Tidal Resource Assessment of the Little Russel

By

Stephanie Louise Campion

Thesis submitted to Plymouth University

in partial fulfilment of the requirements for the degree of

MSc Marine Renewable Energy

Plymouth University

Faculty of Science & Technology

In collaboration with

Guernsey Renewable Energy Team (RET)

September 2012

Disclaimer

The following document has been produced by a student at the University of Plymouth, working in partnership with the Renewable Energy Team, for their dissertation and so is an independent document. As such, while the study is endorsed by RET and was undertaken in conjunction with RET, there may be views expressed and conclusions drawn that are not shared by RET. There may also be some factual inaccuracies within the report, and whilst we appreciate them being brought to our attention, we are unable to alter them.

Copyright statement




Tidal Resource Assessment of the Little Russel

Guernsey Renewable Energy Team (RET)

Marine Institute
UNIVERSITY OF PLYMOUTH

Guernsey

Tidal Stream Resource Assessment of the Little Russel

September 2012

Report Commissioned For:

STATES OF GUERNSEY

Guernsey Renewable Energy Team
States of Guernsey
P.O. Box 459
Raymond Falla House
Longue Rue
St Martins GY1 6AF

Report Commissioned By:

Stephanie Louise Campion
Msc Marine Renewable Energy
University of Plymouth
Drake Circus
Plymouth
Devon
PL4 8AA

Table of Contents

Table of Figures

Table of Tables

Appendices

Equations

Abbreviations & Units

APD-average power density

TW/h -Terra Watt Hours

MW/h-Mega Watt hours

TEC –Tidal Energy Converter

GREC-Guernsey Renewable Energy Commission

RET-Renewable Energy Team

CIEG-Channel Islands Electricity Grid

RGU-Robert Gordon University

EMEC_ European Marine Energy Centre

NREL-Neptune Renewable Energy Ltd

BWEA- British Wind Energy Associate

C&E-Commerce and Employment

ADCP-Acoustic Doppler Current Profilers

MATLAB- Matrix Laboratory

(V_{mn})-Mean neap velocity

(V_{ms})- mean spring velocity

(M_2)- Main lunar tidal constituent

(S_2)- Main solar tidal constituent

Acknowledgements

I would like to thank Dr Phil Hosegood for his support and guidance through this project and for facilitating the engagement of Guernsey RET with Plymouth Marine Renewable energy students.

I would also like to thank Mat Desforges and Peter Barns for their encouragement and communication.

I would also like to acknowledge the support and feedback received from MRE 2012 students.

Lastly, I would like to thank my friends and family. Without their continual support throughout I would not have been able to achieve what I have to date. Thank you.

1. Executive Summary

The Guernsey Renewable Energy Team (RET) is a division set up by the States of Guernsey to explore, license, and regulate all forms of renewable energy for the Island of Guernsey and its surrounding territorial waters. This report was commissioned by Guernsey RET to conduct an investigative analysis to quantify the capacity of tidal streams around the island and assess the feasibility of harnessing energy from these resources.

The publication of Guernsey's 2011 Energy Resource Plan identified that "urgency is needed if we are to meet our low/zero carbon energy targets". The plan outlines an energy vision that aims to facilitate a gradual decarbonisation of Guernsey's energy generation, and to diversify energy production from low carbon and renewable sources. This study will look to contribute to the on-going effort, and previously commissioned research of the RET, in achieving the energy vision.

Currently, Guernsey only generates 22% of its electricity on Island, through diesel generators, owned by Guernsey Electricity. To meet their demand the remaining 78% of electricity is imported from France via the Channel Islands Electricity Grid (CIEG). The low level of self-generation presents a risk of energy security, with the addition of increasing fuel prices and market volatility. Moreover the Islands current energy demand continues to rise at approximately 3.5% per annum.

As an island, with recognised powerful tidal streams, located within the English Channel, Guernsey has a potentially affluent offshore resource. There are development barriers and constraints associated with the uptake of renewable energy such as; the cost of developing new resources, technical challenges and the environmental concerns coupled with the exploitation of natural resources. Conversely, there are many opportunities in the application of mature, cost effective renewable energy technologies such as; reduced climate change effects, improved energy security and diversification to the economy.

Previous studies which have been conducted on behalf of Guernsey RET by the Robert Gordon University (RGU), University of Exeter and Cranfield University identified significant tidal resources around the Channel Islands. Through the acquisition of in situ current measurement data from The Guernsey Water Company, an analysis of the tidal stream resources located within the Little Russel was able to be performed. Full assessment of the tidal stream velocities in conjunction with site characterization allowed for the selection and evaluation of suitable tidal stream technology.

The Little Russel presents operational challenges in terms of limited water depth, which is the primary restriction at this location hindering exploitation of the resource. Additionally the magnitude of the current is low compared to other potential tidal stream developments. With both of these factors taken into consideration the numbers of tidal energy converters (TEC) which are suitable for deployment within the Little Russel are limited.

The assessment site to the south of the Little Russel was found to have the greatest energy potential with an average power density of 0.09 kW/m^2. The only tidal turbine deemed suitable for deployment within this area was the NP1000 manufactured by Neptune Renewable Energy (NREL) Ltd. Deployment of a single turbine would generate 4.4Mw/h of electricity per month. By deploying an array of 5 devices, also known as a 'pod' a total of 264 MW/h of electricity could be generated for the island of Guernsey.

This resource assessment was conducted with consideration for the objectives of Guernsey's Renewable Energy Team (RET). This assessment should contribute to the on-going efforts to quantify the islands marine renewable energy resources and achieve the aim of the 2011 Energy Resource Plan.

2. Introduction

According to the British Wind Energy Associate (BWEA), in the 2009 state of the industry report for Marine Renewable Energy, "the U.K is at the forefront of the marine renewable energy industry through its research and development (R&D) programmes, test facilities and marine and offshore experience". The U.K tidal stream resource has been evaluated to be 110 TWh/year, with approximately 20% of this resource emanating from the Channel Islands, which is the second largest current resource in the United Kingdom (Black & Veatch 2005).

The Channel Islands are an archipelago made up of fourteen islands located off the coast of Normandy, France, in the English Channel. The administration of the Channel Islands falls under two British Crown dependencies; the Bailiwick of Guernsey and the Bailiwick of Jersey (BBC 2010). Guernsey has a population of 65,573 covering a total area of 78 square kilometres. The current electricity demand ranges from 24MW-84MW with an annual requirement of approximately 400,000 MW/h (GREC 2010).

It has been recognised for a long time that the Channel Islands are a significant location for tidal current energy which has attracted substantial interest from developers. As Guernsey is a British Crown dependency it holds ownership over their current territorial waters (3 nautical miles), which allows for territorial resources to be utilised in accordance to their system of governance (Owen, A 2012). As a result of this, there is potential for a more efficient and less complex licensing process than currently employed within the UK mainland, which is attractive to developers. To assist with the optimisation of the licensing process as well as the objectives of Guernsey RET, it is beneficial to know the capacity and location of the tidal current resources.

3. Project Scope

The purpose of this resource assessment is to provide an estimate, of the potential capacity for Guernsey, to harvest energy from selected tidal stream sites within the Little Russel which lays within the Islands 3 nautical mile territorial waters. The primary aim of the assessment is to evaluate the tidal stream resource and calculate the theoretical power available. In addition, an evaluation will be conducted as to whether or not energy extraction is technologically feasible at present or in the future. There will also be focus on the status of tidal stream technology, primarily to assess the most suitable devices for energy extraction at each site. The capacity estimates calculated from this assessment are a realistic estimate of energy potential given current technological capabilities.

3.1.1. RET objectives

The 2008 Energy Policy which was noted by the States of Guernsey gave the department of Commerce and Employment (C&E) the mandate to progress local macro marine renewable energy (States of Guernsey, 2012). This directive was then delegated to the RET in its creation in 2010. The policy, in combination with the 2011 Energy Resource Plan support the States commitment to generate 20% of the islands electricity demand from renewable sources by 2020 (Channel Television, 2011).

As well as the overarching targets set out in the 2008 Energy Policy and the 2011 Energy Resource plan there are also individual aims the RET. To ensure that scope of the project supports the objective of Guernsey Renewable Energy Commission (GREC), and falls within the remit of Guernsey RET, the team's primary objectives must be taken into consideration. The objectives are listed on Guernsey's renewable energy team (RET) webpage http://www.guernseyrenewableenergy.com/about/About-RET.aspx; which are;

- Prepare an initial Environmental Assessment (EA) - this strategic study will establish the likely environmental impacts associated with the deployment of Marine Renewable Energy devices in the seas around Guernsey.
- Develop a consenting regime - to control and permit the deployment and operation of devices and associated works such as cabling and shore connections.
- Develop Policy - We are aware that the introduction of renewable energy has the potential to impact, on numerous other aspects of life on Guernsey. We are working closely with the other Channel Islands, the Guernsey Renewable Energy Forum and the relevant departments within the States to ensure that Renewable Energy is smoothly integrated into our way of life.
- Attract Developers - With the potential to establish a very powerful energy resource, located so close to our shores, we hope to attract responsible energy developers to Guernsey who will want to generate energy for domestic sales or export to Europe. We will work to ensure that we get the best deal for Guernsey in benefiting our environment, reducing our carbon emissions, and in terms of the commercial arrangements.

4. Assessment methodology

4.1.1. Standard tidal analysis methods

To fully quantify the tidal stream resources present at any given location, and for the calculation of energy production from a tidal stream project, there a number of factors which have to be taken into consideration such as:

- The tidal current velocity and the naturally occurring variation resulting through each tidal cycle and each spring-neap cycle;
- The relationship between the water column velocity and the extractable power of the turbine in the form of the Power Curve (Craig, 2007).

The factors listed above are supported by the European Marine Energy Centre (EMEC) within their guidelines for Tidal Resource Assessment. Additionally, it is advised that the device characteristics are defined in the form of:

- power curve;
- cut-in speed;
- rated speed;
- losses within the gearbox, power converter, electrical and transmission system;
- availability (EMEC, 2012)

Where possible, the method parameters defined above will be applied in the completion of the resource assessment for the Little Russel. To fully assess the potential of the tidal stream sites within the channel it was important to effectively analyse data which (i) had been directly collected from the assessment zones through a reliable and quantifiable method, (ii) was recorded over a large enough time frame to allow for temporal representation of environmental fluctuations and cycles. As stated by EMEC (2012) “at least 30 days data from one or more bottom-mounted fixed-position Acoustic Doppler Current Profilers (ADCPs) is likely to be required in order to fully characterise the flow at a given site”. The data analysed within this assessment satisfies these standards as it was collected over a 35 day period by three separate ADCP’s deployed throughout the Little Russel, which is detailed in section 5.

This assessment of the renewable energy potential will also rely on previously published reports conducted on behalf of Guernsey RET, as well as existing literature and publically available information.

4.1.2. Data analysis methodology

The methodology discussed within this section was applied during the analysis of all three assessment sites.

The original data as collated by Titan Environmental Survey's Ltd was provided in the format of .txt and .xlsm files. At this point the data had undergone minimal processing with SeaZone Geo-Temporal Editor. The files were imported into high level technical computing software (MATLAB, 2011) so that it could undergo processing.

Initially, the data was sorted so that current speed, direction and velocity were allocated in a logical time step of ten minute intervals for their given depth bin. To remove anomalous values a smoothing function was used which applied a moving average filter throughout the data set with a default averaging range of five.

To create a visual representation of current magnitude and primary current direction pseudo colour velocity profiles were created. The month's long profiles were reduced to show a 12.25 hour tidal cycle, for the two spring and two neap tides which occurred at each assessment site. The profiles created at this stage were representative of the full vertical magnitude from seabed to surface, thus included all bin depths. This allowed for the current to be examined throughout a flood and ebb tide as well as between slack water and high water which was representative of the full dataset variability. For the remainder of the analysis as well as computation of power, the peripheral depth bins were discounted given there close proximity to the free surface, to prevent data contamination.

i) Harmonic analysis

As part of the data processing standards followed for this assessment (EMEC, 2012) harmonic analysis was applied using function toolbox - 't-tide toolbox', (Pawlowicz, Beardsley and Lentz, 2002) within MATLAB. The shape of the Little Russel as depicted by the topography of the Guernsey coast, does not have a directly north to south orientation. Through visual assessment it was calculated that site H1, which is nearest to the coast in the middle of the channel, has an orientation of 20 ^{0} north. Sites H2 and H3 were calculated to have an orientation of 10 ^{0} north. The velocities were rotated to match the channel orientation by applying a cosine equation. By doing this the east velocity component (U) was represented as a vector across the channel, and the north velocity component (V) was represented as vector along the channel. Horizontal currents are two dimensional (Bryden *et al*, 2007) which meant that the individual constituents could be combined and reported using the following ellipse parameters;

$$u = A cos\ \sigma\ t + A' sin\ \sigma\ t$$

$$v = B cos\ \sigma\ t + B\ ' sin\ \sigma\ t$$

The supporting equations for the theory of harmonic analysis are discussed within section 7.1.3. The analysis was conducted using 59 standard tidal constituents, which are detailed in appendix A. The purpose of applying the harmonic analysis was to achieve the following outputs;

1. Maximum current velocity that occurs along both the Semi-major and Semi-minor axis
2. Inclination of tidal ellipse
3. Phase angle of maximum velocity with respect to Greenwich time

The outputs above were extracted for the principal lunar tidal constituent (M_2). They were analysed to determine if; (i) there was any decay in the current velocity with increased depth caused by sheer from the seabed and, (ii) to determine the level of velocity flowing perpendicularly through the channel along the semi-minor axes. A velocity profile was created displaying how the flow of the current varies within the vertical across and along the channel and therefore determining the optimum height which a TEC should extract kinetic energy from. This is an important aspect to consider as turbines have a finite vertical extent across which the velocity might vary. Furthermore, analysis of the tidal ellipse orientation helps to assess the angle of the current along the semi-major axis. This is an important consideration in relation to device positioning, as the maximum extractable power will only be achieved from the current passing through the centre of the turbine (Bryden, 2007).

ii) Velocity distribution

The speeds of tidal currents cannot simply be represented by a generalised probability distribution function due to the fact that they are governed strongly by the deterministic harmonic constituent functions, which are site specific. Therefor to generate a profile of the velocity distributions for a site specific history of tidal current speeds a histogram analysis needs to be applied (Hagerman and Polagye, 2006).

To determine how the speeds were distributed at each site a histogram analysis was performed using the results from the tidal harmonic analysis. Ten minute intervals were used as the standard time count and velocity ranges of 0.1 m/s as the bin size (EMEC, 2012). A ten minuet time averaging is an appropriate interval for such a dynamic environment. It is a fair approximation that the velocity is constant for the given speed throughout that period. The number of velocity occurrences per bin were recorded and converted to a percentage of occurrences, then integrated over time for each interval. Once the velocity distributions were obtained for the sites, the distribution of power density could be calculated and then averaged to define the average power density (APD) per site (Hagerman and Polagye, 2006). To calculate the mean spring velocity (V_{ms}) and mean neap velocity (V_{mn}) an average was taken over the spring and neap tidal cycles which occurred throughout the measurement period.

iii) Calculation of power

From the preceding harmonic analysis it was determined that the frictional effects of the seabed can be negated due to the fact that there was no visible decay in velocity with depth along the semi-major axis. Therefore the height in the vertical, at which the specific value of velocity (V) to calculate power would be obtained from, is irrespective in relation to shear. With this being said, the turbine depth beneath the sea surface had to be accounted for. This is to ensure that the velocity and power density averaged over the swept rotor area of the turbine could be determined (Hagerman and Polagye, 2006). Thus the depth chosen for each site represented this range and velocity bin No 8 was selected corresponding to 5.3, 9.9, and 5.3 meters above the seabed for sites H1, H2 and H3 respectively.

Tidal currents which occur within channels are topographically constrained, and as a result the flow is nearly always rectilinear along the axis of the channel (Forrester, 1983). In this case, tidal current prediction can be limited to one component direction, that which flows along the semi-major axes of the channel.

The tidal stream power density, as stated by Hardisty (2009), is "the kinetic energy of the fluid which passes through a unit area of the flow normal to the dominant flow direction". To calculate the average power density (APD), the given velocity component (V), at the selected depth bin, was applied to (Equation 2), and calculated over a thirty day time series of ten minute intervals. To ensure that the calculated power density was within the expected range for the current speeds experienced within the Little Russel, the data was validated against results from the electronic power research institute (EPRI). It was established by EPRI that incident power density as a function of speed for currents between 0.5-1.5 m/s ranges between 1-4 Kw/m^2. Form the derived parameters of (Equation 2) the mean electrical output per bin was calculated by applying (Equation 3).

Calculation of the instantaneous power extractable by the selected tidal energy converters (TEC's) was performed using (Equation 4). This provided a representation of the extractable power for a cross-sectional area of the tidal flow, captured by the diameter of the swept rotor area, taking the device capacity factor into account. As a result, the monthly total device power output could be determined at each assessment site for the TEC's under examination.

5. Data Acquisition & Site Characterisation

5.1.1. Data acquisition

The Data analysed, which forms the basis of this report, was gathered by Titan Environmental Surveys Ltd on behalf of Guernsey Water Company. The information was collected through the deployment of three bedframe mounted 600MHz Acoustic doppler current profilers (ADCP's) (Appendix B). The ADCP's were deployed from the 19.07.2011-24.08.2011 providing a total of 37 days (35 complete days) for analysis.

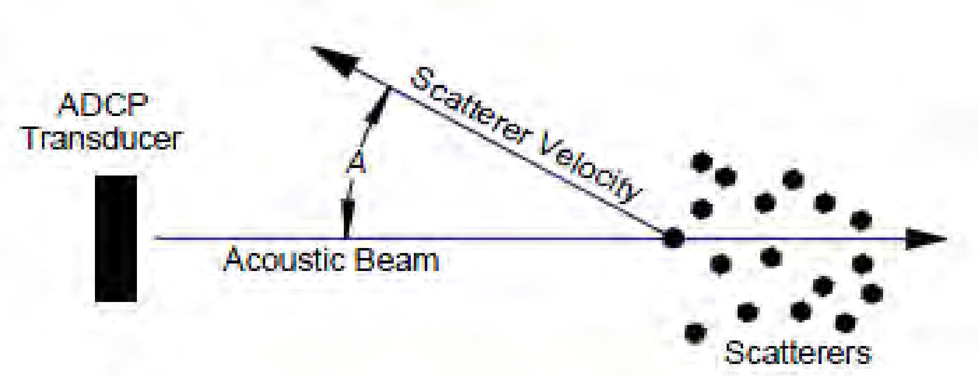


Figure 5.1.1: Relative velocity vector. The ADCP measures only the velocity component parallel to the acoustic beams. A is the angle between the beam and the water velocity (RD Instruments RDI , 1996).

An Acoustic Doppler current profiler (ADCP) is a device which uses an acoustic signal and the principle of the Doppler shift to measure current velocities. Applying the Doppler shift allows for calculation of the current velocities at different depths; the following equation (1) accounts for transmitted and received signals and for radial motion (Armijo 2007), displayed in figure 5.1.1

Equation 1: Doppler Shift equation with radial component

$$F_d = 2F_{s\,V/C}\cos(A)$$

Where Fd = Doppler shift frequency, Fs = frequency of sound (standing still), V = relative velocity (between source and receiver), C = sound speed (m/s) A = angle between acoustic beam and scatter velocity (Gordon, 1996).

The instrument emits an acoustic signal "ping" and then measures the rate of the return echo from backscatters in the water, which measures the current velocity to produce a "current profile". The ADCP uses a multiple beam solution to calculate the current velocities and assumes the currents are homogenous throughout the water column. Trigonometric relations are then applied between the beams to calculate three-dimensional current velocity vectors that represent the u, v and w directional components (Armijo 2007).

5.1.2. Assessed Sites

The Channel Islands are located on the western margin of the Normandy-Brittany Gulf, in close proximity to the boundary with the western English Channel. The islands, in general, have a low topography and are surrounded by shallow offshore shoals and rocky coastlines. The currents within the Gulf are influenced locally by the complexity of the number of islands and shoals present. The Gulf is known to fill and empty rapidly in all directions due to the large amplitude of tidal range. The tidal currents operate in an anticlockwise gyre, but localized differences within narrow passages or in close proximity to islands can transform the gyre into an alternating tidal current. This is particularly prominent in both the Big and Little Russel to the east of Guernsey (GREC-REA, 2011).

The Little Russel is a channel of water which flows between the east coast of Guernsey and the west coast of Herm, approximately 3 nautical miles wide. There were 3 sites at which ADCP's were deployed throughout the channel, displayed below in the figure 2, (a larger version of which can be found in Appendix C). Site H1 is located east of St. Peter Port, near the centre of the Little Russel, with an average water depth of 14.5m; site H2 is located in the Northern end of the channel in an average water depth of 16.5m; and site H3 is located in the southern end, in an average water depth of 11.5 meters. As the ADCP's were deployed throughout the channel this should allow for data to be acquired that reflect longitudinal variation within the tidal currents.

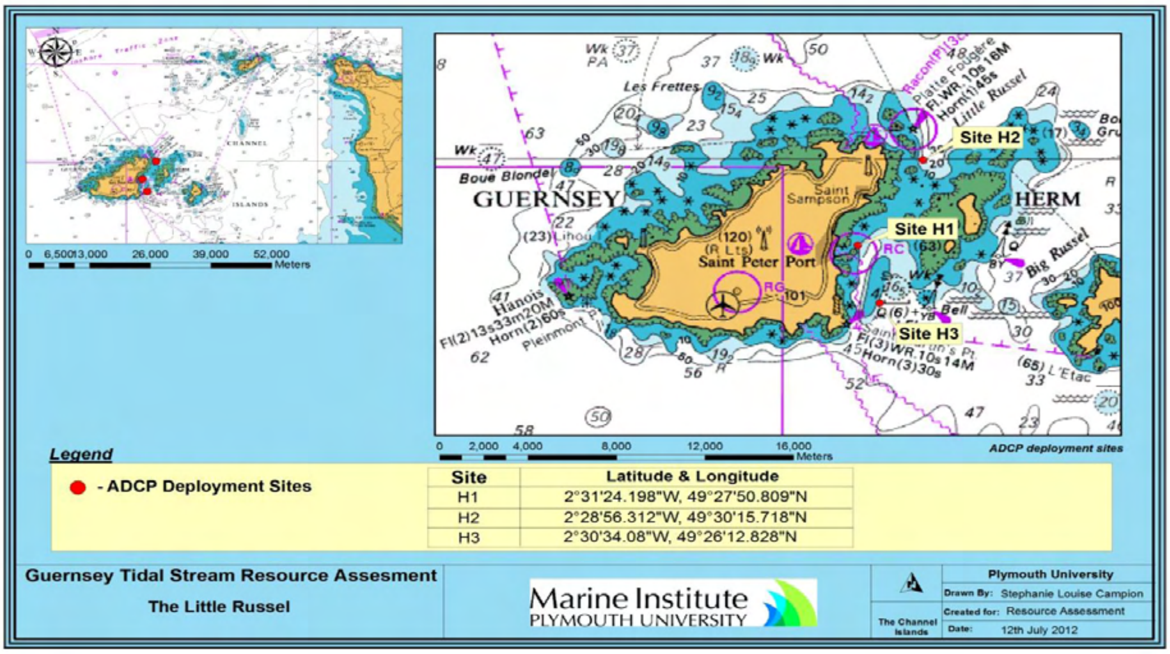


Figure 5.1.2.1: ADCP Deployment sites located within the Little Russel

The tidal elevation within the Little Russel ranges from 7.6m (site H2) to 8.9m (site H3). The tides are semi-diurnal showing sinusoidal oscillation containing two main cycles per day. There is also presence of a strong fortnightly cycle of spring and neap tides, which is visible in figure 5.1.2.2. The fortnightly variations in tidal elevation amplitude are caused primarily by the main lunar (M_2) and Solar (S_2) tidal constituents. The resulting tidal currents generated over spring tides have a greater kinetic energy potential. Maximum tidal elevation occurs during the spring tide ensued by the new or full moon. The period of minimum elevation, at neap tide, occurs after the first and third quarter of the lunar phase. The dominant tidal constituent around the Channel Islands is the M_2 tide, also known as the 'principal lunar semi-diurnal', with a period of 12.25 hours (Hardisty, 2009).

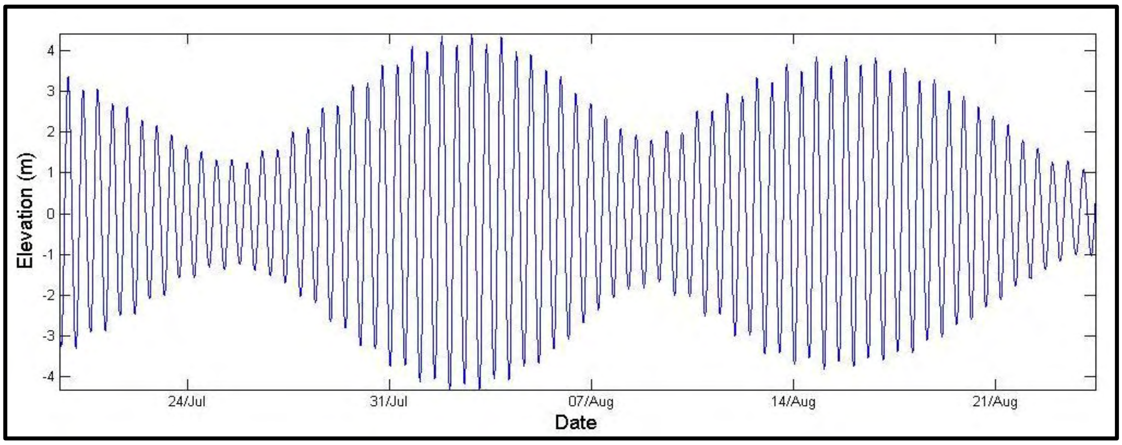


Figure 5.1.2.2: Tidal range for site H1 (8.78 meters) over ADCP deployment period

5.1.3. Primary site constraints

Shipping-The English Channel and the sea areas around the Channel Islands are essential shipping routes and at present there are a number of shipping measures to ensure these routes are controlled such as;

- Le Casquets' Traffic Separation Scheme (TSS), which assists large ocean-going vessels to navigate the shipping lanes of the southern English Channel.

