FLOWBEC

A REVIEW OF MEASURED AND MODELLED DATA FOR THE WAVE HUB SITE

Report prepared by the University of Exeter

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August 2012

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INTRODUCTION

The Wave Hub development was conceived as a wave energy site to accommodate developers wishing to test arrays of devices. It has four sub-sea electrical grid connections of 1MW, each associated with a 1km x 1km area of sea. It is located approximately 20km north of the town of Hayle on the North Cornwall coast, situated in a depth of approximately 50m. The construction and cable lay were completed during October 2010, and the site is ready for the deployment of WEC. Since the project conception, a large amount of survey, scientific, and research work has been undertaken.

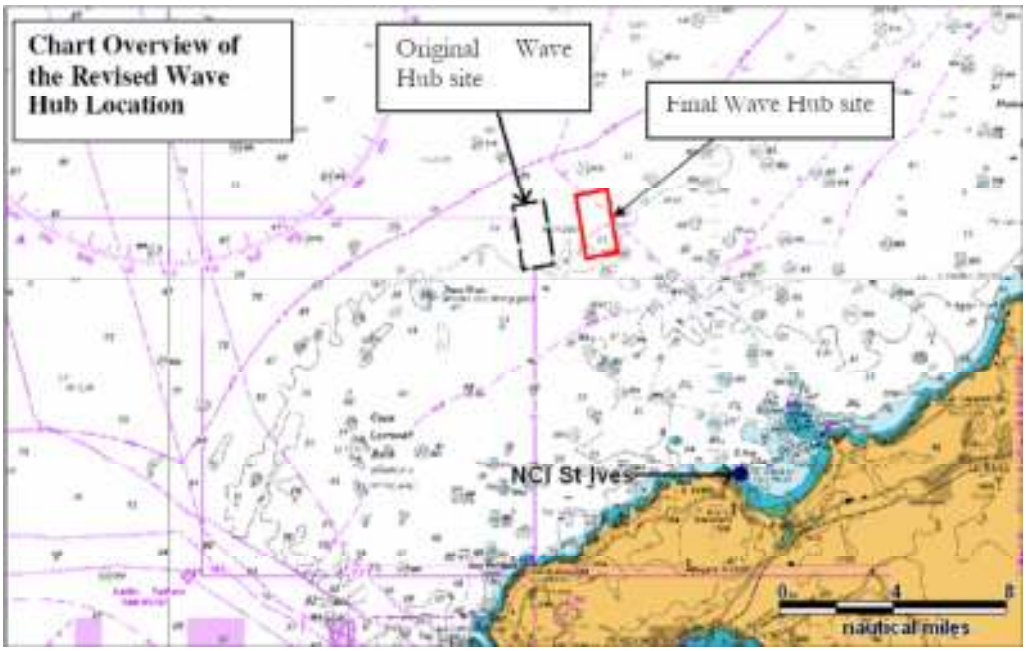

Figure 1. Location of the initial and final Wave Hub sites

Much of the initial work was completed by contractors for the Wave Hub, in order to fulfil the requirements of environmental assessment procedures, and other permitting processes. This provides a significant data resource for the site, although much of this dates back to 2004-2008. At the time, the consenting procedures for marine renewable energy (MRE) had few precedents, and were based on limited information. Consequently, procedures did not necessarily follow guidelines now in place. A list of reports is provided in Appendix B – List of reports produced for the Wave Hub, and the resources are described under the relevant sections of this document. Where a particular output on this list is referred to in this document, it will be referenced to this table by a number in square brackets, e.g. [1].

Additionally, research support has been provided since 2007 by the Peninsula Institute for Marine Renewable Energy (PRIMaRE), a joint initiative between the University of Exeter and Plymouth University. It operated in parallel with the Wave Hub project, providing independent research into marine renewable energy in the region. Research at the site includes wave and current measurements, biological sampling, oceanographic studies, and surveying. This work benefitted

from the foresight available to academic research, and is contributing to the development of best practice for the industry. The resultant body of work serves to provide robust baseline data for on-going research, on which the potential impact of wave energy conversion can be identified. They also provide high quality data sets (Appendix A: Data sources generated by PRIMaRE) for developers wishing to operate at the site, allowing accurate assessment of the hydrodynamic conditions. This research has contributed to numerous publications, which are listed in Appendix C - Papers Published by UoE and PU PRIMaRE Academics, and more information can be sourced from the PRIMaRE website, www.primare.org.

The PRIMaRE project provided a springboard for research in the South West region. The University of Exeter (UoE), and Plymouth University (PU), have built up significant expertise for research in the field of marine renewable energy. These institutions continue to develop their research, securing funding from a range of sources to continue developing the understanding of physical and environmental processes in this region. The region has recently been named the South West Marine Energy Park by the UK government, demonstrating its central role in the development of wave energy for the UK. As a consequence, the body of research contributing to the understanding of the Wave Hub site and surrounds continues to grow. This supports the continuous monitoring of the site, easing the process for the permits and permissions.

This document provides an overview of the resources available for the description of the natural environment at the Wave Hub site, and surrounding region. It aims to provide the reader with an understanding of the mechanisms that have led to the collection of the data resources, and details on how to access them. Detailed information for key research areas is then presented. The document does not aim to provide results of the data collection and analysis, and the reader is referred to the data sources reviewed.

OVERVIEW OF RESOURCES

The body of work that relates to the Wave Hub site consists of initial studies undertaken to establish the feasibility of the project, and subsequently to fulfil requirements laid out in the various permits and licenses required by law. The culmination of this work is in the environmental statement, and supporting documents, published in 2006 [15]. Specific criticisms were raised by stakeholders and the community, based on this document. In response, further work was commissioned to address these concerns, and the site was moved approximately 2km to the east. It follows that the site surveys contributing to the environmental report were not centred on the final site. Between 2006 and the present day, a range of studies have provided an updated assessment of key factors, including fisheries evaluation report [18], hydrographic surveys [48] (and a further survey during 2011), a review of the wave conditions and the power resource [5], and reviews of the potential impact on local coastlines [32,8]. A report reviewing the consents and permitting process is included as Appendix D - A Review of Consents, Permits, and Environmental assessments.

Since 2007, the PRIMaRE project has compiled baseline data, and undertaken detailed analysis in key areas,

- Resource assessment - wave and current conditions have been measured, using both in situ measurements and through the development of robust, high resolution regional models. Research contributes to the development of standards for the monitoring and assessment of marine renewable energy sites.
- Environment and biodiversity – continuous monitoring and analysis includes, sea birds, marine mammals, marine ecosystems, acoustic noise and coastal sediment systems. Research provides unique analysis of the potential impact of marine renewable energy, and develops effective methods for monitoring and assessment
- Marine operations – novel research into mooring design and reliability, supported by the development of unique test facilities; the South West Mooring Test Facility (SWMTF) and the Dynamic Marine Components Test Rig (DMaC).
- Socio-Economic factors – stakeholder and industry engagement, alongside review and analysis of marine renewable energy policy, and development of methodology for the assessment of the impact of policy decisions.
- Marine Electrical systems – an integrated power lab designed to provide solutions to issues regarding power management and integration for marine renewables.

Supported by an excellent natural resource, and projects such as PRIMaRE, the South West has developed significant expertise and excellent facilities for research into marine renewable energy, including the world's largest wave energy test site (Wave Hub), and a nursery site (FabTest). The research described above provides an excellent body of baseline data for these sites. These data are invariably thorough and provide a unique resource for on-going work to support the development of marine renewable energy, and a rigorous assessment of its impact on environmental and socio-economic systems. The research to date has applied this data to support the development of marine renewable energy, tackling key research questions for the sector. Higher education institutions have been working closely with businesses, and collaborating with both national and international bodies throughout the sector.

LOCATION AND ACCESS TO RESOURCES

The development of the Wave Hub project was carried out with public funds and, with few exceptions, the information contributing to the relevant permits is publicly available. A list of reports is provided in Appendix B – List of reports produced for the Wave Hub, and the resources are described under the relevant sections of this document. Much of this literature, including the environmental statement, and appendices, are available through the Wave Hub website; although not all of the supporting documentation can be accessed directly. Where reports are not on-line, access must be sought through direct contact with the Wave Hub office, or through the research institution.

The research efforts of PRIMaRE, has led to a range of academic publications, which are listed in Appendix C - Papers Published by UoE and PU PRIMaRE Academics. Furthermore, Appendix A: Data sources generated by PRIMaRElists the data sets that were collected during PRIMaRE. In all cases these data are held by the institution that gathered them and contacts are provided on this list. The

legacy of PRIMaRE is also an excellent knowledge base in the South West, with the University of Exeter and Plymouth University retaining significant expertise in the core areas. Since PRIMaRE, the region continues to attract research projects, promoting continued high quality research, supported by the excellent natural resources and the growing marine renewable energy community in the region.

