Shetland Islands

Wave and Tidal Resource

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Author: Ross Halliday

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Natural Power
The Green House
Forrest Estate
Castle Douglas
Kirkcudbrightshire

Tel: +44 (0) 1644 430 008

natural power

Client: Shetland Islands Council

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Author	Ross Halliday	21/02/2011
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1. INTRODUCTION

1.1. Context

Within the United Kingdom and Scotland national policy on marine management is being developed under the auspices of the Marine Bills passing through the respective parliaments. This legislation is in turn being driven by the requirement to implement the Europe wide Marine Strategy Framework Directive (MSFD) in domestic law. The MSFD is intended to achieve the good environmental status of European waters while protecting the resource base upon which economic and social activities depend.

Scotland's implementation of this directive is the Marine (Scotland) Bill as introduced to parliament on the 29th April 2009. This Bill provides a statutory requirement for marine planning in Scottish Waters. The bill proposes that a National Marine Plan for Scotland be set out with overarching polices and priorities for the sustainable use, development, management and protection of Scotland's marine and coastal resources.

At a regional level the bill sets out the establishment of Scottish Marine Regions and the development of associated regional marine plans. These plans will establish the regulatory framework for guiding proposed activities, operations and developments. The evolution of these regional plans allows for all potentially impacted activities to be considered through the licensing process, bringing in a wider range of stakeholders than is currently catered for.

The Shetland Marine Spatial Plan has been developed under the auspices of the Scottish Sustainable Marine Environment Initiative (SSMEI). The plan is one of three other pilot projects across Scotland (Firth of Clyde, the Sound of Mull and the Berwickshire Coast) and is an example of how a regional level plan could be set out.

A fundamental task in developing the Marine Spatial Plan has been in gathering the baseline data from both the terrestrial and marine environments to build a GIS database of existing users and resources. Through this process existing data on the wave and tidal resources available to the Shetland Islands was collected. On further examination and in respect of supporting the drive to attract renewable energy development to the islands, this study has been commissioned to increase the spatial coverage of these data sets.

1.2. Scope

The Natural Power Consultants Ltd (NPC) on behalf of Shetland Islands Council (SIC) has been commissioned to carry out a wave and tidal resource assessment of the Shetland Islands based on numerical simulations of the wave and tidal climatology.

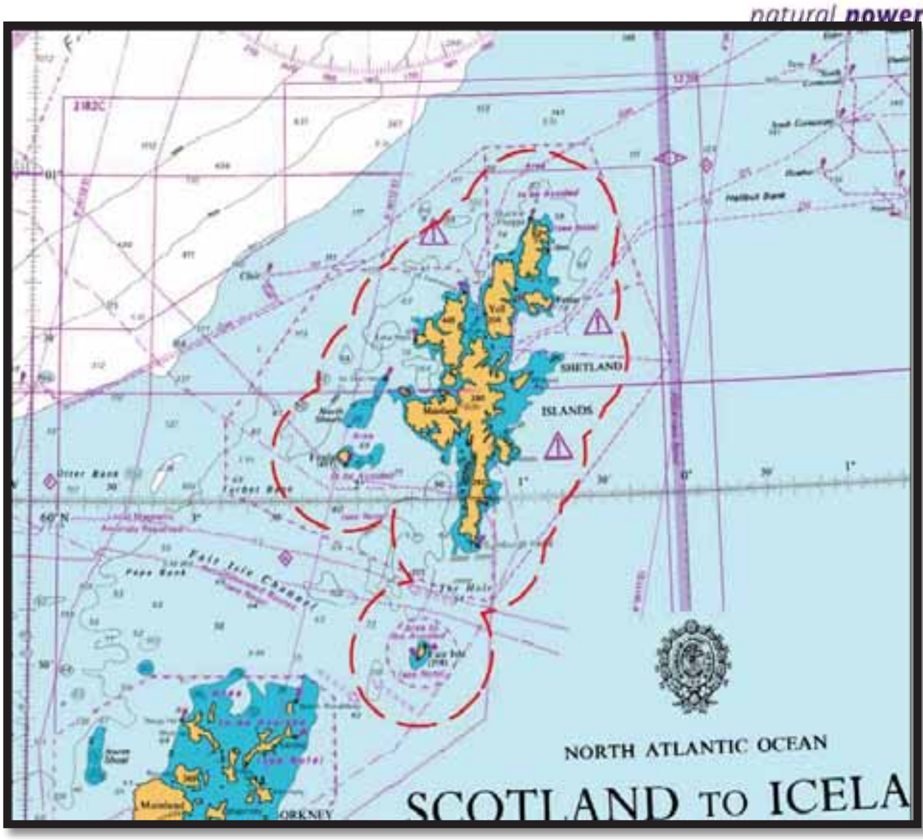

Figure 1: Shetland Islands study area - 12nm indicated

1.3. Study Area

The Shetland Islands archipelago lies approximately 200 km (130 miles) North East of the Scottish mainland, with the Faeroe Islands 350 km (218 miles) to the North West and Norway lying an equivalent distance to the East. In keeping with the existing Draft Marine Spatial Plan for the Shetland Islands[1] NPC have targeted the wave and tidal resource assessment to the waters within 12 nautical miles of the Shetland Coast, as shown in Figure 1. Mapped outputs are available for outside of this boundary but are of lower resolution and not included within this report.

1.3.1. General tidal climate

The position of the Shetland Islands on the edge of the continental shelf that forms the North Sea makes them an effective blockage to the astronomical tides that persist in the North Atlantic. As the tidal wave progresses round the North of Scotland and transitions from the deeper water of the Atlantic it has to pass Shetland, see Figure 2 for a visual representation of this depth transition area. The proximity of the Orkney Islands forces the wave through the Fair Isle Channel with geography of Sumburgh Head causing a further speed up in flow. A similar effect occurs to the North of Unst with the remaining tidal wave progressing into the North Sea and Norwegian Sea. Due to the mass of the Shetland islands the high point of the tidal wave occurs at differing times on the east and west coasts. This differential causes strong tidal flows to form through the inter-island channels.

[1] http://www.nafc.ac.uk/SSMEI.aspx

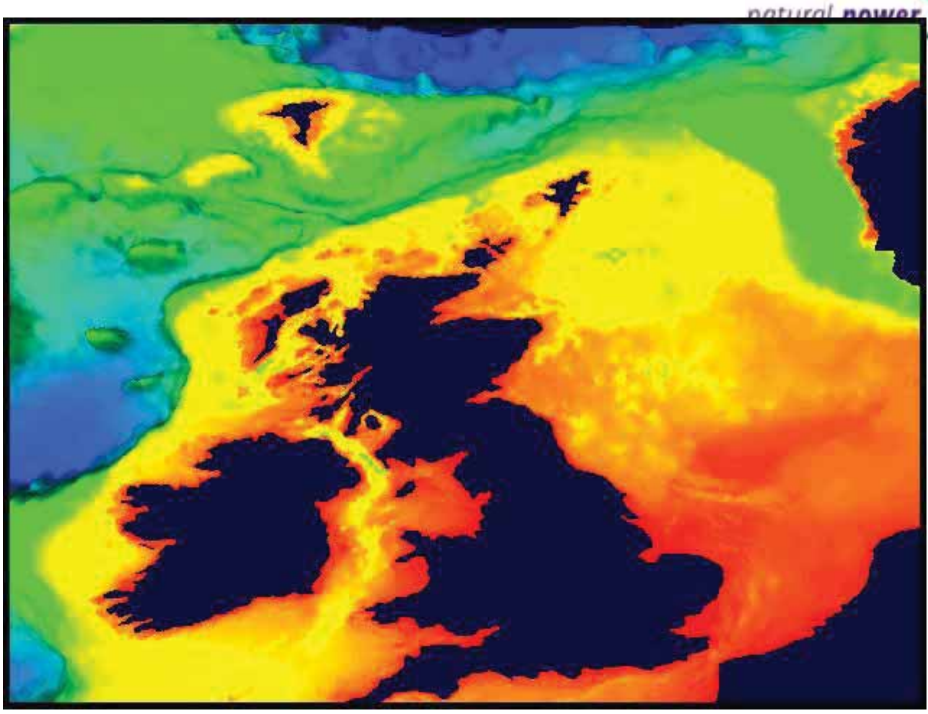

Figure 2: Shelf Bathymetry around the Shetland Islands

1.3.2. General Wave Climate

Located at between 60º-61ºN the islands are in the direct path of the low pressure systems that dominate the North Atlantic weather climate. This exposure and the extended areas of open ocean to the west allows for a powerful wave climate to develop with long period swell and pronounced wind driven seas. The position of the Shetland Islands also allows for wave energy generated through the North Sea and Arctic Ocean to fall on its shores.

1.4. Report Structure

The following report is organised in multiple sections.

- Baseline Data
- Tidal specific modelling
- Wave specific modelling
- Results presentation
- Appendices

The baseline section is intended to present materials common to all modelling processes before each of the separate wave and tidal studies are discussed in more detail. The results are presented in their own section to give greater emphasis and ease of access. The appendices will be used to give greater detail on specific topics such as bathymetry analyses and point extractions from the wave and tidal models.

2. BASELINE DATA

The wave and tidal modelling process relies on input data that is reliable and fit for purpose. These data sets fall into one of four general categories: bathymetry, wave, tidal and mean sea level data.

2.1. Bathymetry data

The bathymetry data utilised in this set of metocean studies has been sourced from the United Kingdom Hydrographic Office in the form of Electronic Navigation Charts (ENCs). These charts of the seas are available at various scale levels and have been created over the past 170 years from multiple hydrographic surveys. As may be expected the age of the survey used in constructing the charts gives an indication of the accuracy with which the data can be considered.

Section 11 details the surveys used by the UKHO in creating the charts from which the bathymetry data was sourced. In general, areas where shipping traffic may be expected to be heavy, the Shetland Islands Council and the Lerwick Port Authority have maintained a good survey programme with particular emphasis on Lerwick harbour, Scalloway harbour and Yell Sound.

The offshore areas surrounding Shetland were last updated using a 1983-85 survey set that provides good coverage to approximately the 12 nautical mile limit of this study, beyond this range bathymetry data consists of miscellaneous soundings gathered by vessels under steam. It is understood that both coastal and offshore areas of Shetland are presently part of a re-survey campaign being carried out as part of Civil Hydrography Programme[2]. This data was however unavailable at the time of writing.

Based on the available bathymetry data, problem areas do exist in nearshore locations. Where the 1983-85 survey was in close proximity to the shore it is surmised that the vessel utilised was not suitable for data collection in these locations. A similar issue may have affected other post 1940 surveys where noticeable gaps in coverage are seen in shallower waters. Where post 1940 surveys have not been available for chart creation lead line surveys taken in the 19th and early part of the 20th century have been incorporated. This lead line survey data is increasingly common away from heavily traffic areas but is most predominant on the western coasts.

For the expected areas of interest the lead line survey appears to be the main source of data for the creation of navigational chart data on which the numerical modelling is based. This leads to the expectation that there will be variation in the modelled results from those that can be expected on site. In terms of model calibration it would be expected that detailed fine tuning will have limited impact on modelling accuracy until such time as the bathymetry data is updated.

[2] http://www.mcga.gov.uk/c4mca/mcga07-home/shipsandcargoes/mcga-shipsregsandguidance/mcga-dqs-hmp-hydrography/the_civil_hydrography_programme.htm

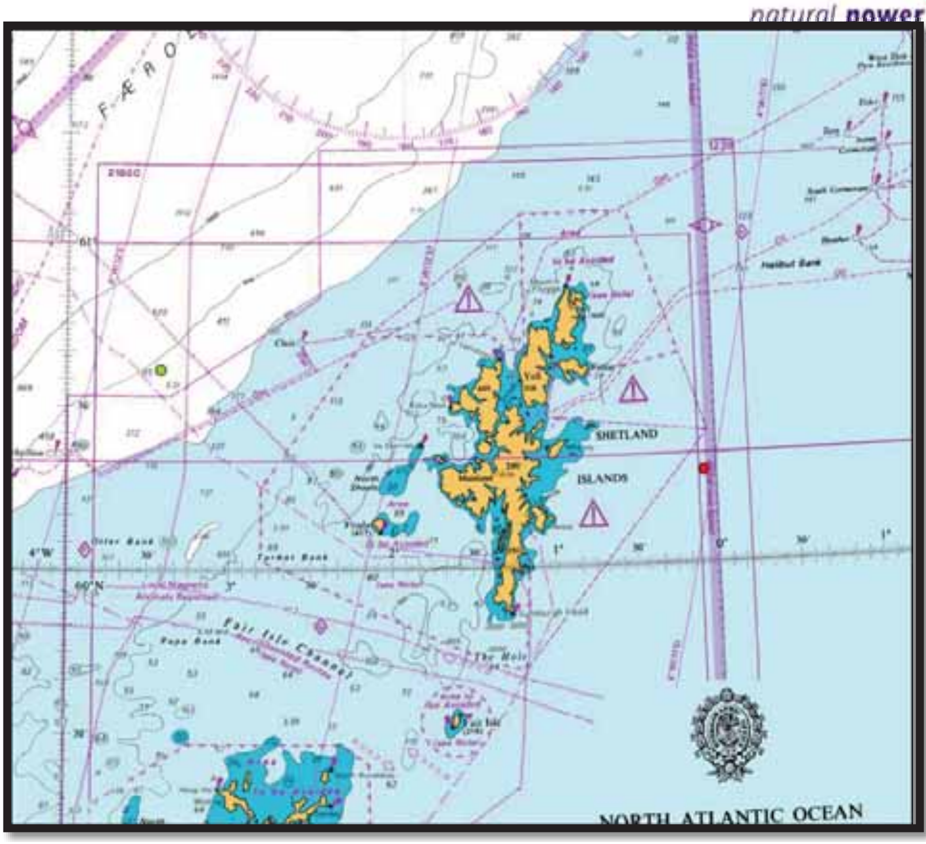

Figure 3: Met Office modelled data points utilised for wave energy studies

2.2. Wave data

The wave data used in this study has been sourced from the United Kingdom Met Office who maintains a numerical wave model of the North Atlantic at a resolution of approximately 12km. This model provides predicted wave forecasts with a three hourly time step that are archived for access at a later date. The wave model experienced a change over to a new version of modelling code in October 2008 and care is required in the interpretation of the two separate data sets.

In order to provide full coverage of the Shetland Islands two data sets were purchased for the Western and Eastern coasts giving coverage over the 10 year period from 29th March 2000 to 28th March 2010. Plots of the data locations and resultant wave roses are given in Figure 3, Figure 4 and Figure 5, with further detailed analysis available in Section 12.

The wave climate of the Shetland Islands can be generalised by this data into Western and Eastern facing climates. The Western facing coastlines are dominated by a South-West to Westerly wave direction, wave heights in the range of 2-4m and zero crossing periods of 7-8 seconds remaining constant throughout the year. In addition to the South Westerly climate the Western coast may also expect to experience waves arriving from the North. This corresponds to the large fetch to the North stretching 2,000km to the coastline of Spitsbergen.

The Eastern facing coasts are to a large degree sheltered from the North Atlantic swell that dominates the Western coasts, though at the distance from shore at which the Met Office data was sourced, swell waves can still be detected after having passed round the Shetland coast. There is a large spread of wave directions arriving from the South West to South East corresponding principally to storms in the North Sea. As with the western data a strong Northerly component is noted. An average wave height of 1.5 m to 3.5 m with peak wave periods of 6-7 seconds is to be expected.

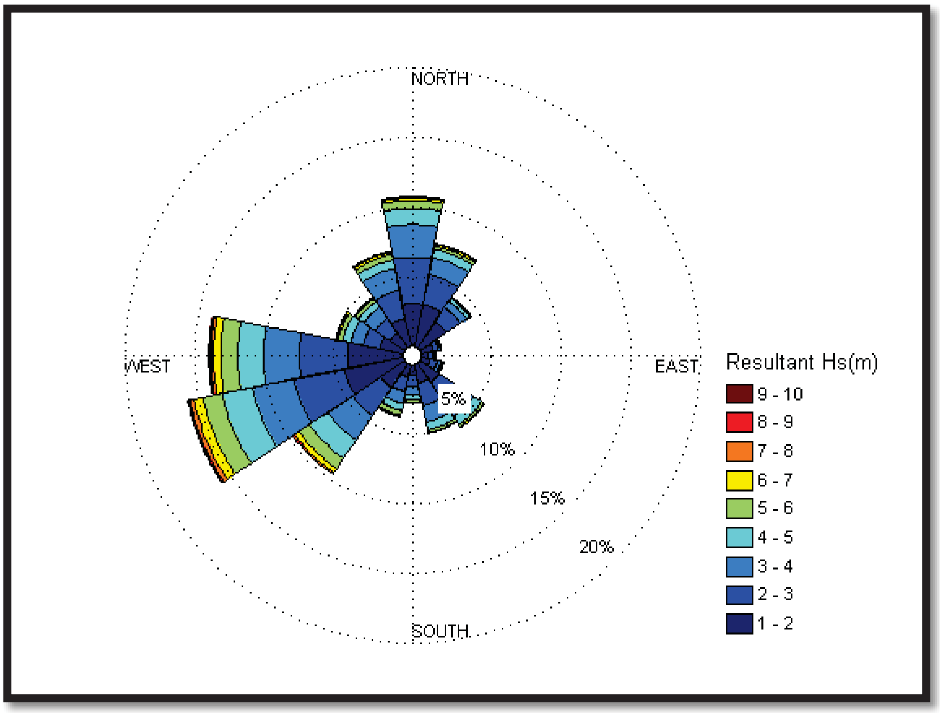

Figure 4: Wave rose of Western Met Office data

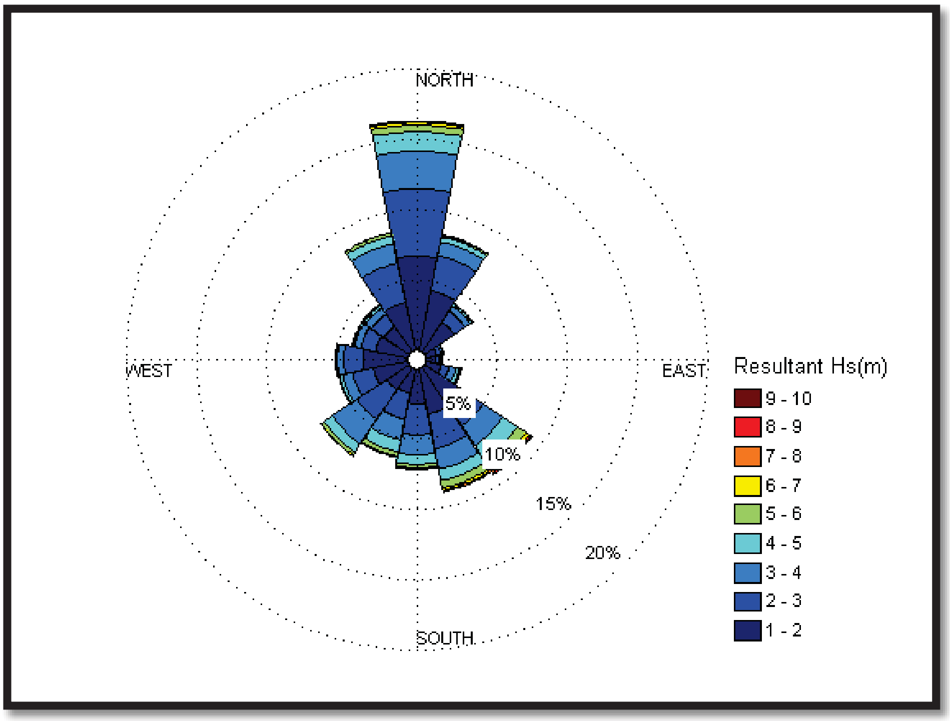

Figure 5: Wave rose of Eastern Met Office data

2.3. Tidal Data

The tidal data required to drive a hydrodynamic model can be broadly split into two categories: that required as boundary conditions to force the motion of the water within the domain and that required as calibration/validation data sets to determine the relative accuracy of the modelling process.

2.3.1. Boundary conditions

As this study is intended to provide information on the spatial distribution of tidal energy only astronomical forcing conditions are considered (i.e. the influence of the wind and waves will not be modelled). These astronomical boundary conditions are derived from a global tidal constituents model of the major diurnal and semi-diurnal constituents. This model is based on TOPEX/POSEIDON satellite altimetry data[3].

2.3.2. Validation data

Lerwick Tidal Gauge

Figure 6: Location and structure of Lerwick tidal gauge

In order to provide validation of the model approach in-situ measurements provide the best data sources. In the Shetland Islands the best example of this is the tidal gauge located within Lerwick harbour (Figure 6).

Tidal elevation data is measured in Lerwick harbour on the inner wall at the breakwater entrance to the small boat harbour. The tidal gauge equipment is housed in a Glass Reinforced Plastic (GRP) building located over the now non-operational stilling well. The present system is based on a pneumatic bubbler with two full tide and mid-tide pressure points mounted on steelwork attached to the harbour wall.

[3] Ole Baltazar Andersen (1995), Global ocean tides from ERS 1 and TOPEX/POSEIDON altimetry, J. of Geophys. Res., 100, C12, p. 25249-25260

Full data for the site was downloaded from the British Oceanographic Data Centre for the period covering years 1981-2010. During this period the following major changes have been made to the tidal gauge station:

1989 – New wooden building erected over the existing system, consisting of a Lea gauge
1995 – Tidal gauge system upgraded with the installation of 2 full tide and a mid-tide measuring system and the lea gauge replaced with an Orr pneumatic gauge
2002 – POL data logger installed with the mid-tide bubbler
2002 – All tidal gauge equipment and building destroyed in fire
2003 – New GRP building erected with new steelwork holding 2 full tide and mid-tide measuring system.

The data files downloaded from BODC are packaged as yearly time series data with a time step of 1hr. Values are given for the measured data and a residual value (calculated from the measured data values minus a predicted value sea level value). Flags are set for data values that are considered: improbable, null and interpolated.

ADCP deployment

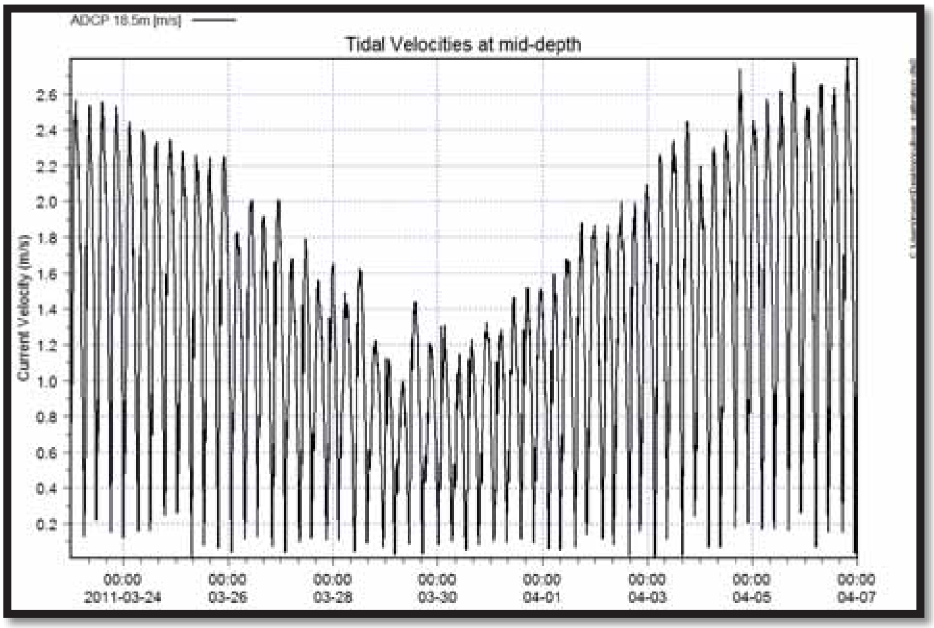

Figure 7: Tidal velocity data from an ADCP deployment in Bluemull Sound

As part of the assessment requirements of fish farm licensing within the Shetland Islands routine deployment of Acoustic Doppler Current Profiler (ADCP) devices are undertaken by Shetland Seafood Quality Control. The majority of these deployments take place in low tidal flow environments where the spread of effluent is of concern. However, on behalf of Shetland Islands Council Development Department a deployment took place in the Bluemull Sound at Cullivoe Ness. This 28 day deployment resulted in a 15 day data series of tidal currents and directions in 1m vertical bins over the period of 23rd March 2004 to 7th April 2004. An example of the velocities expected at this location are shown in Figure 7.

This data set will with the Lerwick tidal gauge form the core calibration data sets for this modelling exercise. A secondary set of data to provide wider spatial calibration is given by the UKHO predicted tidal elevations described in the following section.

UKHO predicted tidal Elevations

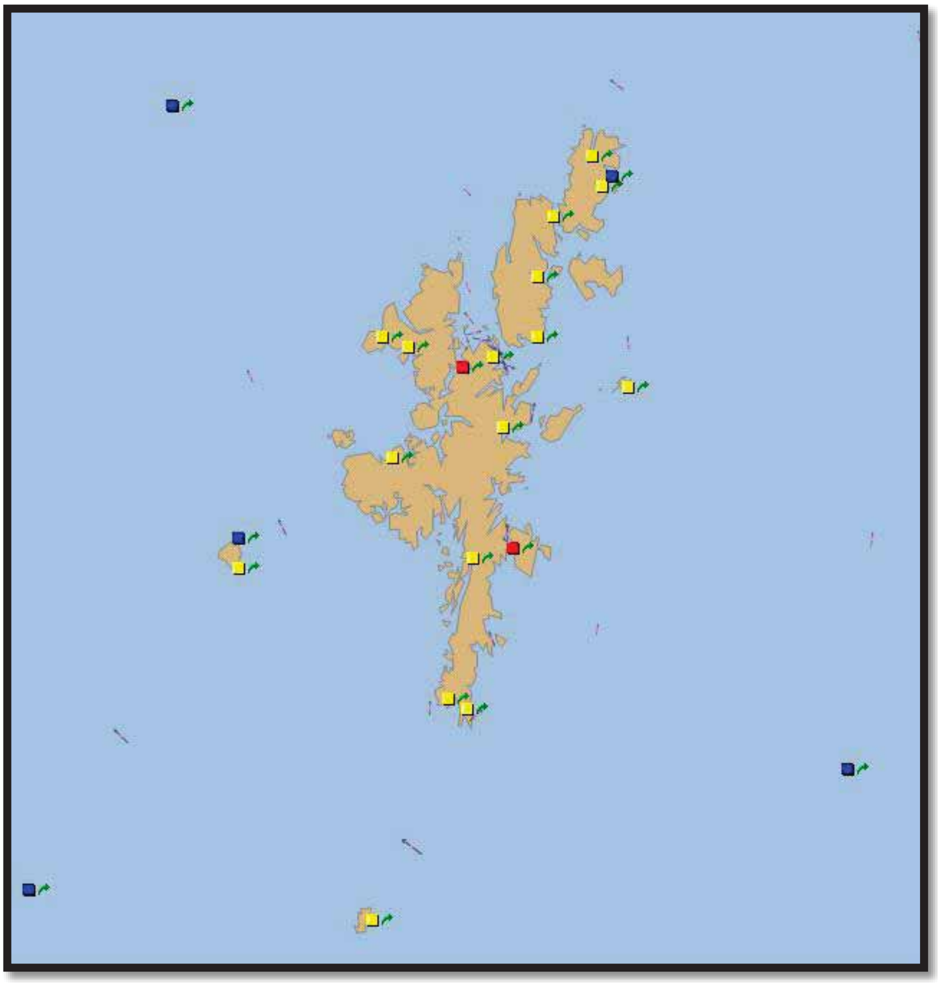

Figure 8: Available UKHO data within Shetland Waters

A secondary calibration data set will be the tidal elevation predictions made by the UKHO and available through their TotalTide product. The tidal elevation predictions are given in three categories with a decreasing degree of certainty regarding their accuracy.

- Standard Port based on an extended set of measured tidal constituents (e.g. Lerwick and Sullom Voe)
- Secondary Port based on a shorted set of measured tidal constituents (e.g. T029G, outside of Baltasound and T029C, north of Foula)
- Secondary Powers (non-harmonic) based on relating time and height distances to a Standard Port (e.g. Scalloway and Out Skerries)

2.4. Mean Sea Level Data

While all bathymetry data is given related to a lowest astronomical tide (LAT) this does not always correspond to a universal mean sea level. In order to account for this the raw bathymetry must be corrected to a common zero surface elevation. To carry this out a map of mean sea level must be generated. This is achieved by making use of the predicted sea level data described in Section 2.3.2. For all ports and offshore predictions made by the UKHO there exists an associated mean sea level. These points and mean sea levels can be gathered into a single data file and used to correct the raw bathymetry.

3. TIDAL RESOURCE ASSESSMENT PROCESS

The process of constructing the hydrodynamic model for use in the prediction of tidal energy resource follows a set of deterministic steps.

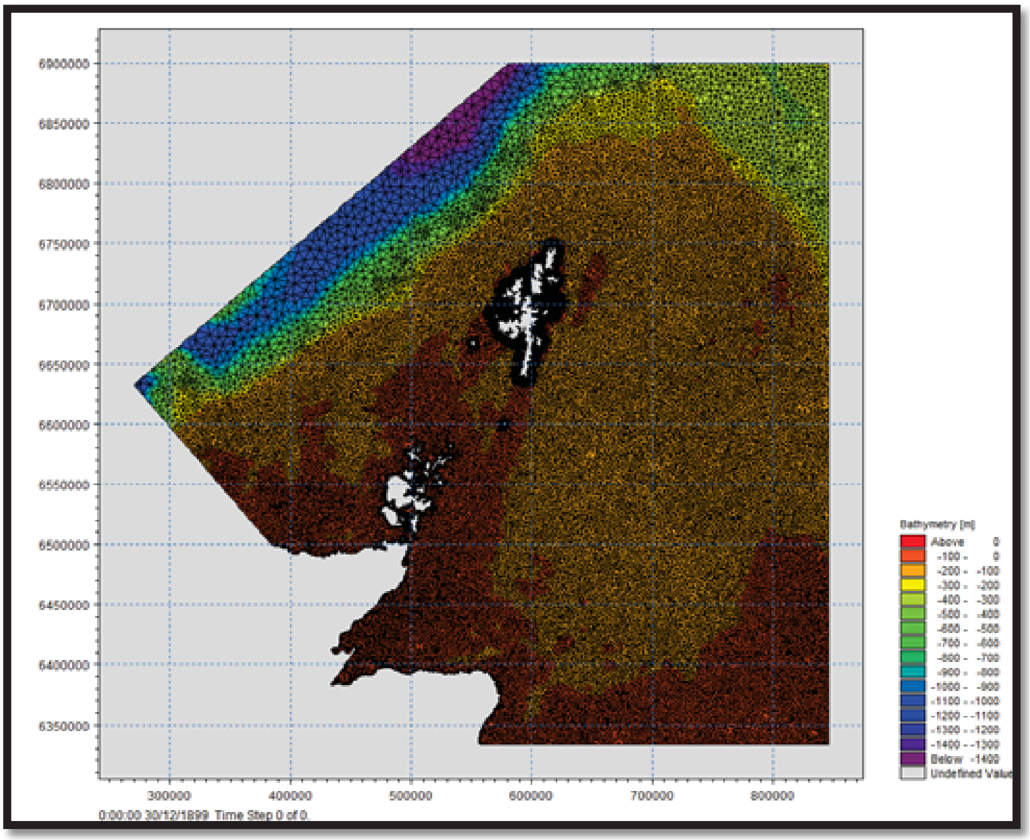

Figure 9: Full hydrodynamic model domain

3.1. Domain and Coastline creation

The selection of the hydrodynamic modelling domain and resolution for the Shetland Islands is a complex issue. With its position on the edge of the continental shelf it would be preferable to model the full North Sea, Norwegian and North Atlantic approaches. However, available time and computational resources dictates that a smaller domain be identified.

Figure 9 above shows the domain arrived at for this study. As stated in the introduction to this report the primary driver of tidal flows in the Shetland Islands is the progression of the tidal wave in the North Atlantic as it leaves and enters the North Sea. The progression of this wave round the Shetland Islands is influenced by two major factors; the continental shelf break and the presence of the Orkney Islands. Both of these factors are accounted for in the model by the inclusion of the Scottish Coastline and from Cape Wrath to Aberdeen, incorporating the Orkney Islands and the North West model boundary being set through the Faeroe-Shetland Channel.

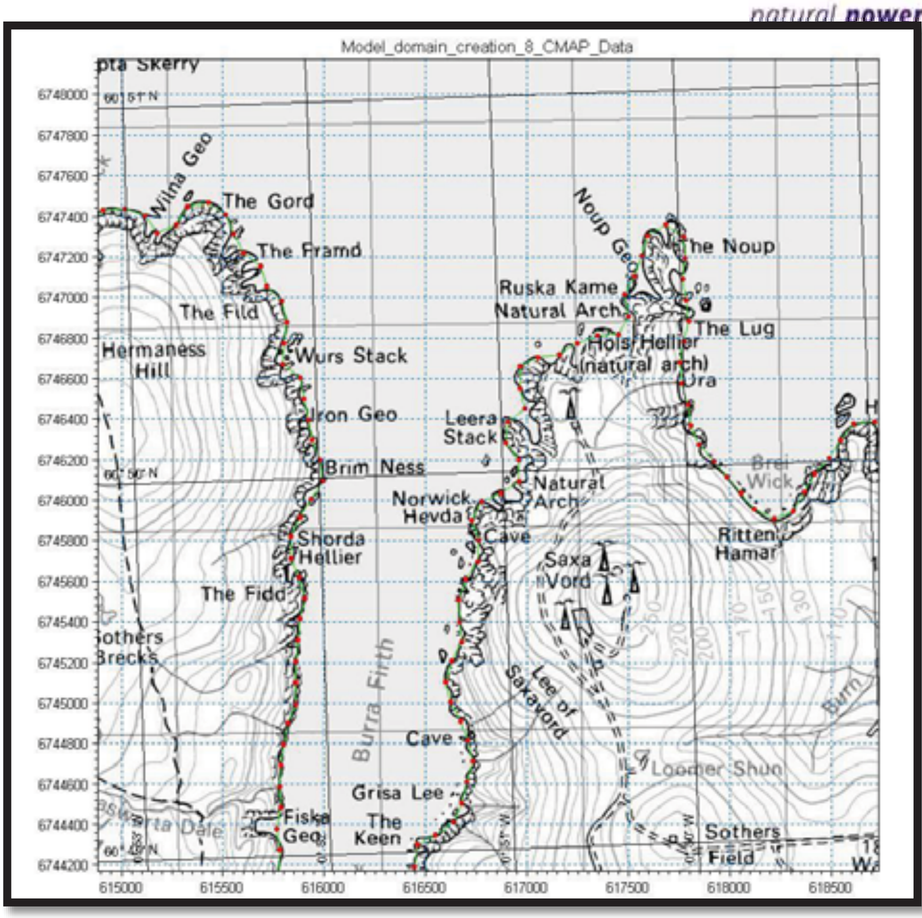

Figure 10: Burra Firth coastline digitisation example

The quality and accuracy of any numerical modelling project depends on the quality and applicability of the source data. In producing the hydrodynamic model the coastline of the Shetland Islands was digitised from geo-referenced 1:50,000 scale Ordnance Survey maps and visually cross checked with available navigational chart sets. Figure 10 above shows the digitisation process for the area around Burra Firth in Unst and highlights one of the issues in carrying out this process for such a fractured coastline as that found in Shetland.

In the figure above the coastline is traced out as the red markers spaced at 100m intervals with care taken to place these as close as possible to the high water line. Unfortunately coastline details of a smaller scale than this must be removed, as must offshore skerries, stacks and islands. This issue of resolution becomes particularly acute when considering the many voes and channels in the Shetland Island waters. In order to allow for a reasonable degree of computational accuracy all channels and voes of width less than 300m (or approximately 3 model elements) have to be removed. Special care was needed with Muckle Roe and West and East Burra.

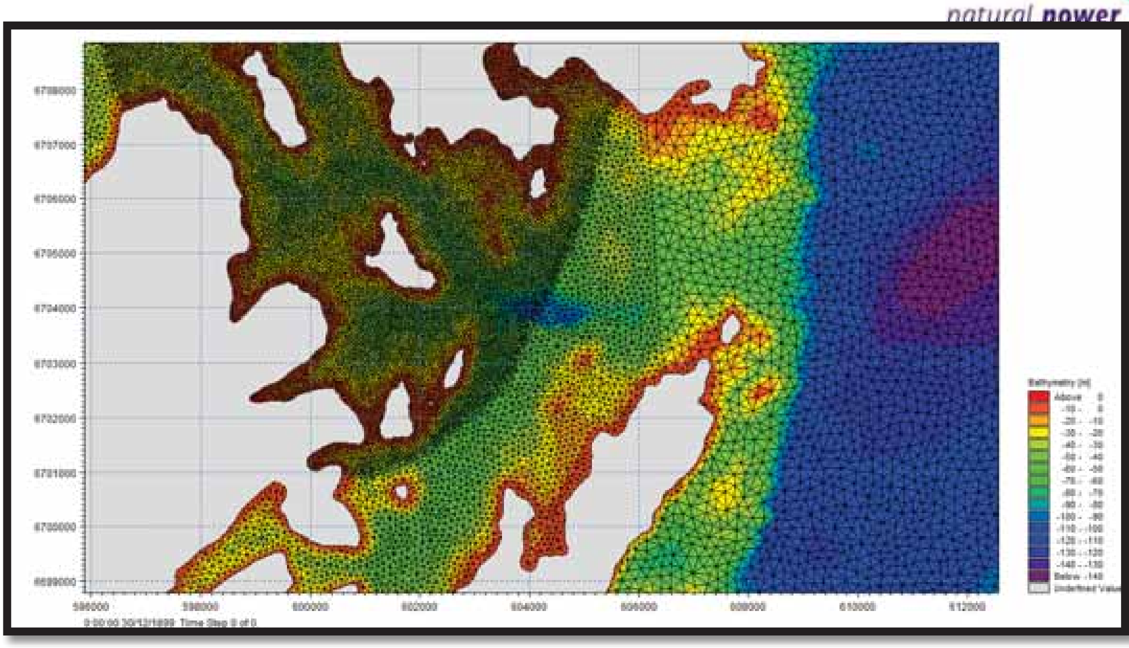

Figure 11: Detail of the mesh resolution in Yell Sound

Model resolutions throughout the domain were carefully calibrated in order to provide maximum coverage in the areas of interest, the waters within 12nm of the Shetland coast, and the maximum size of resultant files that could be stored, handled and processed. Figure 9 shows the variable size mesh used in the modelled domain with an approximate spacing of 5km in all offshore seas. The Scottish and Orkney coastline were digitised at 1000m and 500m respectively allowing their influence on the progression of the tidal wave to be retained but without producing an excessive volume of data.

Within the Shetland Islands themselves all coastlines were digitised at 100m resolution. It was originally intended that all of the Shetland waters were to be modelled at a resolution of approximately 100m. However tests found that the volume of data produced was excessive from both a computational and time perspective. Additionally the review of the source data (see Section 11) from which the bathymetry data was created showed concerns over the accuracy of the original data and in many areas was not of a resolution to support the very high accuracy in modelled results we were seeking to achieve. To balance these two constraints the model resolution was adjusted so that in areas of perceived accurate bathymetry model resolutions were keep at a high value. In all other locations resolutions were scaled back to give a balance between data volumes and computational time.

3.2. Model Calibration

As a regional modelling exercise intended to inform developers and regulators of potential areas of tidal energy resource around a spatially complex island archipelago the degree of certainty in achieving 100% accuracy in model calibration is a difficult balancing act. As stated in Section 2.3 for this project a selection of data existed for the period of 23rd March 2004 to 7th April 2004. This time frame was subsequently used in determining modelling accuracy.

3.2.1. Tidal Elevation - Calibration

Over the period of 15th March 2004 to 28th March 2004 tidal elevation data were extracted from modelled data sets and compared principally to those recorded at the Lerwick tidal gauge (with meteorological residuals removed) and UKHO predictions for Sullom Voe. In both locations shown in Figure 12 - Figure 15 R-squared values greater than 0.98 were found.

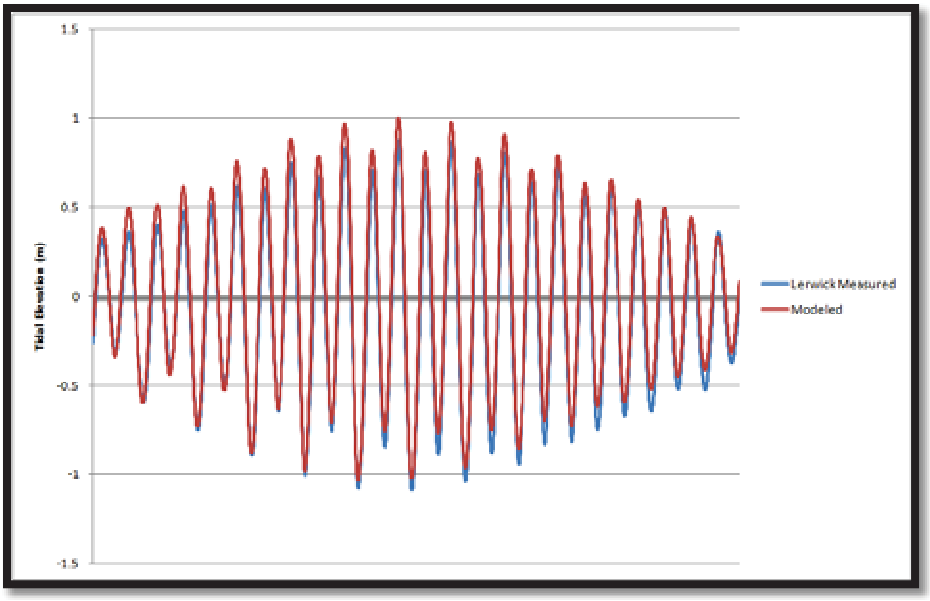

Figure 12: Time Series overlay of measured and predicted tides at Lerwick

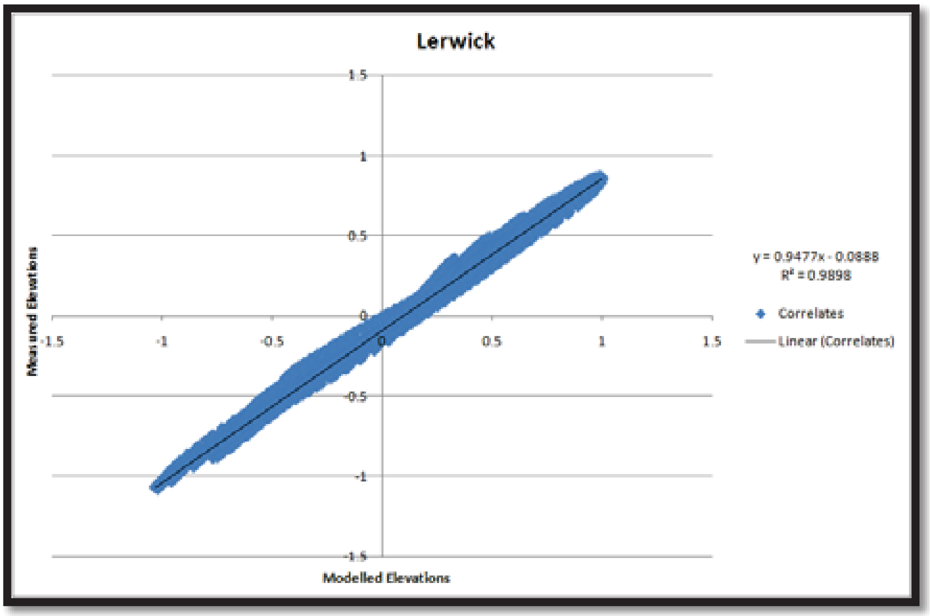

Figure 13: Scatter plot of measured and predicted tides at Lerwick

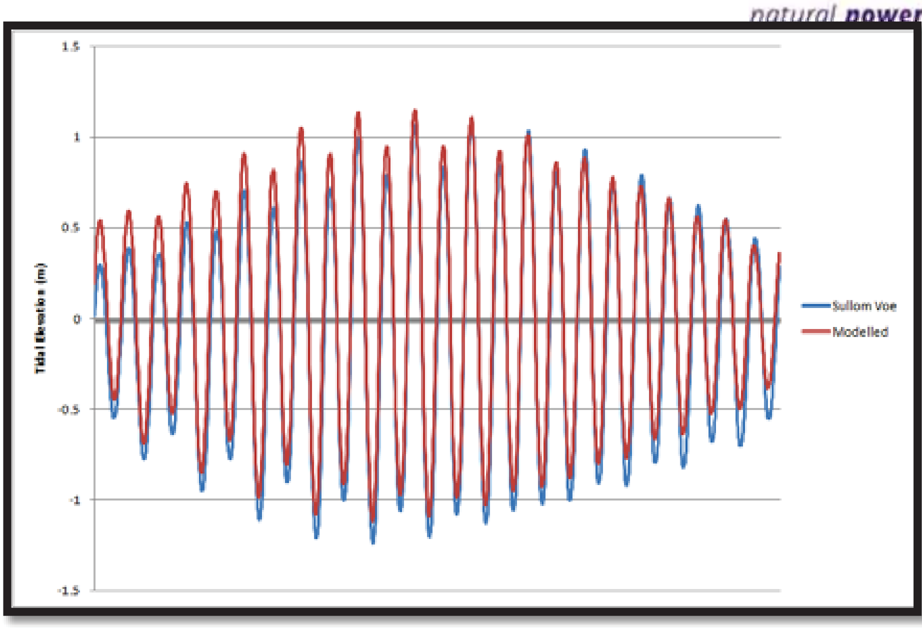

Figure 14: Time series overlay of UKHO predicted and modelled tides at Sullom Voe

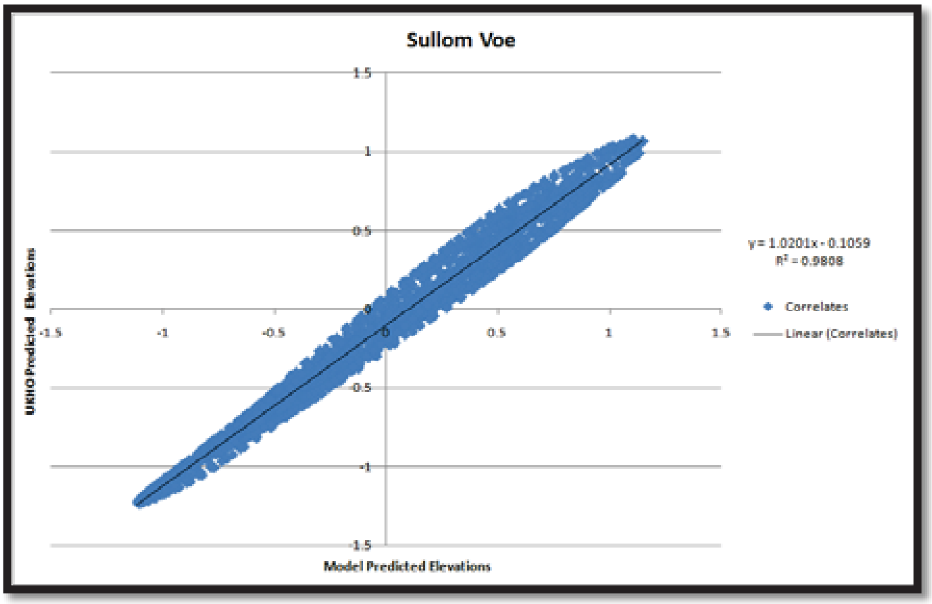

Figure 15: Scatter plot of UKHO predicted and modelled tides at Sullom Voe

Location	R-squared
Balta Sound	0.9884
Bluemull	0.9002
Fair Isle	0.9871
Foula	0.9826
Hillswick	0.9812
Lerwick	0.9898
Outskerries	0.9851
Scalloway	0.9163
Sullom Voe	0.9808
Sumburgh	0.989

Table 1: R-squared values for selected calibration points

Additional model extractions were taken at a range of secondary ports (harmonic and non-harmonic). R-squares values for each of these locations are given in Table 1. It can be seen that values in excess of 0.98 were return for most of the locations considered with the exceptions of Bluemull and Scalloway. Both of these harbours are located within enclosed bays which, within the present model are underrepresented in terms of model resolution to changes in seabed. A focused increase of model resolution within these natural embayments would improve accuracy but in the context of this regional study would impose a large computational overhead.

3.2.2. Tidal Currents - Validation

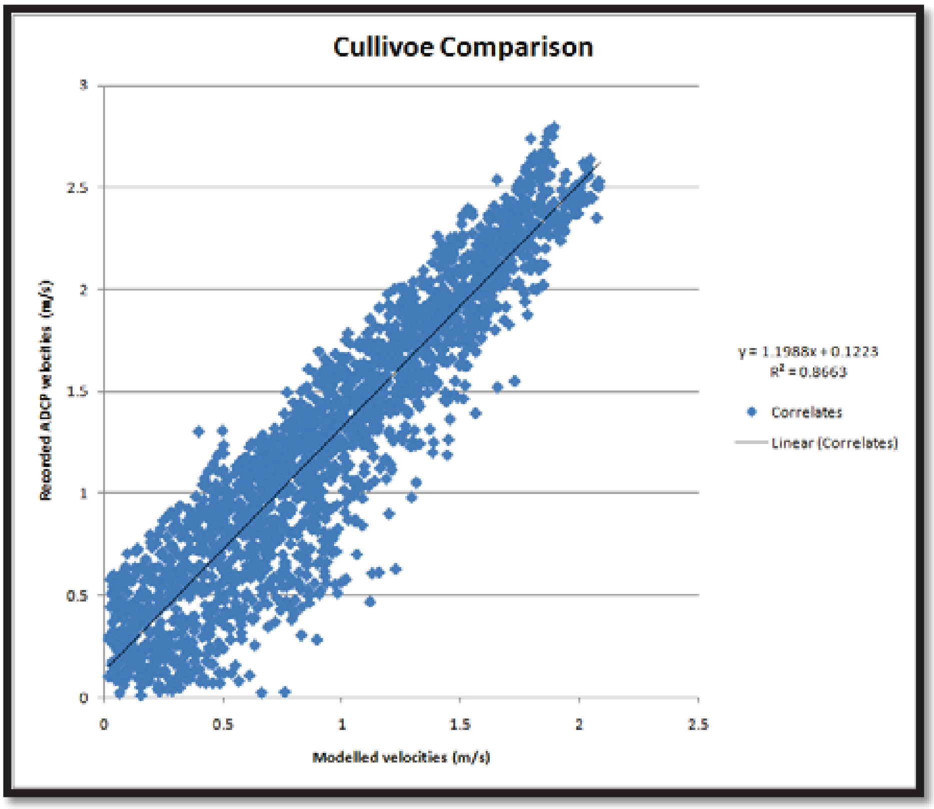

Figure 16: Scatter plot of tidal velocities measured and modelled at Culliove Ness

With a constrained set of in-water measured records the validation of a hydrodynamic model is a challenging and subjective issue. The calibration of the model to tidal elevations as described in Section 3.2.1 shows that it is capable of accurately reproducing the timing and elevation of astronomical tides within Shetland waters. However, this study is focused on providing guidance as to the location and relative magnitudes of exploitable tidal resources. To provide this element of calibration the ADCP data collected at Cullivoe Ness, described in Section 2.3.2 was compared to the predicted velocities from the modelled data set.

As shown in Figure 16 there is a systematic under prediction of tidal velocities at this location by a factor of approximately 20%. The question now arises as to whether this under prediction is present throughout the model domain or is related only to this location. Previous experience of working in high velocity tidal sites would indicate that this under prediction is a result of the underlying physics of the hydrodynamic models working over a depth averaged model domain. The common approach to remedying this issue is to adjust the bed friction of the model in order to allow far a faster/slower current to flow. While this process of micro-managing the bed resistance in a tidal model is appropriate for a focused study on a small area it will tend to have knock on effects in other areas of the domain. Additionally the process of accelerating or decelerating the tidal flows tends to disrupt the timing of high and low water, which in the case of this existing regional model have been shown to be predominately accurate.

Bearing in mind the purpose of this study is to provide guidance on prospective development areas rather than absolute figures of energy yield it was decided not to varying the bed resistance through the model domain. Rather the velocities calculated were scaled by a factor 1.2. This will likely lead to an over prediction of resource levels in some areas however, project developers will focus their attention on areas of maximum resource to carry out field monitoring campaigns. Sites which are indicated to have velocities that may be marginally economic would ordinarily not be explored before the most prospectively economic.

3.3. Output Processing

In order to provide spatially accurate statistics of potential tidal energy development sites the tidal model was used to generate 28 days of tidal velocity data covering the period of 16th March 2004 to 15th April 2004. This period includes the time for which the modelled was calibrated. These tidal velocities are processed into the following parameters for every element in the model domain:

3.3.1. Maximum Velocity

The maximum velocity recorded over the modelled period. This can be thought of as an equivalent to a peak Spring tide.

3.3.2. Root Mean Cubed Velocity

While the maximum velocity relates to a monthly peak in flow rate this occurs for only a short period of time. A more useful parameter to the renewable industry is the root mean cubed velocity. This is a weighted average that relates to the average power that may be expected to be generated.

$$V_{rmc} = \sqrt[3]{\frac{1}{N} \cdot \sum_{j=1}^{N} \left(V_j^3\right)}$$

This value is calculated as an average taken over the full depth of the water column.

3.3.3. Average Power Density

The root mean cubed velocity can be turned directly into an average power density value as:

$$APD = \frac{1}{2} \rho V_{rmc}^3 \; (kW/m^2)$$

Which, when multiplied by the swept area of the turbine, will give an indication of average power production per turbine.

3.3.4. Percentage exceedance of 2.0 m/s

In order for a tidal energy project to maintain a good capacity factor the percentage of time for which the flow exceeds a reasonable velocity must also be calculated. A value of 2.0 m/s (~4 knots) corresponds to the rated velocity at which tidal turbines are thought, by the authors of this report, to become uneconomical.

3.3.5. Flow Type

A further parameter of interest to project developers is an indication of the type of flow which is to be expected. The flow type is given as a magnitude between 0 and 1 relating to the ratio of flow along the principle axis to the flow across the principle axis. A value of 1 would indicate a circular flow that has a fixed velocity rotating equally through all directions. A value of 0 indicates a linear flow with a flood and ebb direction 180 degrees out of phase.

4. WAVE ASSESSMENT METHODOLOGY

The assessment of potential wave energy resource for the Shetland Islands is a complex problem. To clearly put forward the methodology utilised in this study it is helpful to first consider a simplified problem then to build this into a Shetland context.

4.1. Basic methodology

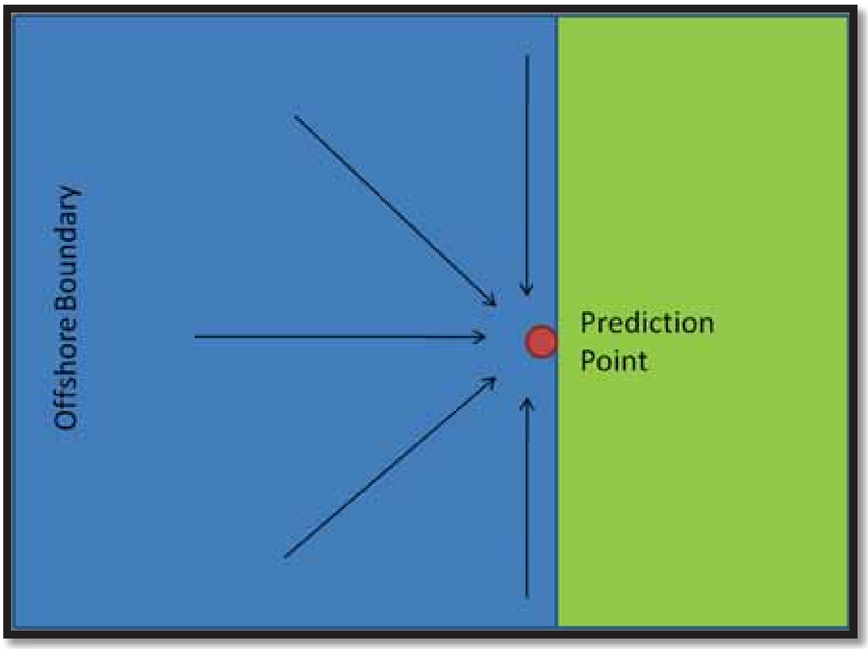

Figure 17: Simplified wave hindcasting domain

A simplified wave resource study can be conceived of by imaging an infinitely long coastline, similar to that found on the West coast of America, and having the goal of predicting the wave climate a single point on the coast. From the point of view of an observer standing on the coast at this prediction location it would appear that all of the wave energy arriving on the coast will come from a constrained range of wave directions from the west and running from North to South, Figure 17.

To carry out this modelling a record of wave heights and periods from an external reference source, such as that from the Met Office wave model, can be sourced for a deep water offshore boundary (Figure 17). This long term record gives an indication of the wave climate in the general region of the target area. The long term record can be analysed to give a series of recurring wave states consisting of an identifiable wave height (Hs), wave peak period (Tp) and wave direction (Dir). An example set of wave states is shown in Table 2 with their relative occurrence shown in the far right hand column.

Wave State	Wave Height	Wave Period	Direction	% Occurrence
1	1.75	7.5	247.5	5.6
2	1.75	7.5	270	4.3
3	3.25	9.5	247.5	3.1
…	…	…	…	…
1200	0.25	9.5	202.5	0.001

Table 2: Example wave states

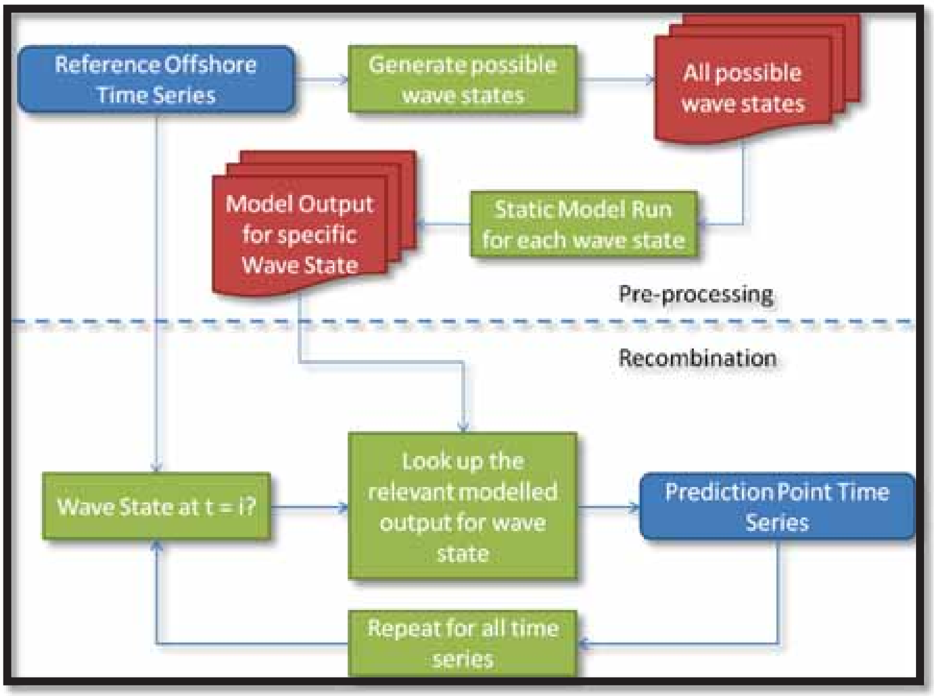

Figure 18: Flowchart for basic wave modelling

For each of the identified wave states a numerical wave model can be run over the area of the model from the offshore boundary to the coastline. The wave state applied at the boundary is said to propagate into the model. From the point of view of the Observer on the coast a set of relationships can be established which, for example, says if we have a 2 metre, 9 second wave arriving from NW at the offshore boundary then you will experience a 1.2 metre 10.2 second wave from WNW. In this case there is an assumption that the seabed is causing the wave to lose energy (height), to be turned slightly and for its period to be stretched by a shoaling process. The analysis phase described above can be thought of as a pre-processing stage which is represented graphically in Figure 18.

Moving on from the pre-processing to recombination stage, for each time series entry given by the external source the wave state can be identified and used to retrieve the associated modelled record. The expected wave conditions at the prediction point can then be calculated by transferring the modelled data to the predicted time series. This process is repeated for the full offshore time series and allows a time series for the equivalent time frame to be calculated at the prediction point.

By using a numerical model the predicted wave behaviour can be calculated for all locations within the model domain. This however becomes restricted as predictions move further away from the targeted prediction location.

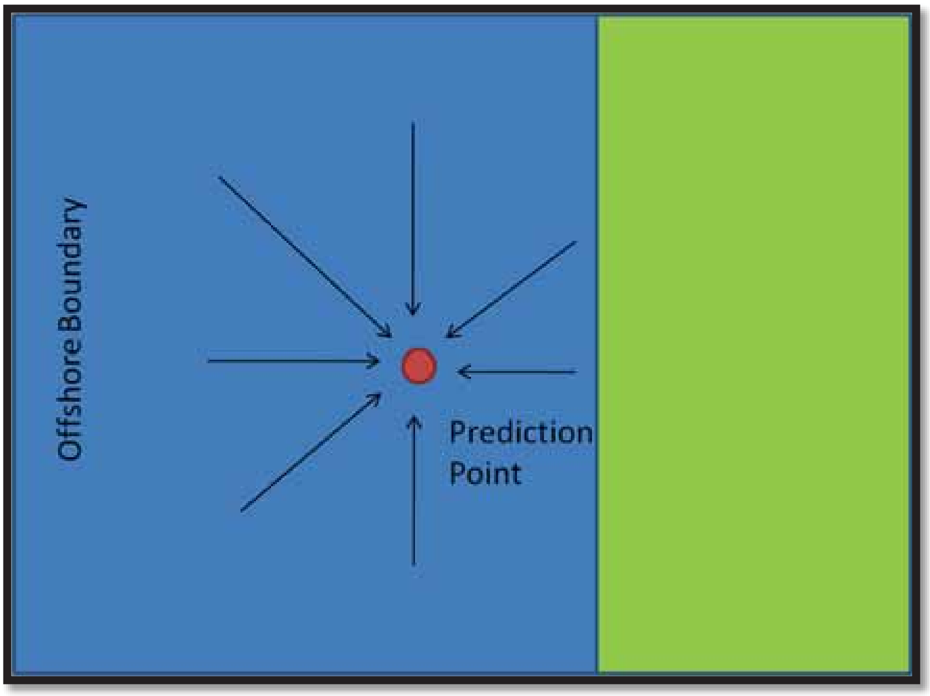

Figure 19: Prediction method located offshore

4.2. Including Wind Generated Waves

Moving the prediction point offshore from the coast allows for it to be influenced by wave conditions arriving from the East, Figure 19. These easterly waves are likely to be generated by local winds.

4.2.1. Resultants, Wind and Swell

The reference data supplied by the Met Office describes three types of wave state: the resultant, the wind and the swell sea. The wind sea corresponds to those parts of the wave spectrum that are directly influenced by wind forcing. All waves on the ocean surface that are commonly experienced are generated by the friction caused by the wind blowing over a large distance (fetch) of open water. The friction between the wind and the ocean's surface transfers energy into the upper layers of the water causing the water particles to move in a circular motion. This manifests itself as the waves that we see. With low wind speeds and short distances you have small, short waves, with higher wind speeds and longer distances larger, longer and steeper waves are generated.

Swell waves occur as the wind forcing is removed from the surface of the ocean. There is no immediate reduction of wave activity as the wind drops or ceases to blow. Instead, the ocean has an effective memory of the energy that has been input. To imagine the process, a strong storm in the North Atlantic will generate a wave spectra dominated by wind forced seas. As the storm passes and the waves radiate away from the storm centre the energy that was previously concentrated in steep, short waves spreads to lower frequency, longer period waves with lower amplitudes. These are the swell waves that fall predominately on the west coast of Scotland and are favoured by surfers.

The wave model operated by the Met Office is based on a spectral approach whereby the energy at every modelled point is represented by a wave spectra assigned as the energy per wave frequency and wave direction. In creating their wave parameters all the energy that falls below a specific frequency is assigned as swell, all that falling above the cut off is assigned as wind seas. From each of these two data sets the wave parameters returned by the Met Office are calculated. The resultant wave parameters are created from the full spectra with no partitioning.

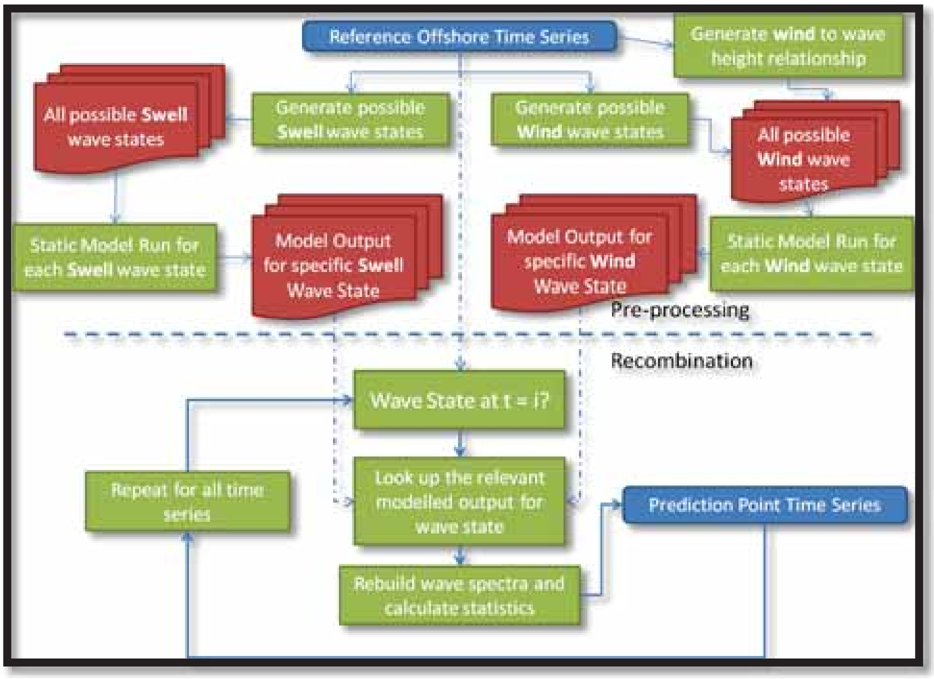

Figure 20: Flowchart for wind and swell modelling

4.2.2. Modelling implications

The implications for the modelling approach as given in Section 4.1 are that two separate sets of input data now need to be considered: the swell and the wind seas. The swell seas can be effectively handled in a similar manner to that given in Section 4.1 whereby the wave states to be modelled are defined by a wave height, wave period and wave direction applied at the offshore boundary.

For wind driven seas the wind state also needs to be defined. For reasons of simplicity in reducing the input parameter set the wind direction is taken to be concurrent with the wave direction, examination of Figure 67 and Figure 88 for the western and eastern Met Office data points show this to be a reasonably valid assumption.

A further step that can be taken is to relate the wave height to wind speed. Examining Figure 66 and Figure 88 again shows that a simple relationship can be established[4]. To build on this approach a relationship between wind speed and wave height can be created for each of the 16 directional sectors into which the records are analysed. Two example relationships are shown in Figure 21 and Figure 22 for the Western Met Office Data. Table 3 and Table 4 in Annex 3 give the full relationship analysis for the two Met Office Data points. For the majority of directional sectors an R-squared fit of around 0.8 is found.

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[4] Further investigation could be made with respect to this assumption in investigating a Pierson-Moskowitz type relationship rather the simple linear relationships established here.

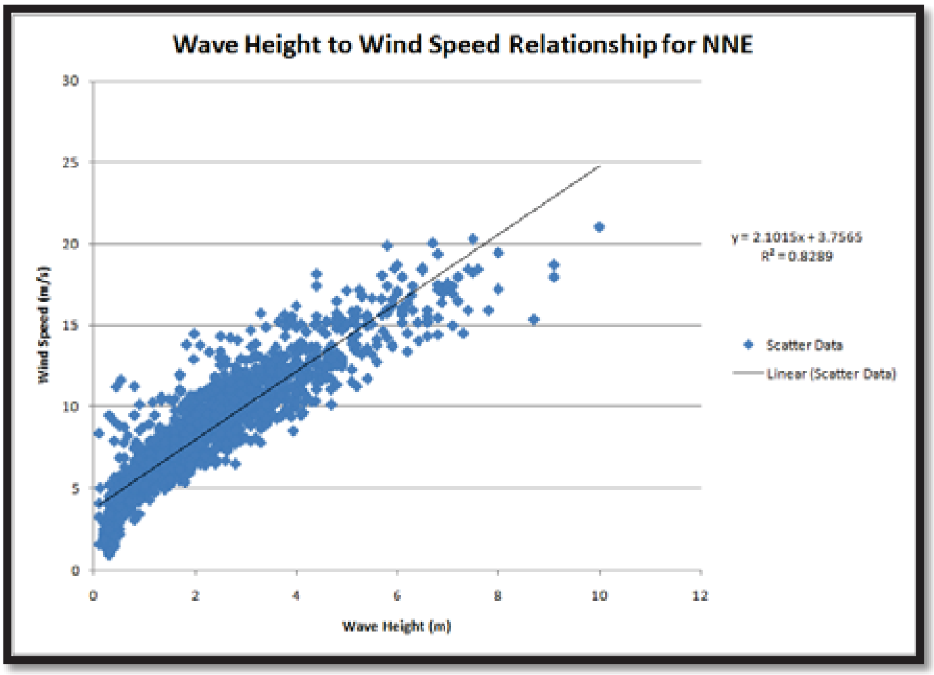


Figure 21: Relationship of wind wave height to wind speed for the NNE sector

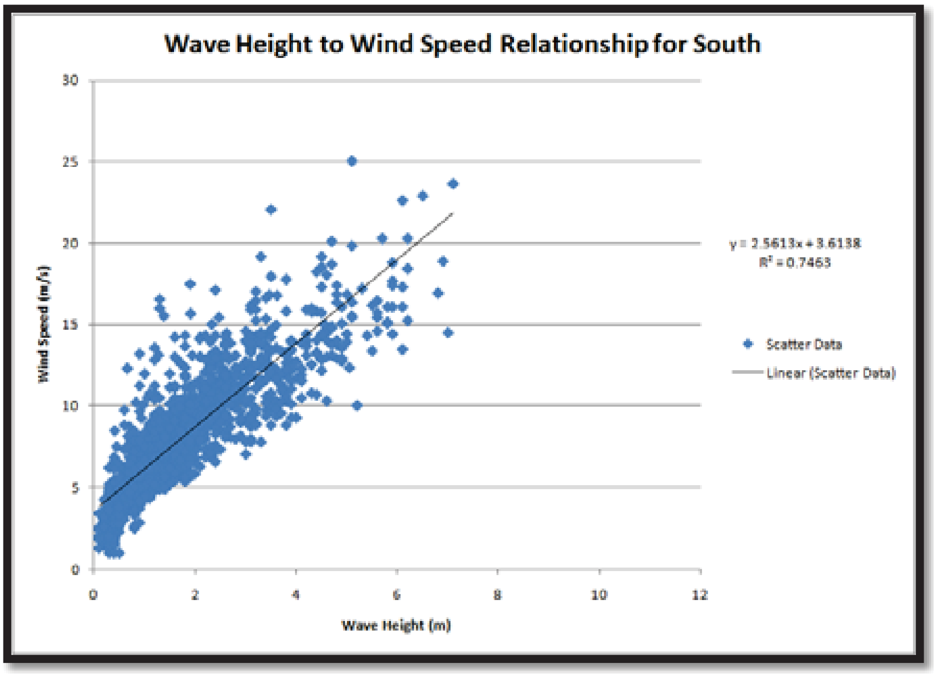


Figure 22: Relationship of wind wave height to wind speed for the Southern sector

Following the establishment of relationship between the wind sea, wave height and the directionally related wind speed the numerical model can be run for each expected sea condition similar to that carried out for swell waves.

4.2.3. Recombination process

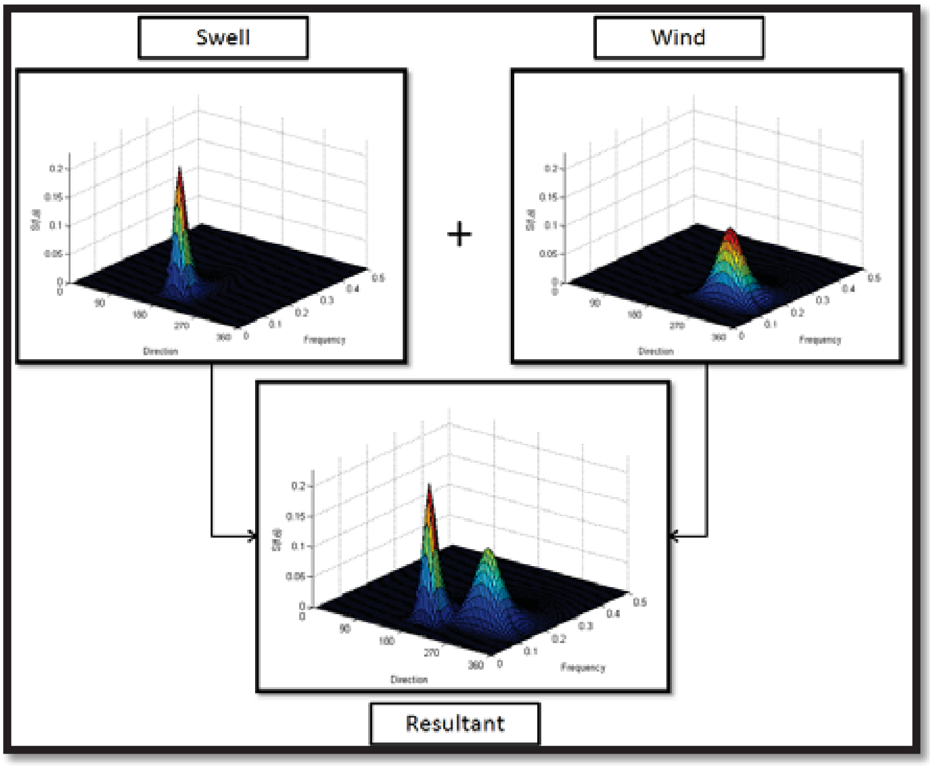


Figure 23: Recombination of wind and swell seas to give a resultant

The recombination phase as shown in Figure 20: Flowchart for wind and swell modelling is slightly more complicated than for our initial non-wind driven example.

The MIKE21 model, as configured for this type of project, produces output files that contain pre-processed statistical values; wave height, wave period and wave direction. These values exist for both the swell and wind seas and must be recombined to give a single set of statistical parameters that can be usefully mapped.

Returning to the description of wind driven waves; the energy that is transferred to the ocean as a result of the wind blowing over its surface can be represented as a spectrum S(f) describing the energy present at specific wave frequencies (periods). To create the standard statistical parameters of wave height and period, the energy in the spectra is translated into spectral moments and a set of standard formula used to produce the statistical values.

The wind and swell data as returned by MIKE 21 cannot be directly recombined to produce a single set of statistical values. However, the data returned can be used to create pseudo-spectra. These energy based spectra can be recombined and the subsequent results used to produce the required single set of statistics. This is illustrated in Figure 23.

This methodology is based on the assumption that over short distance there is minimal interaction between the wind and swell spectra. For further details on methodology please see Section 10.

4.3. Application to the Shetland Islands

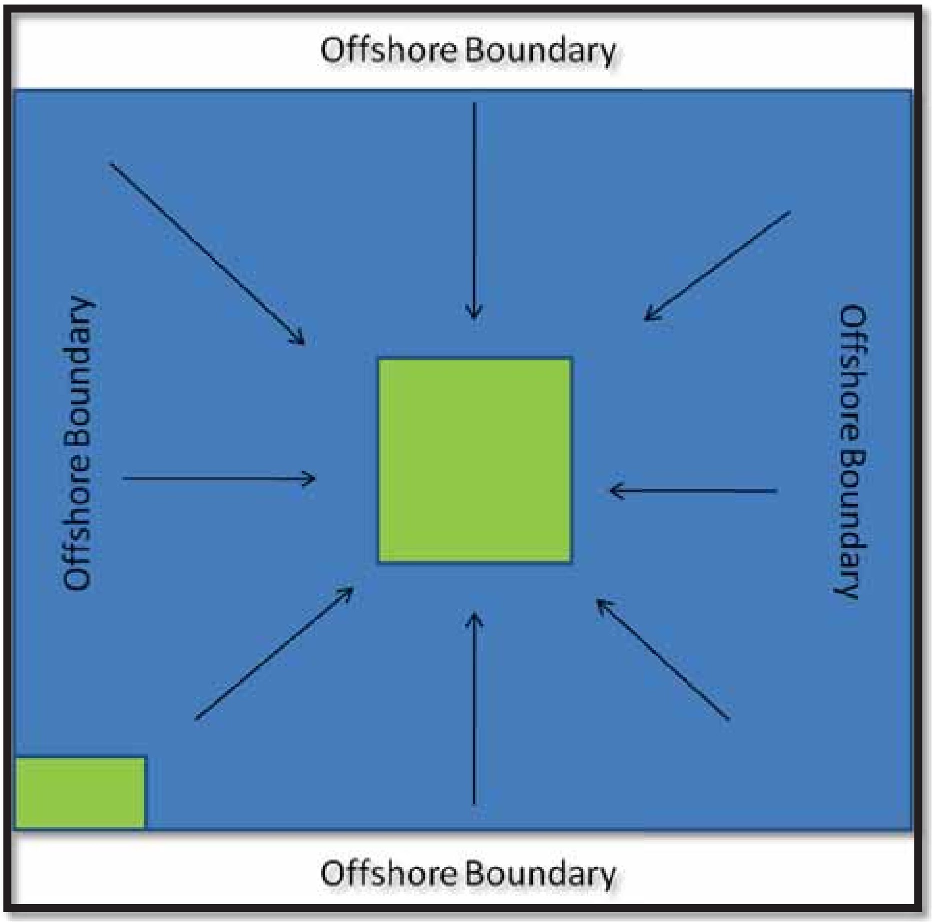


Figure 24: Conceptual diagram of Shetland Islands Model

The application of the standard wave assessment methods, as given in the preceding sections, to the Shetland Islands is complicated by their exposure to three large oceanic bodies. Shown conceptually in Figure 24 the Shetland Islands can experience wave energy arriving from multiple directions. Analysis of the wave data from the Met Office suggests three prospective wave climates that may be experienced.

1. Westerly storms and swell arriving from the Atlantic
2. Northerly storms and swell approaching from the Arctic Sea
3. Easterly and Southerly storms generated in the North Sea

The methodologies proposed in Sections 4.1 and 4.2 are based on the presumption that a single boundary is being forced. For single sites and some major coastlines this assumption proves valid as the analysis of a wave rose for the site in question will commonly show a single dominant climate. With the Shetland Islands being exposed on all four sides a more complex modelling arrangement is required whereby all wave directions can be considered for all coastlines.

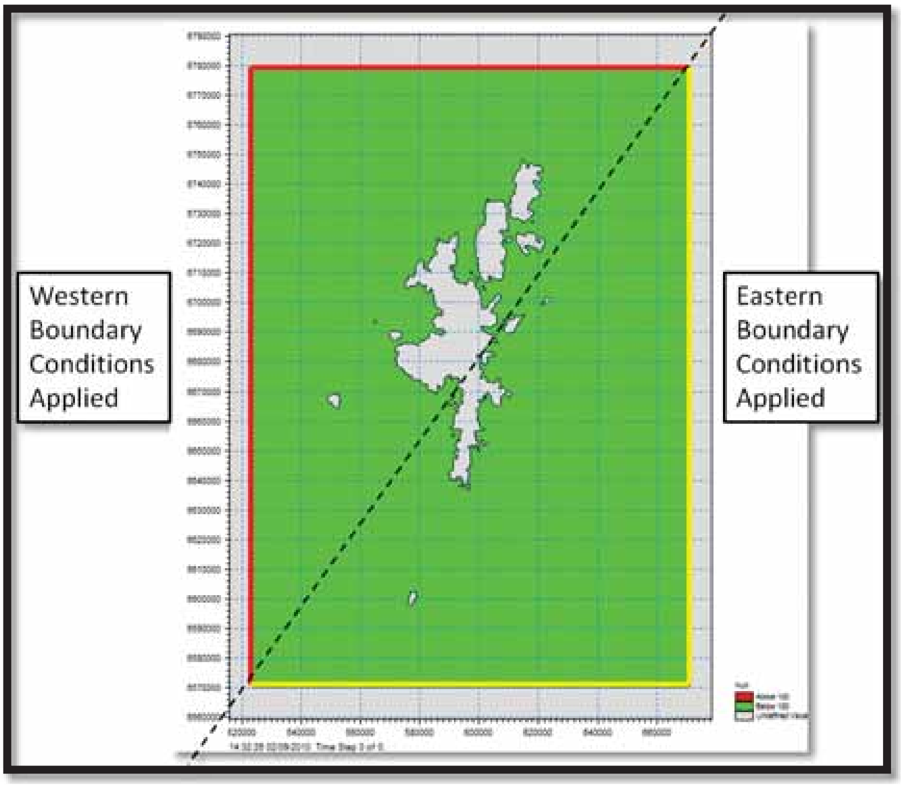


Figure 25: Boundary conditions as applied to the Shetland model. Red indicates boundary data from the Westerly Met Office data were applied. Yellow indicates that the Easterly Met Office data were utilised. The Black dashed line indicates the presumed split in wave climates

4.3.1. Modelling breakdown

From the geographic orientation of the Shetland Islands to these prevailing conditions it is surmised that the Western and Northern facing coasts are most affected by the Westerly and Northerly climates coming from the Atlantic and Arctic oceans and that the Southern and Eastern coasts are more affected by North Sea conditions.

To capture these important aspects in this study the methodology of Section 4.2 is augmented to include multiple swell directions and to distinguish between differing wind generated seas.

4.3.2. Model Domain

The creation of the wave model domain follows similar methods to that given in Section 3.1. A coastline is created from Electronic Navigation Chart data and fitted over a 1:50k Ordnance Survey map geo-referenced to a UTM 30N co-ordinate system. This coastline is at a resolution of 500m to accommodate reasonable detail without producing data heavy output files. Examining Figure 26 it is noted that many of the inland voes and firths, particularly to the south and east of Muckle Roe, have been removed. In these areas the wave climate will be considerably reduced due to local topography and would cause a slowing down of the process. The resolution of 500m is sufficient to allow the Bluemull and Yell Sounds to remain open.

