasi-3D approach which solves the vertical diffusion equation on an intrawave period. Under pure currents an advection diffusion equation is employed and several sediment transport theories are implemented (*Meyer-Peter and Mueller*, 1948; *Engelund and Hansen*, 1967; *Engelund and Fredsøe*, 1976; *van Rijn*, 1984a,c). The mud module also uses an advection-diffusion equation, implements a concentration dependent settling velocity, and models the deposition following *Krone* (1962) and the erosion either with a power law or an exponential law depending on the bed type.

7.6.2.6 Assessment of the modelling approaches

Several shortcomings relating to the models presented can be quickly inferred from table 7.1. The most advanced model would be fully three-dimensional, using unstructured meshes (i.e., finite volume approach), being able to predict sediment mixtures, cohesive sediments and bed load. Different communities may not weight all issues the same, leading to different choices. In particular, the models used so far by ABPMer and HR Wallingford (i.e., MIKE, DELFT3D, TELEMAC) have been chosen following prime concerns for support, ease of use and quality control. In contrast, the research community usually emphasises transparency (i.e., open-source) instead and commercial codes are then be considered negatively. A more thorough overview of some strengths and weaknesses of different approaches follows for a range of important coastal issues. Still, it is particularly important to realise that even the most advanced model can only predict sediment transport within a factor of two at best, due to the strong "amplification" of any small errors made on the hydrodynamics.

Buoyancy statification

Out of of the five models presented only TELEMAC coupled with SISYPHE is a 2DH model. Other models (e.g., *Cookman and Flemings*, 2001) also only solve depth-averaged equations in coastal environments. Although such an approach might yield satisfactory results for unstratified flows, 2DH model are unable to represent baroclinic behaviours which can be of importance in coastal environments and estuaries. For example, *Pandoe and Edge* (2004) showed very different suspended sediment responses to barotropic and baroclinic modes in the idealized case of a barred rectangular basin. *Burchard et al.* (2008) recently also discussed how density differences significantly contribute to the net suspended sediment accumulation in the Wadden Sea.

Grid discretisation

Another crucial issue concerns the discretization method employed. Most models use a finite difference approach but a growing number of coastal hydrodynamic models use unstructured grids and finite elements or finite volume approaches. Recently, *Chen et al.* (2003) and *Chen et al.* (2007) showed that the finite volume method is superior to finite differences in terms of accuracy in cases of complex coastal geometry and steep bottom slope and in terms of geometric flexibility by allowing better fits to irregular coastlines.

Wave-current interactions

All models calculate bed shear stresses following algorithms of varying complexity that account for wave-current interactions, and most have several options available. Even though we do not intend to present a full comparison of the many approaches available, we still wish to point out the advantage of explicit methods for the friction factor calculations (i.e., simplicity and computational cost).

Bed load modelling

In general, several bed load formulations are implemented in the models. Independently from the quality of the bed load predictions, it is important to consider the restrictions associated with the use of a given approach. Many of the formulations implemented are restricted to bed load transport by currents only (*Meyer-Peter and Mueller*, 1948; *Einstein*, 1950; *Engelund and Hansen*, 1967; *Engelund and Fredsøe*, 1976; *van Rijn*, 1984a). The *Bijker* (1968) expression does consider a wave-current bed shear stress but always leads to sediment transport in the direction of the current. Finally, even the formulations that do consider bed load transport under waves and current superimposed at an angle (e.g., *Dibajnia and Wanatabe*, 1992; *Soulsby*, 1997; *Soulsby and Damgaard*, 2005) still make simplifying assumptions, on the shape of the waves for example. In addition of such flow related restrictions, bed load empirical formulas have been developed using data for relatively large particles (in general, sands of diameters larger than 200 to 300 μm). This raises the issue of the validity of such formulas for finer particles. Finally, there is a significant spread in the experimental data itself, leading to substantial uncertainty in the empirical formulas, which are often only deemed accurate within a factor five to ten.