Subsequent sections in this report provide more details about the data available in key areas. It is worth noting that much of the work is on-going. The Wave Hub team continue to gather data in response to their consent requirements. This includes benthic sampling and acoustic monitoring. There are also numerous active research projects in the area. Therefore, the body of data continues to grow rapidly. This report will concentrate on research projects that are considered finished, or have an established data set.

RESOURCE ASSESSMENT

Initial scoping studies used the Seapower SW Review, which analysed the resources and constraints for wave and tidal power in the South West of England based on global model data. Since then, the Wave Hub team have intermittently operated wave measurement devices at the site. The University of Exeter have gained significant experience of deployments in the region, operating an array of up to 4 directional wave buoys and deep water ADCPs close to the site, and have developed a high resolution regional wave model to provide accurate long term data sets. Plymouth University capture direct measurements of the waves and surface currents across a wide area including the Wave Hub site using an HF radar system, supported by point wave measurements in the region.

WAVE MONITORING AND ASSESSMENT

There are a number of measured and modelled datasets of wave conditions available for the waters surrounding the Wave Hub site. Due to the change in the site location during development there is only one measured dataset, obtained using an acoustic Doppler current profiler (ADCP), at the final Wave Hub site location.

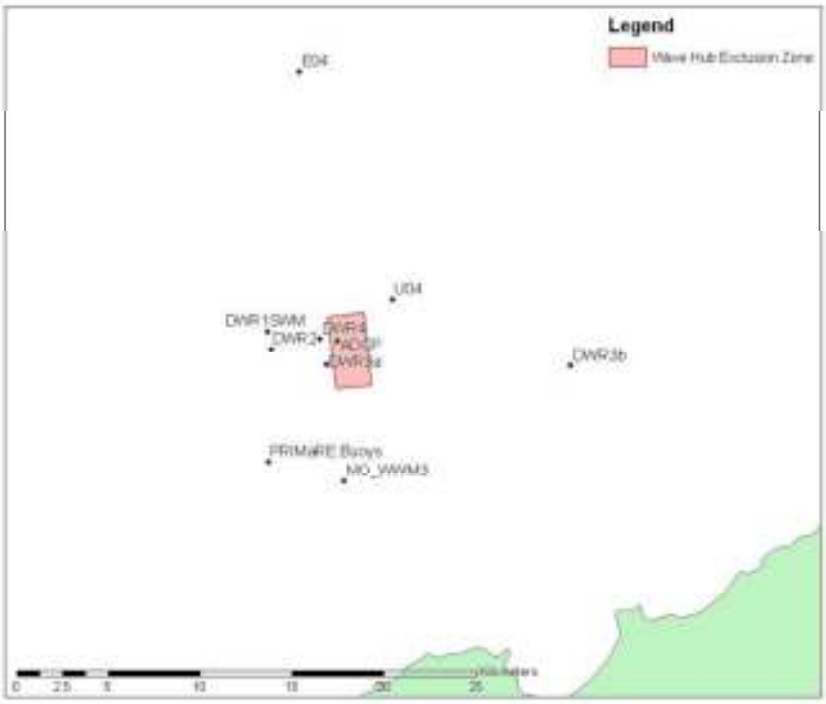

Figure 2. The position of wave measurements and model outputs in relation to the Wave Hub site (Smith et al. 2011).

Initial scoping studies analysed global wave model data for the nearby E04 point (Figure 2. The position of wave measurements and model outputs in relation to the Wave Hub site (Smith et al. 2011).), to estimate the resource at the Wave Hub site [25]. Subsequently global wave model data from a closer point, U04 (Figure 2. The position of wave measurements and model outputs in relation to the Wave Hub site (Smith et al. 2011). 2) were combined with wave data from direct

measurements for the detailed planning phase [42]. Measured data were intermittent, totalling approximately 1 year of data, although they were applied to wave climate predictions of the wave climate in a coastal processes report for the environmental impact assessment [3]. These studies suffer from the accuracy of global wave model outputs and limited in-situ data. A further study was commissioned by Wave Hub to provide a more detailed analysis of the wave power resource, which incorporated some regional modelling from the University of Exeter, using SWAN. Since then, the Wave Hub team continue to take measurements from the site, detailed in [51:53], with data sets available on the web site.

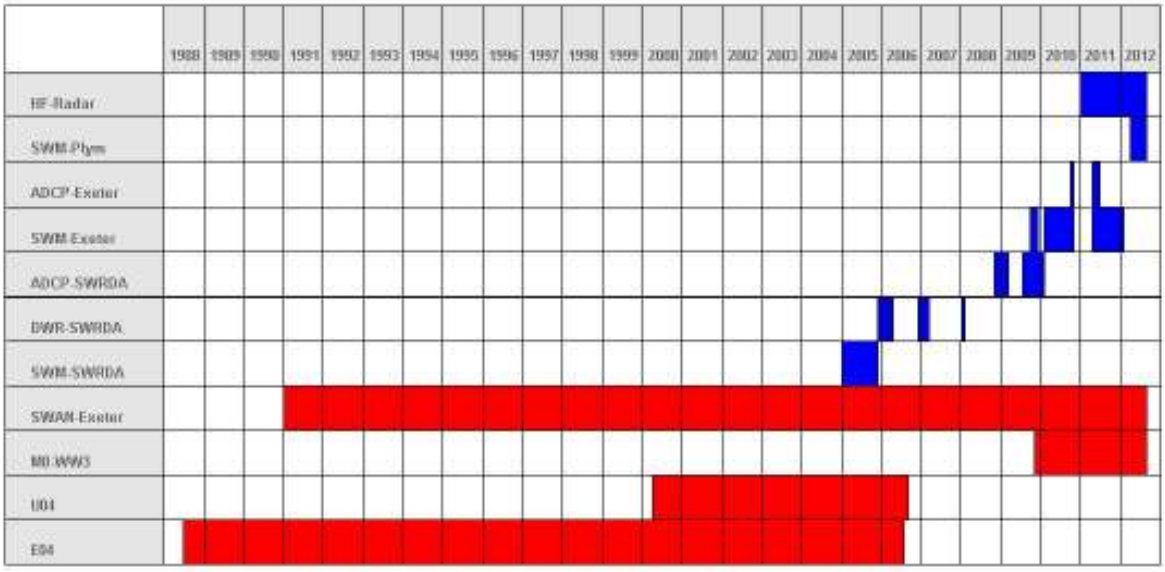

Figure 3. A timeline of measurements and model outputs available for the Wave Hub and surrounds.

Under the PRIMaRE project, the University of Exeter has deployed an array of up to 4 wave buoys simultaneously at a site 5km from the Wave Hub. At this site, deep water ADCP's were also deployed, modified to give accurate wave measurements at these water depths. This facility provides an excellent resource for the assessment of the detailed properties of wave field (Ashton 2011). Furthermore, the unique setup has supported research into the influence of current on wave measurements (Saulnier 2011), the spatial variability of wave fields in this region (Ashton 2011), and to assess the performance of the sensors. UoE also operate a number of wave measurements in the region, including a wave buoy at the Fab Test site, and an ADCP at the near shore SWMTF site. The Channel Coastal Observatory (CCO) provide open access coastal wave data from a directional wave buoy installed at Perranporth. During 2011, PU installed a high frequency wave radar that provides a spatial measurement of surface wave conditions, and surface currents across the Wave Hub area. This is supported by a further wave buoy deployment close to the Wave Hub site.