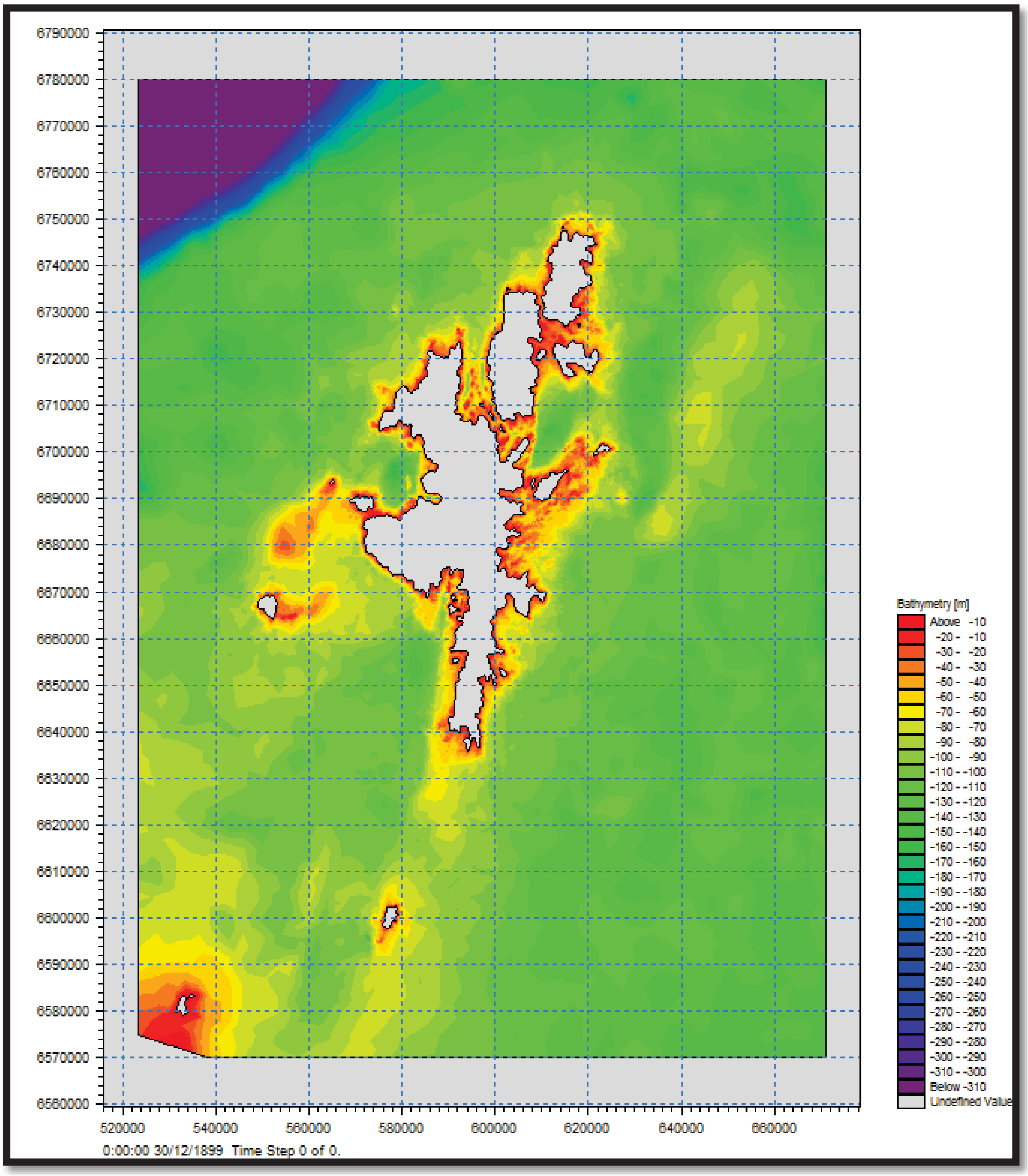


Figure 26: 500m resolution bathymetry as used in wave models

4.3.3. Modelling Process

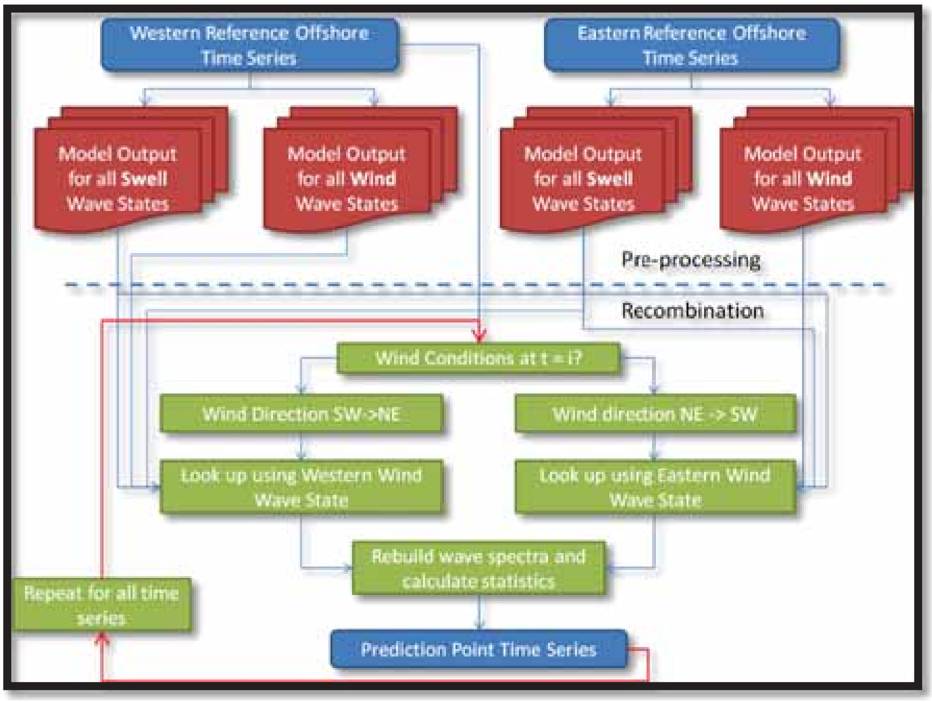


Figure 27: Modelling flow chart for recombining eastern and western wave climates

Following on from the processes described in Sections 4.1 and 4.2 the wave states are determined and modelled for both the western and eastern Met Office reference data sets. For the western data the swell conditions are applied to the red boundaries of the model domain, as shown in Figure 25, to calculate the western swell. The wind speed record from this western point is used to develop the wind speed to wind wave height relationship, as described in Section 4.2.2, with all western wind wave states stored to output files. A similar process is carried out using the eastern Met Office reference data but in this case applying the boundary conditions to the yellow boundaries of Figure 25. This modelling process results in a set of 4 modelled wave states covering the Shetland Islands domain that require recombination to produce resultant statistics.

For the location where the Shetland Islands are situated it is conceivable that a swell can be arriving from the Atlantic and from the North Sea at the same time. At locations in the Fair Isle Channel and to the north of Unst these swells meet and create a confused sea state. Over the small distances of this study area it is a fair assumption that the two swell seas can be added in the recombination process[5].

Over the model domain that is in use there should be little variation in wind speed and direction on a scale that will impact on wind wave generated seas. As such only one wind sea state is to be used in the recombination routine; the choice of which wind sea state is determined by the wind direction at the western Met Office reference location. For wind directions blowing from the southwest to northeast the wind sea state associated with the western Met Office data point, applied to the red boundaries in Figure 25, are utilised as these best represent the passage of westerly and northerly storms. For wind directions blowing from northeast to southwest the eastern data sets are used as these more accurately represent the conditions associated with southerly and easterly events in the North Sea.

[5] A more complex approach can be taken by including wave-wave interactions.

Once the selection of the two swell and one wind sea states has been made the spectral recombination technique as described in Section 10 is again utilised to bring together the three sea states and determine the resultant statistics.

4.4. Post Processing

Following the successful recombination of the wave state files a 10 year time series of wave height, period and energy exists at all locations for the following parameters:

Significant Wave Height

$$H_{m_0} = 4\sqrt{m_0}$$

Energy Period

$$T_e = m_{-1}/m_0$$

Mean Period

$$T_{m_{01}} = m_0/m_1$$

Power

$$P = (\rho g^2/4\pi)T_e\left(H_{m_0}^2/16\right)$$

These parameters are then averaged over the 10 year period to give annual and seasonal statistics of wave height, period and power that are mapped in Section 5

5. RESULTS PRESENTATION

The following section presents a selection of the full set of maps available in A3 format in Sections 7 and 8. The following maps cover:

Tidal Results

- Shetland – Maximum Velocities
- Shetland – Root Mean Cubed Velocities
- Shetland – Average Power Density
- Bluemull Sound – Maximum Velocities
- Bluemull Sound – Root Mean Cubed Velocities
- Bluemull Sound – Average Power Density
- Bluemull Sound – % Exceedance of 2 m/s (4 knots)
- Bluemull Sound – Flow Type

Further localised maps for North of Unst, Yell Sound and Sumburgh Head are included in Section 7.1 with extracts processed to tidal roses taken at three locations for each site.

Wave Results

- Shetland – Annual Wave Height
- Shetland – Annual Wave Period
- Shetland – Annual Wave Power
- Shetland – Seasonal Wave Height
- Shetland – Seasonal Wave Period
- Shetland – Seasonal Wave Power

As with the tidal results localised maps are available for the coastline South and West of Scalloway and for North and West of Esha Ness in Section 8.1. This annex also includes point extractions of wave roses and box plots for 12 the points around the Shetland coast shown in Figure 28.

5.1. Wave Point Extracts

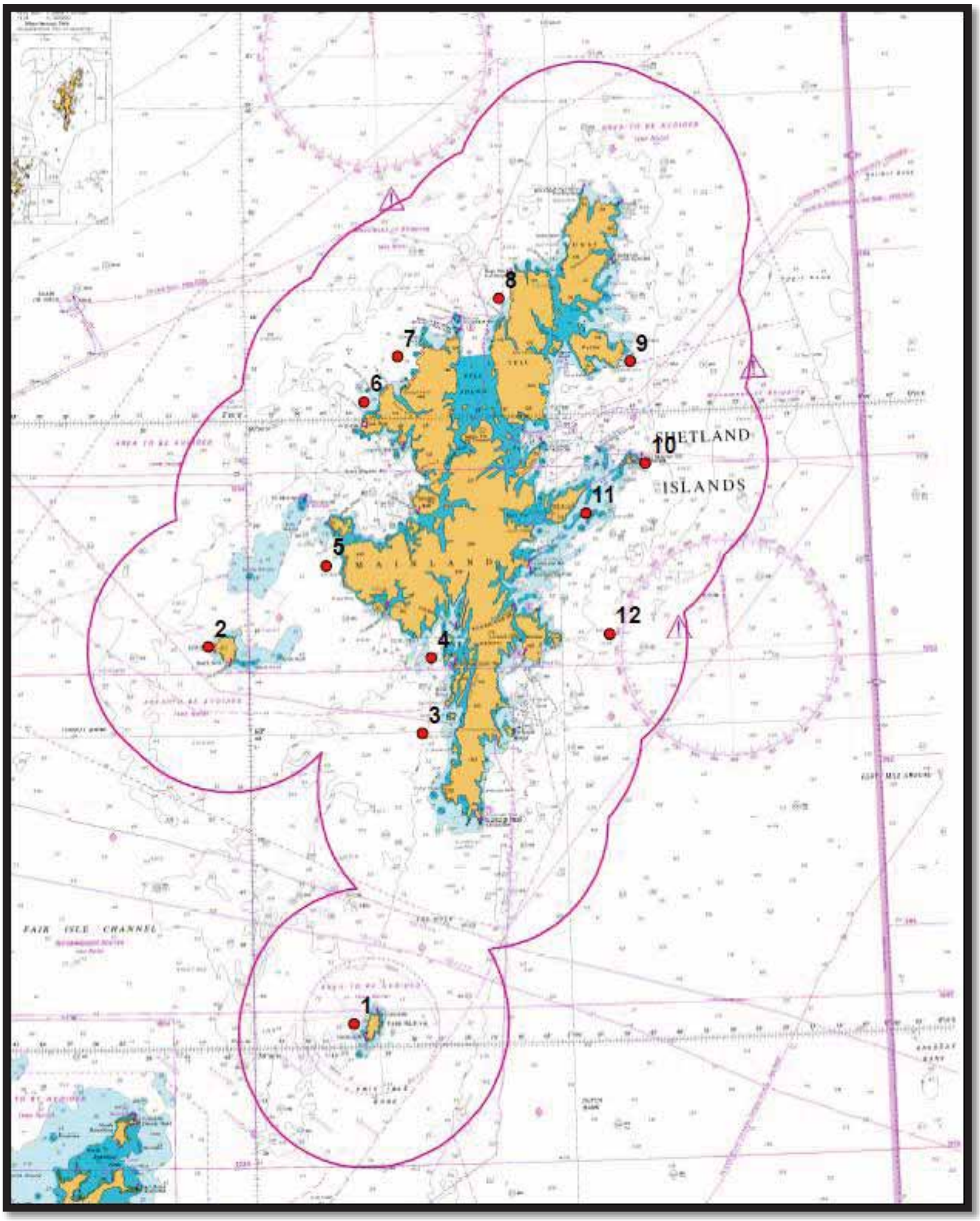
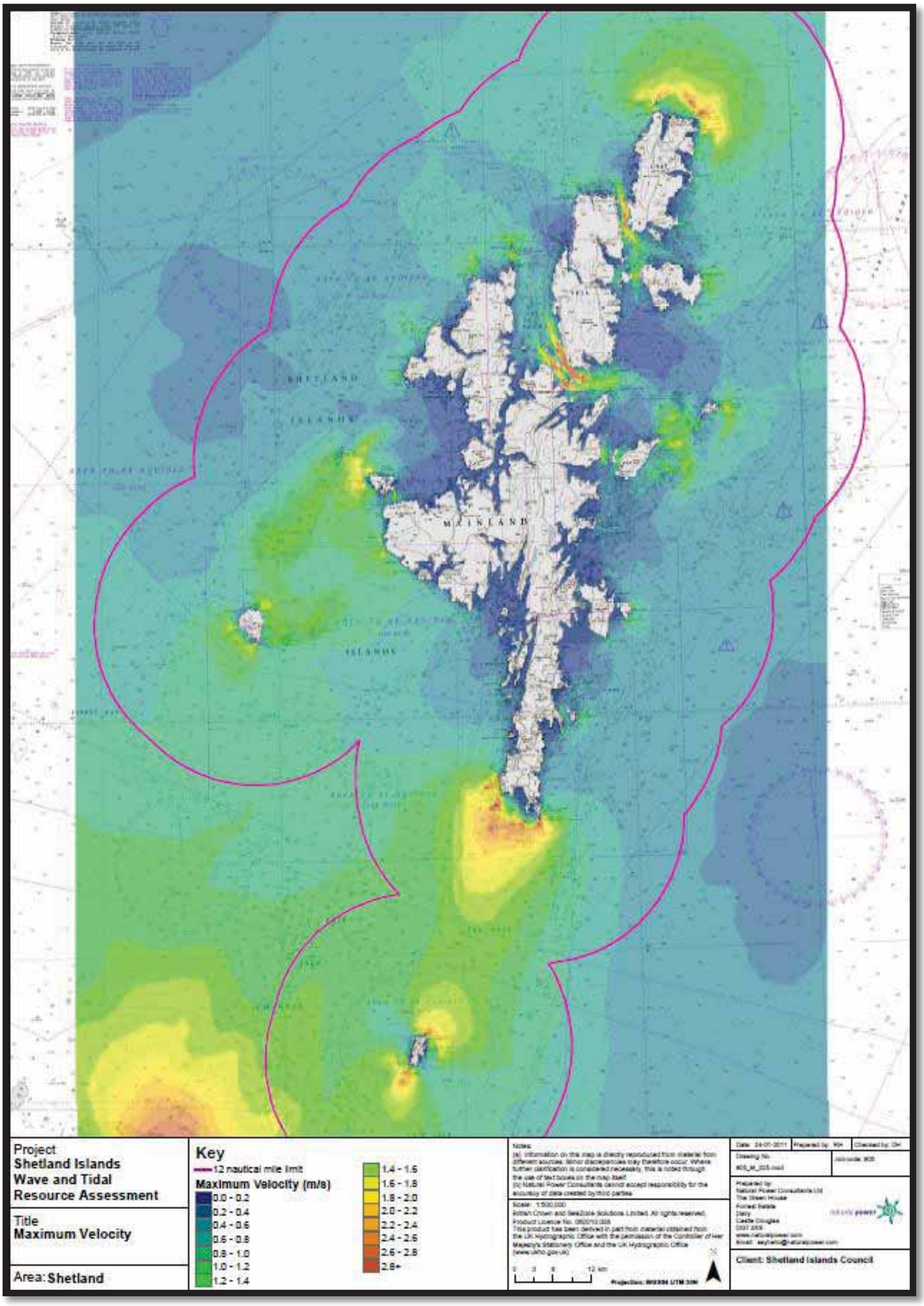


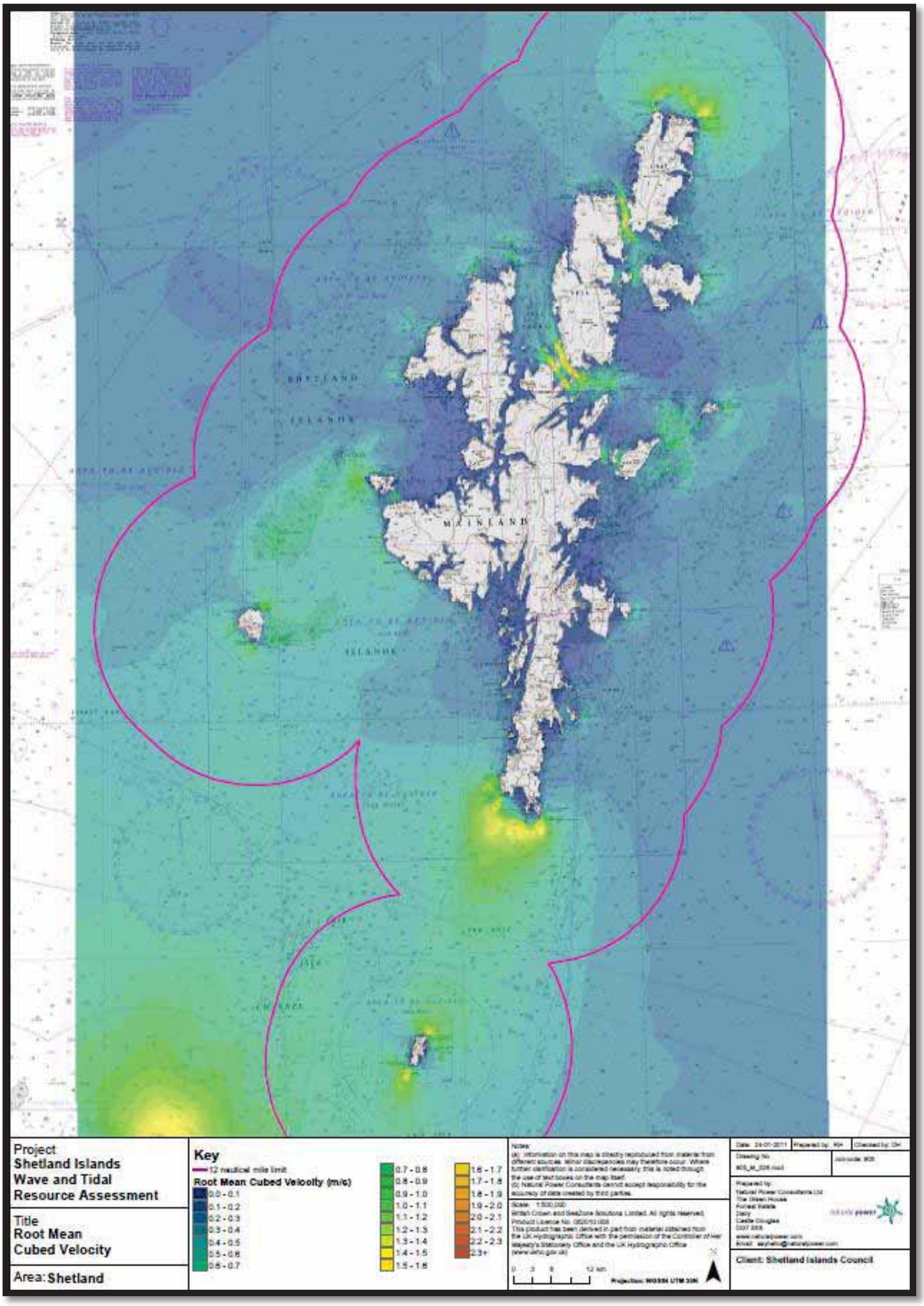
Figure 28: Point extractions for wave rose plotting

5.2. Tidal Results

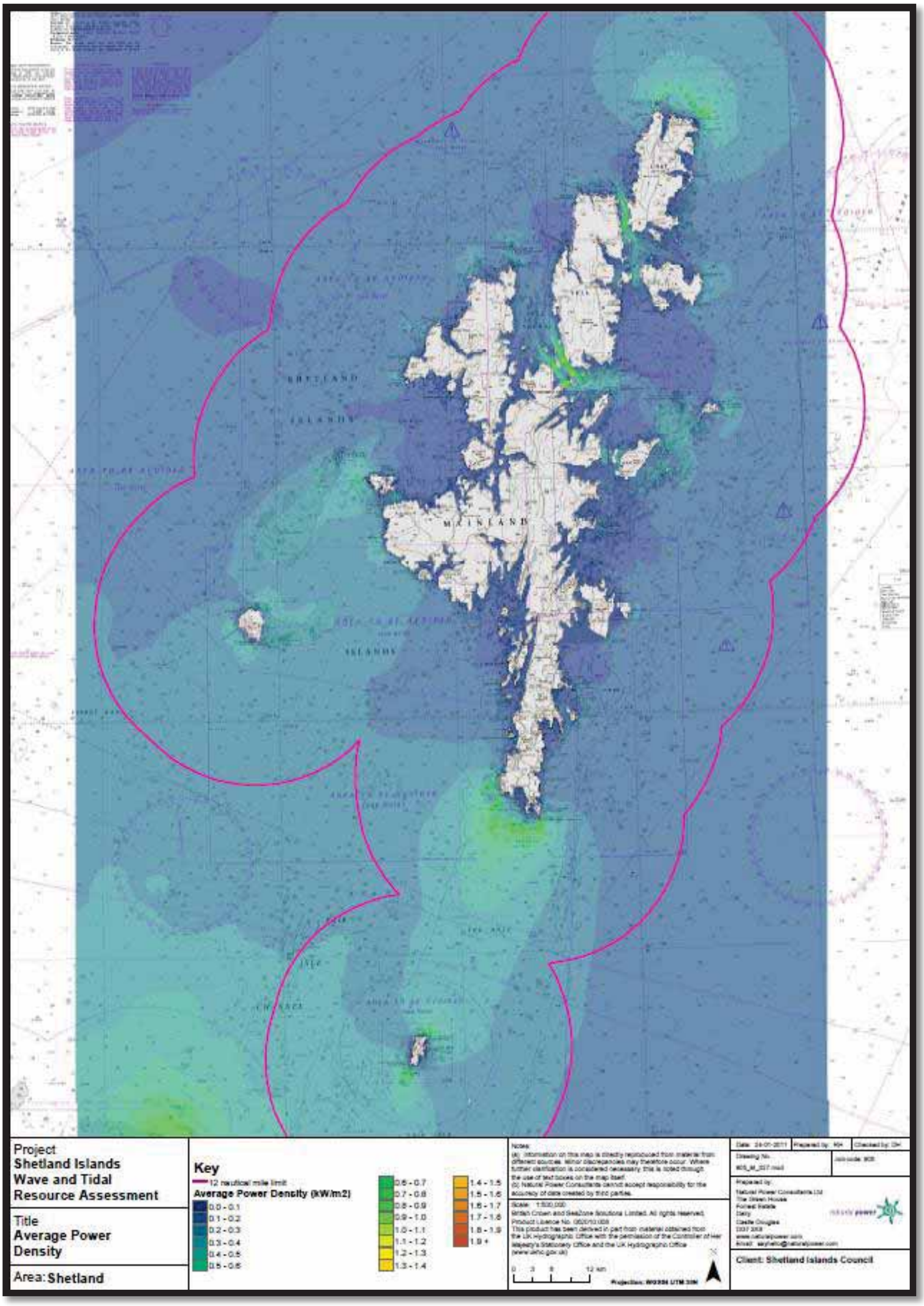
5.2.1. Shetland – Maximum Velocities



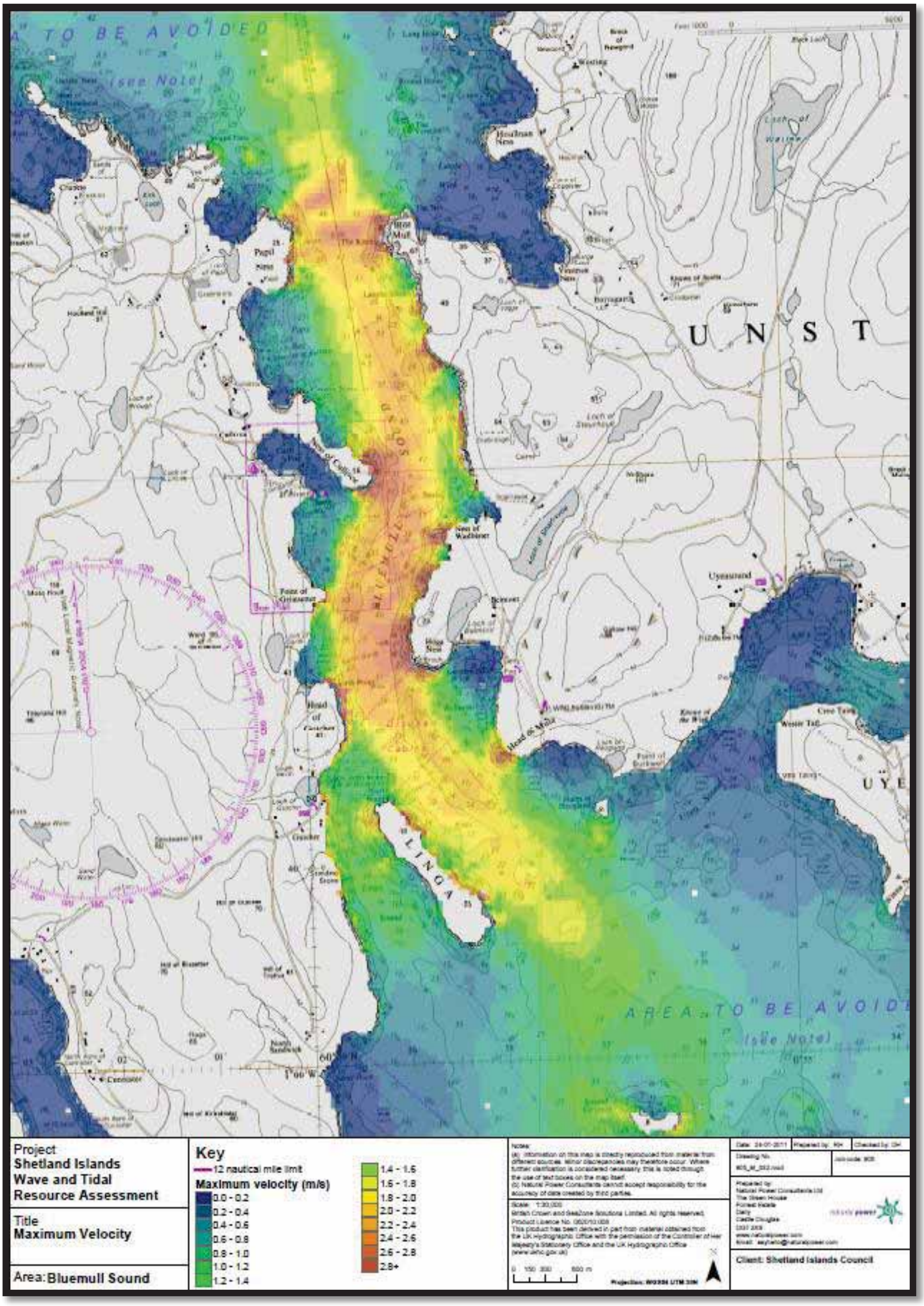
5.2.2. Shetland – Root Mean Cubed Velocity



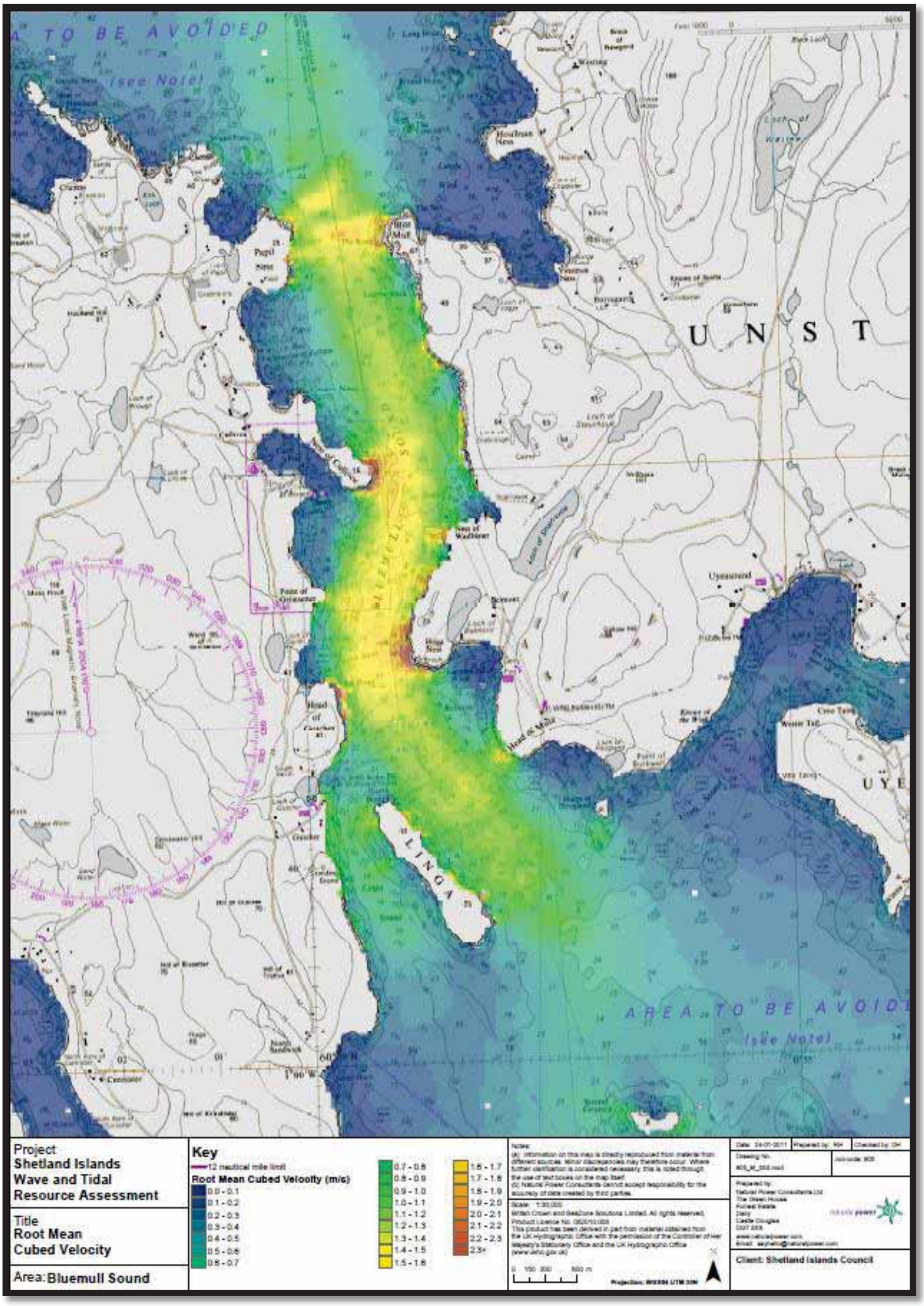
5.2.3. Shetland – Average Power Density



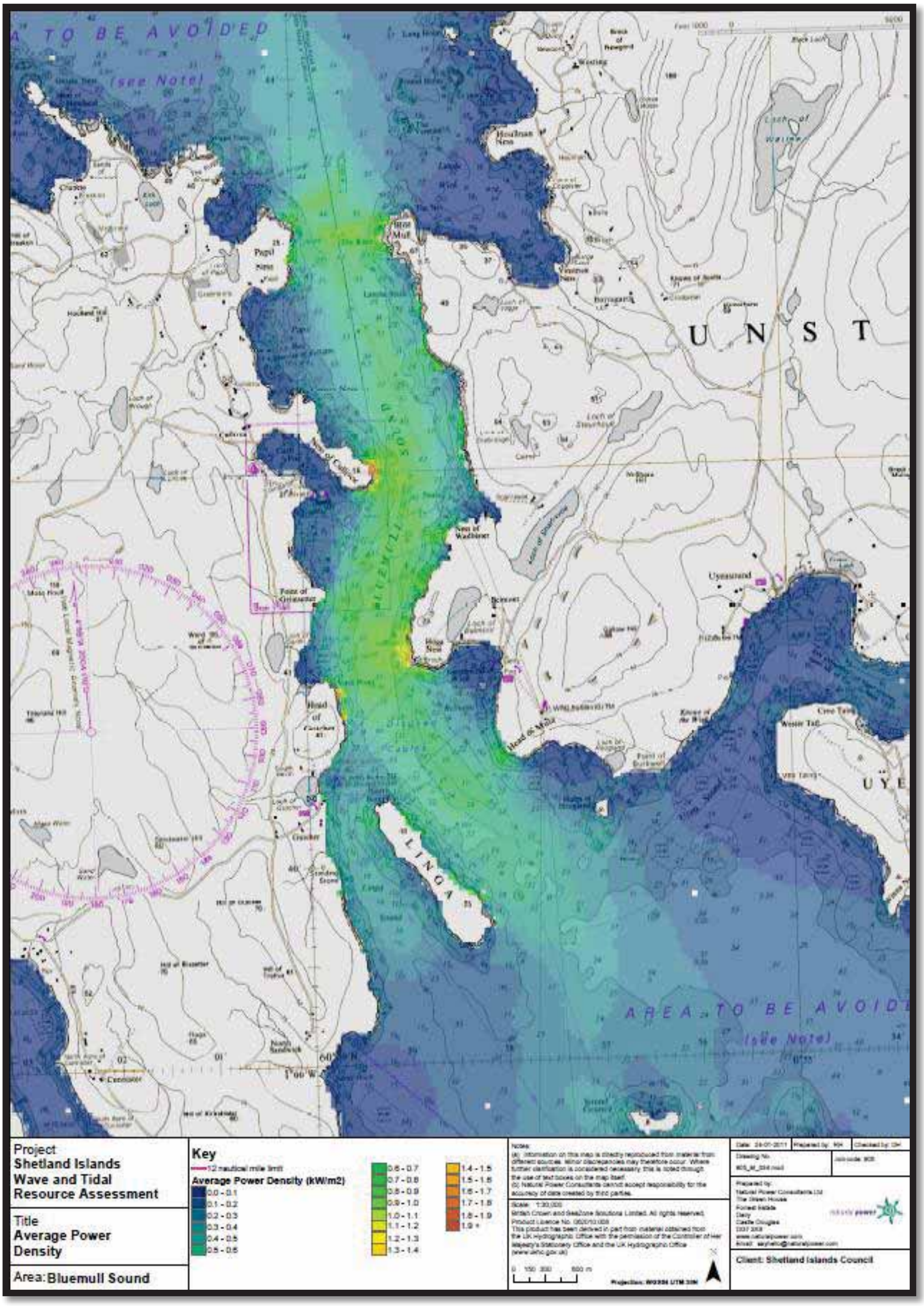
5.2.4. Bluemull Sound – Maximum Velocities



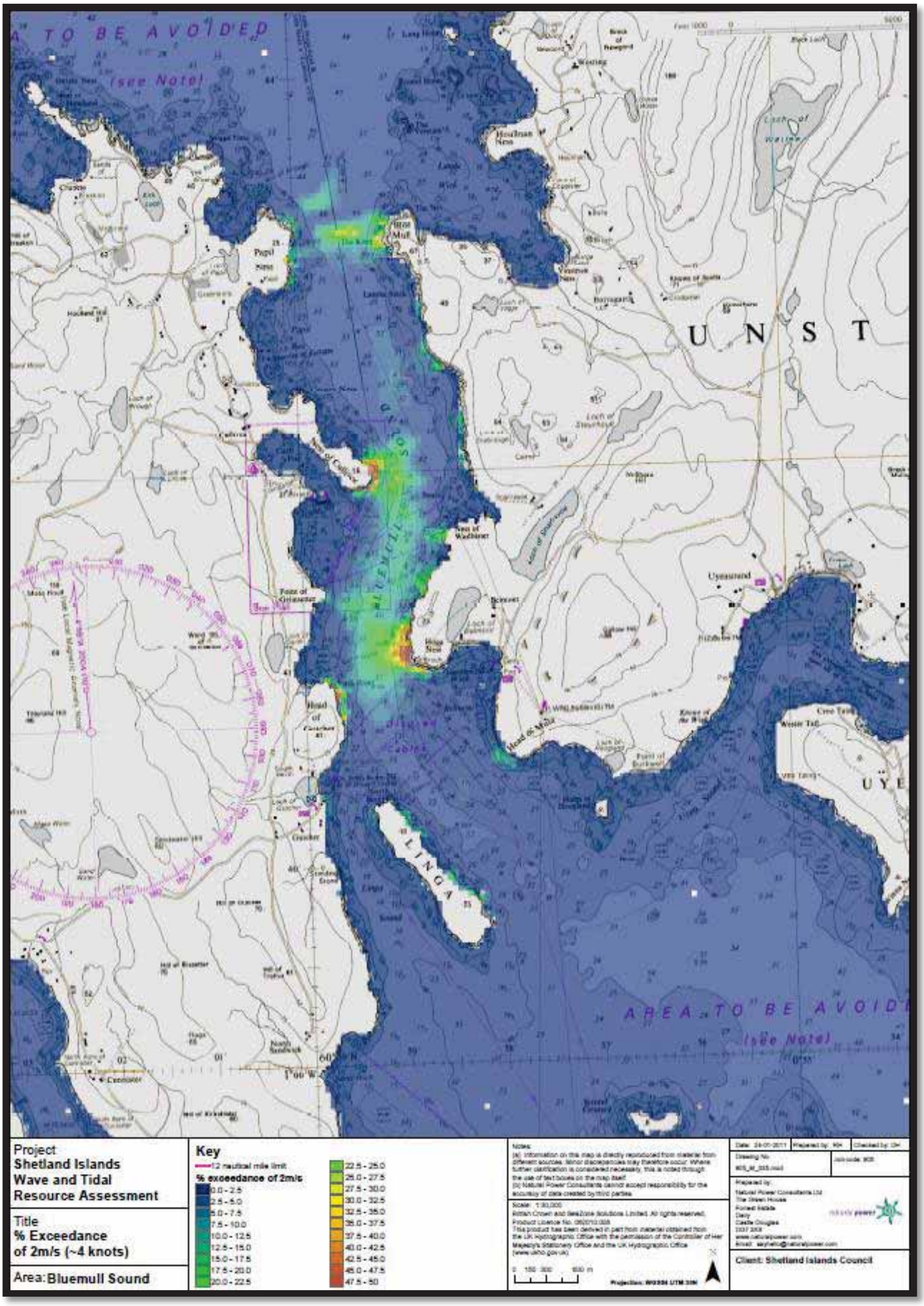
5.2.5. Bluemull Sound – Root Mean Cubed Velocity



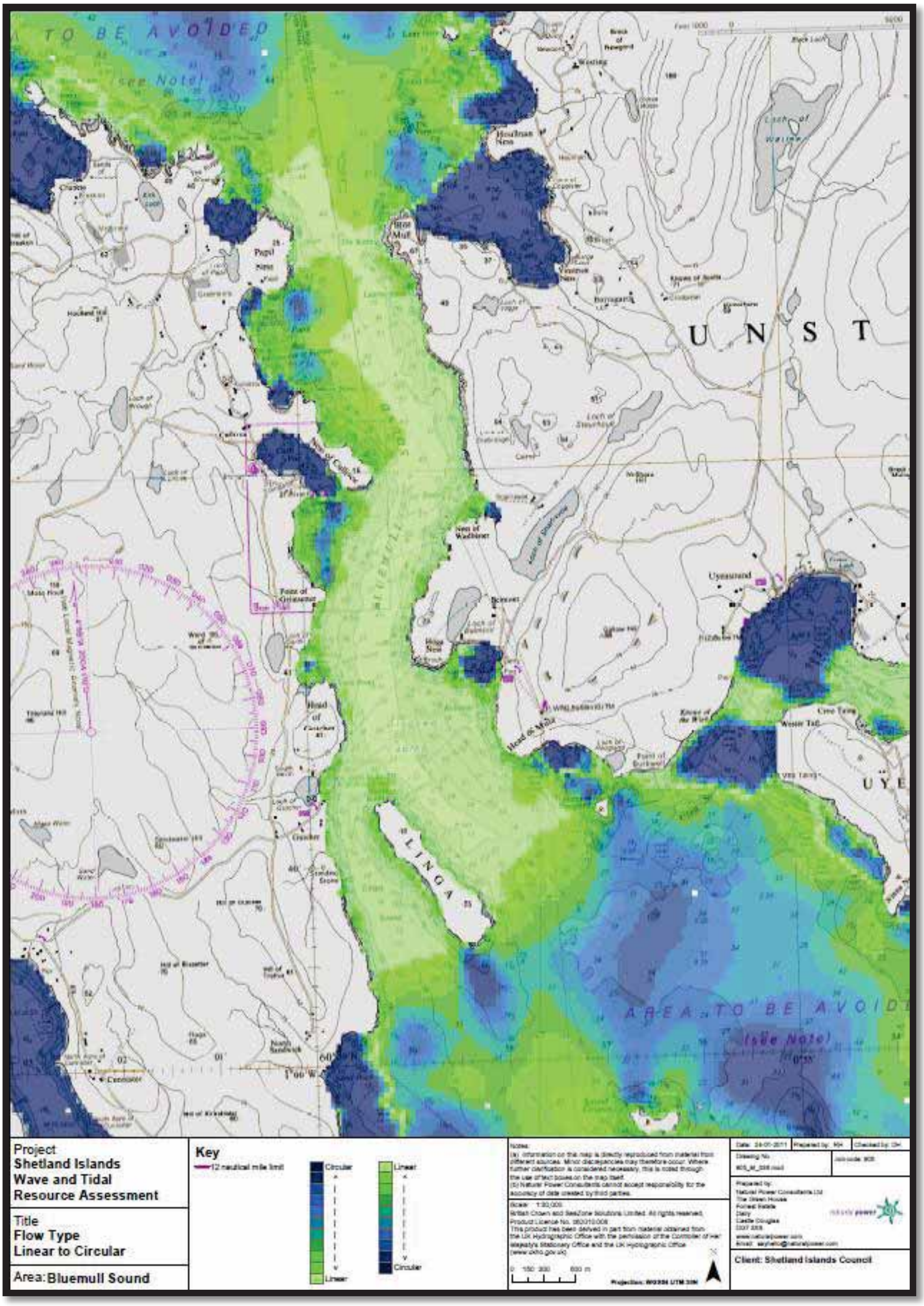
5.2.6. Bluemull Sound – Average Power Density



5.2.7. Bluemull Sound – % Exceedance of 2 m/s (4 knots)

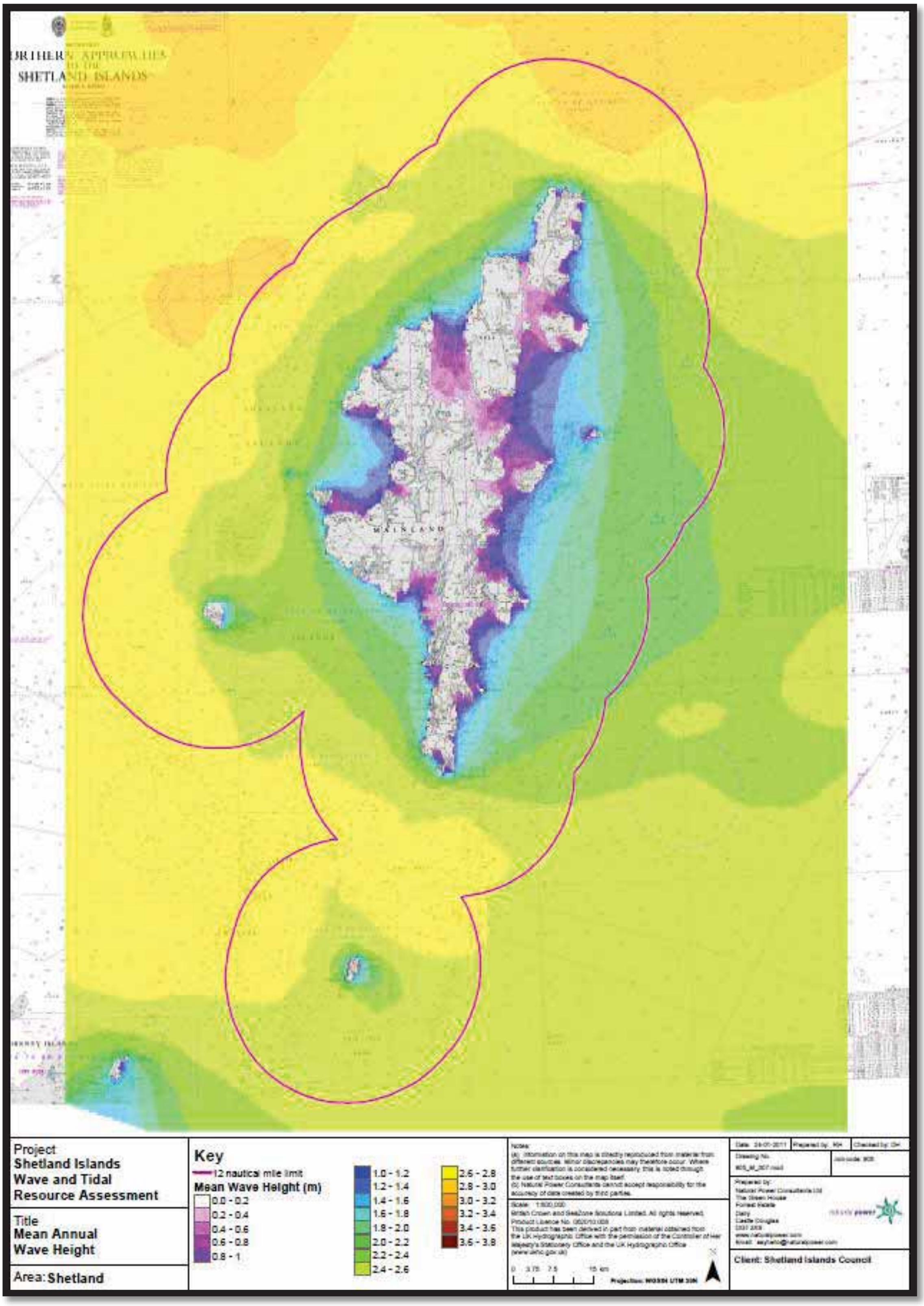


5.2.8. Bluemull Sound – Flow Type

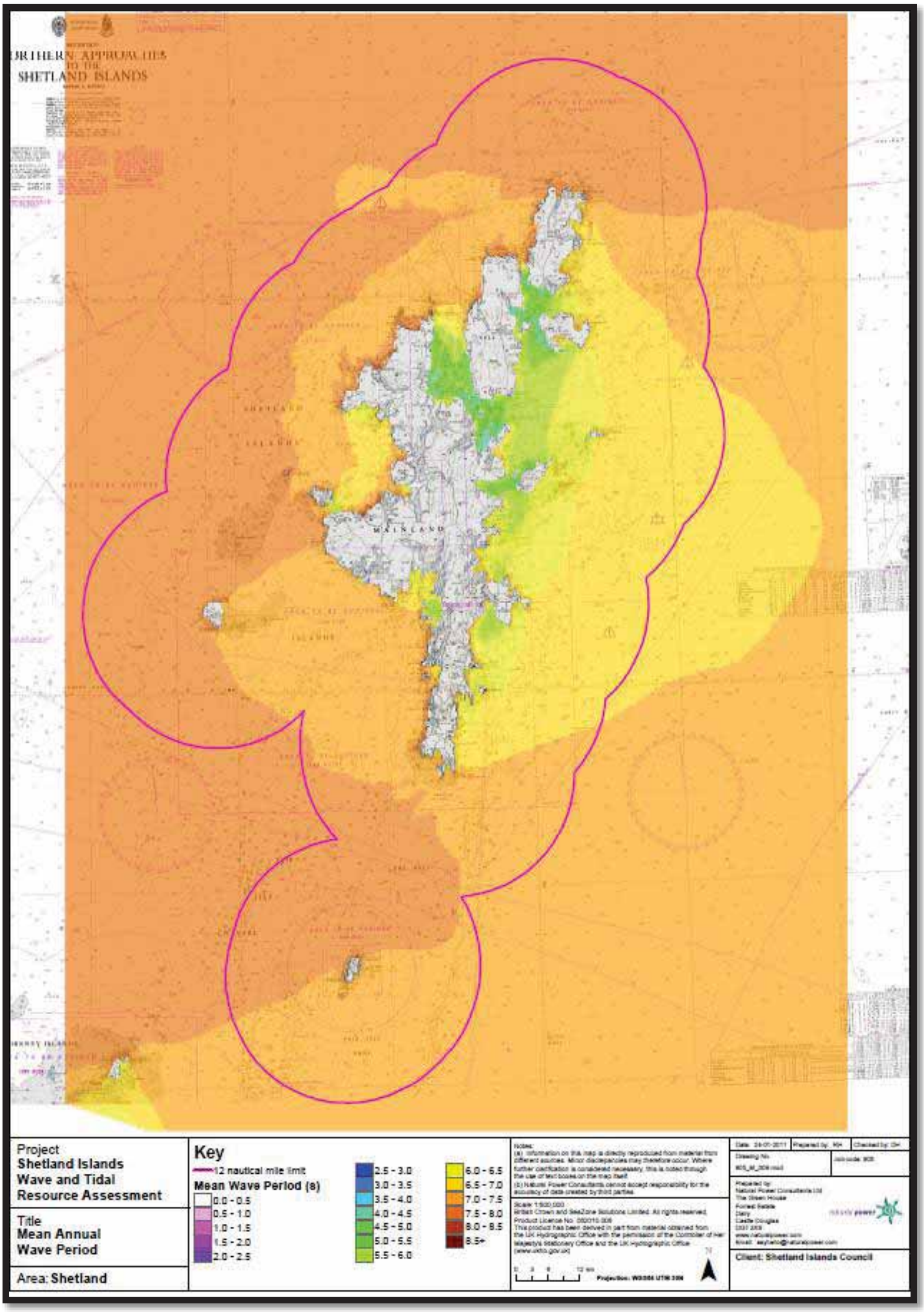


5.3. Wave Results

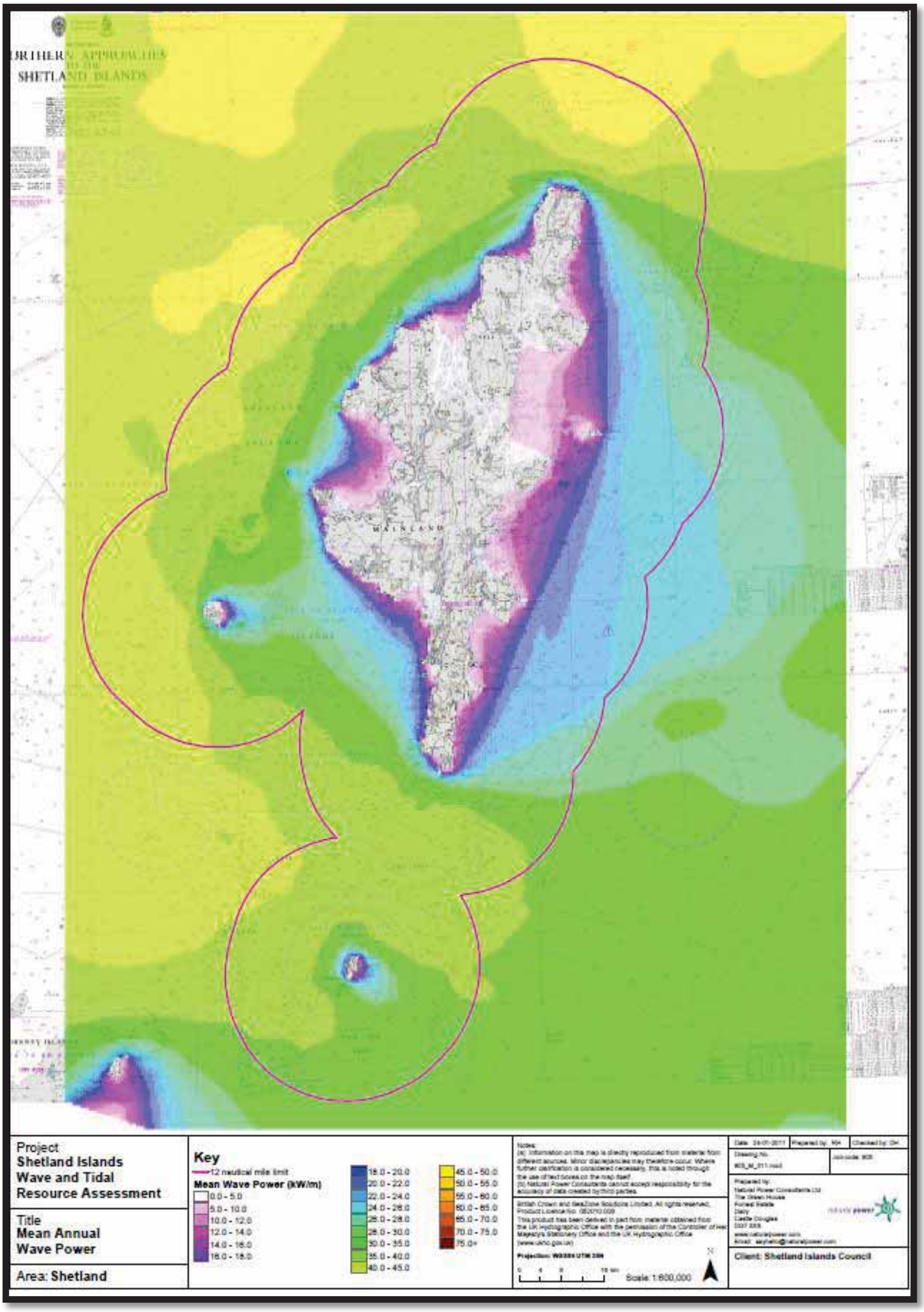
5.3.1. Annual Wave Height



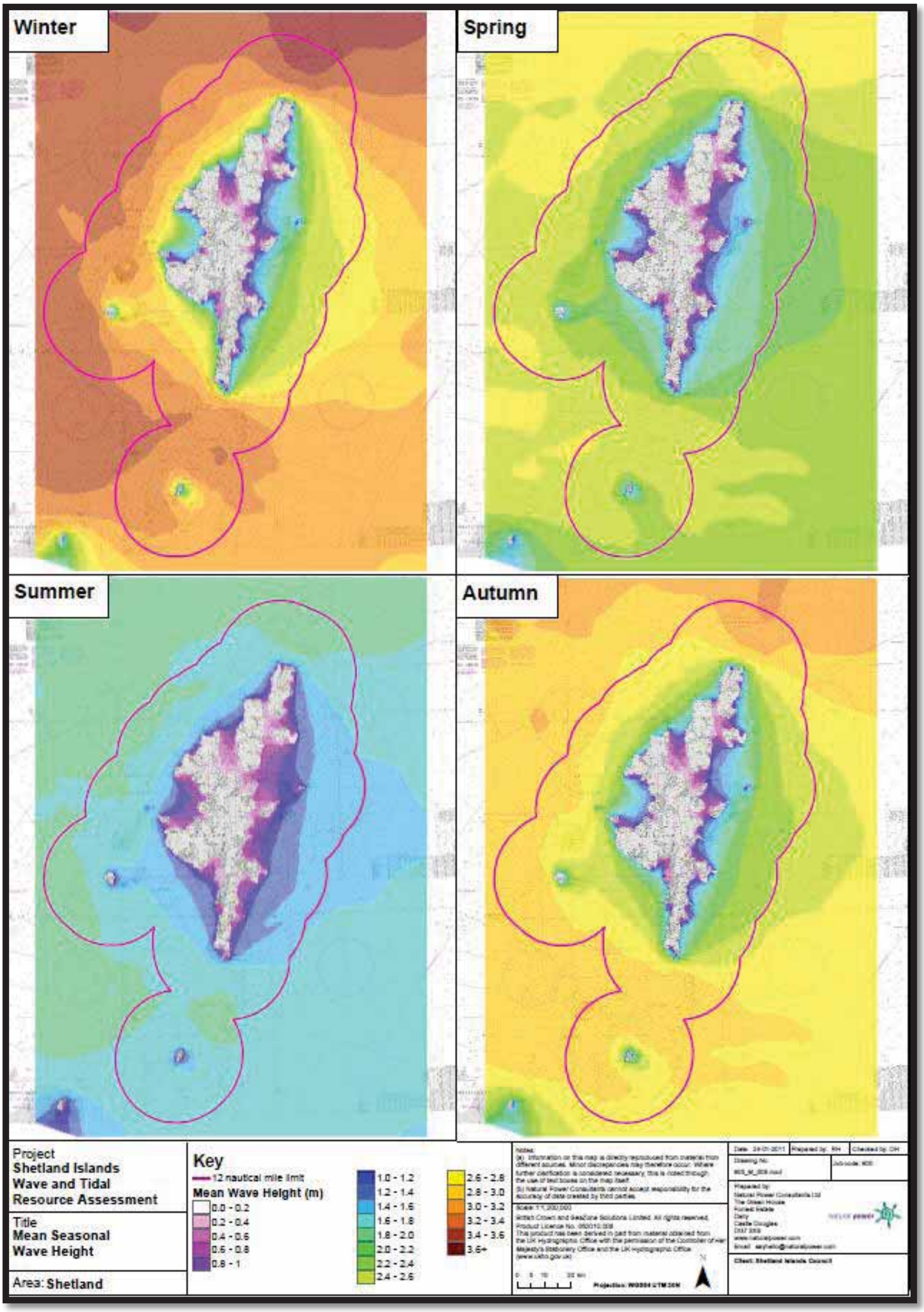
5.3.2. Annual Wave Period



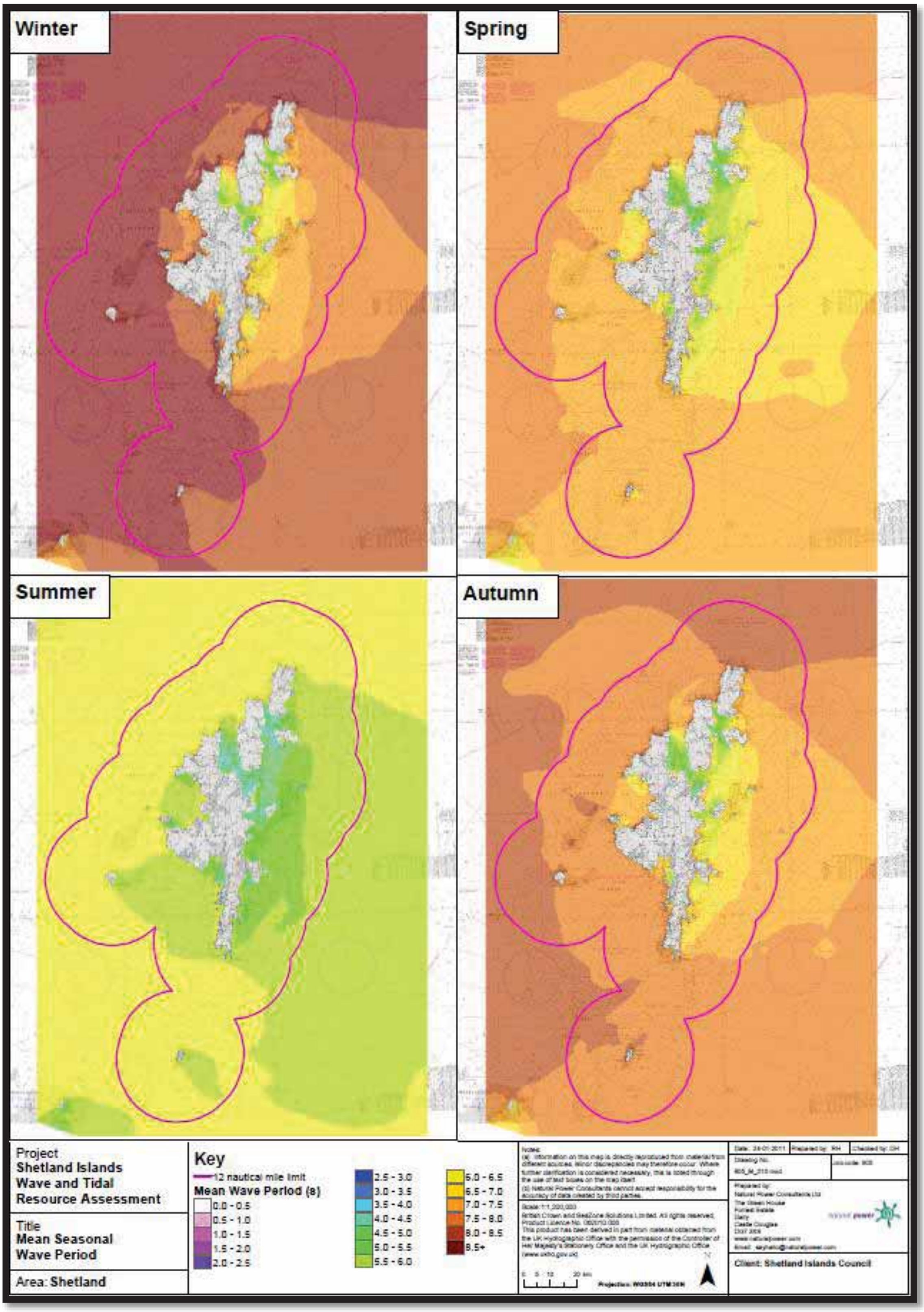
5.3.3. Annual Power



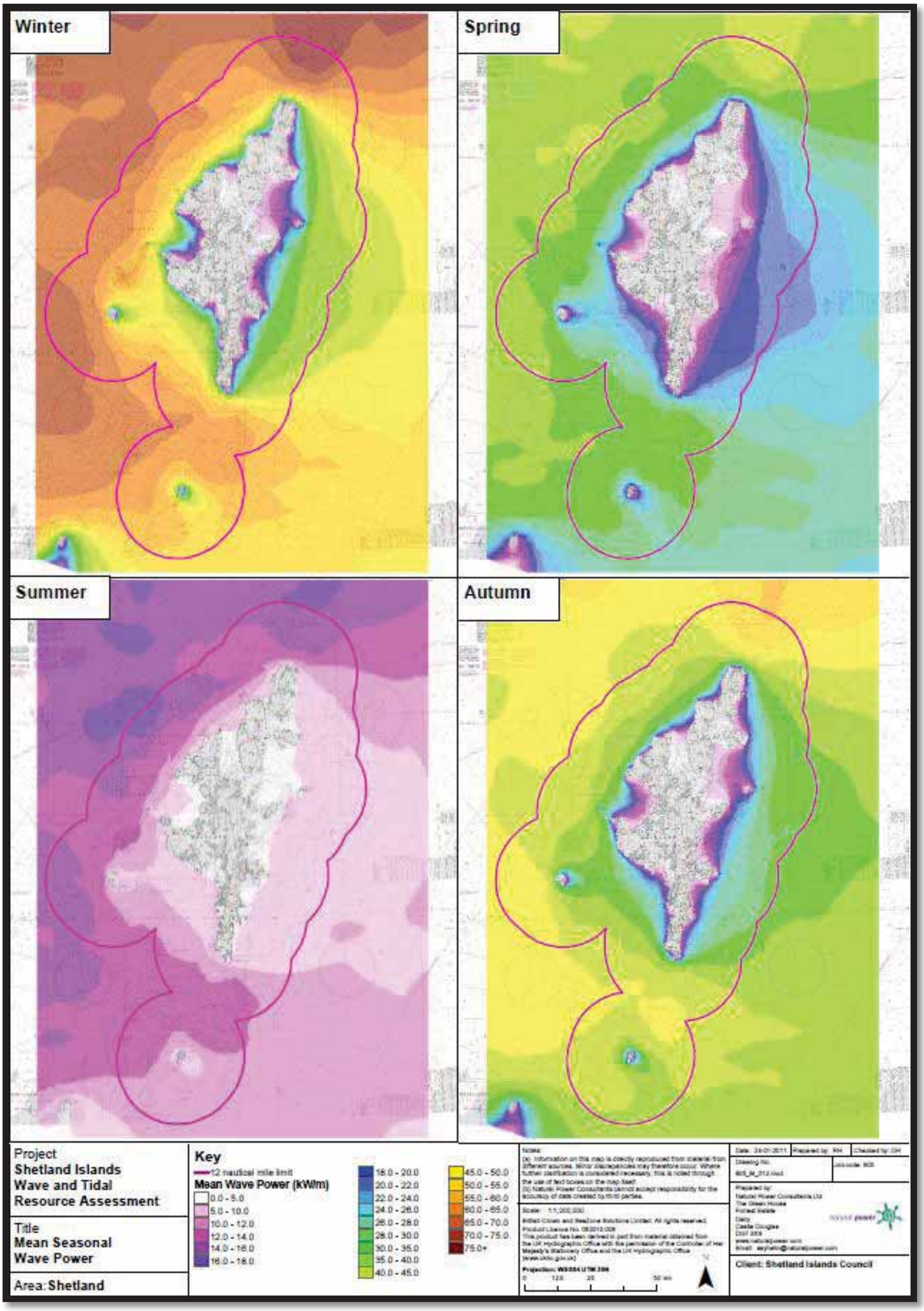
5.3.4. Seasonal Wave Height



5.3.5. Seasonal Wave Period



5.3.6. Seasonal Power



6. CONCLUSIONS

Natural Power Consultants have applied our technical knowledge and skill to the production of a wave and tidal resource assessment suitable for the purpose of filling a specific gap in the Shetland Marine Atlas data sets.

These studies have been split into the numerical modelling of the wave energy resource and the numerical modelling of tidal energy resource. Both of these studies have produced a series of maps showing resource levels on an annual and seasonal basis for the wave resource and as a representative month of tidal velocity data analysed into summary statistics. These GIS map layers have been supplied to the Shetland Islands Council for further dissemination to interested parties.

Through the course of these studies new and innovative methods in the assessment of wave energy resource for island archipelagos have been developed, these allow for existing methods to be extended and produce a viable estimate of wave energy resource. Careful examination of the mapped outputs and associated wave rose extracts show that good resources can be found all round the Shetland Islands with appreciable energy levels to the east where extreme wave conditions may be more tolerable than on the west coast.

While spatial information on the wave energy resource in the Shetland Islands has been available for some time we believe that the tidal energy maps in this report are the first such information made publicly available. With these maps the areas of prospective tidal resource is shown to be concentrated into a limited number of constrained sites. While on first sight this appears to be limiting the potential for tidal energy extraction we would hope that it rather focuses attention on the fact that the tidal energy industry is very localised in scope and that its impact on wider industry can be more easily managed if the extent of these target locations is known a-priori.

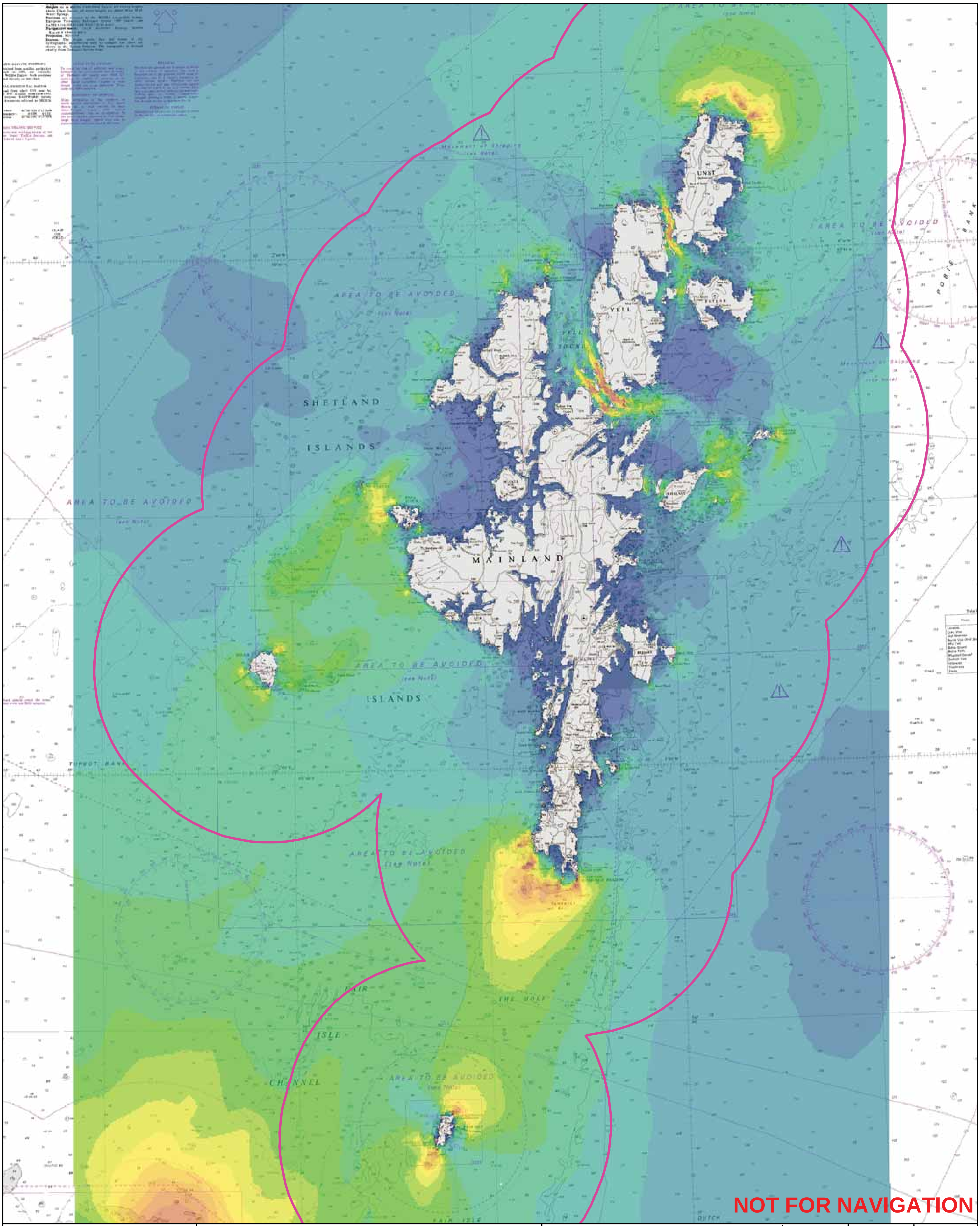
This exercise in the study of the Shetland Islands Marine resource is intended to highlight opportunities for development that when taken with guidance included in the Shetland Marine Spatial Plan will lead to economically successful projects.

7. ANNEX 1 TIDAL RESULTS

7.1. Mapped results

The following A3 maps are included within this Annex:

- Shetland – Maximum Velocities
- Shetland – Root Mean Cubed Velocities
- Shetland – Average Power Density
- North Unst – Maximum Velocities
- North Unst – Root Mean Cubed Velocities
- Bluemull Sound – Maximum Velocities
- Bluemull Sound – Root Mean Cubed Velocities
- Bluemull Sound – Average Power Density
- Bluemull Sound – % Exceedance of 2 m/s (4 knots)
- Bluemull Sound – Flow Type
- Yell Sound – Maximum Velocities
- Yell Sound – Root Mean Cubed Velocities
- Yell Sound – Average Power Density
- Yell Sound – % Exceedance of 2 m/s (4 knots)
- Yell Sound – Flow Type
- Sumburgh – Maximum Velocities
- Sumburgh – Root Mean Cubed Velocities



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Maximum Velocity

Area: **Shetland**

Key

12 nautical mile limit

Maximum Velocity (m/s)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8+

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Scale: 1:500,000

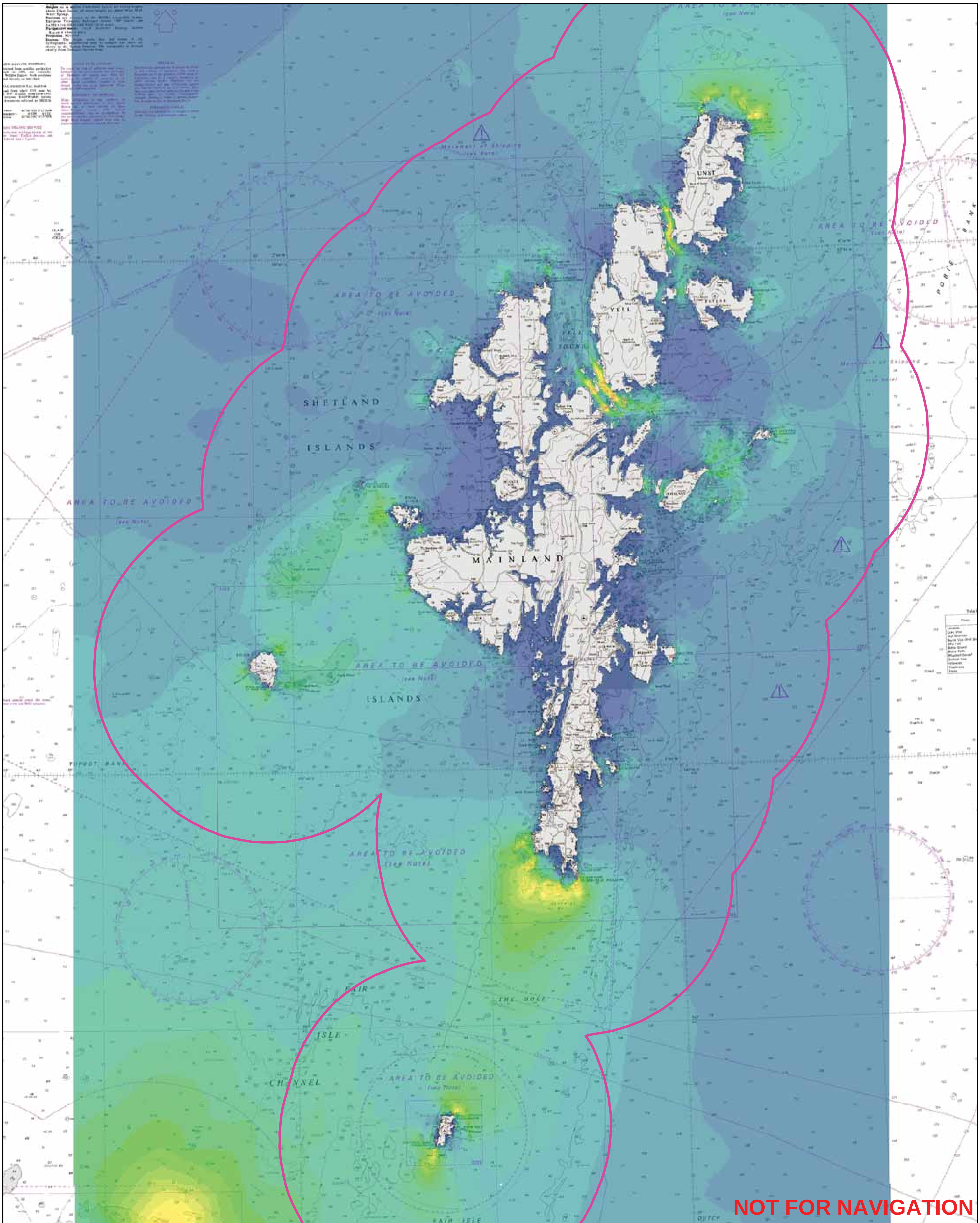
0 3 6 12 km

Projection: WGS84 UTM 30N

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_025.mxd		Job code: 805

Prepared by:
Natural Power Consultants Ltd
The Green House
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
www.naturalpower.com
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Root Mean Cubed Velocity

Area: **Shetland**

Key

12 nautical mile limit

Root Mean Cubed Velocity (m/s)

0.0 - 0.1	0.7 - 0.8	1.6 - 1.7
0.1 - 0.2	0.8 - 0.9	1.7 - 1.8
0.2 - 0.3	0.9 - 1.0	1.8 - 1.9
0.3 - 0.4	1.0 - 1.1	1.9 - 2.0
0.4 - 0.5	1.1 - 1.2	2.0 - 2.1
0.5 - 0.6	1.2 - 1.3	2.1 - 2.2
0.6 - 0.7	1.3 - 1.4	2.2 - 2.3
	1.4 - 1.5	2.3+
	1.5 - 1.6	

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
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Scale: 1:500,000

0 3 6 12 km

Projection: WGS84 UTM 30N

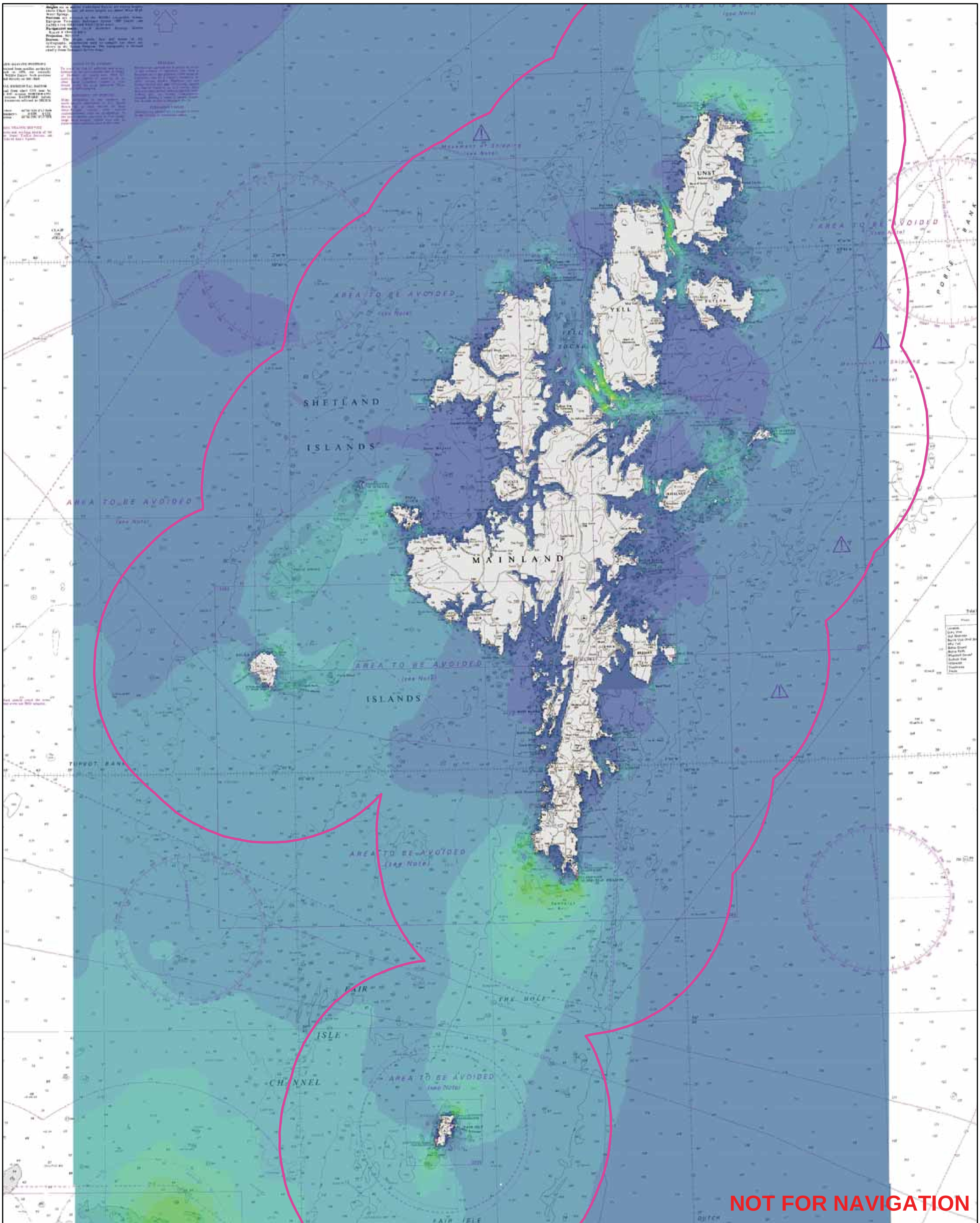
Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_026.mxd

Job code: 805

Prepared by:
Natural Power Consultants Ltd
The Green House
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
www.naturalpower.com
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Average Power Density

Area: **Shetland**

Key

12 nautical mile limit

Average Power Density (kW/m2)

0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
1.0 - 1.1
1.1 - 1.2
1.2 - 1.3
1.3 - 1.4
1.4 - 1.5
1.5 - 1.6
1.6 - 1.7
1.7 - 1.8
1.8 - 1.9
1.9 +

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Scale: 1:500,000

0 3 6 12 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_027.mxd | Job code: 805

Prepared by:
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Dalry
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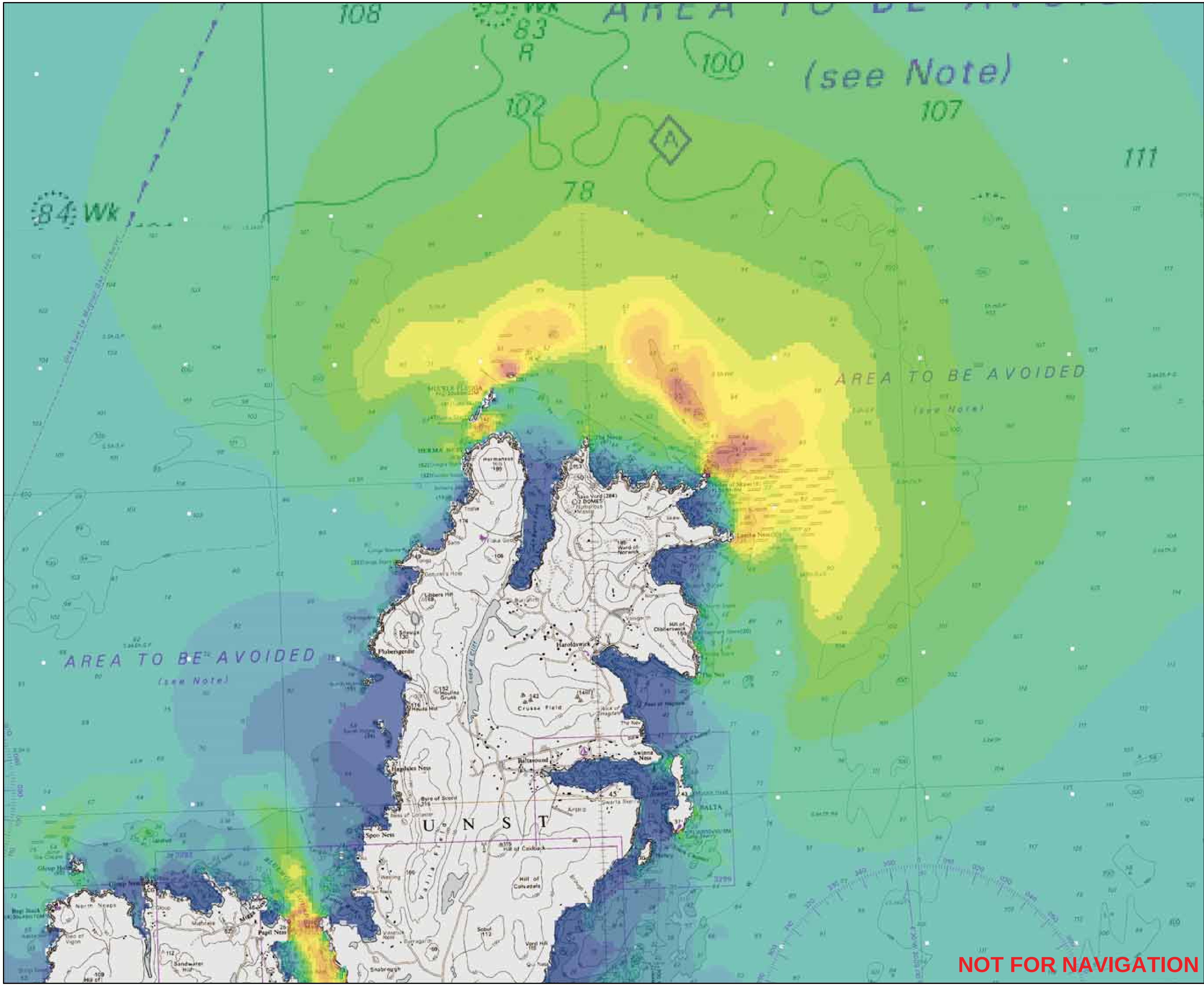

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Maximum Velocity

Area: **North of Unst**

Key

Maximum Velocity (m/s)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8+

Notes:
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Scale:1:100,000

Projection: WGS84 UTM 30N

0 625 1,250 2,500 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_028.mxd		Job code: 805