- The Channel Islands Inshore Traffic Zone (ITZ), which prohibits vessels of over 20m in length from transiting through the ITZ unless they are bound for ports within the ITZ (GREC-REA, 2011).

The installation of any wave or tidal technologies will potentially cause disruption to navigation. More specifically, the Little Russel channel is utilised by Herm, and experiences shipping traffic travelling to or from the Marinas and harbours in Guernsey (Redman *et al*, 2011). Within GREC's Renewable Energy Assessment (REA) published in 2011, the Little Russel was identified as a 'pinch point' being particularly important for local and marine traffic and should be avoided as a potential deployment site if possible. It was also highlighted within the report that the risk presented is highly dependent on the extent which the device is located above or just below the sea surface. Assessment of this factor is discussed in greater detail throughout section 6.4. This is a strong point for consideration, however the primary focus of this report is to determine the exploitable resource and assess suitable technology, not to evaluate the development constraints.

Water depth-A further development constraint that has been identified is the shallow water depth of the Little Russel. The greatest water depth was recorded at site H2, of 20.1 meters. This is however, a maximum depth and is not inclusive of the tidal range experienced between tidal cycles. The majority of tidal stream turbines examined as part of this assessment require to be installed in water depths of greater than 20 meters. As identified by GREC (2009) the typical water depths for offshore deployment of tidal stream devices is 20-50m. This imposes a tight limitation on the available number of devices in the current technology market which can be deployed. This issue is discussed in greater detail in section 6.1.4.

5.1.4. Tidal energy potential

The Channel Islands is estimated to hold 28% of the UK's practical annual energy potential, from a 29TWh technical tidal current resource per year (Carbon Trust, 2011).

In earlier studies conducted on behalf of Guernsey RET the Little Russel has been identified as an energetic site, however it has never been fully assessed due to the constraints discussed in the preceding section. Therefore, it was important to validate the potential tidal stream speeds expected within the assessment area. The UK marine Energy Atlas (ABP-Marine Environmental Research Ltd, 2011) details both spring and neap peak tidal speeds around the Channel Islands as shown in (Figure 5.1.4.1). The spatial resolution available on the atlas does not provide clear detail of tidal flow within the Little Russel channel, but can be used as estimation for both the north and south extremities of the assessment zone. The neap-spring peak flow for the north of the channel ranges from 0.1-0.21 m/s. The neap-spring peak flow in the south of the channel ranges from 0.12-.24 m/s.

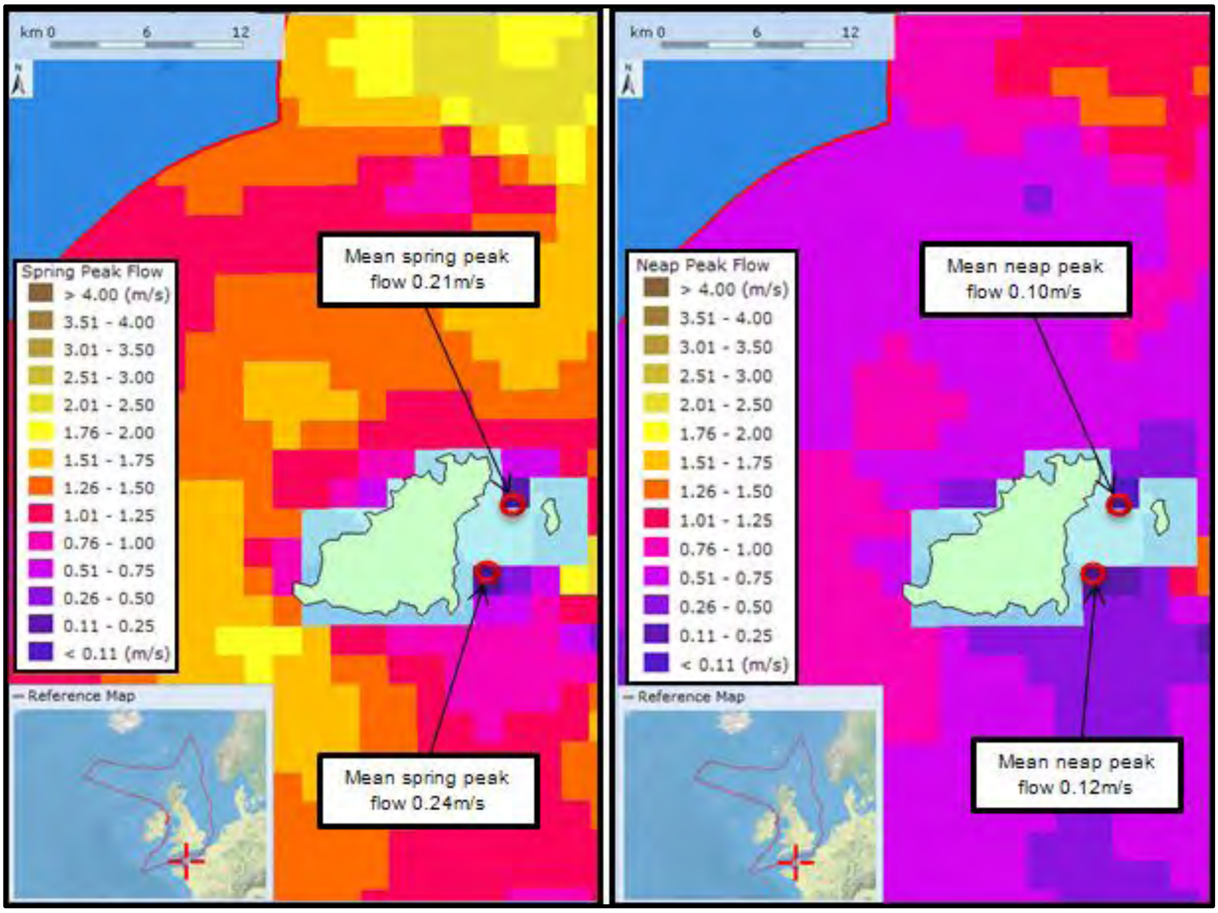


Figure 5.1.4.1: Tidal current flow maps of both spring peak (left) and neap peak (right) velocities for waters in close proximity to the Little Russel, Guernsey. Adapted from UK renewables marine energy atlas (APB-mer, 2011).

A further estimation of the tidal stream velocities can also be obtained from Previmer. This is a pre-operational system aiming to provide a wide range of users with short term forecasts about the coastal environment, along the French coastlines bordering the English Channel. Previmer was established as the Operational Coastal Oceanographic Centre (OCOC) with the aim of providing observation data, modelling tools and real time forecasts (Previmer.org, 2012). This image, (5.1.4.2) was taken from the interactive model on the Previmer website and shows the direction and velocity speeds of the surface currents passing around Guernsey. Again, the spatial resolution is not to a high enough level to allow for exact extraction of current speeds throughout the Little Russel, but moderate speeds are observable in close vicinity to the assessment zone.

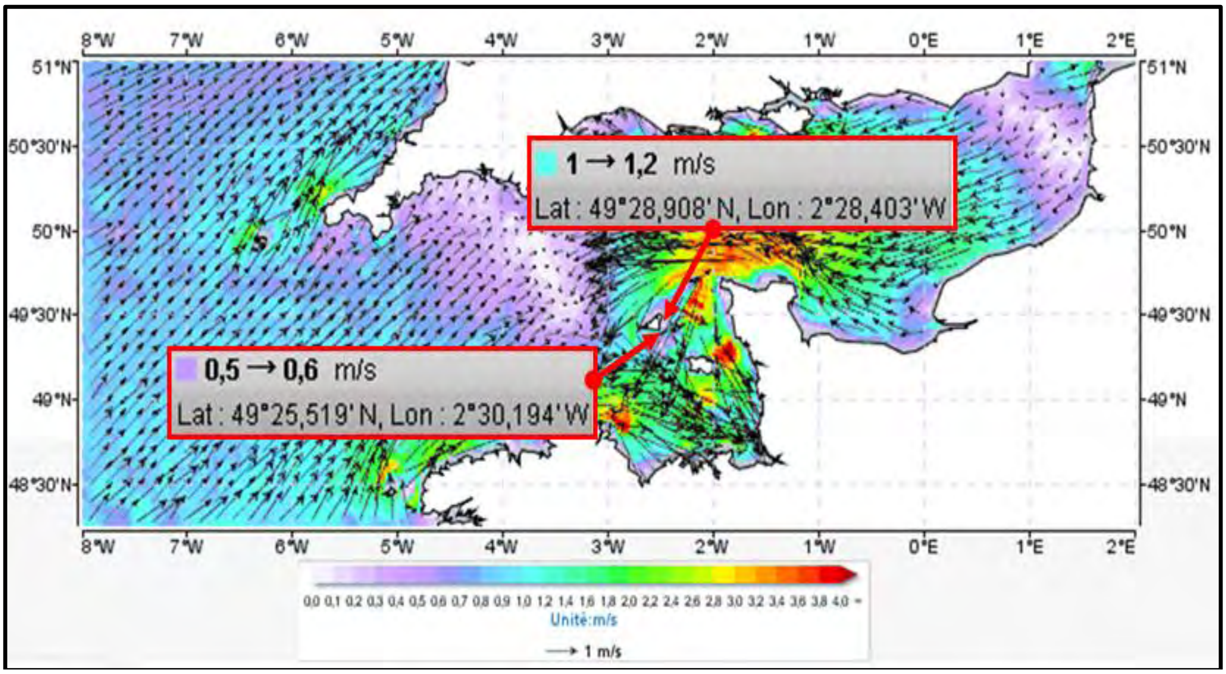


Figure 5.1.4.2: Image of tidal flow direction and tidal flow velocity for waters in close proximity to the Little Russel, Guernsey on the 20.08.2012. Adapted from interactive model (Previmer.org, 2012)

5.1.5. Bathymetry

The bathymetry of a potential renewable energy development site is an important consideration, due to the fact that it not only dictates the water depth for device deployment but also influences the quality and direction of flow.

The presence of topographic features such as peaks and troughs, have the ability to overlay multidirectional flow into the existing mean flow. Contributory to this would be the indirect effects on power quality and turbine stress (Owen, 2010).

The magnitudes of tidal stream velocities in a specific location are highly dependent on the shape of the coastline and the sea bed. Tidal currents which are constrained by the narrowness of the cross sectional areas of flow, experienced between main lands or islands, are amplified (Gomez, 2008). Environmental studies and analysis of bathymetry are an essential requirement within the site assessment stage, with both the water depth and speed of tidal currents being the main parameters dictating the viability of a site (Callaghan and Boud, 2006).

The bathymetry for Guernsey and the surrounding waters is displayed in Figure 5.1.5.1. The raw bathymetry file was obtained from Emodnet hydrography portal; this was in the format of 15 arc second bathymetry. The original files where downloaded in .xyz format, then manipulated in MATLAB to change coordinate systems from WGS36 to UTM30 then resaved as the appropriate .xyz file.

The bathymetry image was created by importing the UTM30 .xyz file of the Channel Islands into Delft-3D by Deltares Systems, which is an integrated modelling suite. The water depths within the Little Russel depicted from the bathymetry data, range from 5-20 meters, not exceeding 25 meters. This data is validated from the depth recordings obtained from the direct deployment of the ADCP devices.

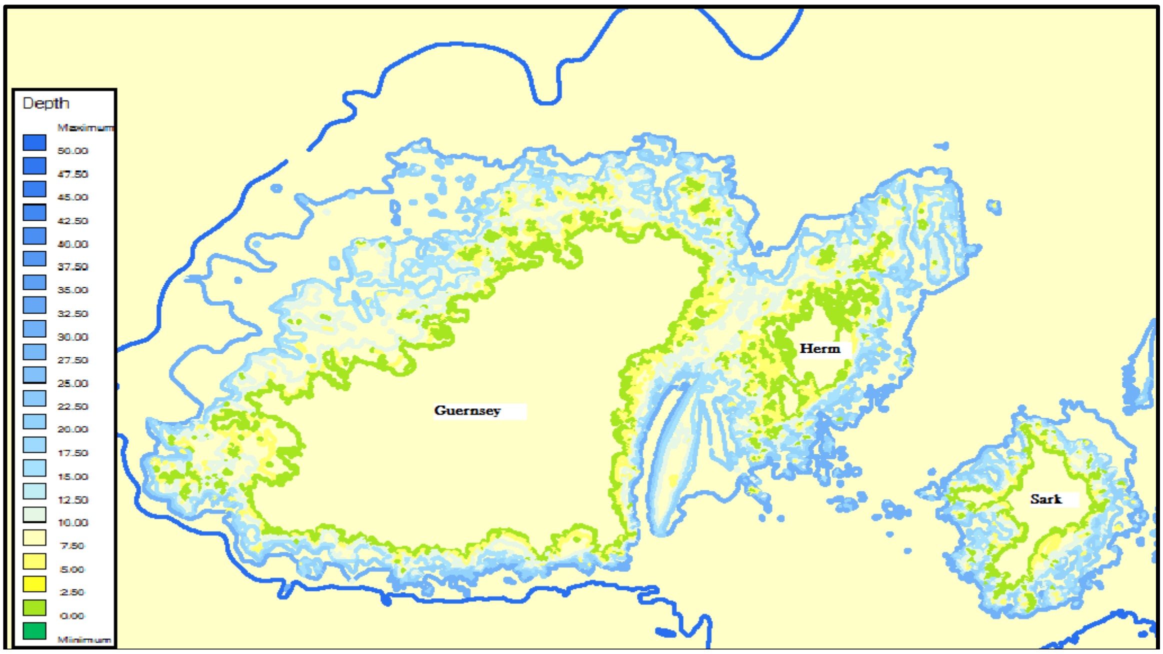


Figure5.1.5.1: Bathymetry of Guernsey, Herm and Sark indicating water depth present within the Little Russel

5.1.6. Bedrock Geology and Sediment

The geology and seabed composition play a significant role in the determination of site suitability and device selection. If the seabed is composed of mud or muddy sediments, this can present unfeasible environmental conditions for the installation of turbines. Furthermore the seabed composition can have bearing on aspects such as securing moorings or anchoring systems as well as affecting the stability of devices (Redman *et al* 2011).

The geological formation of the seabed substratum at the Channel Islands and surrounding offshore locations were forged during different geologic ages. This has resulted in different rock layers occurring on the islands of Alderney, Guernsey, Herm and Sark together with their formation as identified by Moore's and Fairbridge (2006).

As can be seen in Figure 5.1.6.1 the period of the rock formation present around Guernsey and for the Little Russel is Palaeozoic (including Cambrian and Cambrian Ordovician) and Proterozoic. The bedrock associated with these geological formation periods are Sandstone and Gneiss, which are rated medium-strong in terms of hardness (Redman et al 2011). In general, the solid bedrock geology indicates that the area is heavily faulted of limestone, chalk and sandstone, with a number of igneous (volcanic) intrusions (GREC-REA, 2011).

The solidity of the seabed effects the ease of installation of TEC's wither that be for drilling, to secure moorings or to mechanically force a pile (pile driving) into the ground (Redman et al 2011). The majority of tidal stream devices are deployed on the seabed through gravity base installation and therefore would not be restricted by the strength of the bedrock. Nevertheless, a specific assessment of the environmental conditions would always need to be conducted to assess the site suitability for specific device installation.

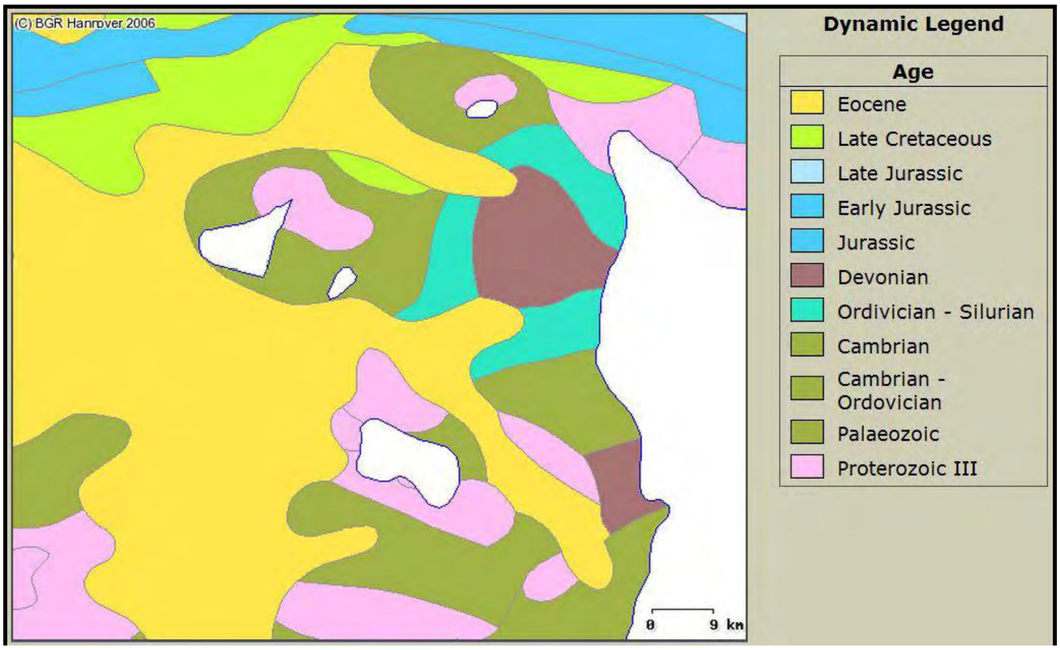


Figure 5.1.6.1: Bedrock geology for the Channel Islands. Sourced from- BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), German Federal Institute for Geosciences and Natural Resources (2011)

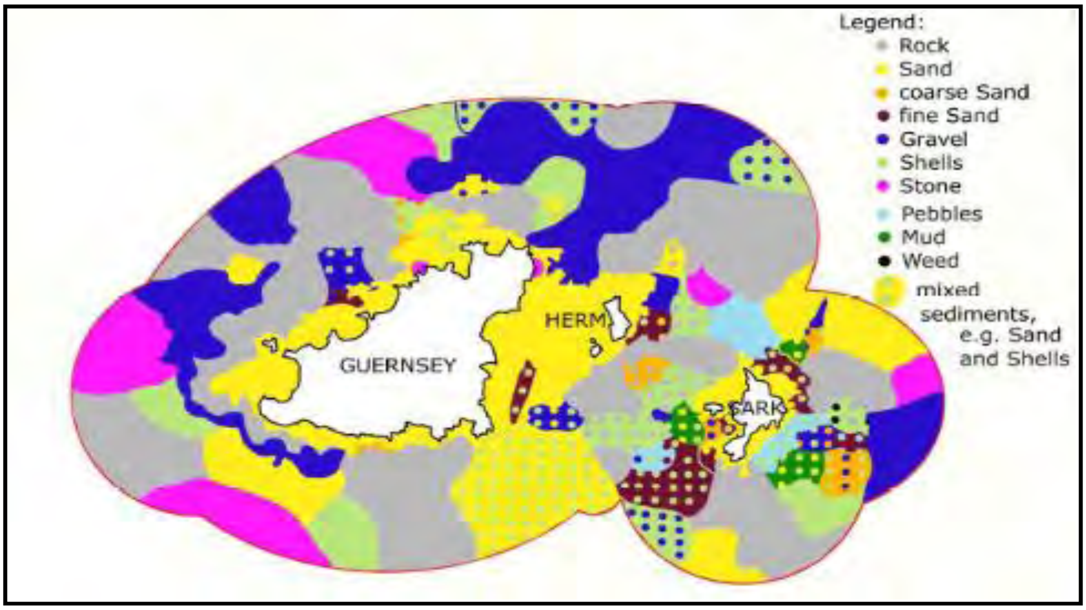


Figure 5.1.6.2: Composition of seabed material present around Guernsey, Herm and Sark (Redman *et al*, 2011)

For TEC's which will undergo gravity base deployment sediment composition of the seabed plays an essential role in site selection. It will also heavily depict the design and routing of grid connections and underwater cabling. A total of 10 different sediment types have been observed around Guernsey, Herm and Sark as shown in Figure 5.1.6.2. The dominant sediment class which was found within the Little Russel is a combination of sand and fine sand.

5.1.7. Site conclusions

In summary, the majority of physical characteristics of the Little Russel appear to be decidedly sufficient for the installation of tidal stream technology. The Little Russel is a narrowed channel of water situated between two land masses, which will experience increased tidal flow due to the nature of its location and surrounding water masses. The composition of the substratum is of firm enough material as to support the deployment of substantially weighted technology. Additionally, the primary seabed material within the Little Russel is sand, which is a perfectly suitable material to support the deployment of turbines (Open Hydro Ltd, 2011). The primary limiting factor, as highlighted through the bathymetric map, is the shallow water depth. This issue in relation to tidal stream conversion technology is discussed in greater depth in section 6.1.4.

6. Marine Tidal Streams & Technology

6.1.1. Tides

In its simplest form 'tides' can be described as the rise and fall if water bodies due to the gravitational interactions of the celestial bodies within our solar system (SKM, 2006). This rise in fall results in the range of tidal patterns exhibited throughout the world with a semidiurnal tide (two high and low tides per day) being prominent throughout the oceans. With each tidal succession (high to low) occurring in a period of 12 hours and 25 minutes, repeated twice within one lunar day (Redman *et al,* 2011). The alignment of the Moon, Sun and Earth occurs periodically at 28 day intervals, causing the power of the tides to be enhanced or decreased, in the form of spring and neap tides (SKM, 2006). As gravitational force is increased when 180^0 alignment of the astronomic bodies occurs, spring tides are not only greater in height, but often have greater amplitude. Neap tides are subjected to a lower level of gravitational force as they occur during the first and last quarter phase of the moon when the resulting earth-moon axis is at 90^0 to the earth-sun axis (Redman *et al,* 2011).

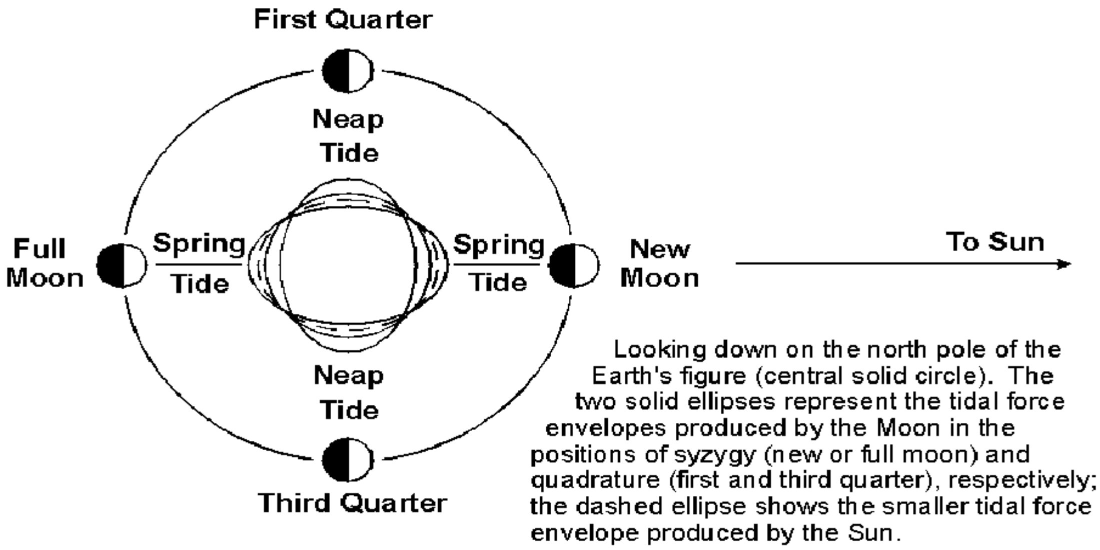


Figure 6.1.1.1: Diagram of spring and neap tidal occurrence in relation to moon phases (International Federation of Surveyors (FIG), 2012)

6.1.2. Tidal current energy

Tidal current energy (or hydrokinetic) can be defined as the direct extraction of kinetic energy from naturally occurring tidal currents in the open sea (AEA, 2007). There is a net fluctuation of both potential and kinetic energy from the deep oceans to the shallow shelf seas. The propagation of this energy which is in the form of long waves is directly influenced by the earth's rotation (Blunden and Bahaj, 2007). The primary advantage of this resource is the predictability of the tides, providing a steady and accurate source of renewable energy as well as low environmental impact (EPRI, 2006).

Strong tidal currents are commonly located near islands and headlands (AEA, 2007) with localised bathymetry concentrating tidal flows into highly energetic activity areas within certain regions (SKM, 2006). Tidal streams usually peak during mid-tide, half way between high and low tide. In combination with the semi-diurnal tides present in the Channel Islands, there are four tidal velocity peaks each day; twice on both ebbing and flooding tides. (Redman *et al,* 2011). Creating the means to harness the raw kinetic energy in the territorial seas around Guernsey could make a significant contribution to the Islands Renewable Energy target.

6.1.3. Tidal technology status

Globally, there is a diverse range of tidal stream energy converters which are in various stages of technological readiness, all of which are listed by the U.S. Department of Energy (DOE) in the Marine and Hydrokinetic Database, available at; http://www1.eere.energy.gov/water/hydrokinetic.default.aspx.

This data base was consulted to assess the range and suitability of current tidal technology. Within the United Kingdom there are 15-20 devices under development (Carbon Trust, 2011). Figure 6.1.3.1 considers the global status of marine renewable technology development, showing the high level of activity in the UK relative to the rest of the world. This is highly beneficial to Guernsey given the close proximity of Channel Islands to primary developers and world leaders in marine renewable energy.