Erosion and deposition parameterisation

The exchange between bed and suspension is generally modelled differently for mud and for sand, using a power or exponential erosion and the *Krone* (1962) deposition in the first case, and a reference concentration approach in the second. We already discussed the pertinence of the *Krone* (1962) deposition in section 7.6.1.2. The notable exception to the general modelling approach is ROMS, in which cohesive sediments (sands) is eroded following an expression similar to equation 7.5. The obvious advantage is the simplicity and the flexibility of such a formulation to accommodate erosion of cohesive and non-cohesive sediments. The issue is then whether such a linear relationship between erosion and bed shear stress is appropriate for non-cohesive sediments. While this form is undoubtedly different from the more typical formulations used in the reference concentration approach (*Garcia and Parker*, 1991), it can be considered as an approximation to these. Furthermore, linear expressions have previously been introduced (e.g., *van Rijn*, 1993). *Amoudry et al.* (2005) also used a similar erosion dependence on the bed shear stress in a one-dimensional intra-wave two-phase dilute model and found that it gave satisfactory results and outperformed the *van Rijn* (1984b) empirical pickup function.

Cohesive sediment modelling Only the sediment transport model in ROMS explicitly does not treat cohesive sediments. However, most of the remaining models only account for cohesive sediments by implementing different erosion/deposition formulations, and concentration dependent settling velocities. As such, these models do not really consider some processes that are truly specific to cohesive sediments such as turbulence induced flocculation and break-up. ECOMSED is the exception since it does relate the settling velocity to both the suspended concentration and the water column shear rate.

7.6.3 Summary of key shortcomings of current state-of-the-art modelling

Even though the level of description of sediment models has greatly improved over the last few decades, there remain some important shortcomings.

- **Effects of biology on sediment dynamics are not yet accounted for in regional models.**
- **The effects of mixed beds (cohesive and non-cohesive or two non-cohesive sediments) are not accounted for either.**
- **Several cohesive sediment processes are often not represented in regional modelling (e.g., flocculation)**
- **The parameterisation of the erosion rate is insufficient for both cohesive and non-cohesive sediments, whether in terms of description of physical processes or validation.**
- **The interaction of turbulence with sediment dynamics is poorly modelled at best.**
- **Bed load parameterisations are still largely speculative for non-coarse sediments.**
- **The description of wave-current boundary layer interation is limited and does not offer an appropriate range of applicability.**
- **Ripple and roughness predictors lack physical description of some processes, range of applicability and validation.**

Due to these limitations present sediment transport models can not yet be used in a fully quantitatative fashion for determining impacts on sediment dynamics due to marine renewables. These models are useful tools but shouldn't be interpreted as an exact representation of a natural coastal sedimentary environment.

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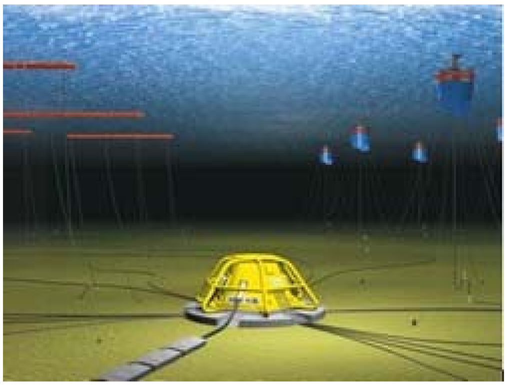
7.7 Appendix 7 - Recommended Future Case Study Sites

Two major test sites for wave and tidal stream devices are in the process of being developed – Wavehub off the Cornwall coast and the Pentland Firth in the north of Scotland. In order to separate natural variability from anthropogenic changes due to such devices it will be critical to monitor such sites for as long as possible prior to device installation, followed by extensive monitoring of sediments and hydrodynamics during installation and once devices are in place. This type of study could assist developers in planning the ideal spacing of devices to minimise impact both of the devices on the environment and the environment on the devices, while maximizing energy yield.