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Dalry
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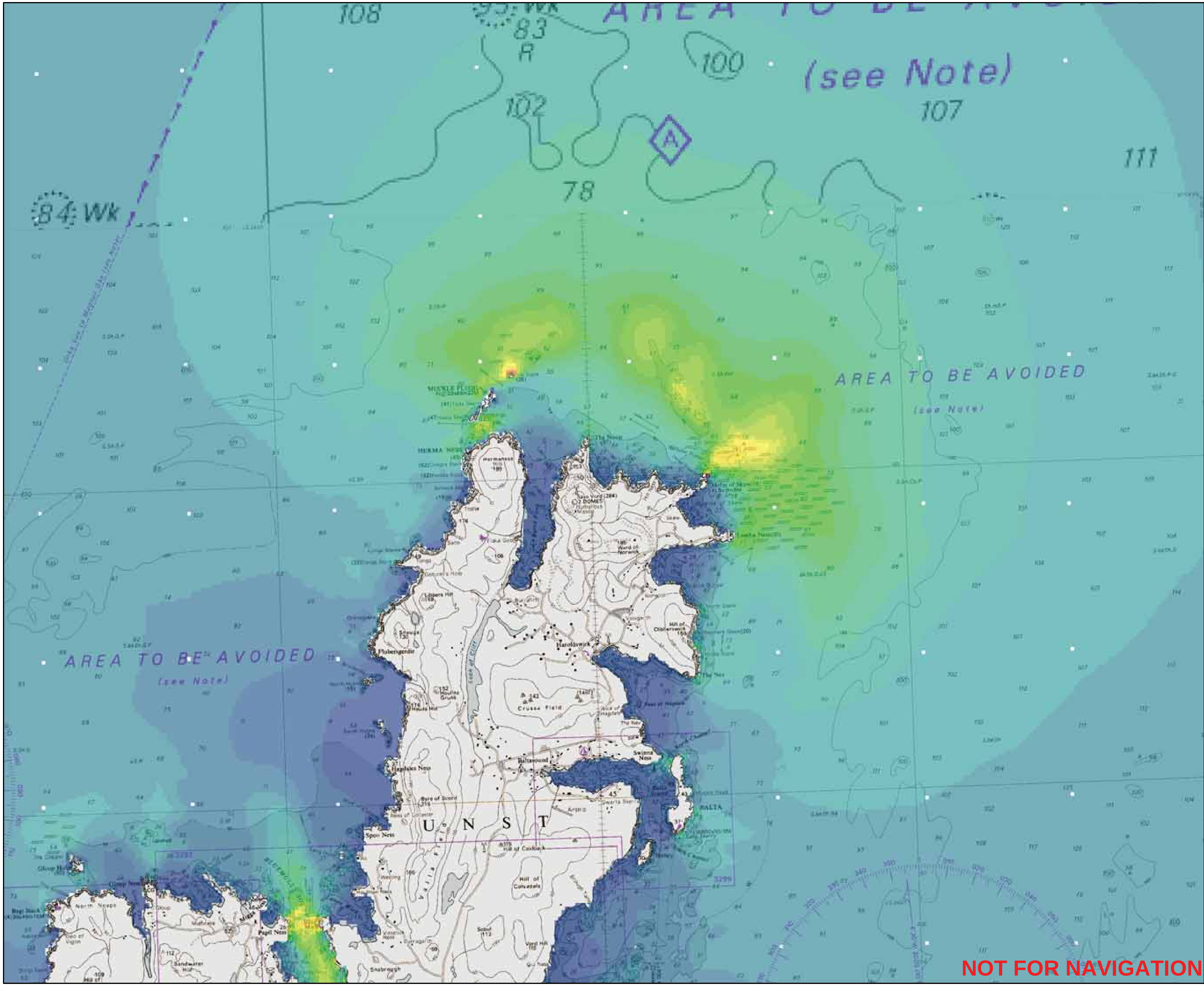

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Root Mean Cubed Velocity

Area: **North of Unst**

Key

Root Mean Cubed Velocity (m/s)

- 0.0 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 0.6
- 0.6 - 0.7
- 0.7 - 0.8
- 0.8 - 0.9
- 0.9 - 1.0
- 1.0 - 1.1
- 1.1 - 1.2
- 1.2 - 1.3
- 1.3 - 1.4
- 1.4 - 1.5
- 1.5 - 1.6
- 1.6 - 1.7
- 1.7 - 1.8
- 1.8 - 1.9
- 1.9 - 2.0
- 2.0 - 2.1
- 2.1 - 2.2
- 2.2 - 2.3
- 2.3+

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Scale:1:100,000

Projection: WGS84 UTM 30N

0 625 1,250 2,500 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_029.mxd		Job code: 805

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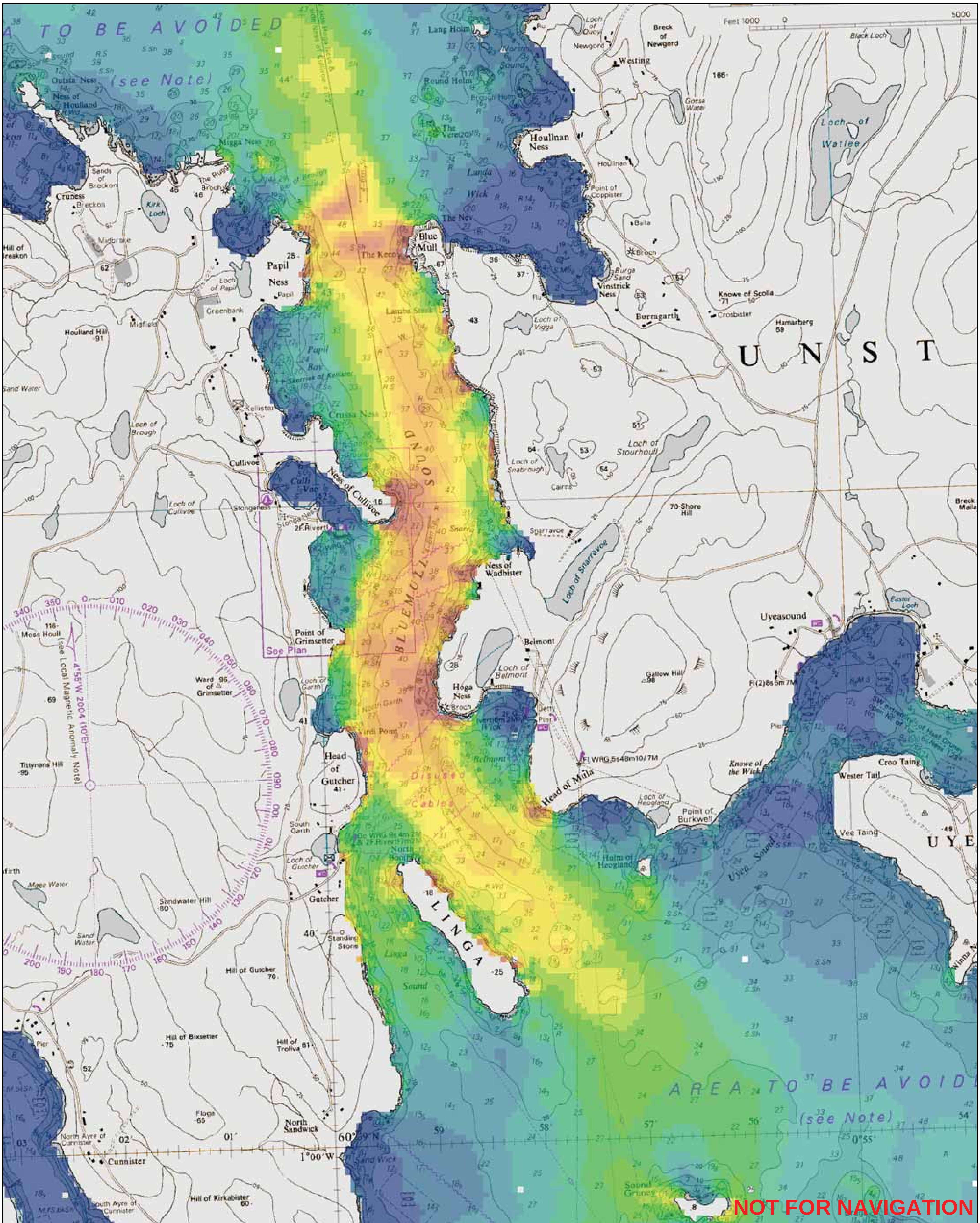

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Maximum Velocity

Area: **Bluemull Sound**

Key

12 nautical mile limit

Maximum velocity (m/s)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8+

Notes:
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Scale: 1:30,000

0 150 300 600 m

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_032.mxd | Job code: 805

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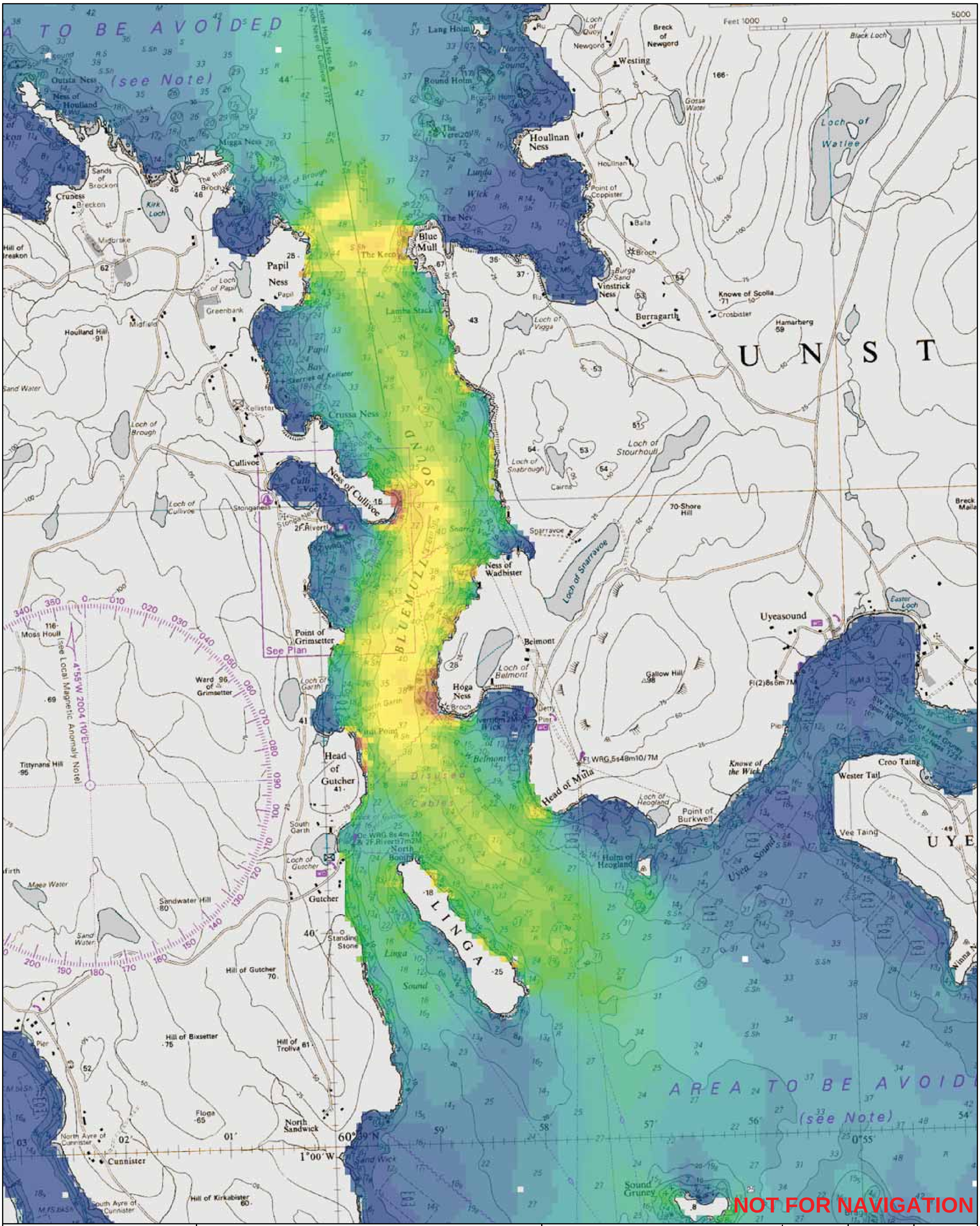

Project	Key	Notes:	Date: 24-01-2011 / Prepared by: RH / Checked by: DH
Shetland Islands Wave and Tidal Resource Assessment	12 nautical mile limit	(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself. (b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.	Drawing No. 805_M_033.mxd / Job code: 805

Root Mean Cubed Velocity (m/s)

0.0 - 0.1	0.7 - 0.8	1.6 - 1.7
0.1 - 0.2	0.8 - 0.9	1.7 - 1.8
0.2 - 0.3	0.9 - 1.0	1.8 - 1.9
0.3 - 0.4	1.0 - 1.1	1.9 - 2.0
0.4 - 0.5	1.1 - 1.2	2.0 - 2.1
0.5 - 0.6	1.2 - 1.3	2.1 - 2.2
0.6 - 0.7	1.3 - 1.4	2.2 - 2.3
	1.4 - 1.5	2.3+
	1.5 - 1.6	

Title
Root Mean Cubed Velocity

Area: **Bluemull Sound**

Scale: 1:30,000

0 150 300 600 m

Projection: WGS84 UTM 30N

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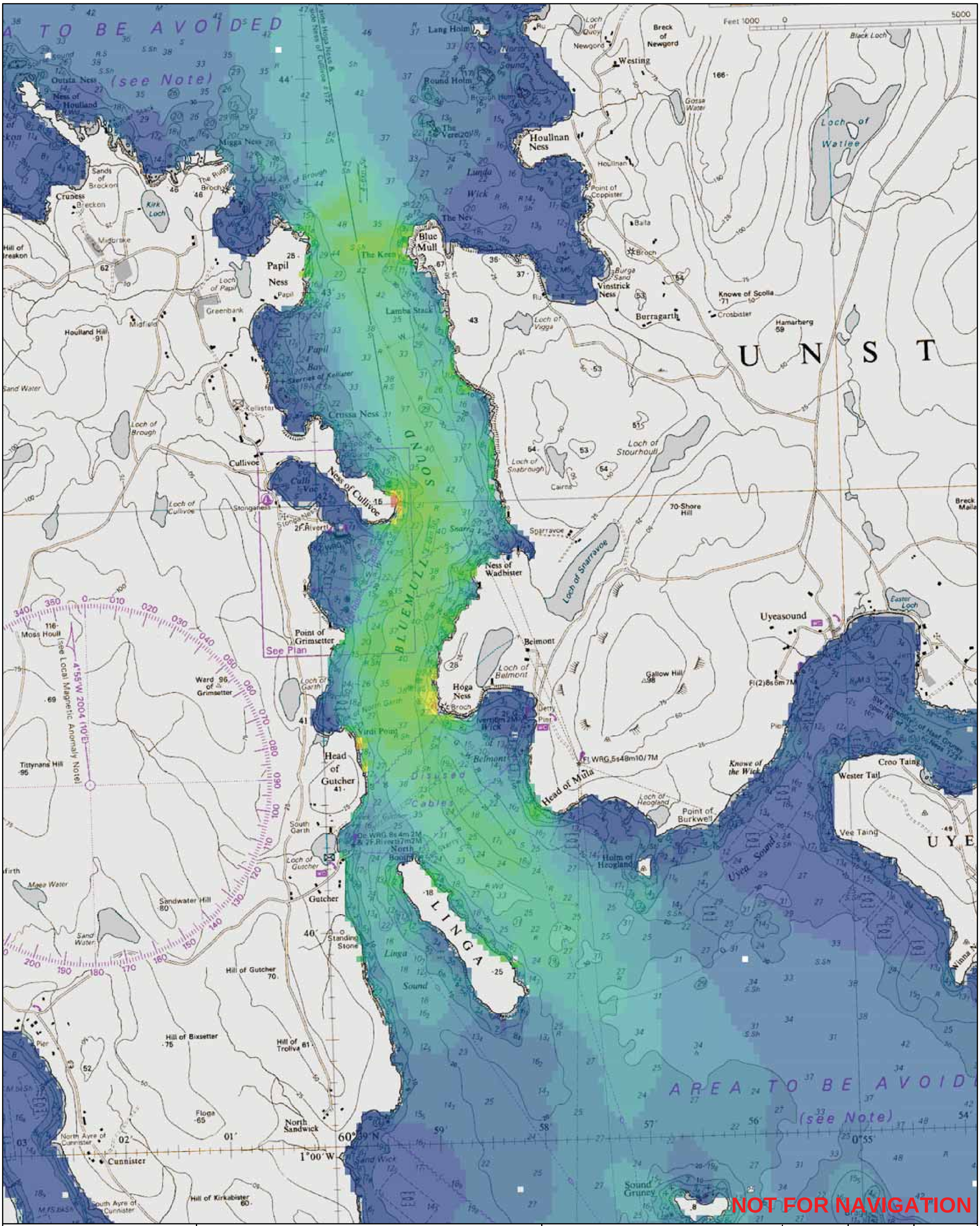

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Average Power Density

Area: **Bluemull Sound**

Key

12 nautical mile limit

Average Power Density (kW/m2)

- 0.0 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 0.6
- 0.6 - 0.7
- 0.7 - 0.8
- 0.8 - 0.9
- 0.9 - 1.0
- 1.0 - 1.1
- 1.1 - 1.2
- 1.2 - 1.3
- 1.3 - 1.4
- 1.4 - 1.5
- 1.5 - 1.6
- 1.6 - 1.7
- 1.7 - 1.8
- 1.8 - 1.9
- 1.9 +

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Scale: 1:30,000

0 150 300 600 m

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_034.mxd

Job code: 805

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Forrest Estate
Dalry
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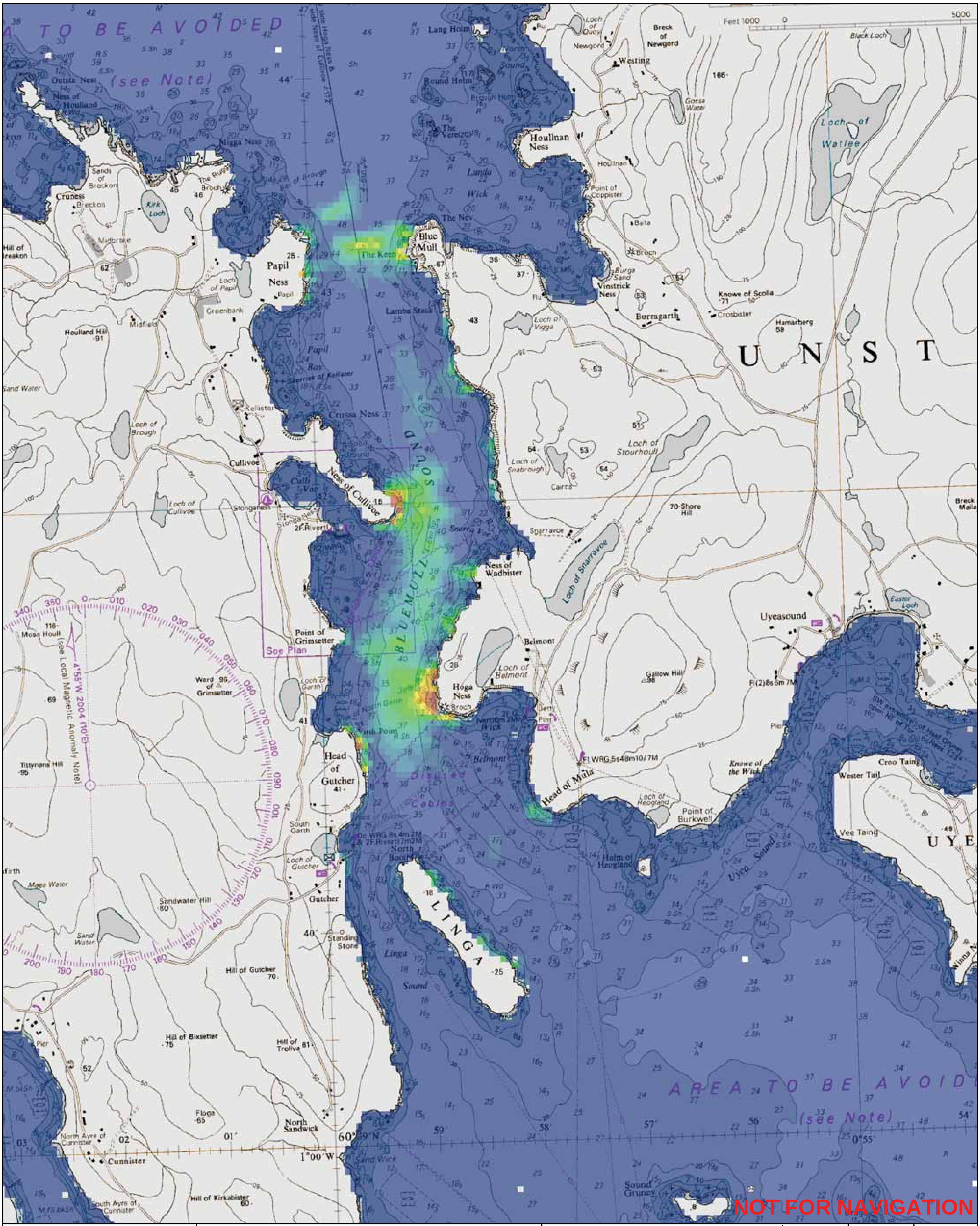

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
% Exceedance of 2m/s (~4 knots)

Area: **Bluemull Sound**

Key

12 nautical mile limit

% exceedance of 2m/s

0.0 - 2.5	22.5 - 25.0
2.5 - 5.0	25.0 - 27.5
5.0 - 7.5	27.5 - 30.0
7.5 - 10.0	30.0 - 32.5
10.0 - 12.5	32.5 - 35.0
12.5 - 15.0	35.0 - 37.5
15.0 - 17.5	37.5 - 40.0
17.5 - 20.0	40.0 - 42.5
20.0 - 22.5	42.5 - 45.0
	45.0 - 47.5
	47.5 - 50

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Scale: 1:30,000

0 150 300 600 m

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_035.mxd

Job code: 805

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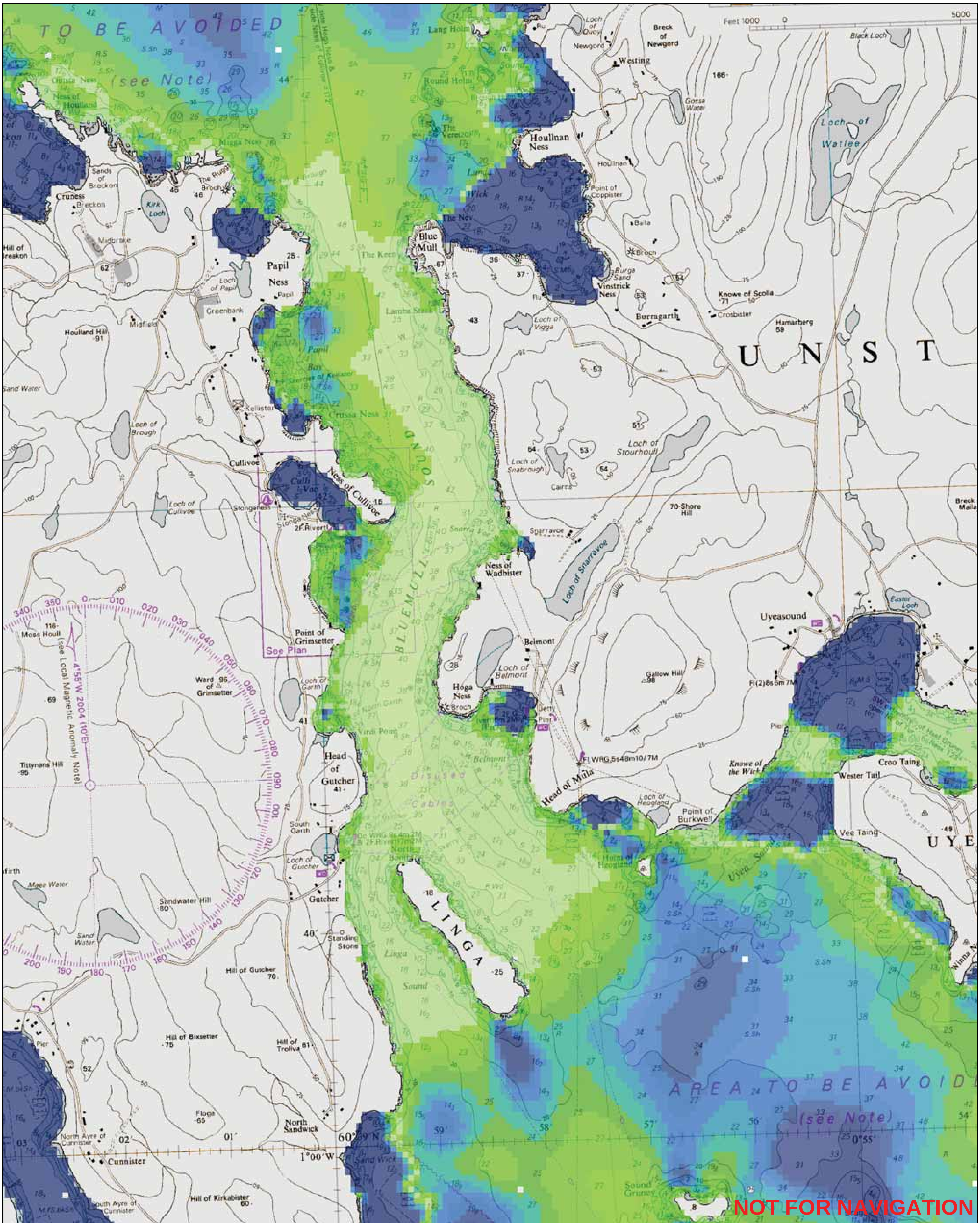

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Flow Type Linear to Circular

Area: **Bluemull Sound**

Key

12 nautical mile limit

Circular ^ | | | | | | | v Linear

Linear ^ | | | | | | | v Circular

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Scale: 1:30,000

0 150 300 600 m

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_036.mxd

Job code: 805

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Dalry
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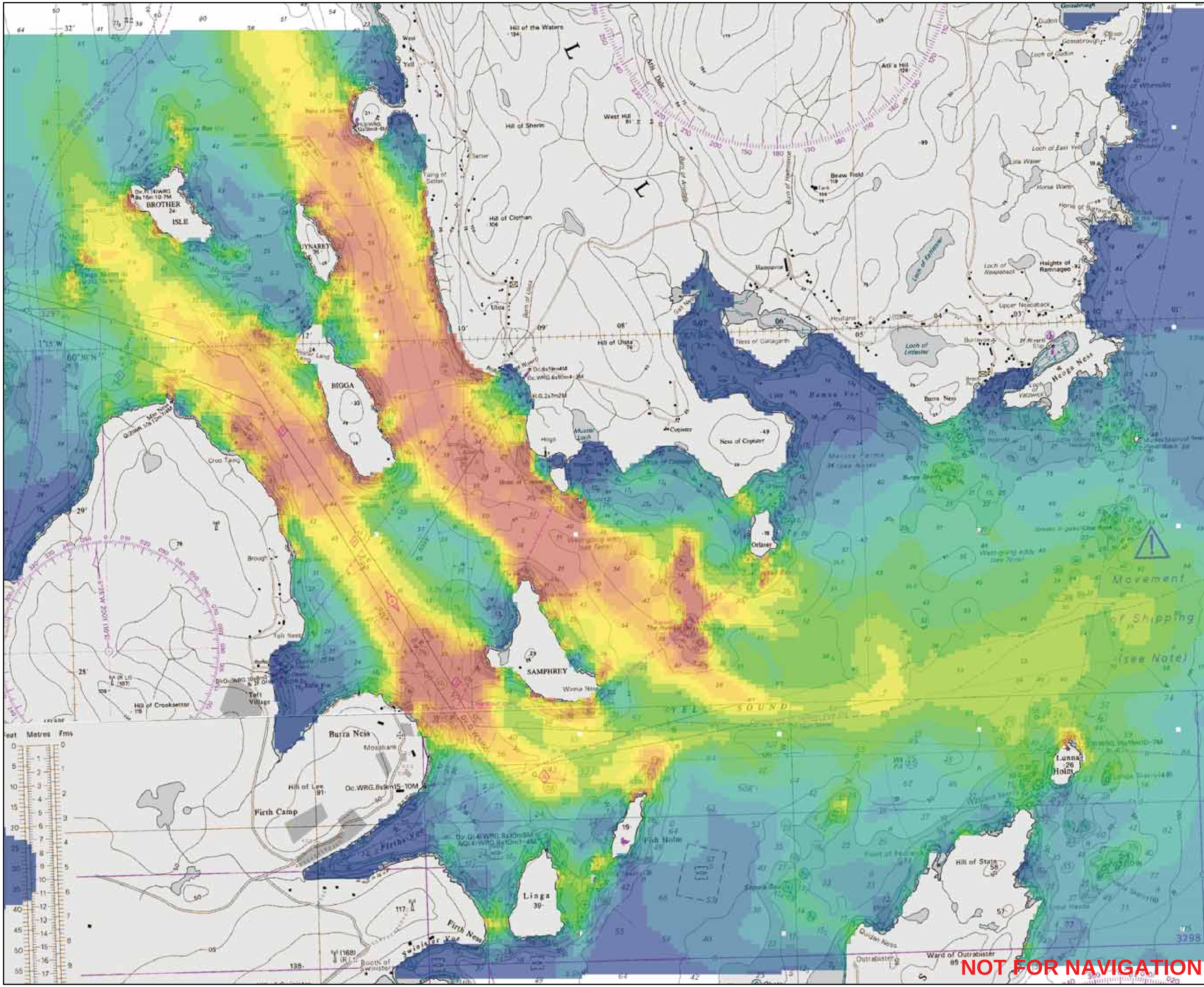
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Maximum Velocity

Area: **Yell Sound**

Key

Maximum Velocity (m/s)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8+

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Scale:1:40,000

Projection: WGS84 UTM 30N

0 250 500 1,000 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_037.mxd		Job code: 805

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Dalry
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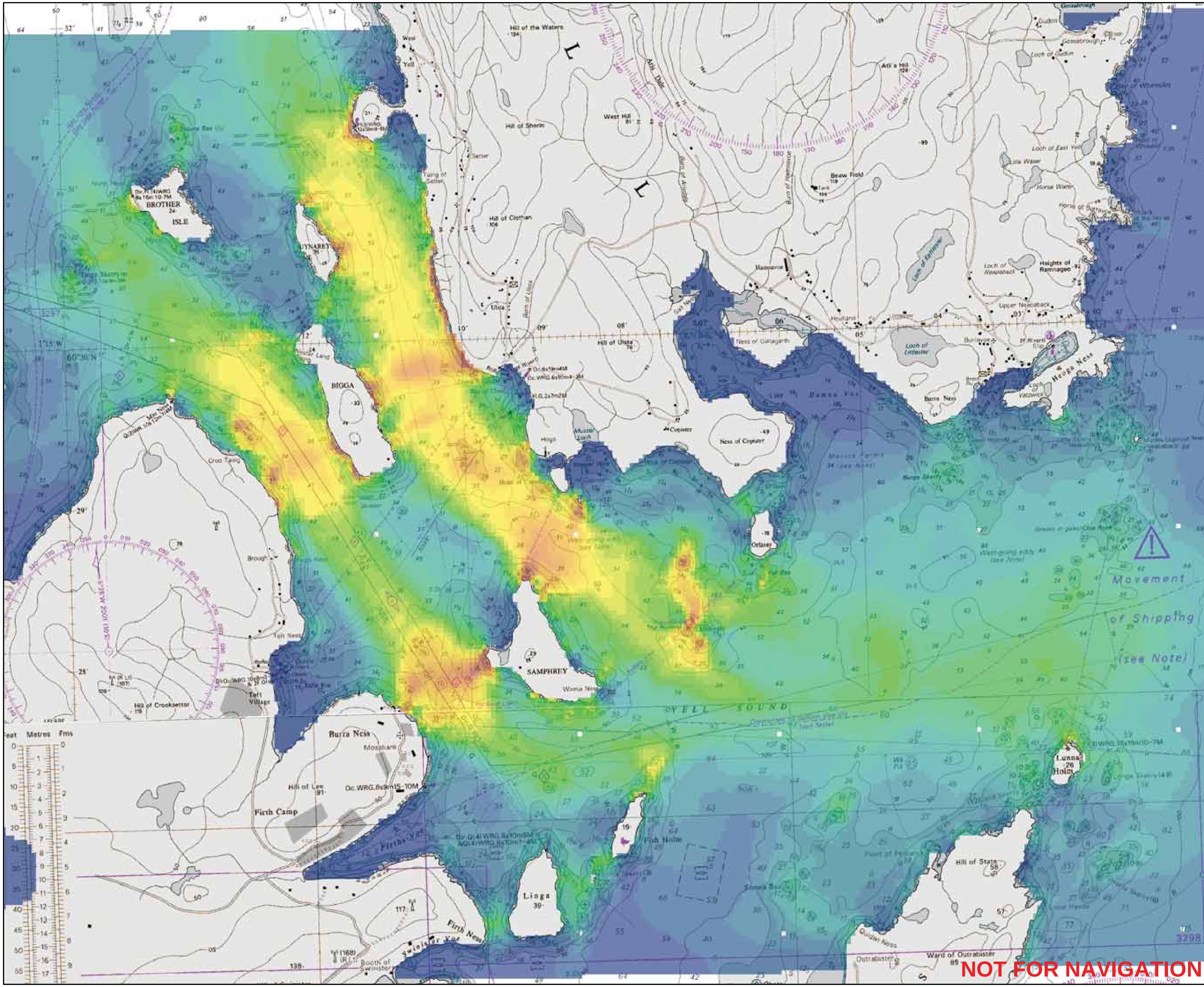

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Root Mean Cubed Velocity

Area: **Yell Sound**

Key

Root Mean Cubed Velocity (m/s)

- 0.0 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 0.6
- 0.6 - 0.7
- 0.7 - 0.8
- 0.8 - 0.9
- 0.9 - 1.0
- 1.0 - 1.1
- 1.1 - 1.2
- 1.2 - 1.3
- 1.3 - 1.4
- 1.4 - 1.5
- 1.5 - 1.6
- 1.6 - 1.7
- 1.7 - 1.8
- 1.8 - 1.9
- 1.9 - 2.0
- 2.0 - 2.1
- 2.1 - 2.2
- 2.2 - 2.3
- 2.3+

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Scale:1:40,000

Projection: WGS84 UTM 30N

0 250 500 1,000 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_038.mxd		Job code: 805

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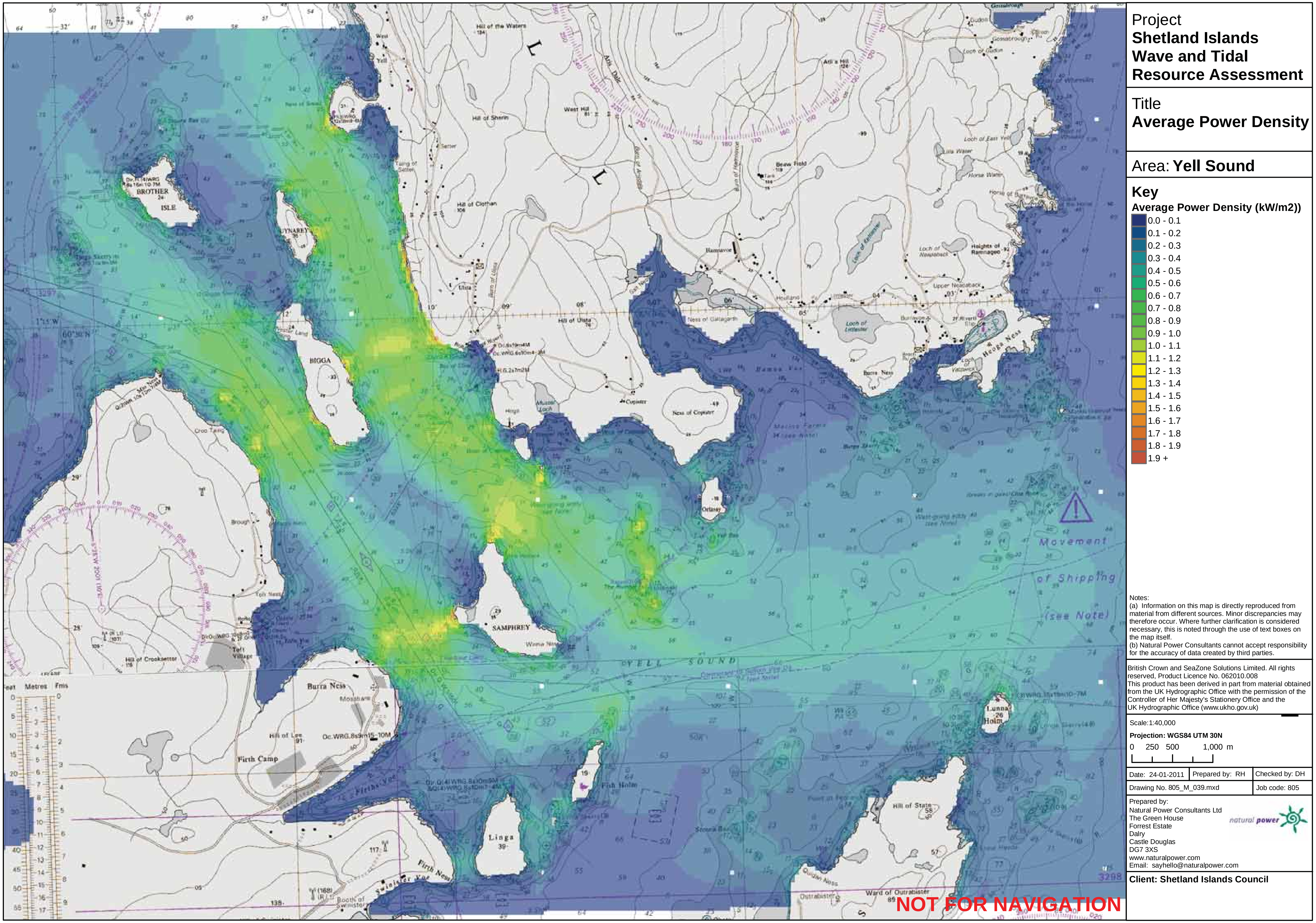
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment
Title
Average Power Density
Area: Yell Sound
Key
Average Power Density (kW/m2))
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
1.0 - 1.1
1.1 - 1.2
1.2 - 1.3
1.3 - 1.4
1.4 - 1.5
1.5 - 1.6
1.6 - 1.7
1.7 - 1.8
1.8 - 1.9
1.9 +
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Scale:1:40,000
Projection: WGS84 UTM 30N
0 250 500 1,000 m
Date: 24-01-2011
Prepared by: RH
Checked by: DH
Drawing No. 805_M_039.mxd
Job code: 805
Prepared by:
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Forrest Estate
Dalry
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DG7 3XS
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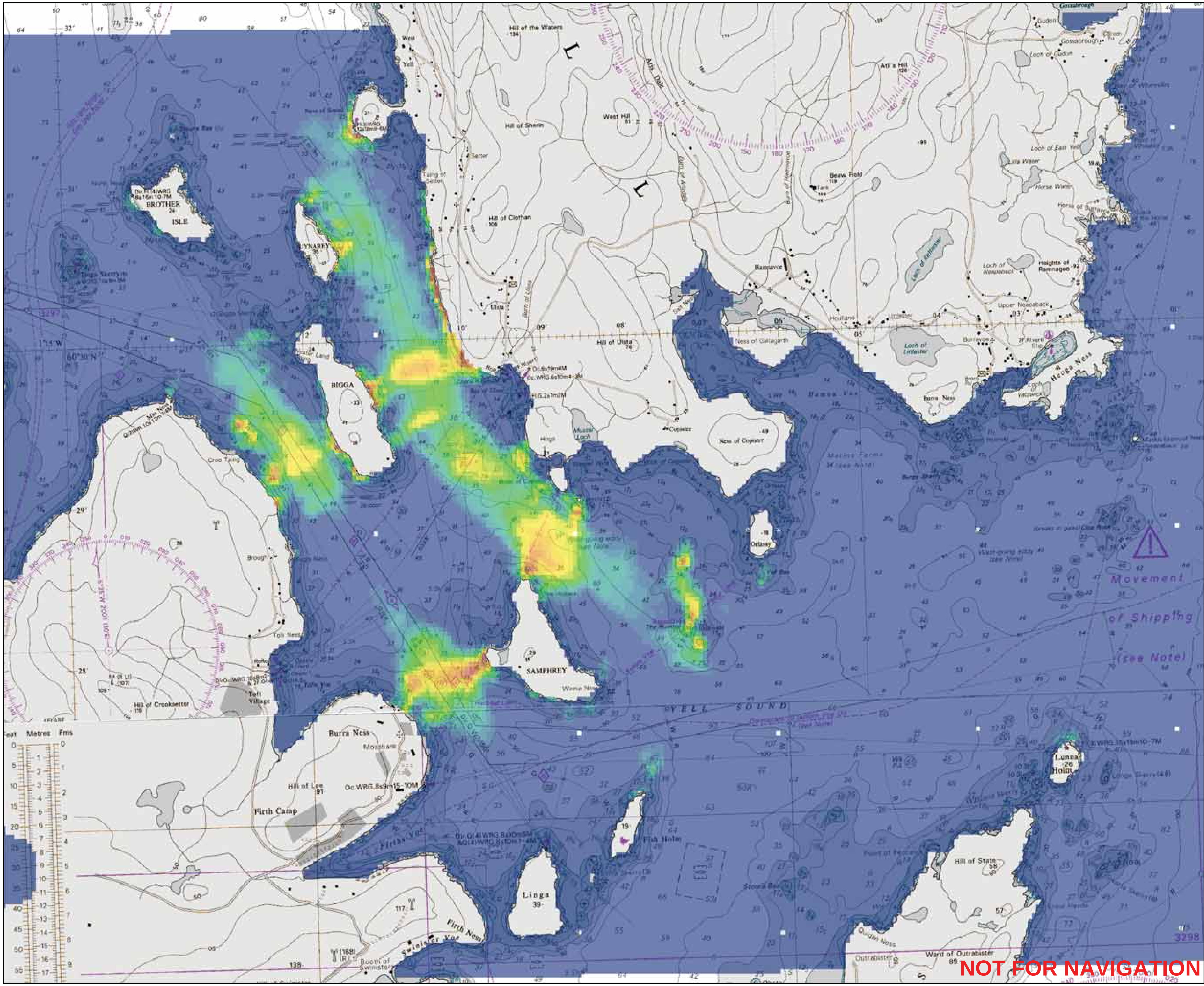
Email: sayhello@naturalpower.com
Client: Shetland Islands Council
NOT FOR NAVIGATION
YELL SOUND
BIGGA
SAMPHREY
BROTHER ISLE
Hill of Sherin
Hill of Ulsta
Burra Ness
Firth Camp
Hill of Lee
Lunna Holm
Linga
Orfasay
Movement of Shipping (see Note)



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
% Exceedance of 2m/s (4 knots)

Area: **Yell Sound**

Key

% exceedance of 4 knots

- 0.0 - 2.5
- 2.5 - 5.0
- 5.0 - 7.5
- 7.5 - 10.0
- 10.0 - 12.5
- 12.5 - 15.0
- 15.0 - 17.5
- 17.5 - 20.0
- 20.0 - 22.5
- 22.5 - 25.0
- 25.0 - 27.5
- 27.5 - 30.0
- 30.0 - 32.5
- 32.5 - 35.0
- 35.0 - 37.5
- 37.5 - 40.0
- 40.0 - 42.5
- 42.5 - 45.0
- 45.0 - 47.5
- 47.5 - 50

Notes:
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Scale:1:40,000

Projection: WGS84 UTM 30N

0 250 500 1,000 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_040.mxd		Job code: 805

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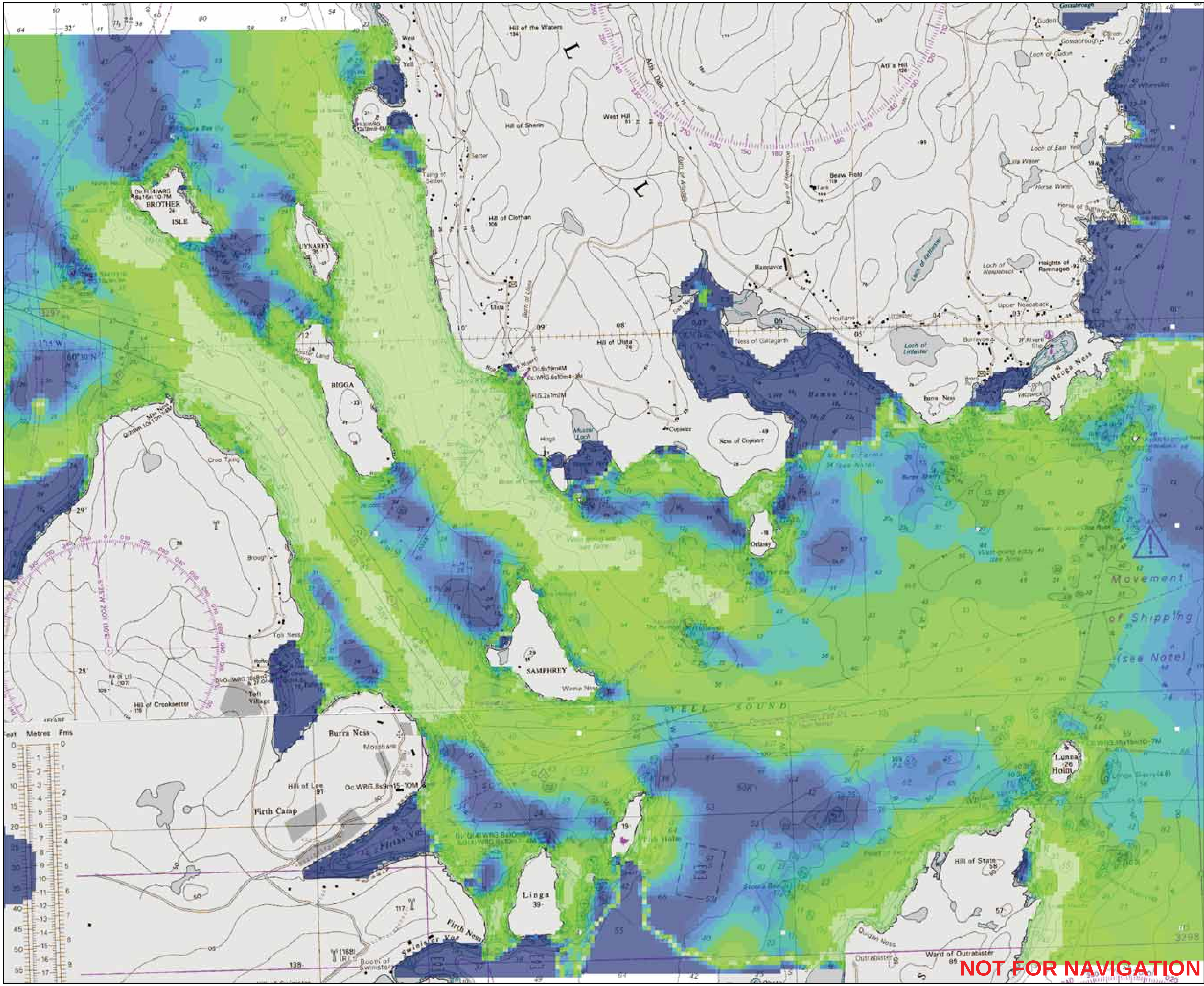
natural power

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Flow Type Circular <-> Linear

Area: **Yell Sound**

Key

Flow Type

Circular
^
|
v
Linear
Linear
^
|
v
Circular

Notes:
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Scale:1:40,000

Projection: WGS84 UTM 30N

0 250 500 1,000 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_041.mxd		Job code: 805

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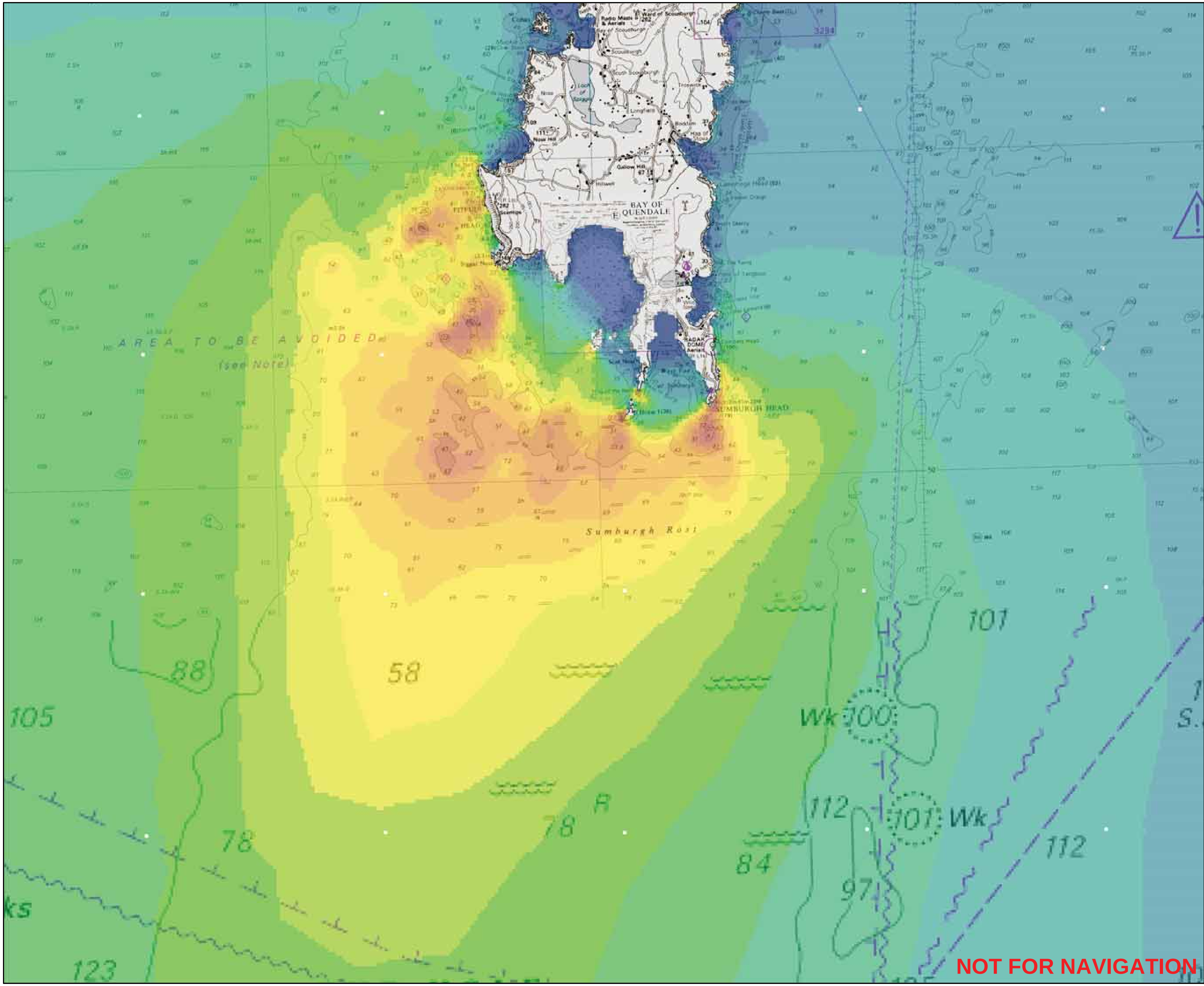
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Maximum Velocity

Area: **Sumburgh Head**

Key

Maximum Velocity (m/s)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8+

Notes:
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Scale:1:100,000

Projection: WGS84 UTM 30N

0 625 1,250 2,500 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_042.mxd		Job code: 805

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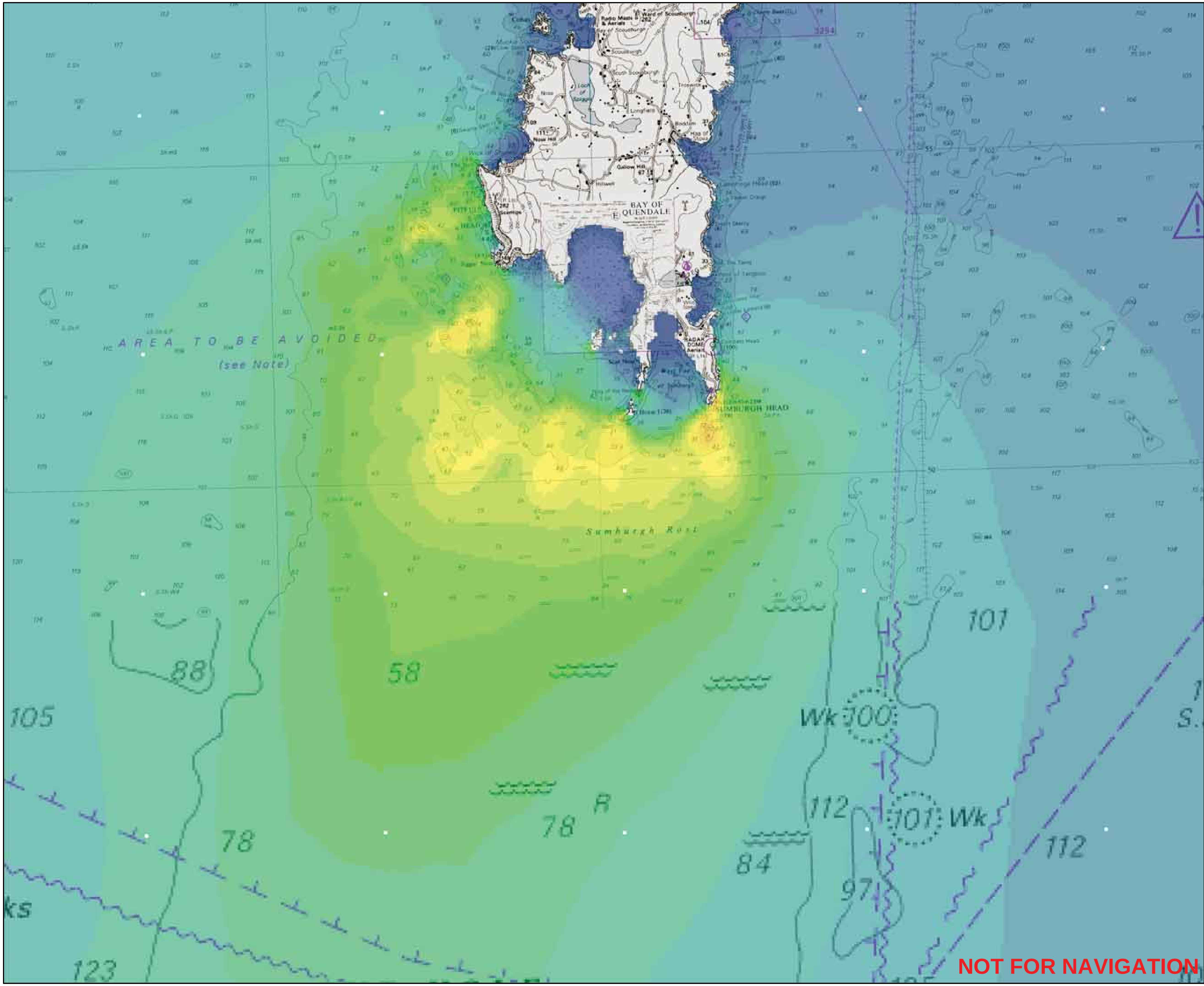

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Root Mean Cubed Velocity

Area:**Sumburgh Head**

Key

Root Mean Cubed Velocity (m/s)

0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
1.0 - 1.1
1.1 - 1.2
1.2 - 1.3
1.3 - 1.4
1.4 - 1.5
1.5 - 1.6
1.6 - 1.7
1.7 - 1.8
1.8 - 1.9
1.9 - 2.0
2.0 - 2.1
2.1 - 2.2
2.2 - 2.3
2.3+

Notes:
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Scale:1:100,000

Projection: WGS84 UTM 30N

0 625 1,250 2,500 m

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_043.mxd		Job code: 805

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Client: Shetland Islands Council

7.2. Point Extracts

Extracts of the modelled time series have been extracted for a variety of locations. This data is presented here as tidal rose plots.