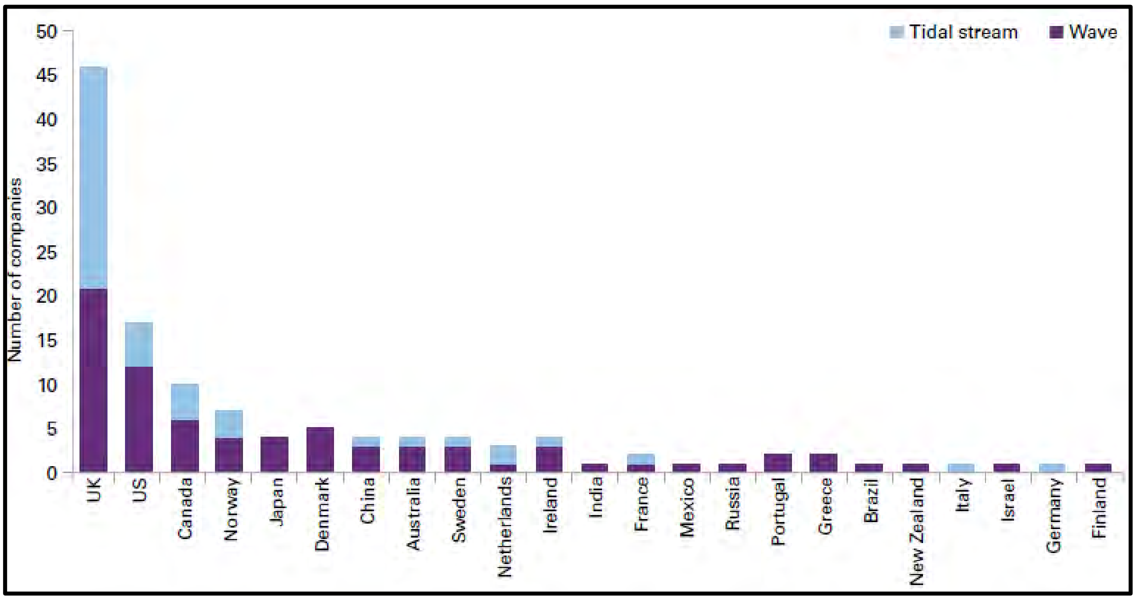


Figure 6.1.3.1: Indicative global wave and tidal activity (Carbon Trust, 2011)

TEC's can be broadly grouped into four main categories by method of energy extraction;

- Horizontal-axis turbines
- Vertical-axis turbines
- Oscillating hydrofoils
- Venturi Turbines

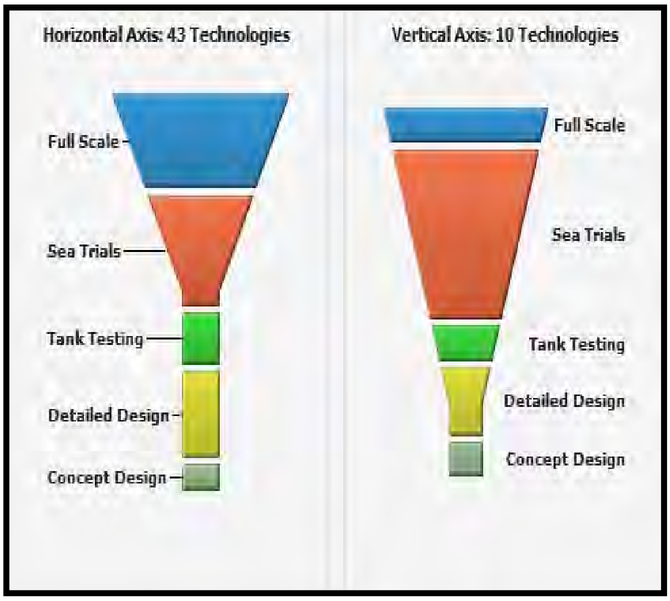


Figure 6.1.3.2: Technology pipeline of Tidal Energy Converters (Green Rhino energy, 2012)

This assessment will focus on the two primary divisions of turbines, horizontal and vertical axis, due to the inferior development level of both oscillating hydrofoils and Venturi turbines (GREC 2012). The developmental stages for the two focus technology fractions are displayed in Figure 6.1.3.2. It can be seen that there are currently a greater number of horizontal axis TEC's available from the concept design stage through to full scale testing, in the current market. Furthermore, the horizontally designed turbines are at a more advanced level of technological readiness compared to the vertical axis technologies (Green Rhino Energy ltd, 2012).

From the multitude of tidal stream device designs that are currently available there were three selected to be assessed, which were deemed suitable for the tidal stream resource under examination. The three devices and there design specifications are listed below in section 6.1.4.

Tidal energy converters can be further classified by the type of moorings or foundation structures used to provide securement to the seabed. These are of course dependant on the selected TEC, which consequently could have implications for deployment and operation. The classifications are;

- **Gravity base** – this mooring foundation is usually comprised of tubular steel and relies purely on its own weight to keep it in place on the seabed.
- **Bolted base** – this division is similar in design to a gravity base foundation, but weighs less and is held in position by bolts drilled into the seabed.
- **Pile mounted** –a large monopile is driven into the seabed from which the turbine is supported in the water column.
- **Moored floating structure** - the turbine is suspended beneath the surface, held inside a floating pontoon or duct. The pontoon is anchored to the seabed by chains or ropes (Craig, 2007).

6.1.4. Selected Devices

From the multitude if tidal energy converter designs that are currently available there were a total of 3 turbines selected to be assessed. The devices were selected under two main criteria; (1) suitability for deployment within the Little Russel and, (2) Technological readiness.

A major limitation posed by environmental parameters at each of the assessed sites is the water depth. The majority of tidal stream turbines available require to be installed in water depths of greater than 20 meters, or have a rotor diameter that is too large to remain submerged at low tide. The table below summarises the range of observed water depths, recorded by the ADCP's at each assessed site, throughout the measurement period.

Site	Mean lower low water (MLLW) (m)	Mean higher high water (MHHW)(m)	Tidal Range (m)
H1	9.8	18.58	8.78
H2	12.48	20.1	7.62
H3	6.4	15.3	8.9

Table 6.1.4: MLLW, MHHW, and tidal range recorded at observation sites H1, H2 and H3 from within the Little Russel during ADCP deployment period

6.1.5. Open Hydro

i) Overview

The Open-Centre Turbine (OCT) by open hydro was chosen as it presented optimal specifications in terms of design simplicity, ease of installation, performance and low environmental impacts such as;

- The simple and robust design is reliable due to few moving parts maximising operational time
- Full installation of a turbine can be carried out within 1 day by the highly specialised deployment barge developed by Open Hydro.
- The device is extremely efficient (52%) and extracts power on both flooding and ebbing tides due to fixed symmetrical blades
- Due to the open centre design and non-requirement of oils or lubricating fluids the environmental impacts associated with the turbines is exceptionally low (Open Hydro, 2011)

There are currently a variety of turbine sizes which have been manufactured and tested by open hydro;

- 6 meters, 250Kw
- 10 meters, 1.0MW
- 16 meters, 1.5MW (Open Hydro Ltd, 2011)

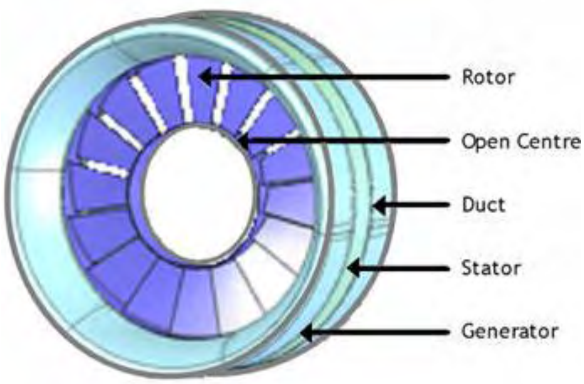
For the purpose of this study the device size which will be examined in terms of power output and specifications is the 6 meter turbine. The performance of this turbine has previously been tested at the European Marine Energy Centre (EMEC).

Aside from the size of the turbine itself it must also be taken into consideration that the turbine has to be mounted onto a gravity base mooring foundation. This will add to the total height above seabed, dependant on the size of the turbine (EPRI, 2005). Additionally, an industry standard clearance distance of 5 meters, between the top of the turbine and the water's surface is usually required. This prevents damage to the turbine caused from boats and other marine traffic (Open Hydro, 2011). However, this clearing distance may be able to be reduced or mitigated to a lower level if an exclusion zone were to be enforced around the deployment zone. A site specific assessment would need to be conducted in due course if this technology were to be considered.

ii) The turbine

The OCT is designed specifically for the extraction of electricity from the marine environment. The tidal stream turbine is a seabed mounted device which consists of a rotor, duct, stator and generator. The engineering design of the turbine is simple and robust, exploiting the kinetic energy present within the surrounding water to generate motion from laminar flow, therefore producing lift around the blades. This rotational movement is accelerated as the flow passes through the duct and over the swept rotor area generating electricity which is then harnessed (Renewable UK, 2012). It has an outer fixed rim (6 m) and an inner single piece rotating disc (5m) that operates without hydraulic fluid, oil or the need for lubricating liquid. Driven by the power of the flowing water, current electricity is generated through a multi pole permanent magnet rim generator which is rated at 97% efficiency for the 16m turbine (EPRI, 2005).

The cross-sectional swept area of the OCT is 29m^2, based on an inlet outer rim diameter of 6m and a turbine hub diameter of 3m. The rated output power for this turbine has been measured at 250kW (EMEC, 2010) given a water speed of 5 knots (2.57m/s). This rated power output will be used as a reference to determine the level of power which can be generated from the Little Russel using this turbine as part of this feasibility assessment.



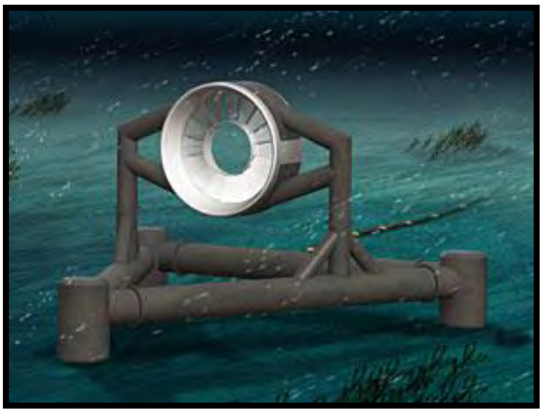


Figure 6.1.5.1: OCT turbine component diagram (left) simulation of turbine mounted on gravity base (right)(Open Hydro Ltd, 2012)

iii) Performance

The 6 meter turbine is rated at a power of 250kW. The permanent magnet rim generator has a calculated efficiency of 97% for power take off (EPRI, 2005). The additional performance parameters are as follows;

- Rated speed: 3.1m/s (based on the 15m turbine)
- Cut in speed: 0.7m/s
- Cut-out speed: 3.8m/s
- Pitch-control: No
- Mooring: Gravity base (Deployed via custom barge developed by Open Hydro)
- Servicing: Annual turbine inspection, serviced every 4/5 years
- Capacity factor ~52% (based in 15m turbine)
- Swept rotor area 29m

Key features which provide reliability as well as low cost for this device are;

1. No gearbox required
2. Electricity generated in the rim via encapsulated coils
3. Lightweight construction (Kevlar/GRP/steel)

Another key feature which is highly relevant to this assessment is that the Open Hydro turbines have no minimum or maximum installation depths, due to the fact that the turbines contain no seals (EPRI, 2005).

iv) Testing and Achievements

A further reason as to why the Open Hydro device was selected is due to the maturity of the technology and its proven power generation ability. In 2006 Open hydro Ltd were the first company to install a tidal turbine at the European Marine Energy Centre (EMEC) and it has been supplying electricity to the national grid since 2008. The technology from Open hydro had continued to prove its reliability and performance and has since deployed a turbine in the Bay of Fundy securing a contract with Nova Scotia Power and Alderney Renewable Energy (Open hydro 2011).

6.1.6. Tocardo International BV

i) Overview

The T500-A Turbine was selected for this assessment as it has been specifically designed for offshore sites where the water velocity is high. The T500-A can be equipped with blades ranging from 7 to 20m, which provides a nominal output of 350-500kW. The turbine has been designed to require minimal maintenance and inspection over its lifetime. It is ideal for offshore applications as a standalone generator or as part of an array (Tocardo International, 2012). Even though a range of blade sizes are available for the T500-A this assessment will focus on the turbine with blades of 8.4m. This size has been highly tested by Tocardo and has the greatest performance information available.

ii) The Turbine

The key design focus for the Tocardo turbine is reliability and minimal maintenance. The turbine utilises a bi-directional patented stall-blade concept. The fixed pitch axial flow turbine consists of two blades, which drive a permanent magnet, direct drive generator (Fundy Tidal Inc, 2012). The full length of the Nacelle is 11m, with a 2.82m diameter weighing 20kg. The swept area of the turbine is 56m^2 with a rotor diameter of 8.4m weighing 1400kg (Tocardo International, 2012).

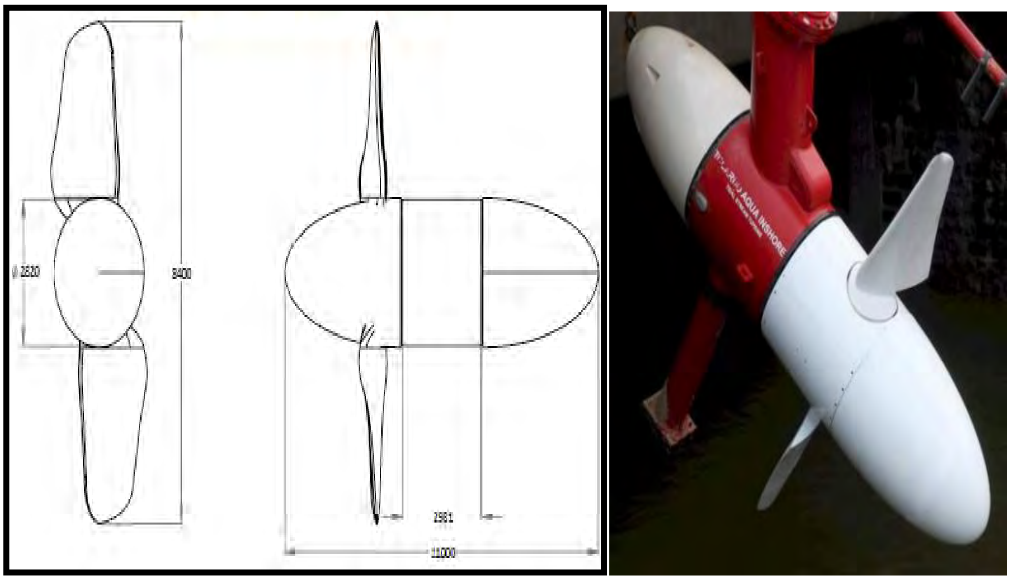


Figure 6.1.6.1: Design schematic of the Tocardo T500-A Turbine (left) image of inshore Tocardo turbine of same design(right) from Tocardo International, 2012)

iii) Performance

The turbine has a rated power of 500kW at water speeds of approximately 3.5m/s, and has an output power of 50-60Hz. The Generator is a 45-pole, permanent magnet, direct drive generator with variable speed. The additional performance parameters are as follows;

- Rated speed: 3.5m/s
- Cut in speed: 0.7m/s
- Cut out speed: 4.5m/s
- Pitch-control: No
- Mooring: client provided*
- Servicing: stated as 'minimal' but precise information unavailable
- Capacity factor 40%
- Swept rotor area 56m^2

*The foundation requirements will be supplied by Tocardo International however the foundation structures expected to be provided by the client. It is however stated within the company's website (www.torcado.com) that, "Depending on geographic location, market type (inshore, river, offshore) and project size, we can also deliver turn-key solutions covering complete site development (foundation, consenting, and grid-connection).

Full design specifications for the T500-A are available directly from the Tocardo BV International website; http://www.tocardo.com/cms/files/PDF-downloads/tocardo-t500-a-product-brochure-v1-0a-compact.pdf.

iv) Testing and Achievements

Tocardo International BV is currently the only company in the world commercially marketing mass produced water turbines. They have been developing their own patented tidal technology for over 12 years with there in stream energy turbines (T100 and T200) being commercially available.

The T500 is there first offshore turbine and is currently still under development, due to be complete in 2012. The T500-A turbine is presently being customised for application within the Pentland Firth, Scotland. Tocardo has had the device on ground in the Pentland Firth area since summer 2007, in preparation for a 10MW offshore tidal demo park.

6.1.7. Neptune Renewable Energy Ltd (NREL)

i) Overview

The Neptune Proteus NP1000 (Mark III) was selected for this assessment as it has been specifically designed for deployment in shallow water environments. Each device will be deployed as part of a Proteus Pod, consisting of 5 units with a total installed capacity of 1.25MW, which could generate up to 6GWh/year based on a mean spring tidal current speed of 3m/s (NREL, 2012). The other overarching advantages associated with this technology as stated on Neptune's website www.neptunerenewableenergy.com are;

- Proximity to the shore and demand
- Low CapEx: mooring in sheltered areas with the absence of wave activity on the structure
- Ease of installation – the device can be towed to site using a small tug
- Low OpEx: all machinery is above water, substantially reducing operational costs
- Minimal impact on environmental energy flows
- The steel construction is mostly recyclable
- Cross sectional shape – the square turbine cross section generates 30% more electricity per unit channel width than circular turbines
- Patented turbine and control software maximize efficiency

The Neptune Proteus tidal stream generator is a floating device, designed to extract the kinetic energy from both flooding and ebbing tides, to be converted into grid synchronized high voltage electricity (NREL, 2012).

Figure 6.1.7.1: Neptune Proteus 1000 deployed within Hull's Albert Dock (Professional Engineering, 2010)

The floating pontoon design of the NP1000 means that when it is deployed, it is largely unobtrusive. With more than 80% of the structure remaining hidden beneath the water surface (Professional Engineering, 2010).

ii) The Turbine

The NP1000 (Mark III) is a vertical-axis device which utilises the force of drag over multiple blades. It is comprised of a large steel housing (160 tonnes) supported by buoyancy hulls throughout (saddle tanks mid-structure, and buoyancy tanks in all four the bows). The outer steel sheeting of the turbine forms a Venturi Duct, designed to accelerate the tidal flow over computer controlled flow vanes, onto the 6m x 6m vertical axis, cross flow rotor (NREL, 2012). The flow guide vanes create a rectangular cross-section to the inflowing water jet, causing it to flow through the blade ring of the cylindrical rotor. The flow passes over the turbine in a two-step process; (i) from the outside inward then, (ii) after passing through the inside of the rotor, from the inside outward (International Water Power & Dam Construction, 2010).A standardised industrial gearbox (1:200) delivers the torque from the upper end of the rotor shaft to a DC generator (NREL, 2012).

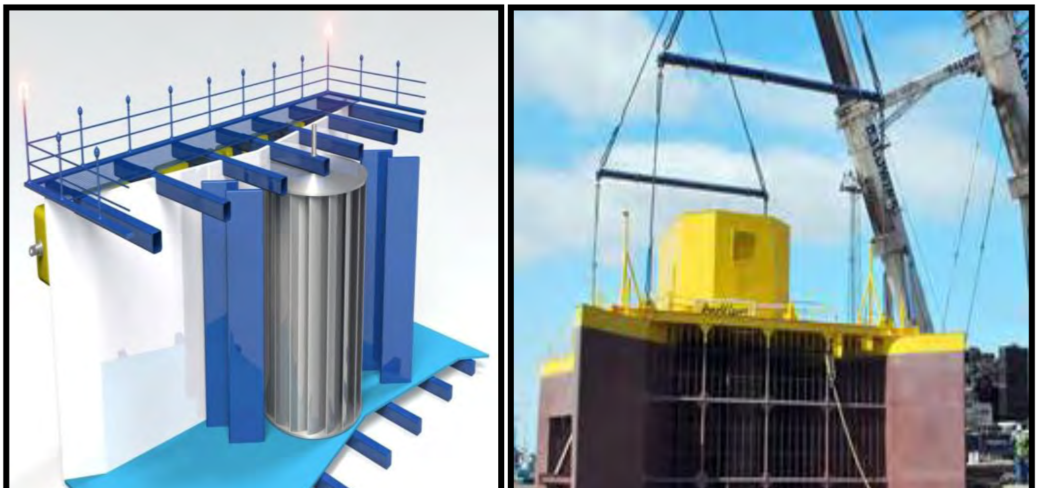


Figure 6.1.7.2: Simulation of Neptune Turbine ¾ view front (left), side view of Neptune demonstrator being deployed (right) (NREL, 2012)

iii) Performance

- Cut in speed 0.4m/s
- Cut out speed 4m/s
- Capacity factor 35%
- Mooring: suspended by floating pontoon, secured fore and aft.
- Swept rotor area 97.5m^2
- Tip Speed Ration (TSR) .035
- Rated Power 1.25MW

iv) Testing and Achievements

The NP1000 has undergone vigorous testing by the University of Hull. Computational fluid dynamics (CFD) was used to improve the rotor and duct design from the preceding Mark (I) and (II) versions.

In 2010 Neptune deployed the full scale demonstrator NP1000 (mark III) into the Humber Estuary. Upon success from its power generation it was agreed by Hull City Council that the output from the demonstrator will help to power Hulls Aquarium 'The Deep' which is also located at Humber Estuary. The device will continue to undergo in situ testing within the North Bank of the Humber to maximise performance. The information extracted from this testing and in situ device analysis will help in the creation of newer Neptune models, such as the emerging NP1500 (NREL, 2012).

6.1.8. Device selection conclusions

The turbines which have been discussed fully reflect a range of TEC's that are currently available in today's market, yet have the feasibility to be installed within the Little Russel given such limited water depths. Further consultation would need to be conducted with the chosen developer and Guernsey RET to ascertain wither the Little Russel would be suited to a fully submersed or surface protruding turbine design. The devices which have been examined within this section were chosen as they were deemed to be the most suited for deployment given the primary limitation of water depth. After this initial technology assessment further analysis has been conducted to ascertain the devices ability to harvest the resources of the Little Russel. The details of this analysis are displayed in section 8.

The table below indicates the technology and the turbine size which could potentially be installed as each assessment site based on the lowest observable water height.

Site	MLLW	Potential Technology	Turbine size (m)	Clearance height to water surface at lowest tide (m)
H1	9.8m	• OCT • T500-A • NP-1000	• 6 • 8.4 • 6	• 3.8m • 1.4m • n/a
H2	12.48m	• OCT • T500-A • NP-1000	• 6 or 10 • 8.4 • 6	• 6.48 or 2.48 • 4.08 • n/a
H3	6.4m	• NP-1000	• 6	• n/a

Table 6.1.8: Site suitability for TEC size, with given turbine clearance heights to surface (excluding mooring foundation)

The OCT by Open Hydro could potentially be deployed at both assessment sites H1 and H2, however only the 6 or 10 meter turbine would be suitable given the shallow water depth. Tocardo International's T500-A would also be suitable for deployment throughout sites H1 and H2. Both the OCT and the T500-A would be able to remain fully submersed as they are moored by gravity based structures. However, further assessment would need to be conducted as to the exact height of their associated foundation structures and the overall height from seabed post installation, to calculate the turbine surface clearances. The NP1000 from Neptune Renewable Energy is potentially suitable for deployment at all three of the assessment sites, due to the 'floating pontoon' nature of the design. However the primary design intension of the NP1000 was for deployment within estuarine environments therefore it would only be suitable for sites with high velocity currents, but low in wave exposure (International Water Power & Dam Construction, 2010).

7. Tidal stream theory

7.1.1. Energy extraction

The theory of power extraction through turbines is well established. Particularly in the form of horizontal-axis wind turbines and the classic analysis of power extraction from wind by an actuator disk (Blunden, 2009). The comparison of energy conversion from wind and tidal streams is very similar. Energy is harnessed via a turbine, which extracts kinetic energy from environment. However, there are two distinct differences; firstly, the density of air (1.225 kg/m^3) is approximately one thousand times less than water (10225 kg/m^3) and secondly, tidal currents are more predictable, but comparatively have lower velocities (EPRI, 2006).

To calculate the theoretical availability of power at a given site for tidal stream assessment the following equation (2) is applied where N_B is the number of bins and i is the corresponding bin index.

Equation 2: Average Power Density

$$APD = \frac{1}{2} \cdot \rho \cdot \sum_{i=1}^{N_B} \left(U_i^3 \cdot f(U_i) \right) = \frac{1}{2} \rho \cdot V_{rmc}^3 \quad (\text{kW/m}^2)$$

Equation (2) is used to calculate the power density (Kw/m^2), where **ρ** is the density of water (kg/m^3) and **U** is the instantaneous current velocity (m/s). The tidal stream power density is a measurement of the fluid which passes through a unit area, in relation prominent direction of flow (Hardisty, 2009).From this it can be seen that the tidal power density is related to the cube of the velocity, indicating the importance of strong current velocities for the site selection of tidal stream energy developments, therefore ensuring high power outputs. Given the parameters of equation (2) the mean annual electrical power per bin can be derived using the following equation;

Equation 3: Mean annual electrical power per bin

$$\boldsymbol{P(U_i).f(U_i)}$$

Having established the theoretical power, the power output estimation of a tidal stream energy device can be characterised using the following instantaneous maximum fluid power equation;

Equation 4: Instantaneous device power

$$\boldsymbol{P = \frac{1}{2} C_p \rho A U^3}$$

It is compromised of the same principals as equation (2), but takes into account the cross sectional area of the turbine $\boldsymbol{A}$ (m^2), as well as the rated capacity factor of the specific turbine ($\boldsymbol{C_p}$) (Hardisty, 2009).

The power capacity factor, or power coefficient, is defined as the ratio of the power output over one year, to the power that would be produced if operating at full installed capacity. The calculation is based on the average number of hours in one year (8776) and determined through the application of the following equation;

Equation 5: Capacity factor

$$\boldsymbol{C_p = \int \frac{P_E \, dt}{8776 P_1}}$$

The output power is non-dimensionilsed by the undisturbed flow speed and flow capture area. The capacity factor is a representation of the effectiveness of device power generation, irrespective of the flow speed or swept area of the turbine (Blunden, 2009).