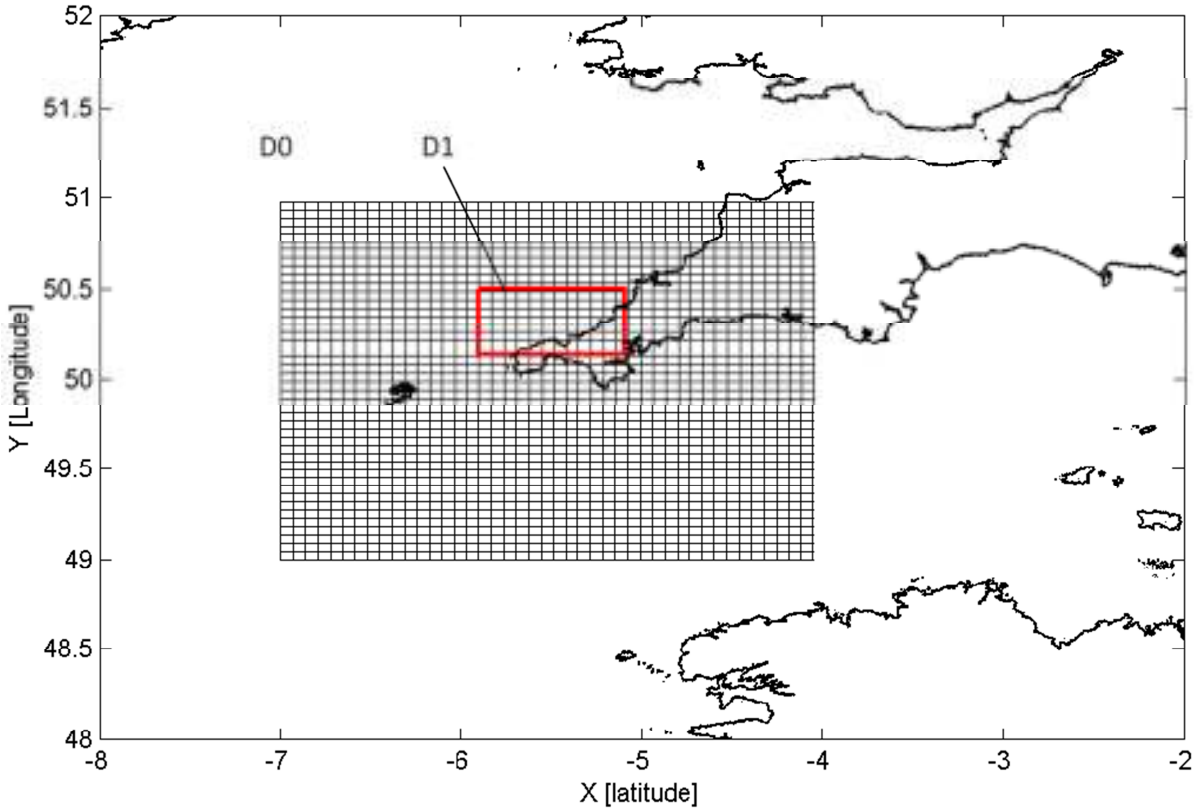

Figure 4. The model domain for the University of Exeter regional SWAN wave model, including the nested grid for the Wave Hub site and surrounds

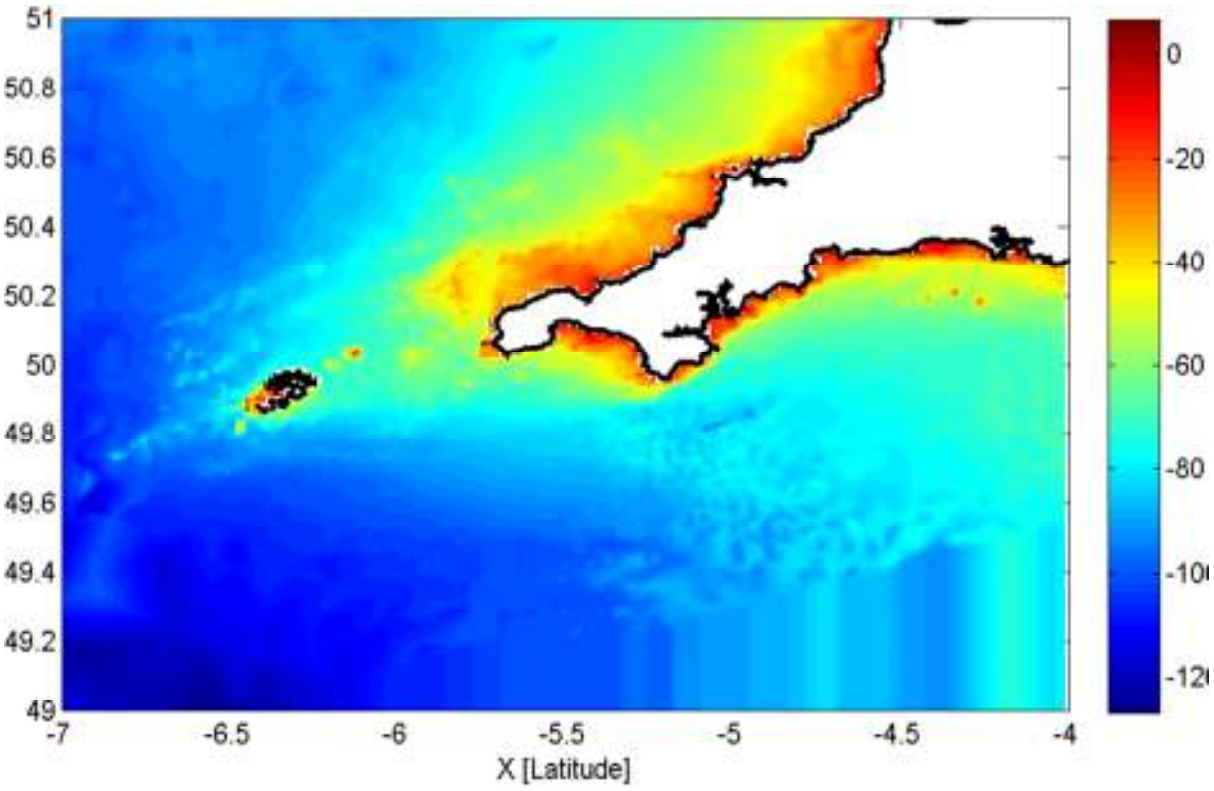

Figure 5. The bathymetry input for the regional SWAN wave model, including high resolution for the nested model

Alongside measurement campaigns, researchers at UoE have developed a high resolution, regional SWAN model that is capable of resolving near shore and coastal processes more accurately than global wave models. The model has been validated with in-situ data throughout the region, providing an improved data set for the Wave Hub site (Van Nieuwkoop-McCall 2011). The wave boundary conditions come from the MetOffice North Atlantic European model (NAE), which is run in WaveWatch III and has a 12 x 12 km resolution. Inputs used are a 200m x 200m bathymetry grid, modelled surface winds, and tidal currents. Outputs are provided at every grid point every 6 hours, or as 30 minute time-series for key locations, including the Wave Hub site. The area surrounding the Wave hub is a nested grid (Figure 4), driven by high resolution bathymetry from site-surveys (Figure 5).

The model provides output data in both hindcast and forecast mode, and data can be made available in real-time via an on-line web portal, currently hosted at www.primare.ex.ac.uk . Here, historical and real-time measurements from regional sensors can also be accessed by collaborators and partners (via secure log-in), to provide a combined data set for the assessment of the resource in the region.

During 2011, researchers at the University of Exeter, collaborated with Marine Energy Matters (MEM), to undertake a full review of the data sets available for the site, and undertake a re-analysis of the wave and current resource (Smith 2011). The study highlights the differences between global model outputs used in initial studies (Figure 6), and through using the combined regional model and measurement data sets described above, provides the most up-to-date resource assessment for the site.

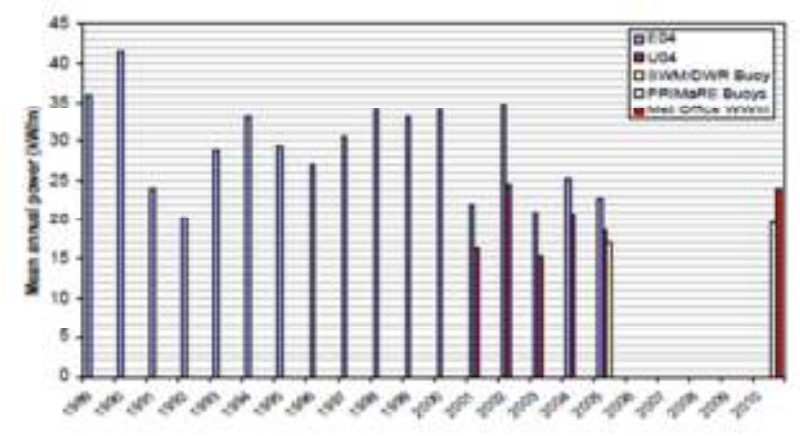

Figure 6. The mean annual power output for the Wave Hub site, from different data sources.

Furthermore, the data sets described, and this body of research, contribute directly to the development of best practice the assessment and comparison of wave energy installations (e.g. Ingram *et al.* 2011).

The Wave Hub team have also continued to gather data, and have commissioned Halcrow to continue to take wave and current measurements for the site, using an AWAC deployment. Problems with the equipment mean that this is not a continuous data set, and full details, including the data, can be found in monitoring reports available on the Wave Hub website. In addition, the Channel Coastal Observatory have operated a near shore wave buoy at Perranporth, which provides

a valuable coastal assessment of waves in the area, and data is freely available through their website www.channelcoast.org.