7.2.1. North Unst tidal extracts

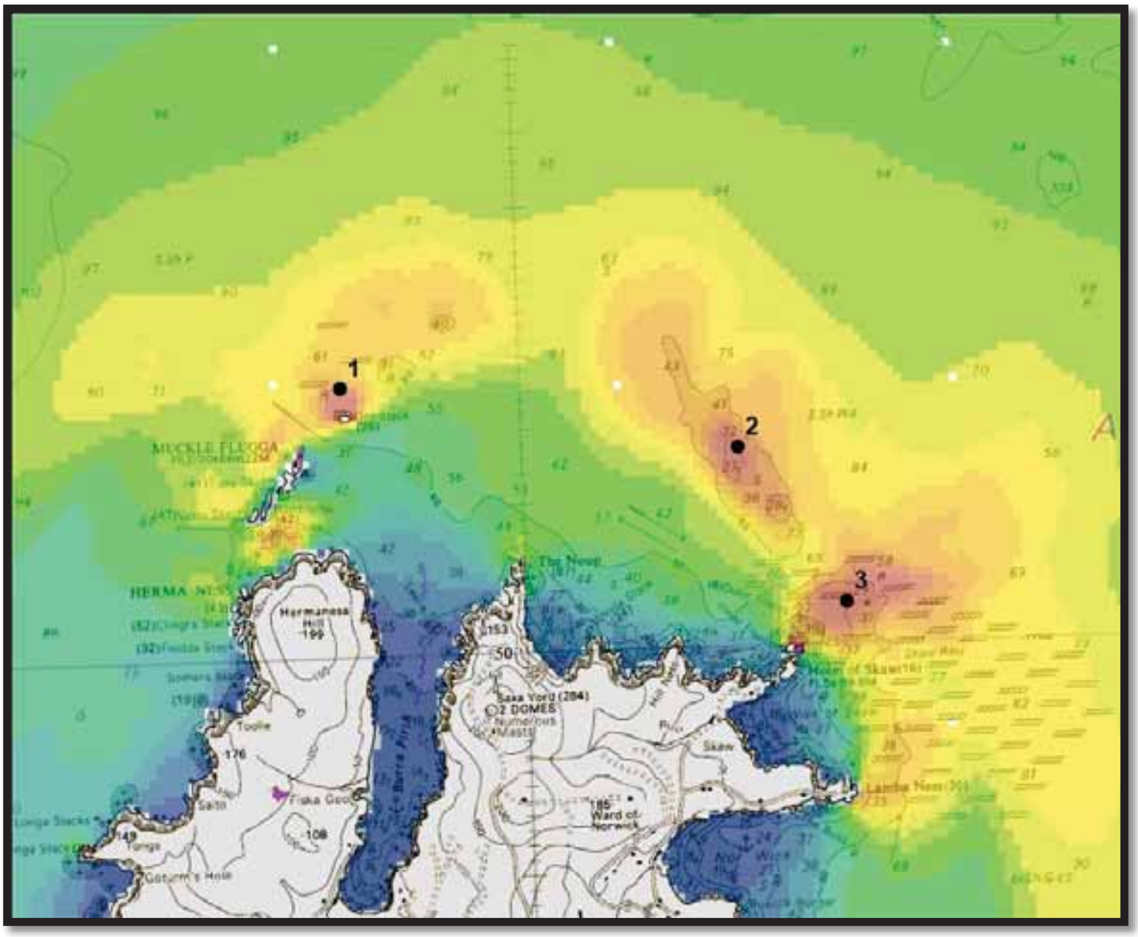


Figure 29: Overview map of extract locations for North Unst

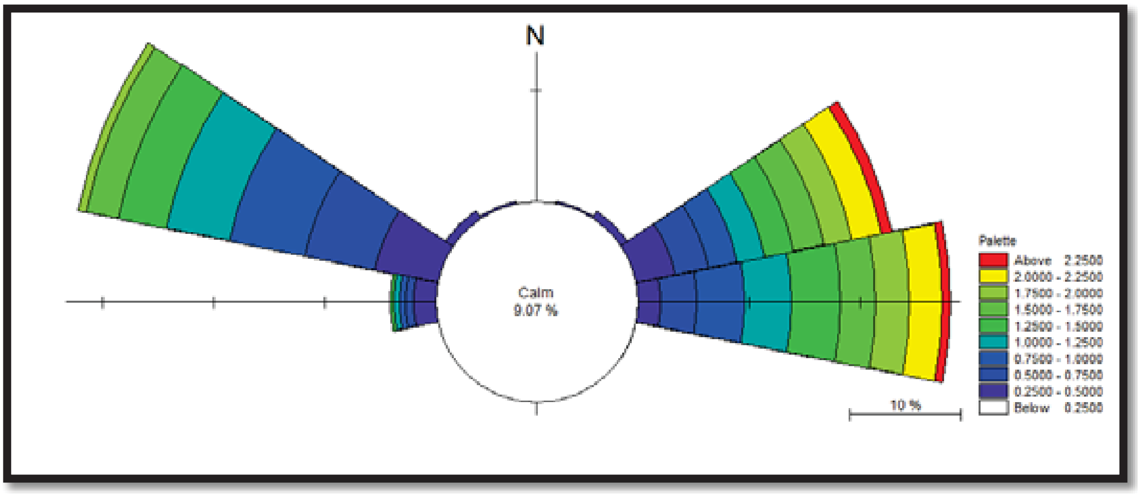


Figure 30: Tidal extract location 1

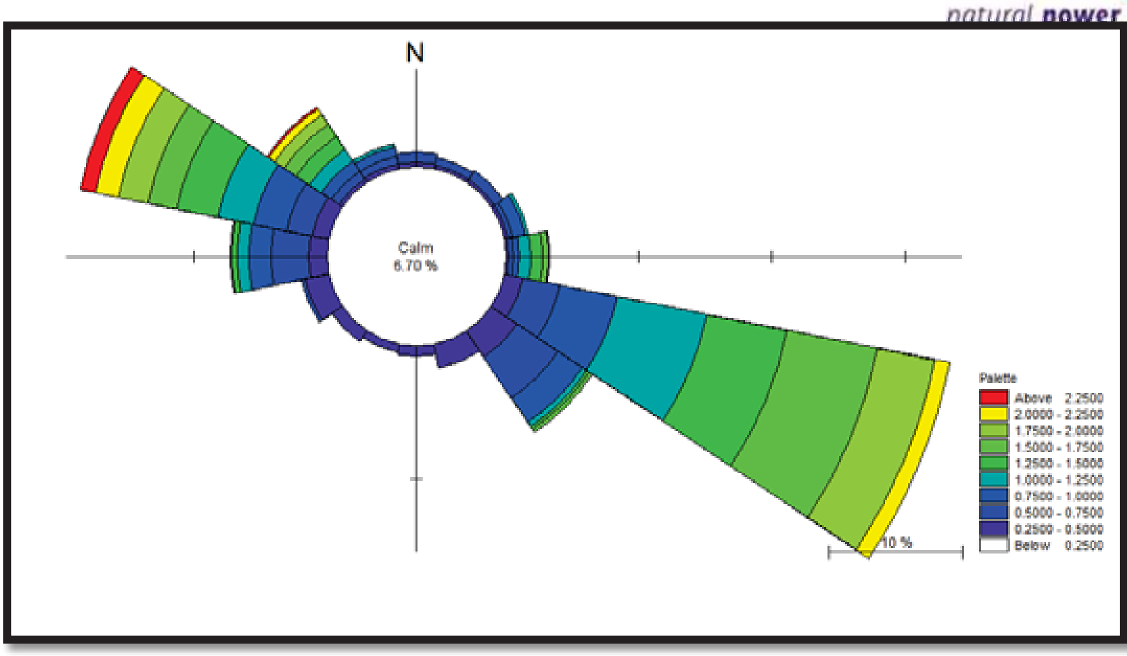


Figure 31: Tidal extract location 2

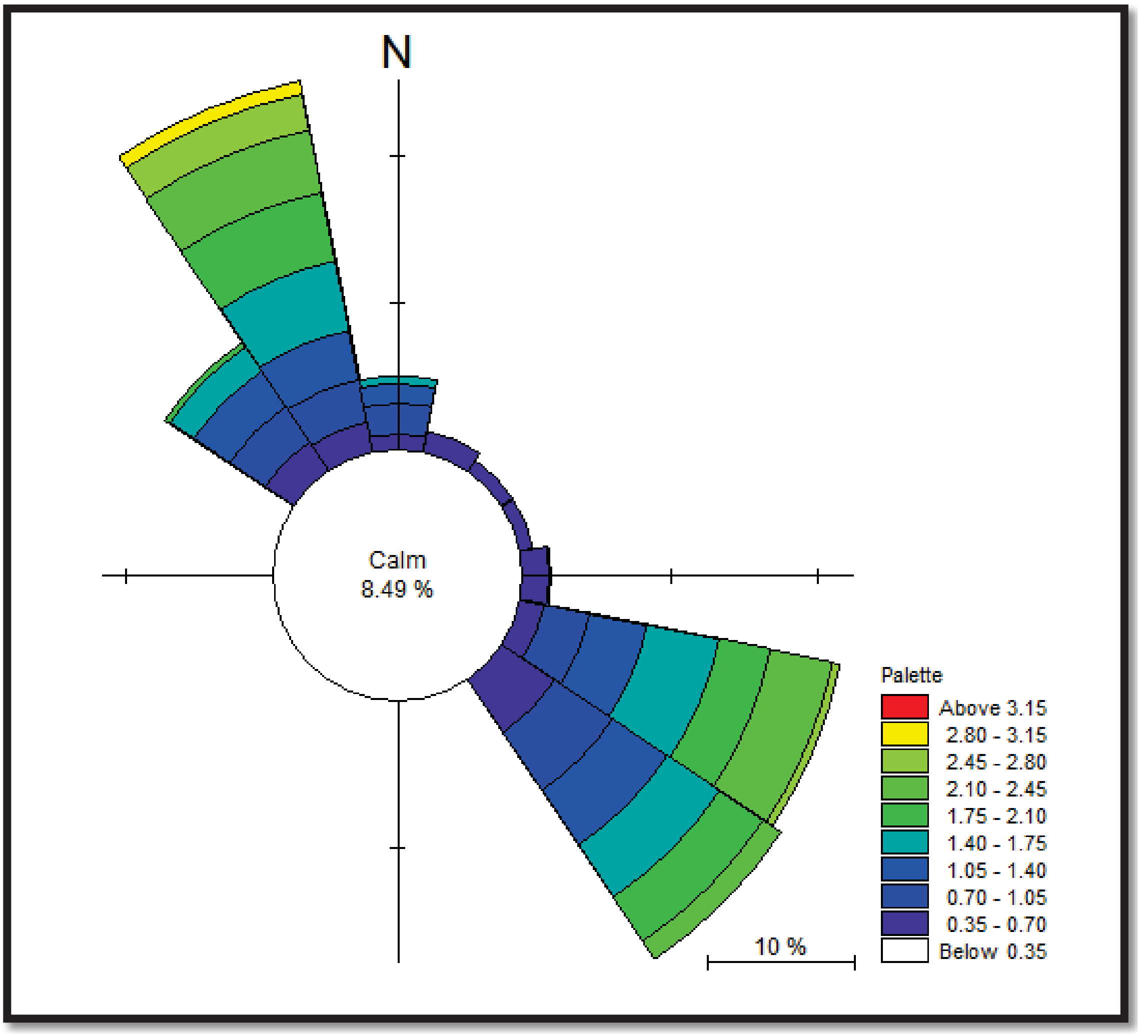


Figure 32: Tidal extract location 3

7.2.2. Bluemull Sound tidal extracts

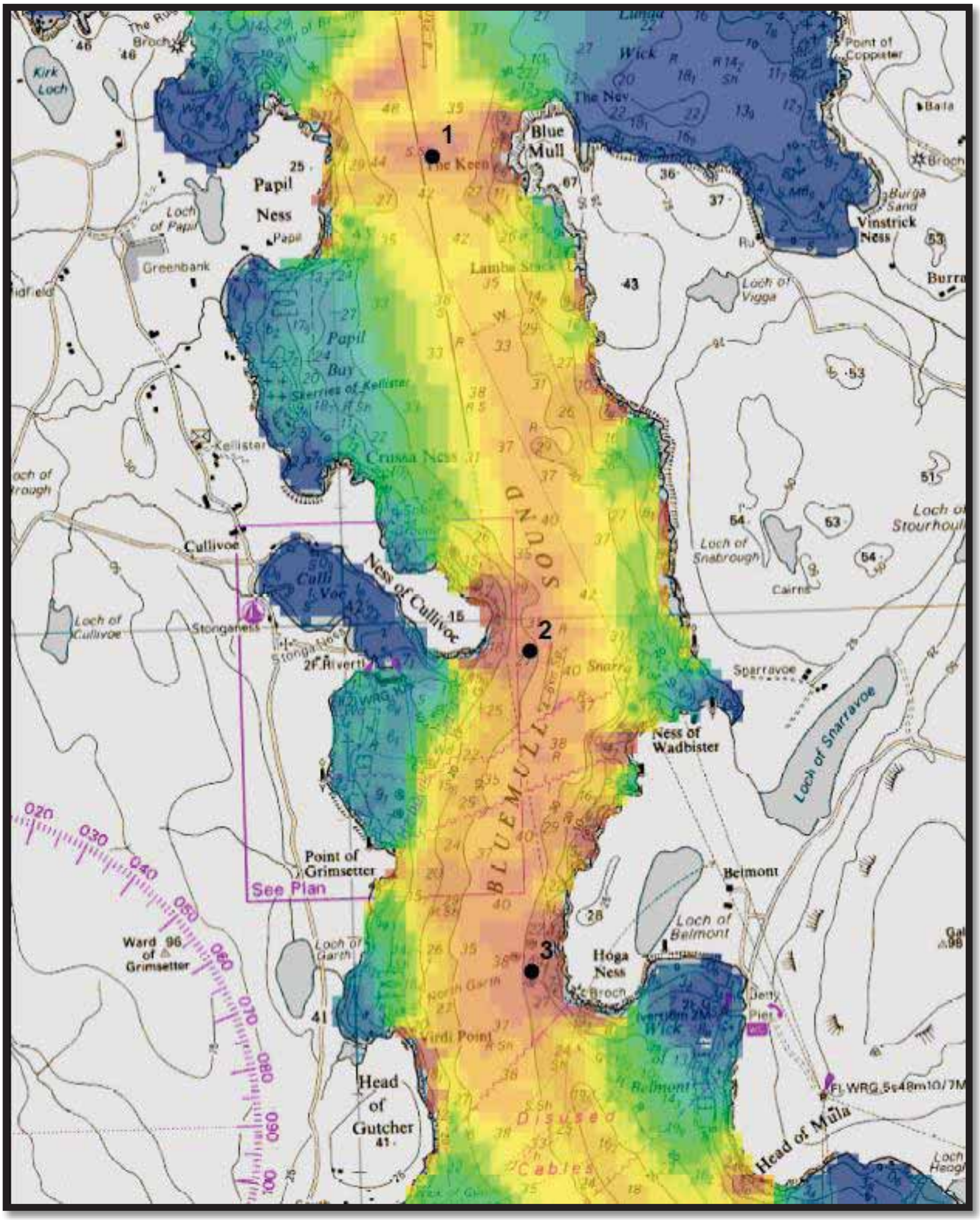


Figure 33: Overview of extract locations for Bluemull Sound

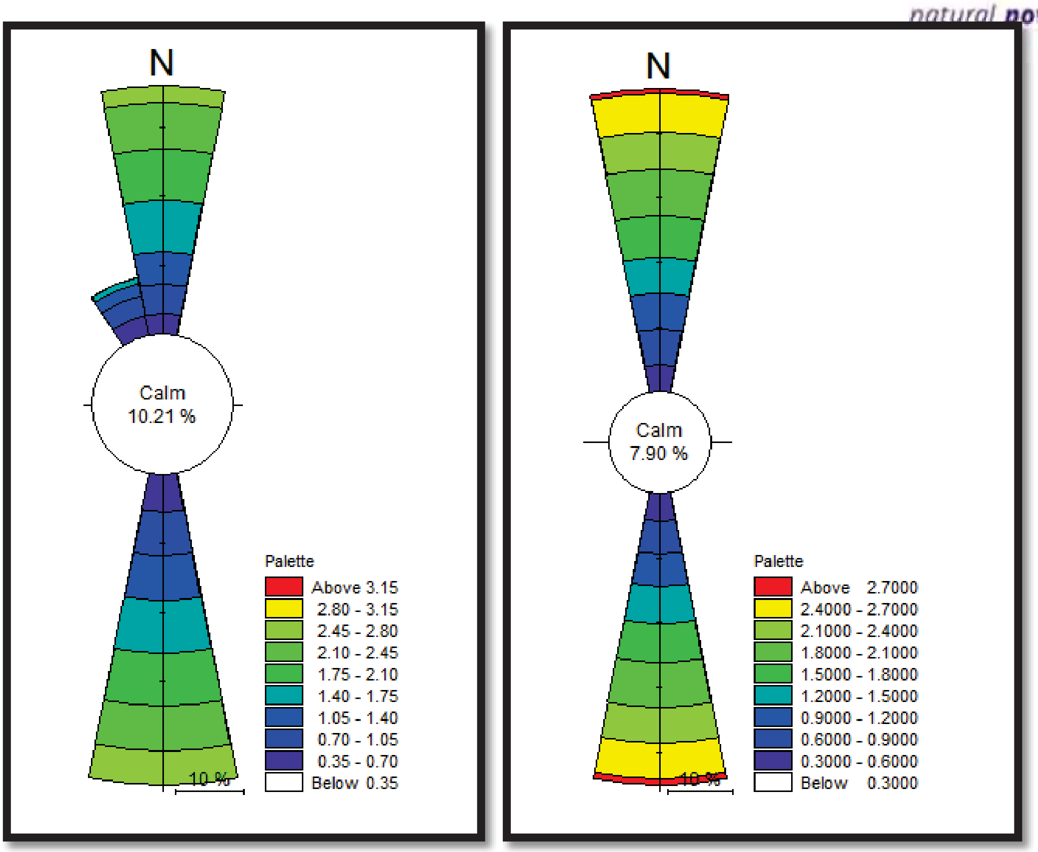


Figure 34: Tidal extract data at Bluemull for locations 1 and 3

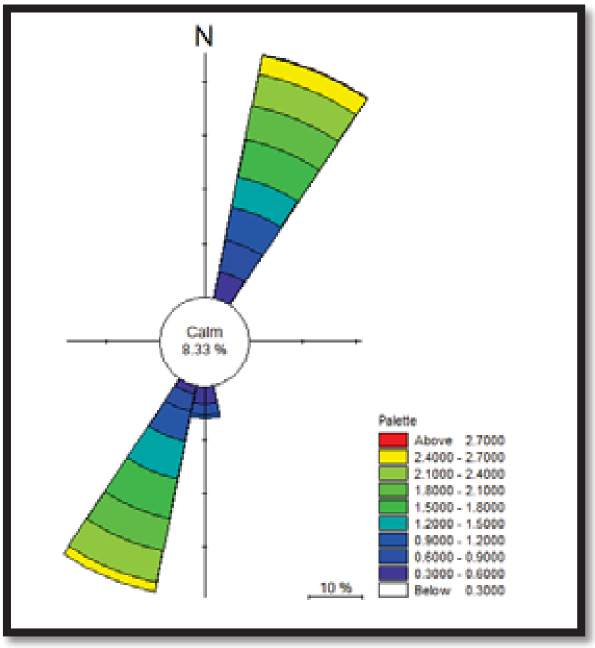


Figure 35: Tidal extract data for location 2

7.2.3. Yell Sound tidal extracts

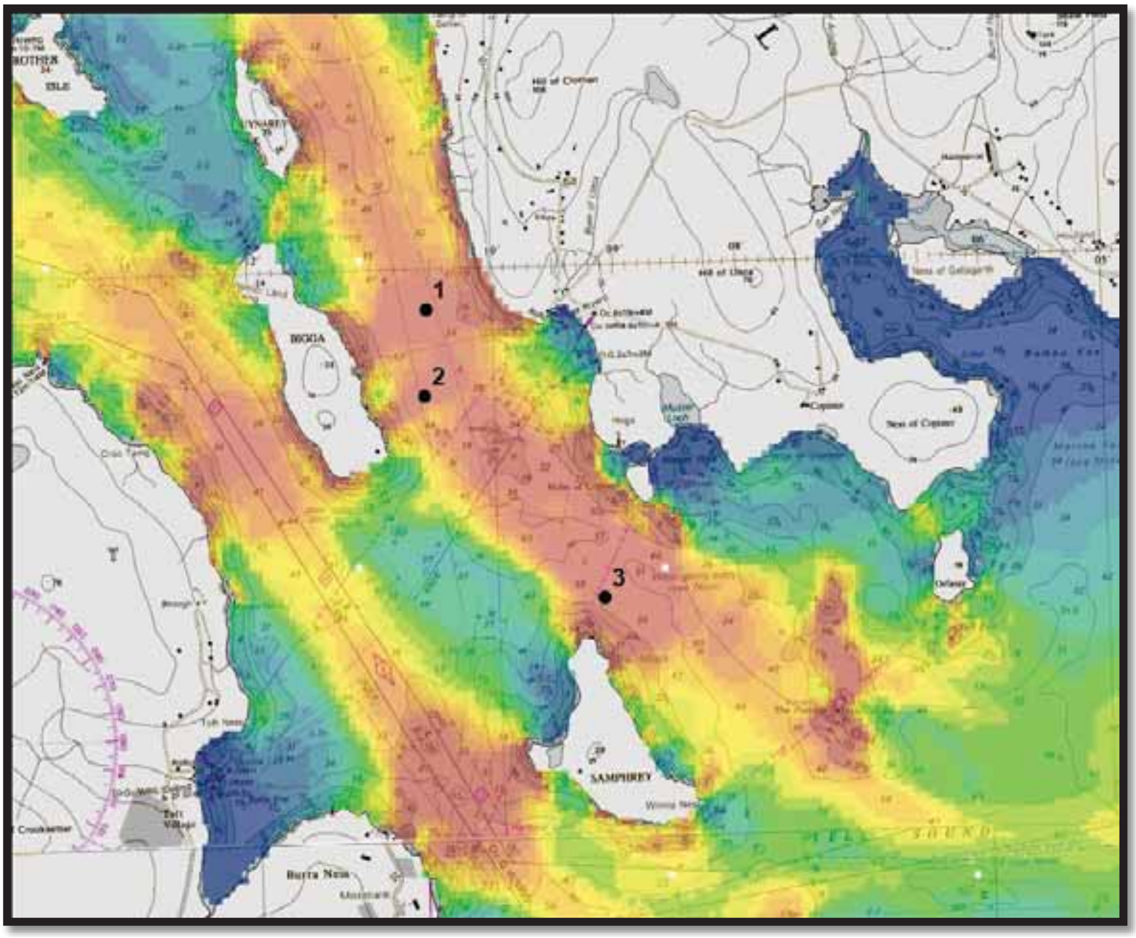


Figure 36: Overview map of tidal extraction locations for Yell Sound

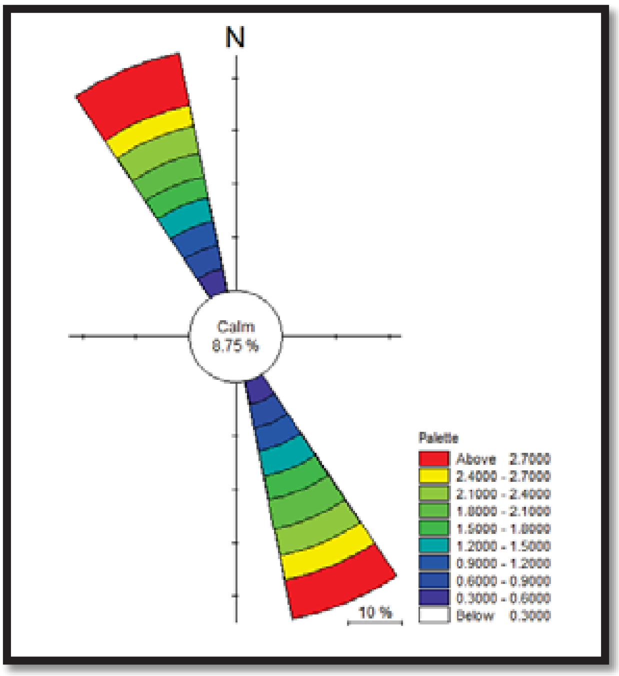


Figure 37: Tidal rose for extract location 1

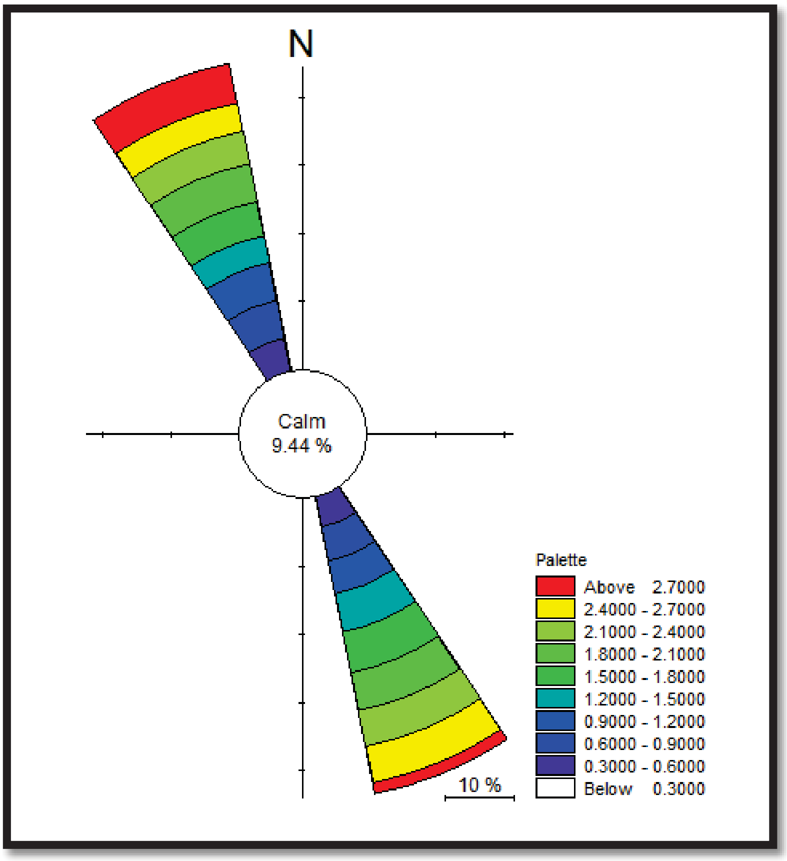


Figure 38: Tidal rose for extract location 2

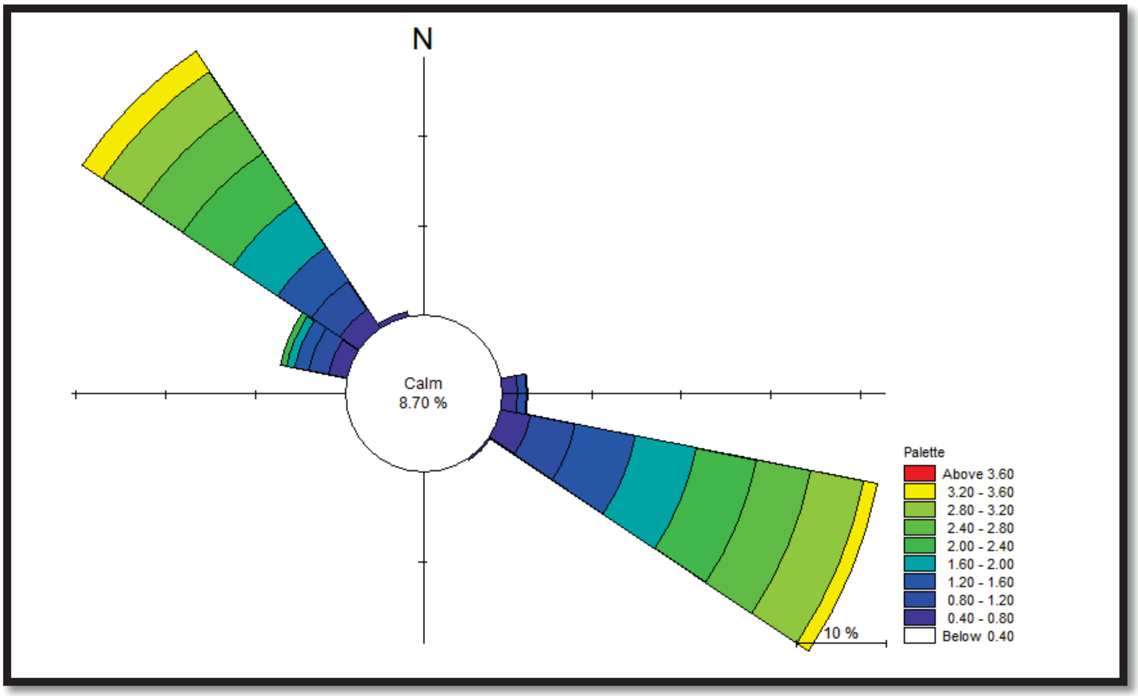


Figure 39: Tidal rose for extract location 3

7.2.4. Sumburgh Head tidal extracts

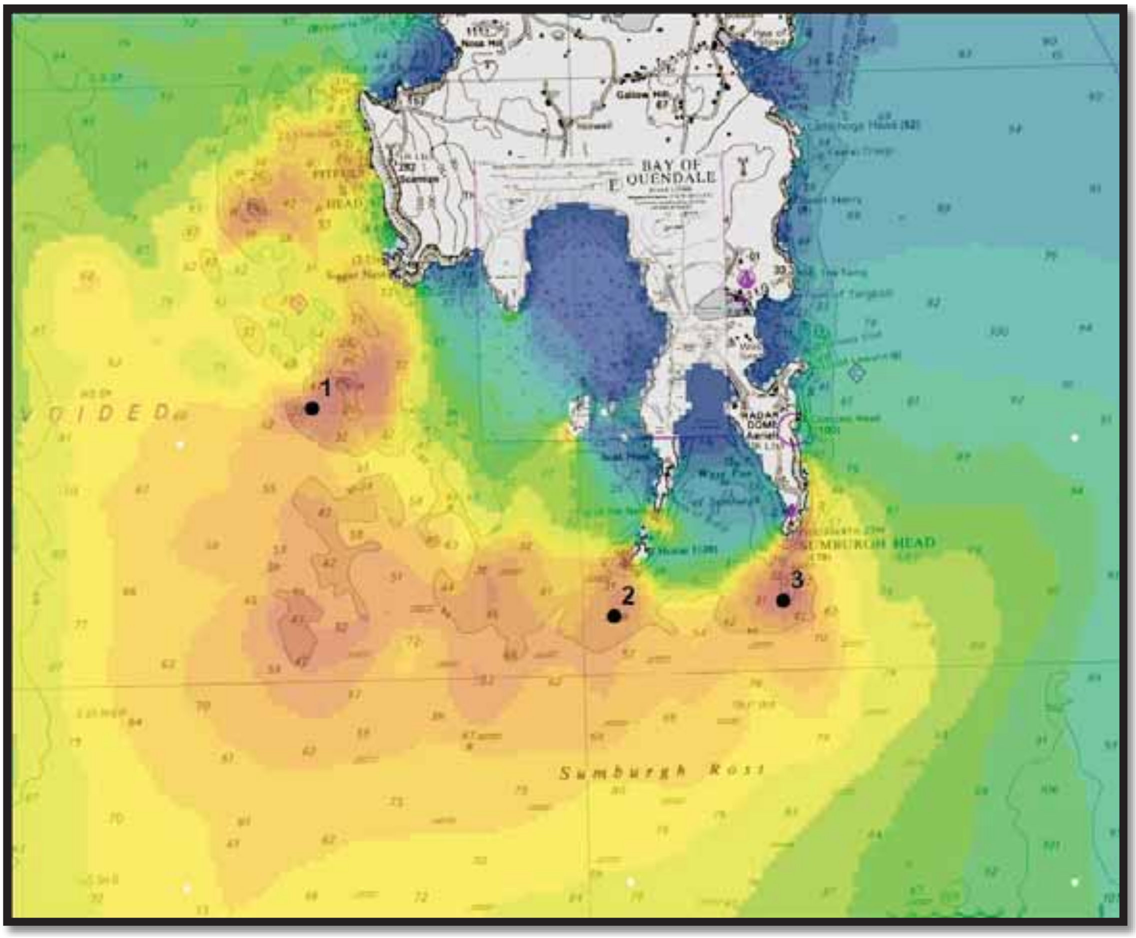


Figure 40: Overview map for tidal extraction locations at Sumburgh Head

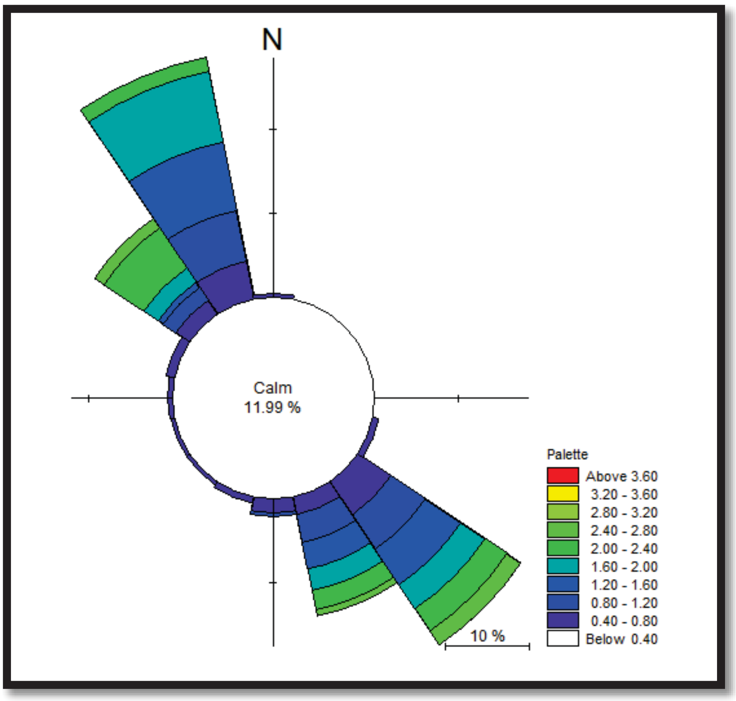


Figure 41: Tidal rose for extract location 1

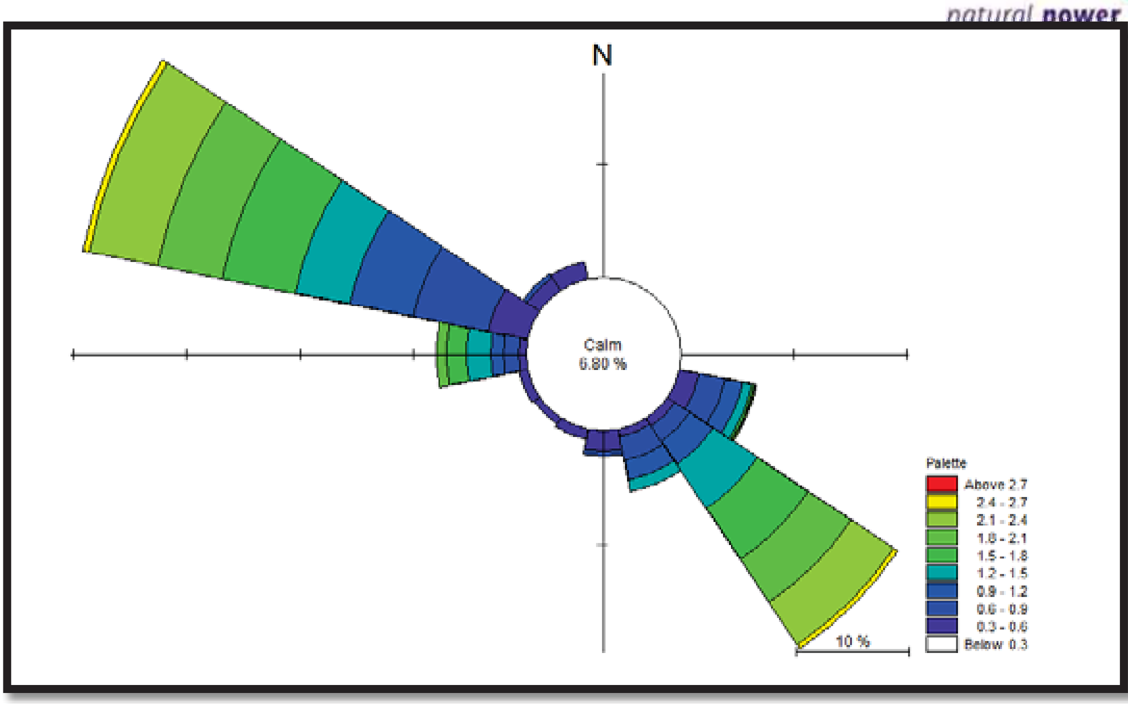


Figure 42: Tidal rose for extract location 2

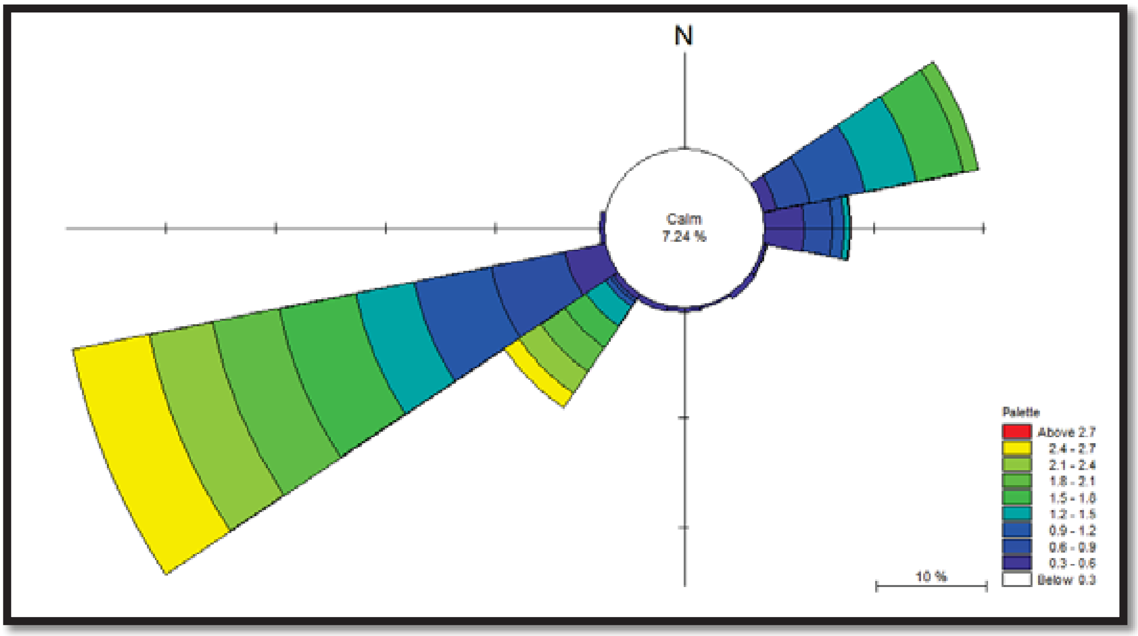


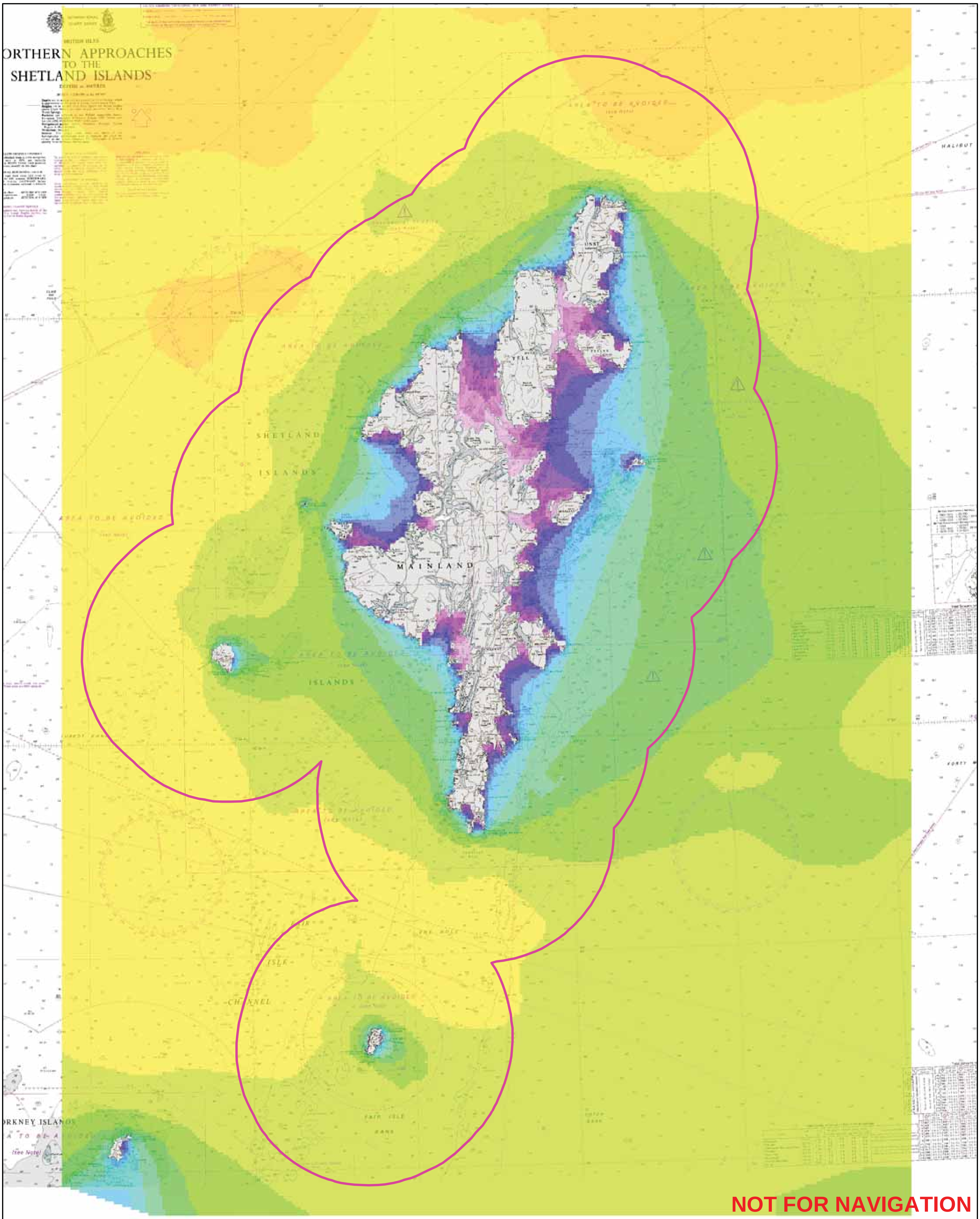
Figure 43: Tidal rose for extract location 3

8. ANNEX 2 WAVE RESULTS

8.1. Mapped results

The following A3 maps are included within this Annex:

- Shetland – Annual Wave Height
- Shetland – Annual Wave Period
- Shetland – Annual Wave Power
- Shetland – Seasonal Wave Height
- Shetland – Seasonal Wave Period
- Shetland – Seasonal Wave Power
- South Shetland – Annual Wave Height
- South Shetland – Annual Wave Period
- South Shetland – Annual Wave Power
- South Shetland – Seasonal Wave Height
- South Shetland – Seasonal Wave Period
- South Shetland – Seasonal Wave Power
- Esha Ness – Annual Wave Height
- Esha Ness – Annual Wave Period
- Esha Ness – Annual Wave Power
- Esha Ness – Seasonal Wave Height
- Esha Ness – Seasonal Wave Period
- Esha Ness – Seasonal Wave Power



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Height

Area: **Shetland**

Key

12 nautical mile limit

Mean Wave Height (m)

0.0 - 0.2	1.0 - 1.2	2.6 - 2.8
0.2 - 0.4	1.2 - 1.4	2.8 - 3.0
0.4 - 0.6	1.4 - 1.6	3.0 - 3.2
0.6 - 0.8	1.6 - 1.8	3.2 - 3.4
0.8 - 1	1.8 - 2.0	3.4 - 3.6
	2.0 - 2.2	3.6 - 3.8
	2.2 - 2.4	
	2.4 - 2.6	

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
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Scale: 1:600,000

0 3.75 7.5 15 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_007.mxd

Job code: 805

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Natural Power Consultants Ltd
The Green House
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
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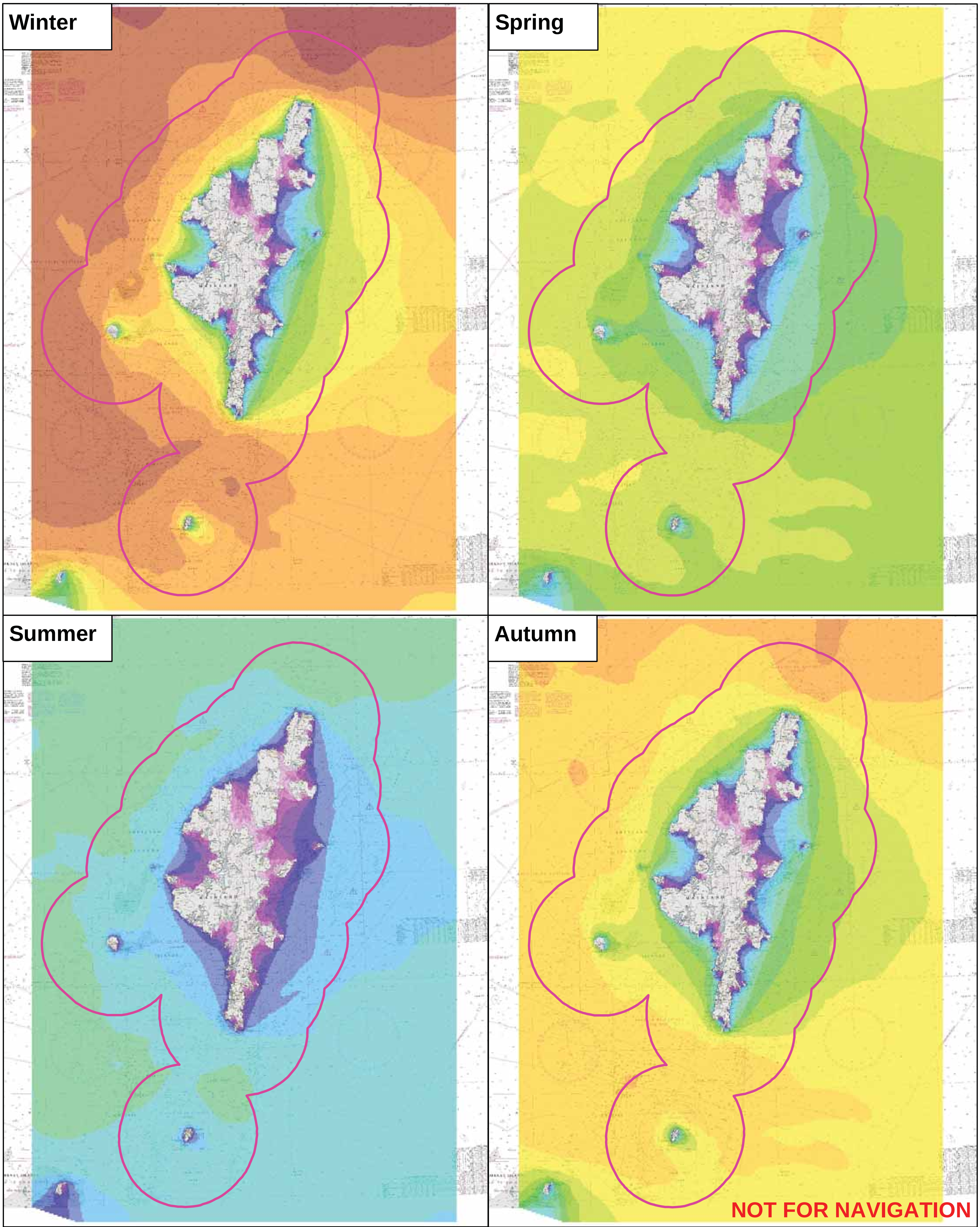
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Height

Area: **Shetland**

Key

12 nautical mile limit

Mean Wave Height (m)

0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1.0 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2
3.2 - 3.4
3.4 - 3.6
3.6+

Notes:
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Scale: 1:1,200,000

0 5 10 20 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_008.mxd

Job code: 805

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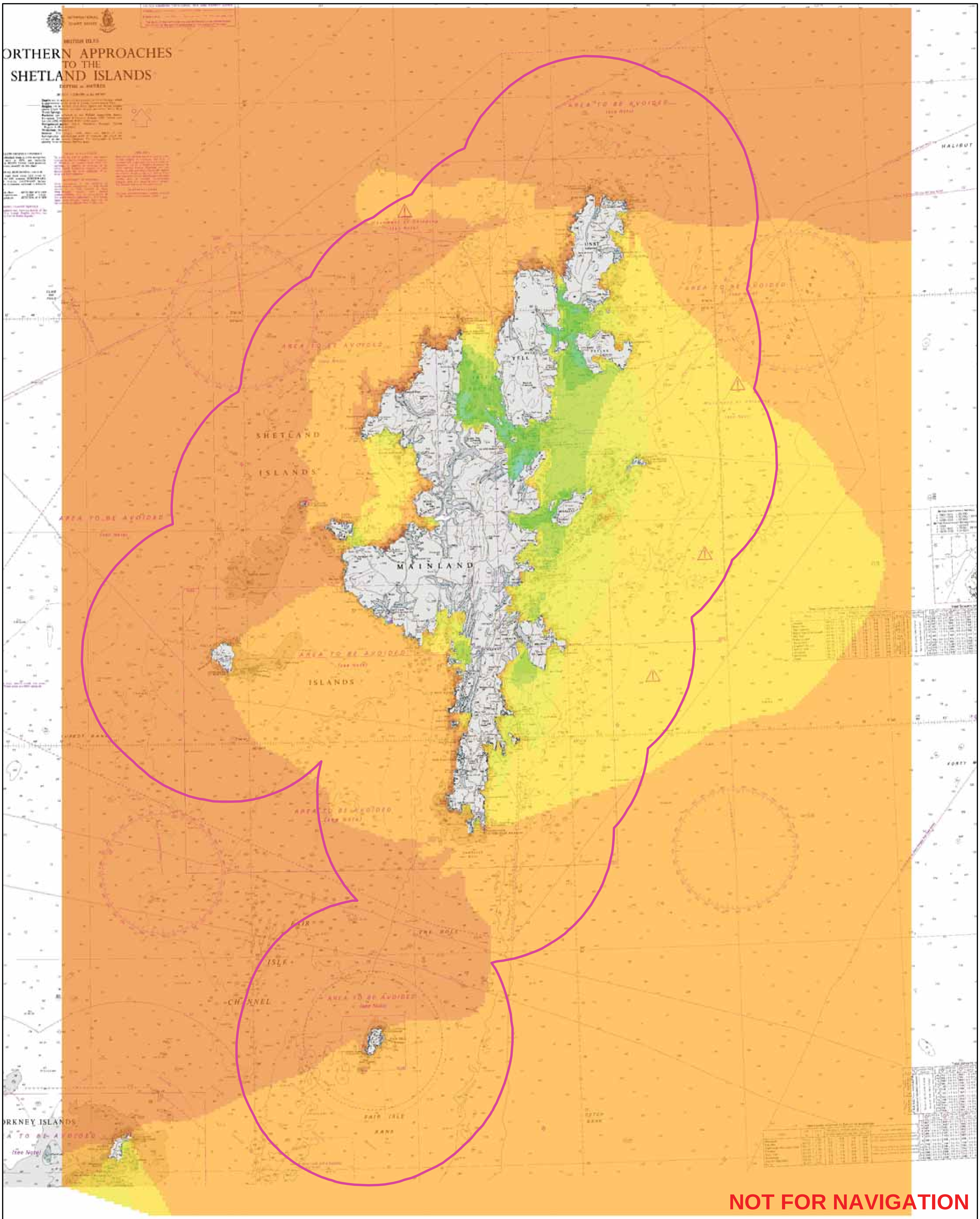
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Period

Area: **Shetland**

Key

12 nautical mile limit

Mean Wave Period (s)

0.0 - 0.5	2.5 - 3.0	6.0 - 6.5
0.5 - 1.0	3.0 - 3.5	6.5 - 7.0
1.0 - 1.5	3.5 - 4.0	7.0 - 7.5
1.5 - 2.0	4.0 - 4.5	7.5 - 8.0
2.0 - 2.5	4.5 - 5.0	8.0 - 8.5
	5.0 - 5.5	8.5+
	5.5 - 6.0	

Notes:
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Scale: 1:600,000

0 3 6 12 km

Projection: WGS84 UTM 30N

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_009.mxd		Job code: 805

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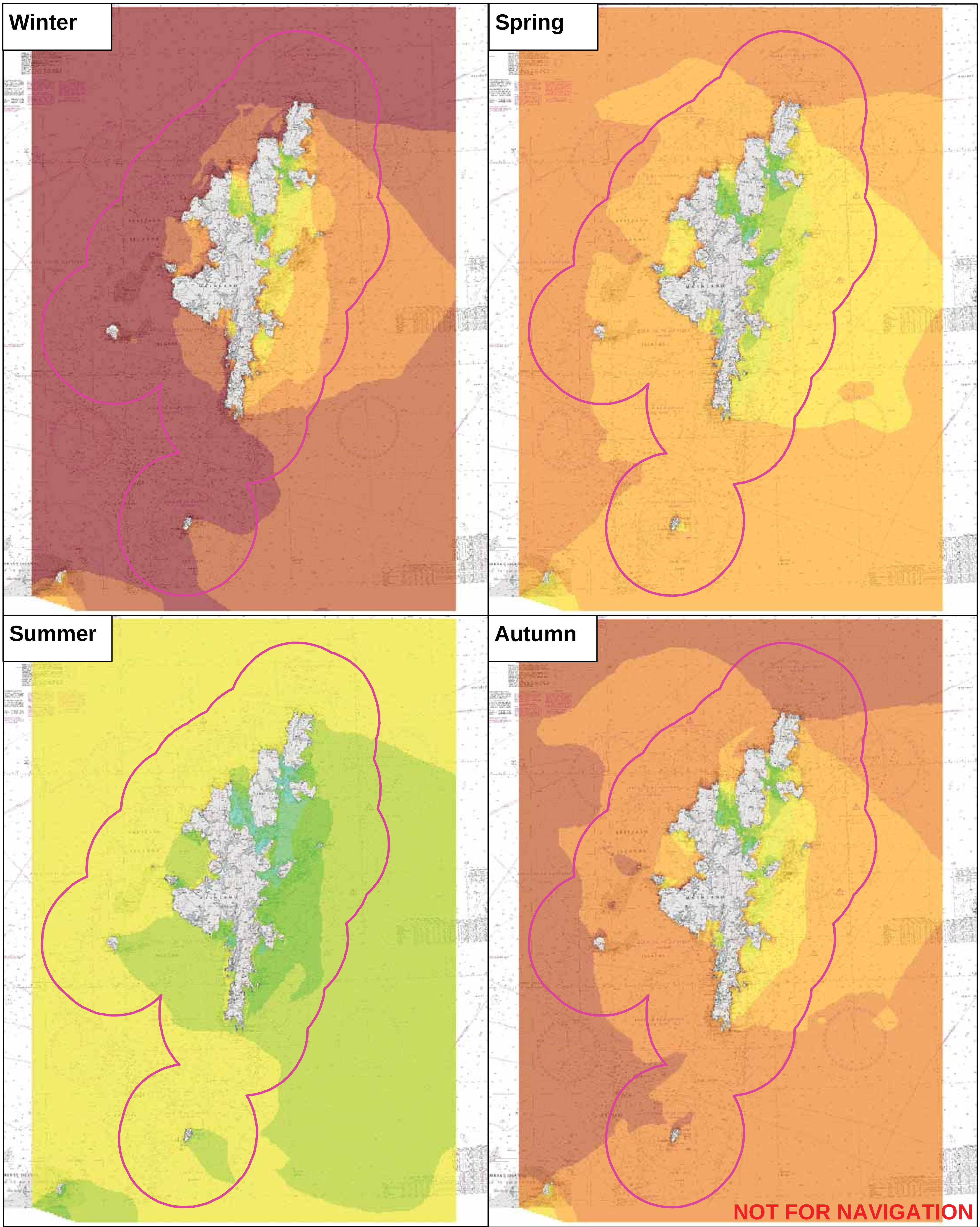

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Period

Area: **Shetland**

Key

12 nautical mile limit

Mean Wave Period (s)

0.0 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 3.5
3.5 - 4.0
4.0 - 4.5
4.5 - 5.0
5.0 - 5.5
5.5 - 6.0
6.0 - 6.5
6.5 - 7.0
7.0 - 7.5
7.5 - 8.0
8.0 - 8.5
8.5+

Notes:
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Scale:1:1,200,000

0 5 10 20 km

Projection: WGS84 UTM 30N

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_010.mxd		Job code: 805

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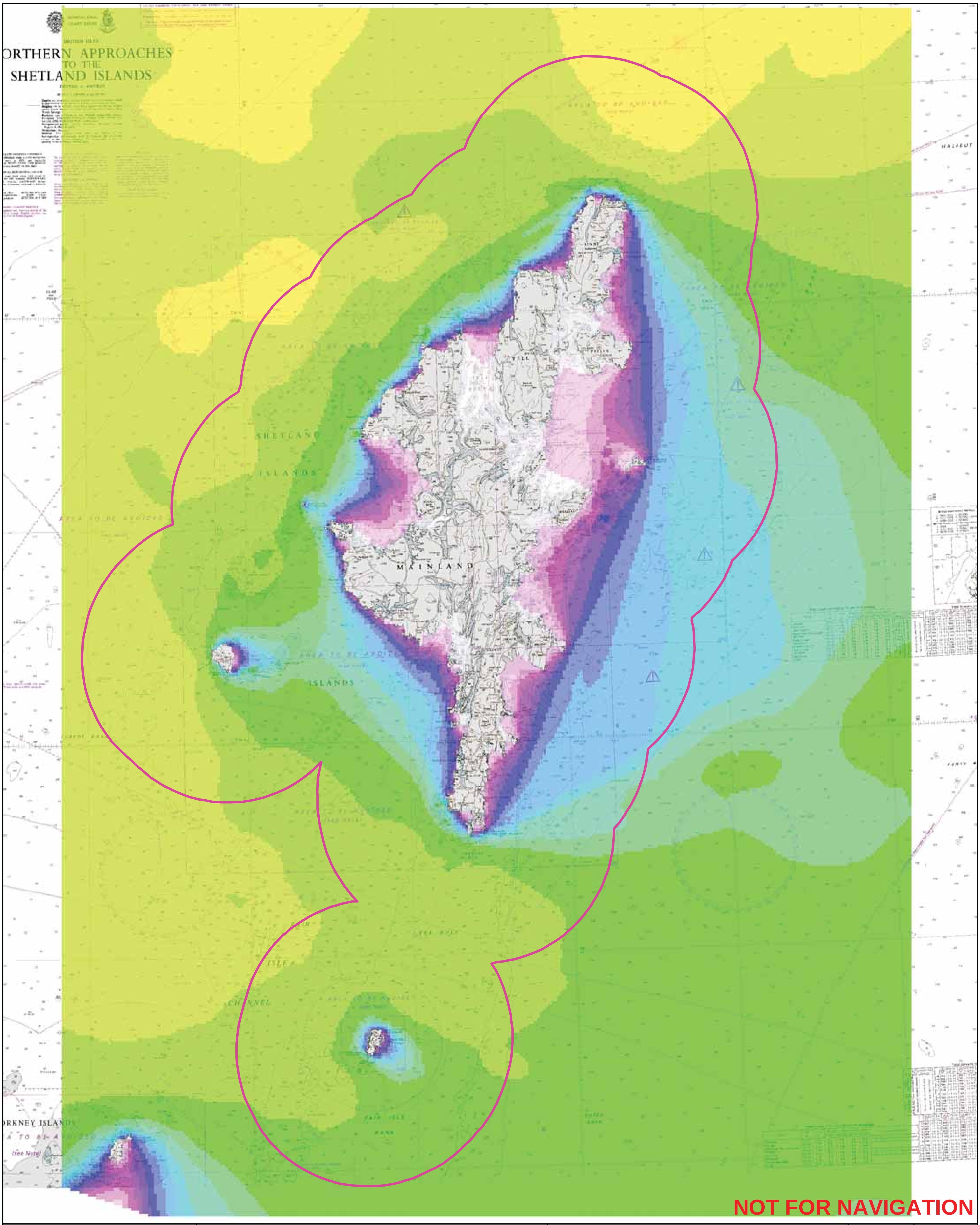

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Power

Area: **Shetland**

Key

12 nautical mile limit

Mean Wave Power (kW/m)

0.0 - 5.0	18.0 - 20.0	45.0 - 50.0
5.0 - 10.0	20.0 - 22.0	50.0 - 55.0
10.0 - 12.0	22.0 - 24.0	55.0 - 60.0
12.0 - 14.0	24.0 - 26.0	60.0 - 65.0
14.0 - 16.0	26.0 - 28.0	65.0 - 70.0
16.0 - 18.0	28.0 - 30.0	70.0 - 75.0
	30.0 - 35.0	75.0+
	35.0 - 40.0	
	40.0 - 45.0	

Notes:
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Projection: WGS84 UTM 30N

0 4 8 16 km
Scale: 1:600,000

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_011.mxd | Job code: 805

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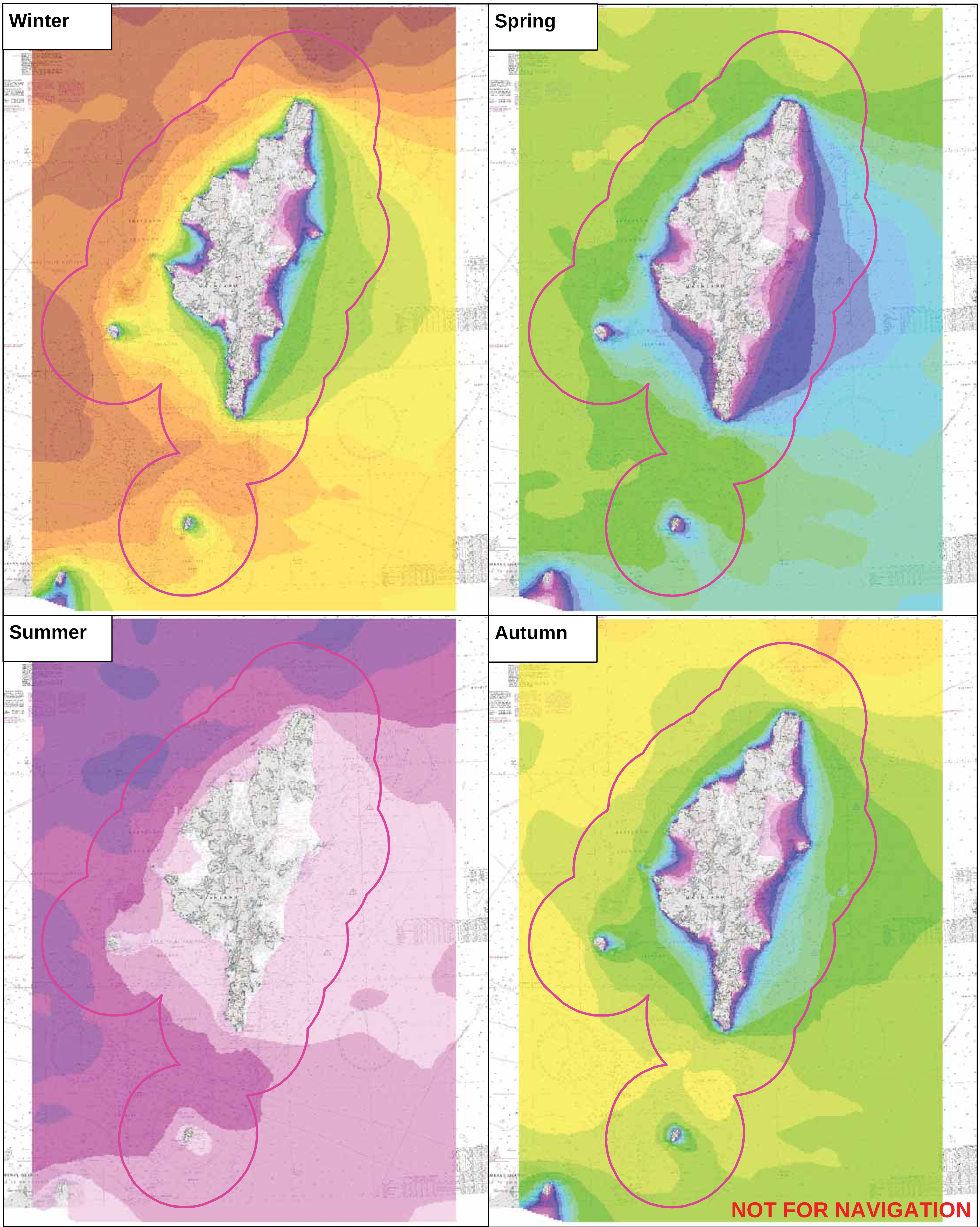

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Power

Area: **Shetland**

Key

12 nautical mile limit

Mean Wave Power (kW/m)

0.0 - 5.0	18.0 - 20.0	40.0 - 45.0	75.0+
5.0 - 10.0	20.0 - 22.0	45.0 - 50.0	
10.0 - 12.0	22.0 - 24.0	50.0 - 55.0	
12.0 - 14.0	24.0 - 26.0	55.0 - 60.0	
14.0 - 16.0	26.0 - 28.0	60.0 - 65.0	
16.0 - 18.0	28.0 - 30.0	65.0 - 70.0	
	30.0 - 35.0	70.0 - 75.0	
	35.0 - 40.0		

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
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Scale: 1:1,200,000

Projection: WGS84 UTM 30N

0 12.5 25 50 km

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_012.mxd | Job code: 805

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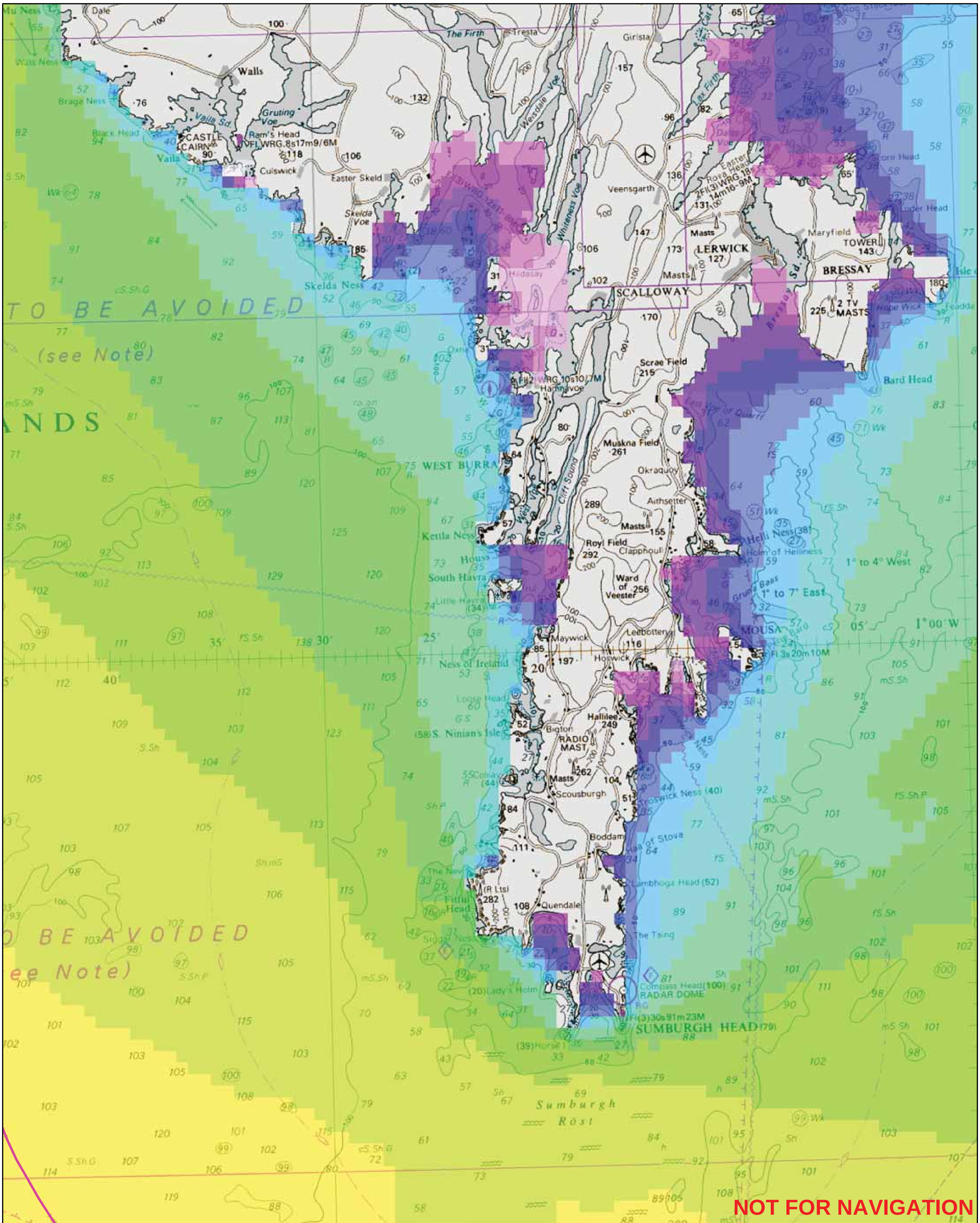

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Height

Area: **South West Coast**

Key

12 nautical mile limit

Mean Wave Height (m)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8 - 3.0
- 3.0 - 3.2
- 3.2 - 3.4
- 3.4 - 3.6
- 3.6 - 3.8

Notes:
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Scale: 1:150,000

0 1 2 4 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_013.mxd

Job code: 805

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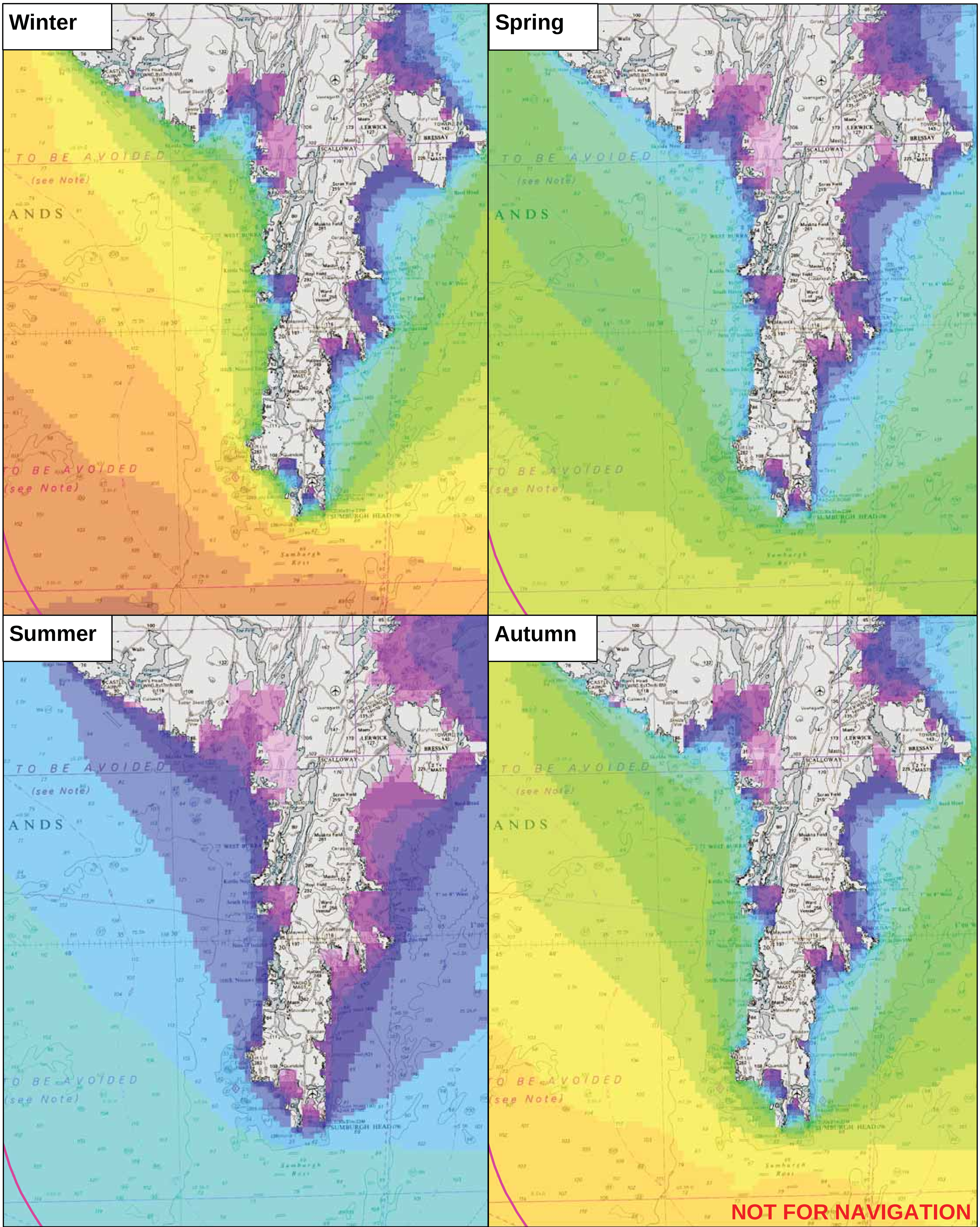

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Height

Area: **South West Coast**

Key

12 nautical mile limit

Mean Wave Height (m)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8 - 3.0
- 3.0 - 3.2
- 3.2 - 3.4
- 3.4 - 3.6
- 3.6+

Notes:
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Scale: 1:300,000

0 1.5 3 6 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_014.mxd

Job code: 805

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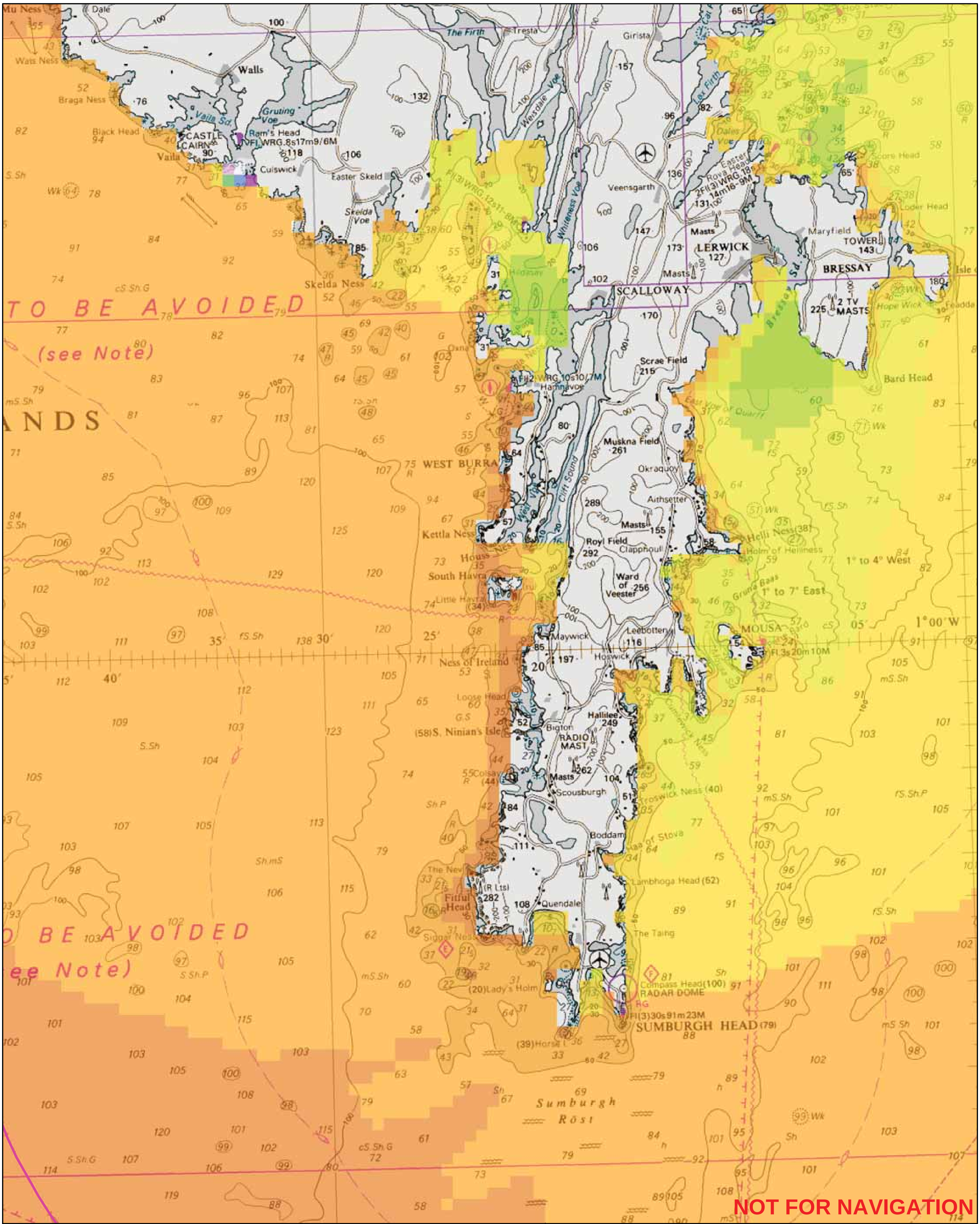

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Period

Area: **South West Coast**

Key

12 nautical mile limit

Mean Wave Period (s)

- 0.0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- 3.0 - 3.5
- 3.5 - 4.0
- 4.0 - 4.5
- 4.5 - 5.0
- 5.0 - 5.5
- 5.5 - 6.0
- 6.0 - 6.5
- 6.5 - 7.0
- 7.0 - 7.5
- 7.5 - 8.0
- 8.0 - 8.5
- 8.5+

Notes:
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Scale: 1:150,000

0 1 2 4 km
Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH
Drawing No. 805_M_015.mxd | Job code: 805

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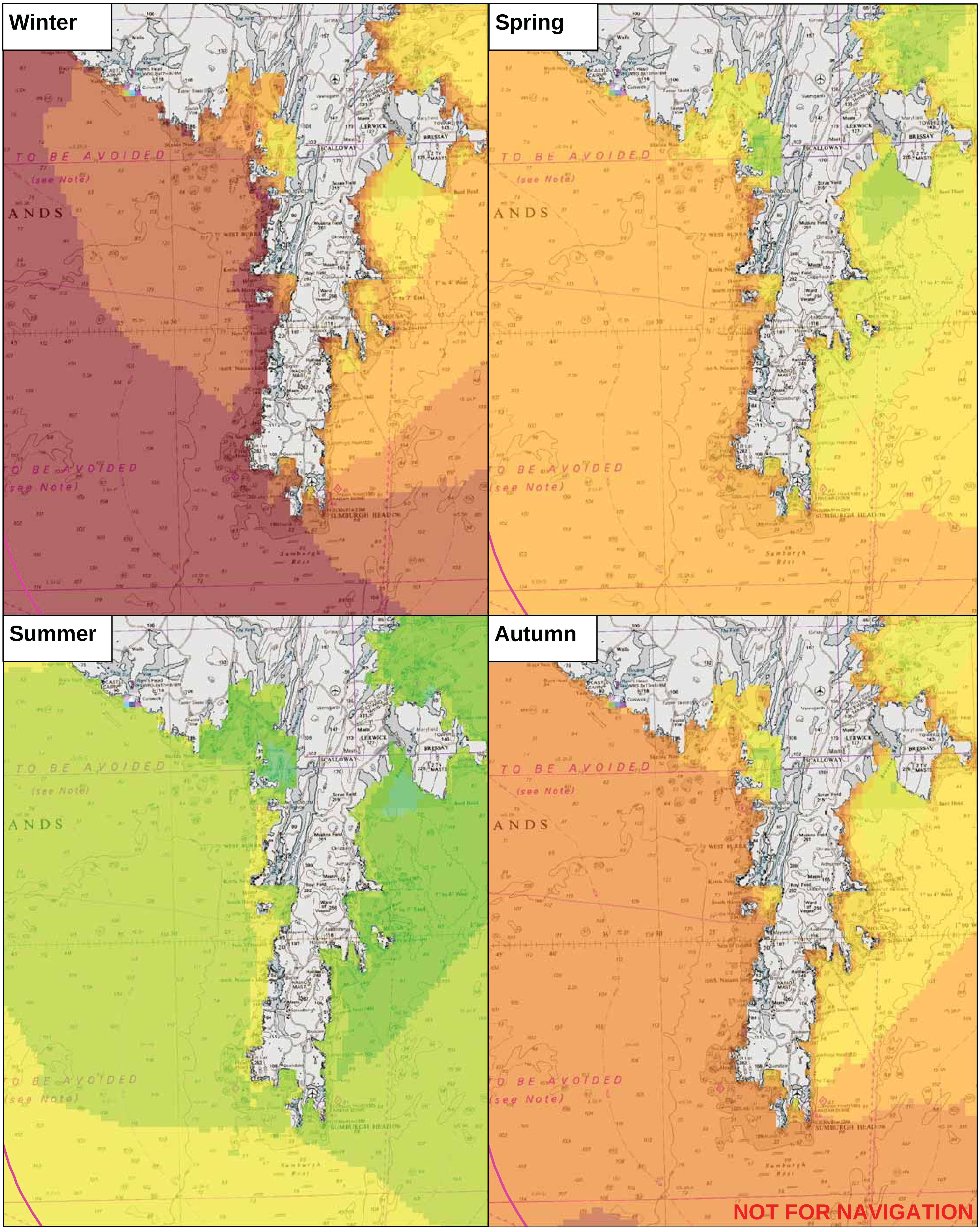

Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Period

Area: **South West Coast**

Key

12 nautical mile limit

Mean Wave Period (s)

- 0.0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- 3.0 - 3.5
- 3.5 - 4.0
- 4.0 - 4.5
- 4.5 - 5.0
- 5.0 - 5.5
- 5.5 - 6.0
- 6.0 - 6.5
- 6.5 - 7.0
- 7.0 - 7.5
- 7.5 - 8.0
- 8.0 - 8.5
- 8.5+

Notes:
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Scale: 1:300,000

0 1.5 3 6 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_016.mxd

Job code: 805

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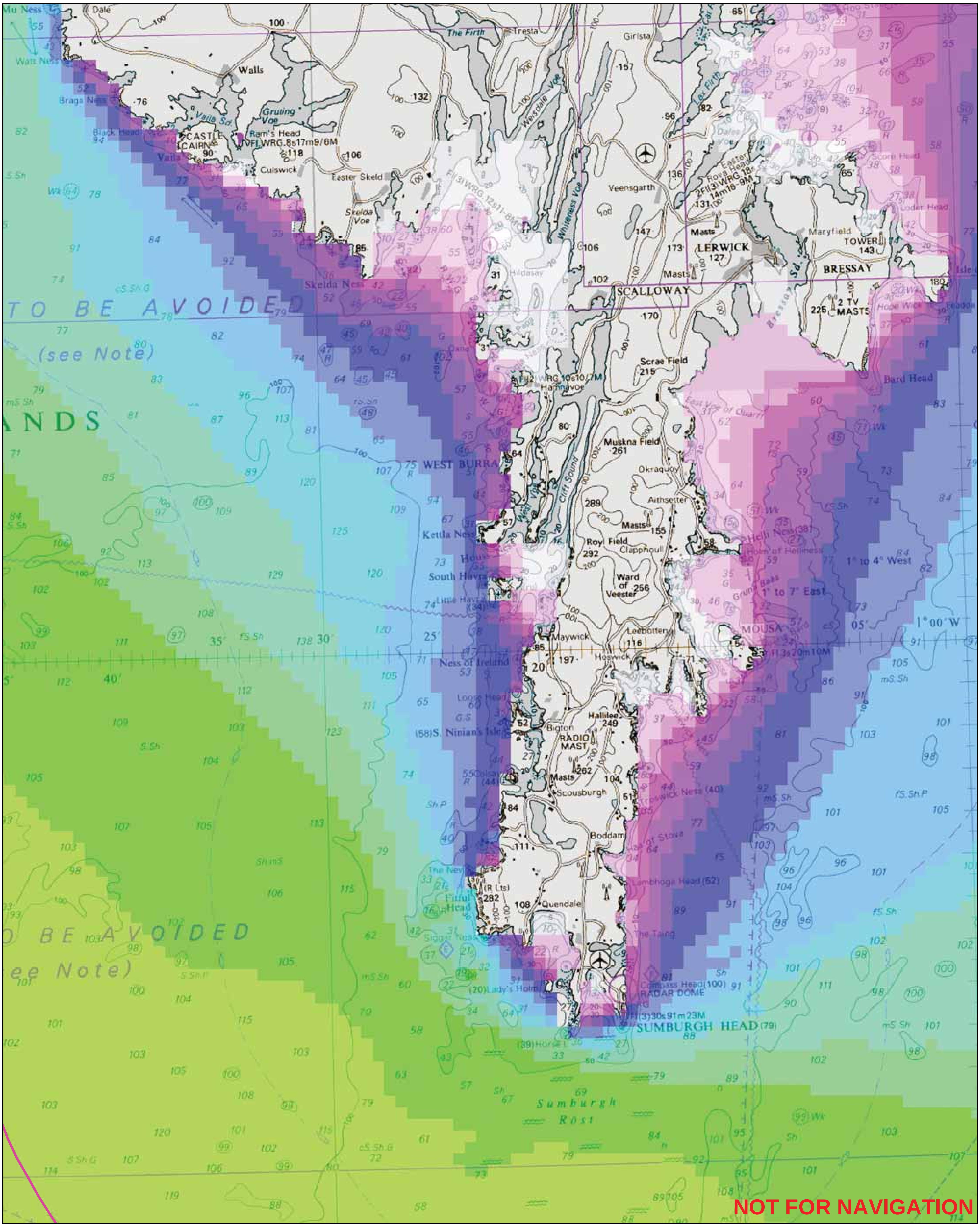
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Power

Area: **South West Coast**

Key

12 nautical mile limit

Mean Wave Power (kW/m)

0.0 - 5.0
5.0 - 10.0
10.0 - 12.0
12.0 - 14.0
14.0 - 16.0
16.0 - 18.0
18.0 - 20.0
20.0 - 22.0
22.0 - 24.0
24.0 - 26.0
26.0 - 28.0
28.0 - 30.0
30.0 - 35.0
35.0 - 40.0
40.0 - 45.0
45.0 - 50.0
50.0 - 55.0
55.0 - 60.0
60.0 - 65.0
65.0 - 70.0
70.0 - 75.0
75.0+

Notes:
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Projection: WGS84 UTM 30N

0 1 2 4 km

Scale: 1:150,000

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_017.mxd | Job code: 805

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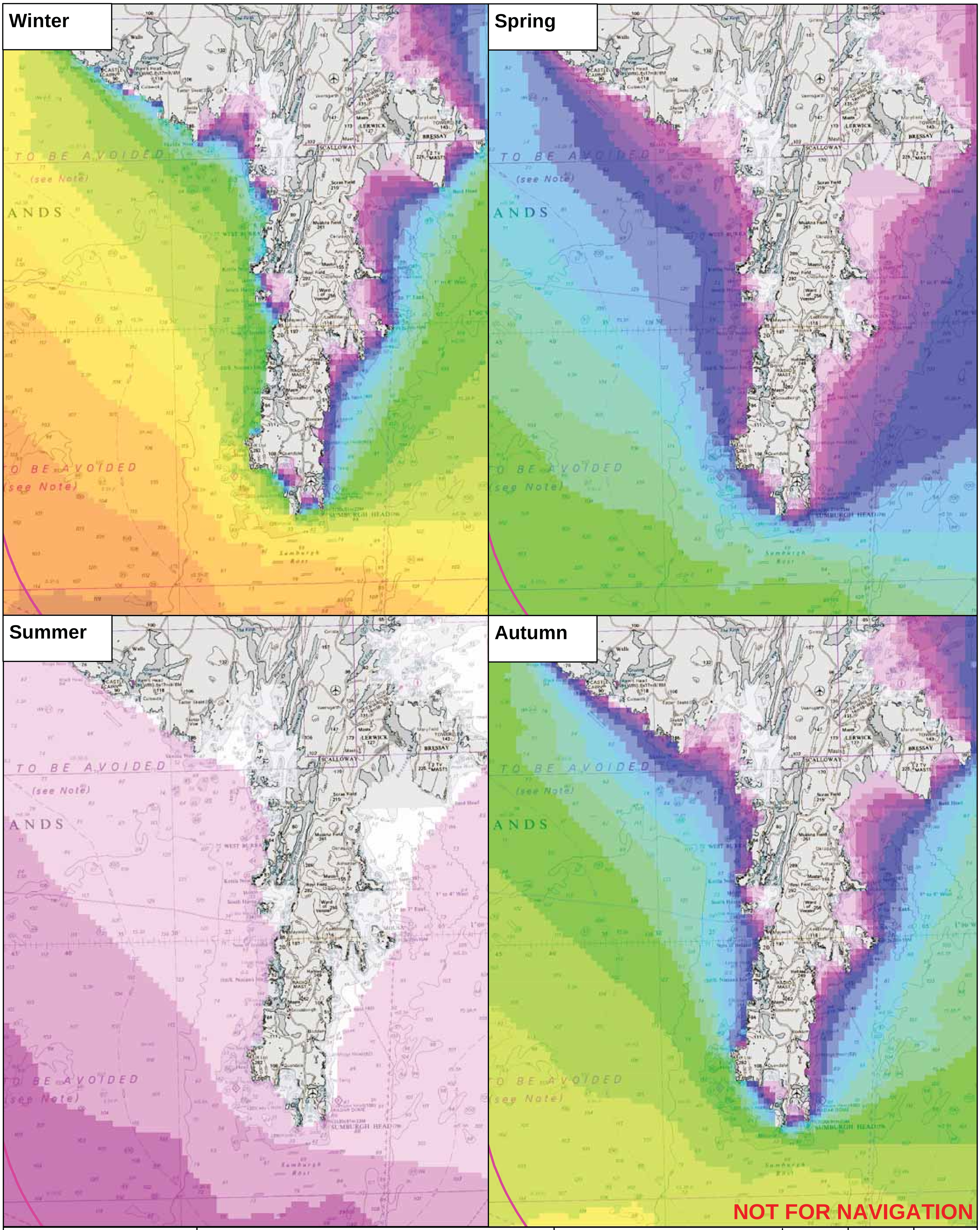
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Power

Area: **South West Coast**

Key

12 nautical mile limit

Mean Wave Power (kW/m)

- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 12.0
- 12.0 - 14.0
- 14.0 - 16.0
- 16.0 - 18.0
- 18.0 - 20.0
- 20.0 - 22.0
- 22.0 - 24.0
- 24.0 - 26.0
- 26.0 - 28.0
- 28.0 - 30.0
- 30.0 - 35.0
- 35.0 - 40.0
- 40.0 - 45.0
- 45.0 - 50.0
- 50.0 - 55.0
- 55.0 - 60.0
- 60.0 - 65.0
- 65.0 - 70.0
- 70.0 - 75.0
- 75.0+

Notes:
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(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Scale: 1:300,000

Projection: WGS84 UTM 30N

0 3 6 12 km

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_018.mxd

Job code: 805

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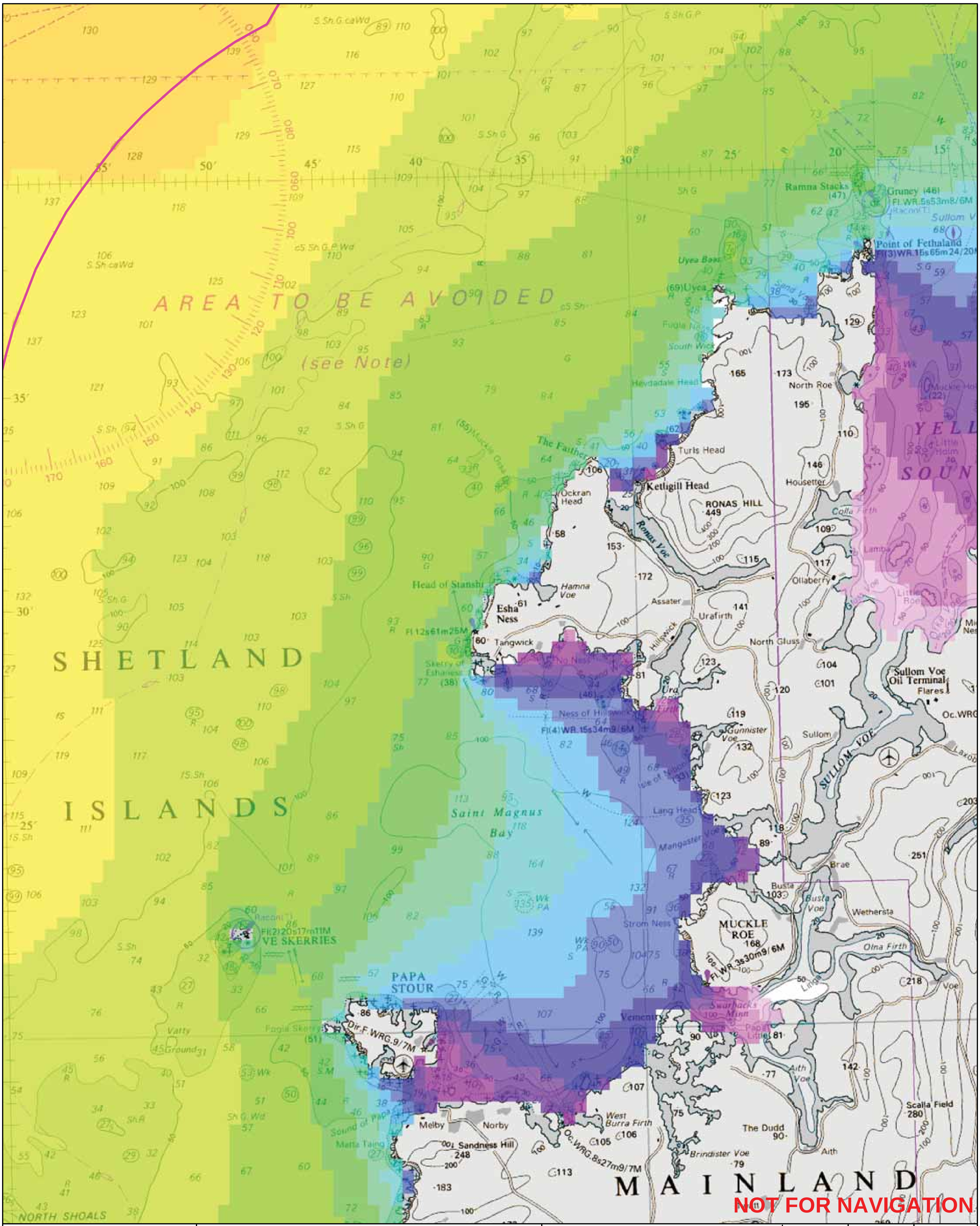
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Height

Area: **North West Coast**

Key

12 nautical mile limit

Mean Wave Height (m)

0.0 - 0.2	1.0 - 1.2	2.6 - 2.8
0.2 - 0.4	1.2 - 1.4	2.8 - 3.0
0.4 - 0.6	1.4 - 1.6	3.0 - 3.2
0.6 - 0.8	1.6 - 1.8	3.2 - 3.4
0.8 - 1	1.8 - 2.0	3.4 - 3.6
	2.0 - 2.2	3.6 - 3.8
	2.2 - 2.4	
	2.4 - 2.6	

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Scale: 1:150,000

0 1 2 4 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_019.mxd

Job code: 805

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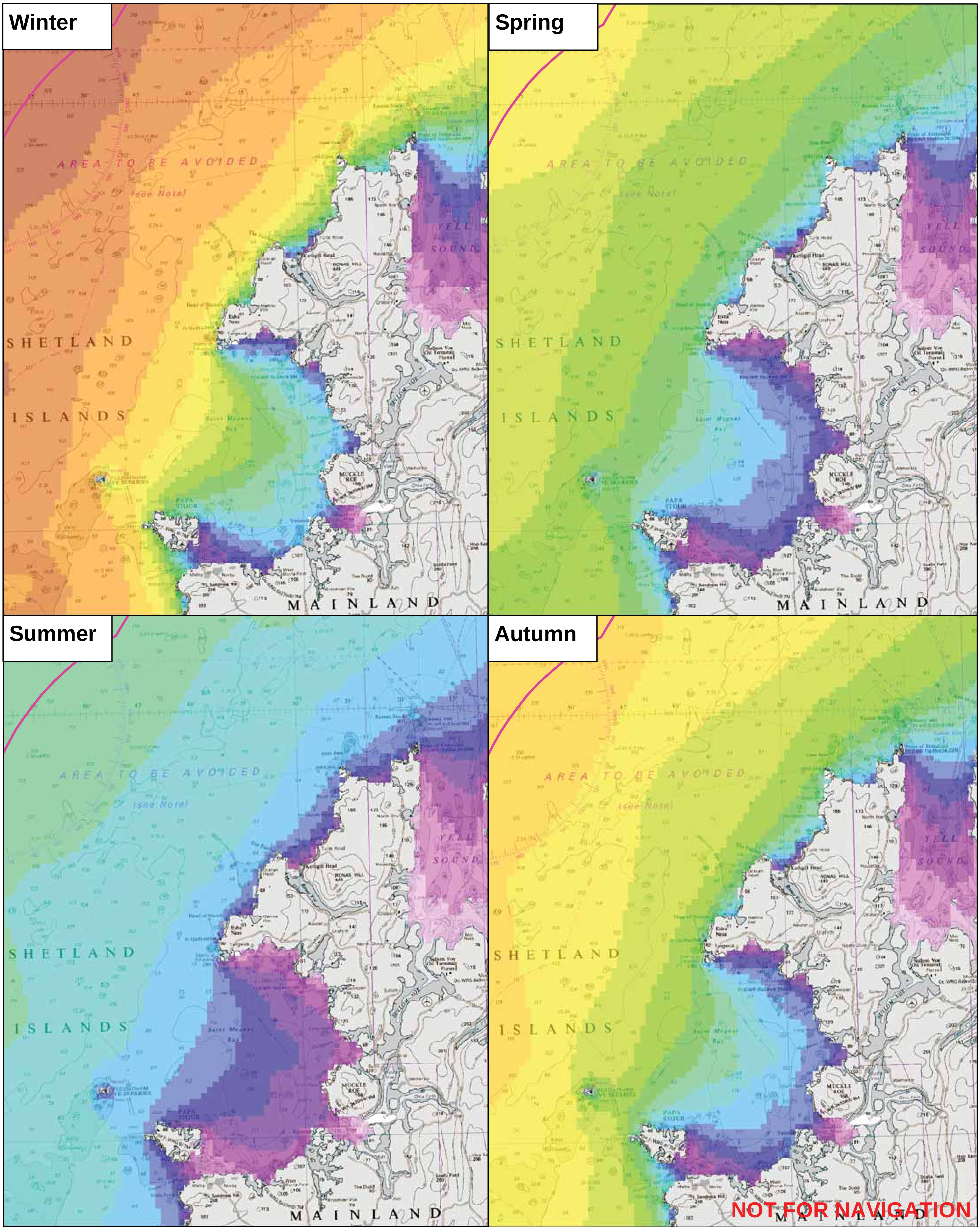
The Green House
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
www.naturalpower.com
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Height

Area: **North West Coast**

Key

12 nautical mile limit

Mean Wave Height (m)

- 0.0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.2
- 2.2 - 2.4
- 2.4 - 2.6
- 2.6 - 2.8
- 2.8 - 3.0
- 3.0 - 3.2
- 3.2 - 3.4
- 3.4 - 3.6
- 3.6+

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Scale: 1:300,000

0 1.5 3 6 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_020.mxd

Job code: 805

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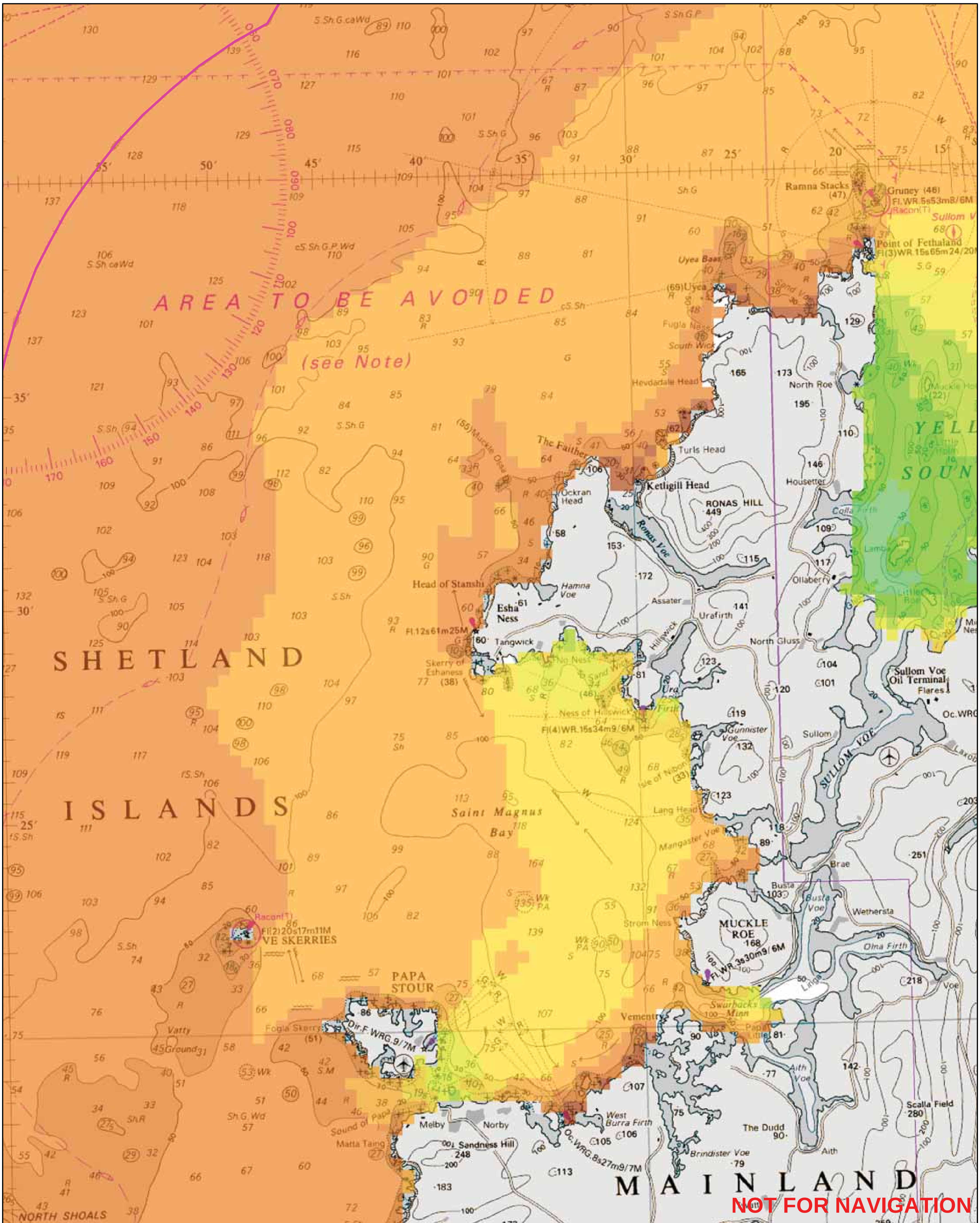
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
www.naturalpower.com
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Annual Wave Period

Area: **North West Coast**

Key

12 nautical mile limit

Mean Wave Period (s)

- 0.0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- 3.0 - 3.5
- 3.5 - 4.0
- 4.0 - 4.5
- 4.5 - 5.0
- 5.0 - 5.5
- 5.5 - 6.0
- 6.0 - 6.5
- 6.5 - 7.0
- 7.0 - 7.5
- 7.5 - 8.0
- 8.0 - 8.5
- 8.5+

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Scale: 1:150,000

0 1 2 4 km

Projection: WGS84 UTM 30N

Date: 24-01-2011	Prepared by: RH	Checked by: DH
Drawing No. 805_M_021.mxd		Job code: 805

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The Green House
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
www.naturalpower.com
Email: sayhello@naturalpower.com

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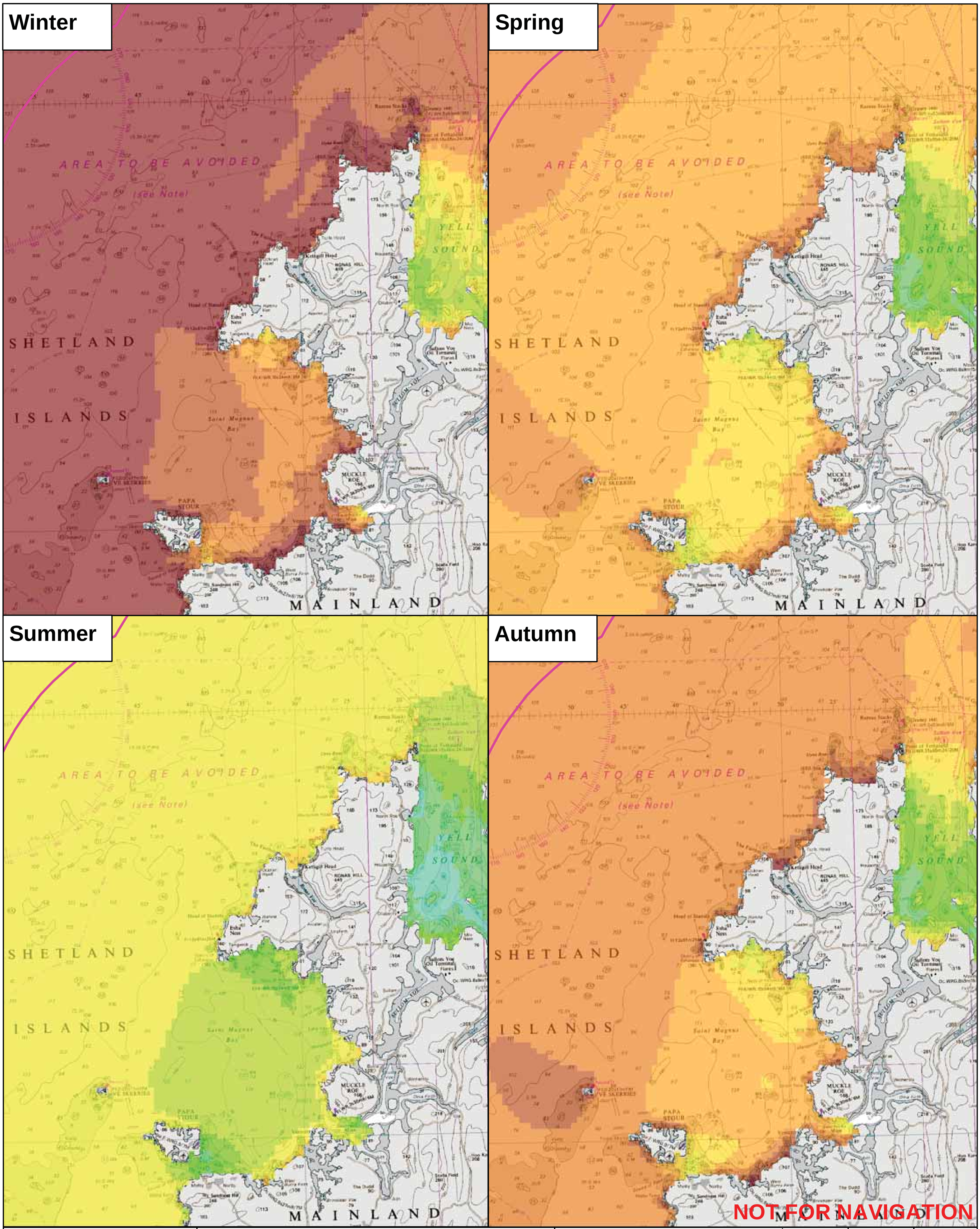
Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Period

Area: **North West Coast**

Key

12 nautical mile limit

Mean Wave Period (s)

0.0 - 0.5	2.5 - 3.0	6.0 - 6.5
0.5 - 1.0	3.0 - 3.5	6.5 - 7.0
1.0 - 1.5	3.5 - 4.0	7.0 - 7.5
1.5 - 2.0	4.0 - 4.5	7.5 - 8.0
2.0 - 2.5	4.5 - 5.0	8.0 - 8.5
	5.0 - 5.5	8.5+
	5.5 - 6.0	

Notes:
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Scale: 1:300,000

0 1.5 3 6 km

Projection: WGS84 UTM 30N

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No. 805_M_022.mxd | Job code: 805

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Castle Douglas
DG7 3XS
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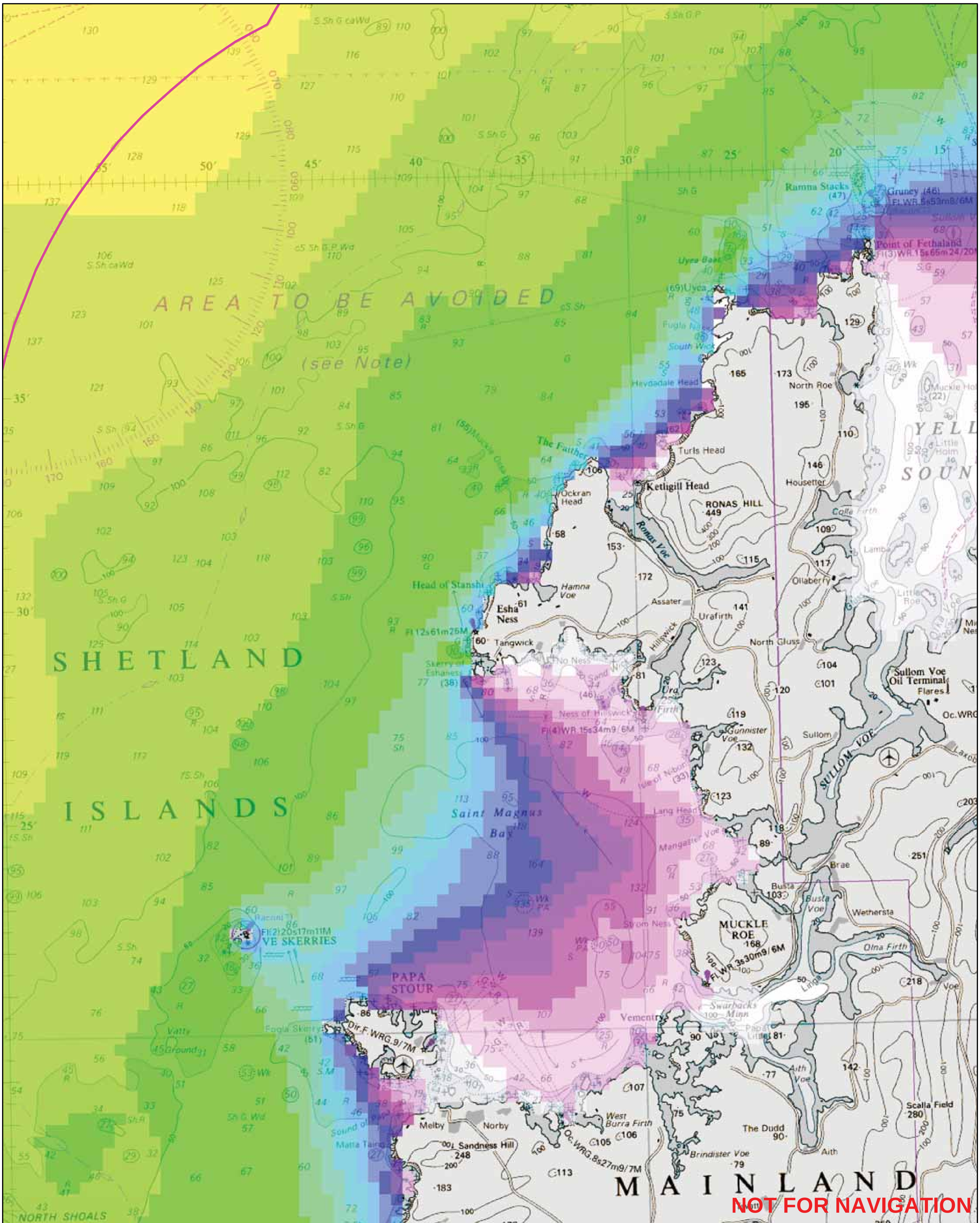
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands
Wave and Tidal
Resource Assessment

Title
Mean Annual
Wave Power

Area: **North West Coast**

Key

12 nautical mile limit

Mean Wave Power (kW/m)

- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 12.0
- 12.0 - 14.0
- 14.0 - 16.0
- 16.0 - 18.0
- 18.0 - 20.0
- 20.0 - 22.0
- 22.0 - 24.0
- 24.0 - 26.0
- 26.0 - 28.0
- 28.0 - 30.0
- 30.0 - 35.0
- 35.0 - 40.0
- 40.0 - 45.0
- 45.0 - 50.0
- 50.0 - 55.0
- 55.0 - 60.0
- 60.0 - 65.0
- 65.0 - 70.0
- 70.0 - 75.0
- 75.0+

Notes:
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(b) Natural Power Consultants cannot accept responsibility for the accuracy of data created by third parties.