7.1.2. Betz Law

Tidal energy convertors extract kinetic energy from a moving flow; therefore they are bound by the limits of Bet'z Law. The law assumes that the cross sectional area of the flow upstream of the turbine increases in approach up to, and after leaving, with consequent pressure change. The change in pressure causes a decrease in flow speed and the linear momentum, as kinetic energy is extracted from the flow (Gomez, 2008). In light of this, it is demonstrated that flow speed must be sufficient in energy to leave the rotor region on the other side. This theory is known as the Betz limit, and states that the theoretical upper limit of the extraction potential from an individual turbine in the unconstrained flow is the fraction $\frac{16}{27}$ (0.59), of the kinetic energy flux through the rotator disk (Blunden, 2009). This classic analysis of theoretical upper limits of extraction for wind turbines applies to the case of a similar turbine in a tidal stream, and is represented by the capacity factor. Further limitations to the extractable energy are resultant from channel geometry and environmental considerations, since it is not feasible to occupy the breadth of the channel completely with turbines (Hagerman and Polagye, 2006).

Furthermore, the upper and lower possible extraction capabilities of TEC's are also defined by their cut-in and cut-out speed. The flow speeds at which a turbine will start generating power are typically 0.5-1.5m/s. The cut-in speed is the minimum flow speed required for the turbine blades to overcome friction and begin to rotate. As a direct result of the cube-law relationship between velocity and power, the amount of energy produced at lower velocity speeds is slight in comparison to the total power production. Therefor even if a turbine has a high cut in speed this does not appreciably affect the annual energy output (Craig, 2007).

Generally tidal turbines achieve maximum power efficiency in current speeds of 2-3m/s. Once beyond this maximum point, additional energy is unable to be harvested and may cause damage to the turbines. This is why tidal turbines have a defined cut out speed, at which the device is shut down and no longer harnesses energy (Hardisty, 2009).

7.1.3. Harmonic Analysis

Harmonic analysis is a diverse field of mathematical analysis, which can be used for the processing of signals. Tidal harmonic analysis is the process by which data collected from the tidal currents can be separated into the basic harmonic constituents defining the tide.

The analysis is based on the assumption that variations within the tide can be represented a number (n) of harmonic terms signified by:

Equation 6: Harmonic terms

$$V_n \cos(\sigma_n - g_n)$$

Where V_n is amplitude, g_n is phase lag on the equilibrium tide at Greenwich, and σ_n is an angular speed (EMEC, 2012).

The classic analysis of harmonic analysis decomposes the tidal signals into a number of components, displayed through the following equation:

Equation 7: Harmonic analysis

$$\eta = \sum_{harm=\{list\}} A_{harm} \cos(\omega_{harm} t - \phi_{harm}) list = \{M_2, S_2, O_1, K_1, P_1, Q_1, N_2, K_2, M_4, \ldots\}$$

Where ω_{harm} is the frequency, and $\emptyset_{harm}$ is the phase of component harm (EquiMar, 2011).

The Number of components that may be resolved is directly dependant on the length of data available to analyse. Reeve *et al* (2004) states that the minimum length record required to determine the main tidal harmonics of a particular location is approximately one month, resulting in two spring-neap cycles, which is satisfied by the sampling period for this assessment.

8. Results

This section of the report will look at the overall results obtained from analysing the data that was collected from the period of measurement of 35 days within the Little Russel. Each site will be examined individually, in terms of the velocity, current direction and extractable power. These parameters are assessed and measured in conjunction with the selected technology to determine the aptness of the devices for each site.

8.1.1. Tidal stream site H1

i) Measured velocity and distribution

Spring tides within the Little Russel occurred on the 2nd and 16th of August providing a mean spring velocity (V_{ms}) of 0.26 m/s. For the first spring tide, on the flooding tide (low to high), the current velocity ranges between 0-0.3 meters per second, with a similar velocity pattern experienced on the ebbing (high to low) tide. The magnitude of the current appears to remain constant throughout the water column. The uniformity of the tidal magnitude through the vertical binning is further displayed in figure 8.1.1.6. However, near the surface at approximately 16 m from the bed, the current velocity peaks at 0.8 m/s in conjunction with high tide. However this could be attributed displacement from free surface inflicting constant perpendicular normalised stress in the form of waves (Blunden and Bahaj, 2006). The infliction of the free surface is further demonstrated in appendix D, displaying a surface plot of current over the full bin range.

Neap tides occurred on the 25th of July and 9th of August providing a mean neap velocity (V_{mn}) of 0.08 m/s. Figure 8.1.1.2 displays the velocity profiles over a 12.25 hour tidal cycle for each of the neap tides. The tidal elevation is approximately 3m lower compared to spring tides, reaching a maximum water depth of 14.8m at high tide. The greatest velocity is generated on the flooding tide between 0-0.4m/s, peaking at high water. For neap tide two, a maximum velocity of 0.5m/s is reached on the flooding tide in the surface waters. Again this can be attributed to the free surface and is not representative of the velocity throughout the vertical.

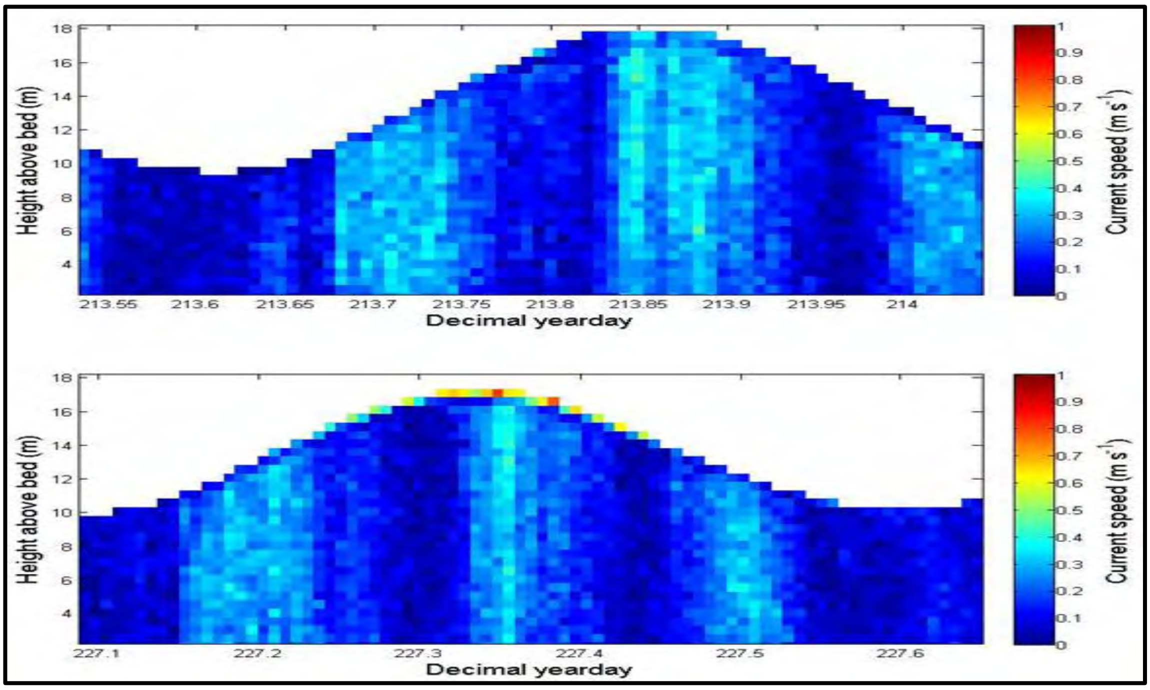


Figure8.1.1.1: Current velocity over a 12.25 hour `spring tidal cycle for site H1. Occurrence for spring tide one (top) 02.08.2011, for spring tide two (bottom) on 16.08.2011.

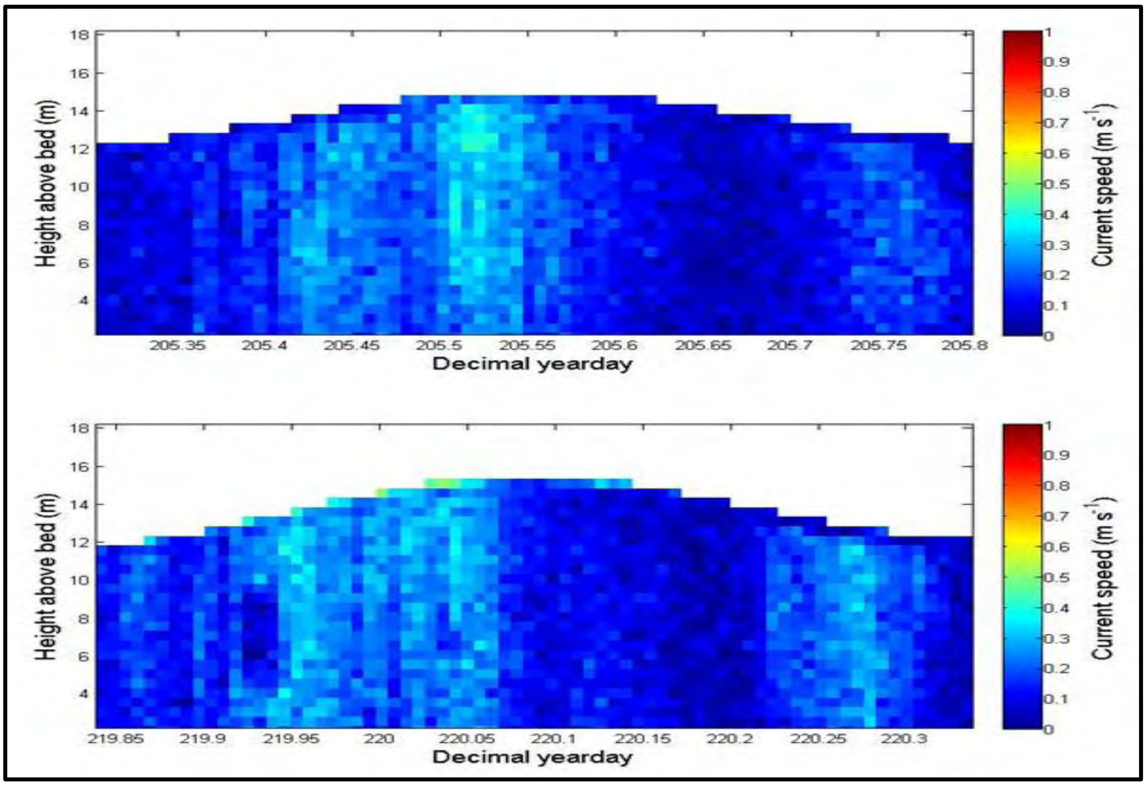


Figure 8.1.1.2 Current velocity over a 12.25 hour neap tidal cycle for site H1. Occurrence for neap tide one (top) 25.07.2011, for neap tide two (bottom) on 09.08.2011.

ii) Current direction

The primary current direction for site H1 is between 0-20^0 north east (Figure 8.1.1.3.). This direction is maintained from slack water, though the flooding tide and for the first half of the ebbing tide. Half way through the ebbing cycle the primary current direction changes to 150-210^0 degrees south/south west. Elements of the south westerly current are present within the flooding tide however the north easterly current remains dominant. The composition of current directions (Figure 8.1.1.5) shows that the duration of the north easterly current last twice as long than the southern current.

Tidal current ellipses calculated using harmonic analysis indicates that the flow is primarily rectilinear throughout the vertical, represented for bin number 8 (Figure 8.1.1.5) corresponding to a depth 5.3m from the bed. The orientation of the currents is consistent with depth, confirmed by tidal ellipses from depth bins 1-8, (appendix G) which correspond to device hub height. The ellipses are aligned at a heading of approximately 315^0 relative to the long channel direction (20^{0}N).

Current direction as depicted by the M_2 constituent (Figure 8.1.1.6) ranges between 100-200^0, with the current along the semi-major and minor axes showing little variation (0.2-0.4 m/s) in magnitude from 0-11m with increasing depth from the bed..

During the periods of increased elevation, over spring tides, changes are observed in current orientation and phase (Figure 8.1.1.6) for the dominant semidiurnal tidal constituent. The change in phase is resultant of a change in amplitude of the tidal harmonic constants, resulting in modification to the sinusoidal pattern of the tidal currents waves.

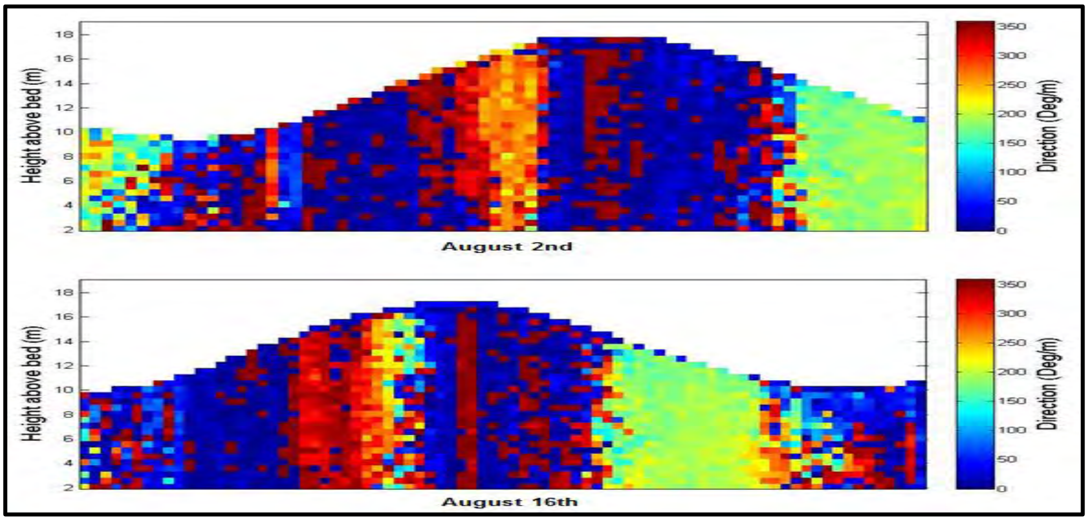


Figure 8.1.1.3: Current direction over a 12.25 hour spring tidal cycle for site H1. Occurrence for spring tide one (top) 02.08.2011, for spring tide two (bottom) on 16.08.2011.

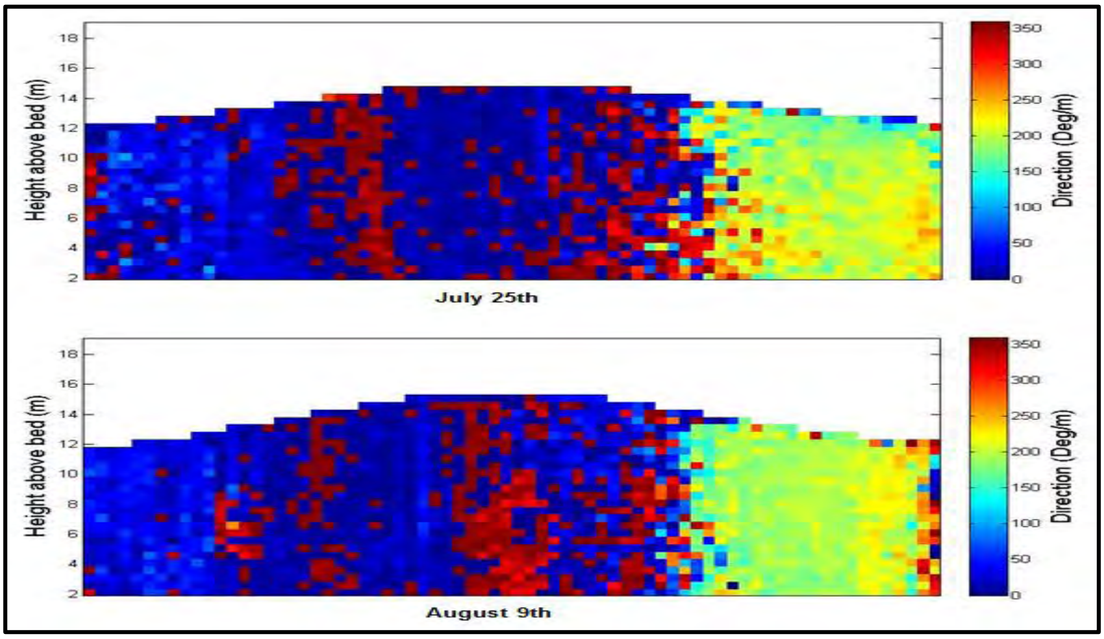


Figure 8.1.1.4: Current direction over a 12.25 hour neap tidal cycle for site H1. Occurrence for neap tide one (top) 25.07.2011, for neap tide two (bottom) on 09.08.2011.

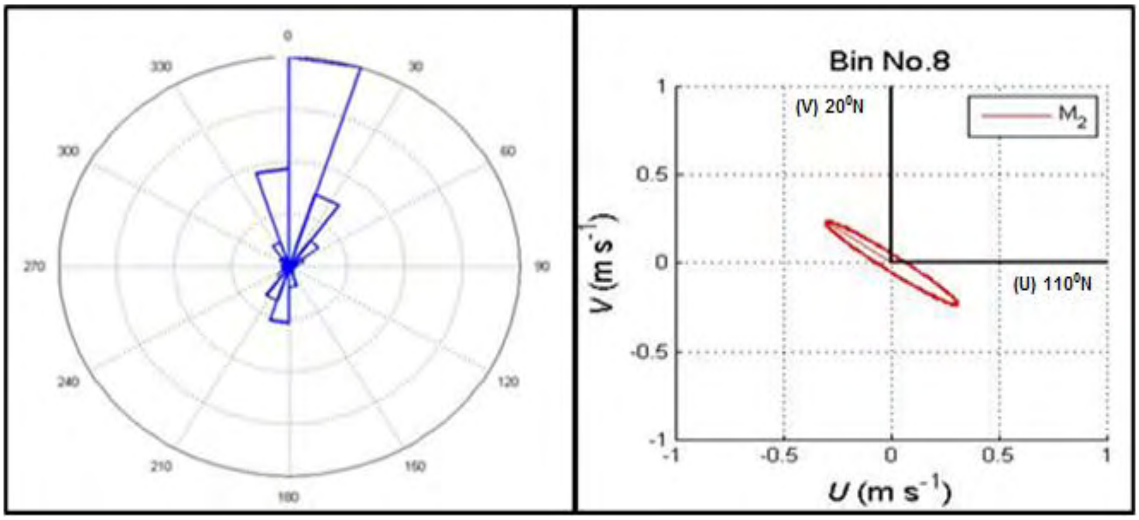


Figure 8.1.1.5: Rose plot of current direction (degrees) (left), tidal ellipse indicting velocity orientation along the semi-major (V) and semi-minor (U) axis for depth bin 8 (right). Axes have been rotated so that the long channel direction (20^{0}N) is orientated to view vertically and the cross channel horizontally.

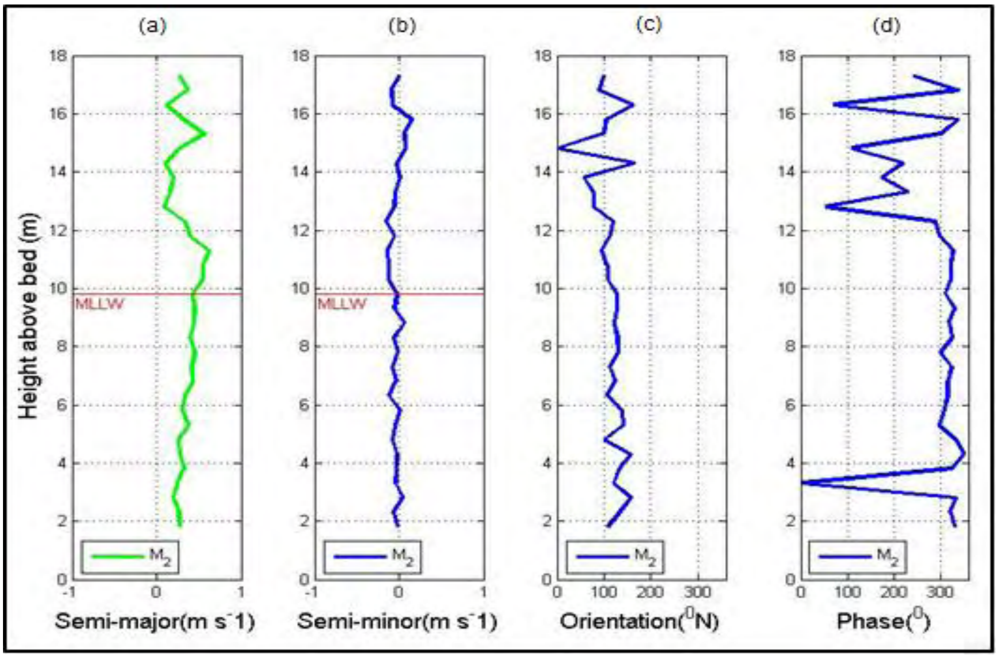


Figure 8.1.1.6: Depth profiles of (a) semi-major axes, (b) semi-minor axes, (c) orientation and (d) phase of M_2 tidal constituent from assessment site H1 as calculated by harmonic analysis. Height of the Mean low lower water (MLLW) indicated at 9.8m.

iii) Extractable power

Velocity distributions range from 0-0.3 (Figure 8.1.1.7) over 0.1 m/s bins. The most frequent velocity is in the range is 0.2-0.29 m/s occurs 38% of the time, with a mean velocity of 0.13 m/s. The total power density extrapolated over a 30 day period (Figure 8.1.1.8), for the long channel velocity component (V), at a depth of 5.3m from the seabed is 15kW/m^2. The mean spring power density is 0.02kW/m^2 and a mean neap power density of <0.1 kW/m^2. The associated velocity exceedence curve is located in appendix J.

Due to the velocity speeds not exceeding 0.4 m/s device power estimates could not be calculated for site H1 as the minimum turbine cut in speed is 0.4 m/s for the NP1000, and 0.7m/s for both the OCT and T500 turbines.

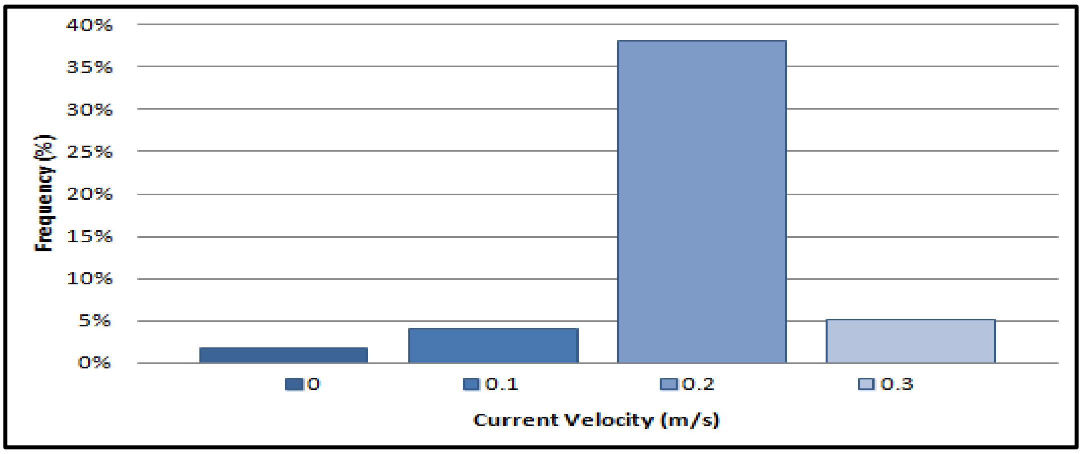


Figure 8.1.1.7 Velocity distributions recorded over the period of 30 days for site H1.

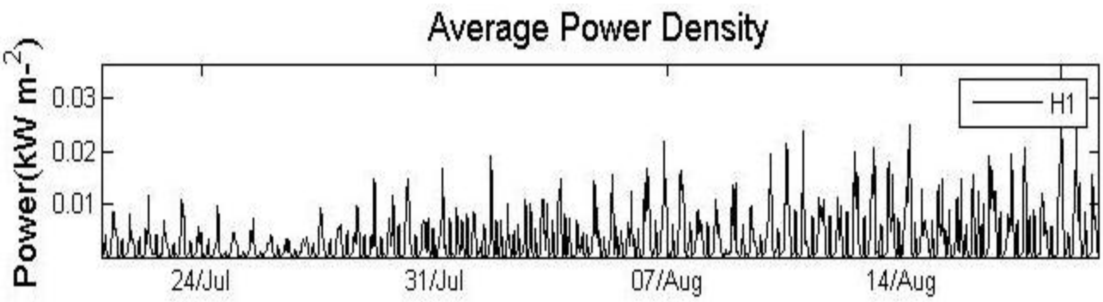


Figure 8.1.1.8: Average power density for long channel velocity component (V) at 5.3 meters from the bed, calculated over a 30 day period from the 21.07.11 to 20.08.11 for assessment site H1.

8.1.2. Tidal stream site H2

i) Measured velocity and distribution

At this location the calculated (V_{ms}) is 1.15 m/s. On the flooding tide (low to high) the current velocity ranges between 0-0.6 m/s over both springs. For the spring tide on August 2nd, the velocity peaks at 1.2m/s, (Figure8.1.2.1) and for the second springs 1m/s, entering into the ebbing tide. For the remainder of the flood tide through to slack water the current speeds fall to 0-0.2 m/s. For both cycles the velocity profiles remain fairly constant throughout the water column from depths of 3-12m (Figure 8.1.2.6), with the greatest magnitude observed past this. The lower vertical magnitude uniformity, with increases near surface is further visualised in appendix E.

The calculated (V_{mn}) is 0.062 m/s, with an overall reduced magnitude compared to the spring tidal cycle. The maximum velocity does not exceed 0.4 m/s for both neap cycles (Figure 8.1.2.2), remaining at a fairly uniform speed of 0-0.2 m/s over both flood and ebb tide.