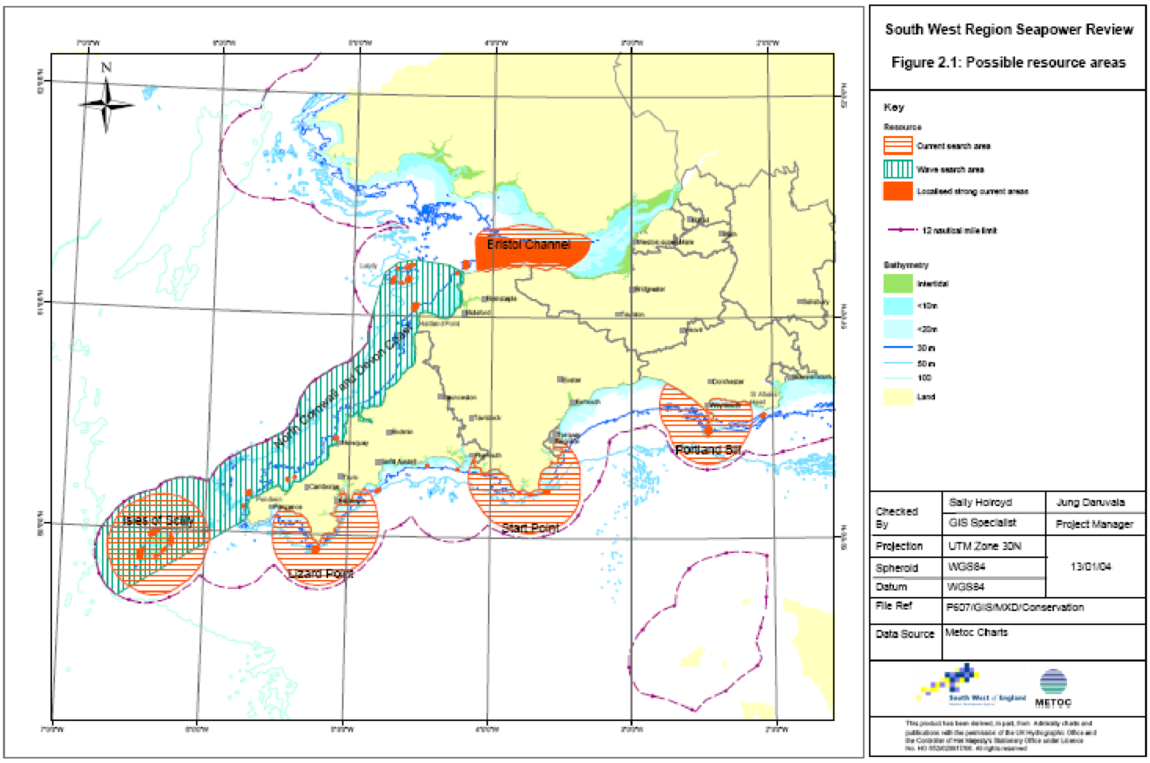
7.7.1 Wavehub

Wave Hub (www.wavehub.co.uk) is a renewable energy project in the South West of England that aims to create the UK's first offshore facility for the demonstration and proving of the operation of arrays of wave energy generation devices.



An artist's impression of the Wave Hub. Image by Industrial Art Studio Ltd, St Ives, Cornwall. www.ind-art.co.uk

It is intended to be a connection point about 10 miles offshore of St Ives Bay with a capacity of 20MW, with four zones for use by different developers for the connection of up to 5 devices in each zone. However, the Wavehub should be seen in the broader context not just as a test site, but as the pilot for large arrays of devices that could harvest the wave and tidal stream resource offshore of the Cornish coast.



Map Extract from the Seapower SW Review (2004) conducted by Metoc and showing areas with potential for renewable energy extraction.

The extent of the possible development areas was highlighted by the Seapower SW Review (2004), which showed a map demonstrating that well over 50% of the south west coastline had potential for renewable energy devices

Wavehub has been funded (~£28M) by the South West Regional Development Agency and European Regional Development Fund, so any NERC involvement would be 'buying in' to an already extensive programme.