Current active research projects, including Flowbec, continue to plan and implement data collection efforts at the Wave Hub site. The outcome is an increasingly rich and detailed data set for the assessment of the wave field in the region. At the time of writing, it is Smith (2011) that provides the most up-to-date analysis of the wave climate at the WH site.

TIDAL CHARACTERISTICS

Physical current measurements have been made using ADCP instalments at the site totalling approximately 12 months, and supported by surface current measurements from a wave buoy. This provides a reasonable data set to establish the current flow at the Wave Hub site. The following data were collected by Halcrow

- SeaWatch wave buoys additionally instrumented with an Aanderaa Doppler Current Sensor (DCS), which measures the surface current at 1Hz. Current data were recorded between 30/01/05 and 08/11/05 at a sampling interval of 120min.
- Nortec AWAC-ADCP measured 20 minutes of velocity data in 4 m depth bins, based on burst data recorded over 1 minute, and water depth. It was deployed from November 2008 to January 2010 with a four month gap in 2009 (grid location 50 22.090'N, 5 37.620'W)
- Metoc applied the CS20 Proudman Oceanographic tidal current model to simulate tidal streams around the cable track and the Wave Hub location [10]. This provides a long term data set of currents and was analysed form the permitting process.

The University of Exeter has measured currents at the location of their wave buoy array using an ADCP. This has been applied to analysis of wave-current interactions (Saulnier 2012), and how these affect the resource assessment of wave energy devices, including through spatial variability (Ashton 2011)

The HF Radar system installed by Plymouth University is currently operational, delivering a measurement of the surface currents every 30 minutes, with a spatial resolution approximately 1km x 1km and a range of 50 – 100km, across an area incorporating the Wave Hub site close to the centre.

WIND MEASUREMENTS

Wind data were measured at Seven Stones Light Vessel over the period from Sep 2001 - Jan 2009. The location of the Seven Stones Light Vessel is 50 6’9’’N, 6 6’0’’W, and measurements were 14m above still water level. The wind speed measurements are presented [10, p57 & p59] in a tabular form and in a graphical representation of numbers of occurrence and percent exceedence, respectively. The measured speeds are higher than the modelled data used by Metoc in [10], possibly because the model uses spatial averaging. The author is not aware of any meaningful campaigns of direct measurements of wind speed at the Wave Hub site.

ENVIRONMENT AND BIODIVERSITY

Certain environment and biodiversity issues were covered as part of the initial environmental impact assessments undertaken primarily by contractors, for the Wave Hub. This information is combined in the environmental statement, submitted in 2006, and consents, permits, and environmental assessments were the subject of a recent review (Appendix D - A Review of Consents, Permits, and Environmental assessments), which gives an overview of the work done and the recommendations. At that time, consenting procedures for MRE test sites had few precedents, and were the subject of on-going research to determine best practice. The work underpinning the applications was undertaken gain the necessary permits and consents at that time. Subsequent research, supported by efforts at and around the Wave Hub site, have helped develop understanding of the potential impacts of MRE on the environment and biodiversity, and the current requirement s for consents has also been advanced. It follows that although it represents a significant body of work, in certain cases, the initial environmental statement may not provide a suitable baseline for a rigorous assessment of the site.

The research community in the South West, supported through PRIMaRE, had the benefit of attracting world leading expertise, and resources, to establish robust baseline studies and develop new methodologies for the assessment of impacts in key areas. With the foresight available to academic research, the data collected, and the methodologies in place, allow a rigorous assessment of the impact of MRE. This supports on-going research in key areas, which provides an ever-increasing body of data to assess the environment and biodiversity of the region.

This section provides a synopsis of environmental and biodiversity research undertaken for the Wave Hub site, with emphasis on the resources that are now available as a result. For more details about the research streams, Witt *et al.* (2012) provides a detailed overview of environmental and biodiversity research within PRIMaRE. Figure 7 provides details of on-going research campaigns initiated by PRIMaRE, and now supported by various projects, QBEX (NERC), SOWFIA (EU), and MERIFIC (InterReg).

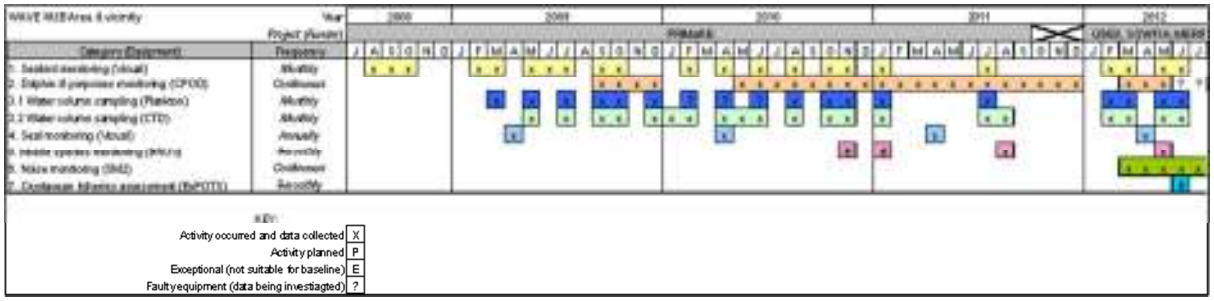

Figure 7. Details of on-going research campaigns initiated by PRIMaRE

BENTHOS

Several studies gathered information about the benthic ecology. A survey that took place between the 29/05/06 and the 02/06/06 with the vessel: MFV Valhalla aimed to evaluate the subtidal benthic communities within the revised Wave Hub deployment area. This is described in [39]. Ten benthic stations were established within the survey area with two replicates taken at each station, producing a total of 20 subtidal benthic samples. Due to the coarse nature of the seabed sediments, a 0.1m^2 Hamon grab was employed to ensure sufficient material was collected at each sampling station. Results are available for; sediment characteristics, biotopes, and subtidal benthic communities.

The Environmental baseline survey report, Volume I [12] provides a baseline survey for physico-chemical and macrofaunal benthic environment.

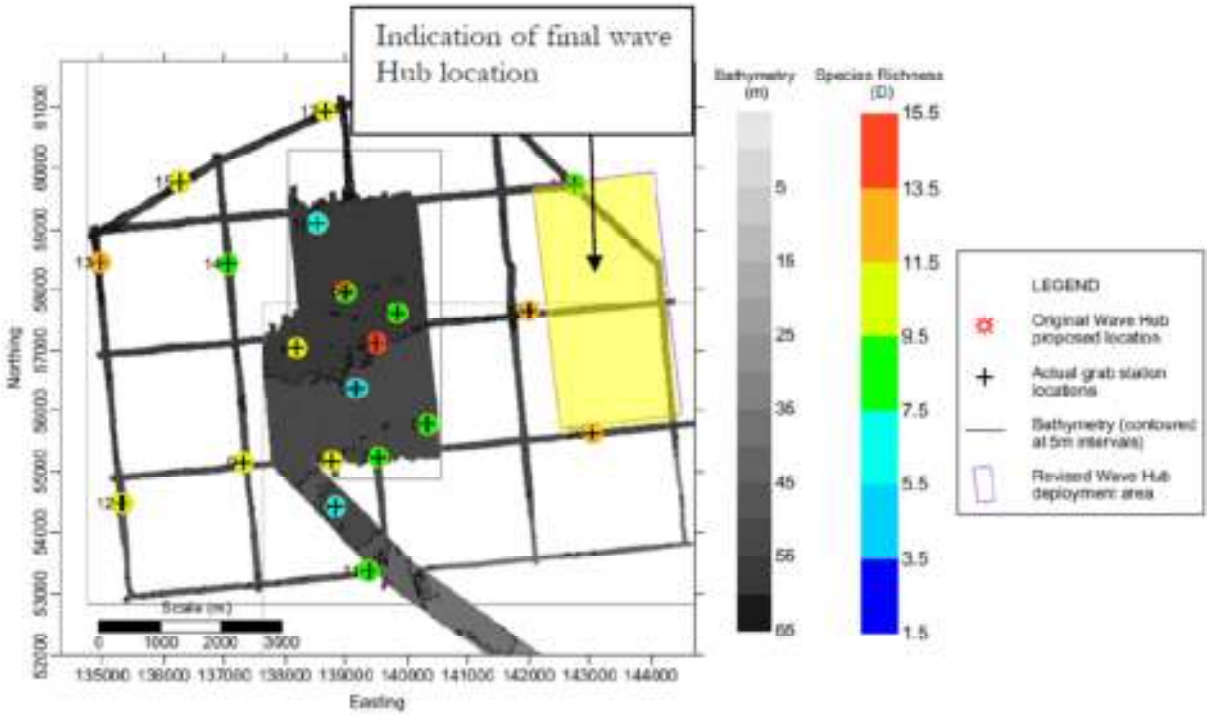

Figure 8. Species richness for the (original) Wave Hub site and surrounds, estimated with the macrofauna analysis [12]p91.