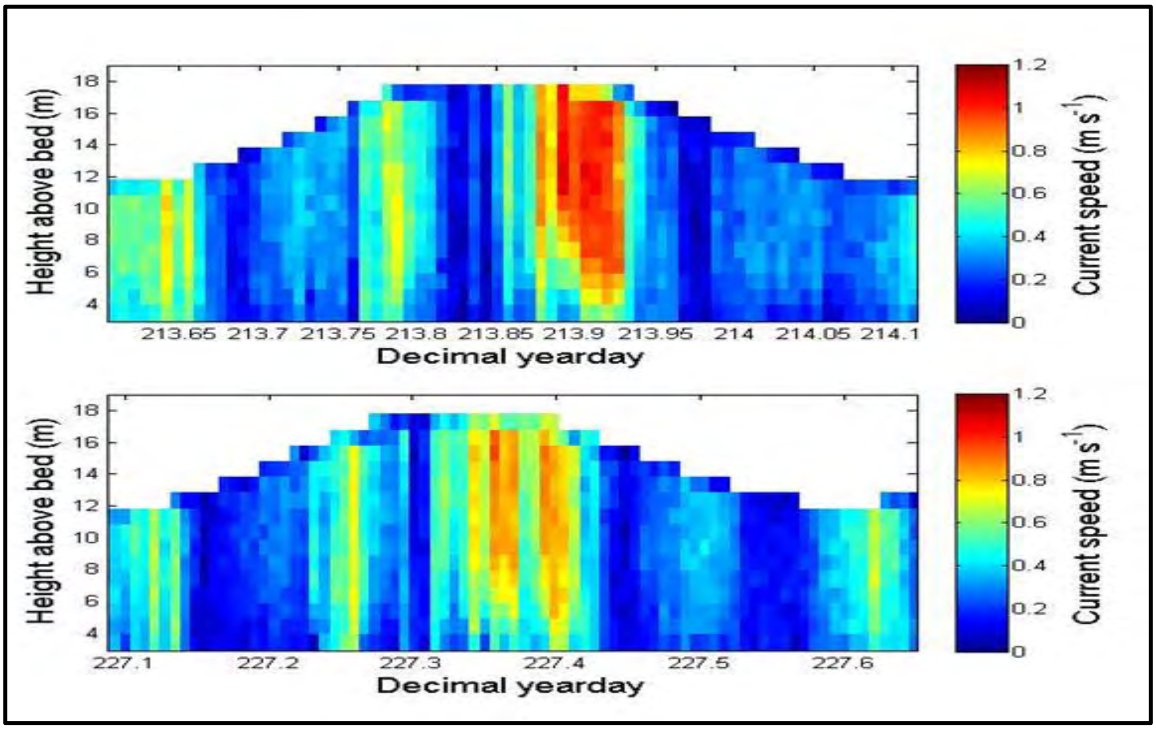


Figure 8.1.2.1: Current velocity over a 12.25 hour spring tidal cycle for site H2. Occurrence for spring tides one (top) 02.08.2011, for spring tide two (bottom) on 16.08.2011.

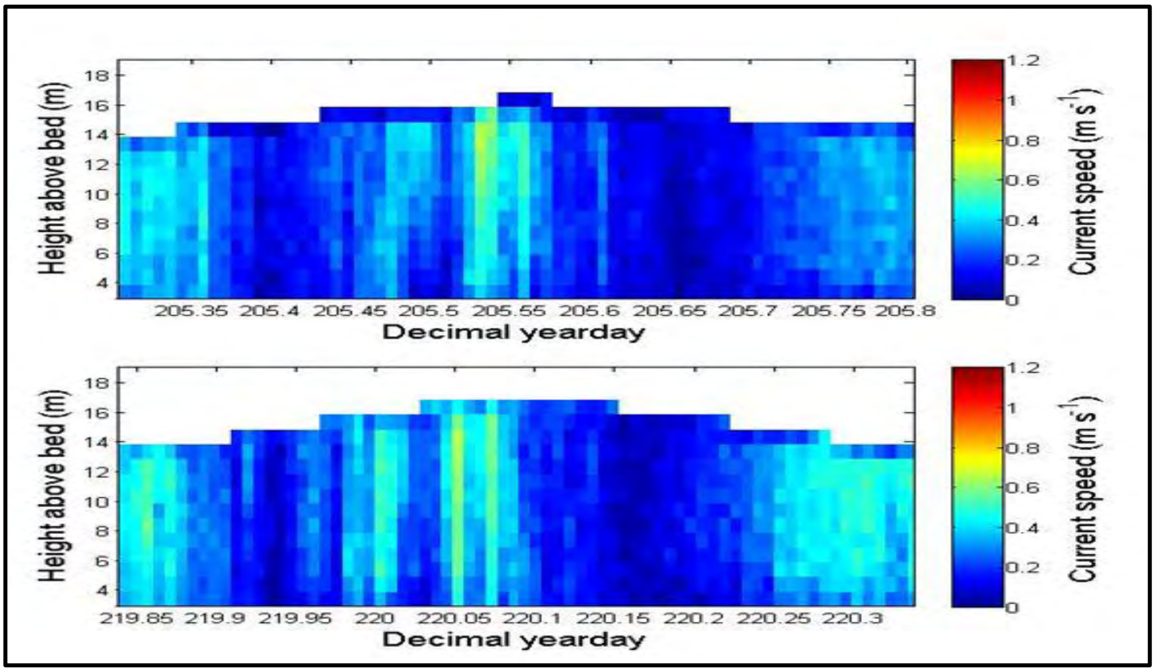


Figure 8.1.2.2: Current velocity over a 12.25 hour neap tidal cycle for site H2. Occurrence for neap tides one (top) 25.07.2011, for neap tide two (bottom) on 09.08.2011.

ii) Current direction

Over the spring tidal cycles (Figure 8.1.2.3) the primary current direction is from the north east, (0-100^0) during flood tide and continuing past high water onto the ebbing tide. Half way through the ebbing tide, in conjunction with a decreasing depth the direction changes to 150-210^0 (Figure 8.1.2.5) coming predominantly from the south.

The pattern of current direction exhibited over the neap cycle shows very little variation form springs, only with a lower tidal range (Figure 8.1.2.4). The transition period during which the current alters direction over the ebbing tide, is less instantaneous over neaps.

Tidal current ellipses calculated using harmonic analysis indicates that the flow is rectilinear (Figure 8.1.2.5) but with significant influence from cross channel velocity. The ellipses are more ovate, than the constricted, as a result of only 0.1 m/s difference between the long and cross channel velocity (Figure 8.1.2.6). Again, an apparent uniformity of magnitude is observed up to the MLLW.

The alignment of the current ellipse from depth bin 8, corresponding to 9.9 m from the bed, is approximately 45^0 (Figure 8.1.2.5) relative to the long channel direction (10^0N). This is consistent from depth bins 1-8 (Appendix H) corresponding hub heights for OCT and T500 turbine dependant on size of foundation structure.]

Current direction as depicted by the M_2 constituent (Figure 8.1.1.6) ranges between 0-100^0. The velocity magnitude along the semi-major and minor axes shows little variation up to the MLLW. Past this, the magnitude increases in conjunction with a change in both the phase and orientation of the M_2 signal, most significantly at 14 and 16 meters from the bed. This can be attributed the periods of increased elevation, altering the shape of the current waves, especially in conjunction with the free surface.

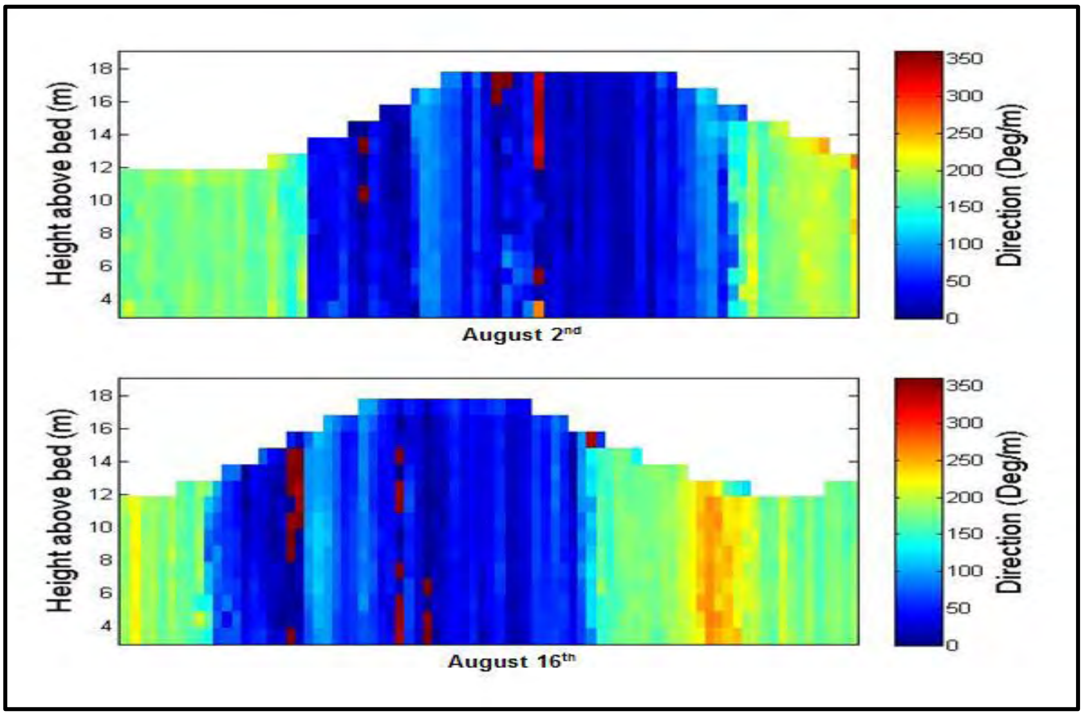


Figure 8.1.2.3: Current direction over a 12.25 hour spring tidal cycle for site H2. Occurrence for spring tide one (top) 02.08.2011, for spring tide two (bottom) on 16.08.2011.

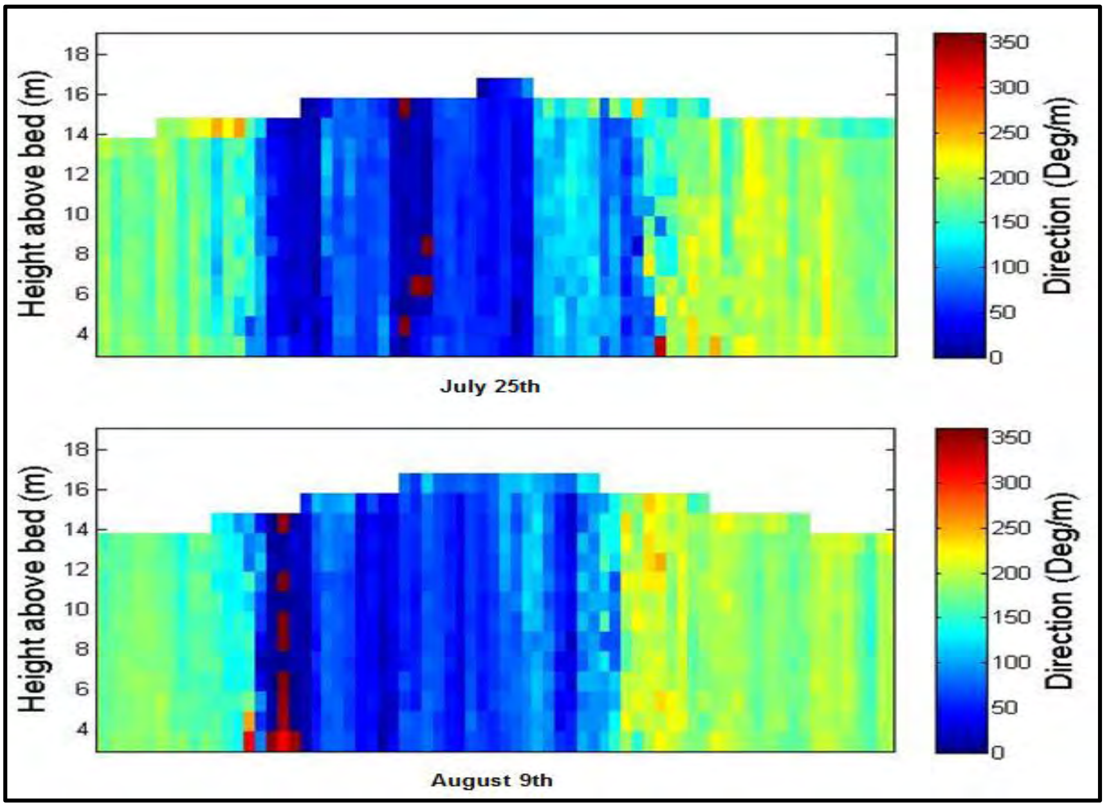


Figure 8.1.2.4: Current direction over a 12.25 hour neap tidal cycle for site H2. Occurrence for neap tides one (top) 25.07.2011, for neap tide two (bottom) on 09.08.2011.

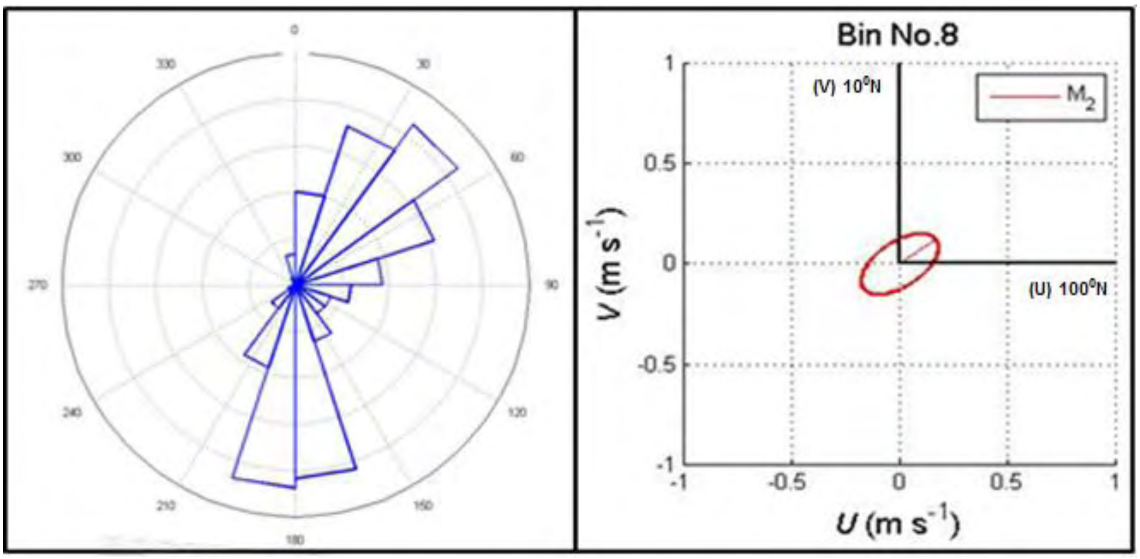


Figure 8.1.2.5: Rose plot of current direction (degrees) (left), tidal ellipse indicting velocity orientation along the semi-major (V) and semi-minor (U) axis for depth bin 8 (right). Axes have been rotated so that the long channel direction (10^0N) is orientated to view vertically and the cross channel horizontally.

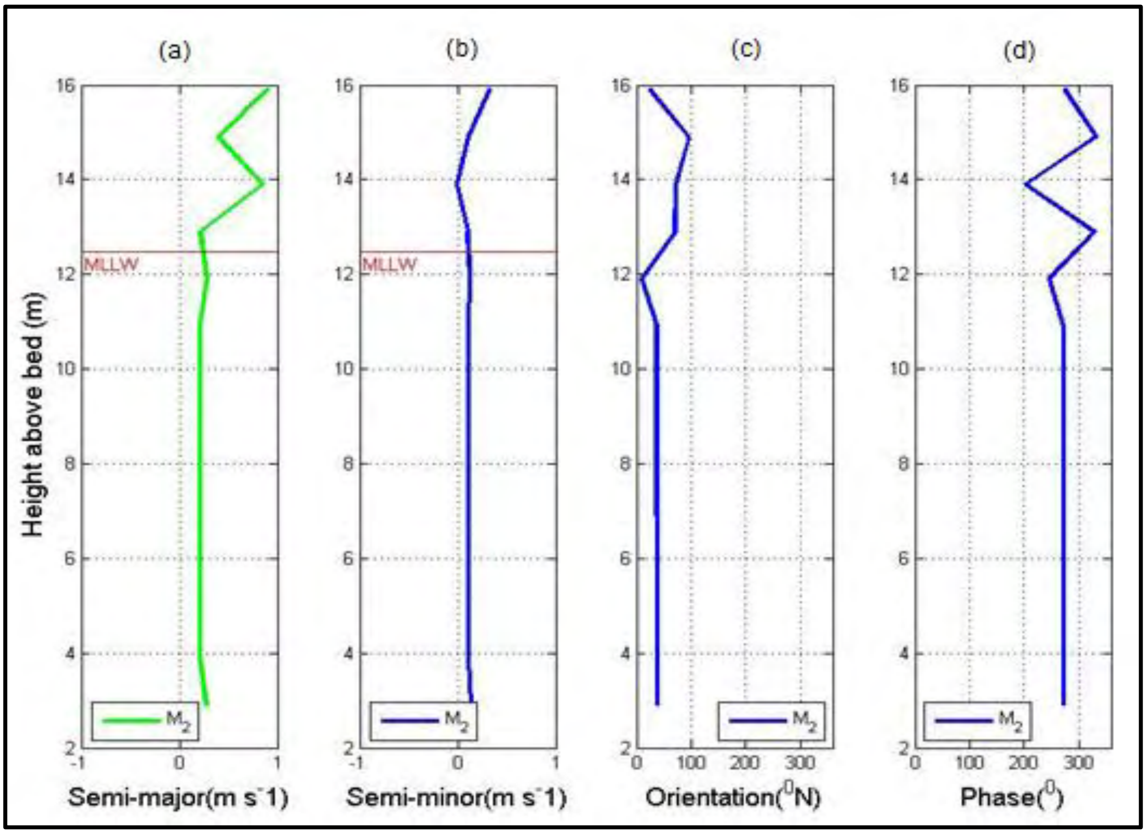


Figure 8.1.2.6: Depth profiles of (a) semi-major axes, (b) semi-minor axes, (c) orientation and (d) phase of M_2 tidal constituent from assessment site H2 as calculated by harmonic analysis. Height of the Mean low lower water (MLLW) indicated at 12.48m.

iii) Extractable power

The site velocities range from 0-1.1 m/s (Figure 8.1.2.7) over the 0.1m/s bin distribution. The velocities which occur most frequently, 38% of the time, are <0.1 m/s. The mean velocity is of 0.3 m/s, with speeds greater than 0.7 m/s occurring only 2% of the time. The associated velocity exceedence curve comparing distribution between the 3 ties is located in appendix J.

The APD calculated for the long channel velocity component (V), at a depth of 9.9 meters form the bed (Figure 8.1.2.8), is 0.05 kW/m^2. The power density summed over 30 days is 207 kW/m^2. The mean spring power density is 0.73 kW/m^2 and <0.1 kW/m^2 for the mean spring power density.

Figure 8.1.2.9 displays the electrical power generated for each of the considered TEC's assuming that 100% of energy extraction was achieved over the month. However current speeds at which the OCT and T500 could operate (=>0.7) only occur 2% of the time. At a 2% operational period the maximum power output would be 0.06MW/h for OCT and 0.09MW/h for the T500. The NP1000 could produce 1.27MW/h at an 18% operational frequency given speeds 0.4 m/s and greater

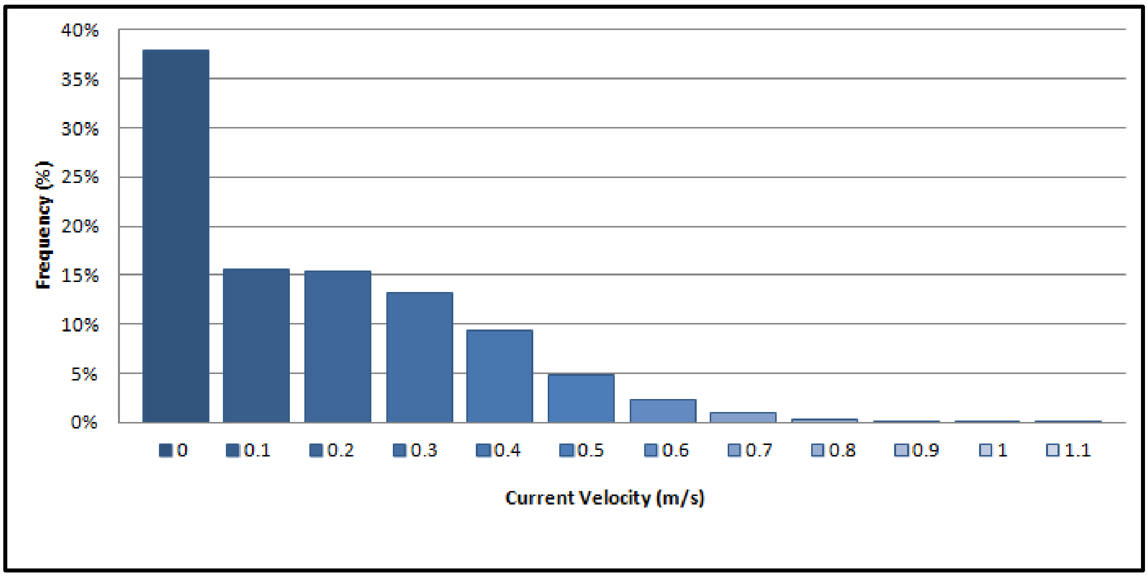


Figure 8.1.2.7: Velocity distributions recorded over the period of 30 days from 10 minute intervals, for site H2.

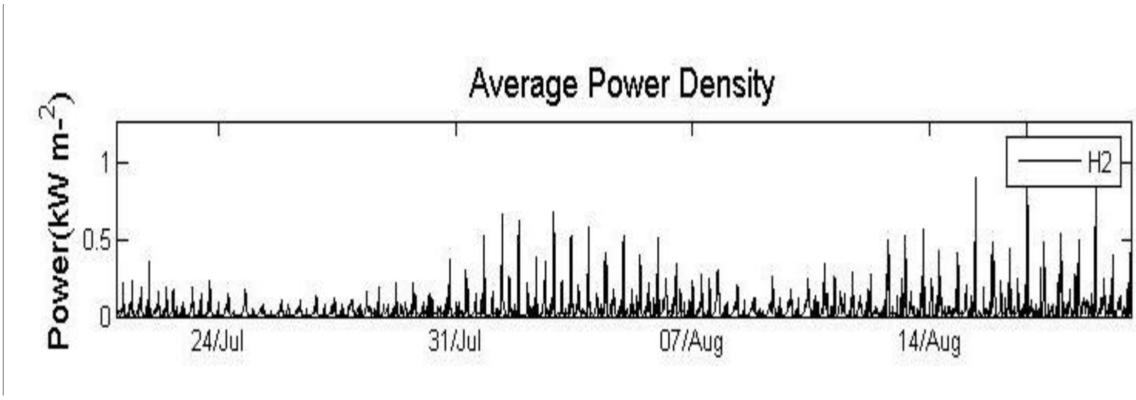


Figure 8.1.2.8: Average power density for long channel velocity component (V) at 9.9 meters from the bed, calculated over a 30 day period from the 21.07.11 to 20.08.11 for assessment site H2.

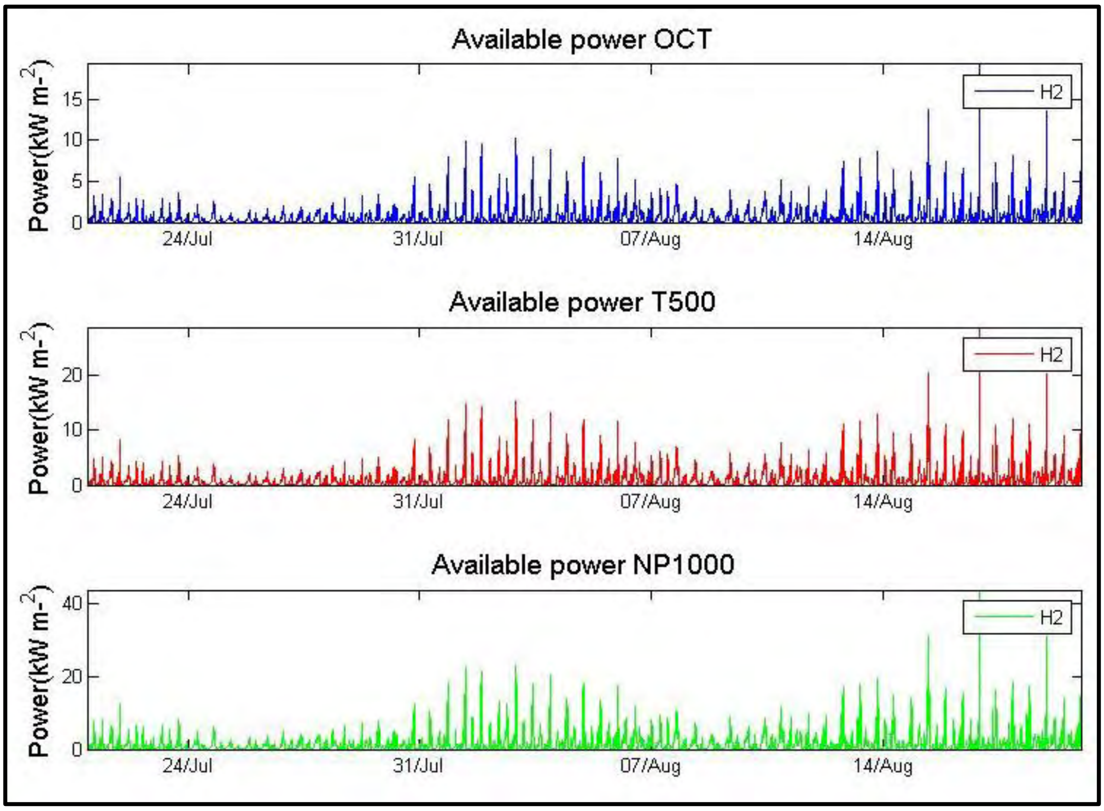


Figure 8.1.2.9: Extractable power output from OCT, T500 and NP1000 turbines assuming 100% power extraction independent of cut-in speeds for site H2 over one month.