Research has also been funded by the SWRDA (~£5.9M) at the Peninsula Research Institute in Marine Renewable Energy (PRIMaRE) (www.primare.org) comprising researchers at Plymouth University and Exeter University. Under the umbrella of PRIMaRE, the Wave Hub Impact on Seabed and Shoreline Processes (WHISSP) project and Dynamic Response to Energy Extraction and Mixing (DREEM) project aim to study the physical processes influenced by the installation of wave energy devices. These studies will aim to meet the immediate needs of the emerging marine renewable energy sector in the Peninsula and to address the wider considerations for renewable energy globally. Pump-priming funds over a period of three years have been provided by the South West RDA, this includes £1.4 million revenue to invest in staff and £6 million capital to invest in research infrastructure and equipment. The capital includes the 2 year lease of a WERA HF radar capable of mapping surface currents and wave spectra to ranges of 50-100km, which if continued through to wave device deployment would be capable of observing any changes in wave and current climate caused by the Wavehub. However, the funding will not take these projects beyond the baseline study and further funding will be needed to take them through to installation of the Wave Hub (approx 2010) and installation of the devices (approx 2011).

Significant knowledge gaps identified by the PRIMaRE group include wide area sea bed & sediment type mapping, without which any analysis of impact of devices on sediments is difficult. BGS are ideally placed to address this issue. Other gaps include a lack of detailed bathymetric (water depth) maps in the region between the low water mark and approximately the 10m depth contour line – due to the fact that larger survey vessels will not go closer than this to shore, and beach surveys are limited to the region above the low water mark. This is a critical region for studying nearshore changes in morphology and sediment movements as these are the depths where waves have most impact on the coast.

Taking a broader view, added value from investing in and maintaining research at this site comes in the form of a long baseline of data should large scale Severn barrage or tidal pond schemes be built – any farfield effects of such schemes on the open coastline should be quantifiable as a result of the extensive studies carried out here.

7.7.2 The Northern Isles of Scotland

The North of Scotland and the Pentland Firth in particular has been identified as an area with large potential for wave and tidal renewable energy developments.

A marine renewables testing centre is already established in the Orkneys – the European Marine Energy Centre.

The £12.6 million EMEC project has been led by Highlands and Islands Enterprise (HIE) on behalf of a public sector consortium consisting of The Scottish Government, Department for Business, Energy and Regulatory Reform, The Carbon Trust, Scottish Enterprise, Orkney Islands Council, with European support from the Highlands and Islands Partnership Programme.

EMEC is centred around three sites on Orkney: a small, partially underground building at Billia Croo on Orkney's Atlantic coastline which houses switchgear and other control equipment for the wave test bed facilities off the coast in that area; the EMEC offices and data centre situated in the Old Academy in Stromness; and the tidal device testing area off the Island at Eday.