Due to adverse weather conditions experienced, the environmental survey was completed in two Phases,

- Phase I using the survey vessel Vos Baltic between 18/10/2005-31/10/2005
- Phase II using the survey vessel Portree II between 18/11/2005 and 24/11/2005.

The following sampling and photography were also carried out,

- Samples taken during the Environmental baseline survey were also used to evaluate the benthic macro fauna. Samples were processed through a 1mm mesh and all specimens were identified to the lowest taxonomic level possibly (generally to species level).
- Epibenthic samples were collected using a 2m beam trawl with a 20mm mesh net and 4mm mesh coded liner. The majority of the catch was identified in the field, with specimens that could not be identified returned to the laboratory for subsequent identification. 20 beam

trawl transects were used for this survey. Trawls 10, 11 and 12 are closed to the updated Wave Hub area.

- 18 camera transects were positioned after preliminary review of grab and beam trawl data. Transects 9 and 10 are close to the updated Wave Hub deployment area.

Organic carbon analysis was undertaken on the samples, showing that the proportion of organic carbon within the sediments was relatively homogeneous across the site. Macrofauna analysis provided maps showing the number of individuals per area, the species richness (Figure 8) the evenness, the Shannon-Wiener diversity, and the Simpson's D.

PRIMaRE research highlighted that traditional grabs and trawls were not suitable for long term monitoring due to their destructive nature. Digital imaging methods were pursued, including a towed HD camera system, providing video footage of transects of the sea floor (Figure 9) (Sheehan 2010). These have been used prior to deployments to establish a baseline, and will be used to monitor the effects of WEC on the benthos (Witt *et al.* 2012). Stationary video using baited cameras has also been captured on a regular basis since 2011 (see Appendix A: Data sources generated by PRIMaRE), although these are primarily targeted at fauna.

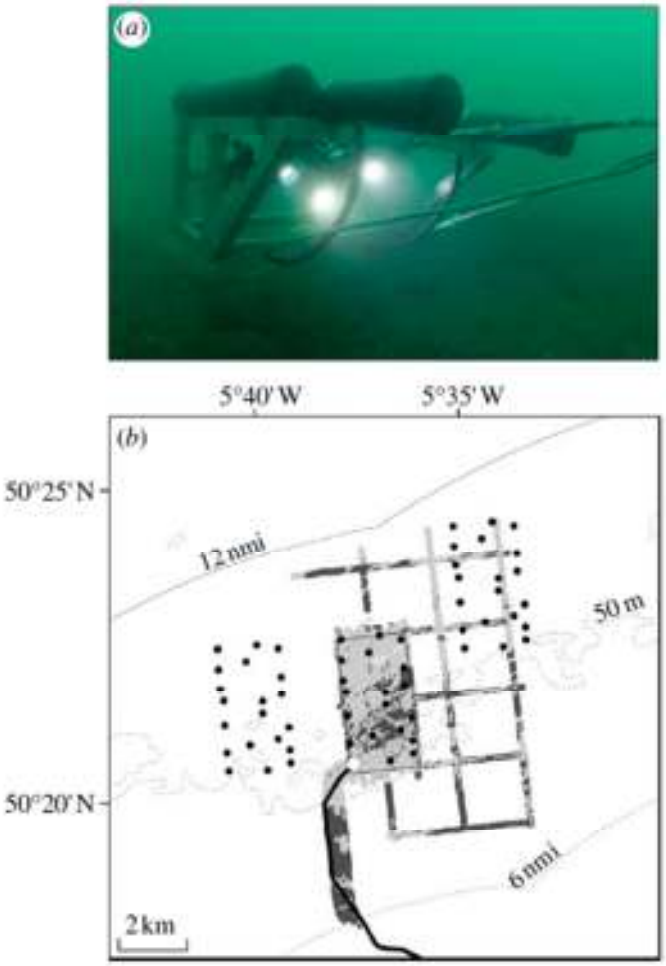

Figure 9. a) Towed camera system and b) start location of video transects (Witt et al. 2012)

FISH

University of Exeter researchers gathered data on the activity of the fishing fleet, including an inshore fisheries model for 2007-2008, and a record of fisheries activity of vessels greater than 15m in length using the vessel monitoring service. Some information is given in (Witt *et al.* 2012), or a more completed description in (Witt *et al.* 2007). The aforementioned baited stationary camera systems are in use, which provide wide-angle HD images of mobile species at the seabed, from which they can be identified (see Appendix A: Data sources generated by PRIMaRE). Witt *et al.* (2012) discusses the difficulties of monitoring the inshore fishing

fleet. Votier *et al.* (2008) and (2010) describe research under PRIMaRE into spatial constraints of fisheries.

PRIMaRE researchers have been developing advanced methods of fish tagging. However, these remain in their early stages of development and were not considered for the Wave Hub site

In work commissioned by the Wave Hub, *Commercial fisheries study* [4] (2006) reports on data gathering and assessment of commercial fishing activity in the study area. This was collated from a range of sources,

- DEFRA fisheries surveillance data (Annual and monthly distribution, distribution and activity by nationality, fishing method, seasonality of gear types, spatial distribution of all fishing activity, of trawling, potting and netting by nationality)
- Consultation with the local fishing industry (Main target specie, Spatial distribution and seasonality of fisheries, main fisheries in the offshore area, approximate number of vessel and fishermen by port)
- Analysis of DEFRA landing statistics (Overview of fisheries at St Ives and Hayle)
- Estimate of the values of the proposed deployment area to the fishing industry
- Potential impacts associated with the proposed deployment (Perceived and likely actual effects from the Wave Hub area, suggested mitigation and/or alternatives)

A further report entitled, *Fisheries evaluation report* [18] (2007) had the primary objective of improving the knowledge base on the nature and valuation of fishing operations in the vicinity of the proposed Wave Hub Deployment area. This study used field surveys, site visits and statistics collected by the MFA. This report identifies potential impacts and possible options for mitigations.

MARINE BIRDS

The report *Wave Hub EIA Offshore Bird Surveys* (2006) [46] describes survey work to establish the extent of use by seabirds in the vicinity of the proposed wave hub deployment area. A modified method from offshore wind farm surveys was used, based on visual counts from six 10km transects, each 2km apart, covering a 10x10km square.

Birds were first detected by the naked eye and if required, binoculars are used to aid species assignment. Detected birds are in a radius of 300m around the vessel. Other information recorded during the survey included environmental conditions (weather, sea state) and the presence of shipping and fishing vessels. All cetaceans and elasmobranchs observed were also recorded. These data are then post processed to estimate the abundance of birds, using a standard correction factor. They are then classified to give, total birds, birds in flight, birds on the sea surface, and number of birds per guild. Both raw data and monthly summaries are available.

PRIMaRE researchers have adopted a similar technique, undertaking monthly surveys where conditions allow. In this method, stationary sampling stations within and surrounding the Wave Hub site are visited by two surveyors and counts are made over approximately a 4hr period (Witt *et al.* (2012). Birds are spotted, identified, and categorised as within 300m, or beyond 300m. A note is

made of their behaviour at the time. The duration and consistency of these measurements can be seen on Figure 7, providing a multi-annual study of bird populations in the area, and the most thorough baseline for assessment of impacts from operational devices.

Research has also been underway to improve methodologies for tracking seabirds. *B*io-logging devices have been trialled on sea-bird populations in the region, including the Isles of Scilly, and Grassholm island (Wales) (Witt *et al.* 2012). The data from these studies allow an assessment of sea bird behaviour in the region, and understanding of the behaviour that underlies activity at the Wave Hub site.

MARINE MAMMALS

For the environmental statement, marine mammals were monitored at the Wave Hub site using a T-Pod attached to the mooring limb of a wave buoy. Further details can be found in [36].

The presence, behaviour and potential impacts on marine mammals have been the subject of significant research under the PRIMaRE project. The research has concentrated on establishing a regional picture of cetacean populations, including the Wave Hub site. The work is carried out using acoustic monitoring, C-Pods (Chelonia, UK), which detect echolocation clicks (Witt *et al.* 2012). These have been in place in locations around the region since 2009 (see Appendix A: Data sources generated by PRIMaRE).

This approach provides a long-term data set of the abundance of cetaceans throughout the region, establishing their behaviour, and highlighting geographical areas that are of importance. On this basis, research is on-going to establish the importance of the Wave Hub site to these species, allowing a more complete assessment of impacts from operational devices.

In addition to the use of C-Pods, JASCO AMAR broadband sound recording equipment has also been used to measure a larger range of acoustic noise at the site. Measurements of the ambient sound field will be critical for identifying the noise from operational devices, and the data captured from these in-situ recorders provides extended measurement of conditions at the site (see Appendix A: Data sources generated by PRIMaRE).