8.1.3. Tidal stream site H3

Measured velocity

For assessment site H3, the greatest velocity speeds take place over the flood tide and peak at 1.2 m/s (Figure 8.1.3.1). A mean velocity of 1.06 (V_{ms}) was calculated over the spring tides. During the period of high water the overall current speeds increase, ranging between 0.6-1.0 m/s but reduce over the ebbing tide. Again, there is a consistency in the velocities (Figure 8.1.3.6) along the semi-major and semi minor axes around 0.6 m/s observed beneath the MLLW. Beyond this depth there is a gradual increase in velocity towards the surface for the (V) velocity component. Noticeable changes are observed in the orientation, phase and cross channel velocity for the M_2 component beyond the (6.4 m) MLLW.

A maximum current speed of 0.6 m/s is reached over the flood tide for the neap cycle with a (V_{mn}) of 0.03 m/s.

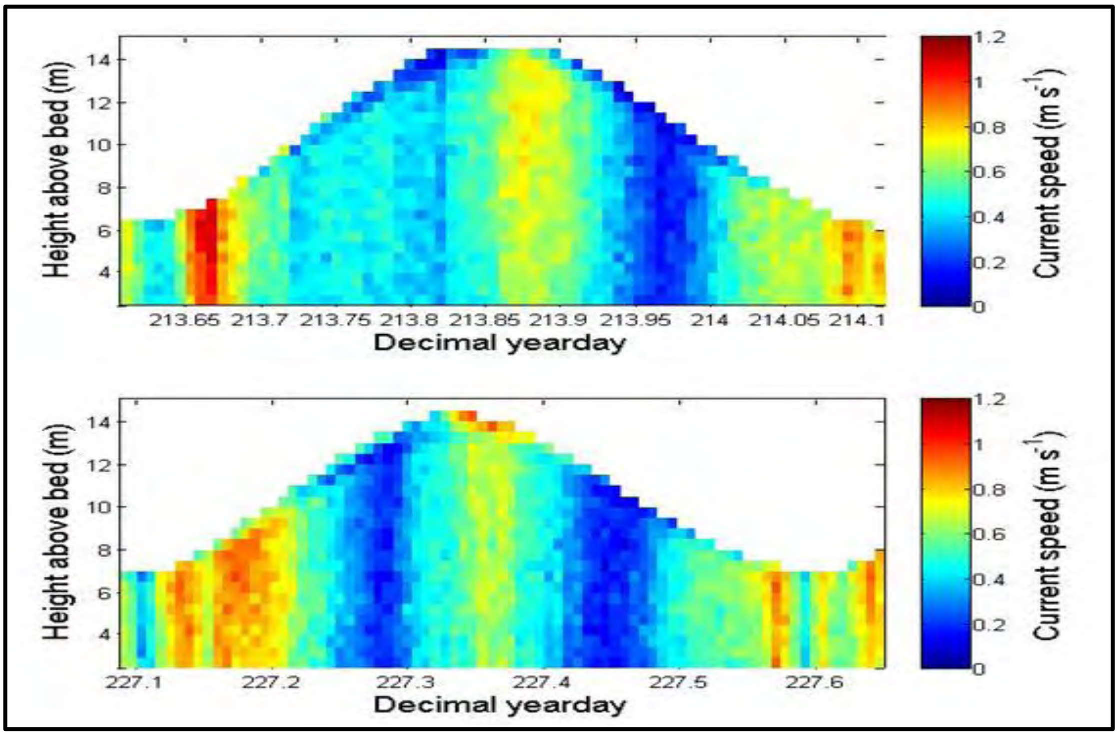


Figure 8.1.3.1: Current velocity over a 12.25 hour spring tidal cycle for site H3. Occurrence for spring tides one (top) 02.08.2011, for spring tide two (bottom) 16.08.2011.

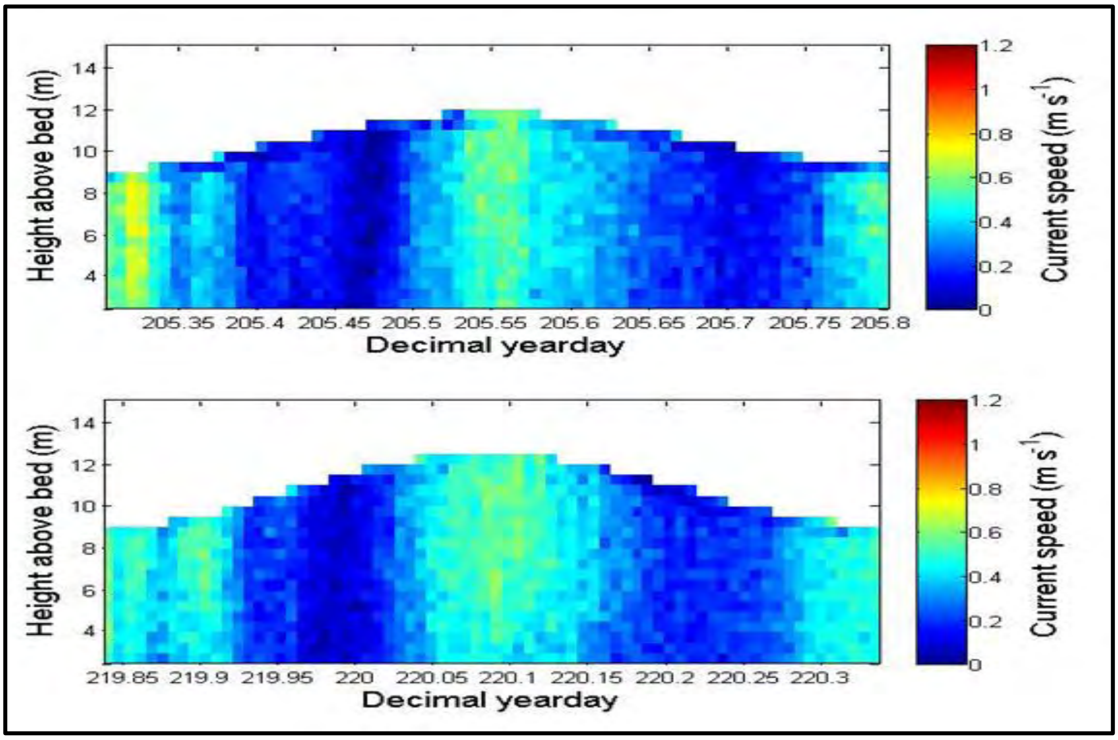


Figure 8.1.3.2: Current velocity over a 12.25 hour neap tidal cycle for site H3. Occurrence for neap tide one (top) 25.07.2011, for neap tide two (bottom) 09.08.2011

ii) Current direction

The primary current direction at site H3 emanates from the west to North West direction (Figure 8.1.3.3), ranging between 270-300^0. From slack water, entering into the start of the flood tide the direction of the current is westerly, which changes rapidly to the north westerly direction during the middle of the flooding tide. The pattern of current direction does not deviate from this over the neap cycle.

Tidal current ellipses calculated using harmonic analysis indicates that the flow is dominantly rectilinear (Figure 8.1.3.5) for depth bin 8, corresponding to 5.9m above the bed. However a range of variability in the extent of the rectilinear flow observed for the current ellipses from depth bins 1-8 (Appendix I) at this site. Additionally, at a height of 11.9m above the seabed (bin 20) the observed velocity is greater than 1m/s along the semi-major and semi-minor axes concurrently. The opposing current forces generate a non-rectilinear flow as displayed from the largely ovate tidal ellipse.

The ellipses for depth bins 0-8 are aligned at a heading of approximately 300^0 relative to the long channel direction (10^0). Current direction as depicted by the M_2 constituent (Figure 8.1.3.6) is at a constant orientation of 150^0, from the seabed up to MLLW. Beyond this, the orientation varies throughout the vertical within the range of 50-150^0.

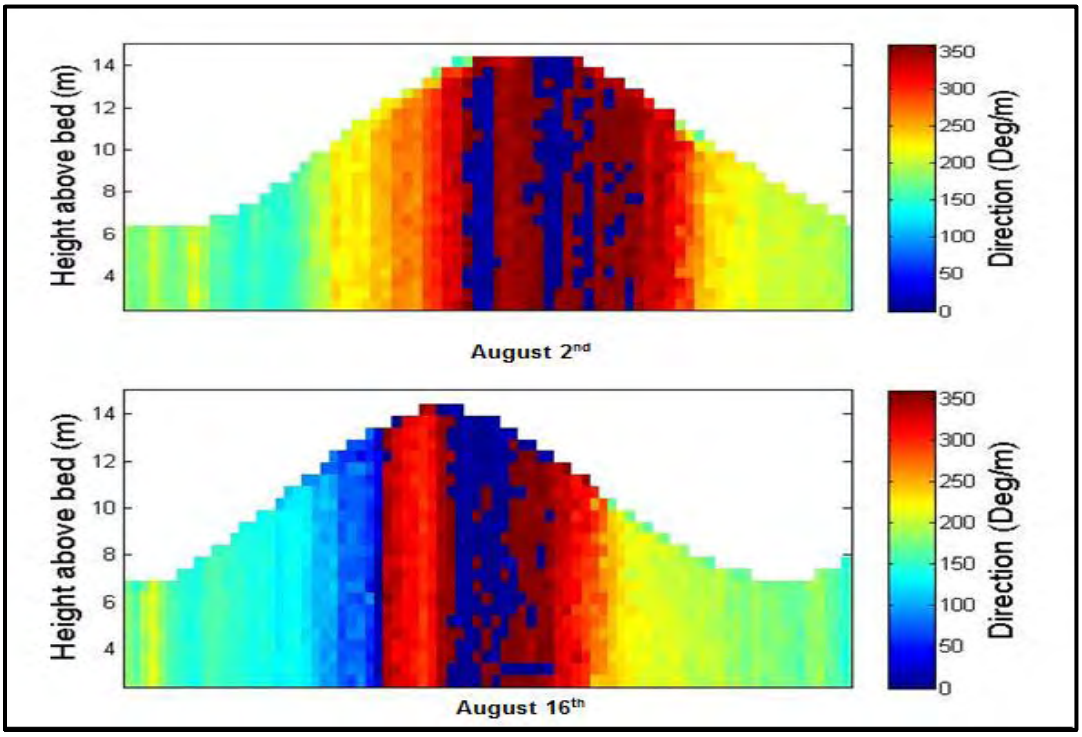


Figure 8.1.3.3: Current direction over a 12.25 hour spring tidal cycle for site H3. Occurrence for spring tides one (top) 02.08.2011, for spring tide two (bottom) 16.08.2011.

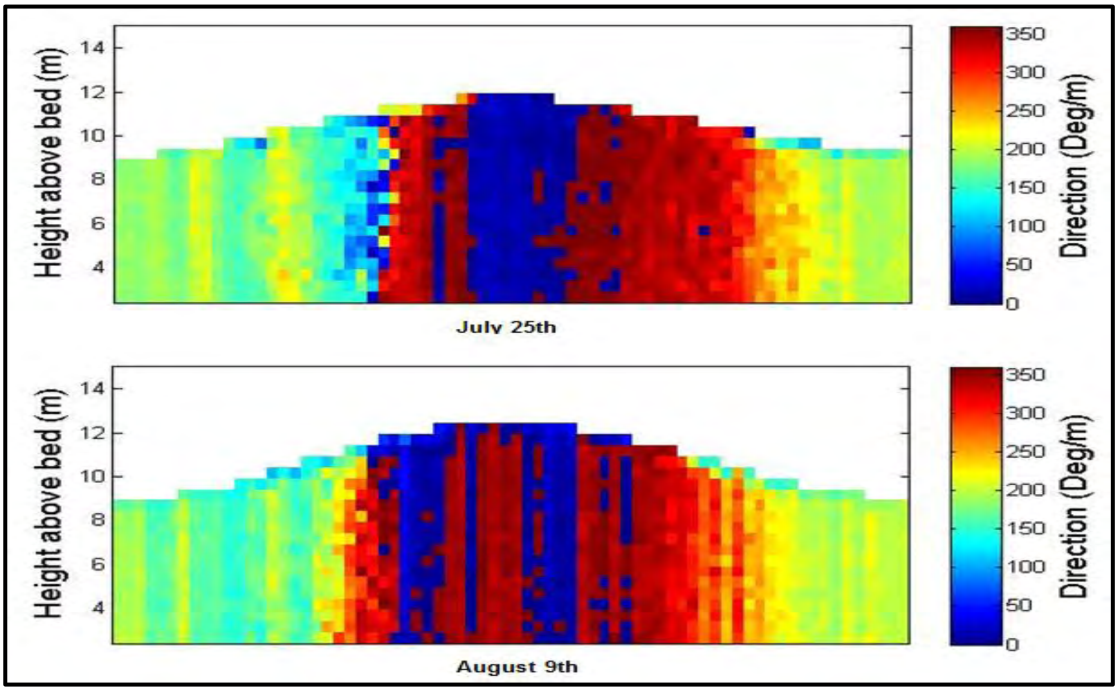


Figure 8.1.3.4: Current direction over a 12.25 hour neap tidal cycle for site H3. Occurrences for neap tide one (top) 25.07.2011, for neap tide two (bottom) 09.08.2011.

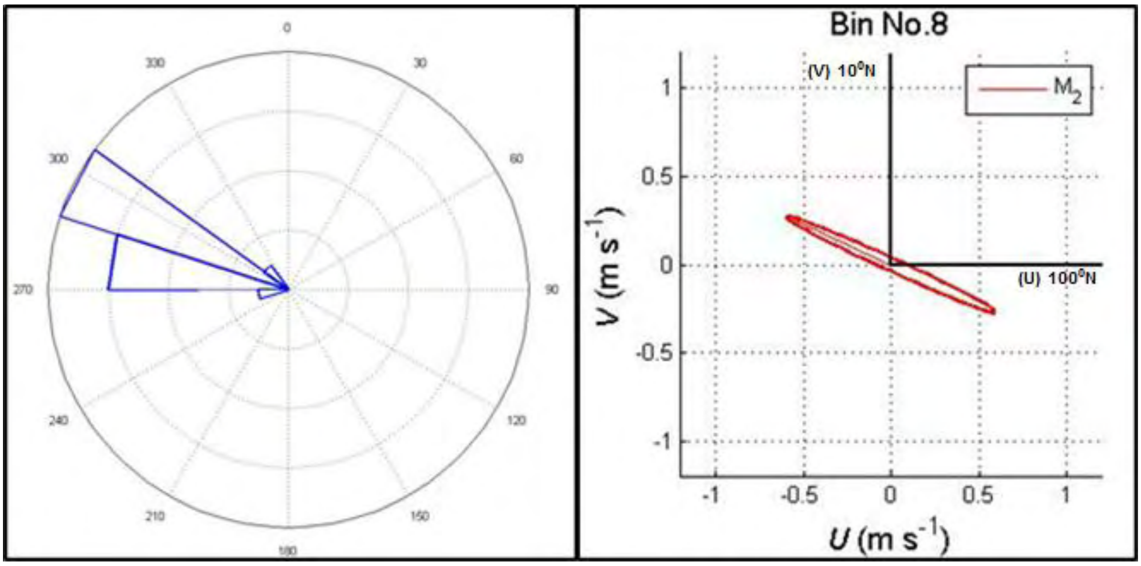


Figure 8.1.3.5: : Rose plot of current direction (degrees) (left), tidal ellipse indicting velocity orientation along the semi-major (V) and semi-minor (U) axis for depth bin 8 (right). Axes have been rotated so that the long channel direction (10^0N) is orientated to view vertically and the cross channel horizontally.

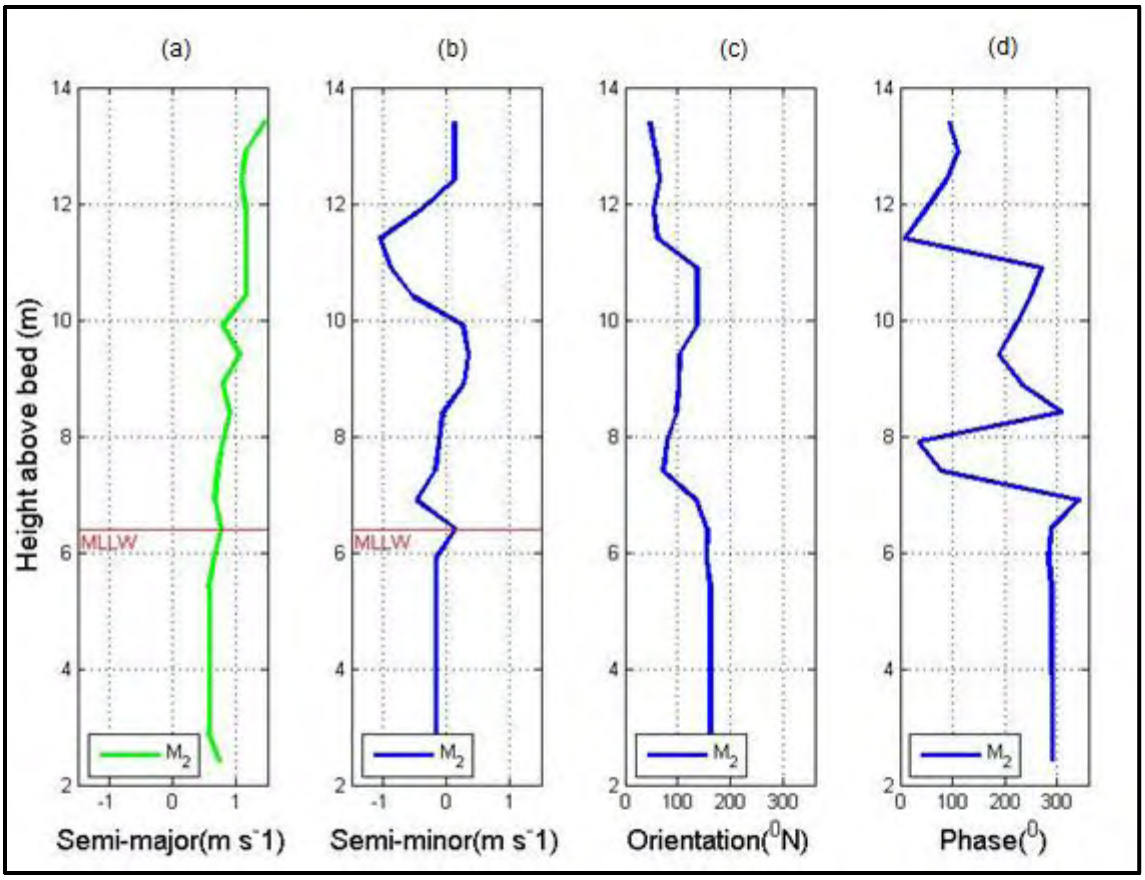


Figure 8.1.3.6: Depth profiles of (a) semi-major axes, (b) semi-minor axes, (c) orientation and (d) phase of M_2 tidal constituent from assessment site H3 as calculated by harmonic analysis. Height of the Mean low lower water (MLLW) indicated at 6.4m.

iii) Extractable power

The observed velocities are distributed throughout a range from 0-1.2 m/s (Figure 8.1.3.7). The velocities which occur most frequently, 39% of the time, are <0.1 m/s. The mean site velocity is 0.4 m/s which occur over 11% of the measurement period. Speeds exceeding 0.7 m/s only comprise 5% of the total observed velocities.

The APD calculated for the long channel velocity component (V), at a depth of 5.9 meters form the bed (Figure 8.1.3.8), is 0.09 kW/m^2. Total power density summed over the month is 308 kW/m^2. The mean spring power density is 1.24 kW/m^2 and <0.1 kW/m^2 for the mean neap power density.

As established in section 6.1.8 the only suitable TEC, from those considered within this assessment, suitable for deployment at site H3 is the NP1000 turbine. Figure 8.1.3.9 displays the electrical power generated by the Neptune TEC over the month's spring and neap cycles, assuming 100% of energy extraction was achieved. Increased peaks of production are observable over the spring tidal cycles.

The NP 1000 produces maximum power output of 28 kW over the time period. Given a 34% operational period for speeds of 0.4 m/s and above, the total achievable power summed over the time period is 4.4 MW/h. Despite the low occurrence of greater velocity speeds, as little power is produced at slower speeds this should have little effect on the mean power output (Hardisty, 2009).

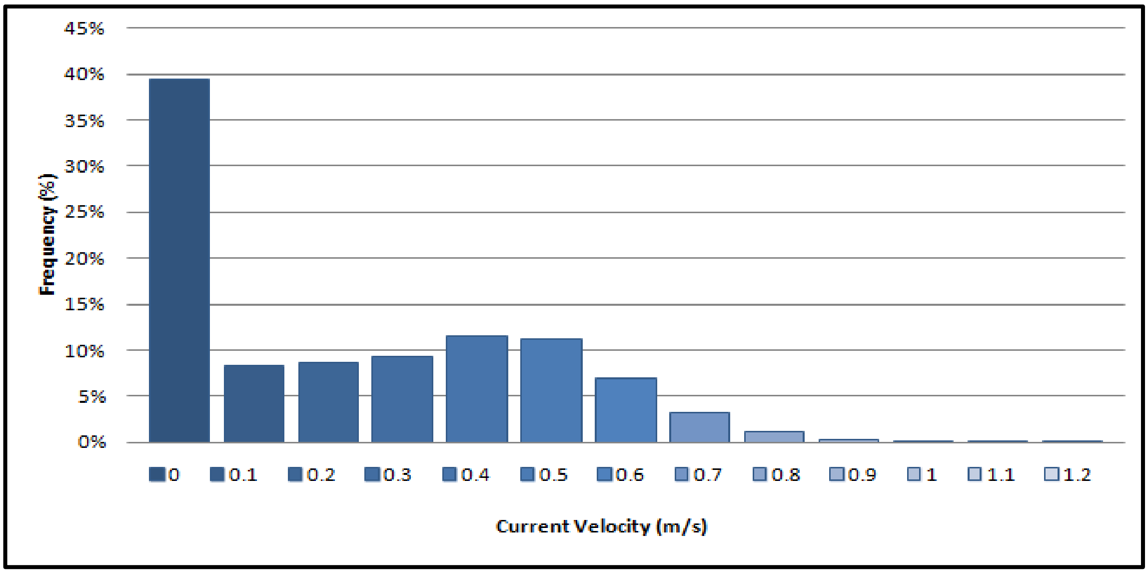


Figure 8.1.3.7: Velocity distributions recorded over the period of 30 days, for site H3.

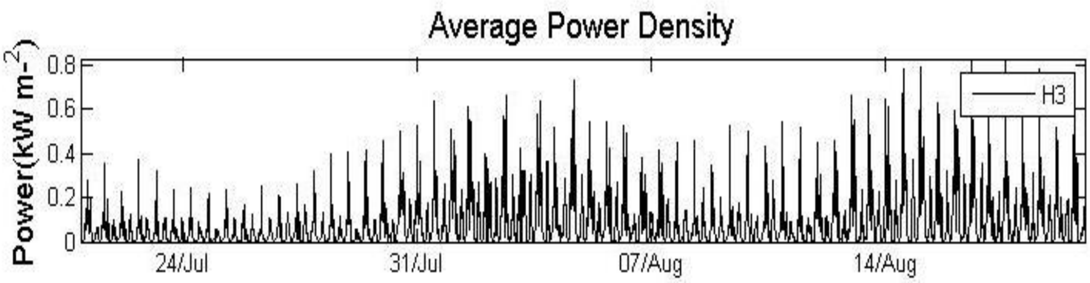


Figure 8.1.3.8: Average power density for long channel velocity component (V) at 5.9 meters from the bed, calculated over a 30 day period from the 21.07.11 to 20.08.11 for assessment site H3.

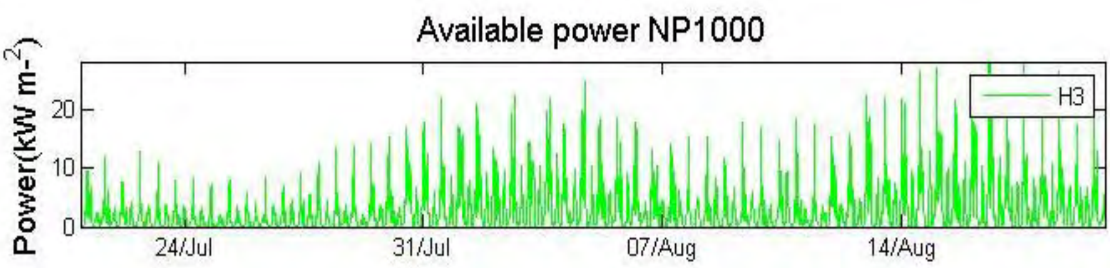


Figure 8.1.3.9: Extractable power output from NP1000 turbine assuming 100% power extraction, independent of cut-in speeds for Site H3 over one month.

9. Discussion

Assessment of data collected over a 35 day period has revealed current speeds exceeding 1 m/s for sites H2 and H3 with the capacity to harness 1.2 MW/h and 4.4 MW/h respectively, per month. The power estimation is based velocities of 0.4 m/s and greater, to meet the minimum cut in speed for the NP1000 turbine. The annual theoretical power production, assuming the exploitation of both sites with a single NP1000 TEC is 67.2 MW/h. Further to this NREL ltd stated that the turbines would be installed in pods of 5 units, with each unit having a 1.25MW capacity. If a 'pod' were to be situated at site H3, then the total annual power production could potentially increase to 264 MW/h. However, there are a number of further parameters, which will be discussed, that would need to be quantified regarding the site conditions if this development were to be pursued. Additionally, there are many logistical and operational barriers that would be associated with deployment of TEC's within the Little Russel given currently available technology.

After assessment it was revealed that site H1 holds no scope for the production of energy through the deployment of tidal turbines due the low average current speeds experienced. It is the assumption that velocities across the width of a channel are constant; however current speeds close to the shore will be slower than those experienced further from the land boundary (EPRI, 2005). This accounts for the variability in observed current speeds as site H1 is located nearest to the shore. Furthermore, at present there is no TEC available which would satisfy both requirements; (a) be suitable for deployment at a site with a maximum water depth of 9.8 meters at low tide and, (b) be able to extract energy from tidal currents <4 m/s.