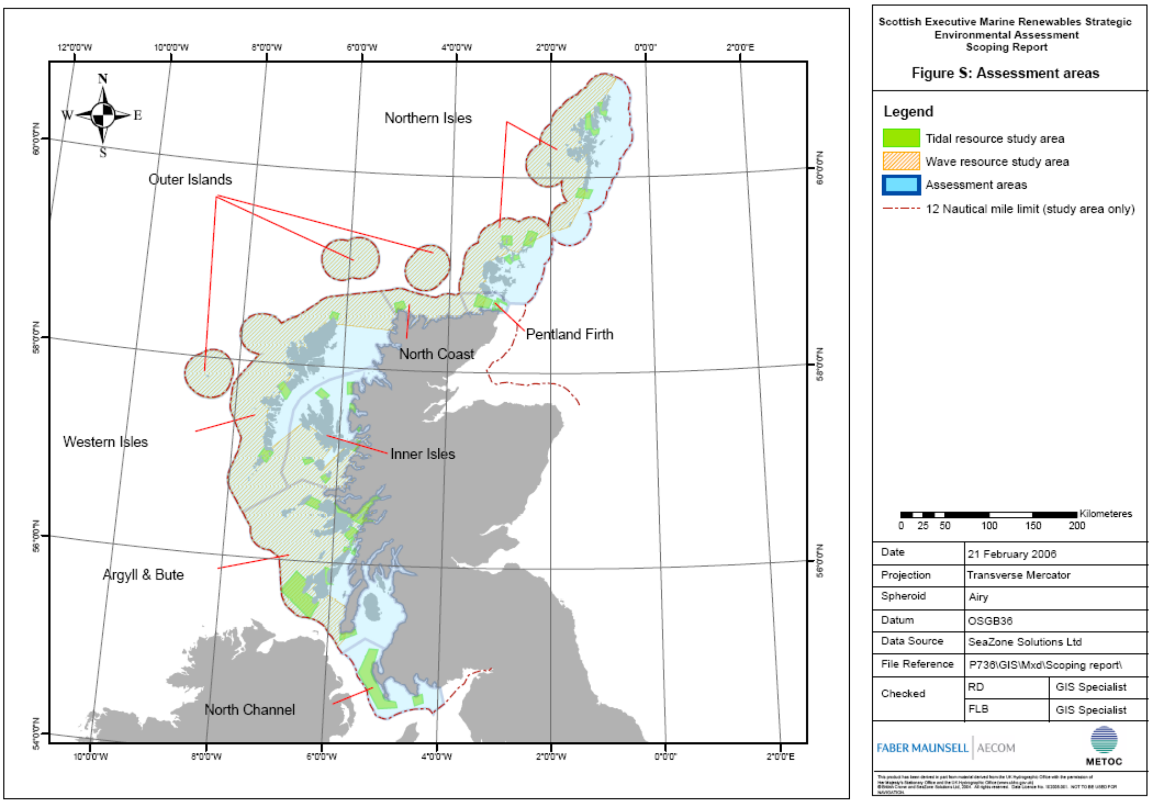
At the deepwater test facility (50-60m) about 2km off Billia Croo, four cables run offshore to deepwater berths for testing wave energy devices, and at Eday five cables run to berthing points at different water depths for testing tidal energy devices. Both sites have communication links back to the Stromness office.

A number of tidal energy developers have committed themselves to testing their devices at EMEC, including OpenHydro, Aquamarine Power Ltd and Lunar Energy.
A number of other studies launched by the various Scottish universities are building on this and include:

- Modelling and measurements including a planned HF radar (WERA) under the RASCAL-PF project led by Heriot-Watt University who have a campus at Stromness in Orkney, together with the Environmental Research Institute (UHI, Thurso), U. Sheffield, U.Edinburgh and Stanford U. (California)
- Strategic and Environmental Assessments for Marine Energy Conversion (SEAMEX) supported with grants from the ESPRC and HIE.

The recent sea bed lease offer by the Crown Estate has excluded some mid-channel areas making it likely that developers may choose to locate devices nearer to the shore where sediment processes need to be considered. Concerns in this geographical area include the presence and potential movement of large sand bars, accumulation of sediment around foundations etc.

Once again, long term research at this site should be seen against the backdrop not only of testing marine energy devices but as establishing a baseline against which to study the impact of future full scale developments intended for the area. The figure below taken from the 2006 SEA Scoping Report carried out by METOC for the Scottish Government illustrates the extent of the potential installations.
(http://www.seaenergyscotland.net/ScopingConsultation.htm)



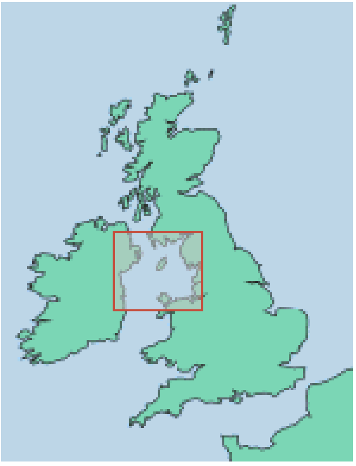
7.7.3 North Wales Tidal Stream Area – The Skerries