Local seal populations have been monitored by UoE, in conjunction with local NGOs in an annual Cornwall Seal census.

WATER COLUMN

Under the permitting process, an analysis of the oceanographic conditions, water quality, and the sediment quality were required. Results of sampling undertaken in conjunction with CEFAS are presented in the Wave Hub environmental statement [15].

This area was covered in a long term study by the International Council for Exploration of the Sea. Temperature, salinity and density of seawater data are based on 12,759 CTD and bottles collected

between 1901 and 2007 in area 49-51°N 5-7°W. These data were examined for the Wave Hub project and a full analysis is found in [10].

Data are supported by more recent temperature measurements taken by an AWAC deployed at the Wave Hub site during 2009/2010. Water temperatures were also measured by the Nortek ADCP at the sea bed, and the AANDERAA DCS device close to the water surface. Details of these results are provided in a series of monitoring reports [51:53].

A water quality survey was undertaken during the winter to establish the baselines conditions for total suspended solids (TSS). This survey was done in collaboration with the Centre for Environment, Fisheries and Aquaculture Science (CEFAS). Five sampling stations were positioned on the cable route (VC1, VC2, VC3, VC4 and VC5) and a sixth station at the Wave Hub deployment area VC6. Three samples were collected at each station at the surface, mid-depth and near-bed positions. (Depth was recorded) The survey should have been done twice to observe seasonal variations but survey vessels were not available and sea conditions were not favourable for a second study. The details of the study are available in the environmental statement [15].

Researchers at UP are undertaking a more complete review of the oceanographic conditions at the site. The core component of the study is a series of field-based process studies to provide measurements of turbulent mixing and stratification during the spring bloom, peak summer stratification and its subsequent breakdown (Witt *et. al* 2012). This work is on-going, therefore little information is available at this point.

GEOTECHNICAL SURVEYS

Comprehensive geotechnical surveys were undertaken during 2005 by EGS, and Fugro. These data were interpreted for Wave Hub by Halcrow, and contribute to the literature compiled for the permitting process. Subsequently, the proposed site was moved to its final location. It follows that these early surveys, although comprehensive, are not concentrated on the present Wave Hub site and they offer only limited information for the site. Bathymetry surveys were subsequently repeated during 2008, providing a hydrographical data set for the site itself (Figure 12. Bathymetry for the Wave Hub site. The hub and cable can be observed in the SW corner). These data were sourced through contact with the Wave Hub office. They are available, although can only be used with permission from the Wave Hub team.

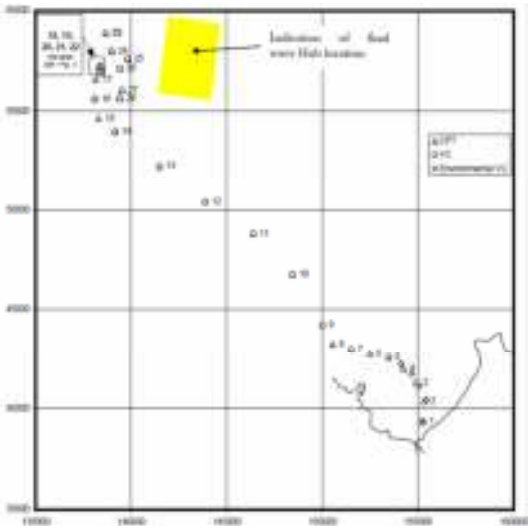

Figure 10. Location of the geotechnical sampling

Detailed bathymetry has been gathered by the UoE for specific locations around the site, in support of detailed wave modelling work, and proposed installations.

INITIAL SURVEY WORK

A geotechnical investigation for the Wave Hub project was performed from MV VOS Baltic between 15th and 17th October 2005. The investigation comprised,

- 26 vibrocores tests at 22 locations, using
- 44 PiezoCone Penetration Tests (PCPT), measuring the porewater pressure at 33 locations

These tests were performed for locations spanning the proposed cable route and Wave Hub site. The site was subsequently moved such that no investigations were done on the final Wave Hub location.

A hydrographic survey was carried out by the vessel FPV Morven between 28th August and 20th September, 2008, on the final Wave Hub location. The following data were recorded,

- multibeam bathymetry using fully motion-aided Reson 8101 multibeam system
- sidescan sonar using an Edgetech 4200 dual frequency (nominally 120kHz and 400kHz, 100 and 200m data collection) sidescan sonar system (50m spacing). Accuracy of +/-10m across track
- magnetometer data using a Geometrics G882 marine magnetometer (50m spacing, resolution of 0.01 nT). Accuracy of +/-10m across track
- seismic boomer, towed from the survey vessel, using a C-Boom - Low Voltage Boomer System

Geophysical surveys were undertaken using the vessel “Wessex Explorer” between the 1st July 2005 and the 13th July 2005, equipped as follows,

- single beam echo sounder Knudsen 320M
- multi beam echo sounder Kongsberg Simrad EM3002 dual head
- side scan sonar EdgeTech 260 recorder + 272TD tow fish. Data were acquired using a frequency of 100kHz and a range setting of 100m over the main site survey area. Survey line spacing was 100m respectively. (nearly 100\% overlap over the main site)
- seismic EGS C-Boom low voltage boomer + C-Phone hydrophone. A sweep time of 67ms was used at a 4Hz repetition rate
- magnetometer Marine Magnetics SeaSPY.

A detailed report of these surveys can be found in [47] pp16-20. Once again, the survey concentrated on the initial site location and limited measurements are available for the new site location (Figure 11).

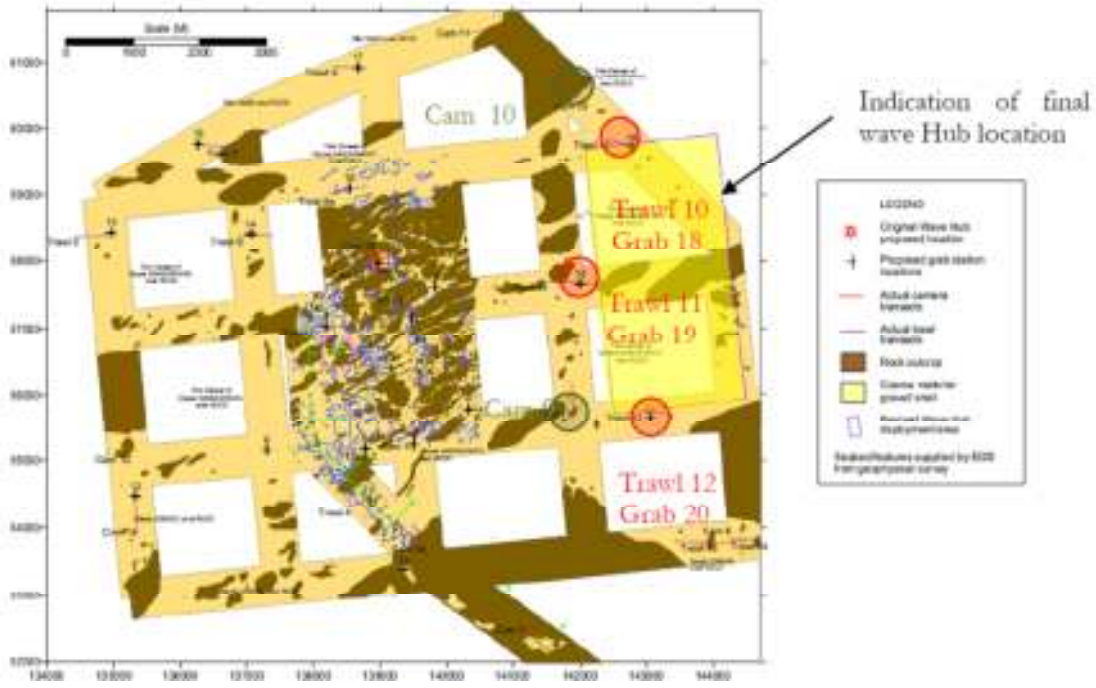

Figure 11. Location of geophysical survey [47]

RECENT HYDROGRAPHIC SURVEY WORK

More recently, hydrographic surveys have been repeated between the 27th September and the 29th September 2011 onboard Nab Cat II, an 11 m survey vessel, by EMU, commissioned by Halcrow. This survey was undertaken in order to provide a baseline for post-construction monitoring of the Wave Hub site, the sub-sea power cable (SPC), and the wreck “Helene” which is close to the cable route. The survey used the following equipment,

- Applanix POS MV positioning system with correction from C-Nav DGNSS Leica 1200 RTK GPS
- Applanix POS MV for heading and attitude
- QINSy 8.0 Hydrographic Navigation System software

Height information was provided to onboard sensors in order to reduce geophysical data to Lowest Astronomical Tide (LAT) within the bounds set by IHO Order 1A survey accuracy. Water depths were then measure to LAT throught the survey area, using a multibeam bathymetry acquisition and processing system with line spacing at 4.5 times water depth. The specific equipment were as follows,

- Reson 7125 240 multibeam system with Mini-SVS
- Applanix POS MV
- Valeport MiniSVP
- QINSy 8 acquisition, navigation and processing software
- IVS3D Fledermaus 7.3.1

The bathymetry for the Wave Hub site, from this updated survey is provided in Figure 10. The hub and cable can be seen in the south west corner of the site.