Assessment site H2 does hold potential to be pursued as prospective site for exploitation in the future but given current power extraction capabilities of tidal turbines it is unlikely for the interim. The current speeds only exceed the minimum requirement of 0.7 m/s for the OCT and T500 turbine for 2% of a 30 day period, so these technologies were discounted. It would not be economically feasible to propose this.

If the site was considered for development by deploying the Neptune Proteus (NP1000) then the resource would have to be further characterised. This is based on the operational limitations of the NP1000 which is specifically designed for shallow water, mesoscale estuarine deployments (Hardisty, 2009). NREL Ltd state that turbine installation takes place in sheltered areas with the absence of wave activity. This is result of lowered engineering costs for the structure which is not built to withstand offshore conditions. Therefore quantification of both the operating limitations of the NP1000 and the prevailing wave climate for the Little Russel is required. From the data acquisition conducted as part of this assessment preliminary conclusions can be drawn. As discussed in section 8.1.1 there is uniformity in current speed and direction throughout the water column up to the MMLW, which is representative of the tidal conditions throughout neap tides and slack water (Hardisty, 2009). This demonstrates that there is no shear in the tidal currents caused by frictional stress from the seabed as no decay in velocity observed with distance from the bed (Blunden, 2009). However it is apparent that in the near surface waters, increases in velocity associated with changes in both phase and orientation of the semidiurnal constituent are resultant from a change in amplitude, further displayed by the surface plots in appendix E. This could further be attributed to the close proximity of the flow boundary from the free surface which is far more dynamically volatile than the lower depths (Blunden and Bahaj, 2007). The key issue being, which requires further assessment, is what the extent of the surface dynamics are.

Site H3 was found to be the most energetic site, and also holds rationalization for further assessment. The same assessment parameters discussed for site H2 would also apply for this site. Furthermore, as this site is located at the southern end of the Little Russel it is exposed to the prevailing current passing around the mainland from the west. This influence is highly visible in the observed the tidal ellipses and non rectilinear flow for site H3. The variability of the tidal ellipses throughout the vertical depicts a highly dynamic region that is strongly influenced by the coastlines, bottom topography, and equally prevailing currents along the semi-major and semi-minor axes. In summary this site has the greatest energy potential but also holds a great potential to be too turbulent for the NP1000.

The operational barriers presented by the bathymetry of the Little Russel propose the greatest restriction to exploitation of the resource. The majority of TEC’s currently available at a level of technological readiness for deployment are either too large, or have cut in speeds which would be restricted by the lower velocity climate of the Little Russel. Consequently, exploitation of the tidal currents within the Little Russel as part of Guernsey renewable energy focus is highly unlikely at present.

10. Conclusions and Recommendations

Through this assessment the main objectives of evaluating the tidal resource and theoretical power availability in relation to the current technological capabilities of TEC's have been achieved. The most southerly site (H3) was found to hold the greatest potential for energy extraction. The Neptune Proteus (NP 1000) was deemed the most appropriate technology for extraction given the limited water depth. This would result in an annual extractable power of 53MW/h per annum form a single device or possibly 264MW/h for an array of five turbines.

Despite this, the overall magnitude of the currents displayed within the Little Russel are low in comparison to other potential tidal stream development sites around the world and in close proximity to Guernsey, such as the Big Russel. The low power output in conjunction with the operational restrictions make the Little Russel an unlikely investment.

If Guernsey RET feel that further investigation of the resource potential is warranted, based upon the findings of this report then the recommendations for the future would be; (i) quantification of the wave climate within the Little Russel to understand the interactions between the free surface in relation to the tidal streams (ii) investigation into the durability of the NP1000 and the extent of the physical extremes (iii) a review of currently available tidal stream technology due to the constantly advancing nature of the renewable energy industry.

References

Armijo, C(LT). (2007). Processing Acoustic Doppler Current Profiler Data for. Operational Oceanography and Meteorology. DOC 3570 . p1-15

BBC. (2010). *The Channel Islands.* Available at: http://news.bbc.co.uk/1/hi/world/europe/country_profiles/7515502.stm . Last accessed 10th Feb 2012

Black and Veatch commissioned by The Carbon Trust. (2005), Phase II: UK tidal stream energy resource assessment, 2, Black and Veatch Ldt, 650 London Road, Isleworth, Middlesex TW7 4EG, United Kingdom.

Blunden, L.S., and Bahaj, A.S. (2007). Tidal energy resource assessment for tidal stream generators. *SPECIAL ISSUE PAPER*. 221 (A), p137-146

Blunden, L.S. (2009). New approach to tidal stream energy analysis at sites in the English Channel. University of Southampton Research Repository. p1-84.

British Wind Energy Associate (BWEA) . (2009). Marine Renewable Energy. State of the Industry report. p1-25.

Bryden, I.G., Couch, S.J., Owen, A., and Melville, G. (2007). Tidal current resource assessment. Special issue paper 125. 221 (A), p125-135.

Callaghan, J. and Boud, R. (2006), Future Marine Energy - Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy, Carbon Trust, UK.

Channel Television, 2011. Available at: http://www.channelonline.tv/channelonline_guernseynews/DisplayArticle.asp?ID=497528 Last Accessed 6th June 2012.

Carbon Trust. (2011). Accelerating marine Energy . The potential for cost reduction-insights from the Carbon Trust Marine Energy Accelerator. p8-38.

Craig, J. (2007). Strategic Tidal Stream Assessment for Alderney. *Alderney Commission for Renewable Energy*. . (ED 43120001 - Issue 1), p1-11

Electric Power Research Institute (EPRI). (2005). Methodology for estimating tidal current energy resources and power production by tidalin-stream energy conversion (TISEC) devices. Power Feasibility demonstration project. Phase 1, p11-52.

European Marine Energy Centre (EMEC). (2012-2013). *Assessment of Tidal Energy Resource.* Available at: http://www.emec.org.uk/assessment-of-tidal-energy-resource/. Last accessed 3rd Aug 2012

Forrester, W.D. (1983). Canadian Tidal Manual. Department of Fisheries and Oceans. . (chapter 3), p39-46.

Funday Tidal Inc. (2012). *Tocardo.* Available at: http://fundytidal.com/index.php?option=com_content&view=article&id=27&Itemid=76. Last accessed 15th Aug 2012.

Gomez, M.G. (2008). University of Strathclyde, Department of mechanical engineering. Marine Current Turbines: Array effects, p3-79

Gordon, Lee, 1996, Acoustic Doppler current profiler – Principles of operation: A practical primer: RD Instruments, San Diego, CA.

Green Rhino Energy (2012). *Tidal Stream Energy.* Available at: http://www.greenrhinoenergy.com/renewable/marine/tidal_stream.php. Last accessed 3rd Aug 2012.

Guernsey Renewable Energy Commission (GREC). (2009). Pre-feasibility Technical Report. Doc No WGREC 2009-09-16 0920 RP. p1-32.

Guernsey Renewable Energy Commission (GREC). (2011). Regional Environmental Assessment (REA) of Marine Energy. Chapter 4-Marine Processes. Version 1. p93-118.

Guernsey Renewable Energy Commission.(GREC) (2012). *About RET.* Available at: http://www.guernseyrenewableenergy.com/about/About-RET.aspx. Last accessed 3rd Aug 2012.

Hardisty, J (2009). The Analysis of Tidal Stream Power. West Sussex: John Wiley & son's Ltd. p55-87.

International Water Power & Dam Construction. (March 2010). New Technology. *A powerful proposition*. p12-14.

Neptune Renewable Energy Ltd (NREL). (2012). *Demonstrator Design.* Available at: http://www.neptunerenewableenergy.com/demonstrator-design/. Last accessed 15th Aug 2012.

Owen, A. (2010). Tidal Resource Mapping for the Territorial Waters of Guernsey. *The Robert Gordon University, Aberdeen*. Final Draft Report. p1-14.

Pawlowicz, R., Beardsley, B., and Lentz, S., "Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE", Computers and Geosciences 28 (2002), 929-937.

Previmer.org. (2012). Coastal observations and forecasts . Available : http://www.previmer.org/en/forecasts/currents/modele_hycom_manche_gascogne/(typevisu)/map/(zoneid)/manchef1#appTop. Last accessed 26th Aug 2012.

Professional Engineering (PE). (2010). *Partner needed to build tidal stream power generator.* Available: http://profeng.com/news/partner-needed-to-build-tidal-stream-power-generator. Last accessed 15th Aug 2012.

RD Instruments (RDI). (1996). Acoustic Doppler Current Profiler. *Principles of Operation, A Practical Primer*. Second Edition (P/N 951-6069-00), p3-19

Redman, A., Abercromby, G., Dufour, E., Franc, P., Garcia Sanabria, I., Mayal Ortiz, J.F., Mbuk, O., Mirval, L.. (2011). A Feasibility Study of Marine Renewable Energy in the Channel Islands . *Cranfield Univeristy*.p10-320.

Sinclair Knight Merz (MRZ). (2006). Renewable Energy Assessment. *Marlborough District Council*. Final Report . p55-64.

States of Guernsey. (2012). Renewable Energy Team (RET) Strategy 2012 and Beyond. Commerce and Employment (DOC453), p1-22.

Tocardo International BV. (2012). *Turbine T500.* Available: http://www.tocardo.com/digi_cms/12/t500.html. Last accessed 15th Aug 2012.

University of Exeter. (2012). Guernsey Renewable Energy Feasibility Report. RE 2012. p14-139.

Software

SeaZone: Geo Temporal Editor. Software Version 2.0.3.7.1

Mathworks: MATLAB. Software version 7.12.0 (R2011a)

ESRI (Environmental Systems Resource Institute): ArcMap 9.2.

Appendices

Appendix A: Harmonic Analysis output script using ‘t-tide toolbox’. MATLAB. Site H1

```
total var= 253.1092   pred var= 3.5782
percent total var predicted/var original= 1.4 %

   number of standard constituents used: 59
   Points used: 5167 of 5168
   percent of X var residual after lsqfit/var original: 94.65 %
   percent of Y var residual after lsqfit/var original: 97.89 %
   Phases at central time
   Using nonlinear bootstrapped error estimates
   Generating prediction without nodal corrections, SNR is 2.000000
   percent of X var residual after synthesis/var original: 97.88 %
   percent of Y var residual after synthesis/var original: 98.68 %
-----------------------------------
date: 07-Sep-2012
nobs = 5168,  ngood = 5167,  record length (days) = 215.33
rayleigh criterion = 1.0
Phases at central time

x0= -2.18, x trend= 0

var(x)= 25.0488   var(xp)= 0.55468   var(xres)= 24.5169
percent var predicted/var original= 2.2 %

y0= 7.47, x trend= 0

var(y)= 228.0604   var(yp)= 2.9884  var(yres)= 225.0524
percent var predicted/var original= 1.3 %

ellipse parameters with 95%% CI estimates
```

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
SSA	0.0002282	0.500	0.384	-0.109	0.61	172.69	120.70	26.19	100.11	1.7
MSM	0.0013098	0.264	0.557	0.046	0.44	178.54	182.56	232.38	92.19	0.22
MM	0.0015122	0.354	0.471	-0.224	0.41	119.12	71.84	118.67	152.41	0.56
MSF	0.0028219	0.290	0.484	0.026	0.40	134.26	68.61	14.80	143.19	0.36
MF	0.0030501	0.284	0.519	-0.039	0.35	124.78	54.63	239.32	122.78	0.3
ALP1	0.0343966	0.228	0.696	0.062	0.38	88.14	45.27	317.28	191.16	0.11
2Q1	0.0357064	0.259	0.665	0.139	0.41	83.13	49.55	153.52	172.57	0.15
SIG1	0.0359087	0.228	0.705	-0.002	0.37	104.63	40.17	315.61	190.45	0.1
Q1	0.0372185	0.426	0.768	-0.116	0.38	83.68	43.10	22.09	141.57	0.31
RHO1	0.0374209	0.628	0.863	0.037	0.39	99.40	32.65	131.07	100.46	0.53
O1	0.0387307	0.298	0.707	0.045	0.37	110.27	45.49	262.84	177.37	0.18
TAU1	0.0389588	0.098	0.651	0.021	0.42	163.89	41.41	3.14	252.35	0.022
BET1	0.0400404	0.899	0.887	-0.141	0.60	120.46	39.34	132.86	58.27	1
*NO1	0.0402686	2.649	1.025	-0.260	0.56	112.78	11.91	71.26	22.01	6.7
CHI1	0.0404710	0.628	0.735	-0.217	0.46	107.48	48.58	253.95	103.98	0.73
P1	0.0415526	0.388	0.702	0.190	0.40	96.70	45.97	67.40	140.78	0.31
K1	0.0417807	0.232	0.647	-0.093	0.38	36.39	53.28	211.47	184.30	0.13

PHI1	0.0420089	0.266	0.624	0.123	0.44	134.72	58.39	300.91	173.90	0.18
THE1	0.0430905	0.382	0.654	0.028	0.35	84.19	45.79	93.93	150.02	0.34
J1	0.0432929	0.253	0.678	0.004	0.40	121.04	45.07	165.84	186.92	0.14
SO1	0.0446027	0.509	0.804	-0.006	0.46	57.25	44.84	80.04	106.52	0.4
OO1	0.0448308	0.306	0.718	0.119	0.38	81.08	45.50	155.46	148.25	0.18
UPS1	0.0463430	0.216	0.659	-0.109	0.45	135.99	58.84	309.42	186.26	0.11
OQ2	0.0759749	0.255	0.326	0.028	0.21	80.18	48.25	171.46	118.27	0.61
EPS2	0.0761773	0.142	0.305	-0.024	0.27	166.26	98.76	76.98	148.30	0.22
2N2	0.0774871	0.302	0.403	0.027	0.25	88.08	43.85	302.05	101.18	0.56
MU2	0.0776895	0.339	0.375	0.104	0.24	67.22	57.10	330.83	89.27	0.81
N2	0.0789992	0.263	0.343	0.056	0.28	96.39	55.90	228.38	112.81	0.59
NU2	0.0792016	0.207	0.359	0.052	0.25	94.29	60.53	0.44	124.54	0.33
M2	0.0805114	0.206	0.277	0.051	0.28	158.22	106.53	334.88	166.66	0.55
MKS2	0.0807396	0.239	0.308	-0.085	0.28	30.89	106.20	130.54	107.36	0.6
LDA2	0.0818212	0.162	0.297	0.115	0.28	107.74	71.54	296.17	151.66	0.3
L2	0.0820236	0.213	0.327	0.000	0.25	120.30	74.50	155.22	139.78	0.42
S2	0.0833333	0.241	0.297	-0.037	0.34	0.28	146.12	250.76	81.02	0.66
K2	0.0835615	0.107	0.293	-0.010	0.26	42.58	62.88	163.15	162.41	0.13
MSN2	0.0848455	0.291	0.383	0.045	0.28	58.23	63.07	292.44	88.03	0.58
ETA2	0.0850736	0.257	0.285	-0.101	0.29	45.55	79.31	354.06	83.60	0.81
MO3	0.1192421	0.111	0.208	-0.097	0.19	89.57	125.82	164.40	160.43	0.29
M3	0.1207671	0.186	0.201	0.048	0.22	106.04	90.21	94.99	109.68	0.85
SO3	0.1220640	0.127	0.179	0.029	0.18	133.91	116.57	216.40	124.67	0.51
MK3	0.1222921	0.194	0.211	0.061	0.23	67.19	76.03	106.66	103.76	0.84
SK3	0.1251141	0.190	0.188	-0.052	0.21	175.21	95.46	326.85	108.92	1
MN4	0.1595106	0.079	0.165	-0.001	0.16	110.04	87.44	162.27	172.91	0.23
M4	0.1610228	0.207	0.217	0.023	0.18	81.06	53.97	115.76	75.84	0.91
SN4	0.1623326	0.150	0.176	-0.028	0.17	78.80	79.13	145.89	103.71	0.73
MS4	0.1638447	0.123	0.162	0.050	0.17	166.63	128.19	276.41	119.91	0.58
MK4	0.1640729	0.162	0.213	-0.037	0.19	145.30	96.20	212.47	85.84	0.58
S4	0.1666667	0.113	0.193	-0.059	0.15	145.50	102.08	63.06	124.33	0.34
SK4	0.1668948	0.153	0.205	-0.041	0.16	142.76	100.67	129.02	94.19	0.56
2MK5	0.2028035	0.161	0.164	-0.024	0.20	161.67	98.52	45.44	109.43	0.97
2SK5	0.2084474	0.216	0.211	-0.080	0.17	102.17	64.82	229.13	86.26	1.1
2MN6	0.2400221	0.111	0.177	-0.045	0.16	111.19	103.48	212.97	120.84	0.39
M6	0.2415342	0.226	0.230	-0.007	0.20	135.73	66.15	112.36	66.01	0.97
2MS6	0.2443561	0.185	0.187	0.042	0.20	92.04	66.66	29.14	97.64	0.98
2MK6	0.2445843	0.162	0.196	0.040	0.18	105.71	82.71	296.61	103.68	0.68
2SM6	0.2471781	0.090	0.175	-0.003	0.18	92.91	123.46	85.09	156.25	0.26
MSK6	0.2474062	0.099	0.177	0.042	0.18	48.89	119.56	240.83	152.73	0.31
3MK7	0.2833149	0.256	0.219	0.070	0.19	147.92	60.32	218.01	57.01	1.4
M8	0.3220456	0.071	0.159	0.005	0.15	146.24	122.33	24.87	197.48	0.2

Appendix B:ADCP Device Specifications-Nortek AWAC 600MHz

Available at: http://www.nortek-as.com/lib/data-sheets/datasheet-awac/view

System	
Acoustic frequency:	1MHz, 600kHz or 400kHz
Acoustic beams:	4 beams, one vertical, three slanted at 25°
Vertical beam opening angle:	1.7°
Operational modes:	Stand-alone or online monitoring
Current Profile	
Maximum range:	30m (1MHz), 50m (600 kHz), 100m (400kHz) (depends on local conditions)
Depth cell size:	0.25 – 4.0m (1MHz) 0.5 – 8.0m (600kHz) 1.0 – 8.0m (400kHz)
Number of cells:	Typical 20–40, max. 128
Maximum output rate:	1Hz
Velocity measurements	
Velocity range:	±10 m/s horizontal, ±5 m/s along beam
Accuracy:	1% of measured value ±0.5 cm/s
Doppler uncertainty	
Current profile:	1cm/s (typical)
Wave measurements	
Maximum depth:	35m (1MHz), 60m (600 kHz), 100m (400kHz)
Data types:	Pressure, one velocity along each beam, AST*
Sampling rate (output):	2 Hz velocity, 4 Hz AST* (1MHz), 1 Hz velocity, 2Hz AST* (600kHz), 0.75 Hz velocity, 1.5Hz AST* (400kHz)
No. of samples per burst:	512, 1024, or 2048. Inquire for options
Wave estimates	
Range:	-15 to +15m
Accuracy/resolution (Hs):	<1% of measured value/1cm
Accuracy/resolution (Dir):	2° / 0.1°
Period range:	0.5-100s (1MHz), 1 - 100s (0.6MHz), 1.5 - 100s (0.4MHz)

Depth(m)	cut-off period (Hs)	cut-off period (dir)
5	0.5 sec	1.5 sec
20	0.9 sec	3.1 sec
60	1.5 sec	4.2 sec
100	2 sec	5.0 sec

Sensors	
Temperature:	Thermistor embedded in housing
Range:	-4°C to 40°C
Accuracy/ Resolution:	0.1°C/0.01°C
Time constant:	<5 min
Compass	Magnetoresistive
Accuracy/Resolution:	2°/0.1° for tilt <15°
Tilt:	Liquid level
Maximum tilt:	30°, AST* requires <10° instrument tilt
Up or down:	Automatic detect
Pressure:	Piezoresistive
Standard range:	0–50 m (1MHz) / 0-100m (0.6MHz) / 0-100m (0,4MHz)
Accuracy:	0.5% of full scale. Optional 0.1% of full scale.
Resolution:	0.005% of full scale

Connectors:	
Bulkhead (Impulse):	MCBH-2-FS
Cable:	PMCIL-8-MP
Environmental	
Operating temperature:	-4°C to 40°C
Storage temperature:	-20°C to 60°C
Shock and vibration:	IEC 721-3-2
Depth rating:	300m
Dimensions:	
	See drawing on front page
Weight in air:	7.3 kg (0.4MHz), 6.2 kg (0.6MHz), 6.1 kg (1MHz)
Weight in water:	3.6 kg (0.4MHz), 2.9 kg (0.6MHz & 1MHz)
Analog inputs	
Number of channels:	2
Supply voltage to analog output devices:	Three options selectable through firmware commands: • Battery voltage/500mA • +5V/250mA • +12V/100mA
Voltage input:	0-5V
Resolution:	16 bit A/D
Data Recording	
Capacity(standard):	2 MB, can add: 32/176/352MB or 4GB
Profile record:	Ncells×9 + 120
Wave record:	Nsamples×24 + 1KB
Data Communication	
I/O:	RS 232 or RS 422
Communication baud rate:	300-115200
Recorder download baud rate:	600/1200 kBaud for both RS232 and RS422
User control:	Handled via «AWAC» software, or ActiveX® controls. «SeaState» for online systems.
ProLog:	Provides NMEA ASCII or Binary output formats for processed wave and current data.
Power	
DC input:	9-18 VDC
Peak current:	3A
Power consumption:	Transmit power: 1–30W, 3 adjustable levels
Sleep consumption:	0.3 mW (RS232) 5 mW (RS422)
Real time clock	
Accuracy:	± 1min/year
Backup in absence of power:	1 year

Offshore Cable

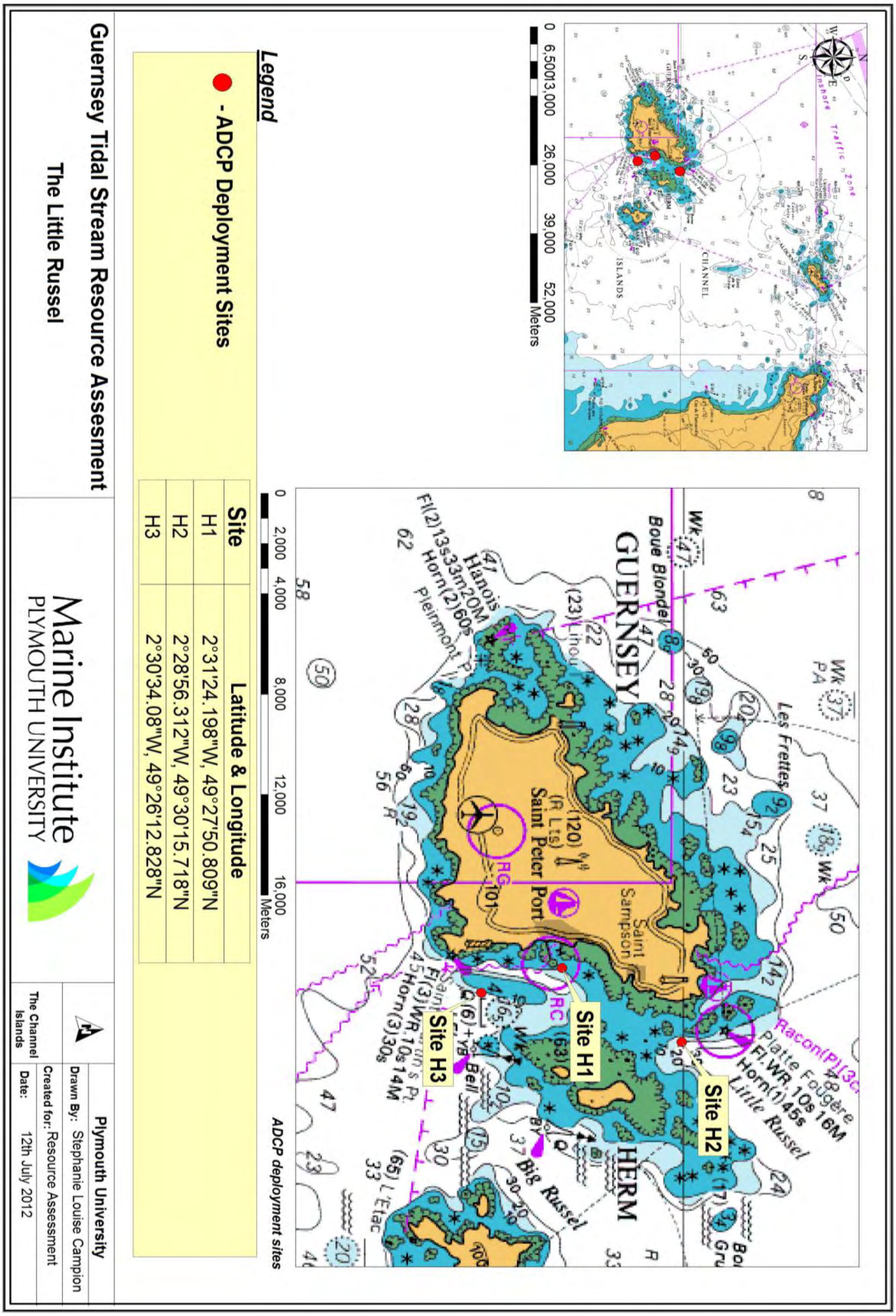
The Nortek offshore cable can, when properly deployed, withstand tough conditions in the coastal zone. In RS 422 configuration, cable communication can achieved distances up to 5 km.