Projection: WGS84 UTM 30N

0 1 2 4 km

Scale: 1:150,000

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_023.mxd

Job code: 805

Prepared by:
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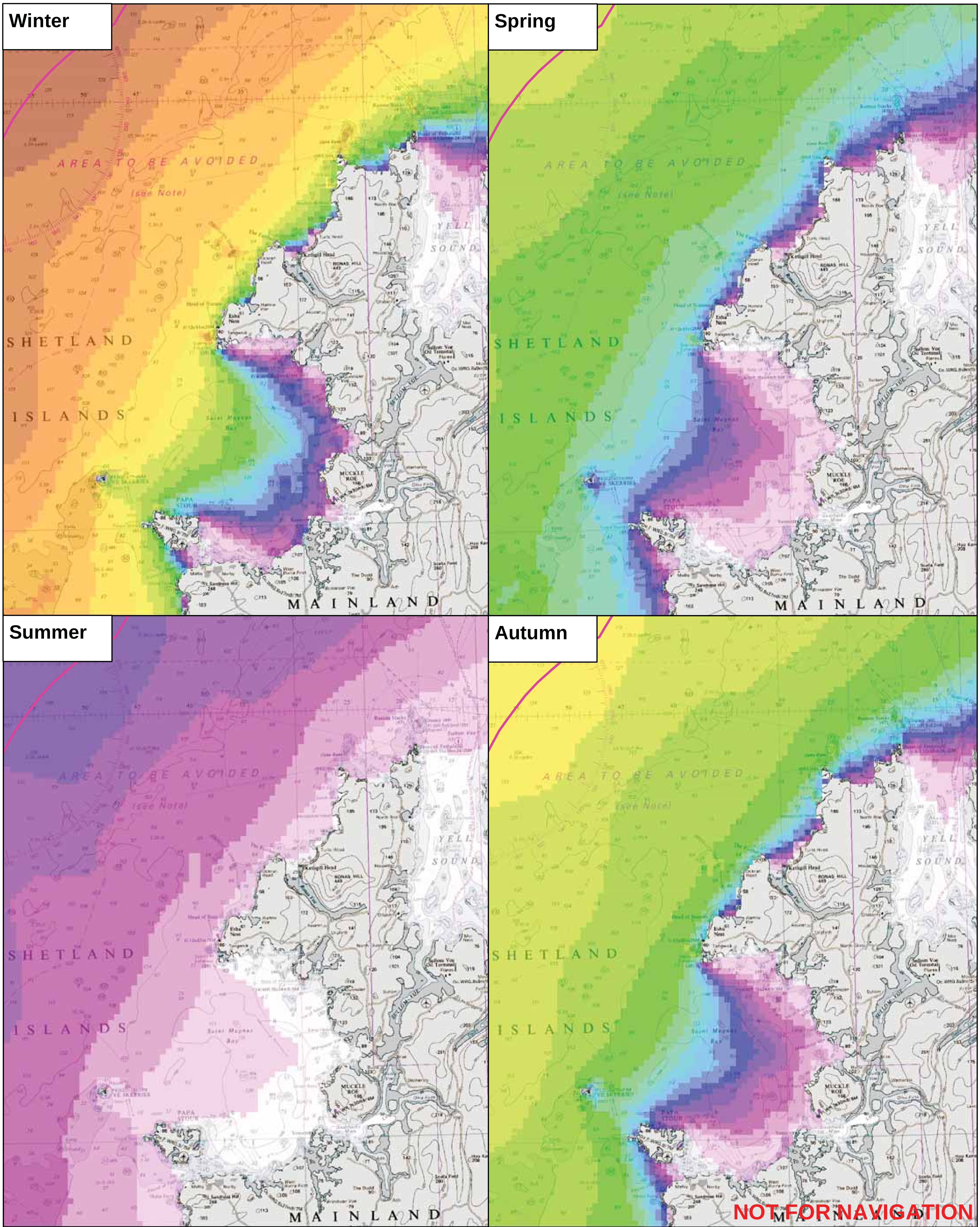
Castle Douglas
DG7 3XS
www.naturalpower.com
Email: sayhello@naturalpower.com

Client: Shetland Islands Council



Project
Shetland Islands Wave and Tidal Resource Assessment

Title
Mean Seasonal Wave Power

Area: **North West Coast**

Key

12 nautical mile limit

Mean Wave Power (kW/m)

0.0 - 5.0	18.0 - 20.0	45.0 - 50.0
5.0 - 10.0	20.0 - 22.0	50.0 - 55.0
10.0 - 12.0	22.0 - 24.0	55.0 - 60.0
12.0 - 14.0	24.0 - 26.0	60.0 - 65.0
14.0 - 16.0	26.0 - 28.0	65.0 - 70.0
16.0 - 18.0	28.0 - 30.0	70.0 - 75.0
	30.0 - 35.0	75.0+
	35.0 - 40.0	
	40.0 - 45.0	

Notes:
(a) Information on this map is directly reproduced from material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the map itself.
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Scale: 1:300,000

Projection: WGS84 UTM 30N

0 3 6 12 km

Date: 24-01-2011 | Prepared by: RH | Checked by: DH

Drawing No.
805_M_024.mxd

Job code: 805

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Natural Power Consultants Ltd
The Green House
Forrest Estate
Dalry
Castle Douglas
DG7 3XS
www.naturalpower.com
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Client: Shetland Islands Council

8.2. Point Extractions

The following point extractions have been taken from the long term data sets created for the development of the mapped results in Section 8.1

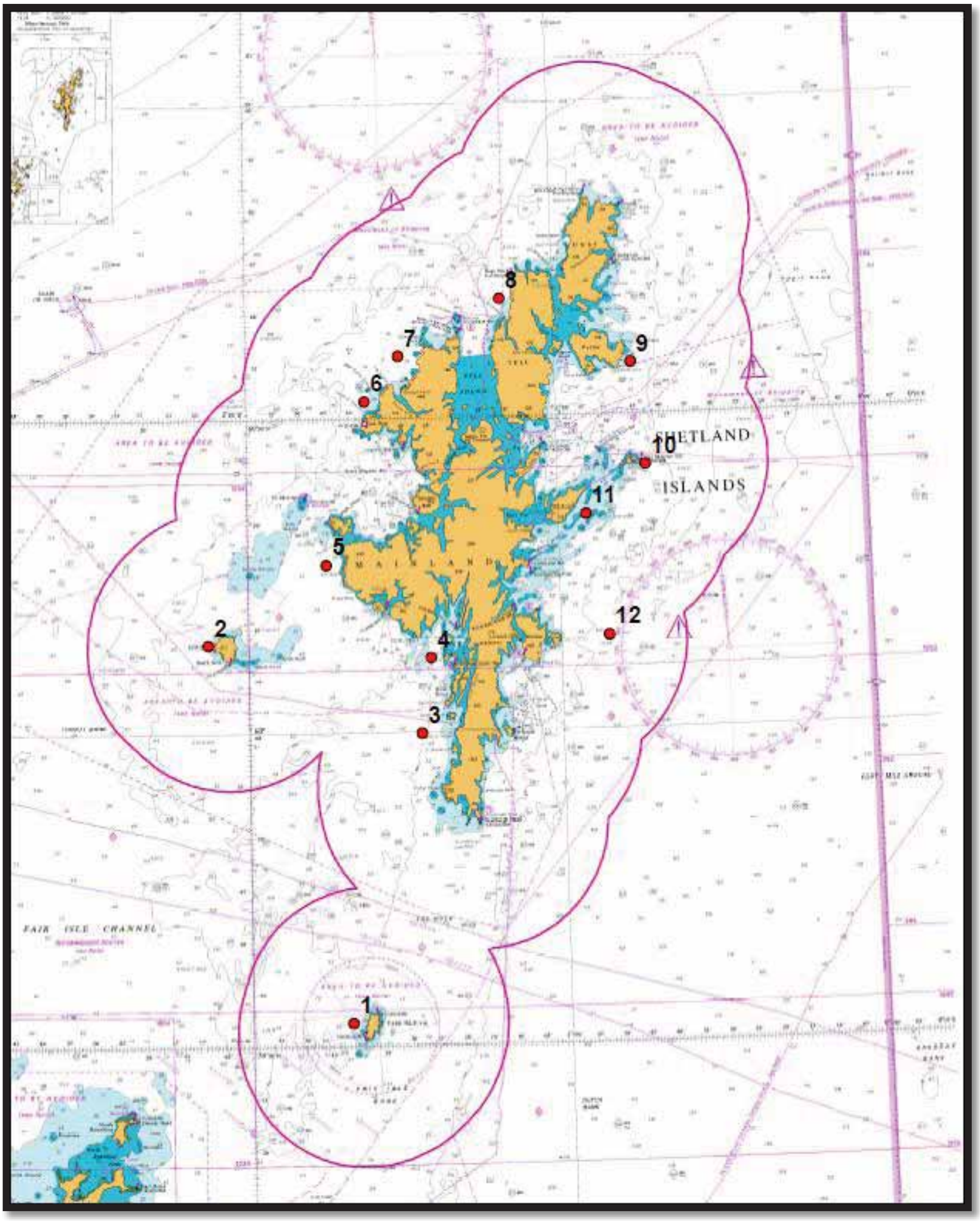
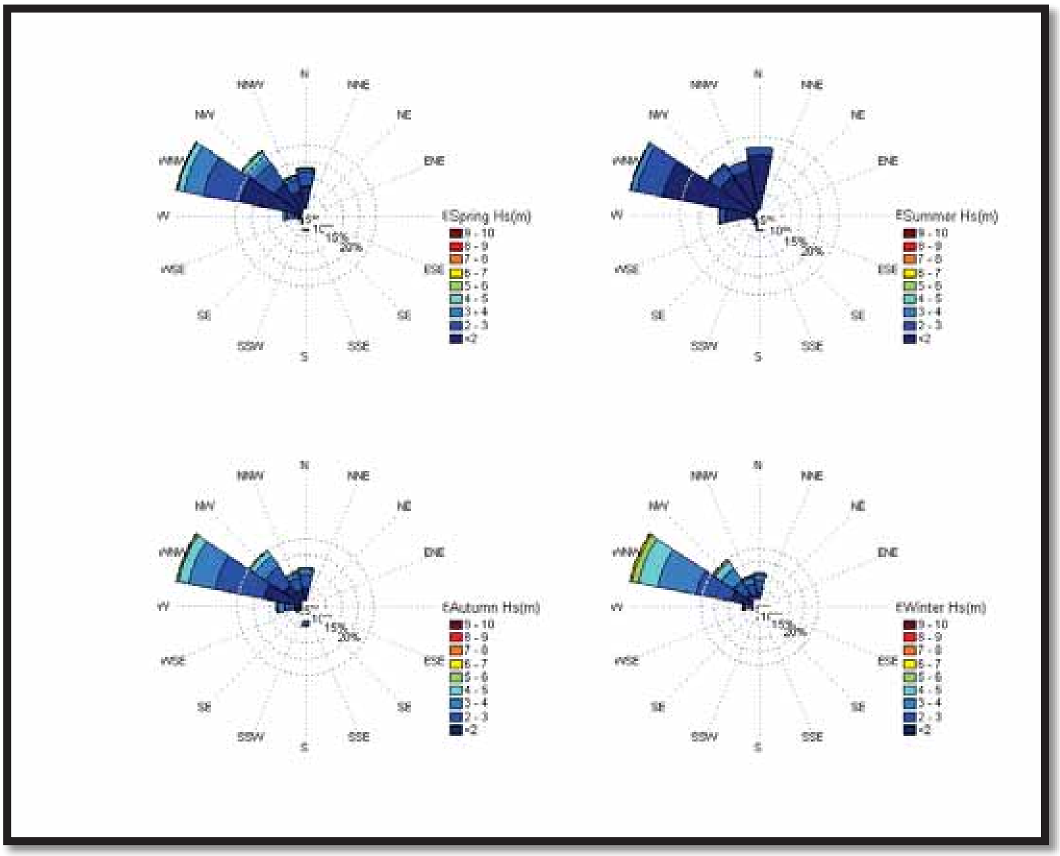
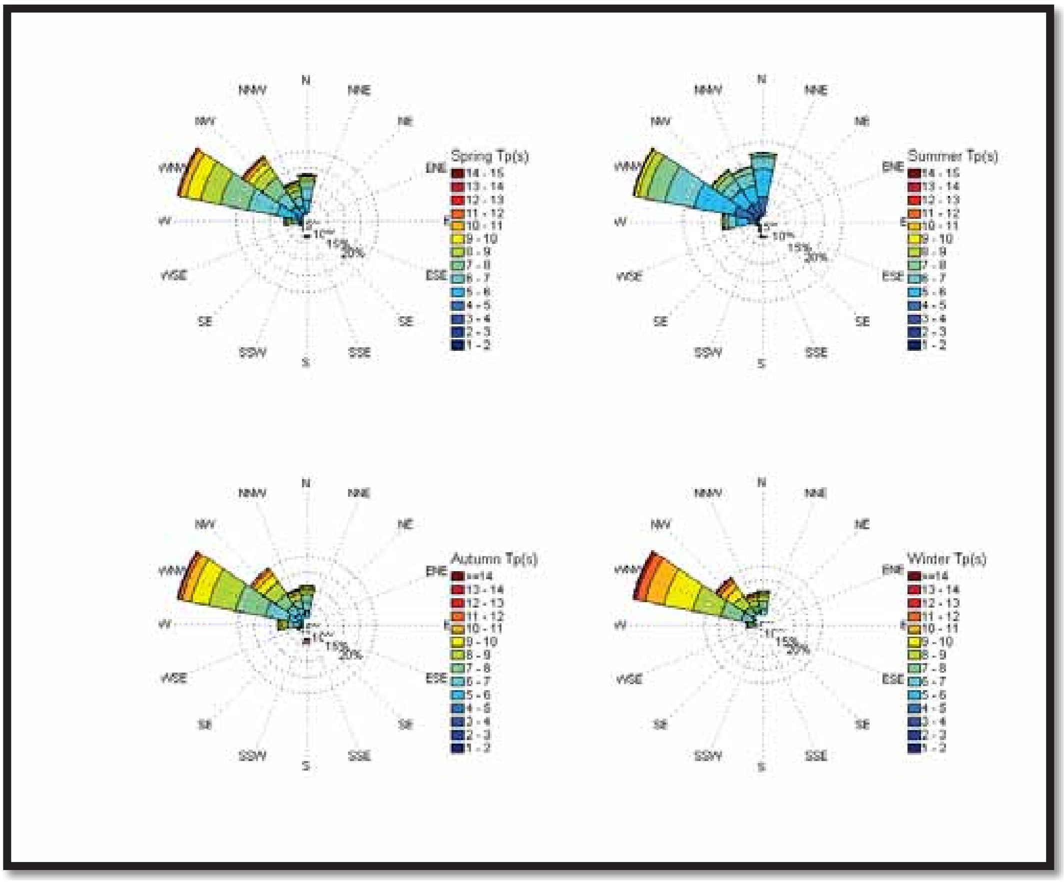
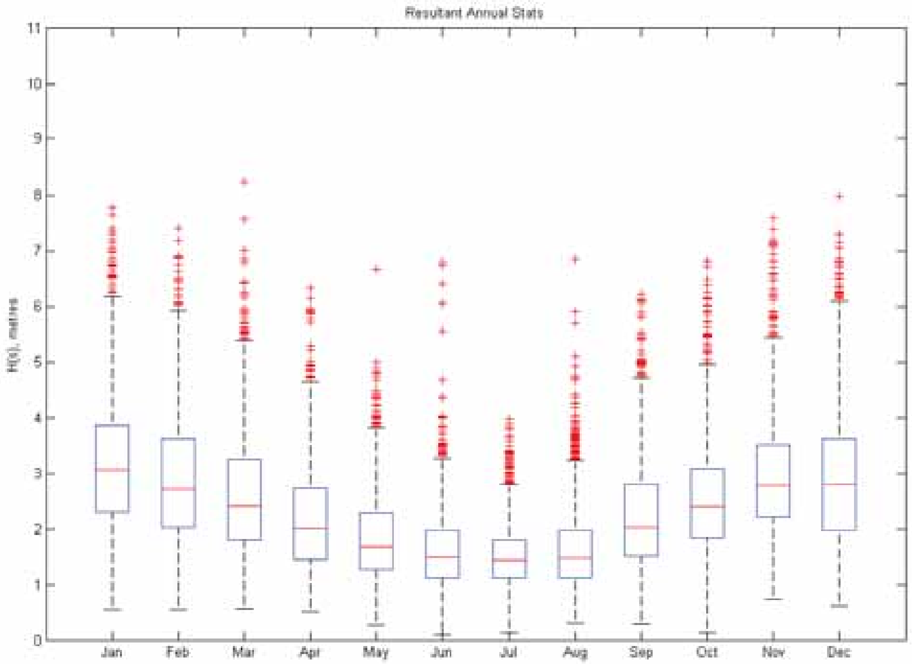


Figure 44: Extract locations taken round the coast of the Shetland Islands

Extract 1 – (59.53N 1.69W)






Resultant Annual Stats
H(s), metres
0
1
2
3
4
5
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8
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10
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Jan
Feb
Mar
Apr
May
Jun
Jul
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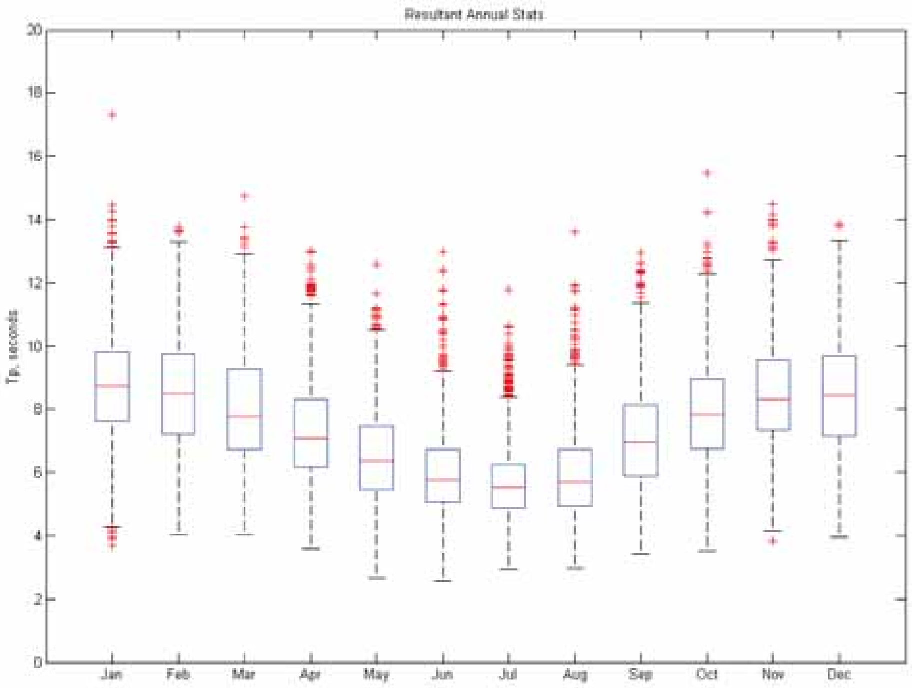
Dec


Resultant Annual Stats
Tp, seconds
0
2
4
6
8
10
12
14
16
18
20
Jan
Feb
Mar
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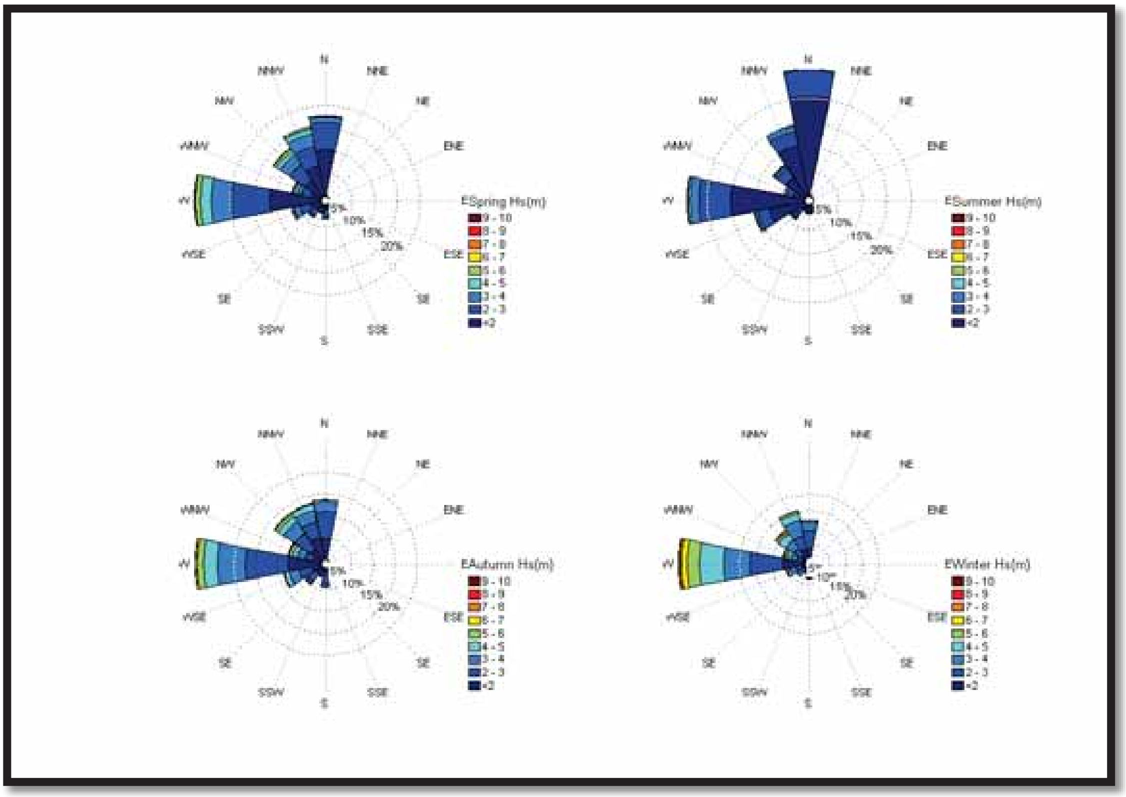
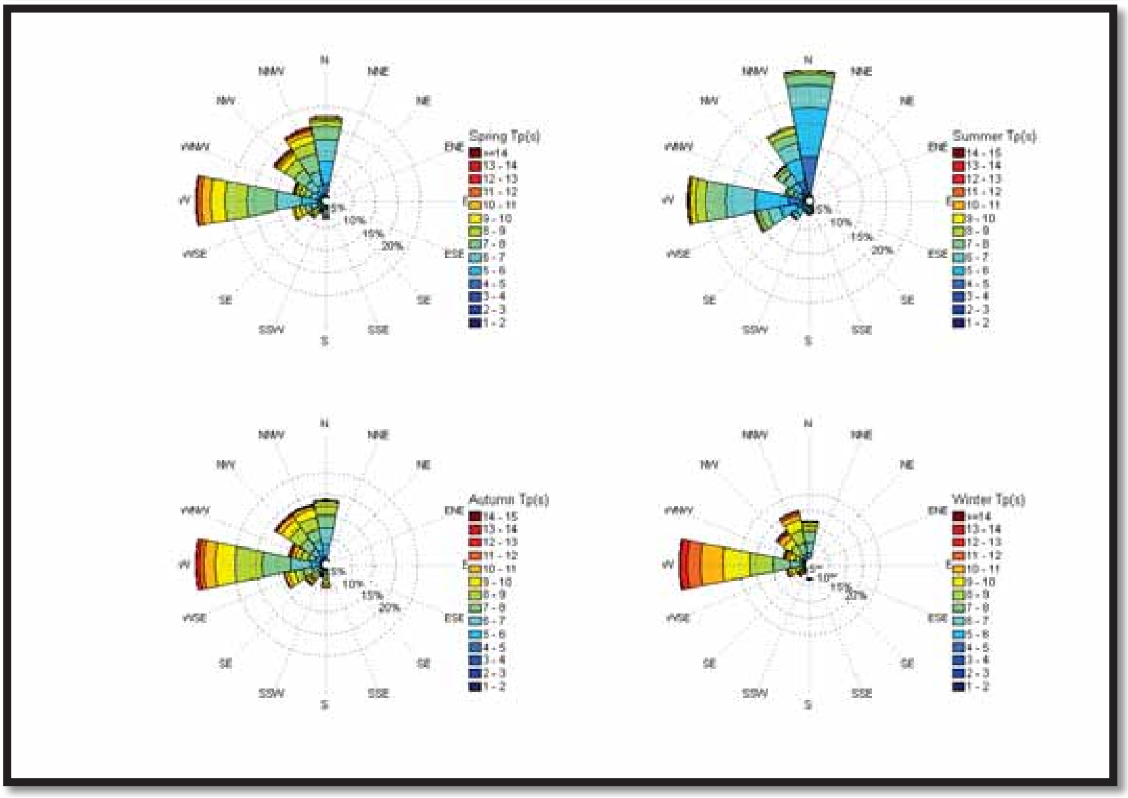
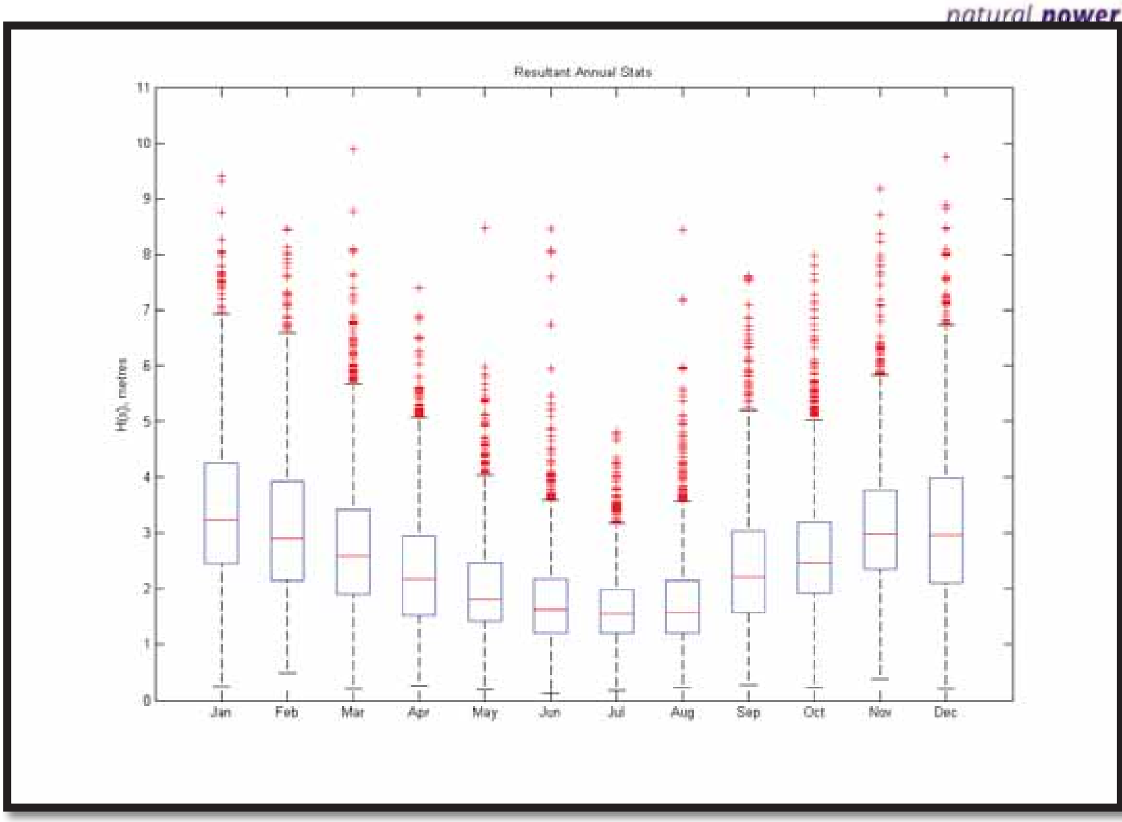
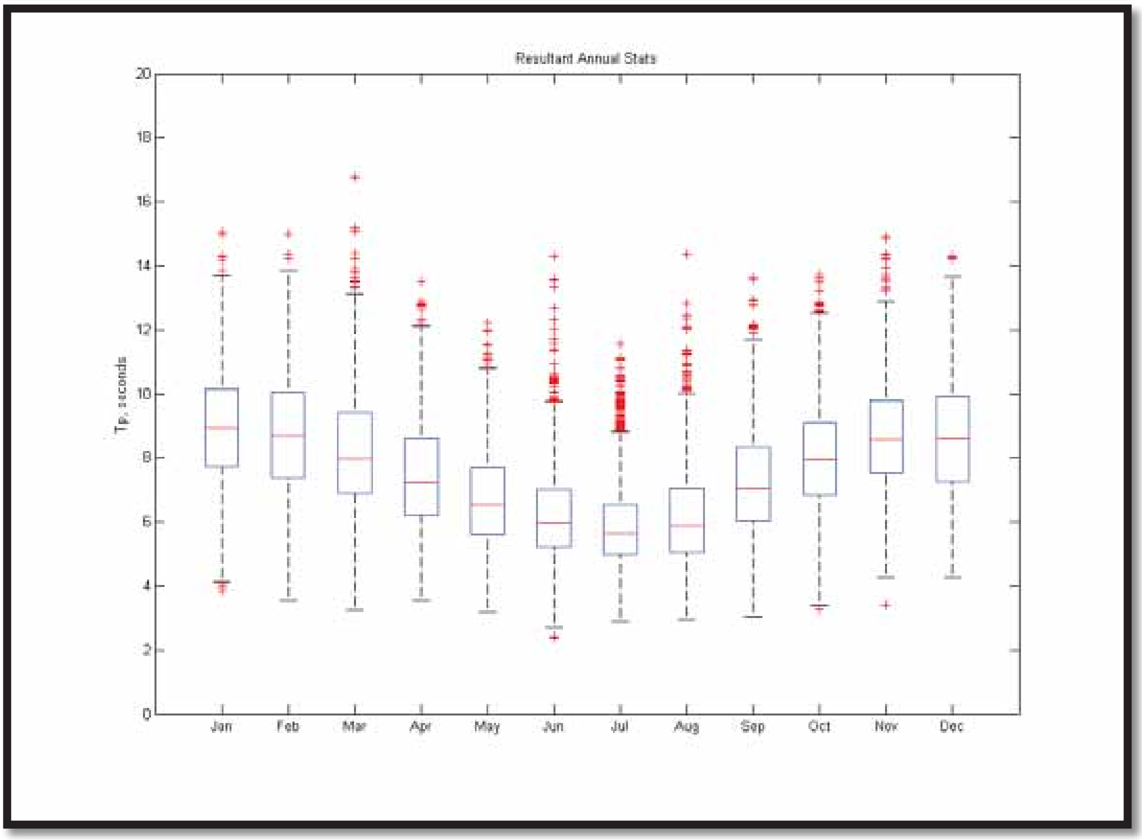
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Extract 2 – (60.14N 2.13W)

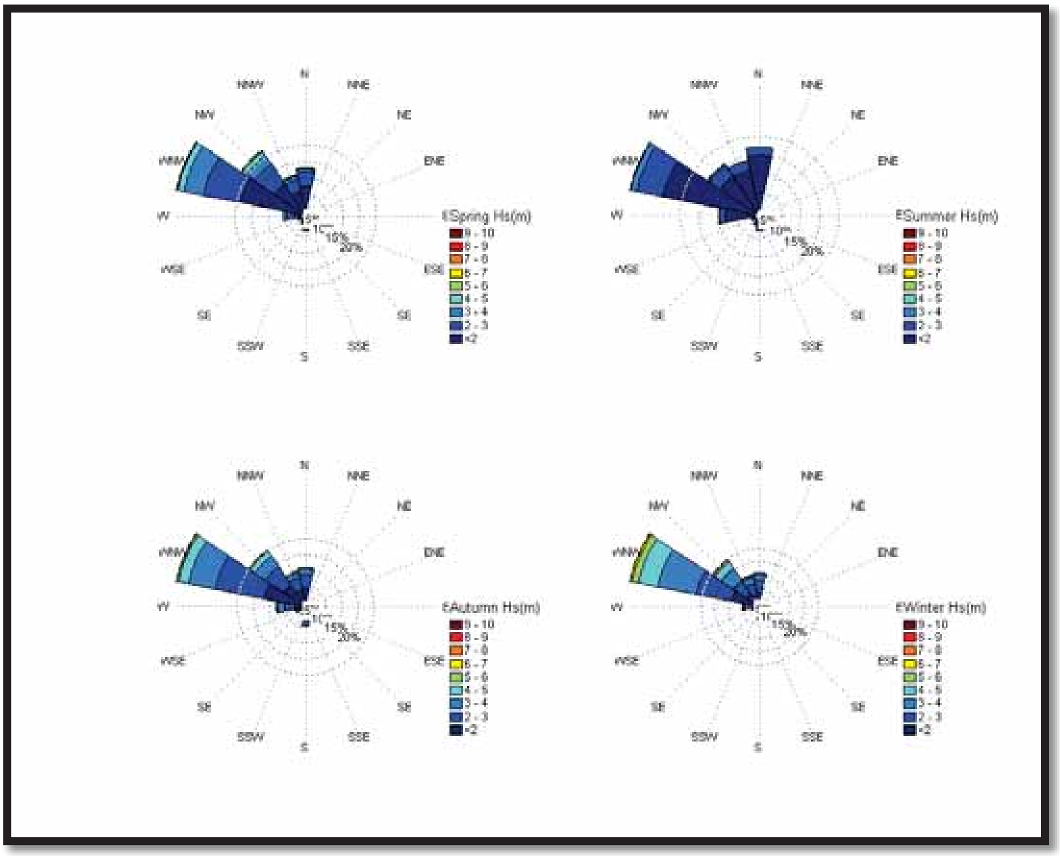


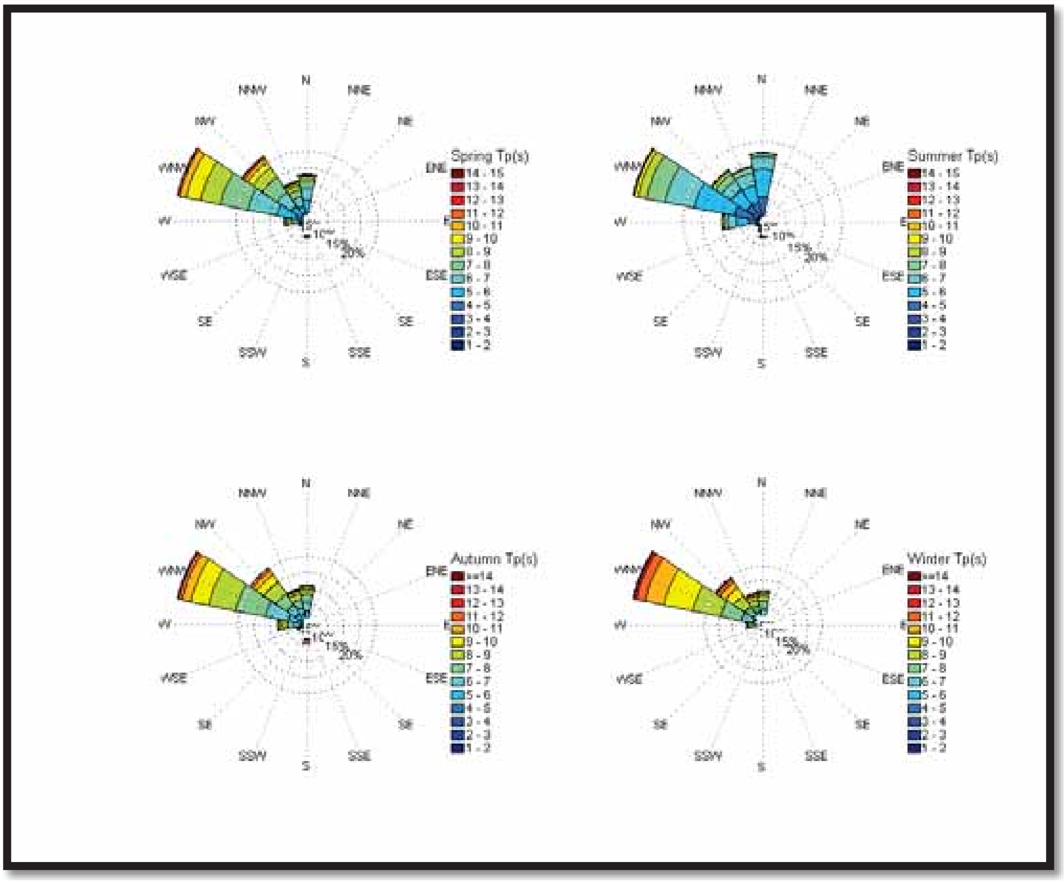


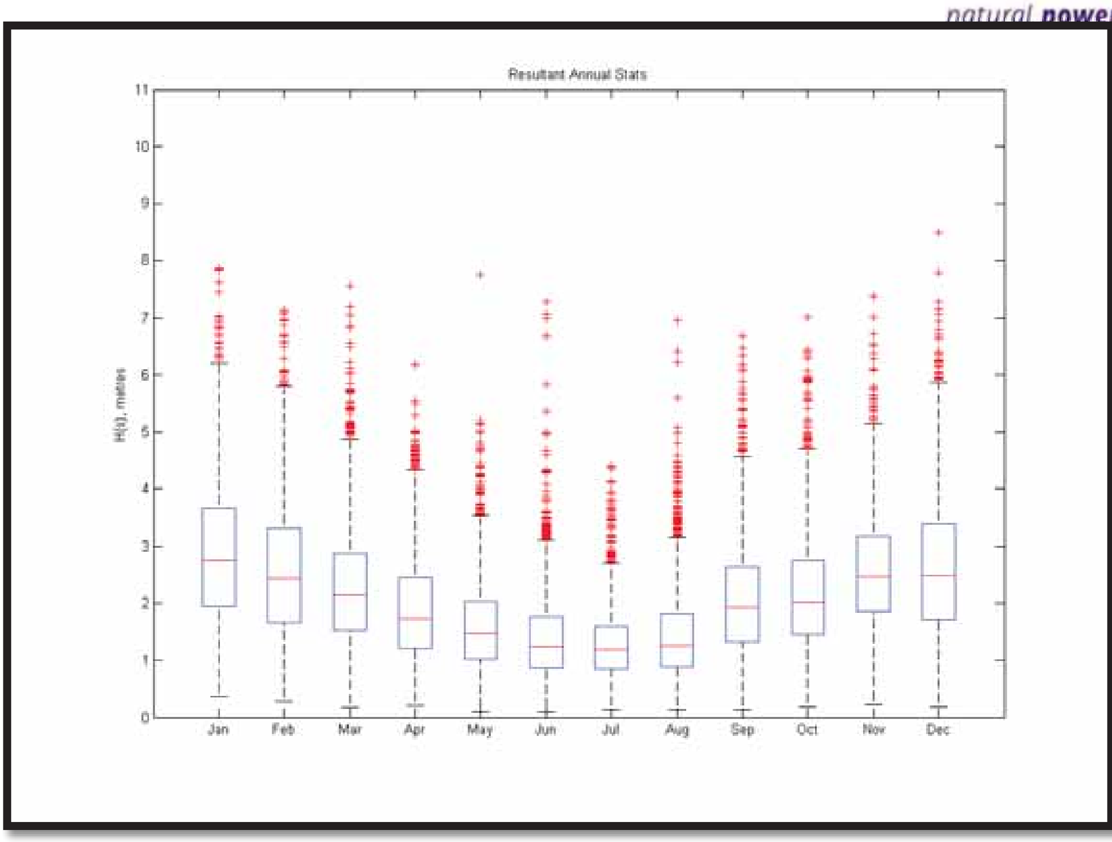

Resultant Annual Stats
H(s), metres
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Resultant Annual Stats
Tp, seconds
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Extract 3 – (59.99N 1.45W)






Resultant Annual Stats
H(s), metres
Jan
Feb
Mar
Apr
May
Jun
Jul
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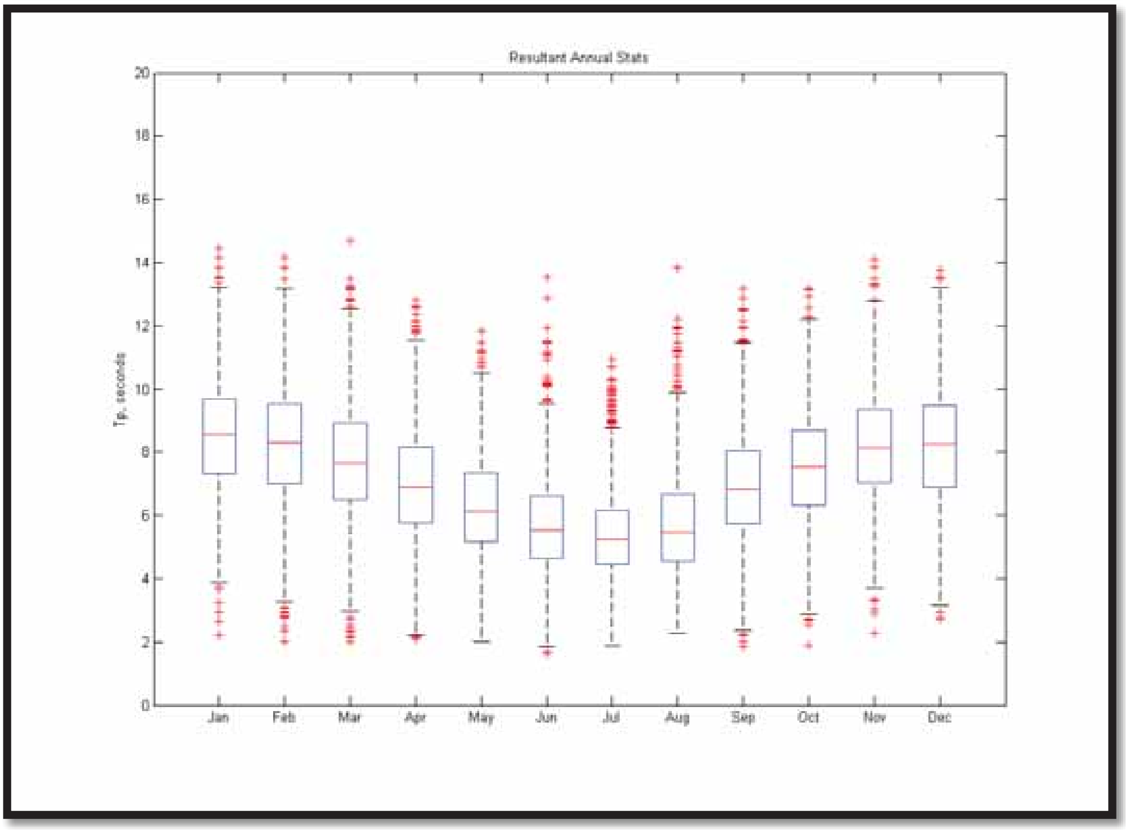
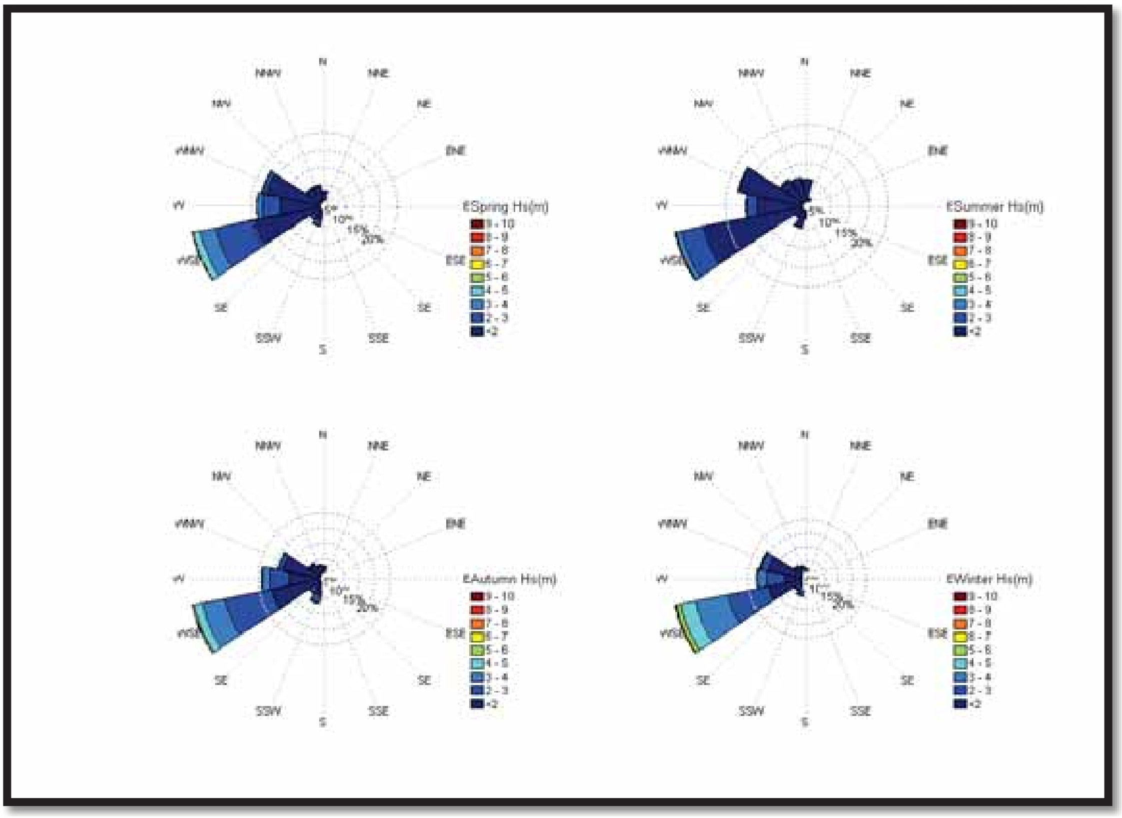
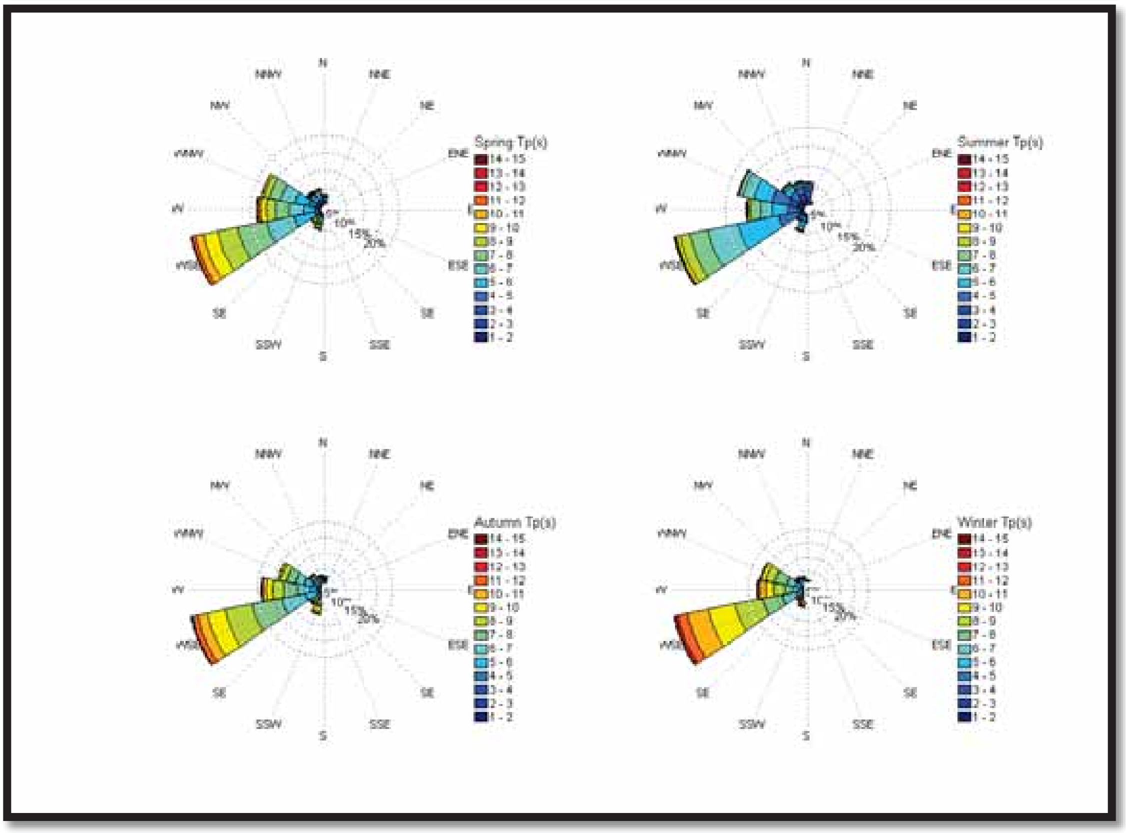
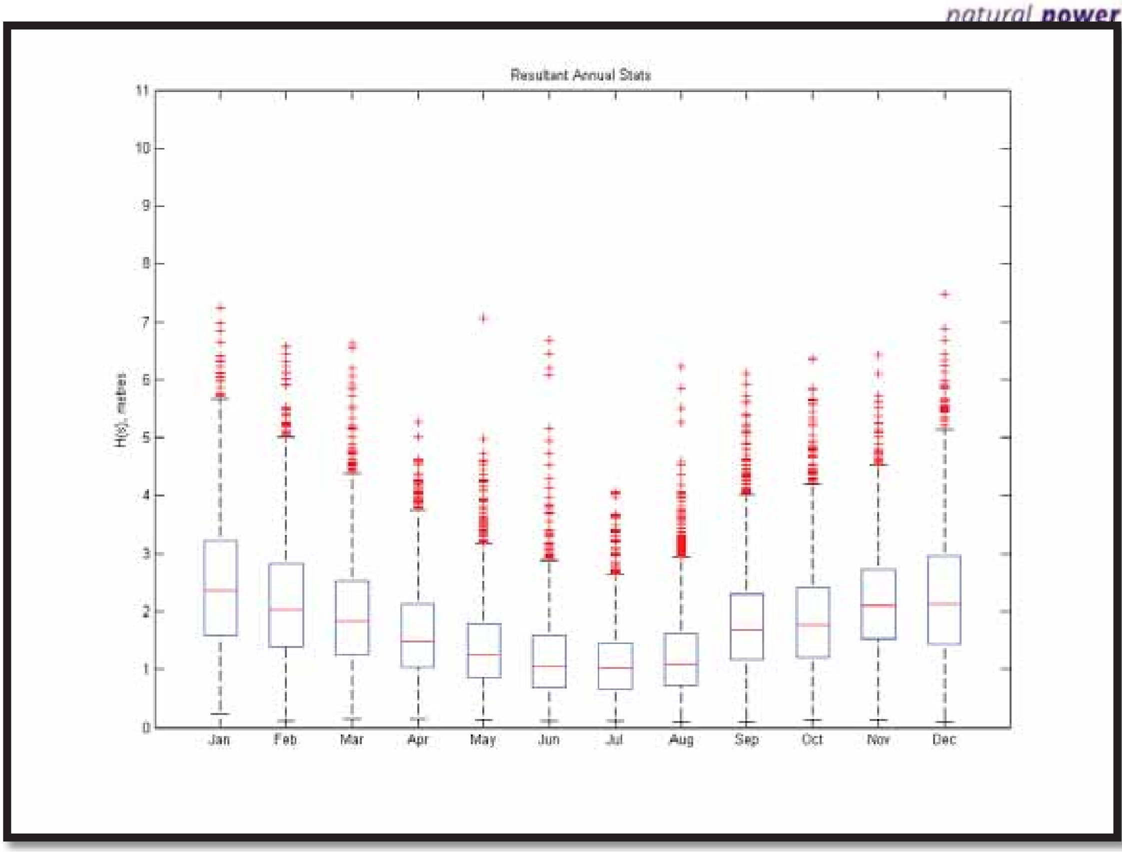
Sep
Oct
Nov
Dec


Resultant Annual Stats
Tp, seconds
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Extract 4 – (60.11N 1.42W)






Resultant Annual Stats
H(S), metres
Jan
Feb
Mar
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Jul
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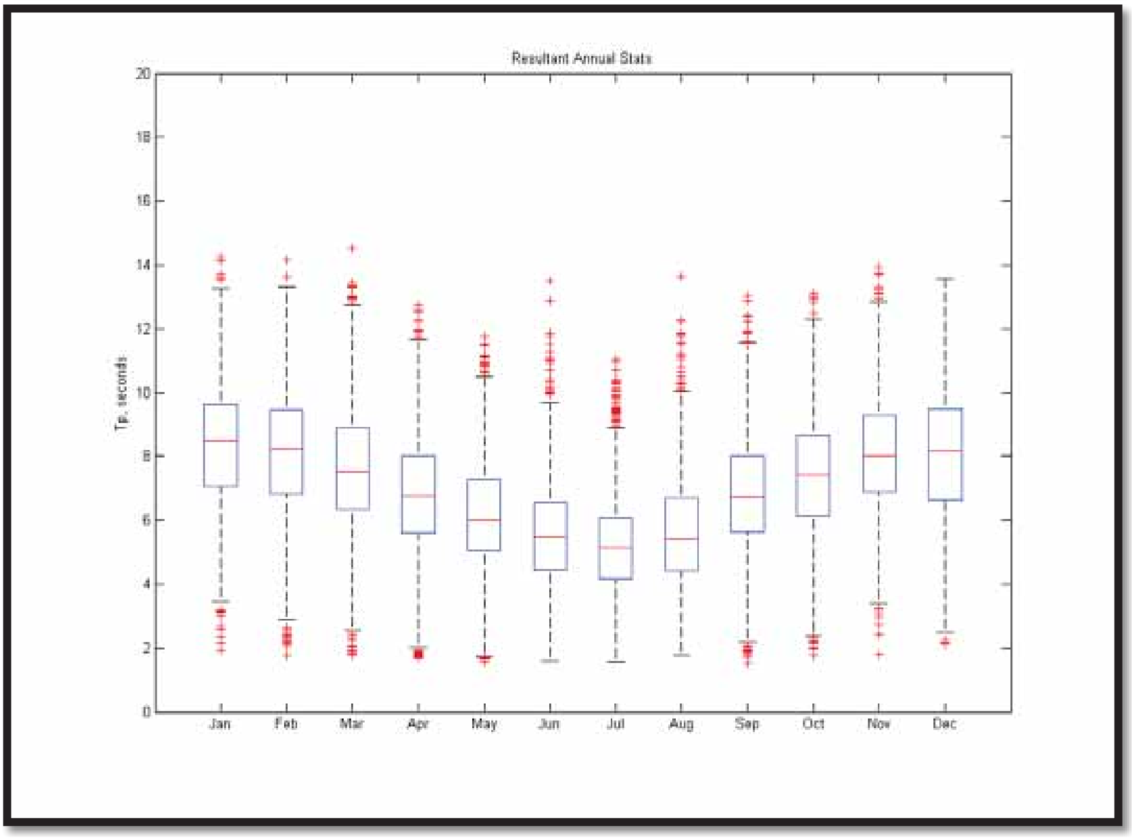
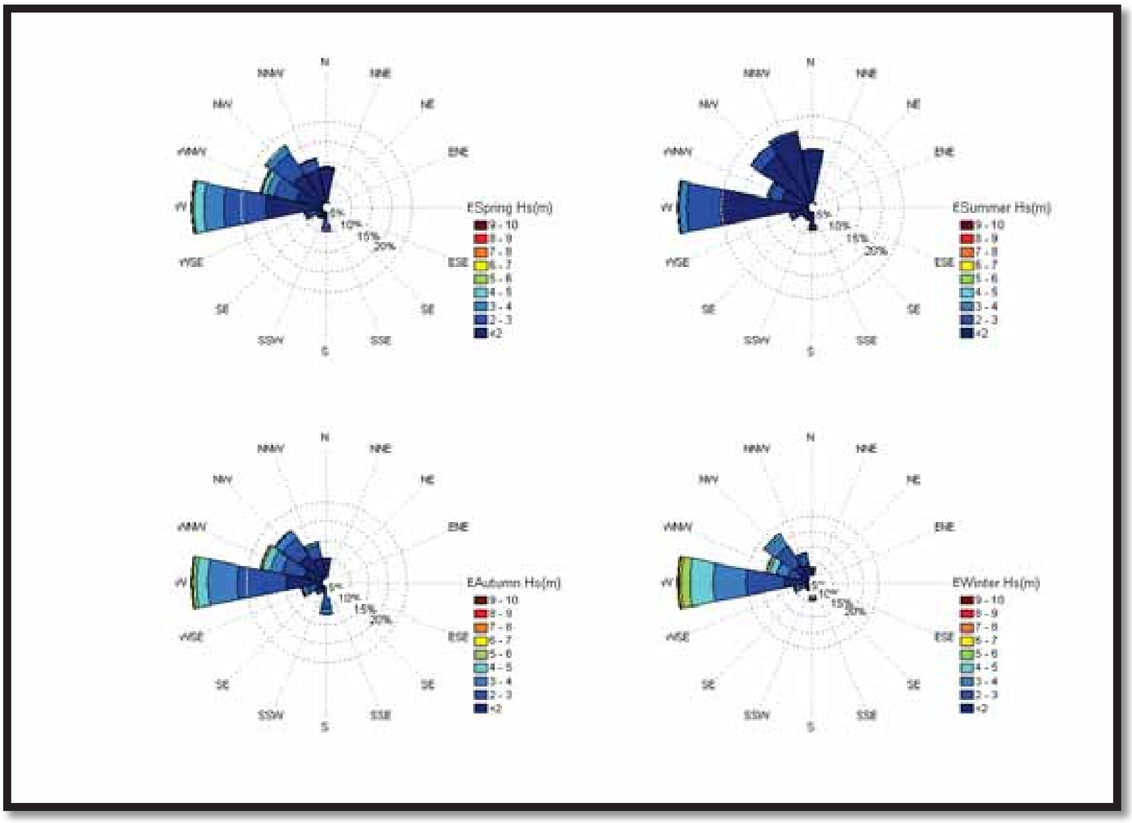
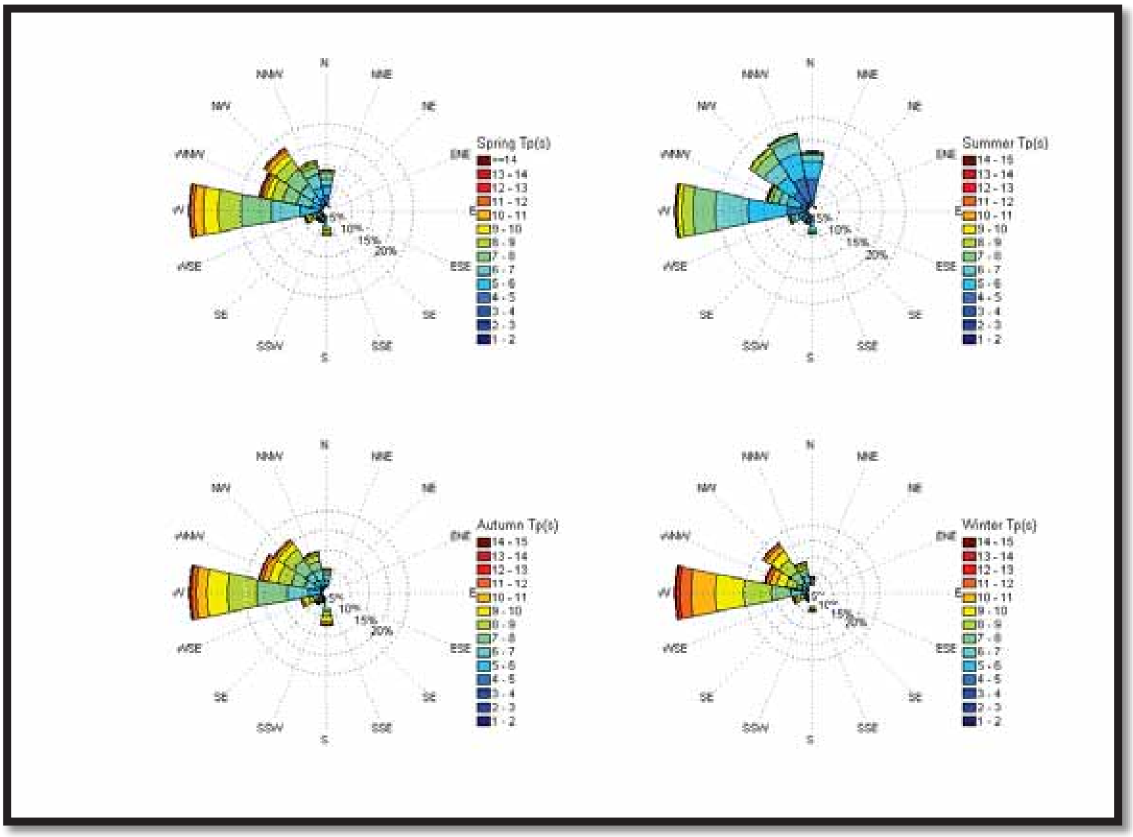
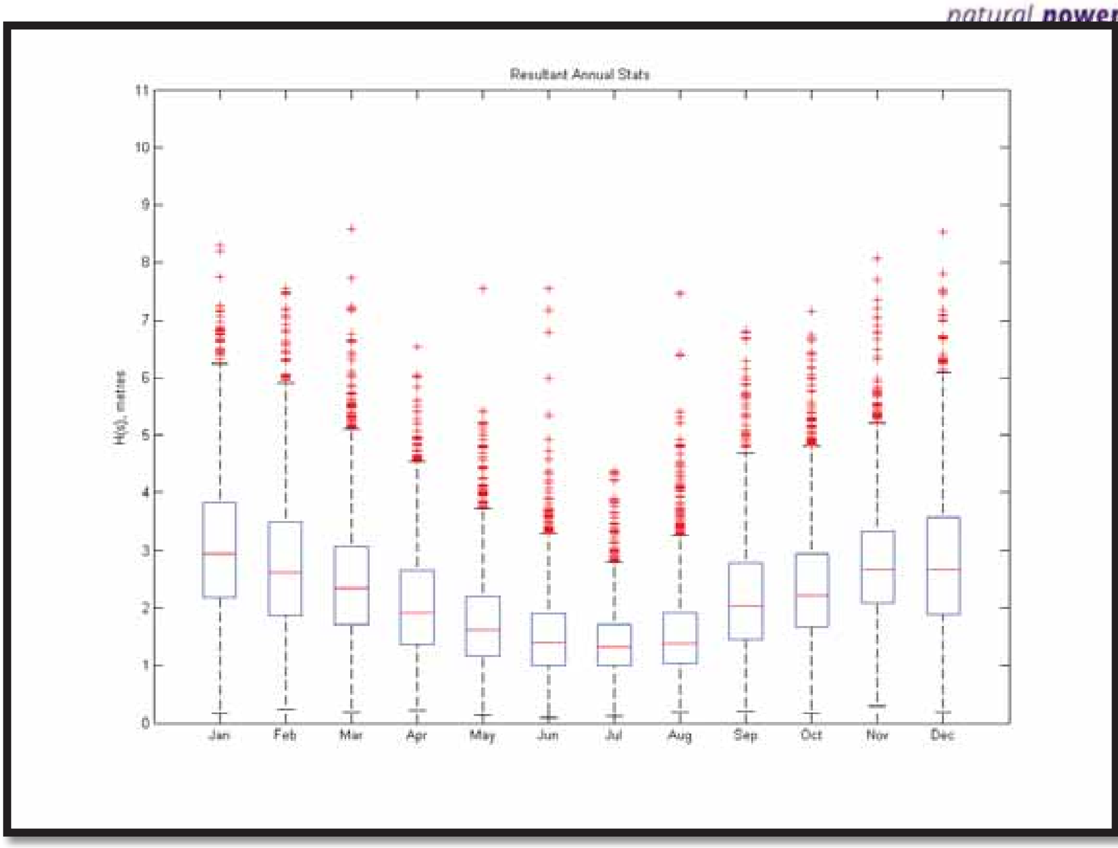
Nov
Dec


Resultant Annual Stats
Tp, seconds
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Extract 5 – (60.26N 1.74W)






Resultant Annual Stats
H(s), metres
0
1
2
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4
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Jan
Feb
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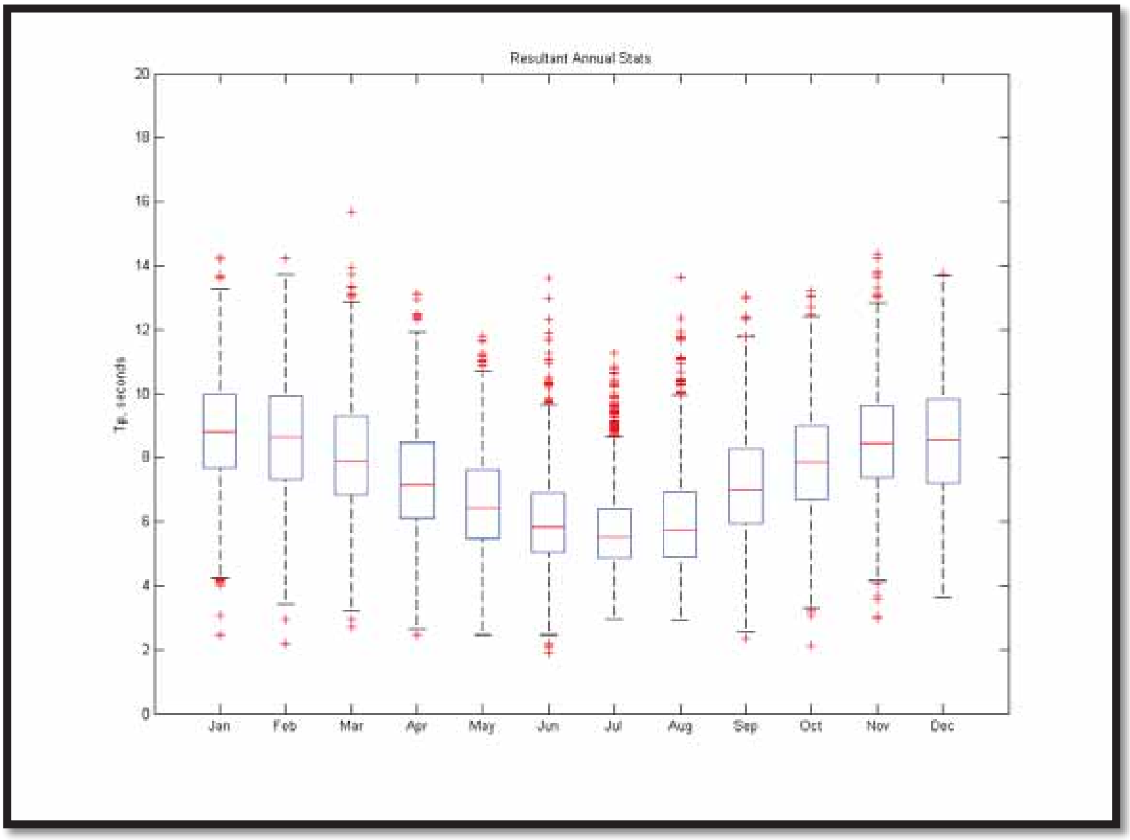
Dec


Resultant Annual Stats
Tp, seconds
0
2
4
6
8
10
12
14
16
18
20
Jan
Feb
Mar
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May
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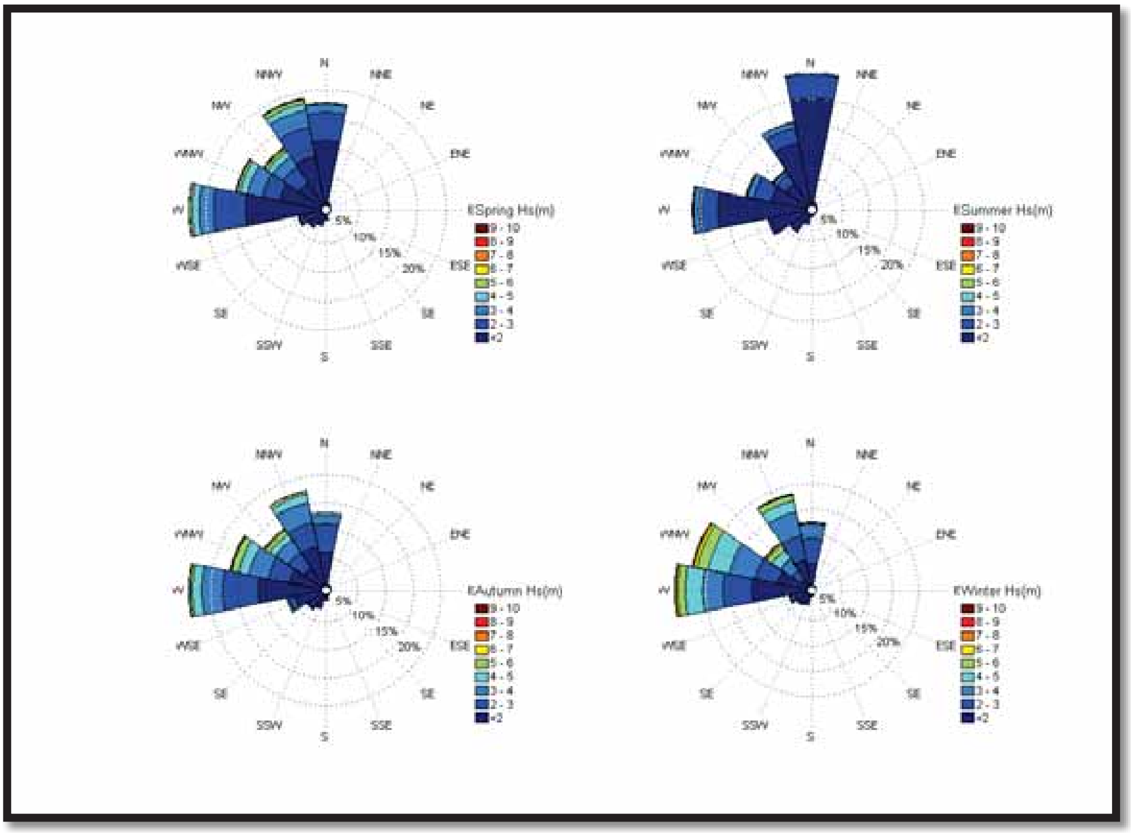
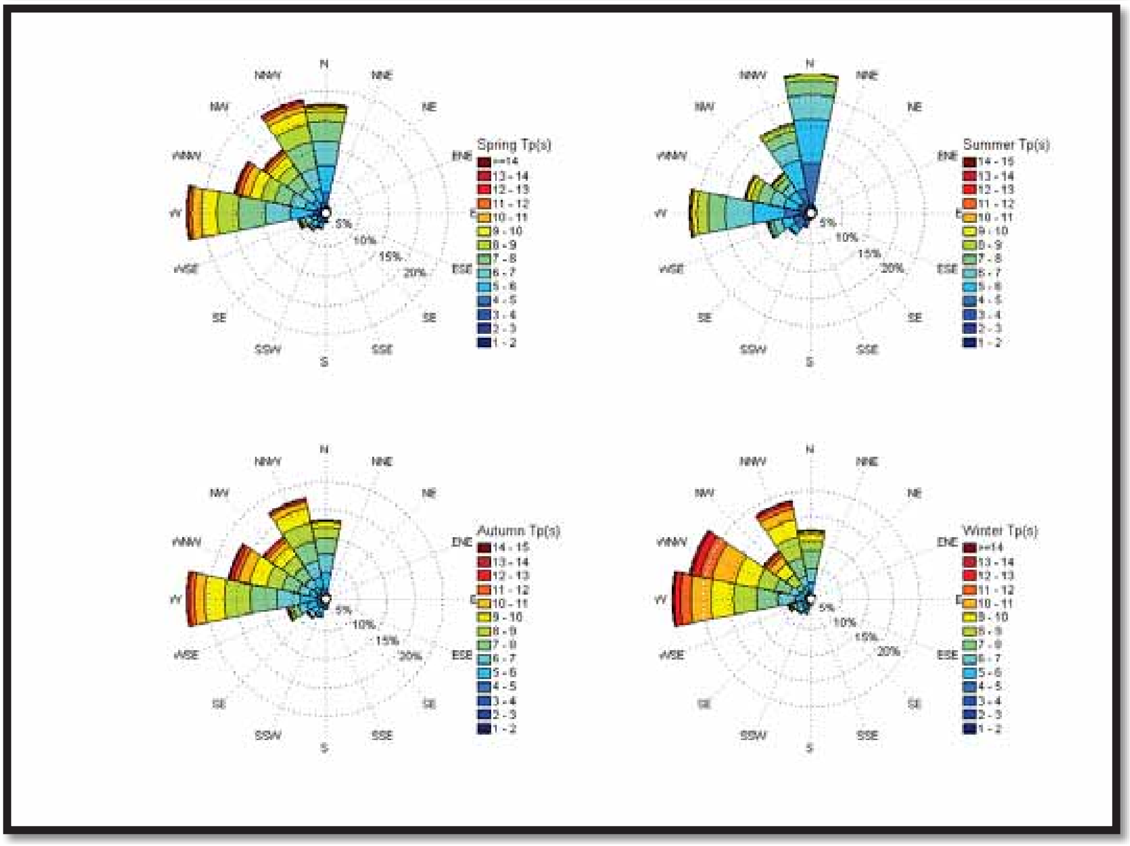
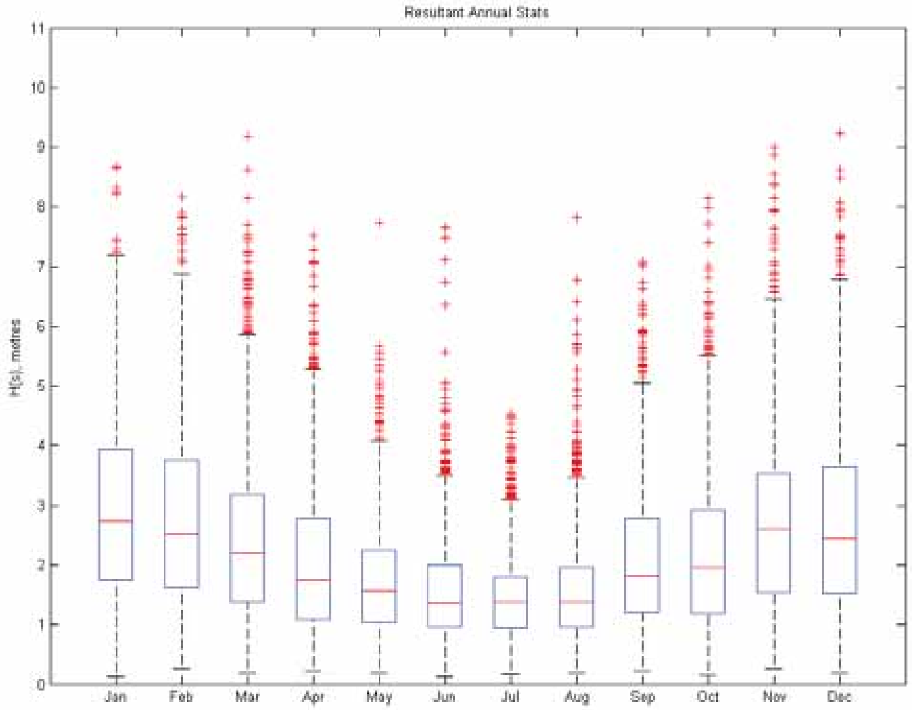
Oct
Nov
Dec

Extract 6 – (60.52N 1.61W)






Resultant Annual Stats
H(s), metres
Jan
Feb
Mar
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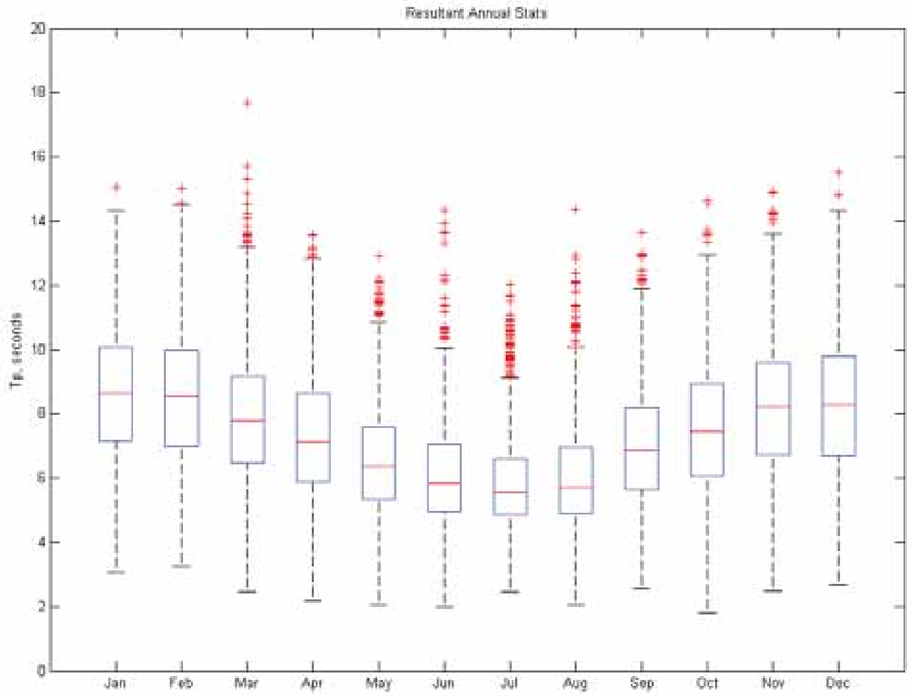
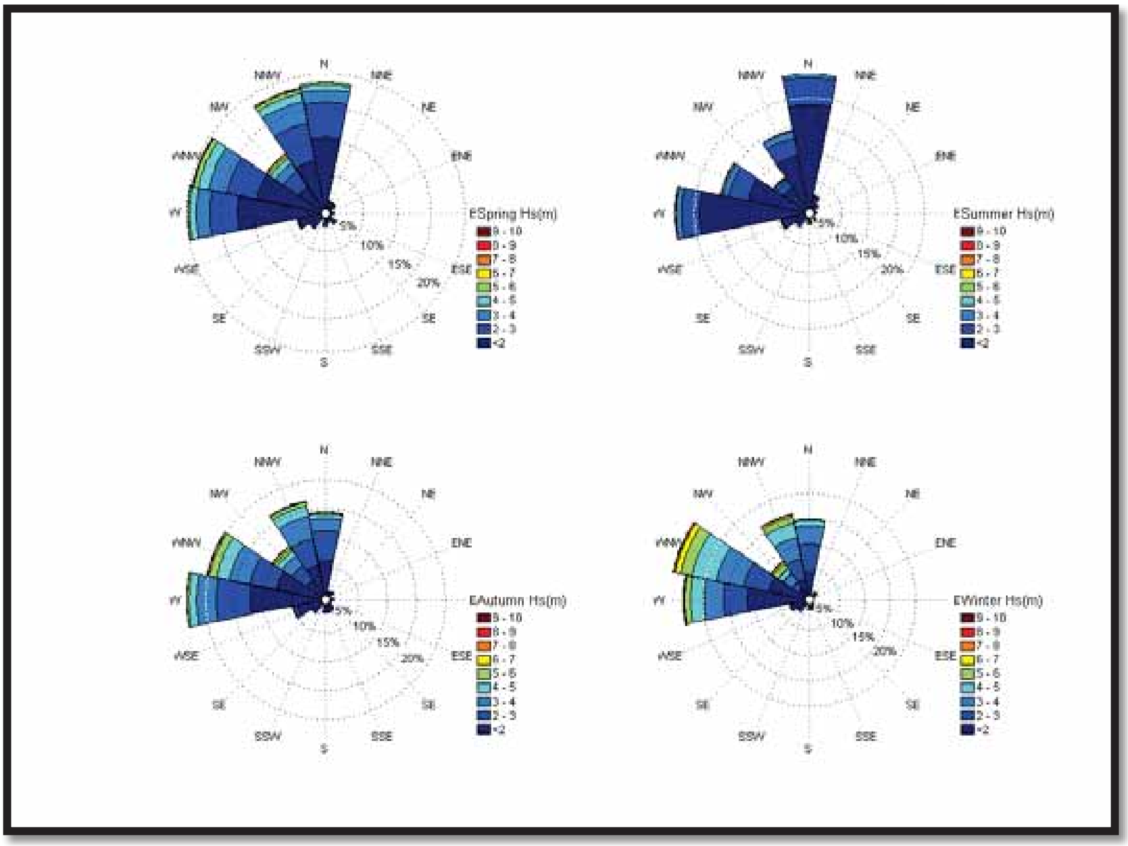
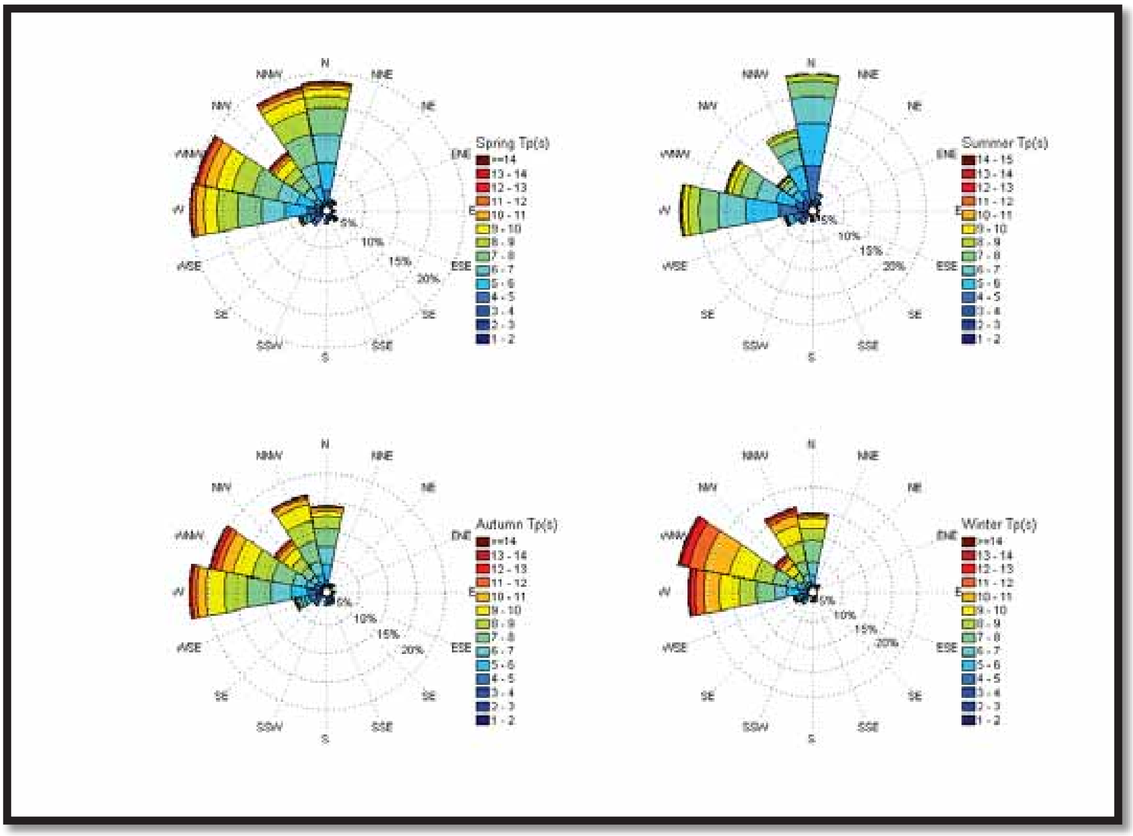
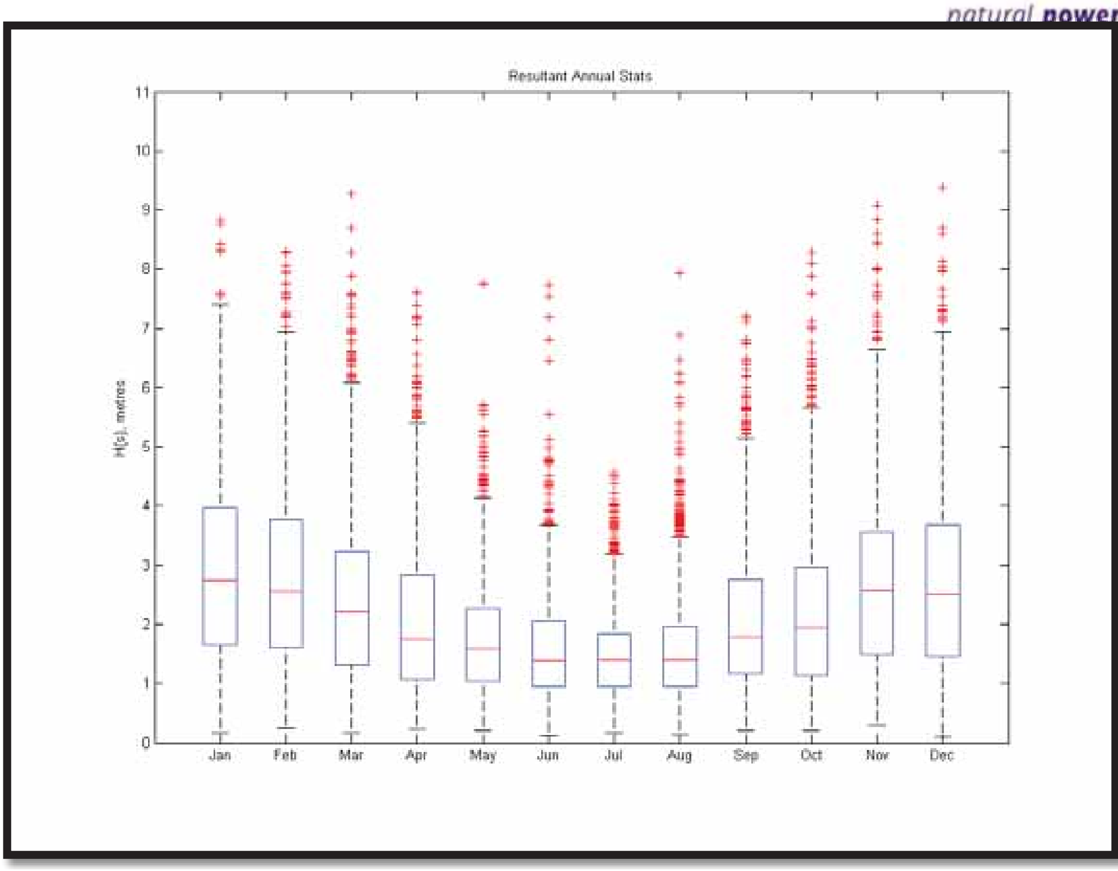
Sep
Oct
Nov
Dec