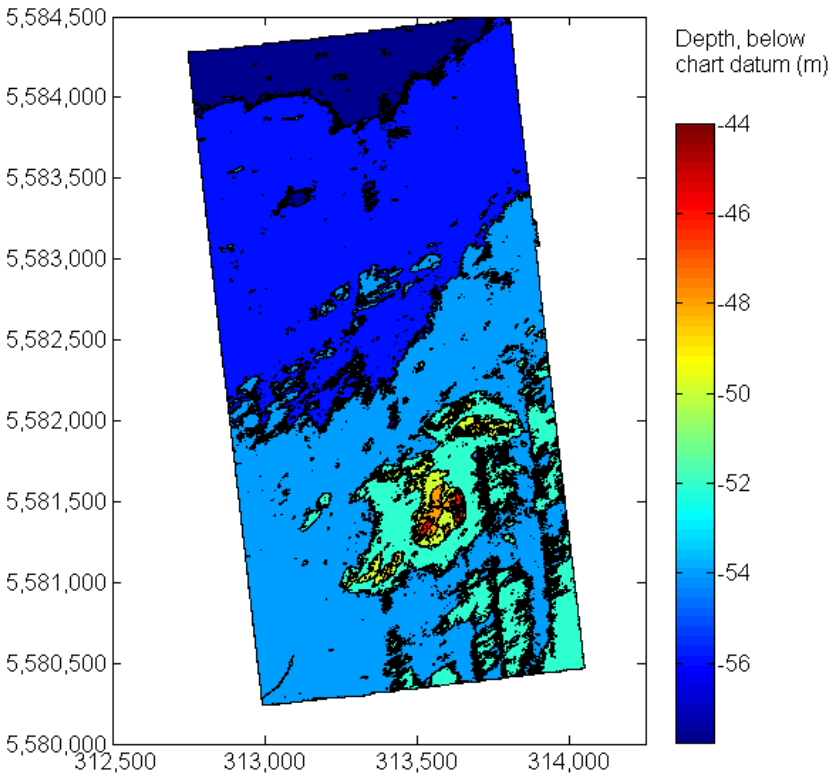

Figure 12. Bathymetry for the Wave Hub site. The hub and cable can be observed in the SW corner

APPENDICES

APPENDIX A: DATA SOURCES GENERATED BY PRIMARE

Description	Instrument name	Measurement period	Location	Temporal resolution	Institution	Contact
Wave data	array of 4 directional wave buoys	Oct 2009 - March 2011	Close to WH site	every 30 mins	UoE	Dr. L Johanning
Wave data	ADCP	Oct 2010 - Nov 2010	Close to WH site (buoy array)	Every 20 mins	UoE	Dr. L Johanning
Current data	ADCP	Oct 2010 - Nov 2010	Close to WH site (buoy array)	Every 20 mins	UoE	Dr. L Johanning
Wave data	ADCP	Jul 2011 - Oct 2011	Close to WH site (buoy array)	Every 20 mins	UoE	Dr. L Johanning
Current data	ADCP	Oct 2010 - Nov 2010	Close to WH site (buoy array)	Every 20 mins	UoE	Dr. L Johanning
Sonar data	WASSP WMB160F multi-beam sonar with WASSP Navigator	2008 - ongoing	WH site, buoy array, SWMTF, mounts bay, Falmouth bay		UoE	Dr. L Johanning
Sidescan Sonar	TriTech Towfish,	2010 - ongoing	Falmouth bay and other locations as required		UoE	Dr. L Johanning
video	VideoRay Pro 4 ROV.	2009 - ongoing	Deployed as required, including buoy array and SWMTF		UoE	Dr. L Johanning Neill Wood
Mooring data	SWMTF	14/03/10 - ongoing	Falmouth Bay	1 to 20Hz	UoE	Dr. L Johanning
Wave data	ADCP	Aug 2010 - ongoing	Falmouth Bay	Every 20 mins	UoE	Dr Lars johanning
Current data	ADCP	Aug 2010 - ongoing	Falmouth Bay	Every 20 mins	UoE	Dr Lars johanning
Water level	RBR TWR 2050	September 2008-Present	Porthtowan, Perranporth	15min	PU	T. Poate, G. Masselink, P.Russell, K Kingston
Video	ARGUS, Delft	September 2008-Present	Porthtowan	30min	PU	T. Poate, G. Masselink, P.Russell, K Kingston
Bathymetric	Valeport Midas Surveyor	9/9/2010	Gwithian	Once	PU	T. Poate, G. Masselink, P.Russell, K Kingston
Topographic	Trimble RTK GPS	February 2008-Present	Gwithian Towans/Porthtowan /Chapelporth/Perranporth Beaches	Monthly	PU	T. Poate, G. Masselink, P.Russell, K Kingston
Sound recording using JASCO Amars, archival hardware	AMAR	2011 onwards	Wave Hub	Variable	UoE	Dr Matt Witt
Monthly plankton time series		2009 onwards	Wave Hub	Monthly	UoE	Dr Matt Witt
Archical detection technology for dolphins and porposes	CPOD	2009 onwards	South West	Continuous	UoE	Dr Matt Witt
Sightings from monthly biodiversity surveys, also from CWT sightings database	Visual	2008 onwards	South West	Day	UoE	Dr Matt Witt
Sightings from monthly biodiversity surveys, also from MCS sightings database	Visual	2008 onwards	Wave Hub	Monthly	UoE	Dr Matt Witt
Satellite tracking of seabirds	PTT	2009 onwards	UK	Variable	UoE	Dr Matt Witt

Annual census for seals in Cornwall and Isles of Scilly	Visual	2007-2010	South West	Day	UoE	Dr Matt Witt
Sightings from monthly biodiversity surveys, also from MCS sightings database	Visual	2008 onwards	UK	Day	UoE	Dr Matt Witt
Vertical upcasts of water column structure undertaken during monthly biodiversity surveys	CTD	2009 onwards	Wave Hub	Monthly	UoE	Dr Matt Witt
Seabed fauna from baited video camera system	Stationary video	2011 onwards	Wave Hub	Seasonal	UoE	Dr Matt Witt
Towed seabed transects using flying array	Towed video	2009-2010	Wave Hub	Annual	UoE	Dr Matt Witt
Modelled effort for inshore fisheries	Model	2007-2008	UK	Annual	UoE	Dr Matt Witt
Fisheries activity of vessels greater than 15m in length	VMS	2000-2007	UK	Variable	UoE	Dr Matt Witt
Reliability data	DMaC	01/01/11 - ongoing	A&P	various	UoE	Dr. L Johanning
Wave and Surface Current Fields	HF Radar	1 January 2011-31 December 2012	Approximately 40 km square region around Wave Hub	30 minutes	PU	Daniel Conley (daniel.conley@plymouth.ac.uk)

APPENDIX B – LIST OF REPORTS PRODUCED FOR THE WAVE HUB

Title of Report/Document	Number	Company	Importance for TSB project	Subject/Category	Date
A Brief Comparison Between In-Situ Wave Measurements and Modelled Wave Data for the RegenSW 'WaveHub' Site, Spring 2005	1	National Centre for Ocean Forecasting	4	Wave Resource and Wave Power	24/05/2006
Archaeological Assessment	2	SWRDA/Halcrow	6	Archaeology	01/06/2006
Coastal Processes Study Report	3	SWRDA/Halcrow	1	Coastal Processes	01/06/2006
Commercial Fisheries Study (Martin Esseen) - Final Report	4	SWRDA/Halcrow	6	Fisheries Study	01/06/2006
Concept Design Report (Rev 01)	5	SWRDA/JP Kenny	1	Design and Development	30/01/2009
Concept Outline Description	6		1	Design and Development	?
Consents and Permitting Considerations	7	Bond Pearce	1	Feasibility - Legal	01/01/2005
CPA Licence (Cable Installation)	8	MMO	1	Consents	24/08/2010
CPA Licence (Wave Rider Buoys) - Amended	9	Marine and fisheries agency	1	Consents	17/09/2007
Design Basis (Rev 03)	10	JP Kenny/METOC	10	Design and Development	29/04/2009
Development of Wave Energy in the South West	11	Garrad Hassan	1	Wave Resource	11/02/2008
Environmental Baseline Survey Report - Vol I	12	SWRDA/Halcrow	3	Environmental	31/05/2006
Environmental Baseline Survey Report - Vol II	13	SWRDA/Halcrow	5	Environmental	01/06/2006
Environmental Impact and Appraisal - Gaining Planning Consent for the South West of England Wave Hub (EWTEC 2007)	14	SWRDA/Halcrow	1	Consents	01/09/2007
Environmental Statement (Appendices not inc)	15	SWRDA/Halcrow	9	Environmental	01/06/2006
FEPA Licence (Construction)	16	MMO	1	Consents	24/08/2010