Online Projects

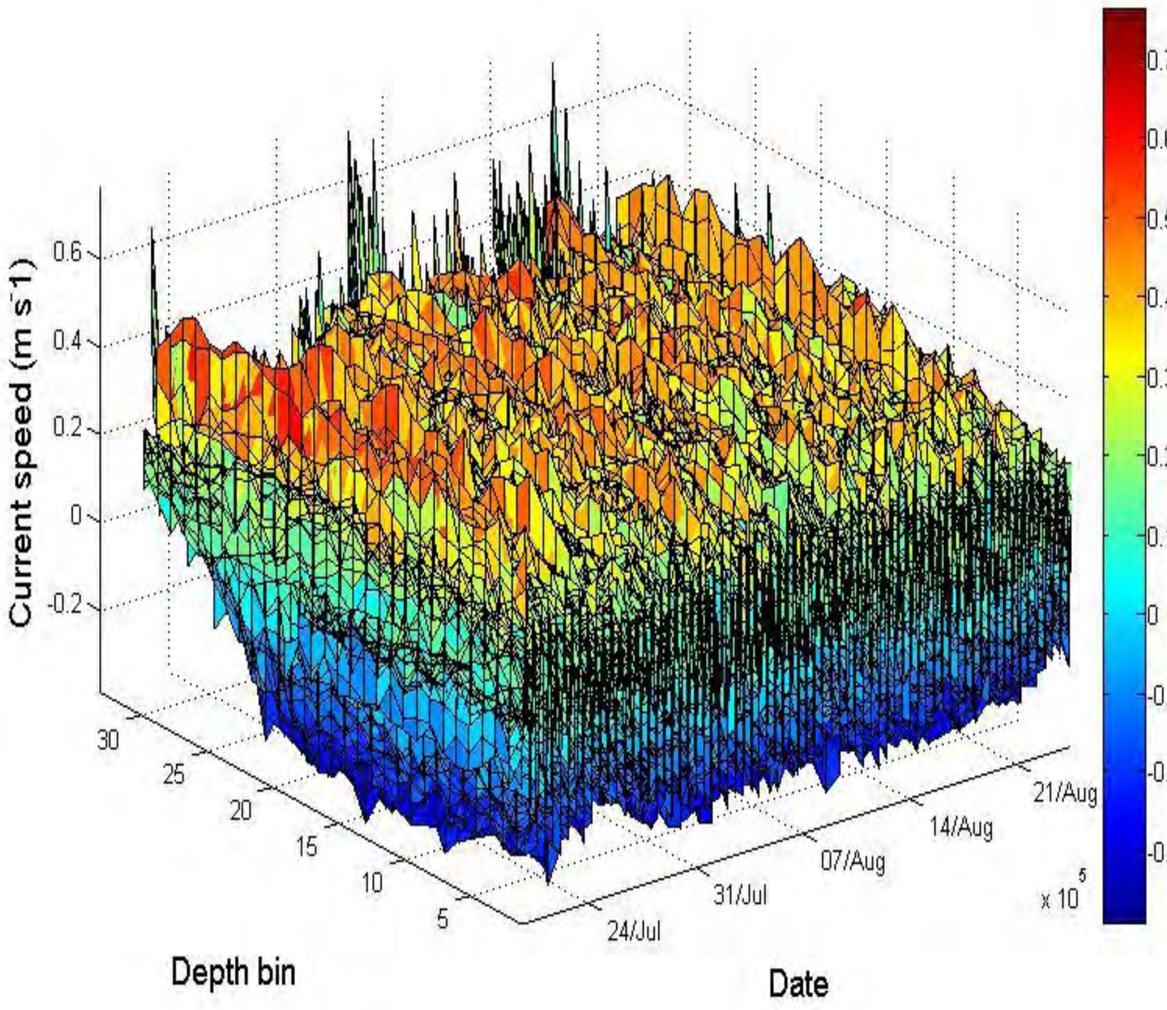
Nortek can provide long cables, radio/telephone communication equipment, acoustic modems, etc., that can meet the requirements of your specific project.

*) AST = Acoustic Surface Tracking

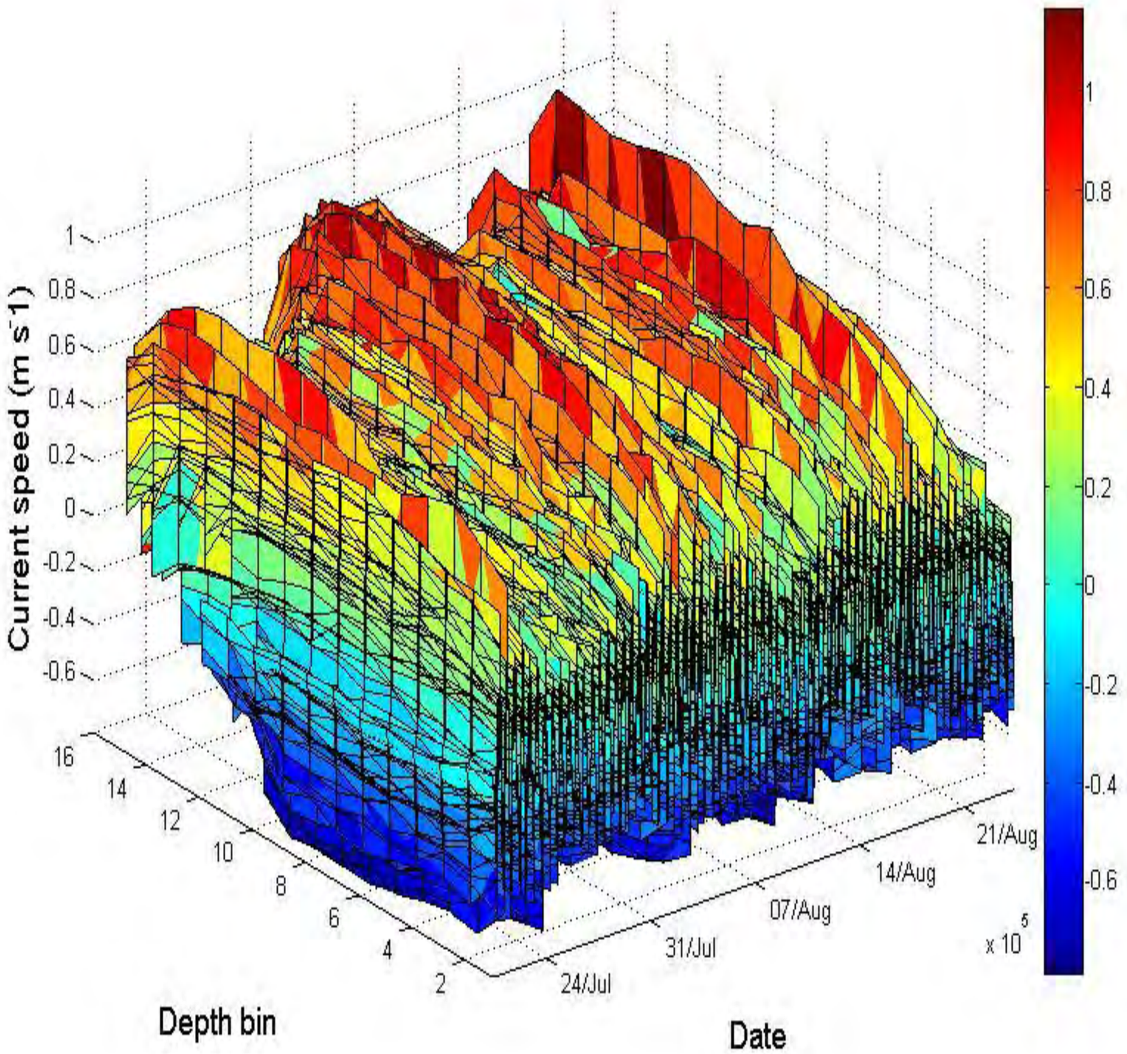
Appendix C: ADCP Deployment sites located within the Little Russel



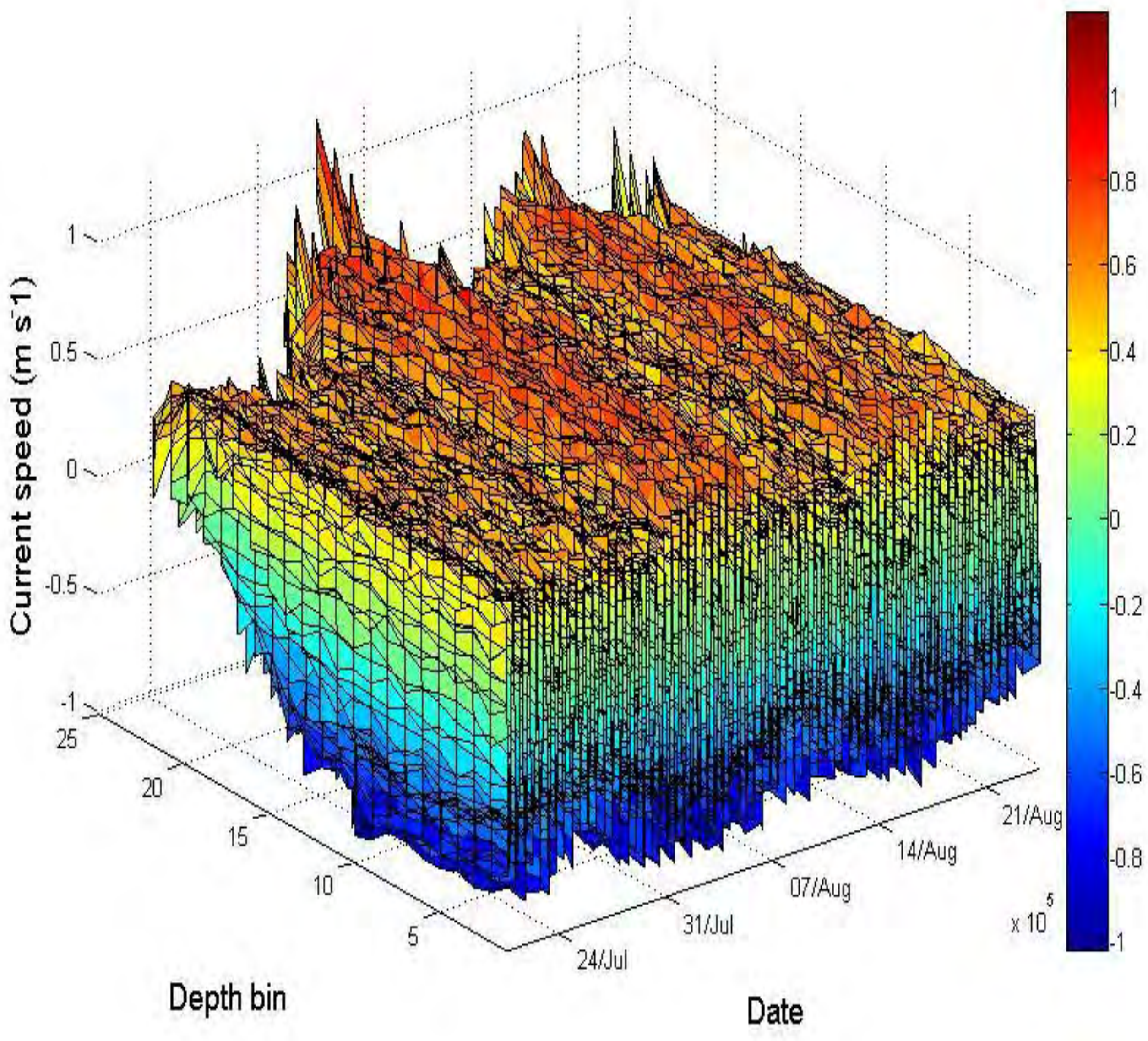
Appendix D: Surface plots of current speed throughout depth bins over data collection period. Raw data for Site H1, inclusive of all bin depths



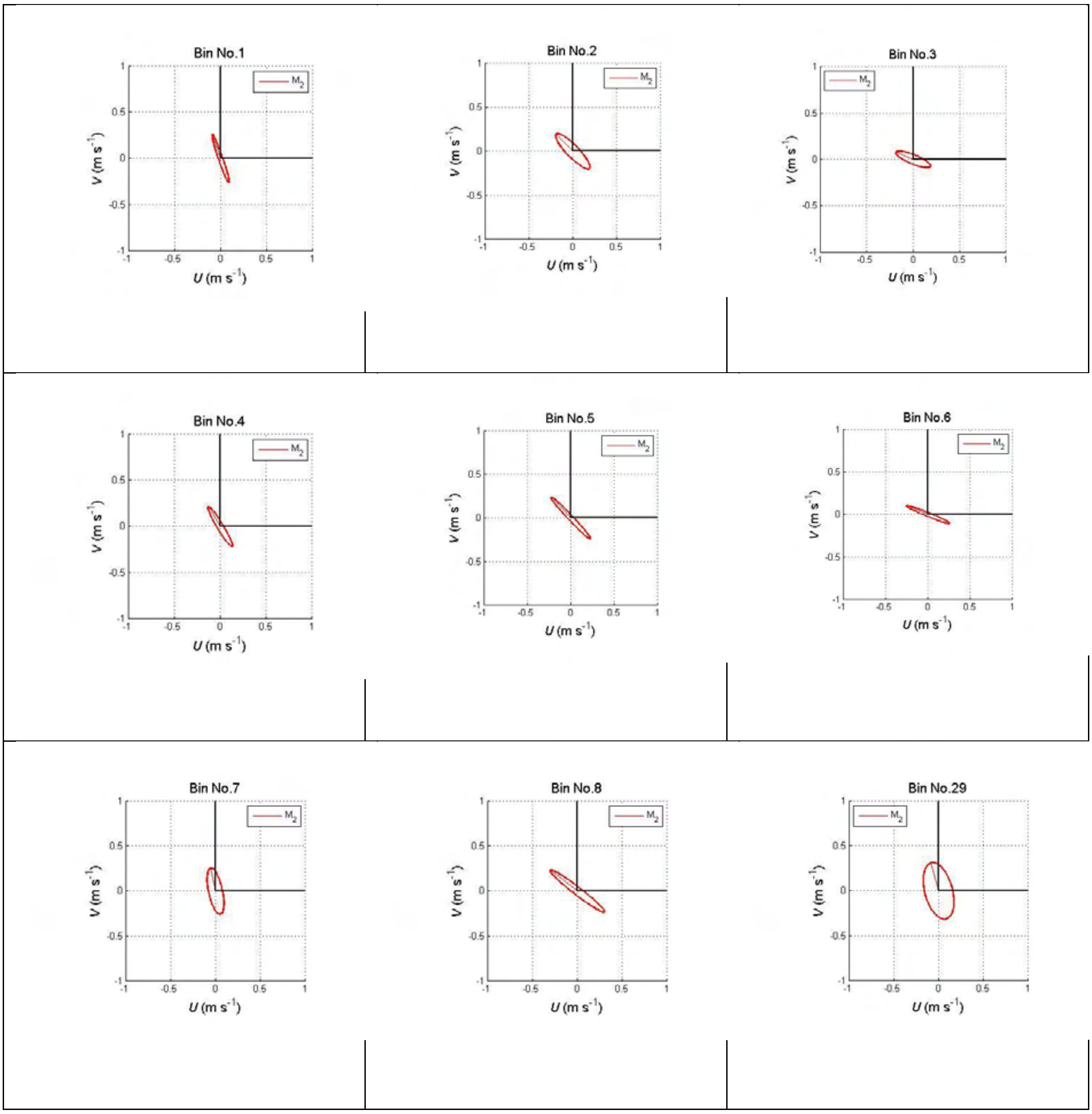
Appendix E: Surface plots of current speed throughout depth bins over data collection period. Raw data for Site H2, inclusive of all bin depths



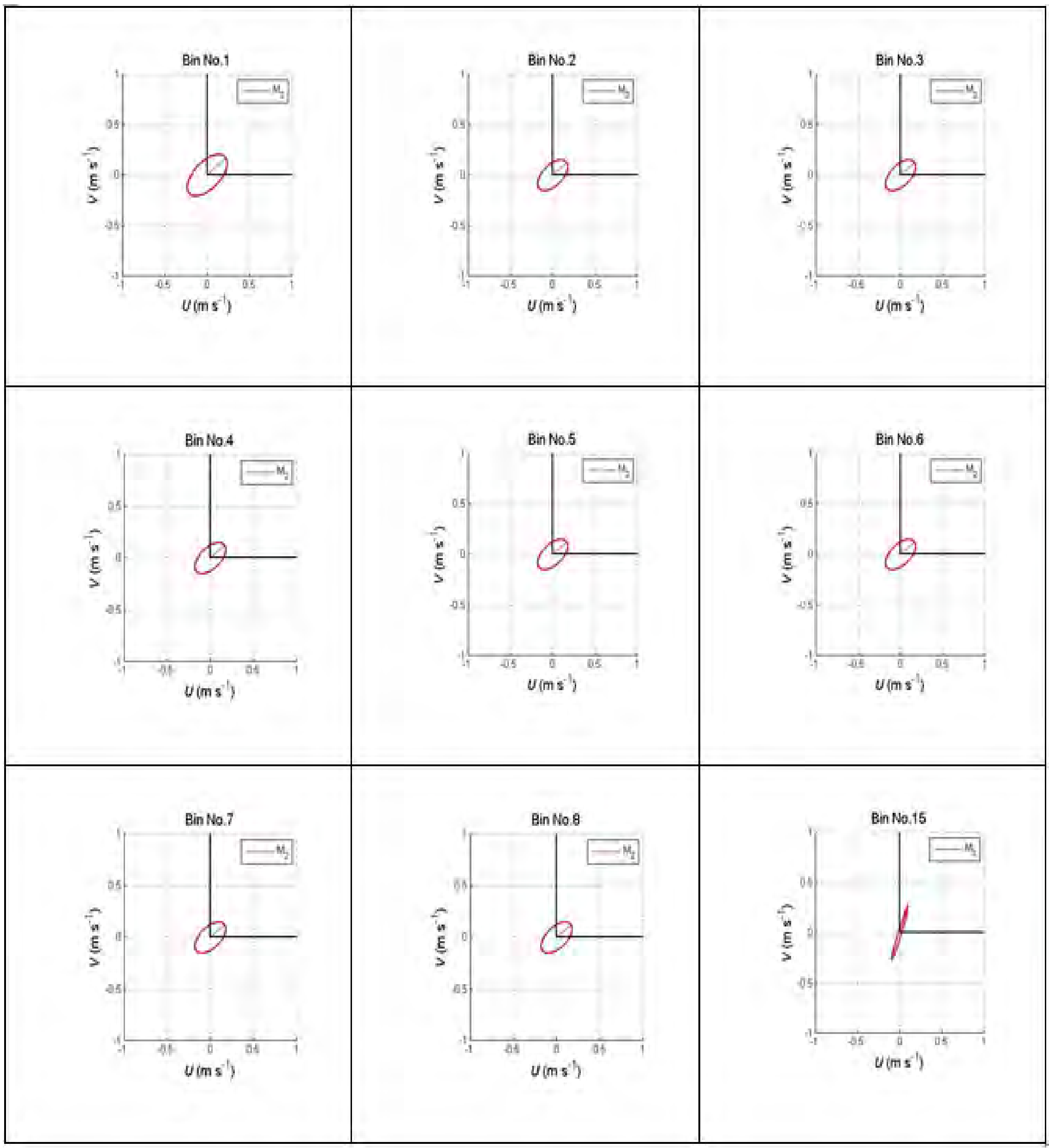
Appendix F: Surface plots of current speed throughout depth bins over data collection period. Raw data for Site H3, inclusive of all bin depths



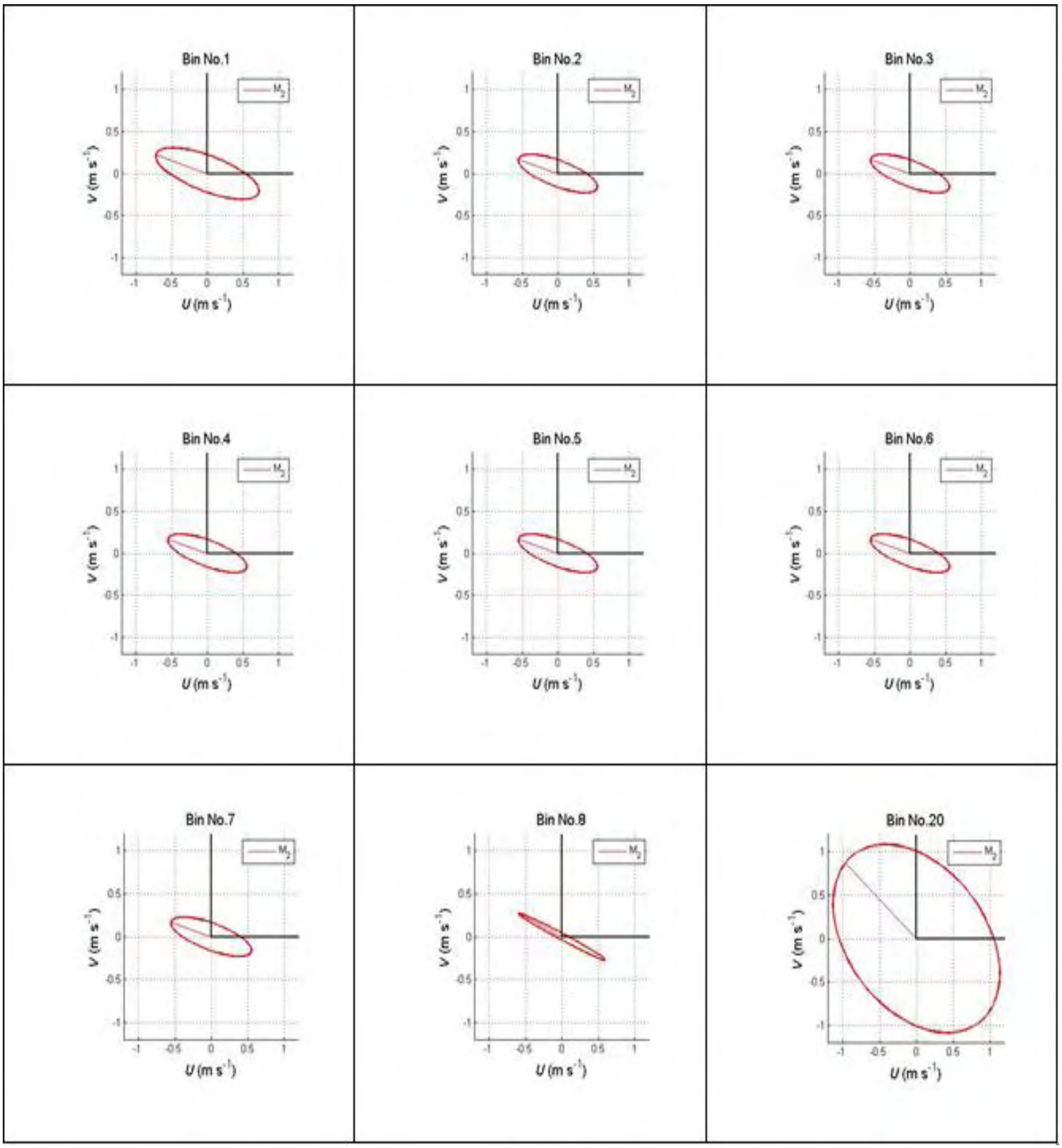
Appendix G: Tidal ellipses for depth bins 1-8 (and for comparison No. 29) , indicating velocity orientation along the semi-major(V) and semi-minor(U) axis for the M2 tidal constituent at site H1.



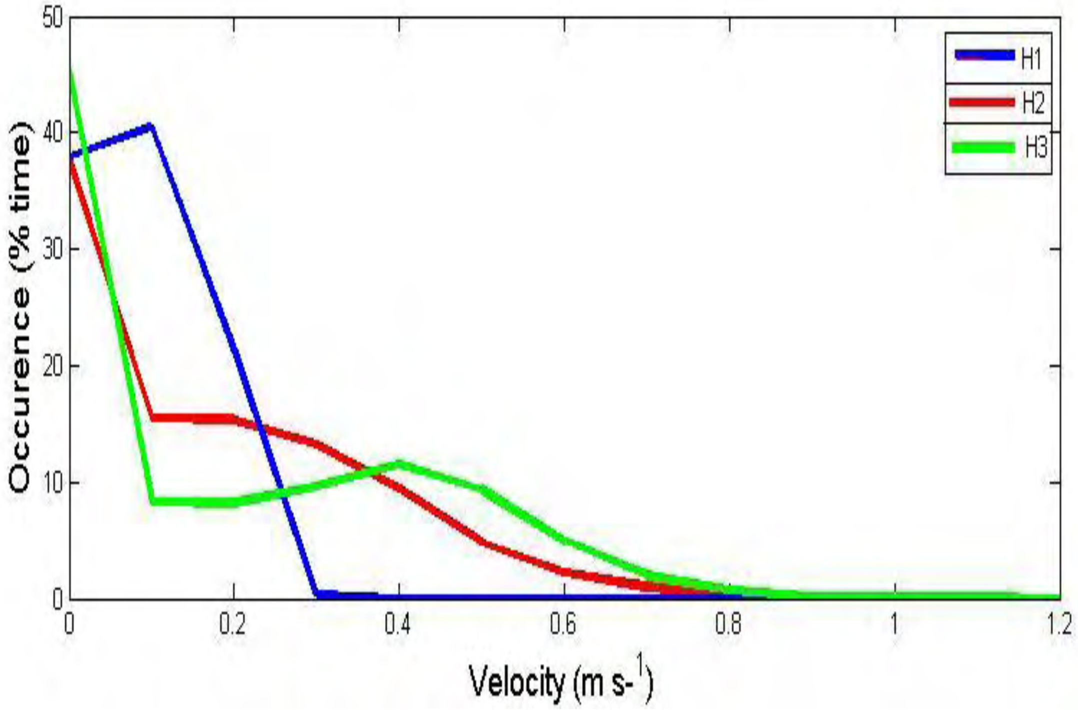
Appendix H: Tidal ellipses for depth bins 1-8 (and for comparison No. 15) , indicating velocity orientation along the semi-major(V) and semi-minor(U) axis for the M2 tidal constituent at site H2.



Appendix I: Tidal ellipses for depth bins 1-8 (and for comparison No. 20) , indicating velocity orientation along the semi-major(V) and semi-minor(U) axis for the M2 tidal constituent at site H3.



Appendix J: Velocity exceedence curve, indicating occurrence of velocity distributions in 0.1 m/s bins as a percentage of time over a 30 day period, for sites H1, H2 and H3.



Appendix K: Bathymetric map of Guernsey territorial waters with tidal ellipses overlaid onto approximate assessment site location to indicate primary current orientation