Resultant Annual Stats
Tp, seconds
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Extract 7 – (60.59N 1.50W)






Resultant Annual Stats
H(s), metres
0
1
2
3
4
5
6
7
8
9
10
11
Jan
Feb
Mar
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May
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Jul
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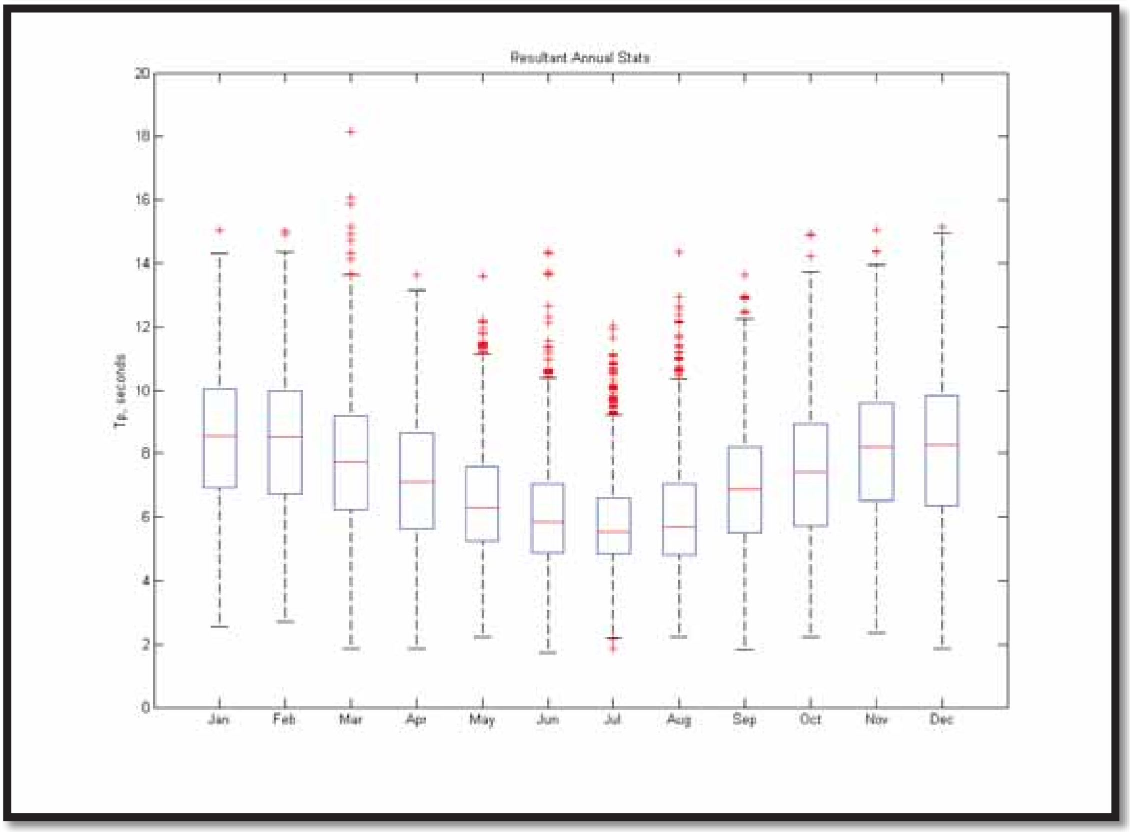
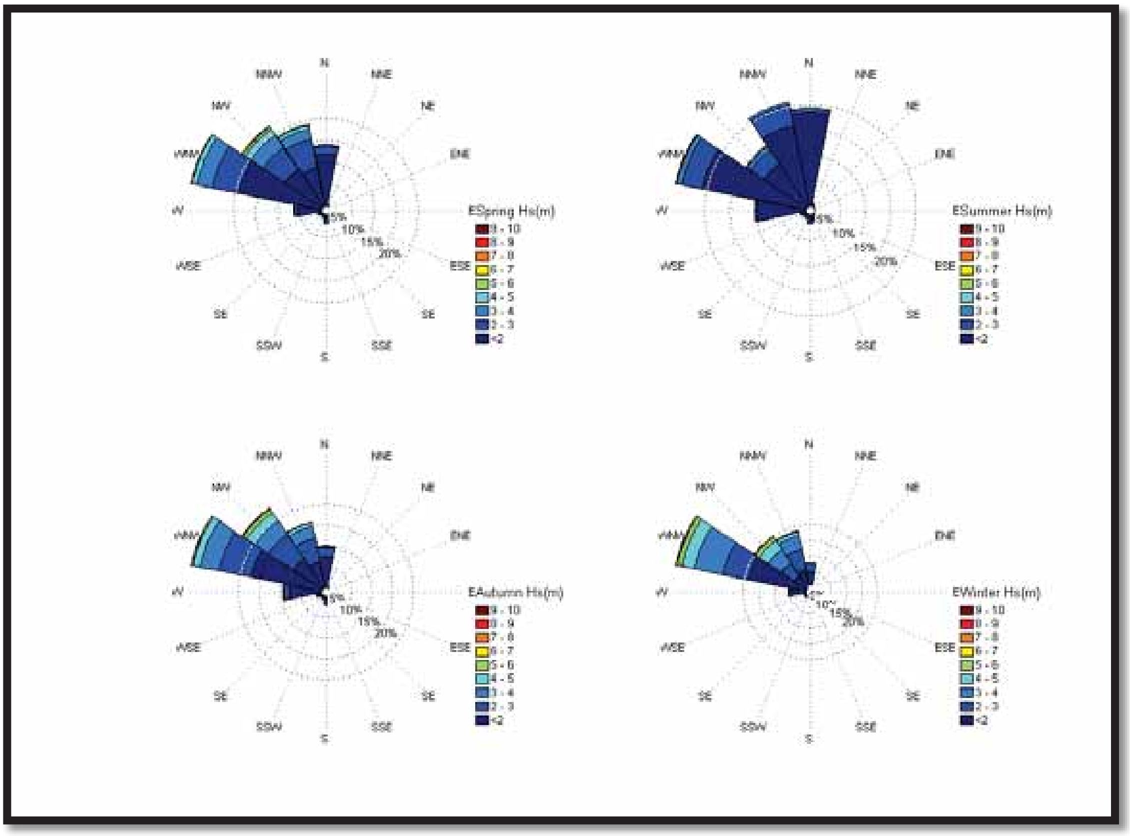
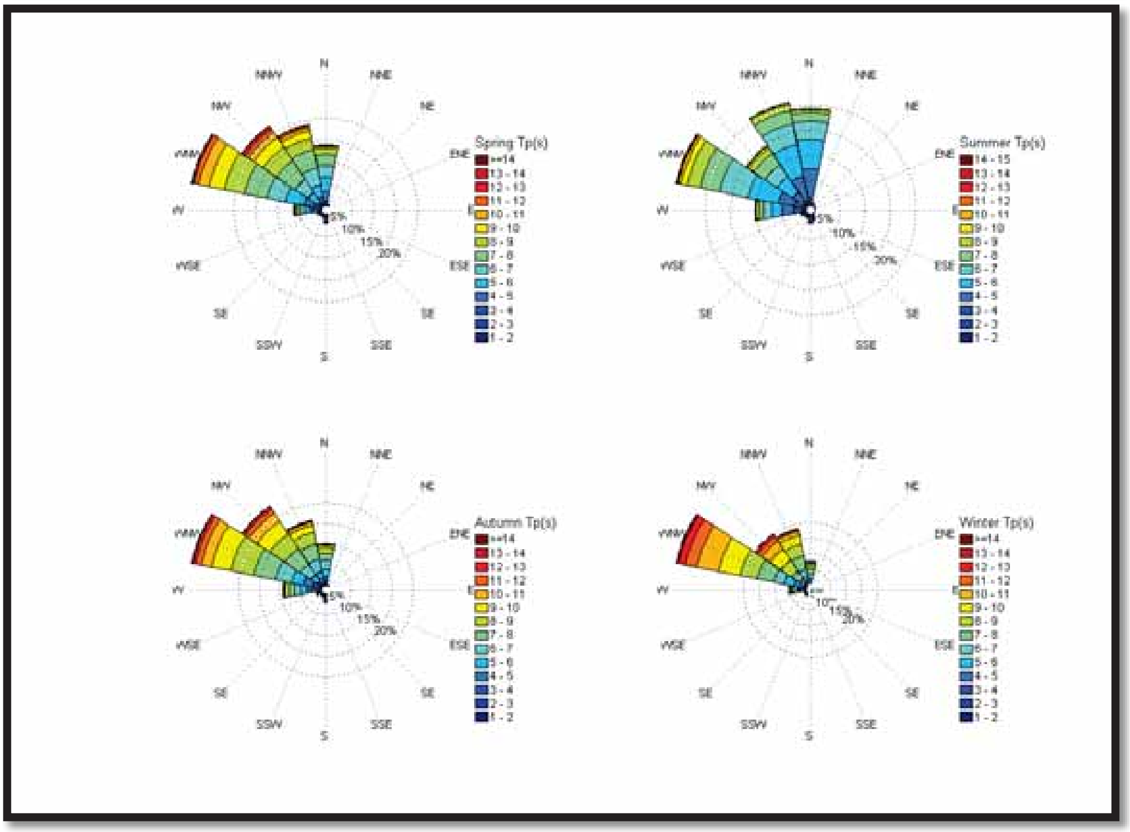
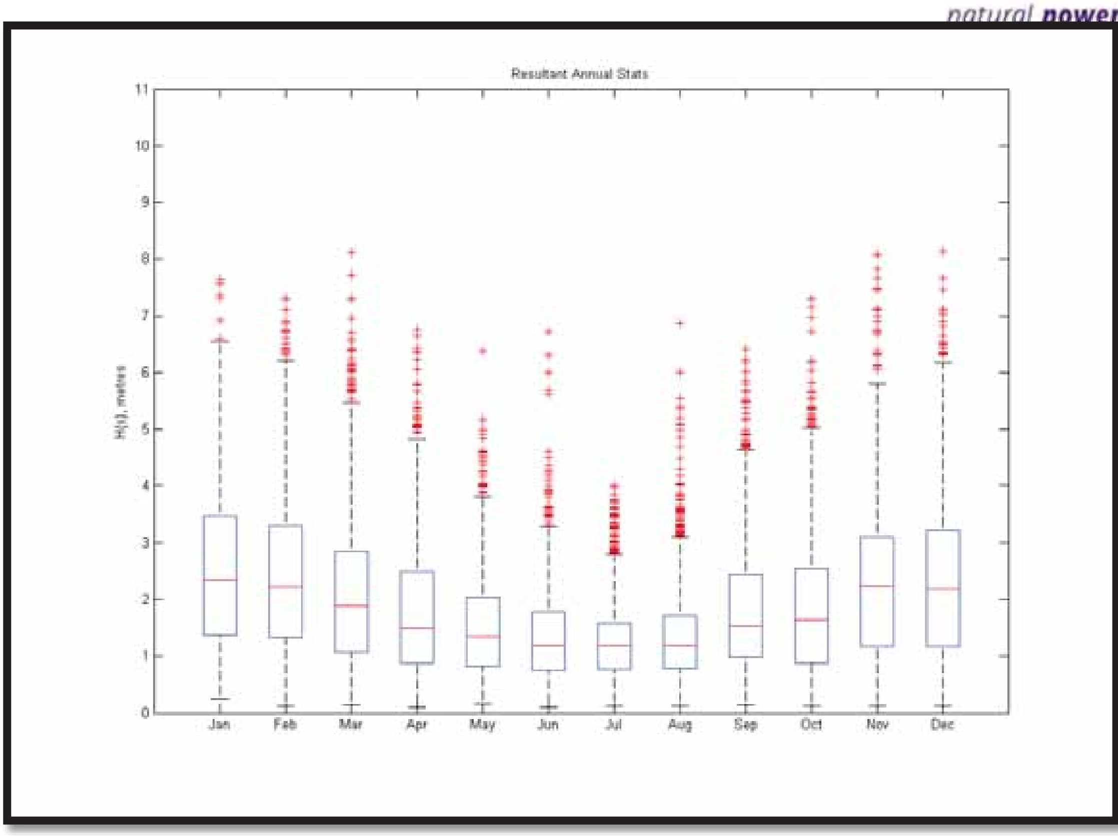
Sep
Oct
Nov
Dec

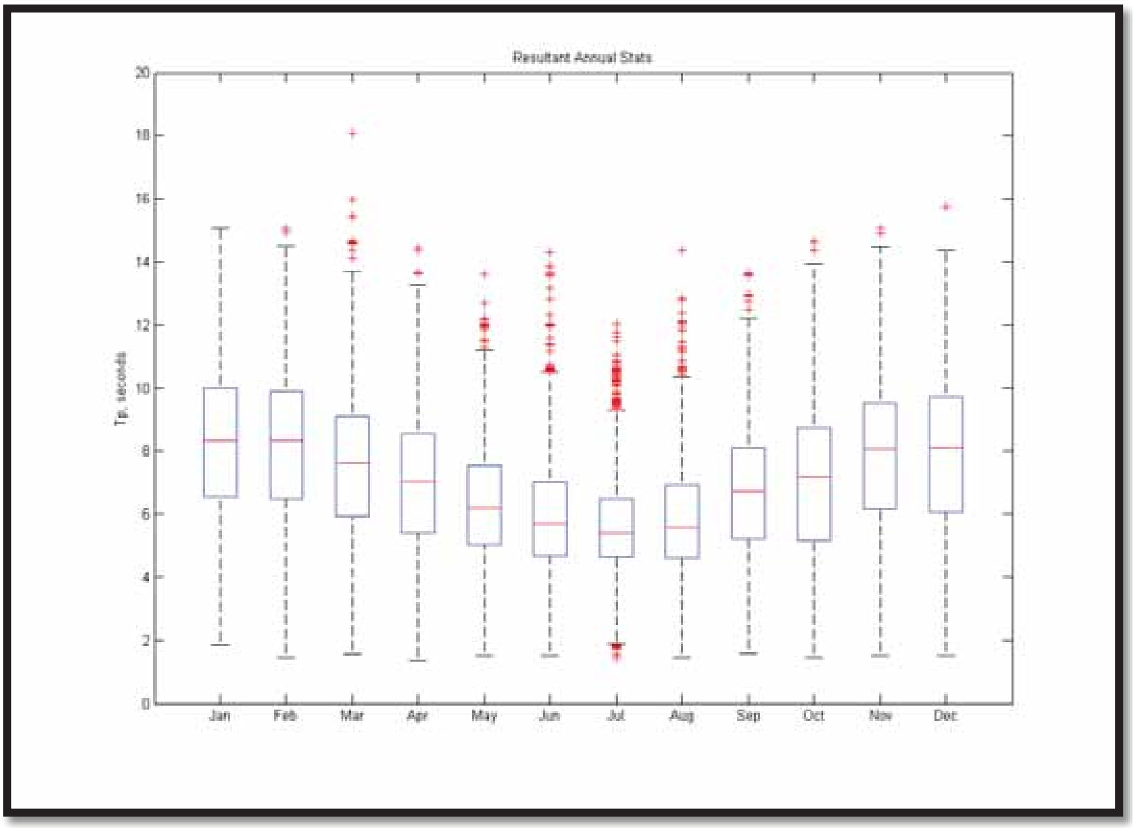

Resultant Annual Stats
Tp, seconds
0
2
4
6
8
10
12
14
16
18
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Extract 8 – (60.68N 1.17W)






Resultant Annual Stats
Hs(t), metres
0
1
2
3
4
5
6
7
8
9
10
11
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Resultant Annual Stats
Tp, seconds
0
2
4
6
8
10
12
14
16
18
20
Jan
Feb
Mar
Apr
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Jul
Aug
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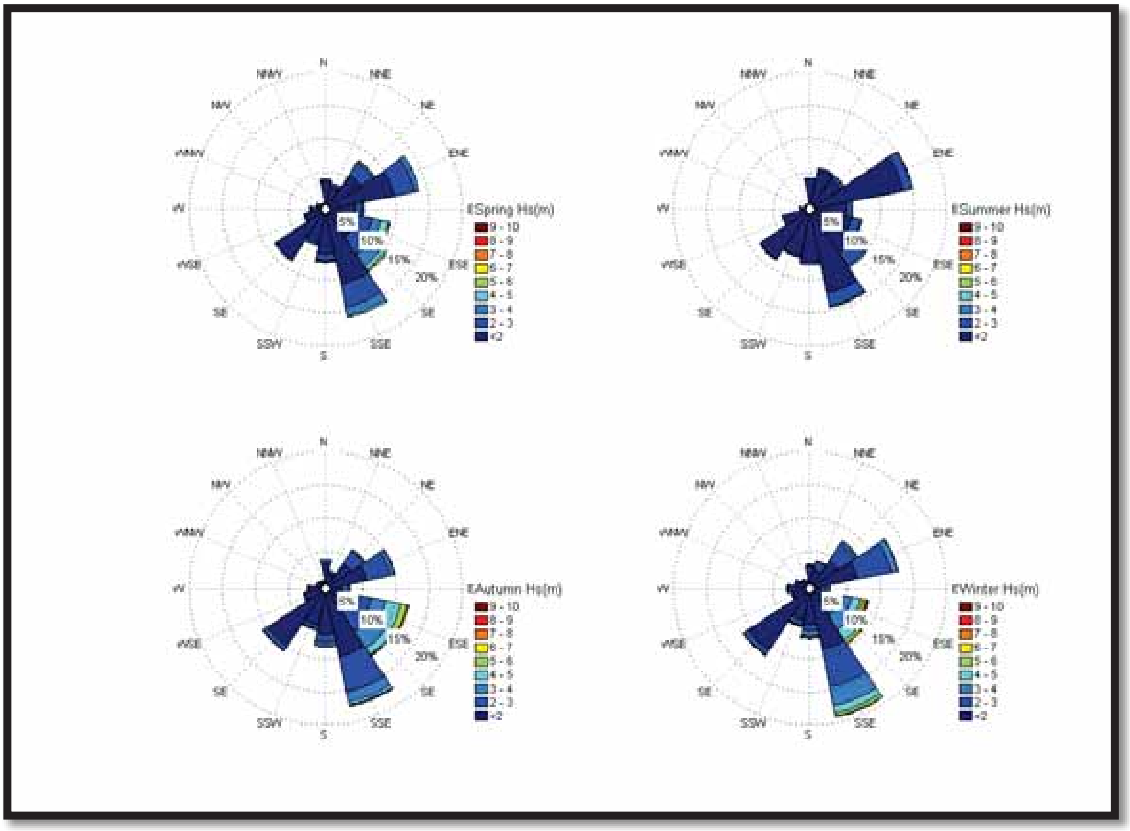
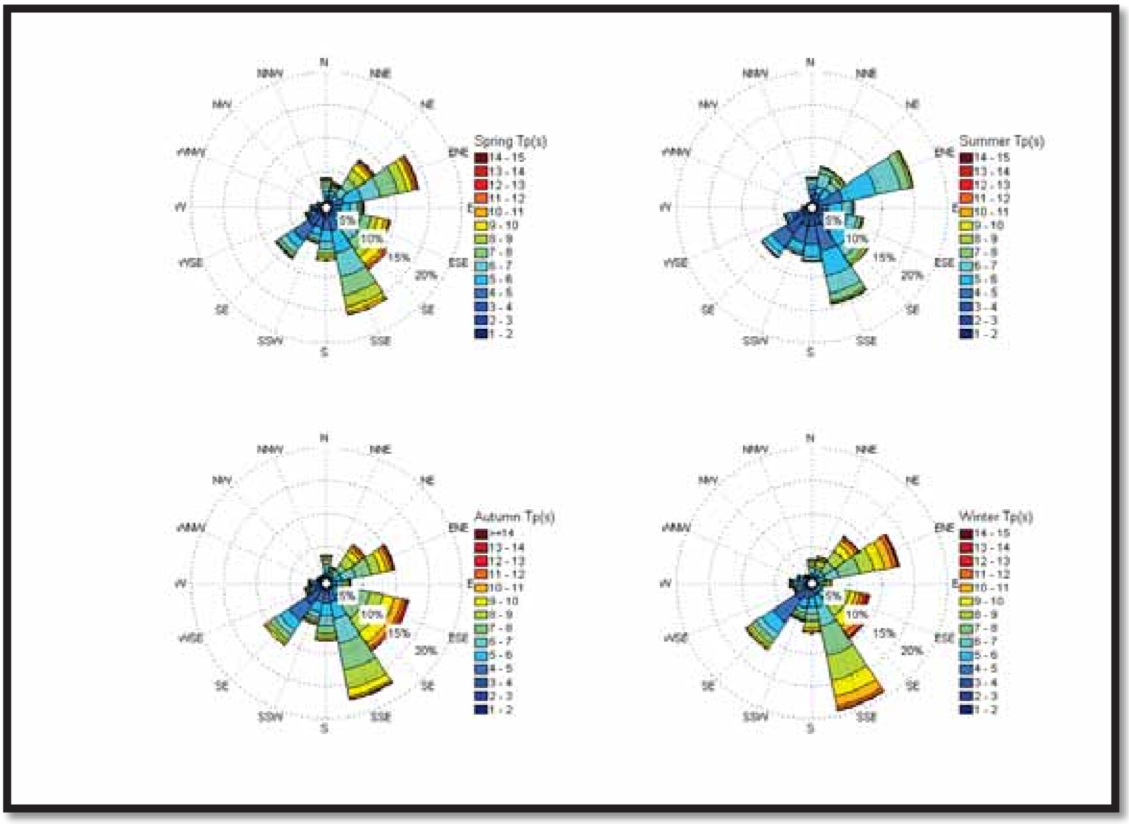
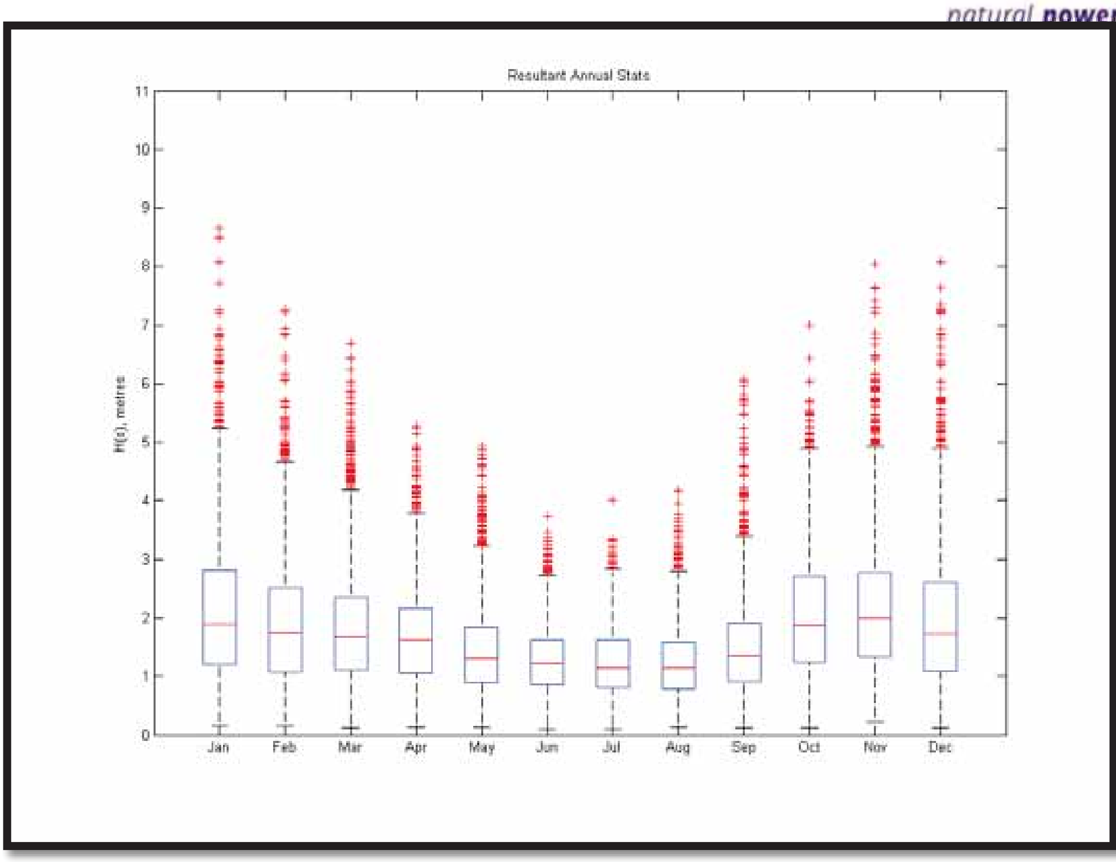
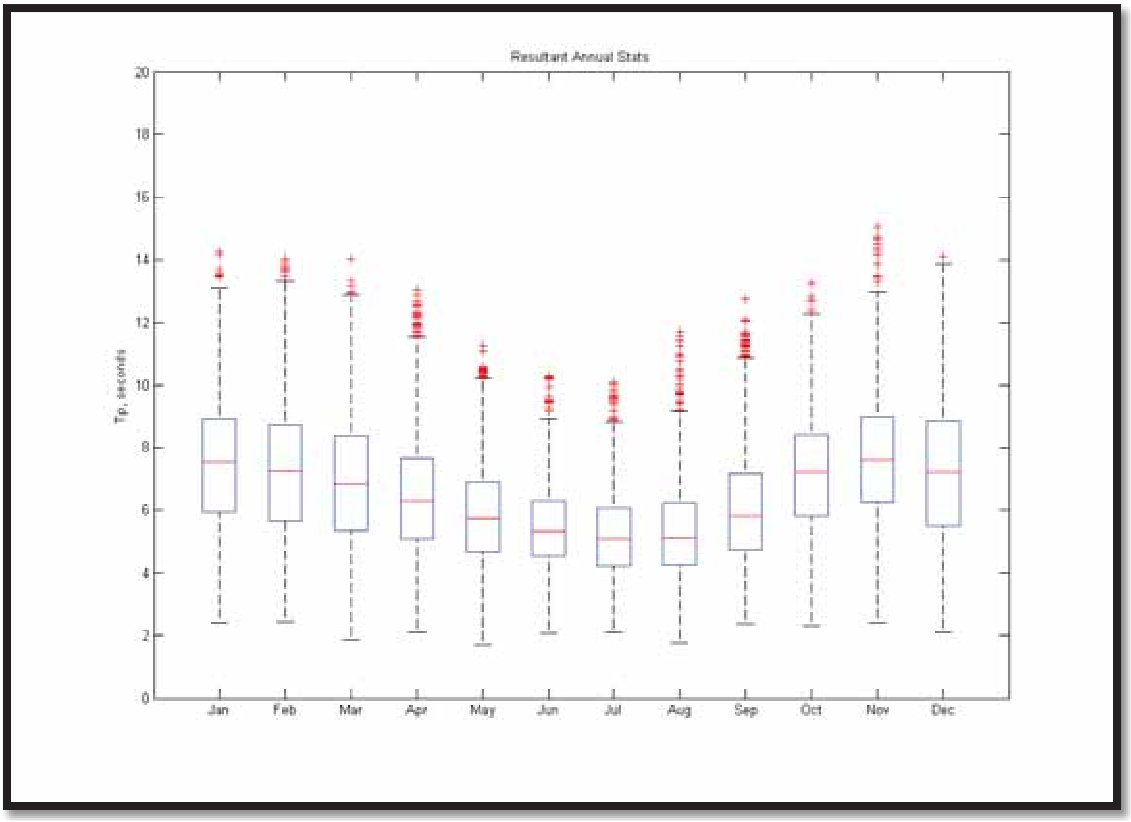
Oct
Nov
Dec

Extract 9 – (60.58N 0.75W)






Resultant Annual Stats
H(s), metres
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec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Tp, seconds
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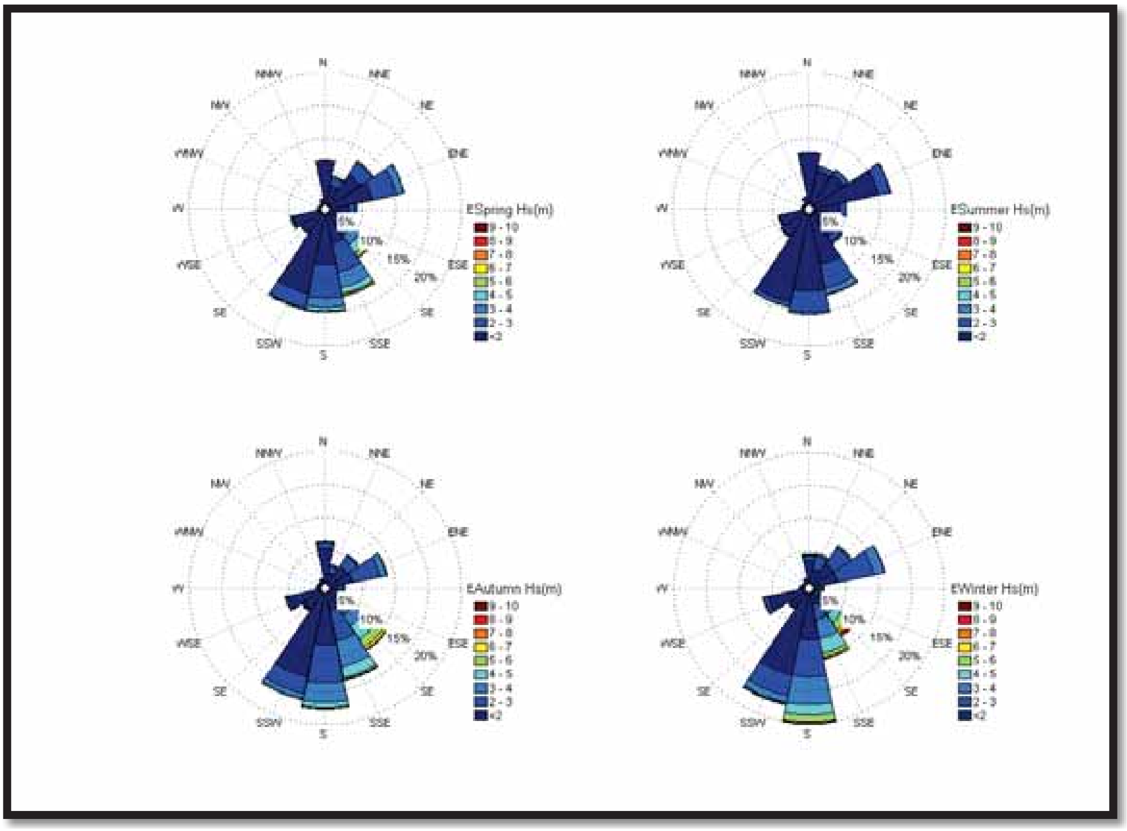
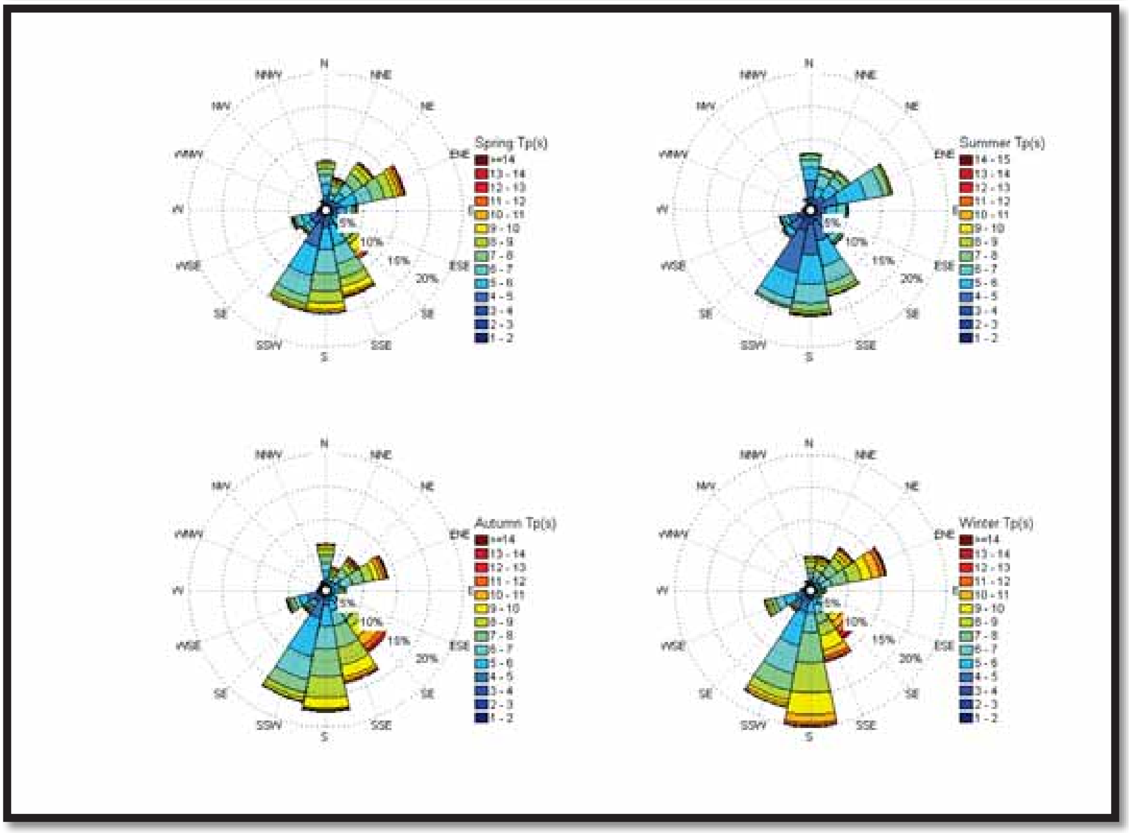
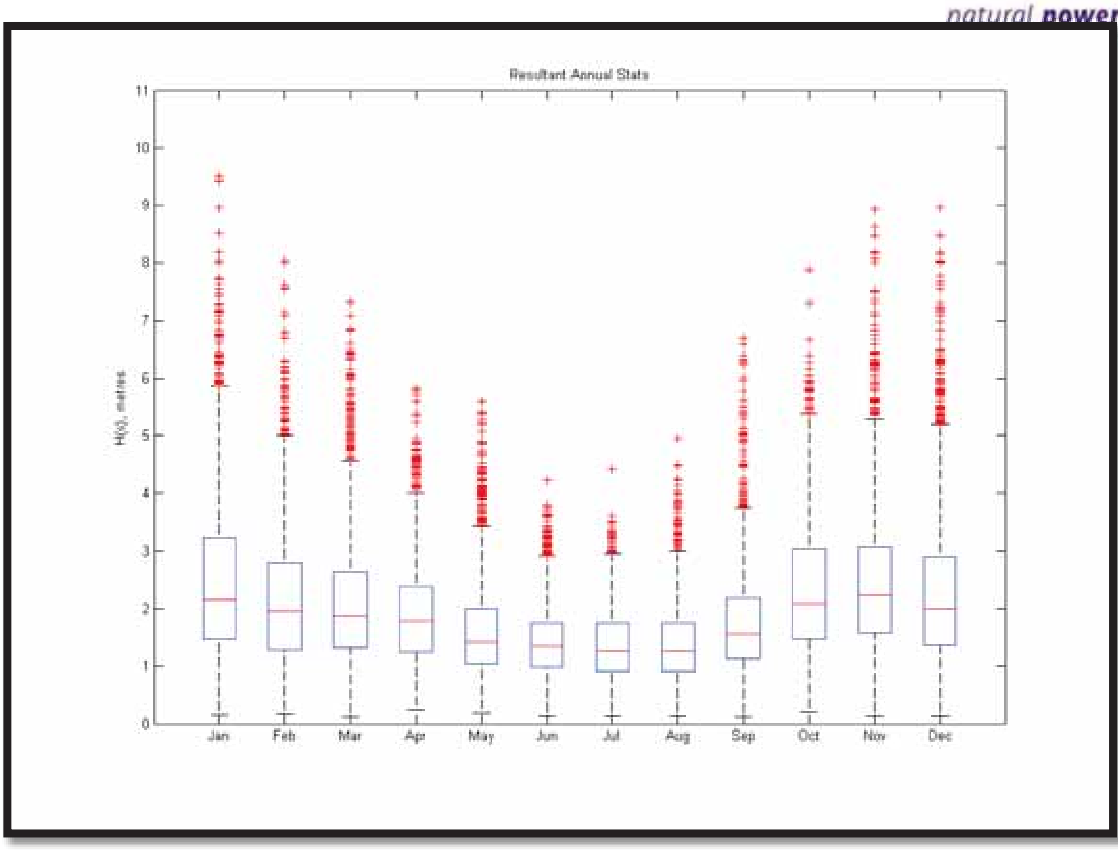
Extract 10 – (60.41N 0.71W)






Resultant Annual Stats
H(s), metres
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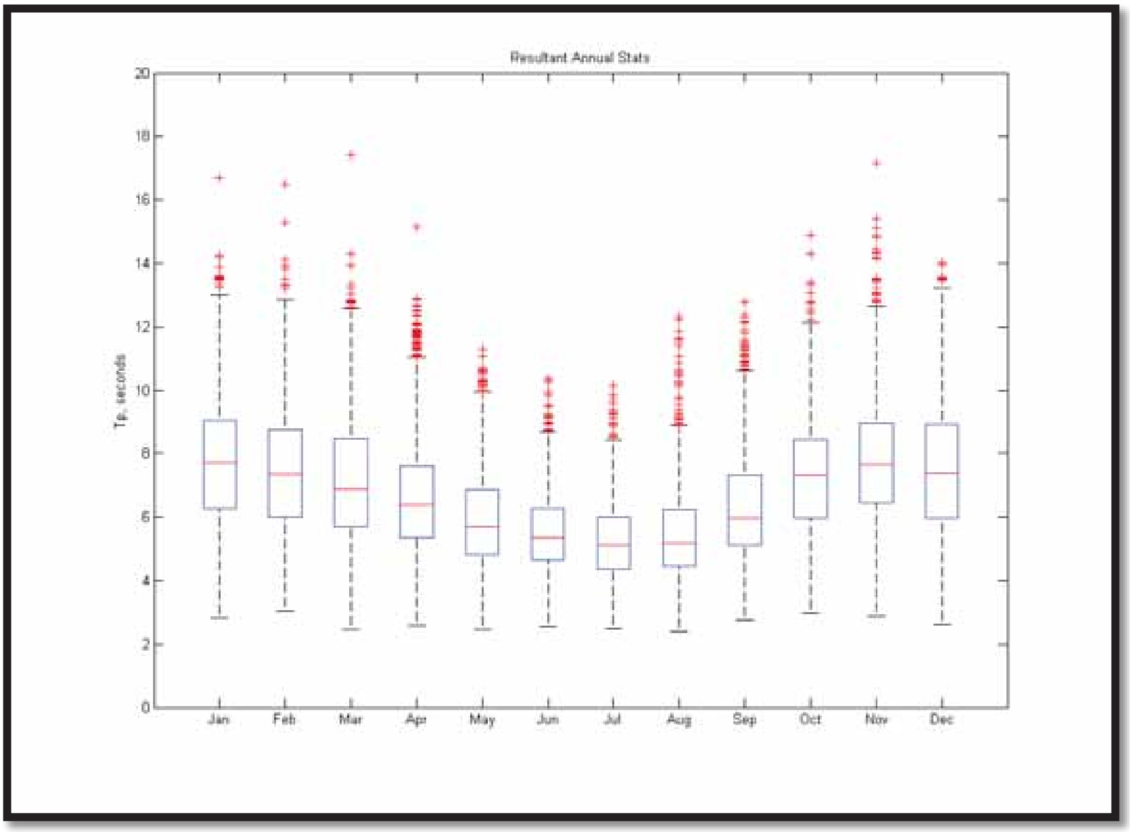
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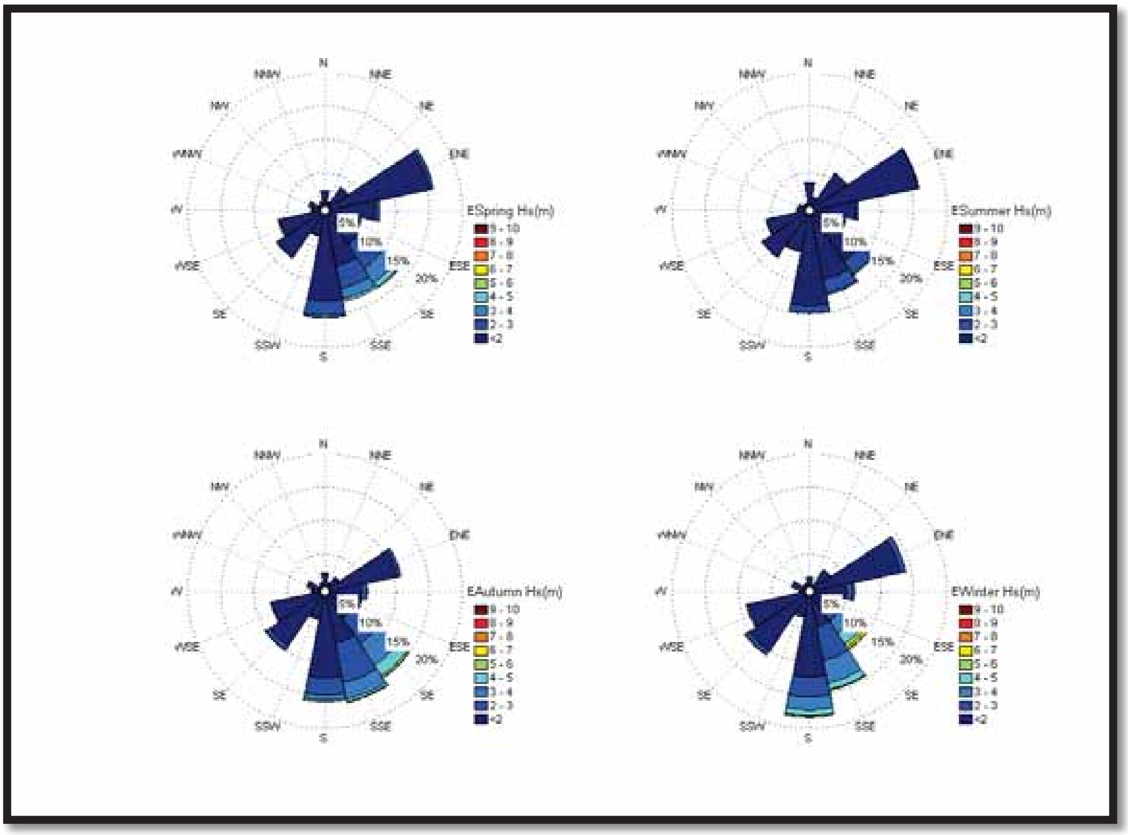
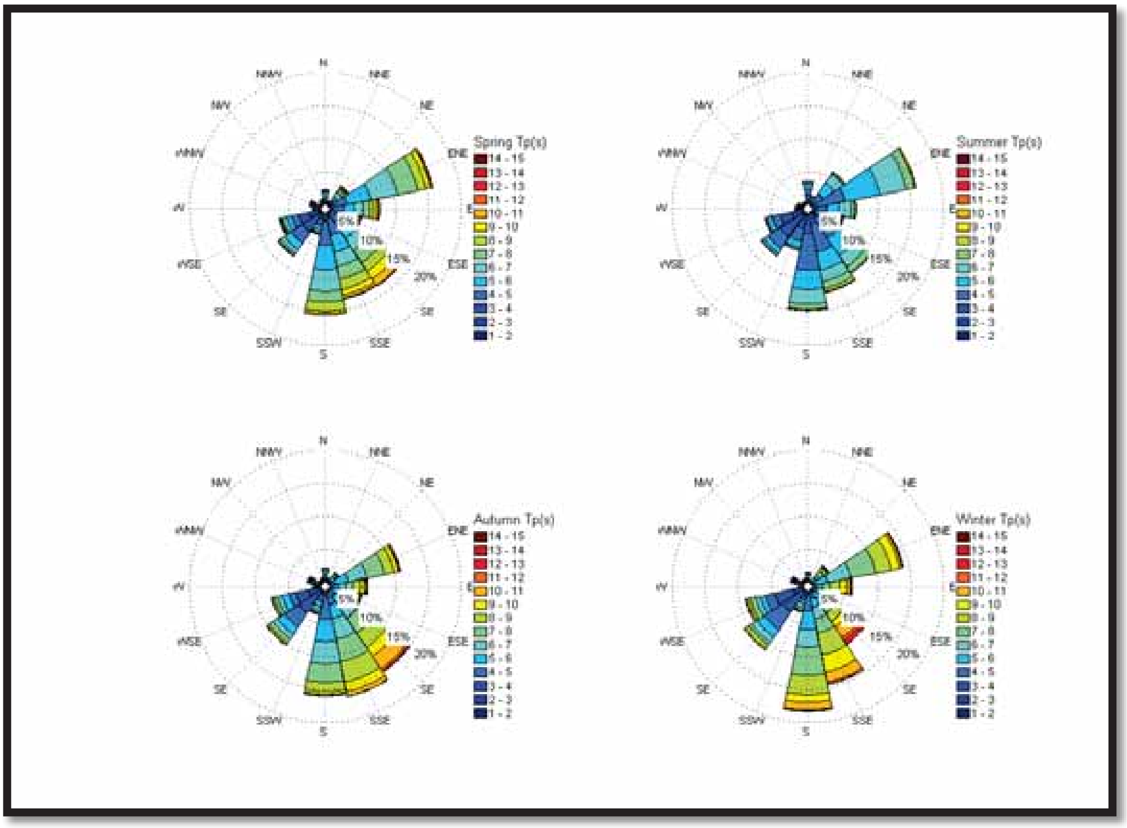
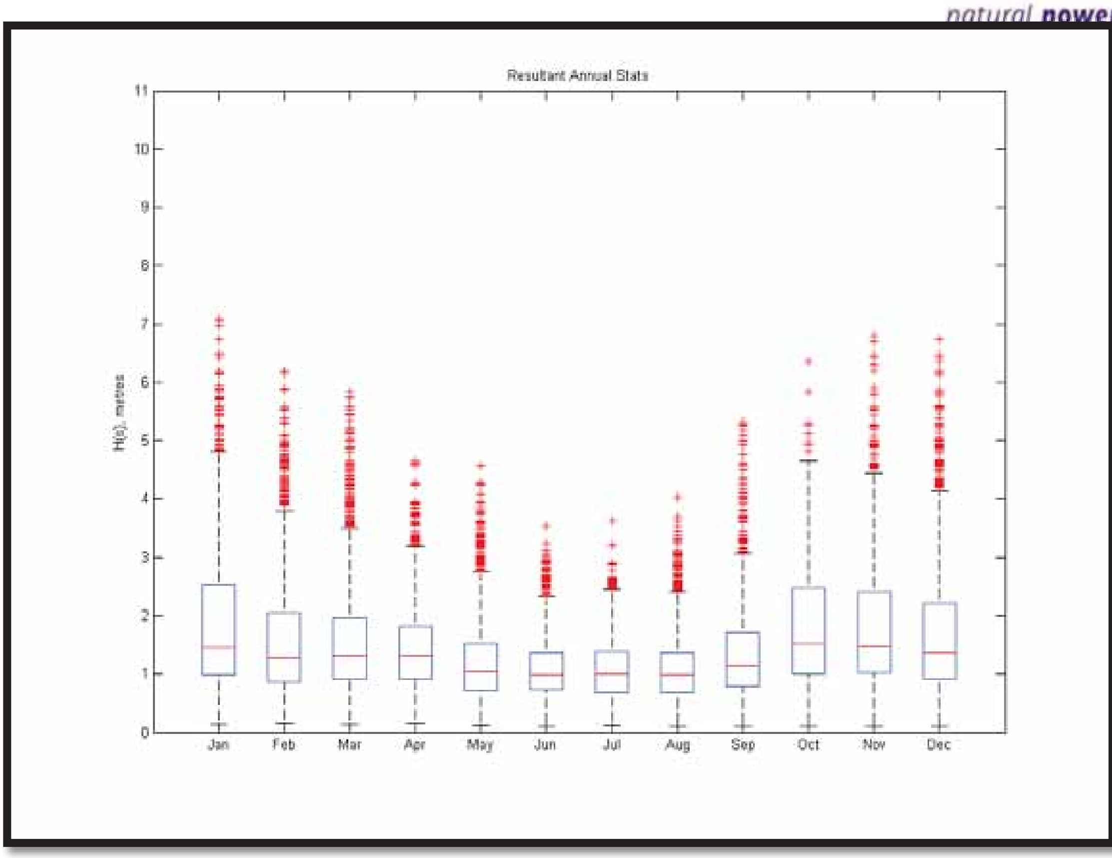
Extract 11 – (60.34N 0.91W)



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H(s), metres
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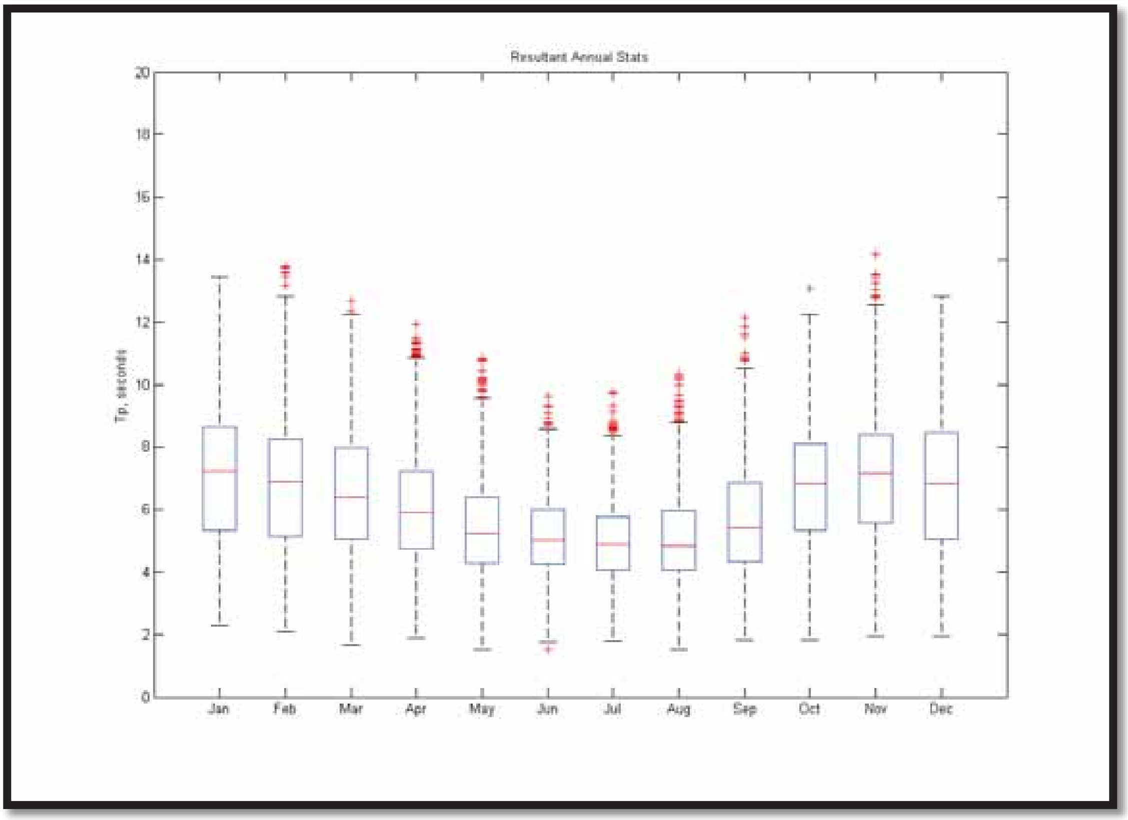
Resultant Annual Stats
Tp, seconds
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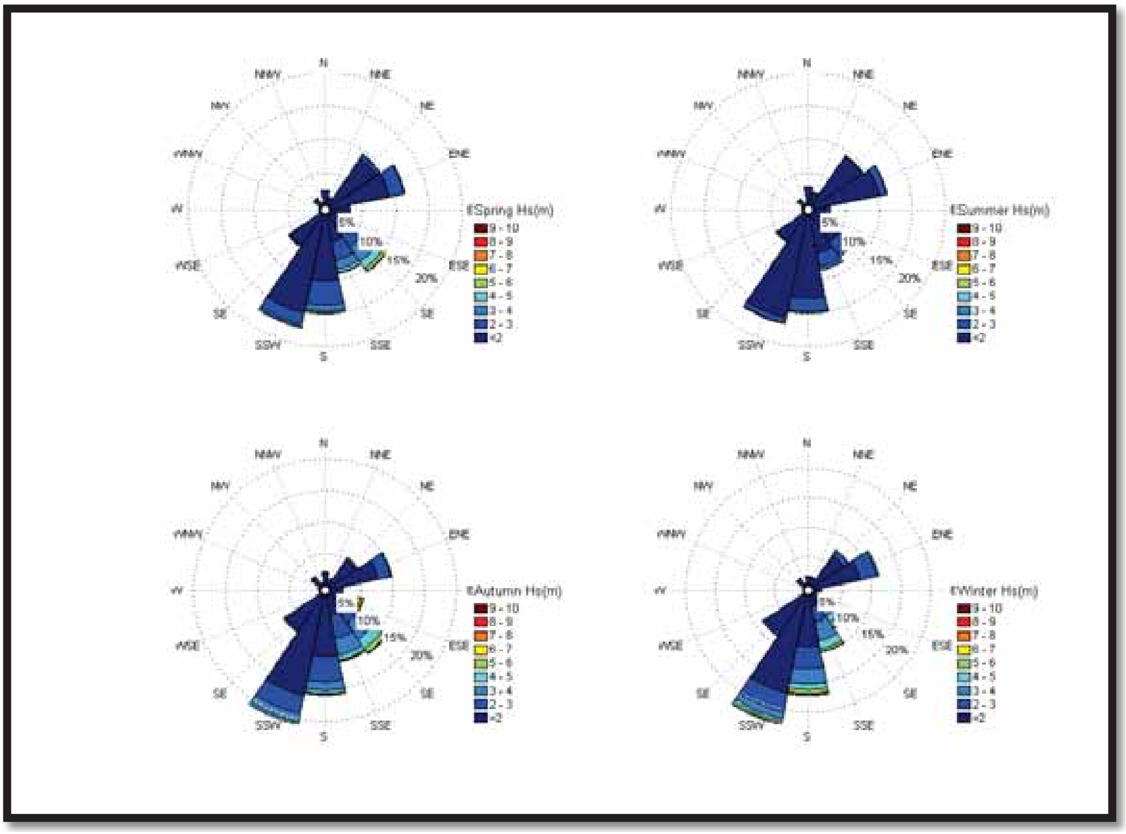
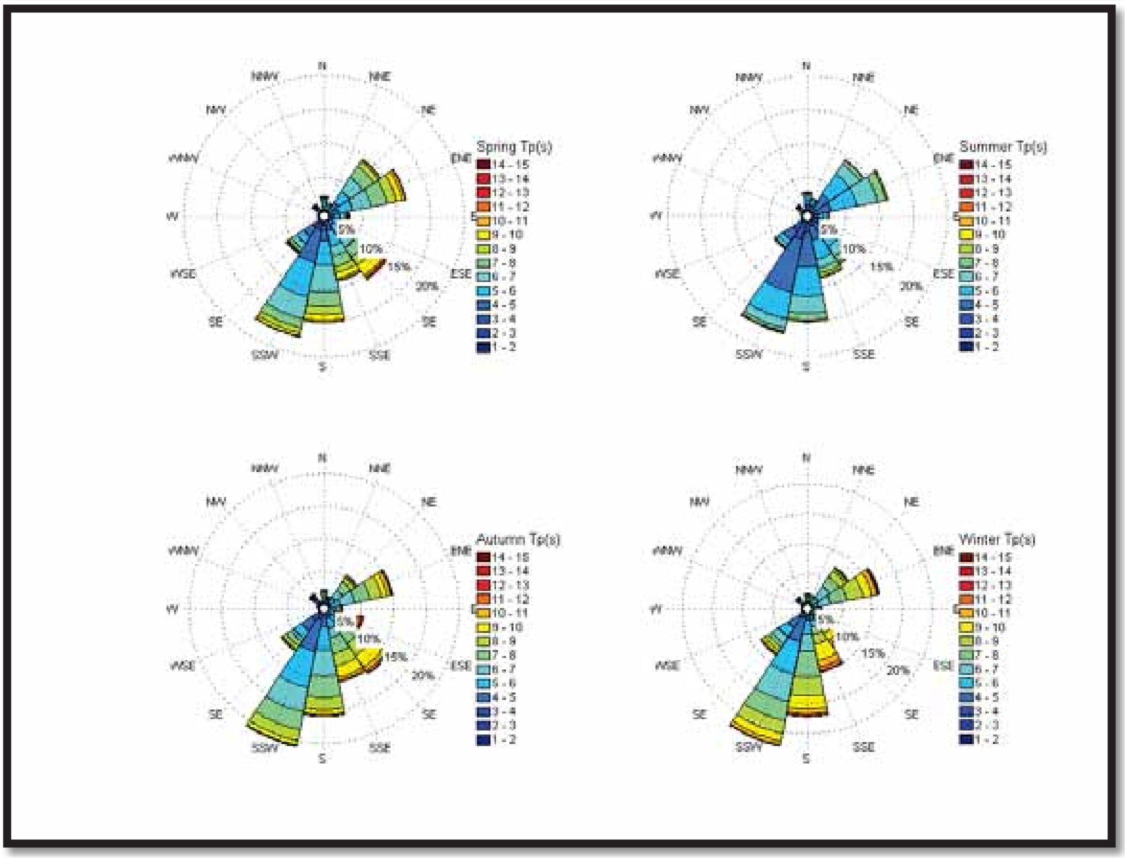
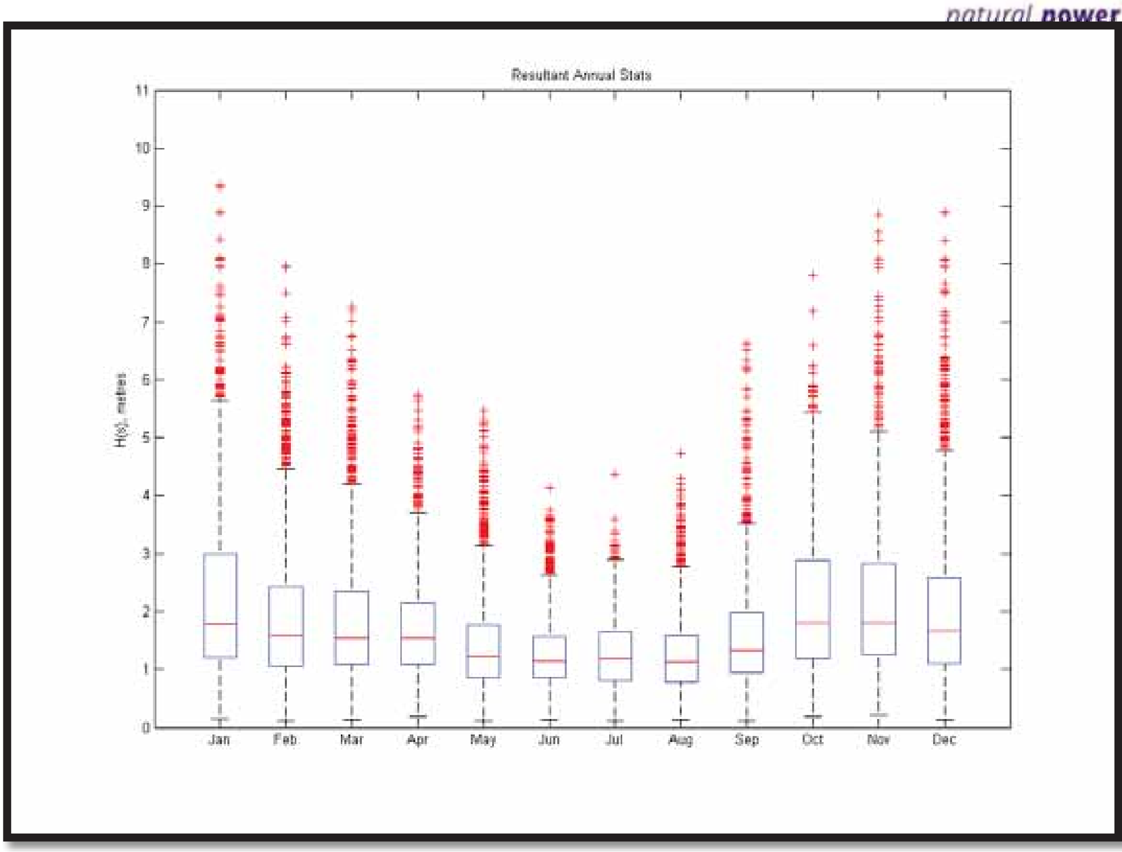
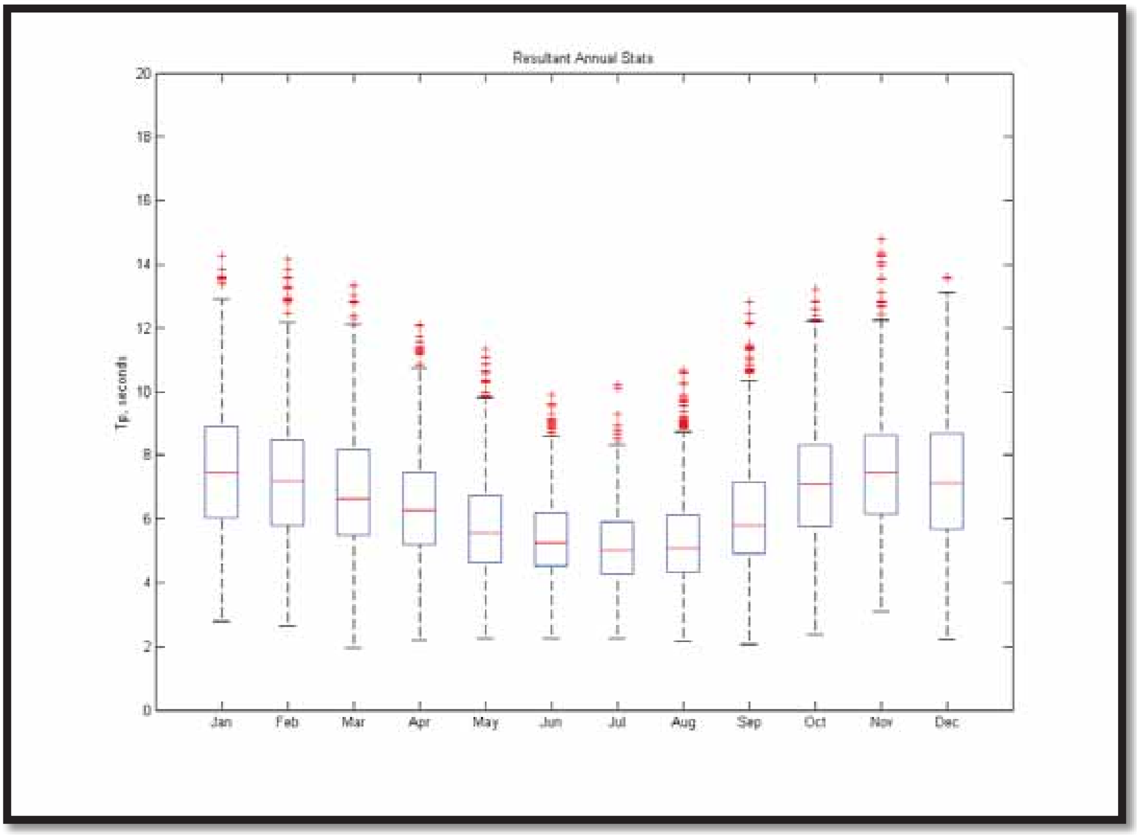
Extract 12 – (60.14N 0.85W)






Resultant Annual Stats
H(S), metres
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Resultant Annual Stats
Tp, seconds
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

9. ANNEX 3: DIRECTIONAL WIND SPEED RELATIONSHIPS

Sector	Relationship	R-squared
N	y = 1.9174x + 4.0601	0.6976
NNE	y = 2.1015x + 3.7565	0.8289
NE	y = 2.513x + 3.3057	0.8216
ENE	y = 3.1821x + 2.9576	0.7571
E	y = 2.7972x + 3.5054	0.7302
ESE	y = 2.7467x + 3.4987	0.7514
SE	y = 2.5157x + 4.0496	0.7994
SSE	y = 2.6817x + 3.7522	0.7584
S	y = 2.5613x + 3.6138	0.7463
SSW	y = 2.3945x + 3.8733	0.7715
SW	y = 2.1993x + 3.9326	0.798
WSW	y = 1.9287x + 4.1693	0.7992
W	y = 1.9052x + 3.9194	0.8134
WNW	y = 2.2077x + 3.3117	0.8338
NW	y = 2.3341x + 3.0568	0.8364
NNW	y = 2.1801x + 3.3338	0.8431

Table 3: Directional Analysis of wave height to wind speed for Western data

Sector	Relationship	R-squared
N	y = 2.3008x + 3.5521	0.8172
NNE	y = 2.3332x + 3.4233	0.8127
NE	y = 2.5904x + 3.1394	0.7927
ENE	y = 3.1901x + 2.5921	0.8173
E	y = 3.014x + 2.9714	0.6962
ESE	y = 2.3896x + 3.6324	0.7522
SE	y = 2.2068x + 4.0746	0.8501
SSE	y = 2.3134x + 4.0361	0.8036
S	y = 2.4917x + 3.7541	0.7828
SSW	y = 2.5764x + 3.753	0.8069
SW	y = 2.82x + 3.7235	0.8296
WSW	y = 3.0606x + 3.515	0.808
W	y = 2.9487x + 3.5067	0.7392
WNW	y = 2.9874x + 3.1795	0.7624
NW	y = 2.8911x + 3.2663	0.7847
NNW	y = 2.7576x + 3.2328	0.8384

Table 4: Directional Analysis of wave height to wind speed for Eastern data

10. ANNEX 4: NOTE ON SPECTRA RECOMBINATION

The MIKE 21 wave modelling configuration used in these studies was setup to calculated integral wave parameters for every model element. These integral parameters are derived from the energy balance equations utilised in the software to calculated wave generation, propagation and dissipation throughout the model domain.

To make best use of available input data, separate model runs were carried out for frequently recurring wind and swell sea states. In order to recombine the wind and swell sea states to give a resultant set of integral parameters they must be returned to their spectral energy distribution S(f,θ), in which form they can be summed and the resultants calculated.

10.1. Creating S(f,θ)

10.1.1. Spectral distribution

The wave modelling process for each wave state produces a file that contains the following integral parameters at every model element:

Wave height	H_{m0}
Peak period	T_p
Mean period	T_{m01}
Mean wave direction	θ
Directional Standard Distribution	DSD

A one dimensional Bretschnider spectrum[6] is created from these parameters using the following equations:

$$S(f) = Af^{-5}\exp\left(-Bf^{-4}\right)$$

Where we are using:

$$H_{m_0} = 2(A/B)^{1/2}$$

And

$$T_{m01} = 0.816B^{-1/4}$$

To derive the A and B values.

This S(f) spectra determines how the energy associated with a particular $(H_{m_0}, T_{m_{01}})$ sea state is assigned across the frequency range of 0-1.0 Hz.

[6] A variation on this method would be to fit a JONSWAP spectrum for wind seas and a Bretschnider spectrum of swell seas.

10.1.2. Directional Distribution

The energy that is present in the one dimensional spectrum, S(f), now needs to be assigned an associated directional distribution. This is carried out by fitting a normalised cosine distribution of wave energy density such that the energy in the one dimensional spectra S(f) is maintained following the process.

$$S(f,\theta) = S(f).D(\theta,f)$$

Where

$$D(\theta,f) = G(s)\cos^{2s}\left(\theta/_2\right)$$

and

$$G(s) = \Gamma(s+1)/(\Gamma\left(s+\frac{1}{2}\right)2\sqrt{\pi})$$

Is a normalisation co-efficient with the width parameter r r related to directional width σ_θ as:

$$\sigma_\theta = \sqrt{\frac{2}{s+1}}$$

With the directional width σ_θ being variable with frequency and given as:

$$\sigma_\theta = \begin{cases} DSD(f/f_{peak})^{-1.05} & in\ degrees, for\ f < f_{peak} \\ DSD(f/f_{peak})^{0.68} & in\ degrees\ for\ f \geq f_{peak} \end{cases}$$

The value of DSD is returned by MIKE21 and in general varies around a mean of 26.9 degrees.

10.2. Spectral addition

To build a recombined spectrum for multiple wind and swell sea states the directional $S(f,\theta)$ distribution as simply added at each (f,θ)bin in order to conserve the energy represented in each spectrum.

The author's acknowledge that this process is highly simplified as wave states arriving from different directions and with differing $(H_{m_0}, T_{m_{01}})$ characteristics will experience a redistribution of energy through wave-wave interaction. However, given that this is a long term study, we make the assumption that these changes to spectral distribution will be minimal.

11. ANNEX 5 – BATHYMETRY DATA

Owing to the spatial resolution requirements of this study, circa 50-100m for tidal studies and 500m for wave studies the sole source of bathymetry data has been the navigational charts published by the UKHO. As a means of determining modelling accuracy the source data and measurement method can be examined.

Chart No.	Chart Title	Scale	Responsibility	Survey Years
219	**Western Approaches to the Orkney and Shetland Islands**	**1:500,000**	**British Government Surveys**	**2005**
				1976-1994
				1968-1977
				1933-1958
				1833-1938 (leadline)
			Commercial Surveys	2003
				1993-1996
				1996
				1974
			Miscellaneous Data	Passage Soundings
245	**Scotland to Iceland**	**1:1,250,000**	**Referred to larger scale charts**	**n/a**
1119	**Orkney and Shetland Islands Fair Isle Channel**	**1:200,000**	**British Government Surveys**	**1994**
				1979-1985
				1975-1977
				1975
				1935-1958
				1937 (leadline)
				1933-1934 (leadline)
				1839-1913 (leadline)
				1833-1995 (leadline)
			Commercial Surveys	2003
				1974
			Miscellaneous Data	Passage Soundings
1233	**Northern Approaches to the Shetland Islands**	**1:200,000**	**British Government Surveys**	**1983-1985**
				1975-1979

				1935-1938
				1934 (leadline)
				1912-1925 (leadline)
				1838-1895 (leadline)
			Shetland Islands Council	1973-1999
			Commercial Surveys	2003
				1996
				1974
			Miscellaneous Data	Passage Soundings
1239	**Orkney and Shetland Islands**	**1:350,000**	**British Government Surveys**	**1975-1994**
				1935-1958
				1833-1938 (leadline)
			German Government Surveys	1950
			Shetland Islands Council	1975-1990
			Commercial Surveys	1986-1996
				1973-1994
				1974
			Miscellaneous Data	Passage Soundings
3272	**Moul of Eswick to Helliness**	**1:25,000**	**Lerwick Port Authority**	**1986-1999**
			British Government Surveys	1985
				1979-1980
				1976-1977
				1934 (leadline)
				1925 (leadline)
				1895 (leadline)
				Unsurveyed
3281	**Shetland Islands North West Sheet**	**1:75,000**	**British Government Surveys**	**1983-1984**
				1977-1979
				1940
				1912-1925 (leadline)
				1833-1883 (leadline)
			Miscellaneous lines of survey	1833-1895

			Shetland Islands Council	1973-1999
				Unsurveyed
3282	**Shetland Islands North-East Sheet**	**1:75,000**	**Shetland Islands Council**	**1975-1999**
			British Government Surveys	1983-1985
				1955-1980
				1979
				1940
				1935-1938
				1934 (leadline)
				1912-1924 (leadline)
				1895 (leadline)
			Miscellaneous lines of survey	1895
			Other Surveys	2003
				1979-1982
3283	**Shetland Islands South Sheet**	**1:75,000**	**British Government Surveys**	**1983-1985**
				1976-1980
				1933-1935 (leadline)
				1912-1925 (leadline)
				1833-1895 (leadline)
				Unsurveyed
3284	**Moul of Eswick to Lunna Holm including Out Skerries**	**1:37,500**	**British Government Surveys**	**1984-1985**
				1934-1937 (leadline)
				1912 (leadline)
			Shetland Islands Council	1983-2000
				1982-1984
			Other Surveys	1981-1982
3292	**Eastern Approaches to Yell Sound, Colgrave Sound and Bluemull Sound**	**1:30,000**	**Shetland Islands Council**	**1999**
				1998
				1982-1984
			British Government Surveys	1984
				1980

				1935-1937
				1912-1922 (leadline)
				1913-1924 (leadline)
3294	**Approaches to Scalloway and Southern Shetland**	**Various**	**Shetland Islands Council**	**1999**
			British Government Surveys	1984-1985
				1976
				1934 (leadline)
				1924-1925 (leadline)
				1912-1925 (leadline)
3295	**Approaches to west coast harbours**	**Various**	**British Government Surveys**	**1984**
				1933-1935 (leadline)
				1912 (leadline)
				1895 (leadline)
				1833 (leadline)
			Commercial Survey	1973
			Miscellaneous lines of survey	-
3298	**Yell Sound**	**1:30,000**	**British Government Surveys**	**1983-1984**
				1935-1940
				1920 (leadline)
				1920-1923 (leadline)
			Miscellaneous lines of survey	1895
			Shetland Islands Council	1998
				1981-1994
				1975-1978
			Other Surveys	1978
				Unsurveyed
3299	**Harbour plans including Fair Isle**	**Various**	**Shetland Islands Council**	**1999**
				1992-1993
			British Government Surveys	1994
				1994
				1979
				1912 (leadline)

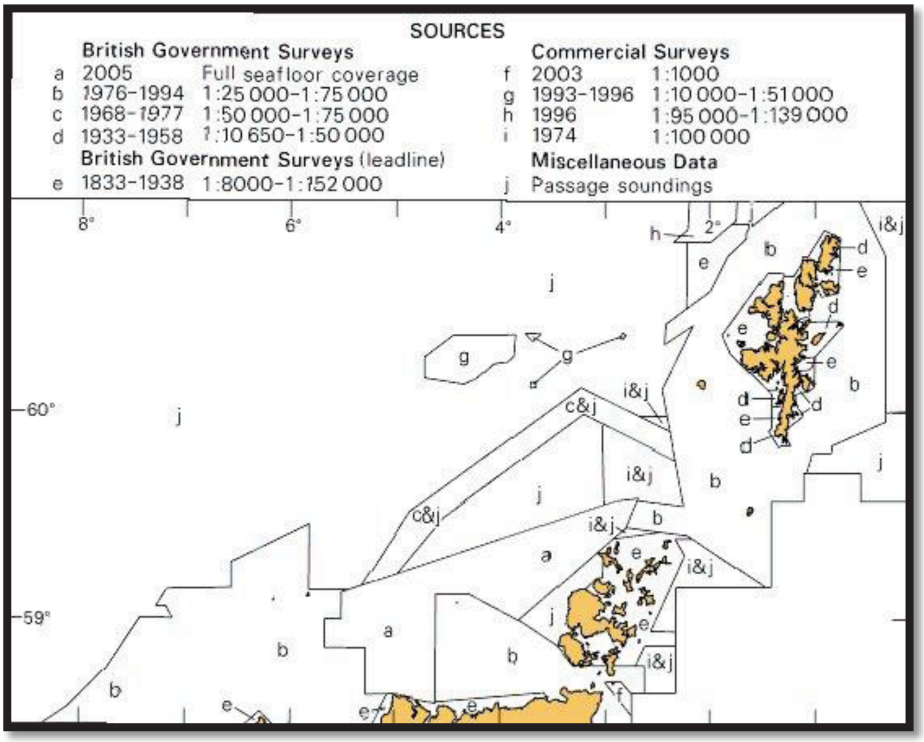
				1912 (leadline)
				1895 (leadline)
				1883 (leadline)
			Commercial Surveys	2003
				1992
				Unsurveyed

Comments:
219 – Offshore Shetland mainly covered under the 1976-1994 BGS surveys, all nearshore areas based on pre 1958 BGS surveys with a large proportion based on leadline surveys. Some commercial infill but located principally in areas of hydrocarbon development.
245 – Chart intended only as overview, comments that most data is based on passage soundings with reference to larger scale charts.
1119 – Waters offshore of Fair Isle examined in some detail during 2003. Majority nearshore data leadline based.
1233 – Areas of Yell Sound surveyed by Shetland Islands Council relatively recently. All other areas predominately surveyed pre-1985.
1239 – Coastline of interest is a mix of leadline, Shetland Islands Council and British Government Data.
3272 – Predominance of nearshore areas not under Lerwick Port Authority are based on leadline surveys from 1895-1934. Some areas remain unsurveyed.
3281 – Coastline west of Eshaness and Saint Magnus Bay largely based on miscellaneous lines of survey. Large areas west of Braganess and Giltarump unsurveyed. Inshore areas with exception of Yell Sound based on leadline surveying.
3282 – Caution is required for the majority of Yell and Unst coastlines where leadline surveying has been used in coastal areas. This would apply to the eastern sections of Yell Sound where interest in tidal energy sites may be presumed.
3283 – Areas adjacent to Foula based on pre 1895 leadline surveys, unsurveyed areas to the western coast and large areas of the nearshore environment based on leadline surveying.
3284 – All inshore waters with exception of approaches to Yell Sound based on pre-1937 leadline surveying, small pockets of high resolution data in Out Skerries and Symbister harbour. 1981-82 'Other survey' is assumed to be related to the electrical cable connecting Out Skerries and Whalsay to the mainland.
3292 – Areas of the map are characterised by the inclusion of pre-1937 data in nearshore areas with exception of Shetland Island Councils surveys of the approaches to Yell Sound and various local harbours. The 1984 British Government Survey completes much of the data used in Colgrave Sound. Care should be given with the Tidal resource area of Bluemull Sound as all data are from pre-1924 leadline surveys.
3294 – As predominant on much of the west coast charts are based on pre-1934 leadline surveying with the exception of Scalloway harbour recently survey by Shetland Islands council. Areas to the east of mainland were nominally surveyed in 1976 through the British Government, though a few spot depths are given in close proximity to the coast with bathymetry contours frequently containing discrepancies.
3295 – With the exception of the commercial surveying of Busta Voe in 1973 all data are based on leadline surveying and should be treated with caution. Large sections of western facing coasts remain unsurveyed.

3298 – The areas of approach to Sullom Voe and Yell Sound have been surveyed to a perceived high degree of accuracy by Shetland Islands Council, however the prospective tidal resources areas have not been surveyed since a 1923 leadline survey. In addition a largely unsurveyed area of the western Yell coastline may be of interest to wave energy developers.

3299 – With the exception of harbour areas surveyed by Shetland Islands Council the areas presented in these charts are based on leadline soundings or remain unsurveyed.