Final Design Report	17	SWRDA/Halcrow	4	Design and development	01/06/2006
Fisheries Evaluation Report	18	MacAlister Elliot and Partners	5	Fisheries Study	28/02/2008
Geotechnical Report, laboratory and in-situ data - Wave Hub detailed offshore survey.	19	Halcrow	5	Ground Conditions	19/01/2006
Interpretation of Geotechnical and Geophysical Conditions of the Revised Wave Hub Site and Offshore Cable Route (Amendment)	20	SWRDA/Halcrow	8	Ground conditions	01/01/2007
Interpretation of Geotechnical and Geophysical Conditions of the Wave Hub Site and Offshore Cable Route	21	SWRDA/Halcrow	10	Ground Conditions	01/05/2006
Landscape & Visual Impact Assessment	22	Met Office	1	Visual Impact Assessment	?
Marine Energy - A New Industry in the Making brochure	23	SWRDA	1	Marketing	01/02/2010
Marine Licensing (Exempted Activities) Order 2010	24	DEFRA	2	Consents	?/2010
Metoc Wave Data - Location E04	25	SWRDA/Metoc	7	Wave Resource and Wave Power	04/02/2004
National Laboratory Service Analysis Report of Batch Samples	26	SWRDA/Halcrow	1	Environmental	01/06/2006
Navigation Risk Assessment	27	SWRDA/Halcrow	1	Maritime Navigation Risk Assessment	01/06/2006
Navigation Risk Review SW Wave Hub Development FINAL 02	28	Anatec	1	Navigation	26/01/2009
Non-Technical Summary	29	SWRDA/Halcrow	10	Summary of Project	01/06/2006
Offshore Renewables Resource Assessment and Development (ORRAD) Project -Technical Report	30	PMSS	1	Offshore Energy	01/10/2010
Report on Terrestrial Ground Investigations	31	SWRDA/Halcrow	1	Ground Investigations	01/04/2006
Review of Wave Hub Technical Studies: Impacts on Inshore Surfing Beaches	32	ASR	1	Coastal Processes	12/04/2007
Review of Wave Measurement Technology	33	Applied Wave research	8	Wave Resource and Wave Power	18/10/2006

Safety Zone Application Letter to DECC - Revised	34	DECC	4	Safety Management	05/03/2010
Seapower South West	35	RegenSW	1	Wave Power	01/10/2003
Seapower SW Review - Resources, Constraints & Development Scenarios for Wave and Tidal Stream Power in the South West of England	36	Metoc/SWRDA	4	Wave Resource and Wave Power	01/01/2004
Section 36 Consent Letter to South West RDA	37	DBERR	1	Consents	17/09/2007
Shipping Review - SW Wave Hub Development, AIS survey to show effects of extended TSS	38	Anatec	5	Navigation - AIS Review	06/05/2010
Subtidal Benthic Survey of the Wave Hub V.3	39	SWRDA/Halcrow	2	Environmental	01/06/2006
Summary Business Case - Final	40	Arthuer D Little	4	Business Case	10/02/2005
SW Wave Hub Cable - Sea Bed Sediment Study	41	JP Kenny/METOC	1	Design and Development	28/04/2009
The Wave Power Climate at the Wave Hub Site	42	SWRDA	7	Wave Resource and Wave Power	07/11/2006
Wave Energy Converters Mooring System Study	43	SWRDA/Halcrow	9	Moorings	01/05/2006
Wave Hub Environmental Impact Assessment - Extended Phase 1 Habitat Survey	44	SWRDA/Halcrow	4	Environmental	01/06/2006
Wave Hub Environmental Impact Assessment - Intertidal Bird Surveys	45	SWRDA/Halcrow	1	Environmental	01/06/2006
Wave Hub Environmental Impact Assessment - Offshore Bird Surveys	46	SWRDA/Halcrow	5	Environmental	01/06/2006
Wave Hub Geophysical Survey - Final Report	47	EGS	9	Ground Conditions	01/01/2006
Wave Hub Hydrographic Survey for Archaeological Assessment	48	EMU	4	Archaeology	01/01/2009
Wave Hub Intertidal Studies	49	SWRDA/Halcrow	2	Intertidal Studies	01/06/2006
Wave Hub Technical Feasibility Study - Operations & Maintenance (Task 8B)	50	SWRDA/Halcrow	4	Feasibility	01/02/2005
Wave Hub Wave Monitoring Project - Interim Report #1 FINAL	51	SWRDA/Halcrow	4	Wave Resource and Wave Power	01/06/2009
Wave Hub Wave Monitoring Project - Interim Report #2 FINAL	52	SWRDA/Halcrow	3	Wave Resource and Wave Power	01/10/2009

Wave Hub Wave Monitoring Project - Interim Report #3 FINAL	53	SWRDA/Halcrow	3	Wave Resource and Wave Power	01/02/2010
Wave Measurement off North Cornwall: Comparison of Recorded Wave Data at Cornwall with Met Office Data	54		5	Wave Resource and Wave Power	26/06/2006
Wave Measurement off North Cornwall: Comparison of Recorded Wave Data at Cornwall with Met Office Data	55		5	Wave Resource and Wave Power	04/07/2006
Wave Measurements St Ives Cornwall - 30 January 2005 to 10 April 2006	56	Fugro	4	Wave Resource and Wave Power	01/06/2006
Waves - supporting information	57	SWRDA/metoc	2	Wave Resource	04/02/2004
WEC Connection Specification (Rev 03)	58	SWRDA/JP Kenny	5	Design and Development	01/05/2009
WEC Instability once connected to Wave Hub System - Technical Note	59		6	System Availability	07/11/2007

APPENDIX C - PAPERS PUBLISHED BY UOE AND PU PRIMARE ACADEMICS

Environmental and Biodiversity Impacts

- **Grecian, W.J., Witt, M.J., Attrill, M.J.,** Bearhop, S., **Godley, B.J**., Grémillet, D., Hamer, K.C., **Votier, S.C.** (2012). A novel projection technique to identify important at-sea areas for seabird conservation: an example using Northern gannets breeding in the North East Atlantic. Biological Conservation.
- **Witt, M.J., Sheehan, E.V**., Bearhop, S., Broderick, A.C., **Conley, D.C., Cotterell, S.P**., Crow, E., **Grecian, W.J**., Halsband, C., Hodgson, D.J., et al (2012). Assessing wave energy effects on biodiversity: the wave hub experience. Philos Transact a Math Phys Eng Sci, 370(1959), 502-529.
- **Votier, S.C.,** Bearhop, S., **Witt, M.J., Inger R.** et al (2010) Links between commercial fisheries and centrally placed marine predators:studying individual level responses using GPS tracking, stable isotopes and vessel monitoring systems. Journal of Applied Ecology 47:487-497.
- **Grecian W.J., Inger, R**., **Attril, M**., Bearhop, S., **Godley, B.J., Witt, M.J**. **& Votier S.C**. (2010) Potential impacts of wave-powered marine renewable energy installations on marine birds. Ibis *152*, 683-697.
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- **Witt, M.J. & Godley, B.J.** et al (invited) On assessing the biodiversity impacts of wave energy: Lessons from the Wave Hub. Philosophical Transactions of the Royal Society A.

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- Leeney, R., Broderick, A.C., **Witt, M.J.** et al (2010)Abundance, distribution and haul-out behaviour of grey seals (Halichoerus grypus) in Cornwall and the Isles of Scilly, UK. *J MAR BIOL ASSOC UK, 90*(5), 1033-1040.
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- **Votier SC**, Hatchwell BJ, Mears M, Birkhead TR; (2009) Changes in the timing of egg-laying of a colonial seabird in relation to population size and environmental conditions. MAR ECOL-PROG SER ; 393, 225-233
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- **Ashton I.G.C.** (2011) Spatial variability of wave fields over the scale of a wave energy test site University of Exeter.
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21.01.2011