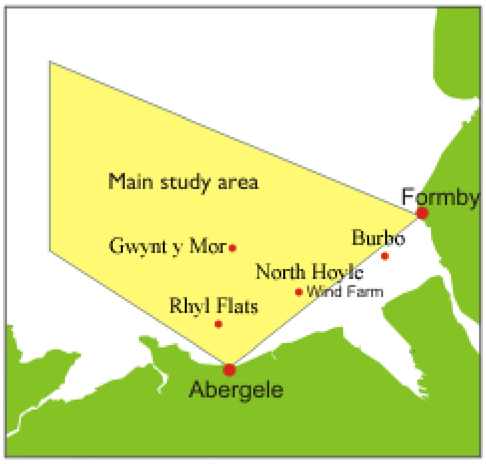
Little information exists in the public domain regarding this site as it is still in the planning stages, however from the research point of view this presents an opportunity to study the site before development occurs.

- Npower renewables and MCT partnership.
- One of world's first commercial scale tidal developments
- To be commissioned 2011/2012.
- 5.4m tidal range. 3.19 m s-1 mean spring current
- Seven seagen turbines (1.5 MW) standing in 25 m of water.
- Identified as a good potential site due to tidal conditions and natural shelter. Also well connected with ports (Holyhead), the National Grid, and good transport links/access.
- Baseline studies completed this year with consent application imminent.

7.7.4 Liverpool Bay – Irish Sea Observatory

http://cobs.pol.ac.uk





Liverpool Bay Location *HF Radar Coverage with wind farm locations*

The Observatory will integrate (near) real-time measurements with coupled models into a pre-operational coastal prediction system whose results will be displayed on the web site.

The concept is founded on obtaining data in (near) real-time, using telemetry, from underwater to the sea surface to land to POL to this web site ('armchair oceanography'). This, the aspiration of every oceanographer, is now feasible.

It will grow and evolve as resources and technology allow, all the while building up a long time series. The foci are the impacts of storms, variations in river discharge (especially the Mersey), seasonality, and blooms in Liverpool Bay.

Relevance to the study comes in the form of four wind farm arrays in the study area – North Hoyle was installed before the HF radar began recording, Burbo is slightly out of radar coverage range but was installed while the radar has been operational, Rhyl Flats is within radar coverage and is under construction so there exists a background dataset, and Gwynt y Mor is a large (150-250 tubine) array that is planned for construction to complete 2011. This array of arrays of monopiles presents n opportunity to identify any effects of lack thereof using existing monitoring infrastructure and a substantial baseline of data held at POL & BODC.

In addition, any tidal schemes planned for the Mersey will also have a significant baseline of data with which to study impacts.

A marine radar is planned for deployment at Ainsdale, north of Formby as part of the COFEE project, overlooking an erosion/deposition hinge point allowing detailed wave, current and bathymetry maps to be generated potentially through the installation of the Gwynt-y-Mor wind farm.

A marine radar has been operational in the mouth of the Dee Estuary since 2006 to monitor waves, currents and bathymetry around the complex of sandbanks in that area and will continue, although the wind farms are out of range.

Monitoring includes:

- In situ time series of current, temperature and salintiy profiles and of waves and weather.
- The CEFAS SmartBuoy for surface properties including nutrients and chlorophyll.
- A triaxys directional wave buoy
- RV Prince Madog to service moorings and for spatial surveys.
- Instrumented ferries for near surface temperature, salinity, turbidity, chlorophyll and later nutrients.

- Met data from Hilbre Island, webcam and marine X-band radar, tide gauge sites
- Shore-base WERA HF radar measuring waves and surface currents out to a range of 50km.
- Satellite data - infra-red (for sea surface temperature) and visible (for chlorophyll and suspended sediment).

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