11.1. Survey Box Extracts



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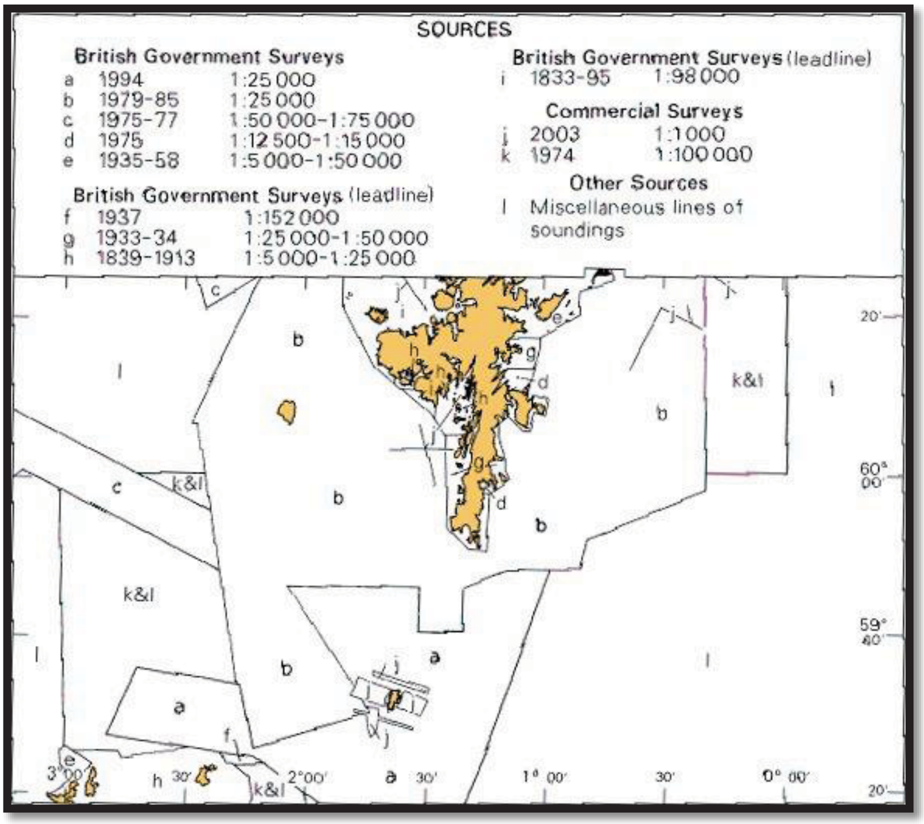

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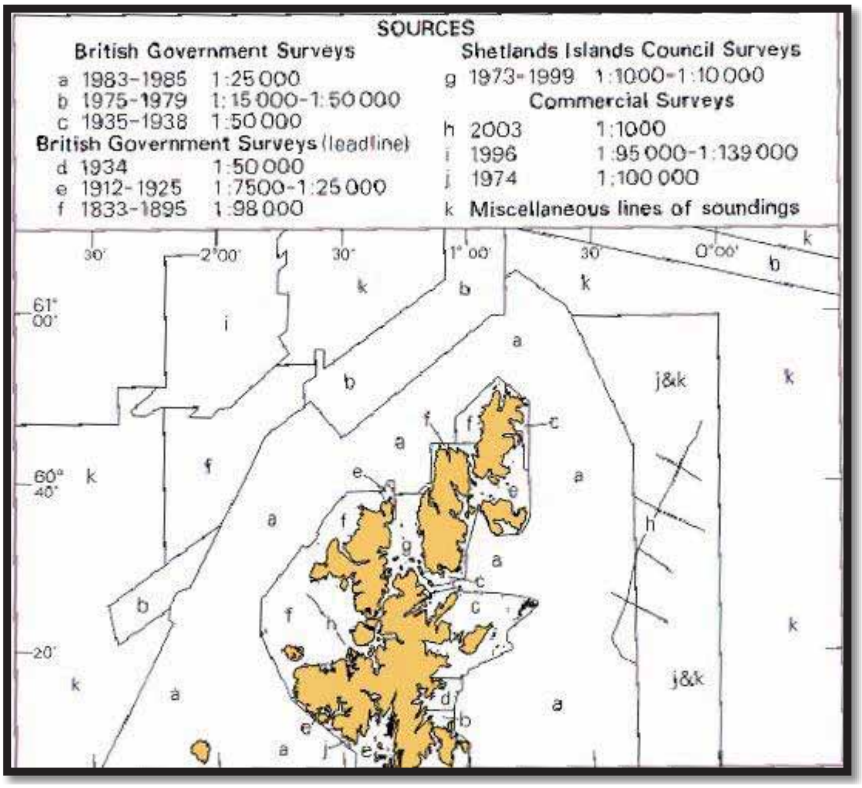

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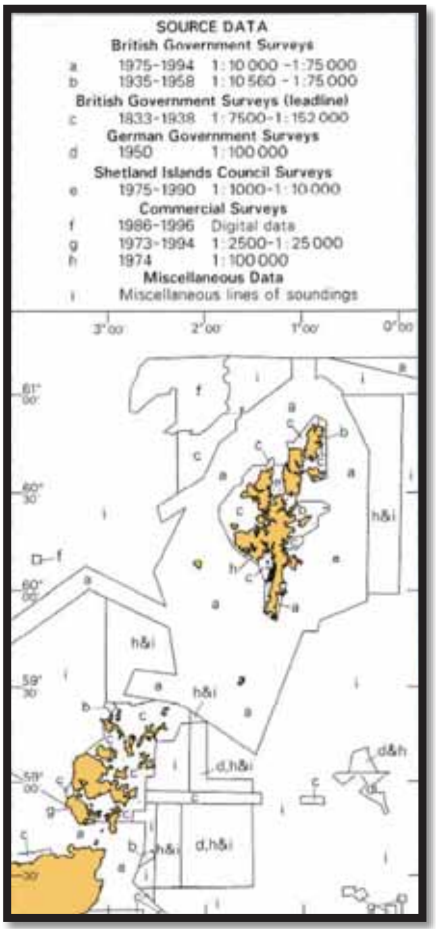


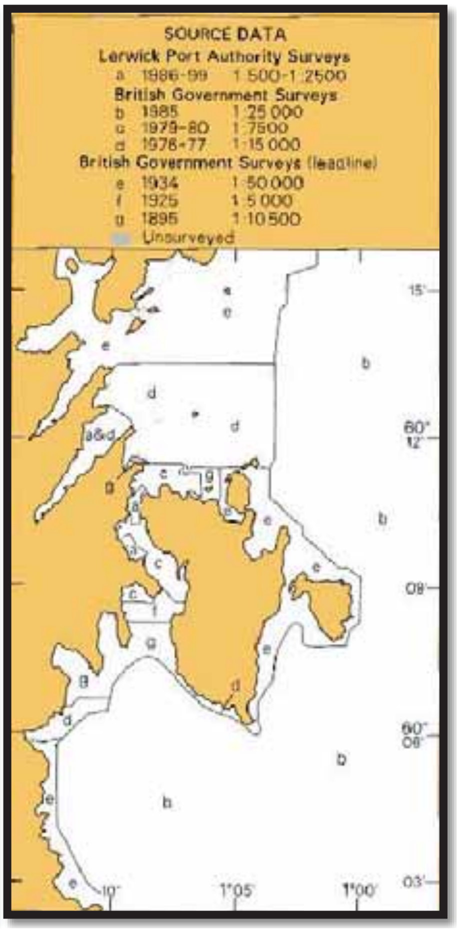
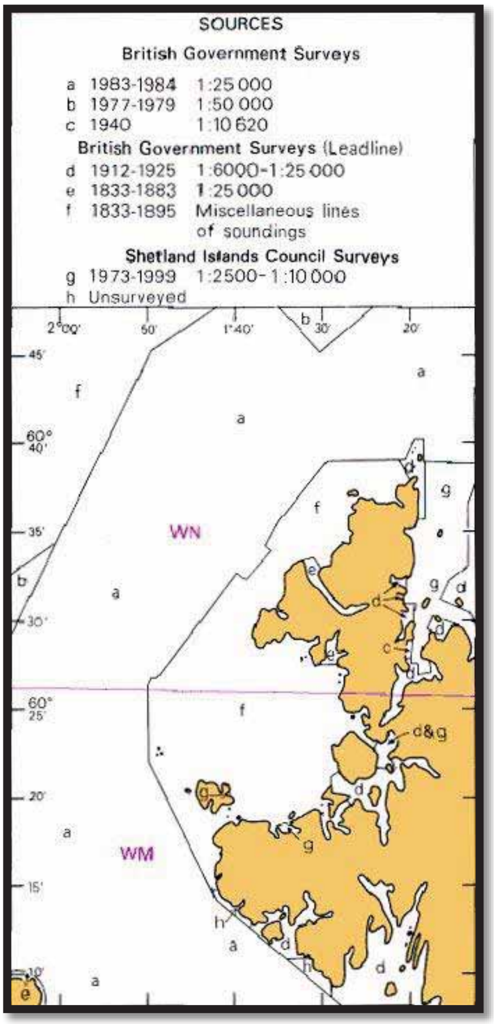


Chart no 1239 *Chart no 3272*



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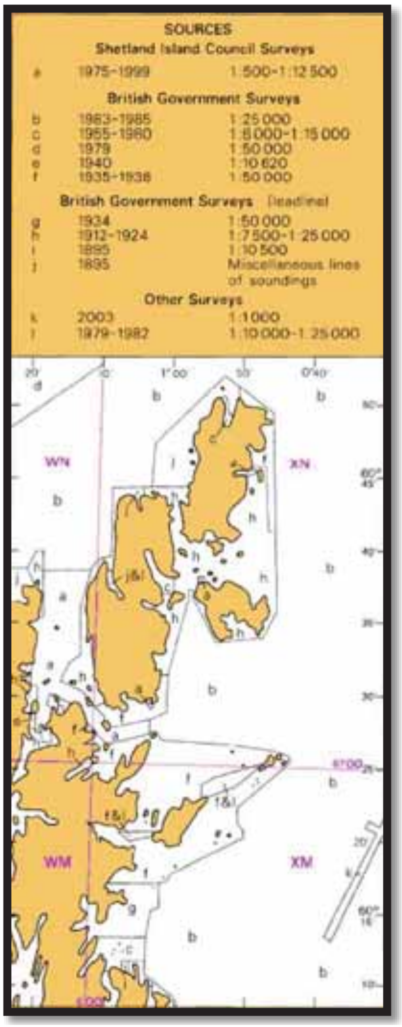

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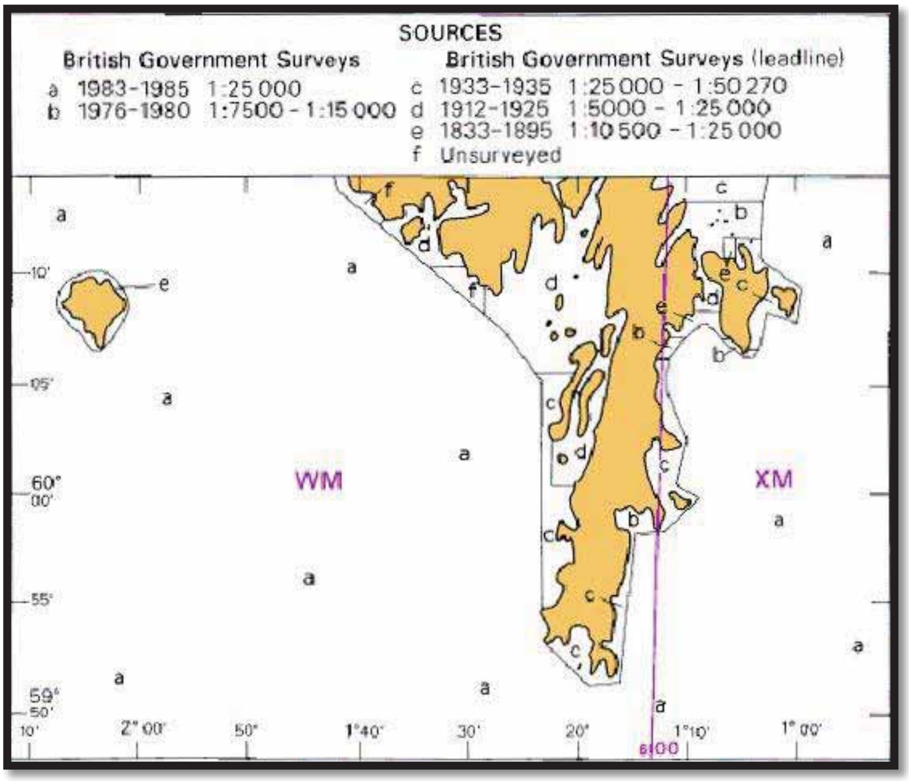

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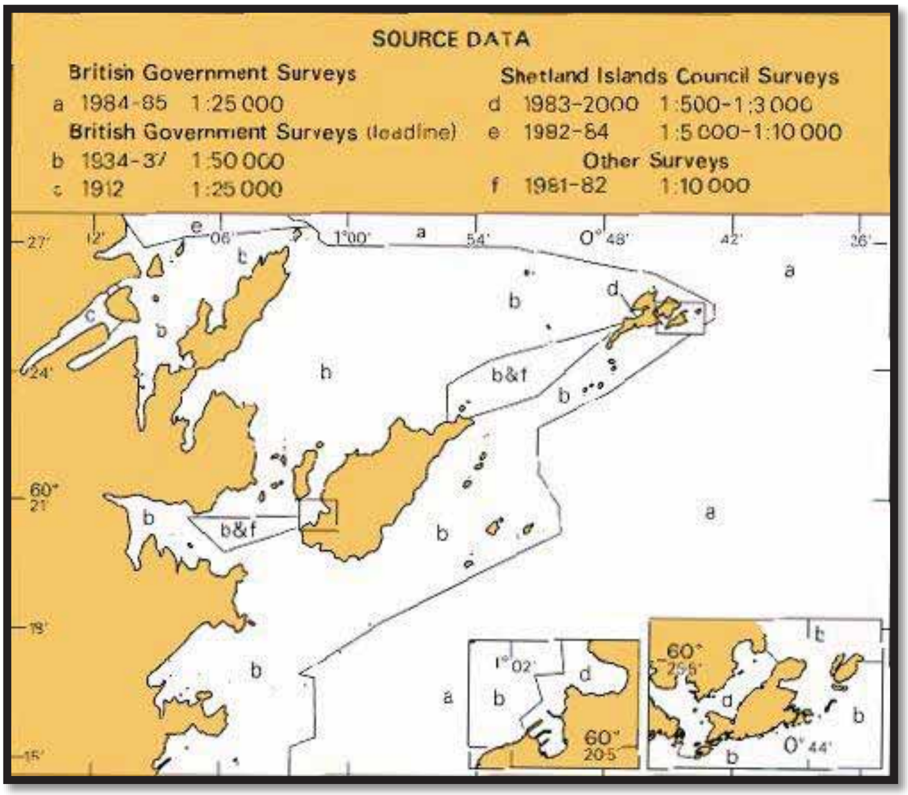

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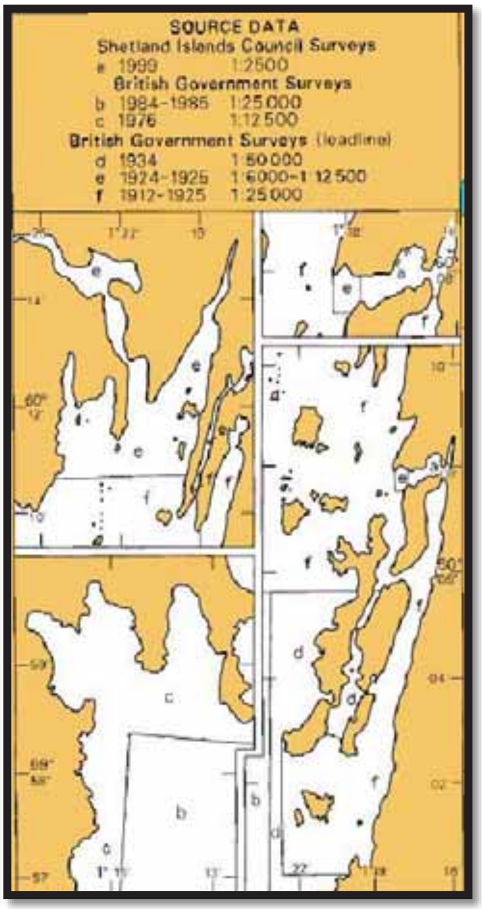

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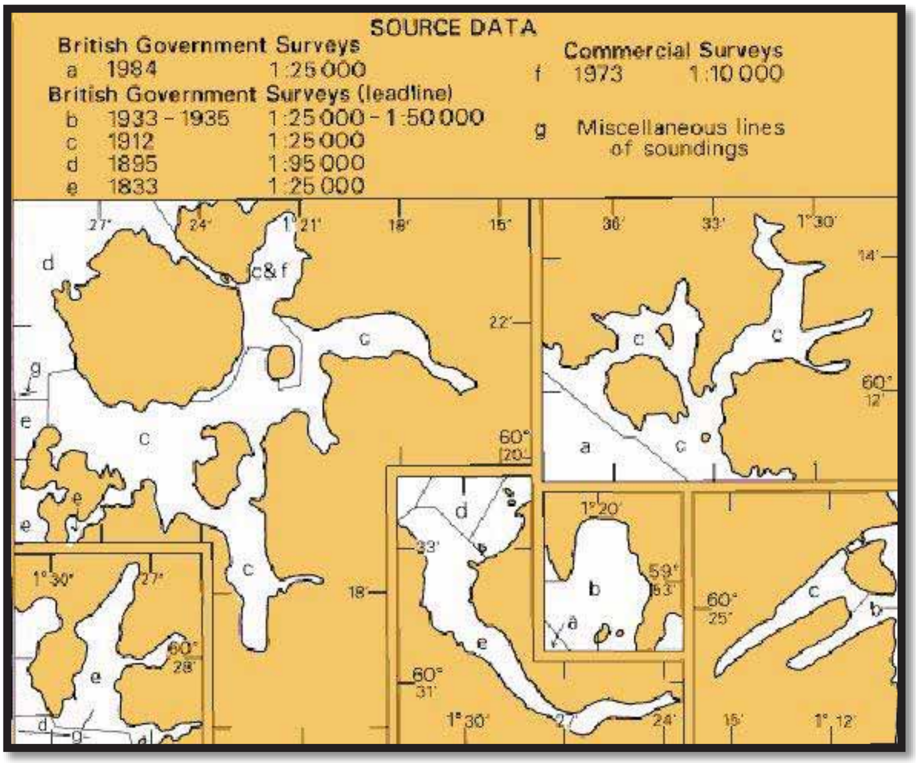

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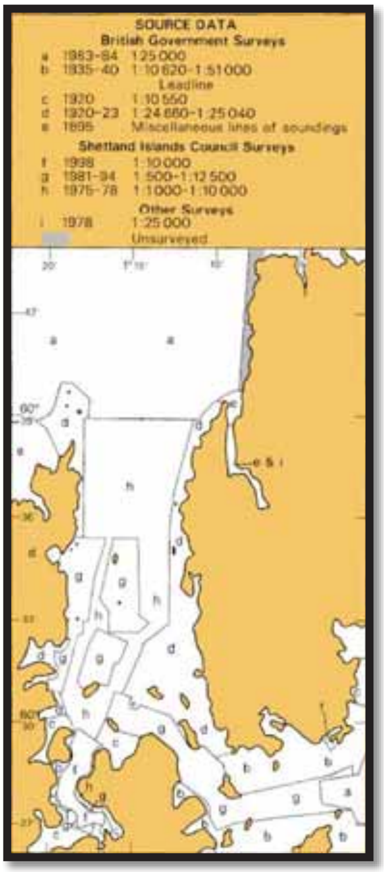

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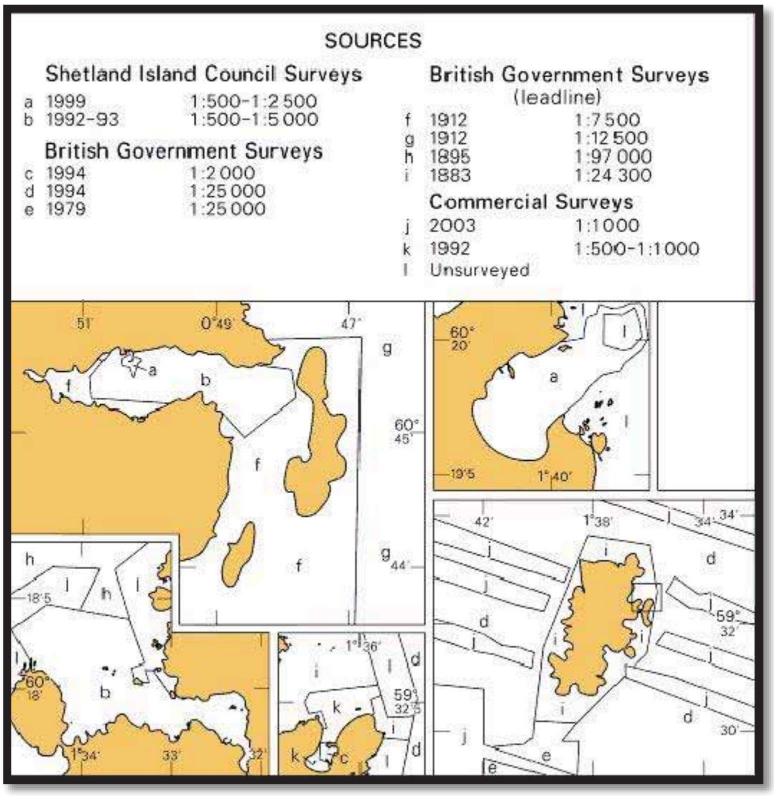


Chart no 3299

12. ANNEX 6: ANALYSIS OF MET OFFICE MODELLED DATA

The following annex presents an in depth analysis of the Met Office data points sourced for the purpose of forcing the boundaries of the wave model utilised in these studies.

12.1. Introduction

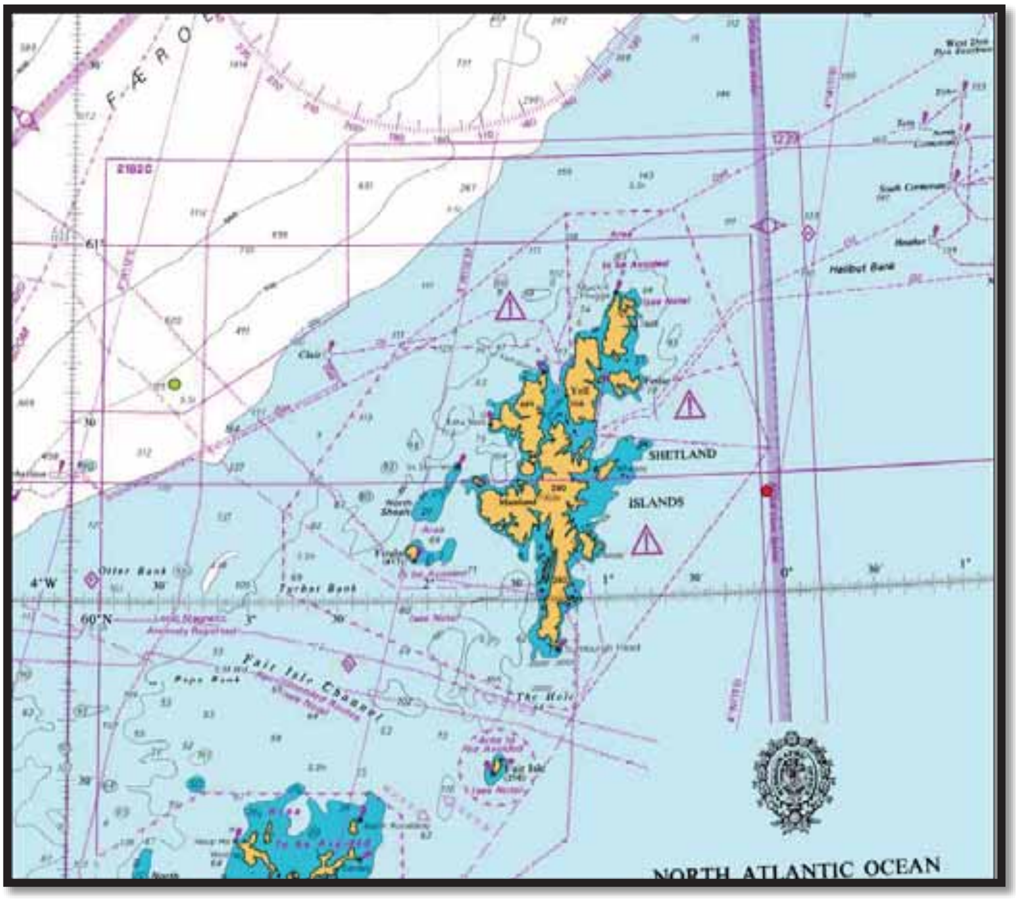


Figure 45: Locations of Met Office Data Extraction

As part of the metocean studies that have contributed to this report data from the Met Office numerical wave model was purchased for locations to the west and east of Shetland, as shown in Figure 45. The data covers the period of 1st April 2000 to 31st March 2010 giving 10 years of continuous wind and wave data at these two locations. With a time series of this extent a relatively good determination of expected wave climatology can be derived.

This annex presents statistical analysis of each source data point in a sequence of chart of tables. For each point the wind and wave climatology are described according to the standards laid out in British Standard EN ISO 19901-1:2005 “Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating considerations”. Distributions, histograms and roses are given for wave height and period on yearly basis with estimates of 50 year return periods calculated through a fitted Weibull distribution method.

12.2. Westerly Location – 60.16N 3.42W

12.2.1. Wave Roses

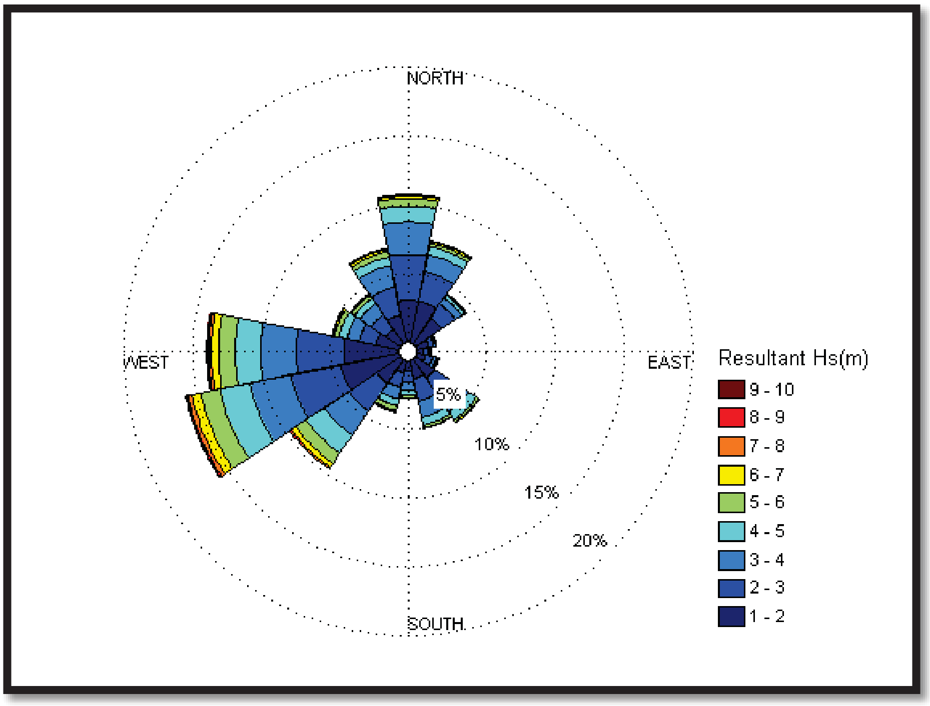


Figure 46: Wave rose of Resultant Wave Height

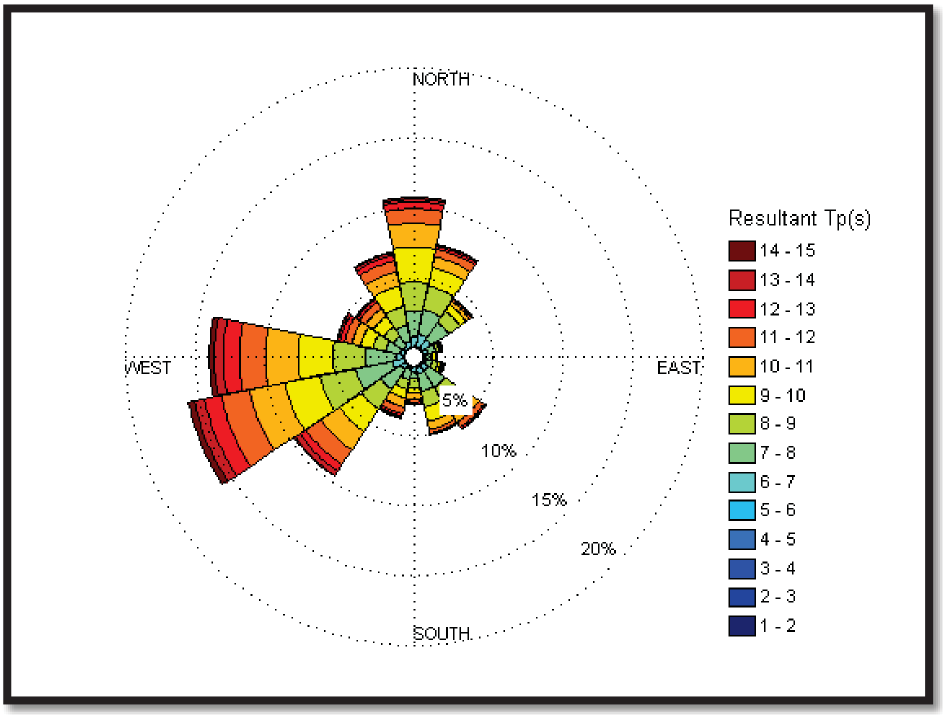


Figure 47: Wave Rose of Resultant Peak Period

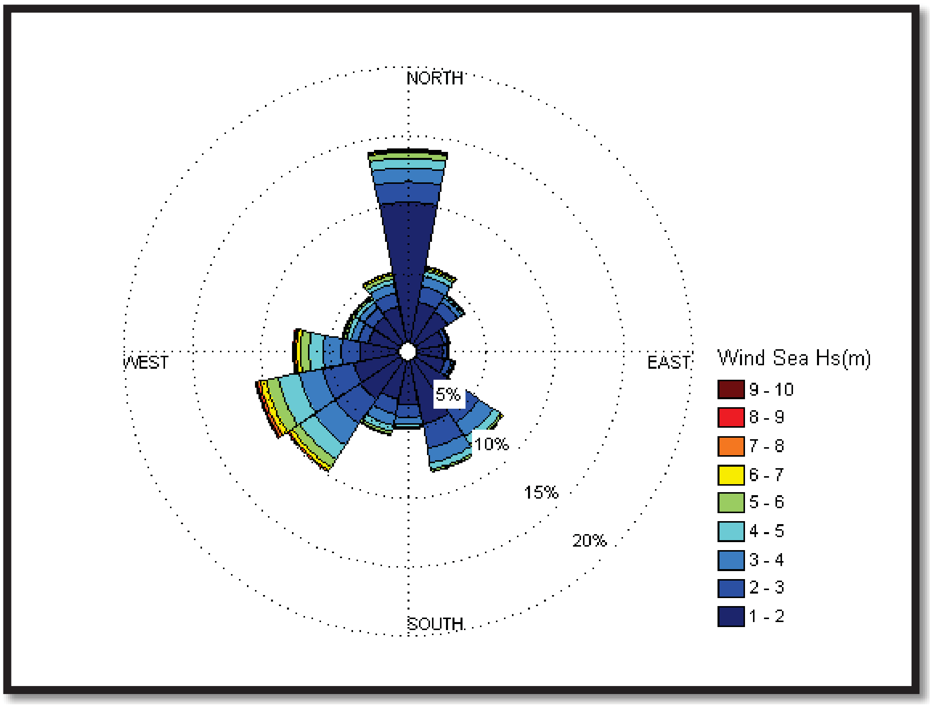


Figure 48: Wave Rose of Wind Sea Wave Heights

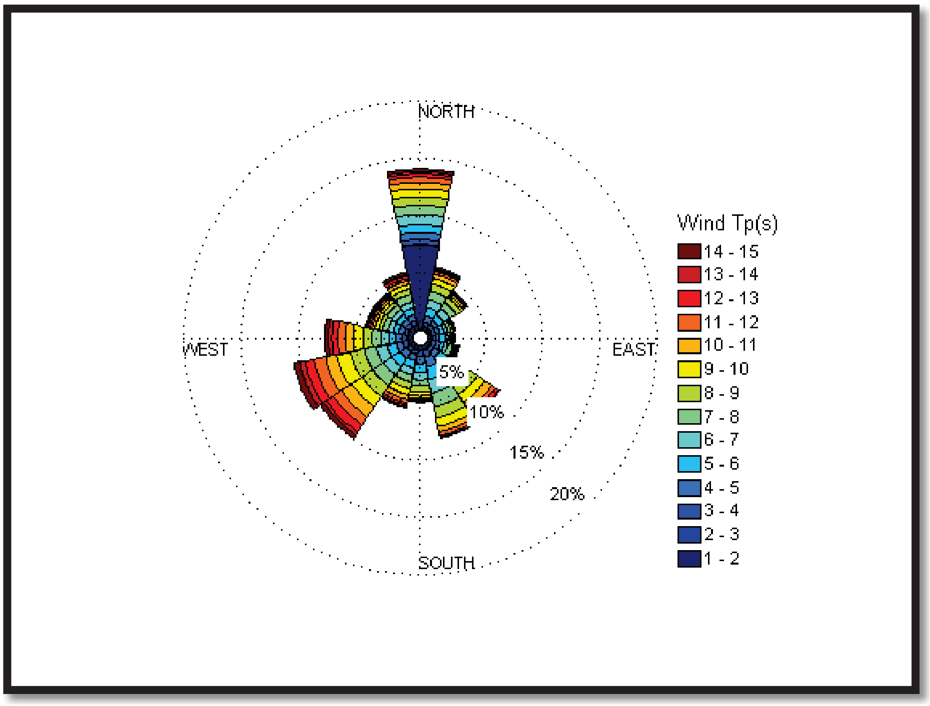


Figure 49: Wave Rose of Wind Sea Peak Periods

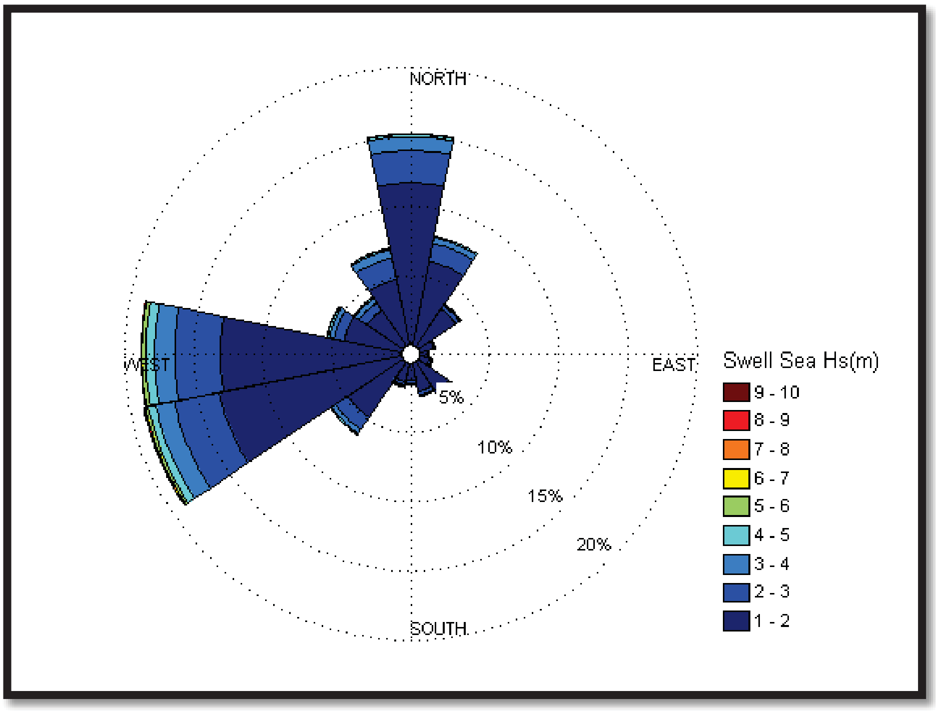


Figure 50: Wave Rose of Swell Sea Wave Heights

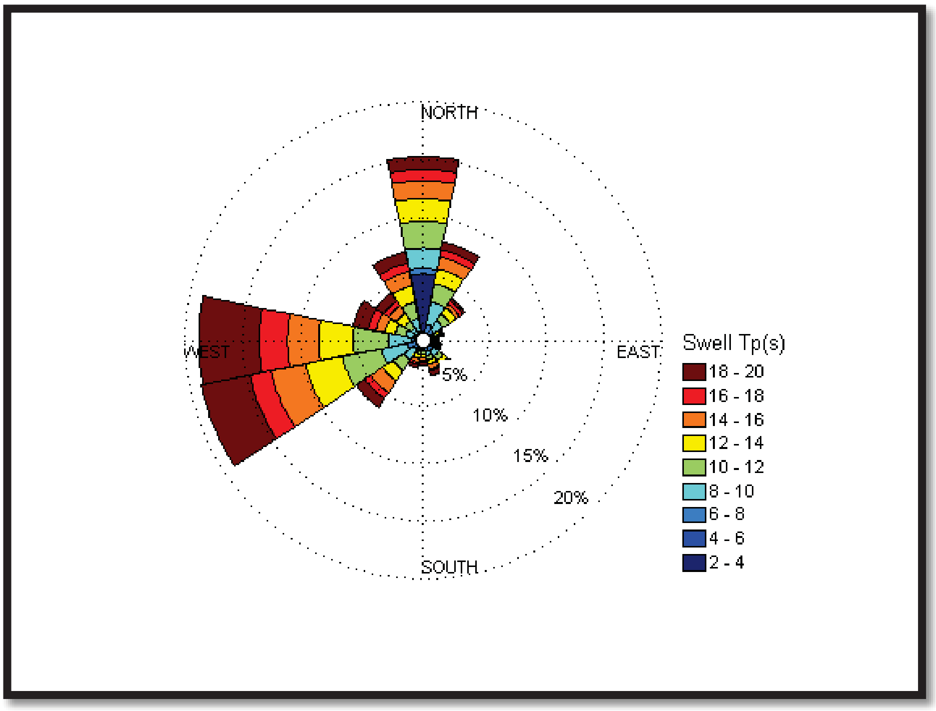


Figure 51: Wave Rose of Swell Sea Peak Periods

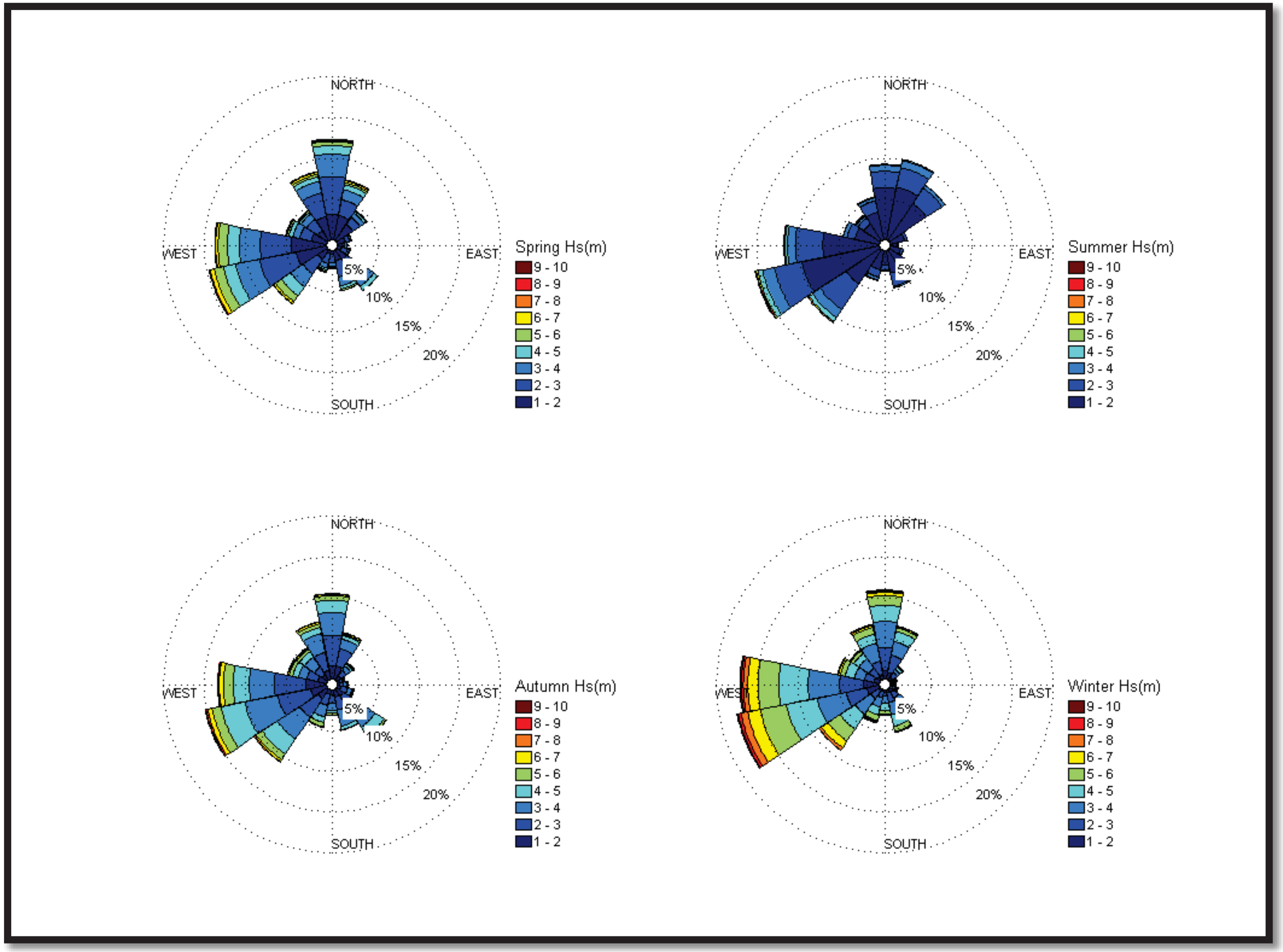


Figure 52: Seasonal Wave Roses for Resultant Wave Height

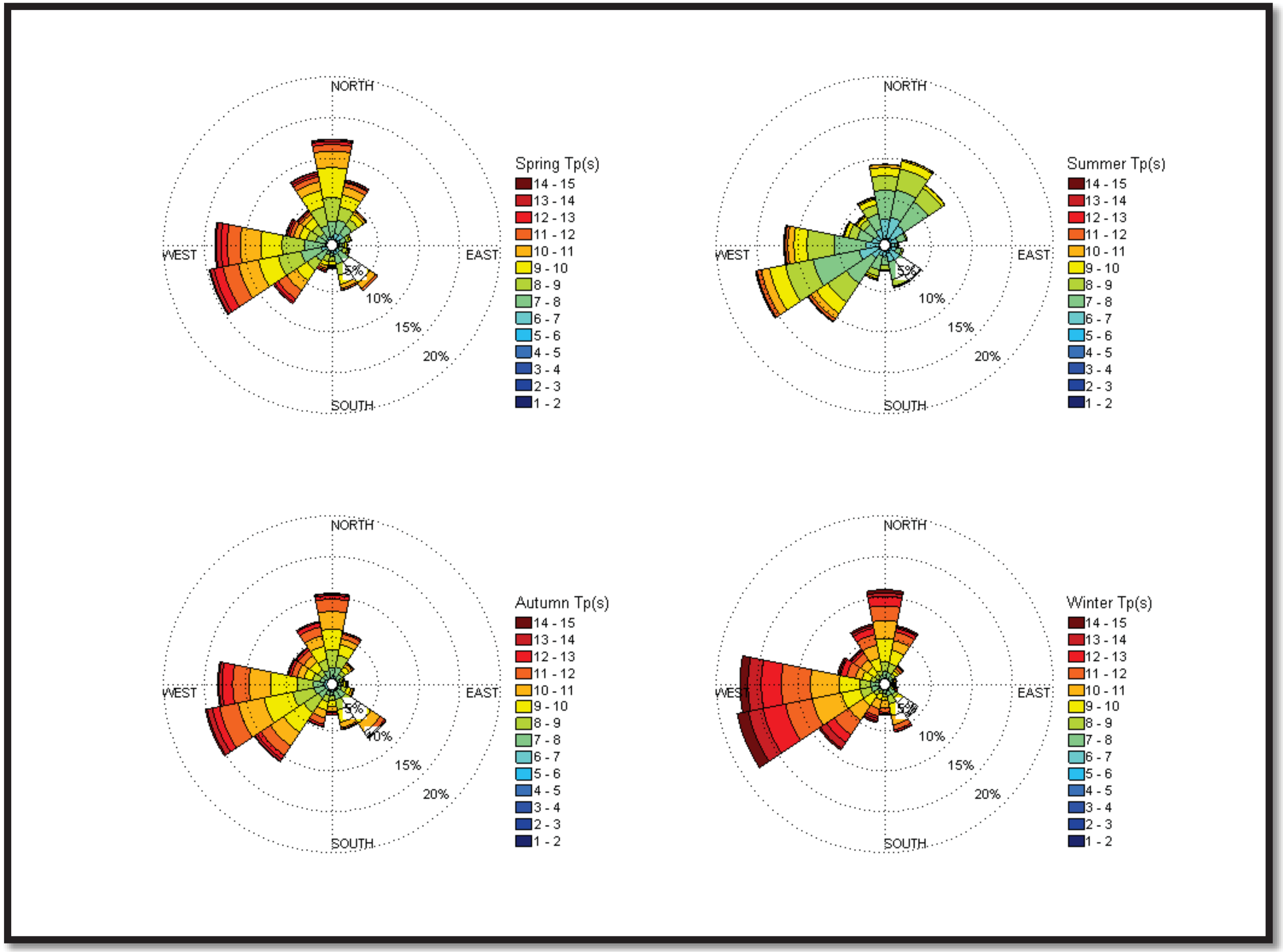


Figure 53: Seasonal Wave Roses for Resultant Wave Period

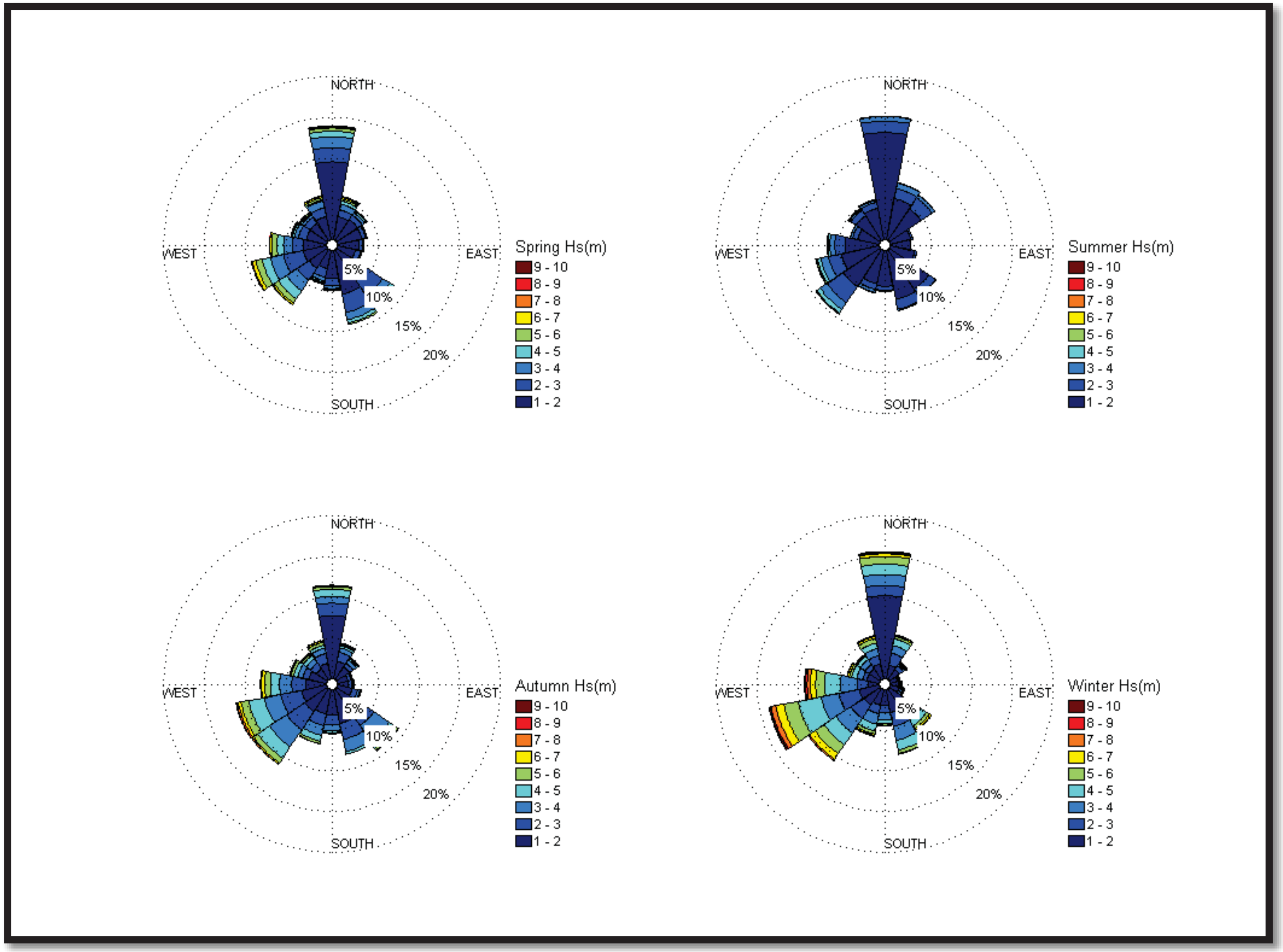


Figure 54: Seasonal Wave Roses for Wind Sea Wave Height

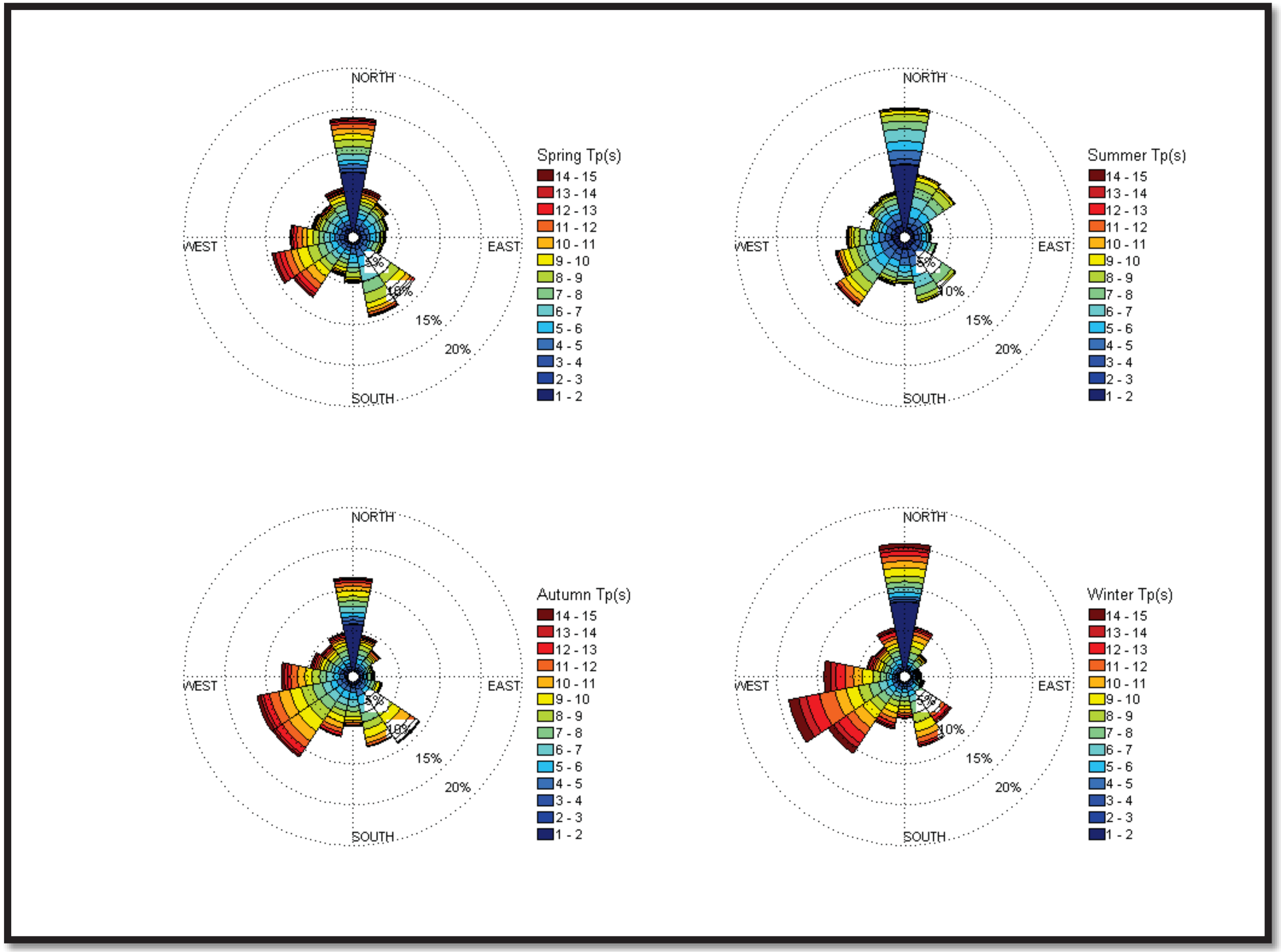


Figure 55: Seasonal Wave Roses for Wind Sea Peak Period

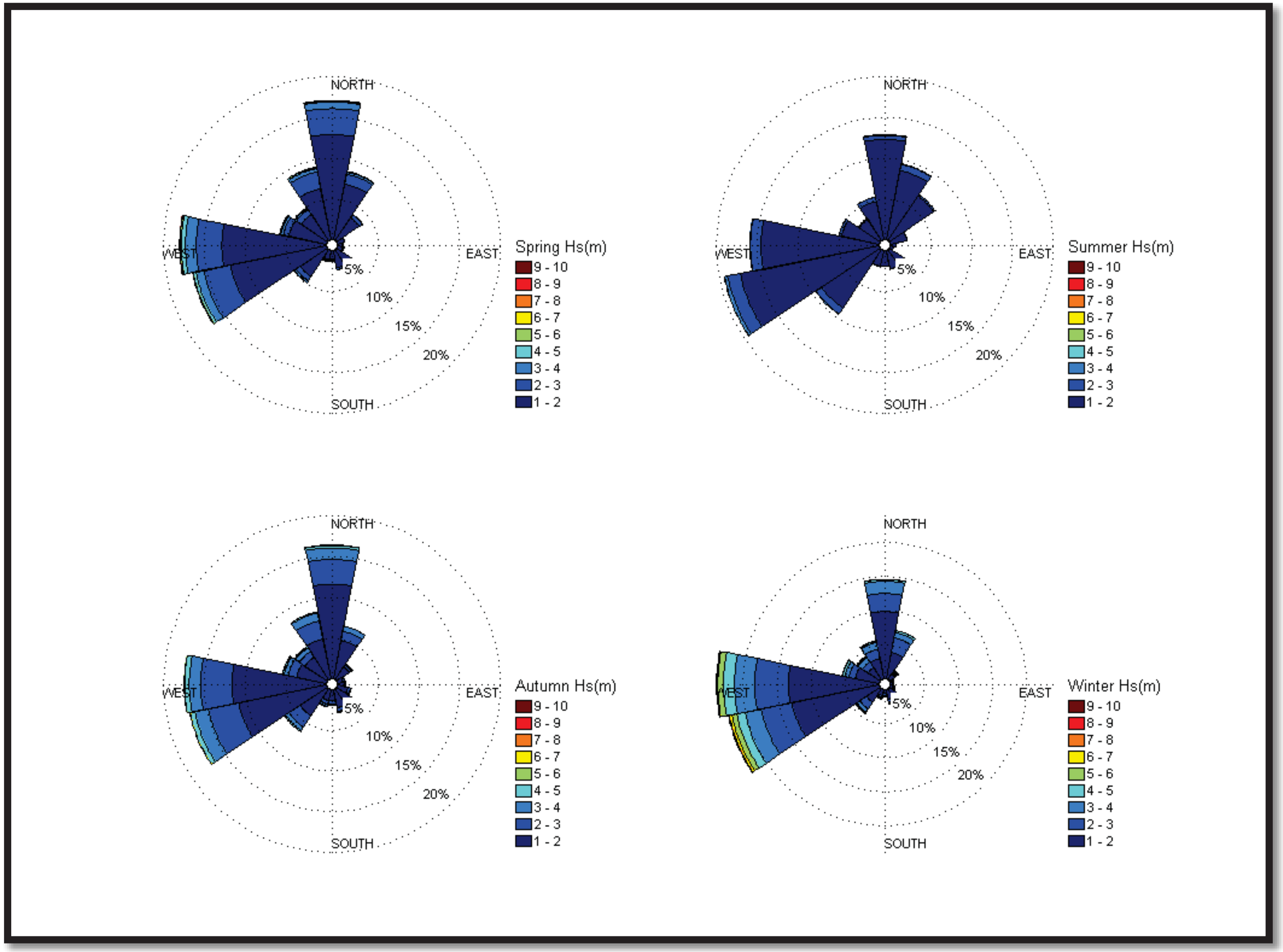


Figure 56: Seasonal Wave Roses for Swell Sea Wave Height

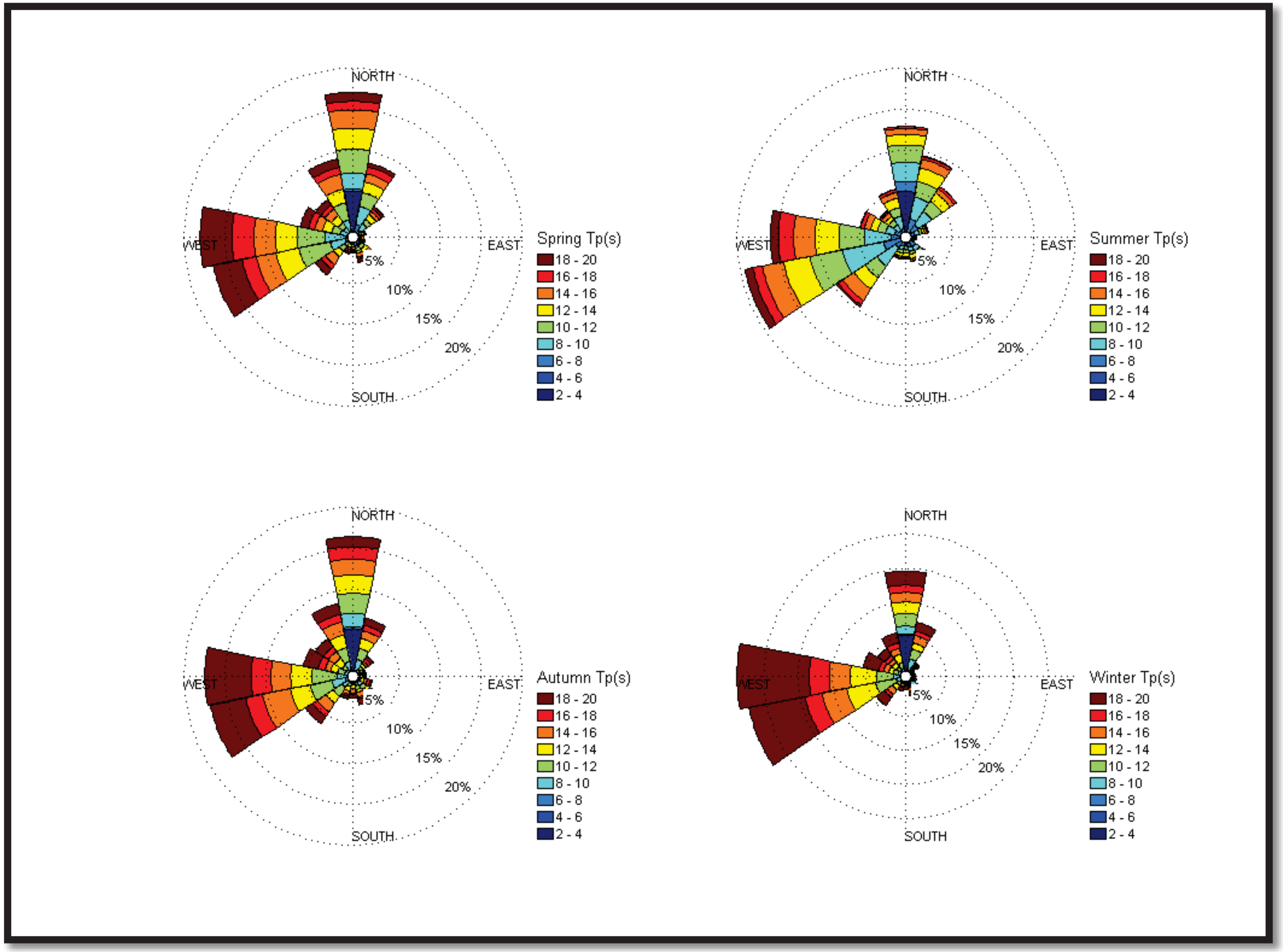


Figure 57: Seasonal Wave Roses for Swell Sea Peak Period

12.2.2. Annual Statistics

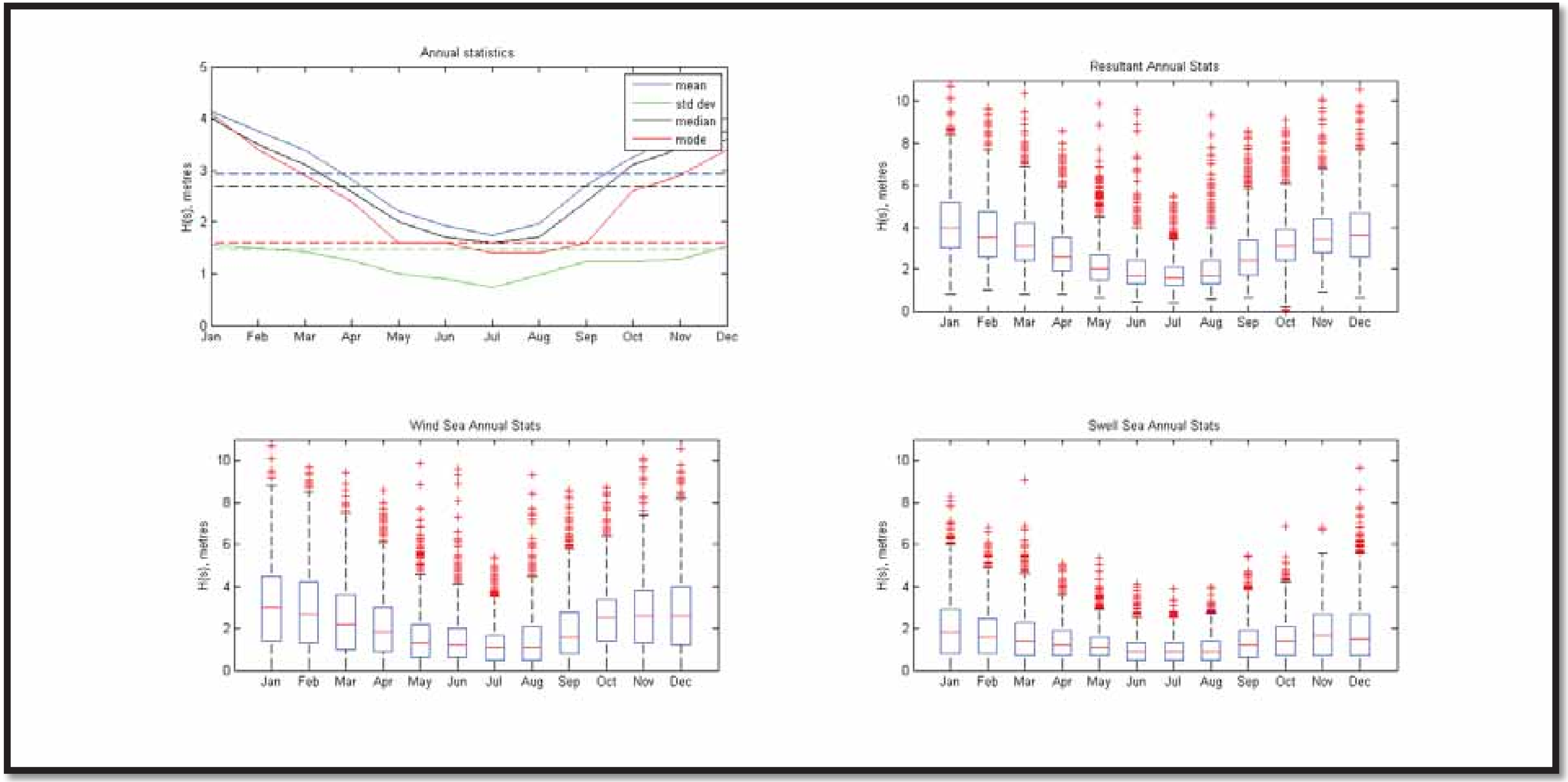


Figure 58: Annual Statistics for Significant Wave Height

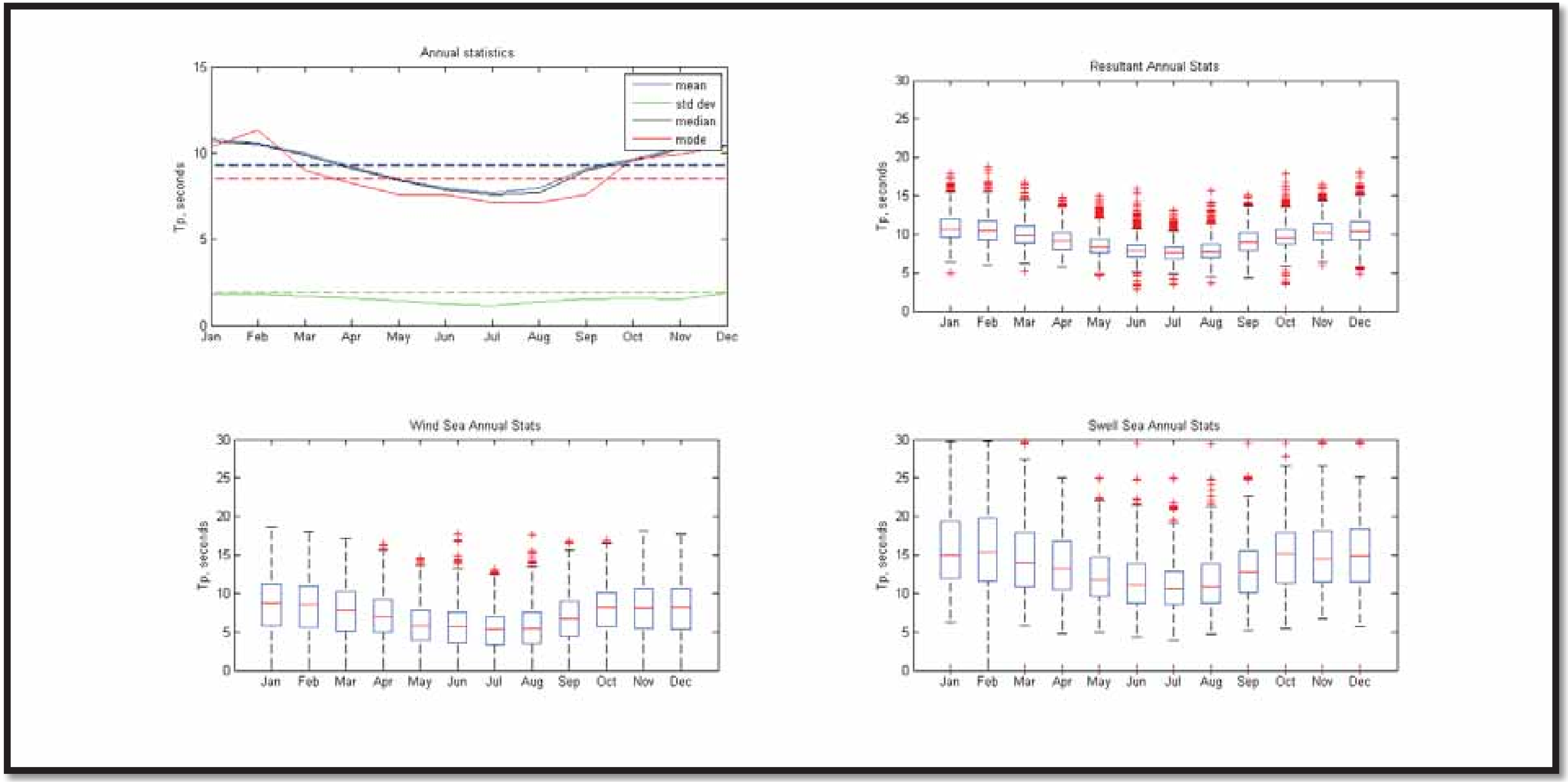


Figure 59: Annual Statistics for Peak Wave Period

12.2.3. Hs vs Tp Distribution

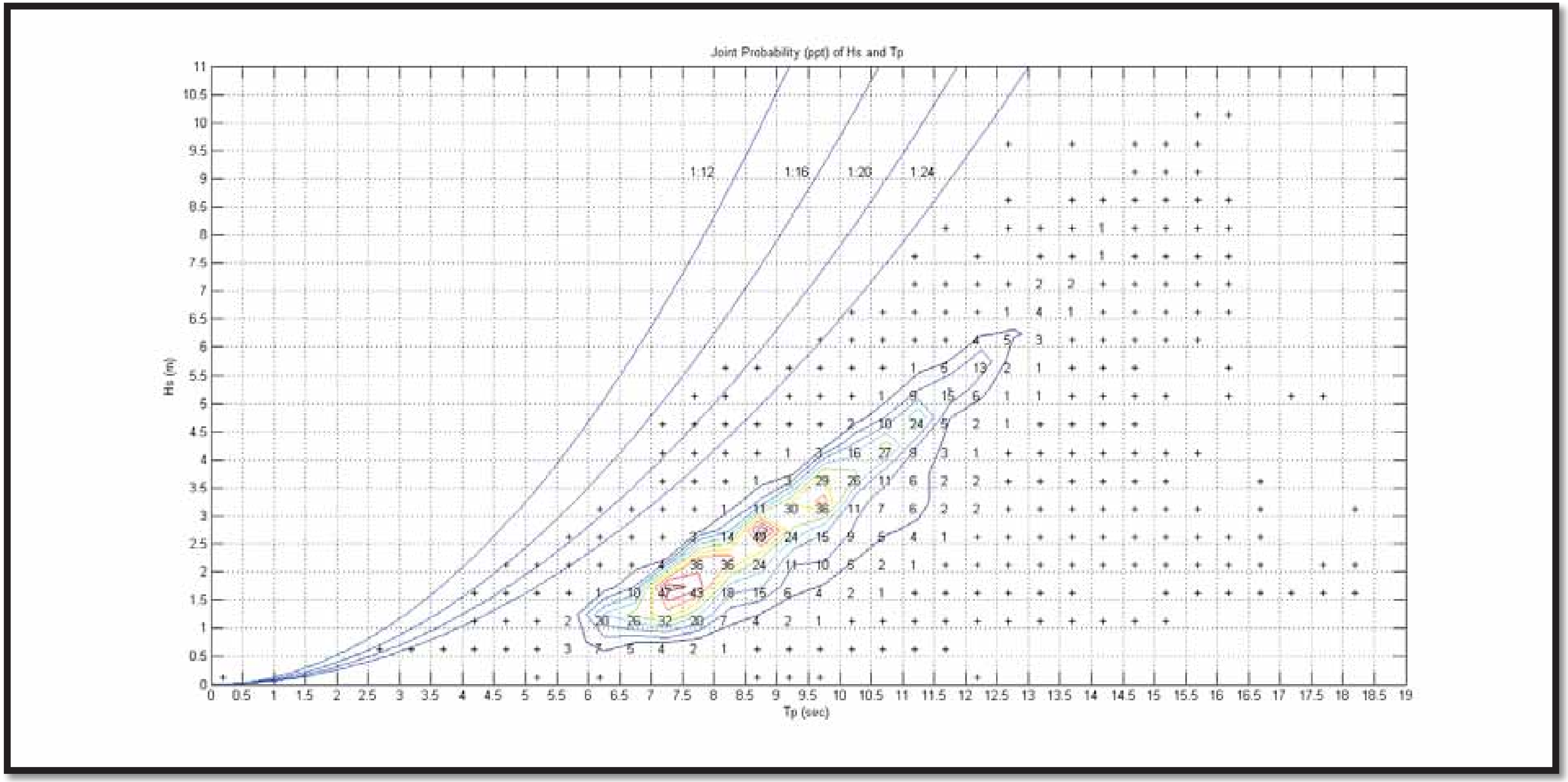


Figure 60: Wave Height vs Wave Period Bi-variate Distribution for Resultant Seas

12.2.4. Resultant Distributions

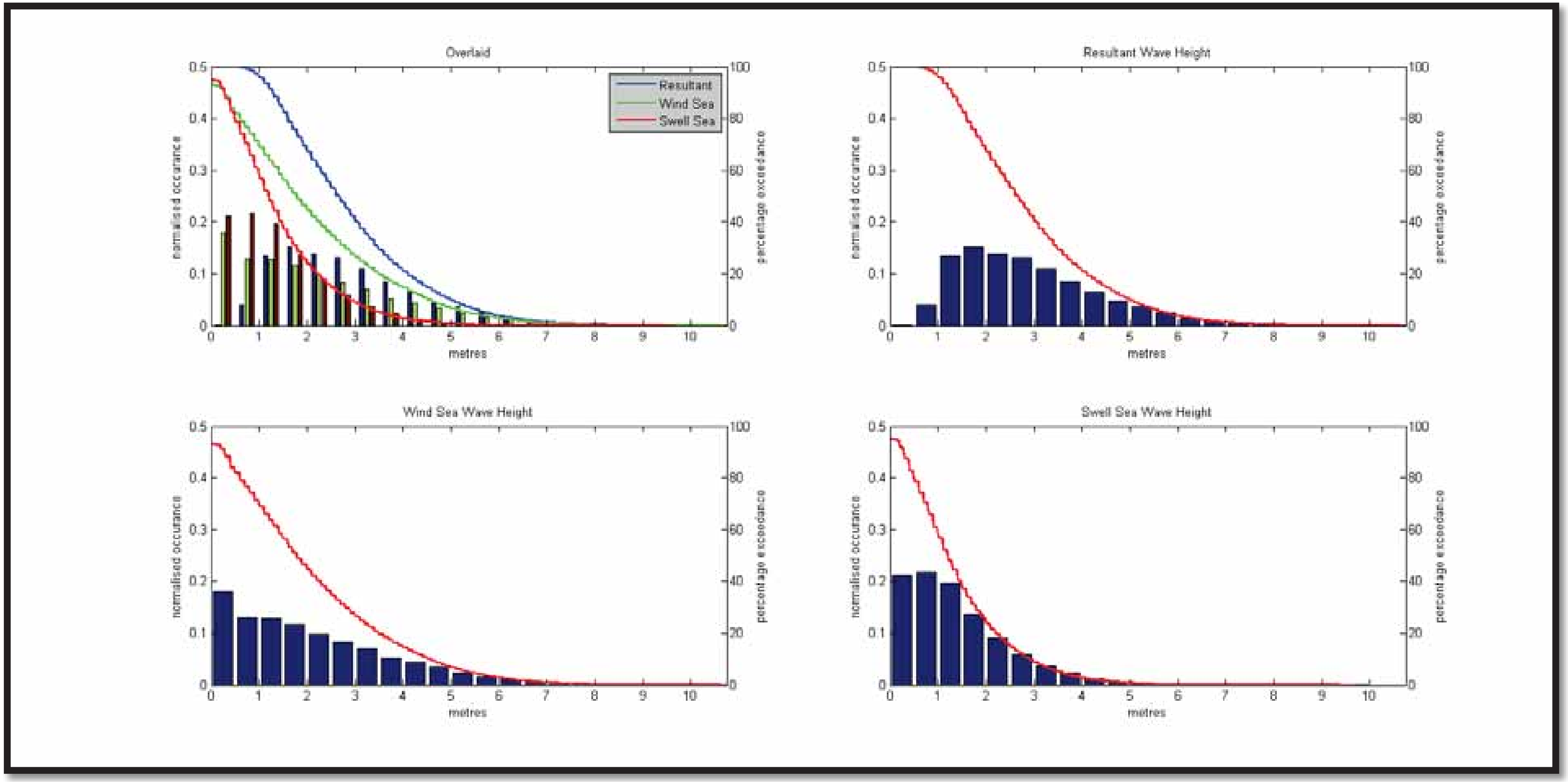


Figure 61: Resultant Sea Wave Height Distributions

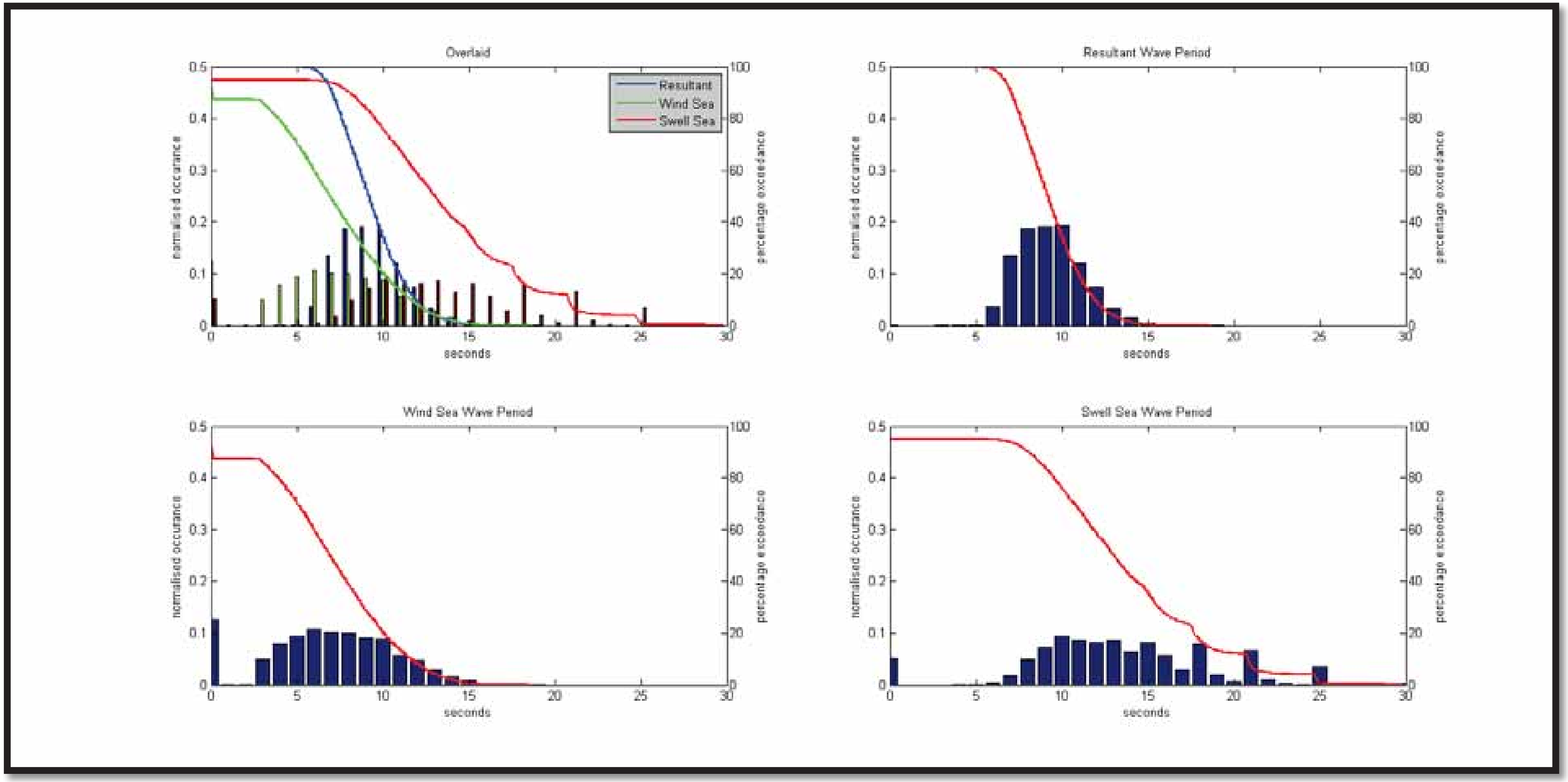


Figure 62: Resultant Seas Wave Period Distributions

12.2.5. Exceedence and Persistence Analysis

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	0	0	0	0	0	0.13	0.2	0	0	0.24	0	0
12 hrs	0	0	0	0	0	0	0.2	0	0	0.24	0	0
24 hrs	0	0	0	0	0	0	0	0	0	0	0	0
48 hrs	0	0	0	0	0	0	0	0	0	0	0	0
72 hrs	0	0	0	0	0	0	0	0	0	0	0	0

Table 5: Persistence of wave height less than 0.5m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	0.2	0	0.56	0.21	3.76	6.43	9.81	8.44	1.08	0.69	0	0.81
12 hrs	0.2	0	0.56	0	3.76	6.3	9.52	8.32	0.96	0.69	0	0.81
24 hrs	0	0	0.32	0	3.76	5.84	9.12	7.71	0.54	0.49	0	0.81
48 hrs	0	0	0	0	2.78	4.59	9.12	5.56	0	0	0	0.81
72 hrs	0	0	0	0	2.04	4.59	5.21	4.75	0	0	0	0

Table 6: Persistence of wave height less than 1m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	2.29	1.98	5.65	11.21	22.52	32.01	40.84	36.85	12.89	3.8	1.48	3.93
12 hrs	2.21	1.89	5.41	11.05	22.11	31.51	40.64	36.77	12.51	3.64	1.25	3.81
24 hrs	1.8	1.44	4.88	9.42	21.05	30.68	39.87	35.23	12.01	3.11	1.25	3.4
48 hrs	1.47	1.08	2.14	7.92	17.37	25.83	35.79	30.07	8.76	1.66	0.83	2.84
72 hrs	0	1.08	2.14	3.54	14.18	16.19	28.81	26.54	6.46	0	0	2.19

Table 7: Persistence of wave height less than 1.5m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	7.16	9.23	14.89	26.8	48.96	60.64	69.9	59.94	33.82	10.8	5.22	12.2
12 hrs	6.91	8.87	14.44	26.43	48.51	60.43	69.45	59.58	33.44	10.48	4.67	11.96
24 hrs	6.22	7.56	13.11	24.84	47.2	60.02	68.97	56.98	30.78	7.44	3.37	10.58
48 hrs	3.72	6.48	9.48	21.76	44.22	55.3	66.46	55.28	25.85	4.29	1.85	6.61
72 hrs	3.72	3.87	7.26	17.76	41.07	49.08	61.9	51.01	20.27	1.13	0	5.03

Table 8: Persistence of wave height less than 2m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	14.44	20.12	27.07	46.39	67.27	77.13	85.55	75.77	50.58	26.21	14	21.97
12 hrs	14.07	19.44	26.1	45.48	66.94	76.46	85.39	75.49	50.08	25.53	12.66	21.16
24 hrs	13.62	17.28	24.28	42.6	65.75	74.83	84.75	72.97	49.42	21.24	11.6	20.63
48 hrs	11.49	14.31	20.49	35.56	61.99	73.83	81.92	71.59	45.29	13.23	8.78	16.98
72 hrs	9.73	12.87	16.7	27.97	58.72	69.12	81.19	68.14	41.28	9.83	1.11	14.71

Table 9: Persistence of wave height less than 2.5m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	23.8	33.66	44.01	62.32	81.57	89.02	92.94	86.53	64.18	44.42	30.45	32.71
12 hrs	23.11	32.45	43.08	61.9	80.96	89.02	92.94	86.12	63.76	43.85	29.25	32.06
24 hrs	20.08	30.2	40.14	59.48	80.38	88.52	92.94	84.58	62.76	39.89	25.14	30.48
48 hrs	17.22	23.13	34.85	58.07	78.3	88.06	92.62	83.32	57.63	29.57	19.13	27.64
72 hrs	14.89	16.74	26.14	50.94	76.05	86.14	91.85	83.32	51.17	21.76	13.03	20.11

Table 10: Persistence of wave height less than 3m

12.2.6. Return Wave Analysis

Return Period	Directional Sector											
	0	30	60	90	120	150	180	210	240	270	300	330
1	8.36	7.67	5.95	7.35	7.26	7.24	8.12	8.85	9.80	9.80	8.57	8.37
2	8.68	7.99	6.18	7.64	7.52	7.48	8.42	9.17	10.19	10.20	8.91	8.69
5	9.09	8.40	6.47	8.02	7.86	7.78	8.80	9.57	10.69	10.71	9.34	9.09
10	9.38	8.69	6.67	8.29	8.10	8.00	9.07	9.86	11.06	11.07	9.65	9.38
20	9.67	8.97	6.88	8.55	8.34	8.21	9.33	10.14	11.41	11.43	9.95	9.66
50	10.03	9.33	7.13	8.88	8.63	8.47	9.67	10.49	11.85	11.88	10.33	10.02
100	10.29	9.59	7.32	9.12	8.85	8.66	9.91	10.74	12.18	12.21	10.61	10.28

Table 11: Extreme wave height analysis based on a Weibull fit to all wave height data

12.2.7. Wind Analysis

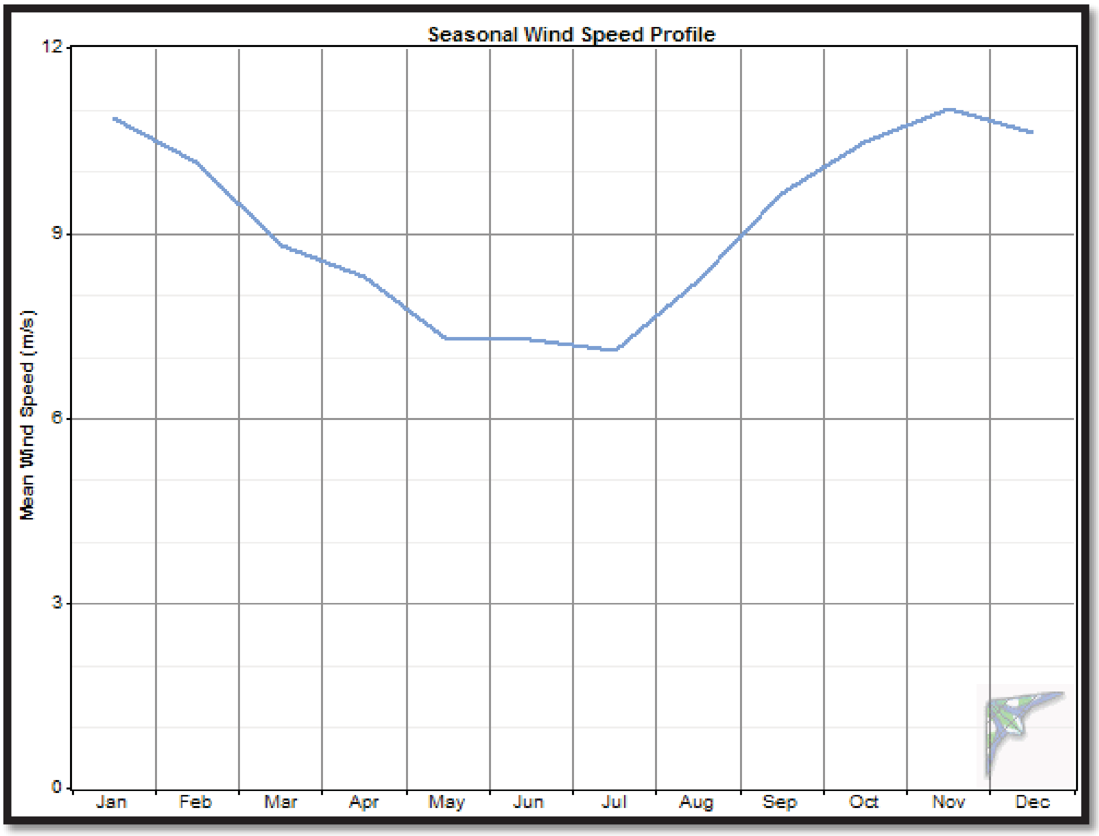


Figure 63: Seasonal wind speed profile

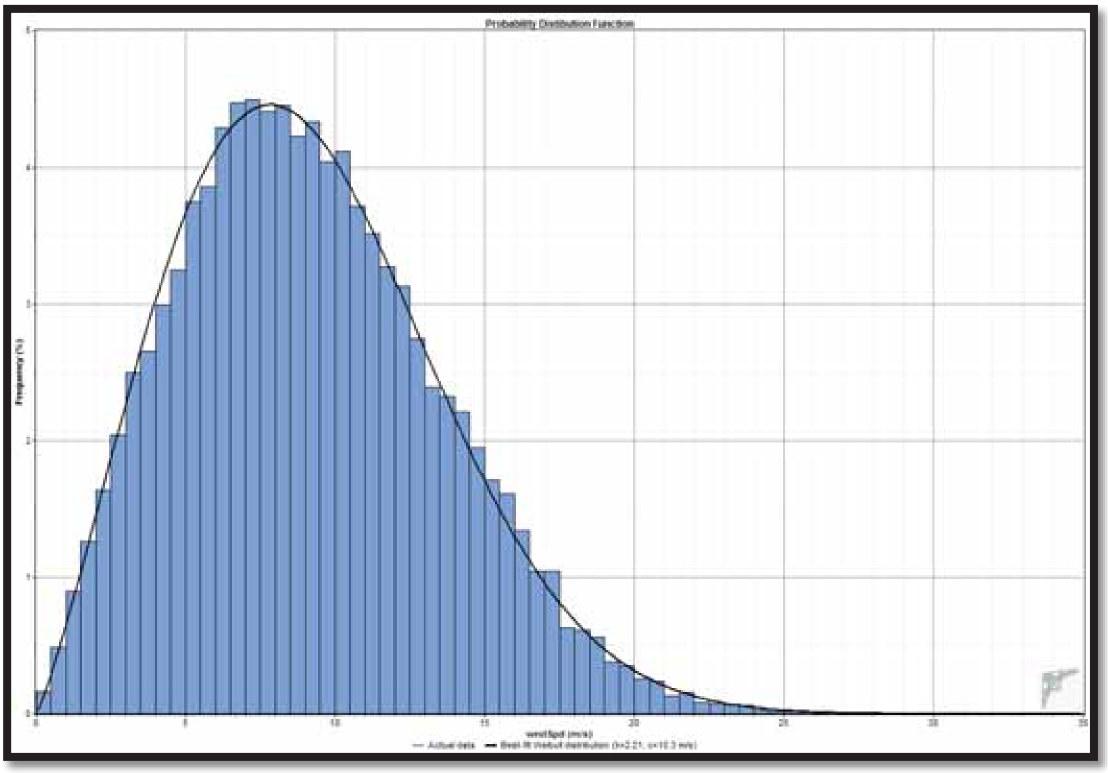


Figure 64: Probability Density Function of Wind Speed

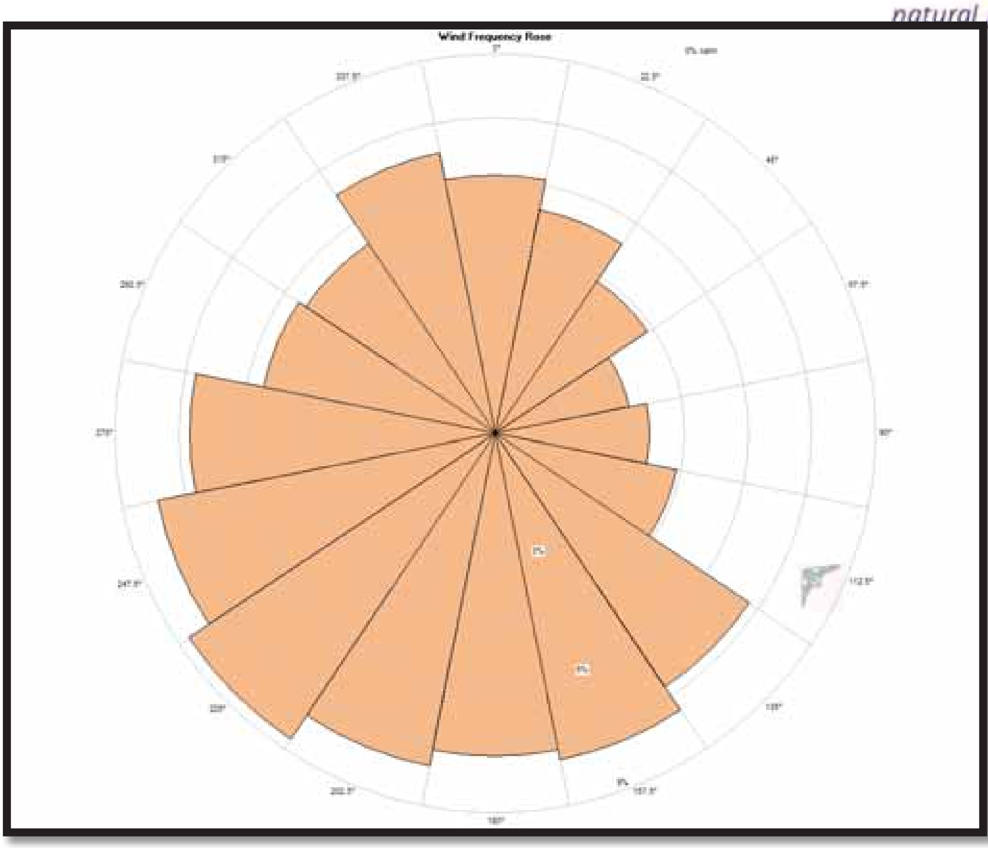
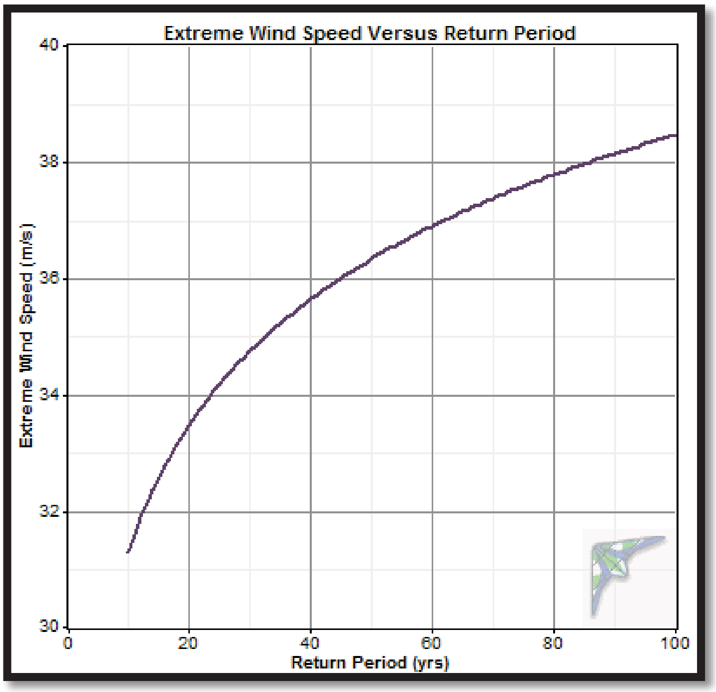


Figure 65: 16 sector wind rose based on frequency of occurrence



Return Period Years	Extreme Wind Speed (m/s)
20	33.5
25	34.2
50	36.3
100	39.5

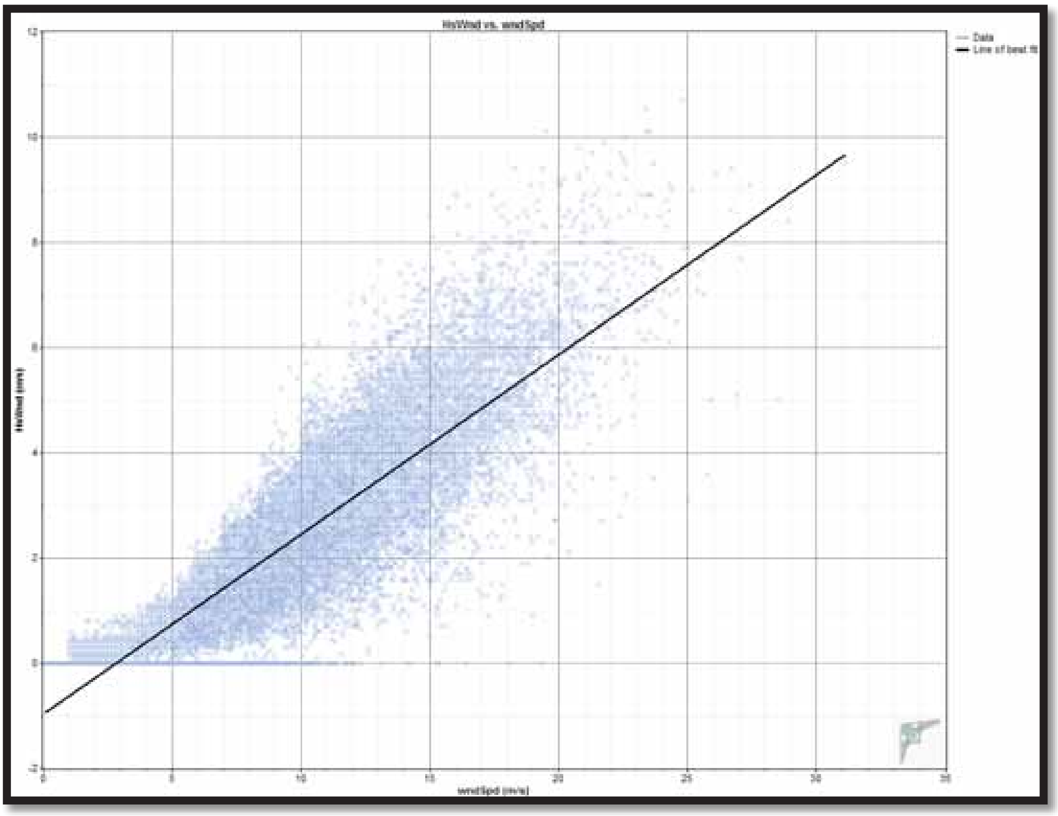


Figure 66: Plot of Wind Speed vs wind sea wave height

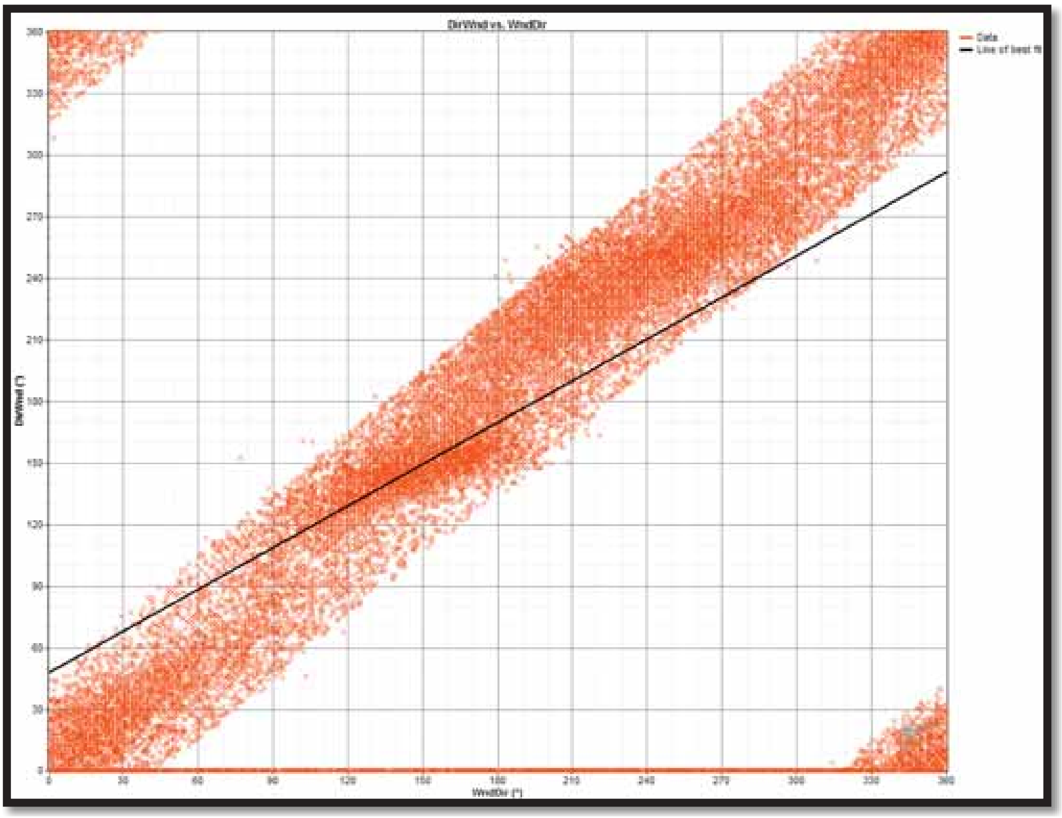


Figure 67: Plot of Wind Direction vs the direction of travel of wind sea

12.3. Easterly Location – 60.28N 0.08W

12.3.1. Wave Roses

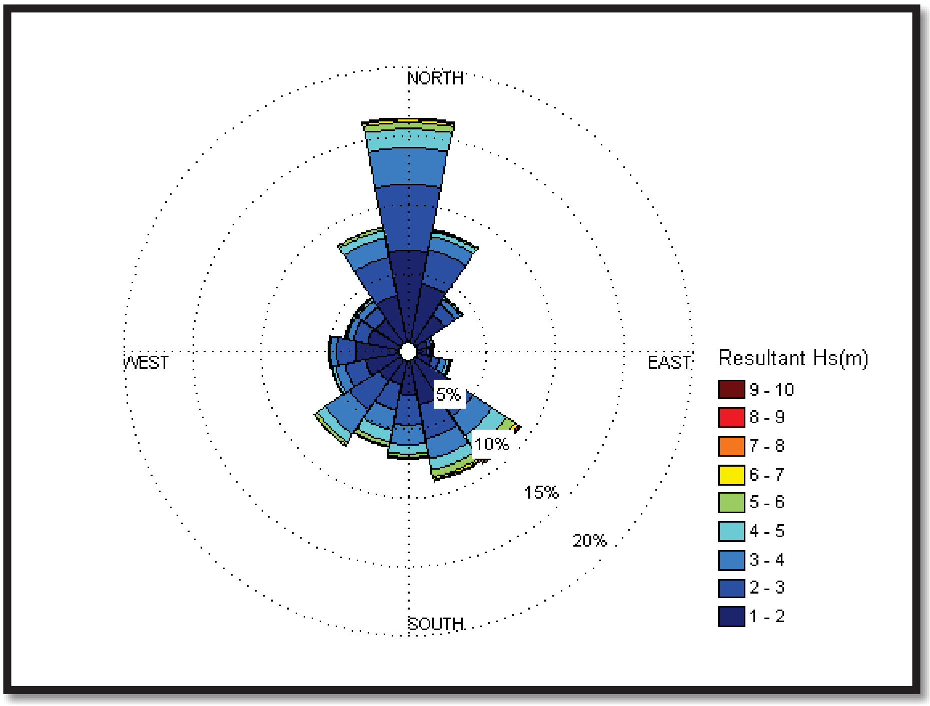


Figure 68: Wave rose of Resultant Wave Height

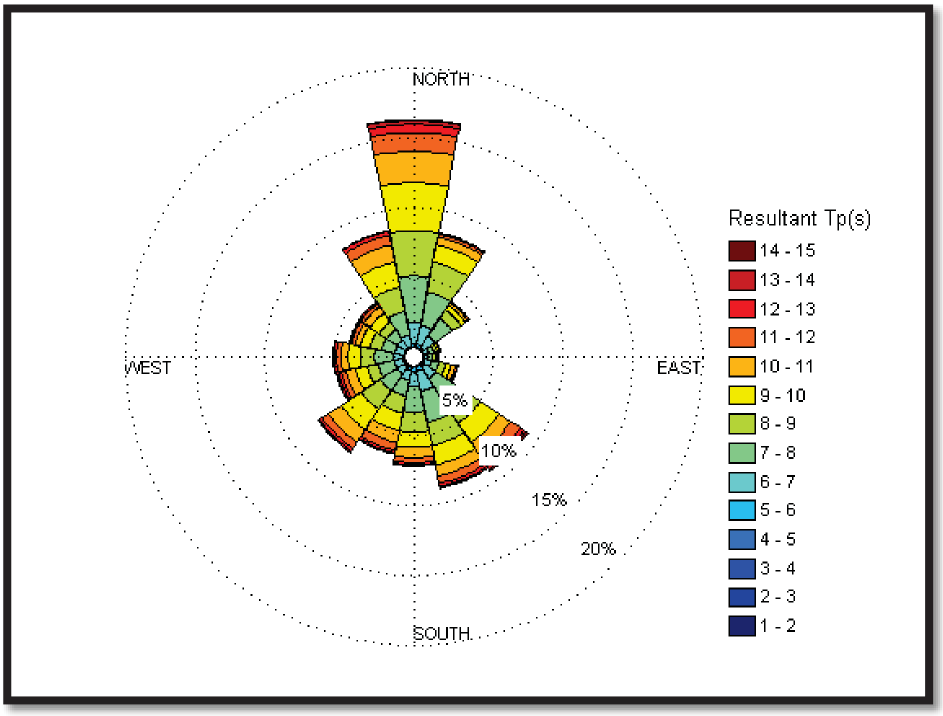


Figure 69: Wave Rose of Resultant Peak Period

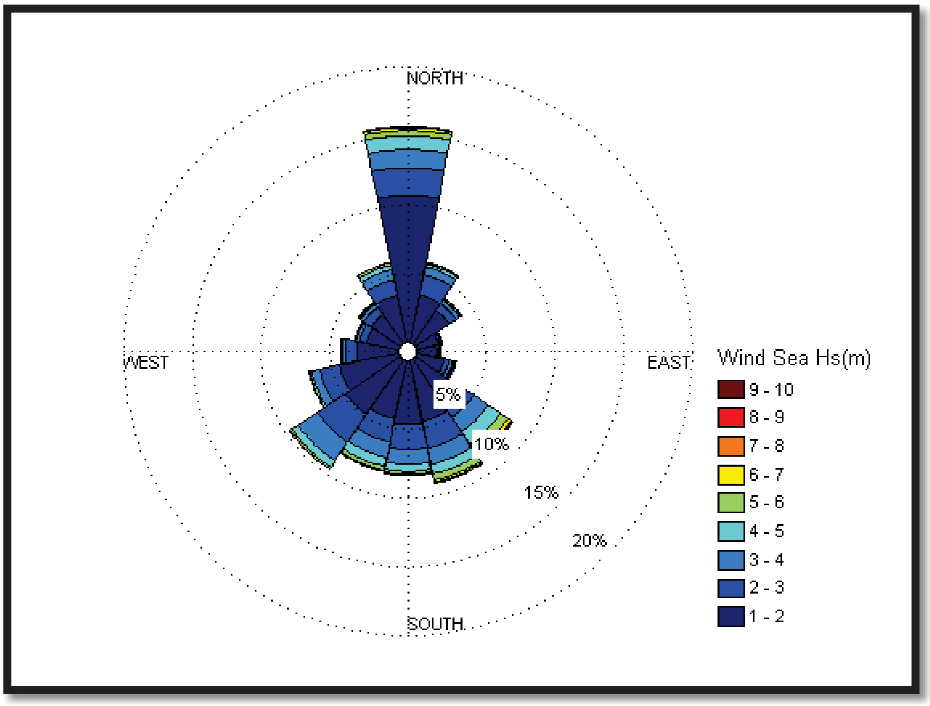


Figure 70: Wave Rose of Wind Sea Wave Heights

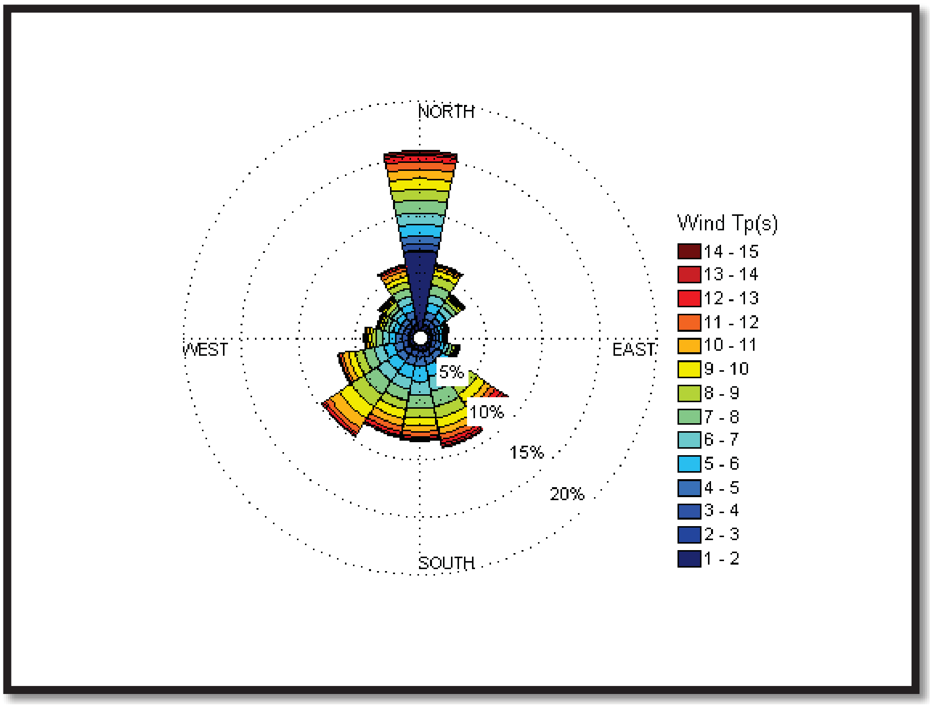


Figure 71: Wave Rose of Wind Sea Peak Periods

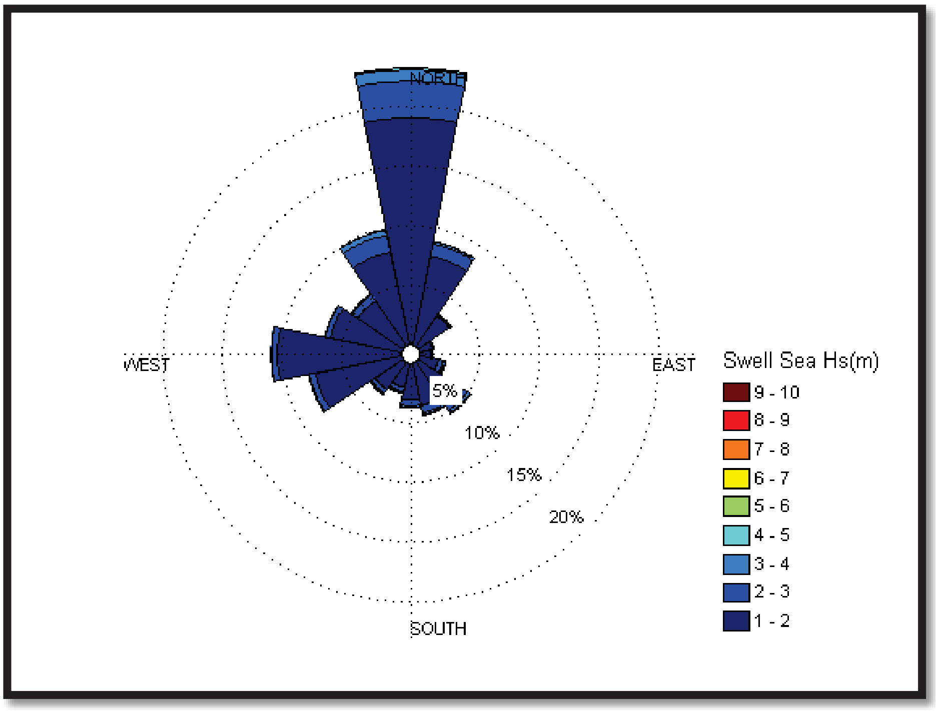


Figure 72: Wave Rose of Swell Sea Wave Heights

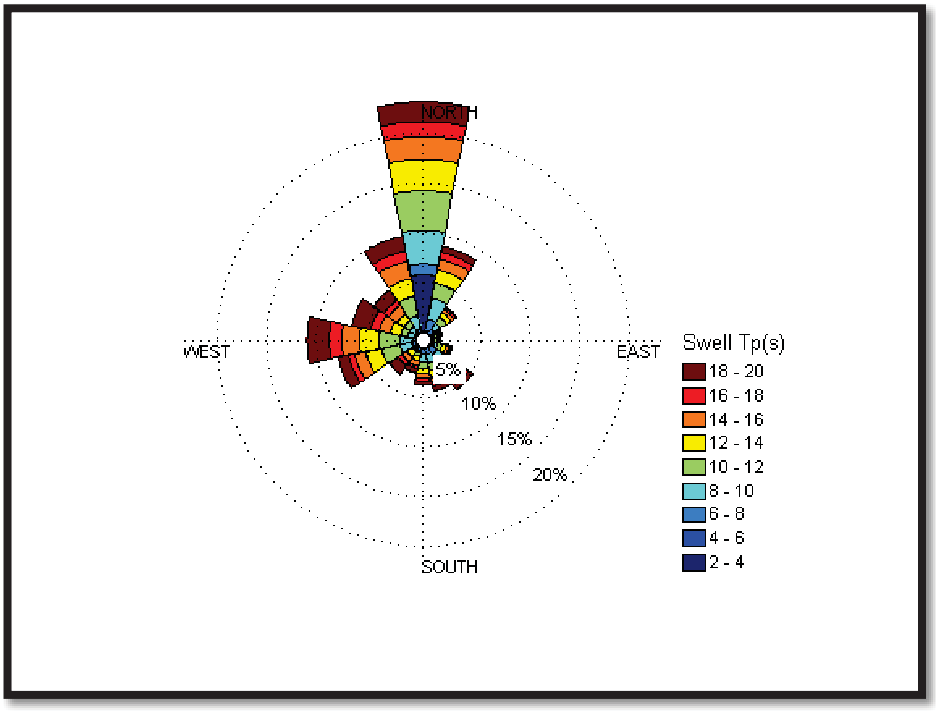


Figure 73: Wave Rose of Swell Sea Peak Periods

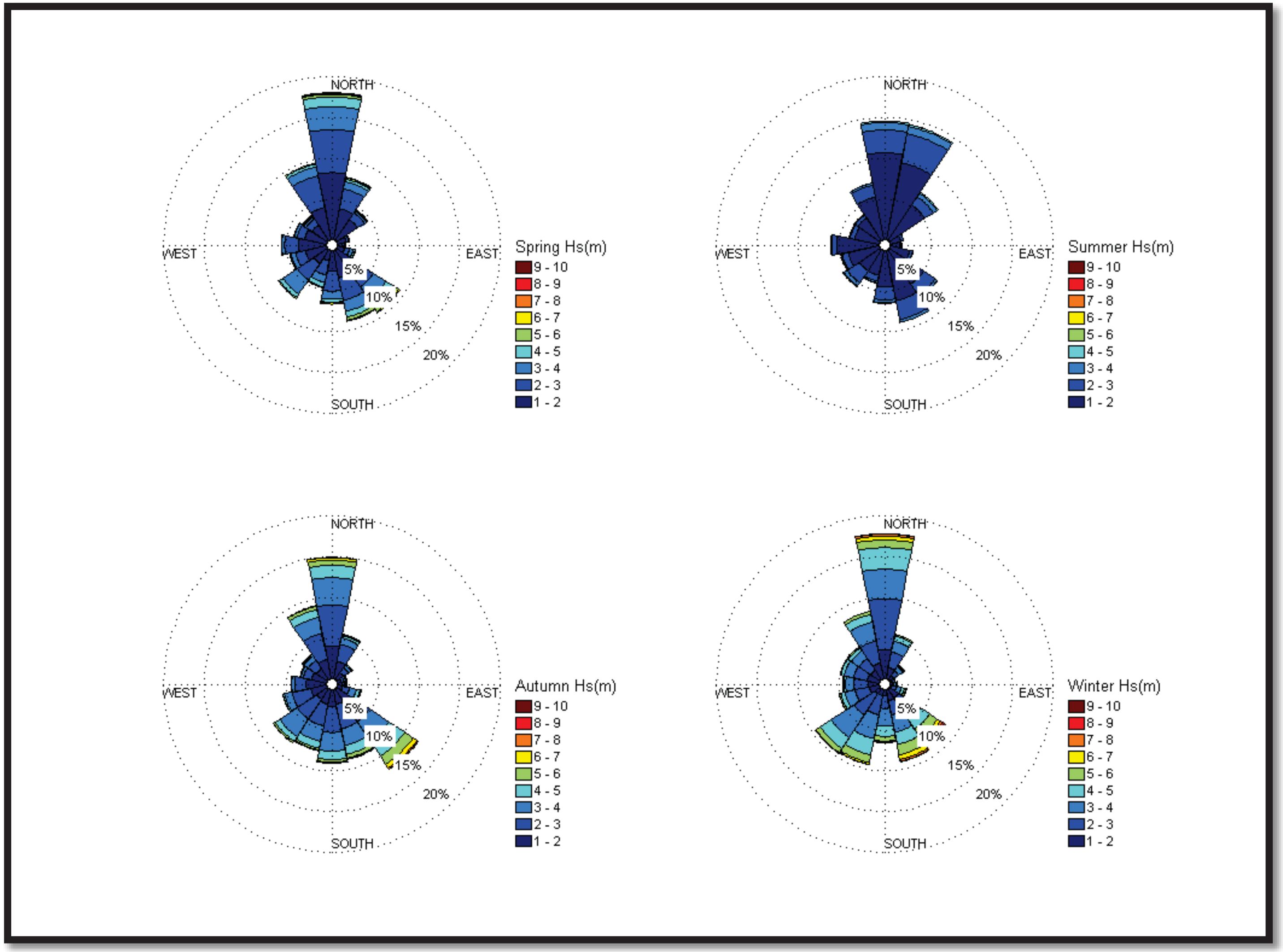


Figure 74: Seasonal Wave Roses for Resultant Wave Height

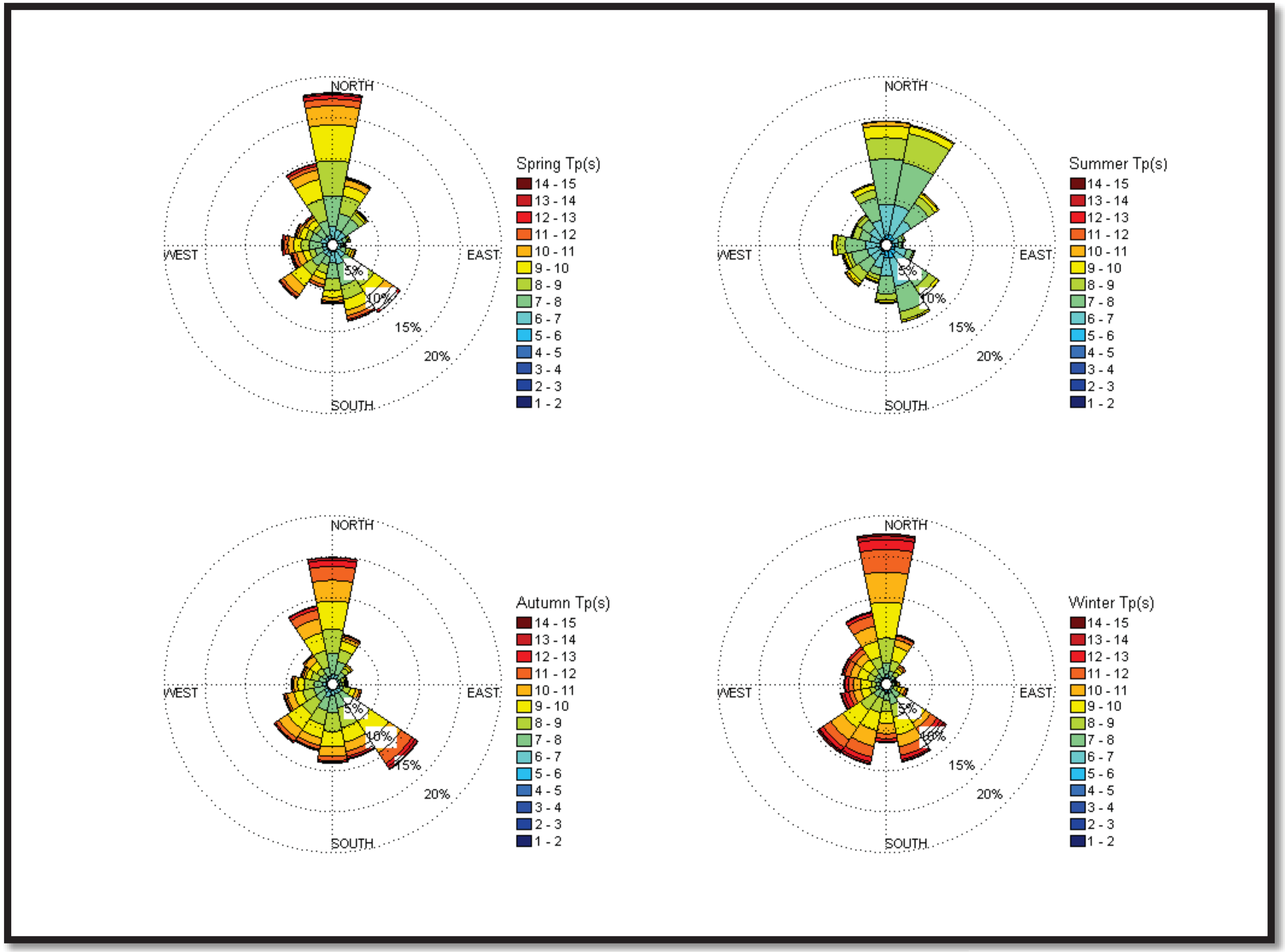


Figure 75: Seasonal Wave Roses for Resultant Wave Period

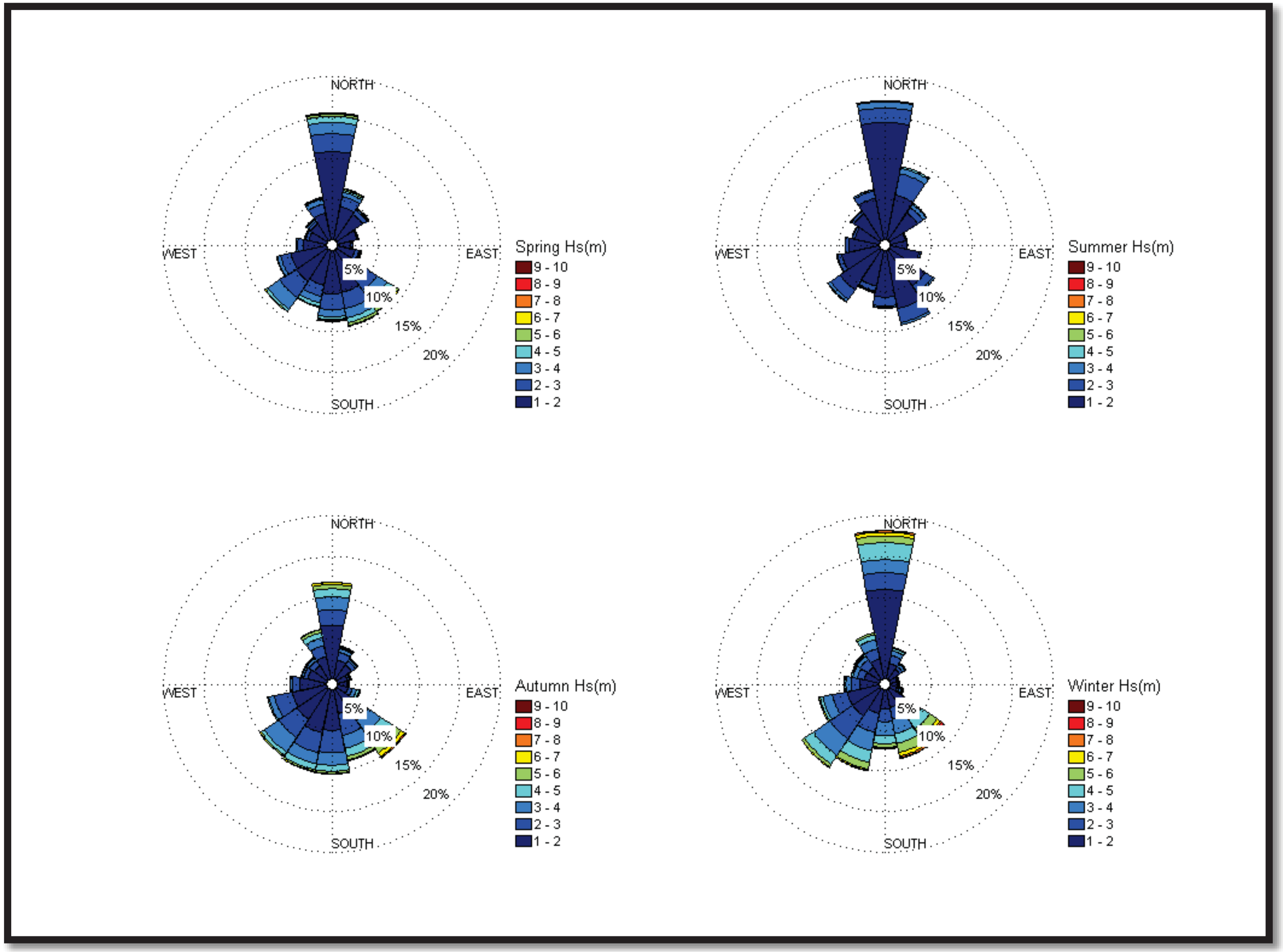


Figure 76: Seasonal Wave Roses for Wind Sea Wave Height

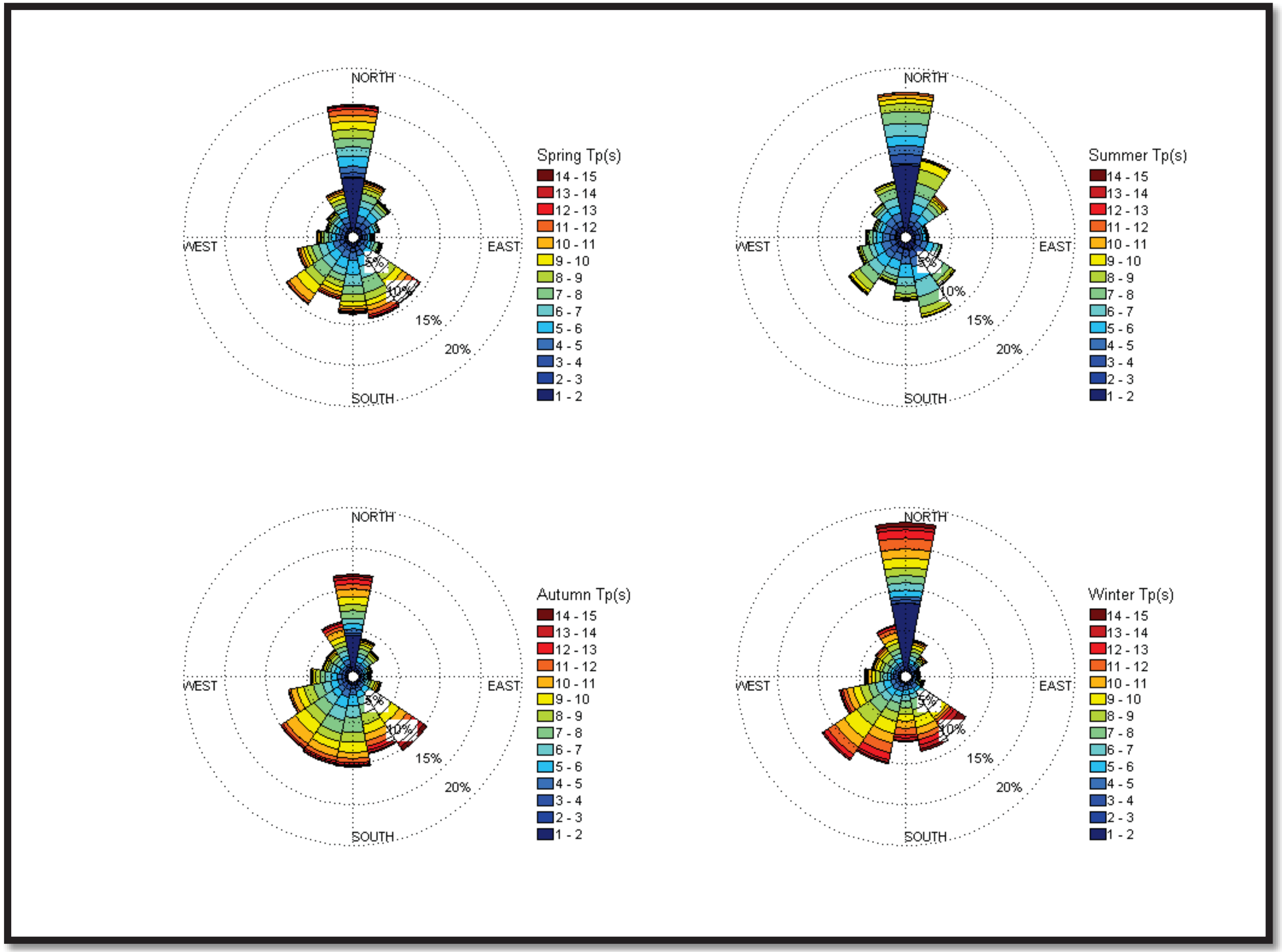


Figure 77: Seasonal Wave Roses for Wind Sea Peak Period

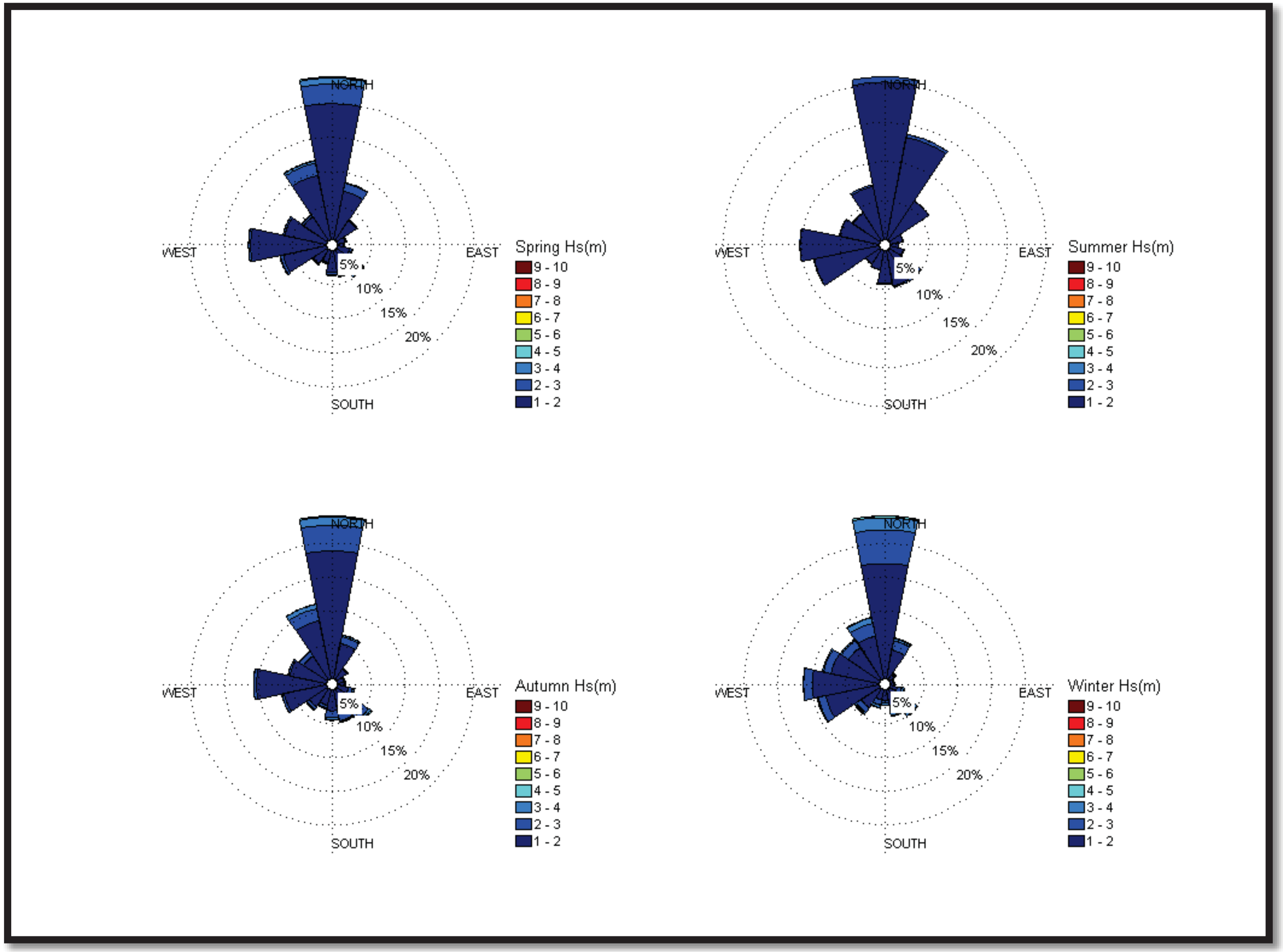


Figure 78: Seasonal Wave Roses for Swell Sea Wave Height

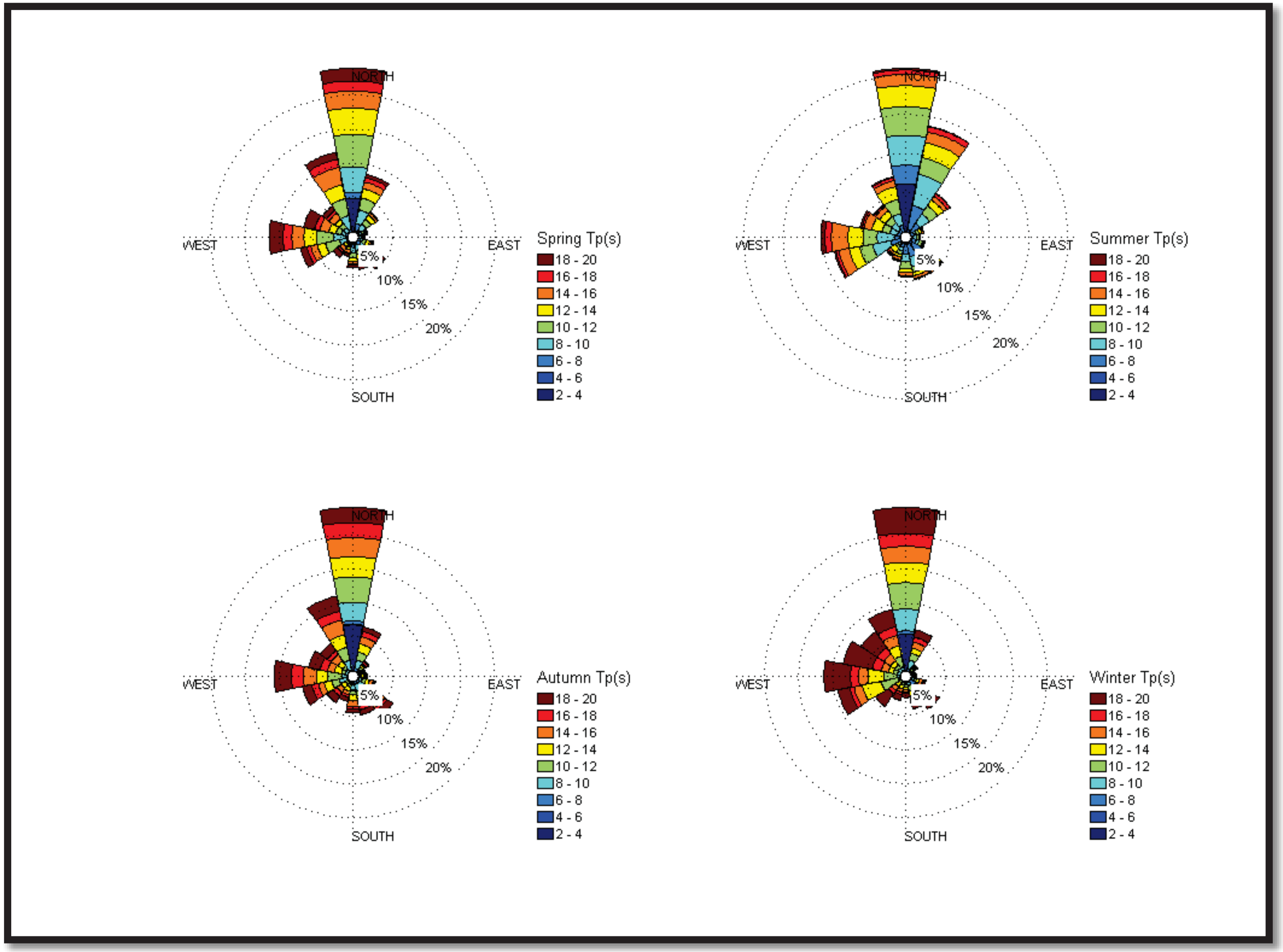


Figure 79: Seasonal Wave Roses for Swell Sea Peak Period

12.3.2. Annual Statistics

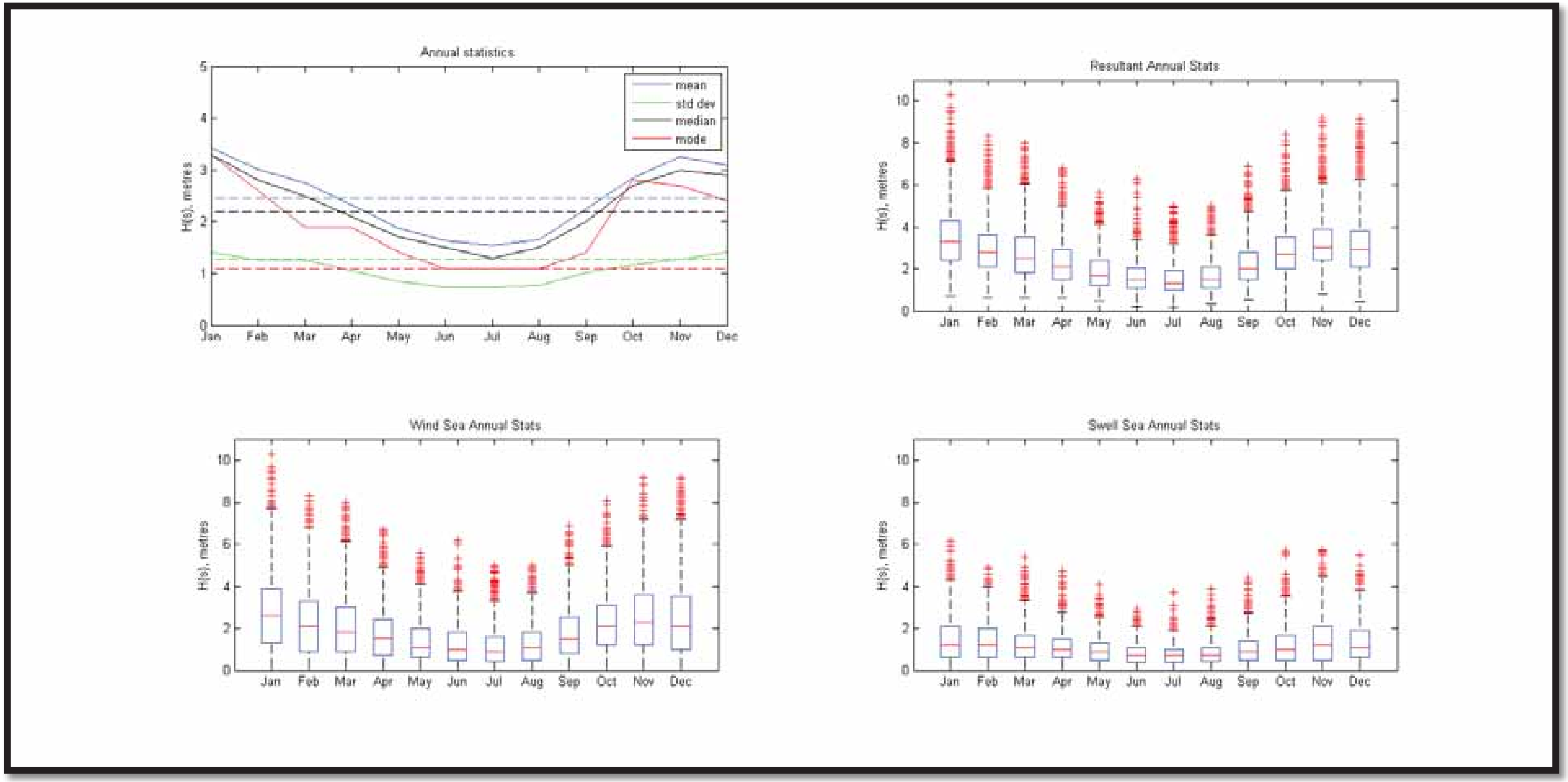


Figure 80: Annual Statistics for Significant Wave Height

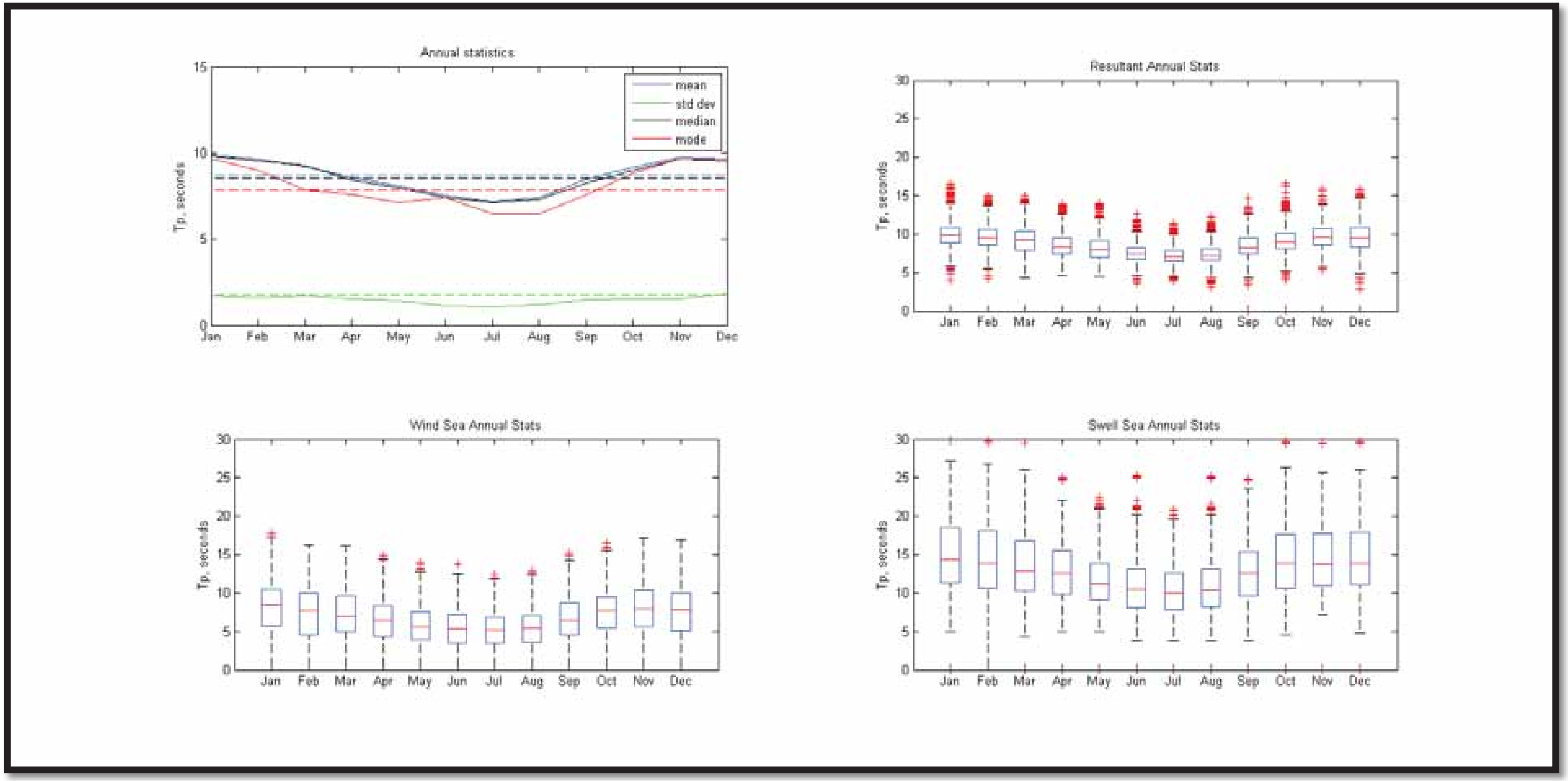


Figure 81: Annual Statistics for Peak Wave Period

12.3.3. Hs vs Tp Distribution

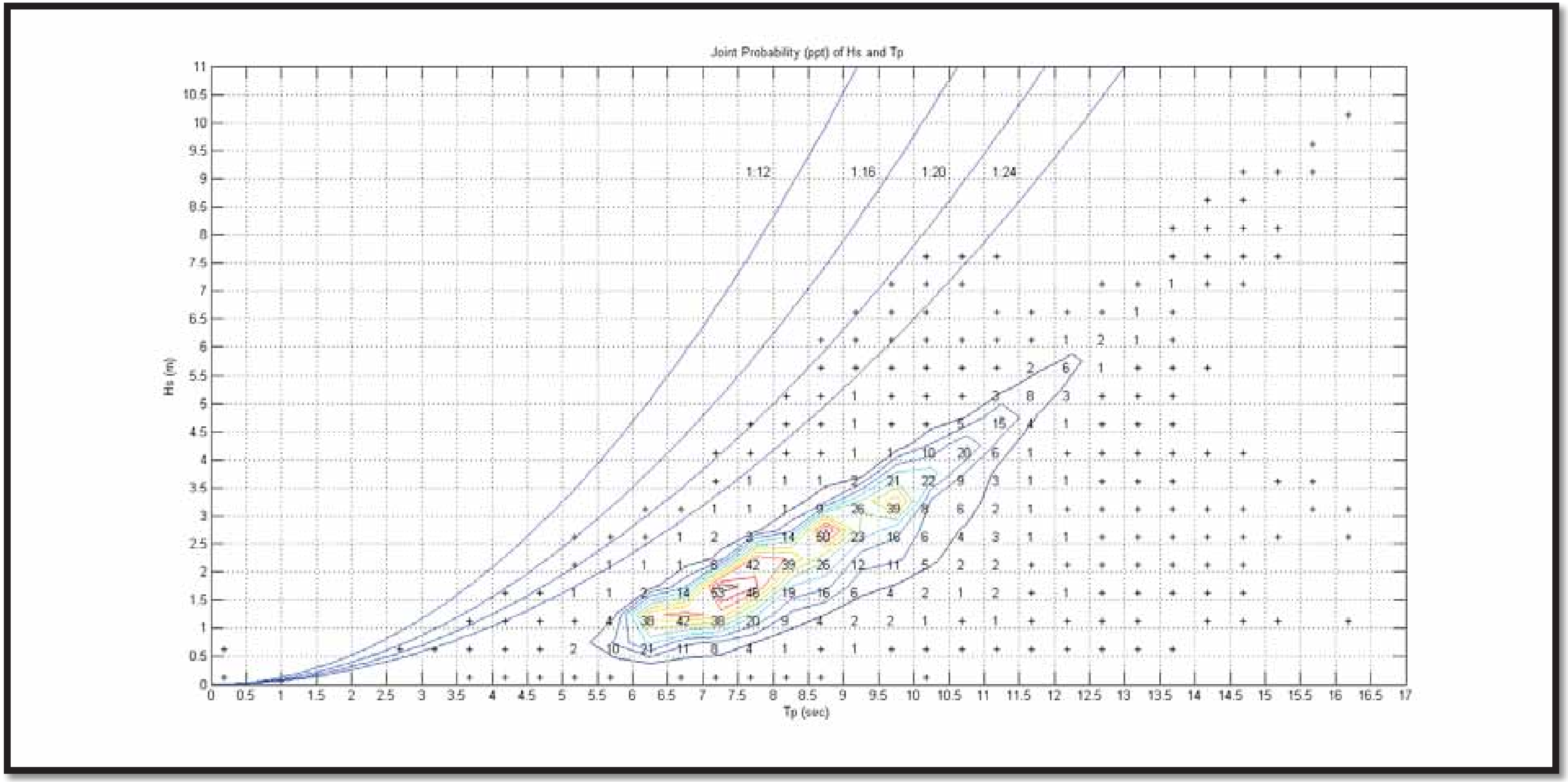


Figure 82: Wave Height vs Wave Period Bi-variate Distribution for Resultant Seas

12.3.4. Resultant Distributions

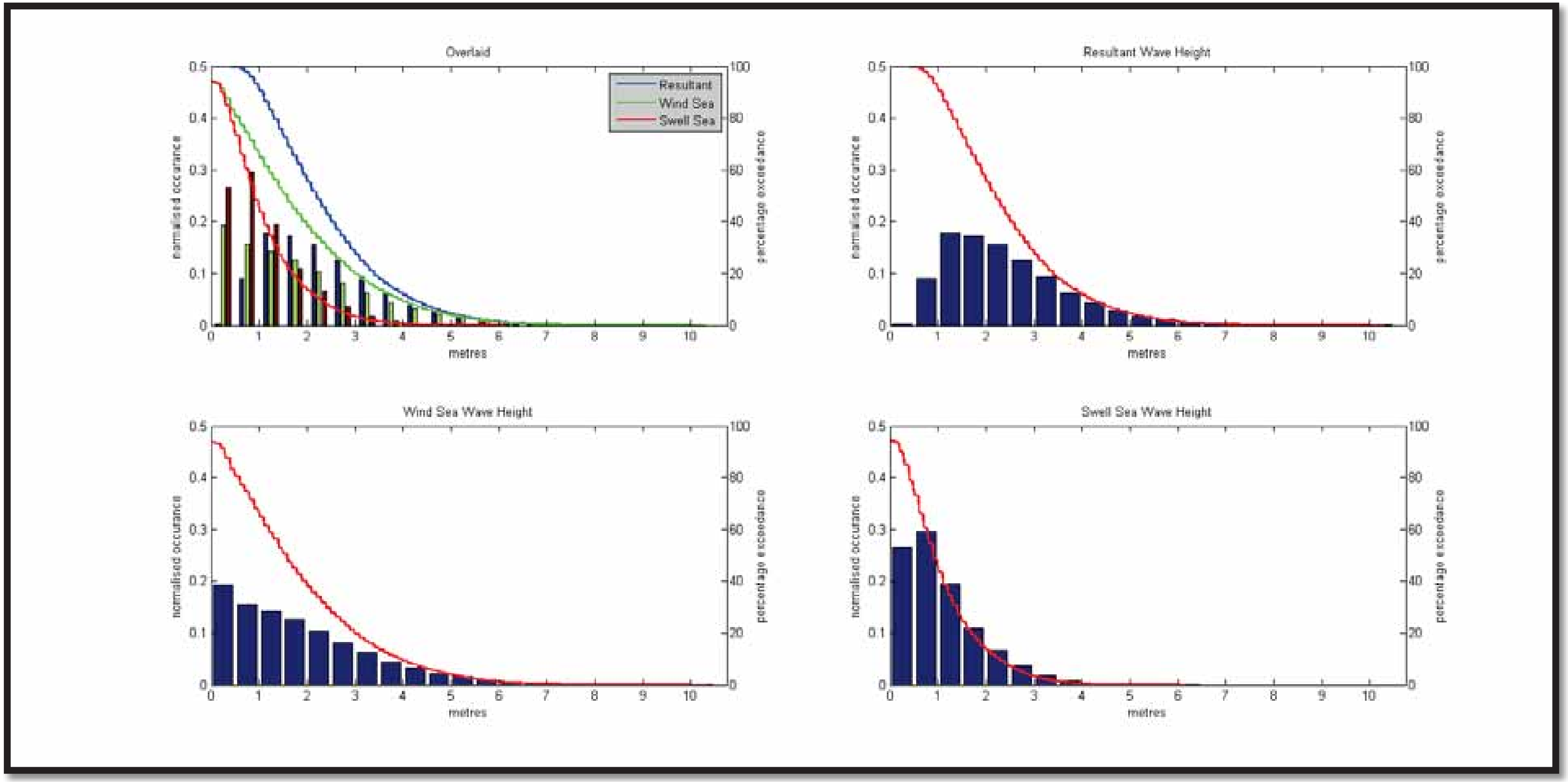


Figure 83: Resultant Sea Wave Height Distributions

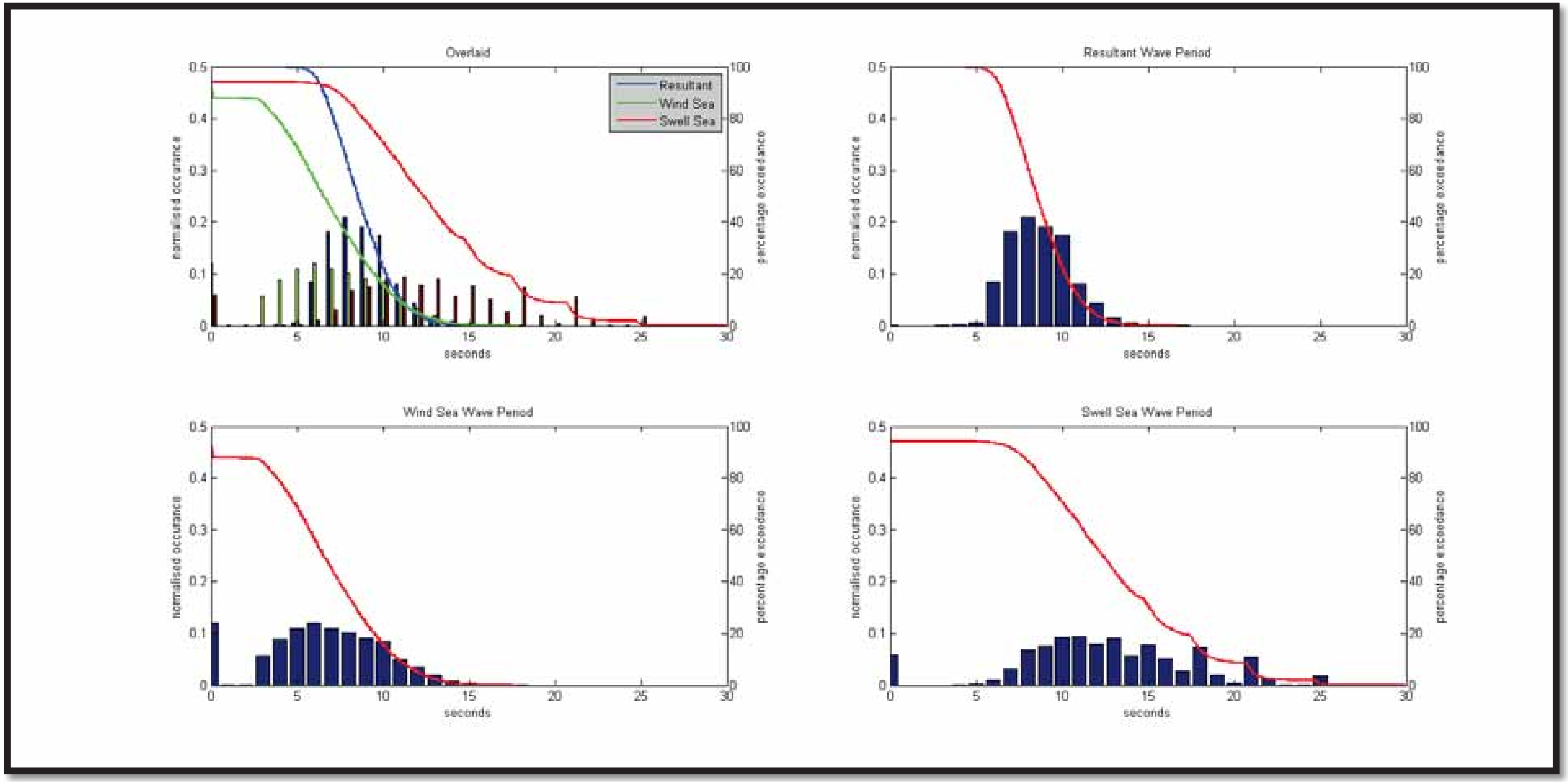


Figure 84: Resultant Seas Wave Period Distributions

12.3.5. Exceedence and Persistence Analysis

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	0	0	0	0	0	1.34	1.05	0.45	0	0.12	0	0
12 hrs	0	0	0	0	0	1.34	1.05	0.45	0	0	0	0
24 hrs	0	0	0	0	0	1.34	1.05	0	0	0	0	0
48 hrs	0	0	0	0	0	1.34	1.05	0	0	0	0	0
72 hrs	0	0	0	0	0	1.34	1.05	0	0	0	0	0

Table 12: Persistence of wave height less than 0.5m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	1.55	1.49	1.82	4.5	10.54	16.78	20.42	17.82	2.84	1.58	0.23	2.76
12 hrs	1.55	1.49	1.69	4.38	10.54	16.53	20.3	17.37	2.5	1.5	0.23	2.68
24 hrs	1.02	1.49	1.37	4.21	10.05	15.23	18.85	16.68	2.13	1.5	0	1.95
48 hrs	1.02	0.99	0.81	2.88	9.32	11.73	16.22	14.69	1.54	0.93	0	1.34
72 hrs	1.02	0	0	2.88	6.87	11.73	12.75	13.15	0	0	0	1.34

Table 13: Persistence of wave height less than 1m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	6.18	6.89	11.98	21.59	37.72	47.75	57.34	48.5	24.1	9.34	4.02	9.4
12 hrs	5.89	6.66	11.78	21.43	37.6	47.29	57.26	48.3	23.73	9.22	3.88	9.2
24 hrs	5.36	6.03	10.85	20.01	35.88	45.95	55.45	45.09	21.43	7.77	2.36	8.51
48 hrs	3.76	5.63	8.96	16.59	31.47	40.61	52.02	41.84	17.6	4.05	1.76	6.65
72 hrs	3.76	4.82	6.17	11.46	26.81	35.98	46.73	35.59	14.35	2.27	0	6

Table 14: Persistence of wave height less than 1.5m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	14.15	21.15	30.58	43.56	60.44	71.74	77.85	70.66	47.87	22.94	13.63	21.08
12 hrs	13.91	20.88	29.69	42.35	60.16	71.45	77.72	70.29	47.46	22.05	12.85	19.82
24 hrs	12.39	18.5	27.07	40.1	57.79	70.28	76.43	67.61	45.75	20.47	11.28	18.28
48 hrs	11	14.99	20.86	35.93	51.16	67.28	75.1	64.2	41.24	14.08	7.07	13.34
72 hrs	9.37	11.52	14.44	31.8	48.96	64.07	68.85	60.92	30.65	11.85	2.54	11.84

Table 15: Persistence of wave height less than 2m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	25.93	35.82	48.93	62.78	78.34	86.44	89.1	86.12	65.3	40.61	27.91	35.35
12 hrs	25.19	34.52	48.2	62.15	77.93	86.35	89.02	85.92	65.1	40.09	26.43	34.33
24 hrs	22.78	31.59	45.91	58.65	77.36	86.06	88.86	85.31	62.89	35.92	22.55	31.54
48 hrs	18.81	26.15	41.19	53.52	73.8	84.93	88.38	83.24	58.97	27.83	14.46	25.05
72 hrs	13.91	20.48	35.98	51.23	71.64	82.35	86.84	79.3	56.76	18.28	11.69	21.97

Table 16: Persistence of wave height less than 2.5m

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6 hrs	39.55	55.13	62.36	77.12	88.8	94.32	94.55	93.26	77.27	60.48	46.77	51.44
12 hrs	38.32	54.64	61.72	76.7	88.43	94.2	94.35	93.02	76.81	59.59	45.47	49.7
24 hrs	34.52	52.3	60.15	75.45	87.7	93.99	94.35	92.86	75.19	57.85	41.54	46.45
48 hrs	27.24	41.13	52.8	70.78	86.76	92.7	93.79	92.05	70.39	48.91	31.89	37.66
72 hrs	22.49	29.84	47.36	68.24	85.86	91.82	92.98	89.65	66.81	40.61	23.8	29.27

Table 17: Persistence of wave height less than 3m

12.3.6. Return Wave Analysis

Return Period	Directional Sector											
	0	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**
1	7.52	6.51	5.40	6.30	9.08	9.46	7.63	7.42	6.48	5.71	5.95	6.68
2	7.82	6.78	5.61	6.55	9.46	9.87	7.93	7.67	6.71	5.94	6.18	6.94
5	8.21	7.12	5.87	6.88	9.95	10.39	8.30	7.98	7.00	6.23	6.47	7.26
10	8.49	7.37	6.05	7.11	10.30	10.77	8.56	8.20	7.21	6.45	6.69	7.49
20	8.76	7.61	6.23	7.33	10.64	11.13	8.82	8.42	7.41	6.65	6.89	7.72
50	9.11	7.91	6.46	7.62	11.08	11.59	9.15	8.69	7.66	6.91	7.15	8.00
100	9.36	8.13	6.63	7.83	11.39	11.93	9.38	8.89	7.84	7.10	7.34	8.21

Table 18: Extreme wave height analysis based on a Weibull fit to all wave height data

12.3.7. Wind Analysis

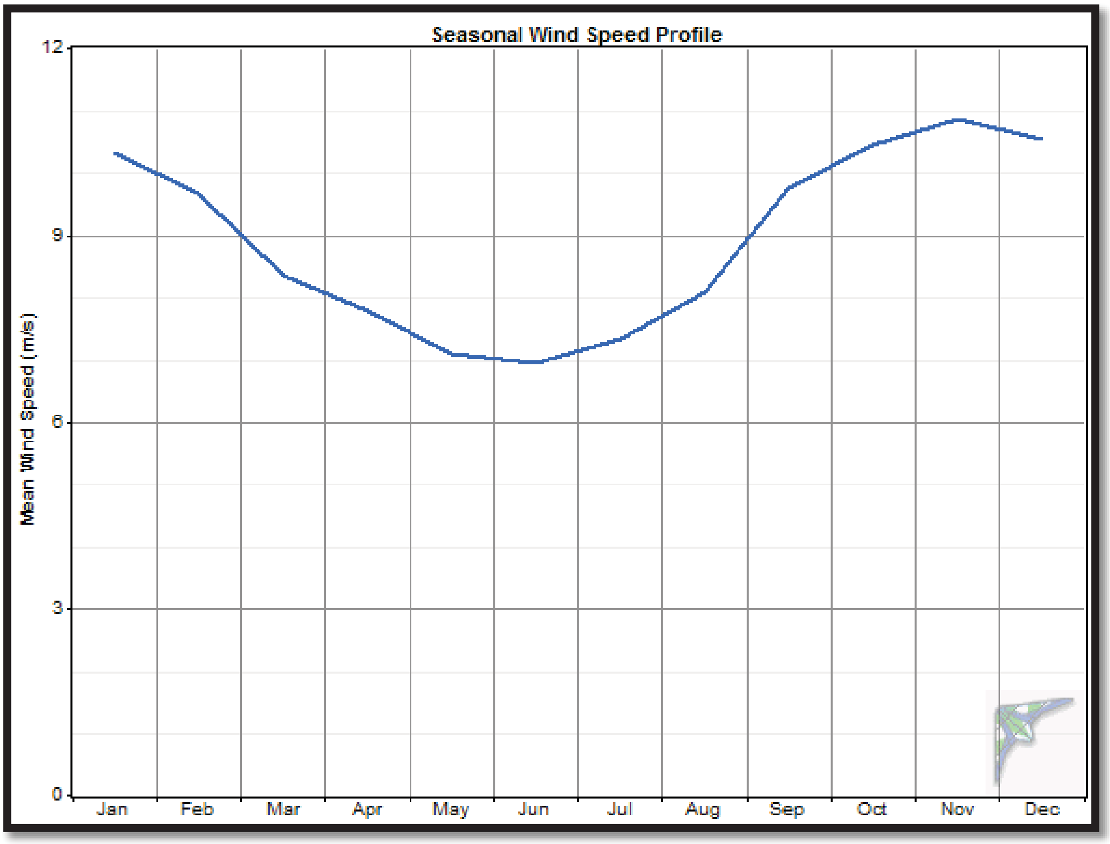


Figure 85: Seasonal wind speed profile

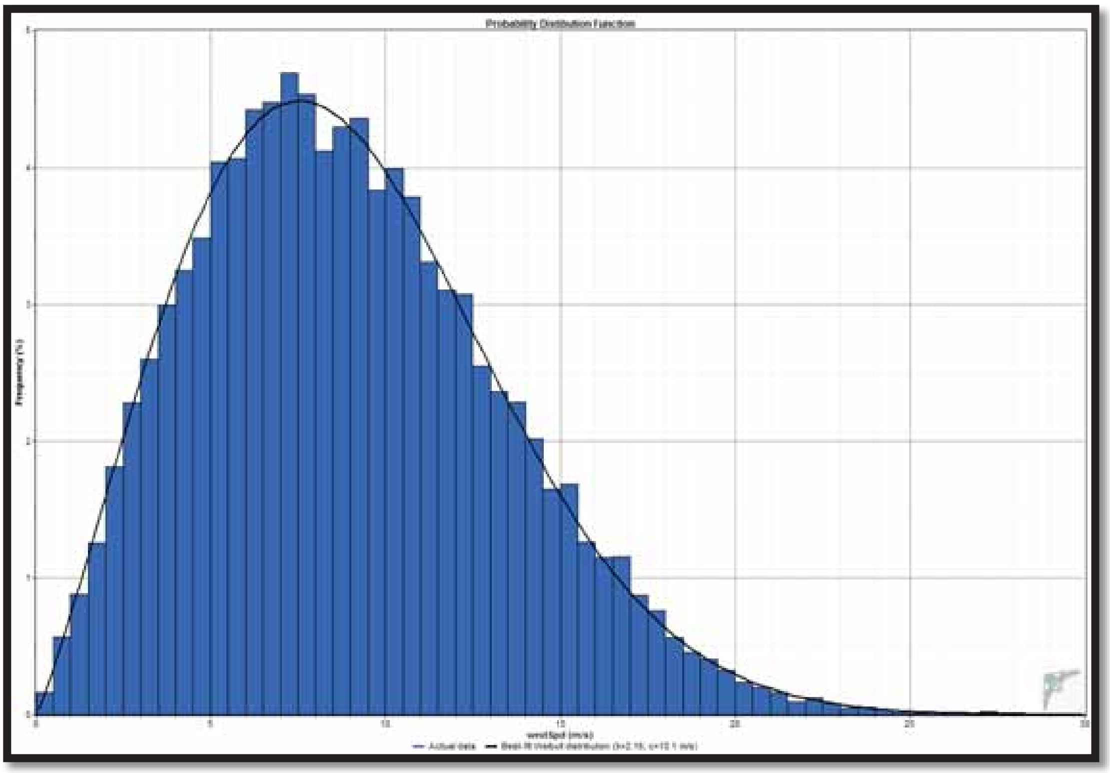


Figure 86: Probability Density Function of Wind Speed

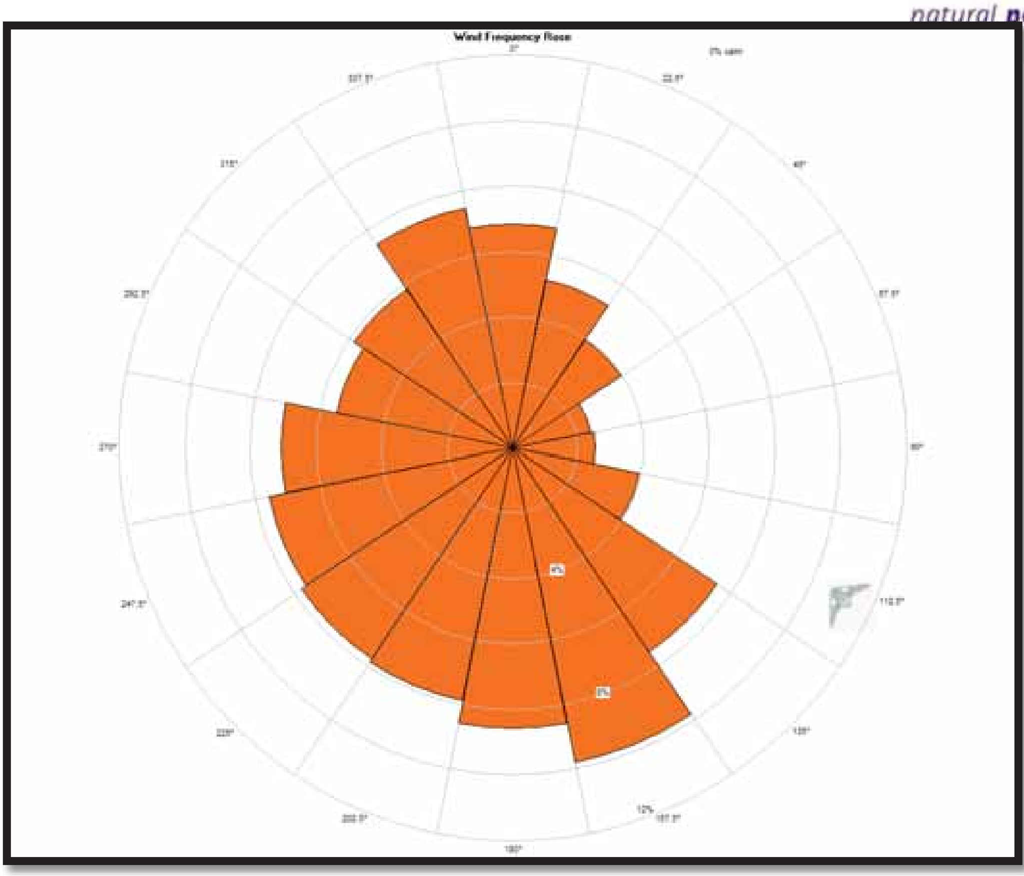
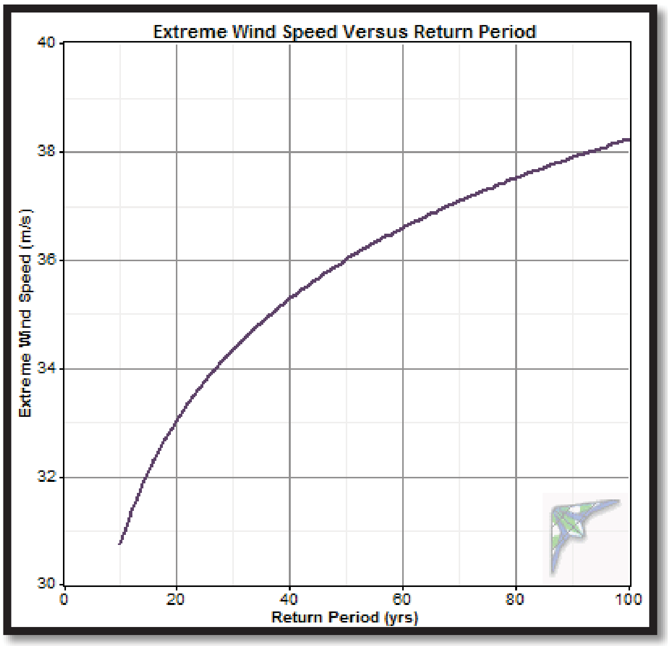


Figure 87: 16 sector wind rose based on frequency of occurrence



Return Period Years	Extreme Wind Speed (m/s)
20	33.5
25	34.2
50	36.3
100	39.5

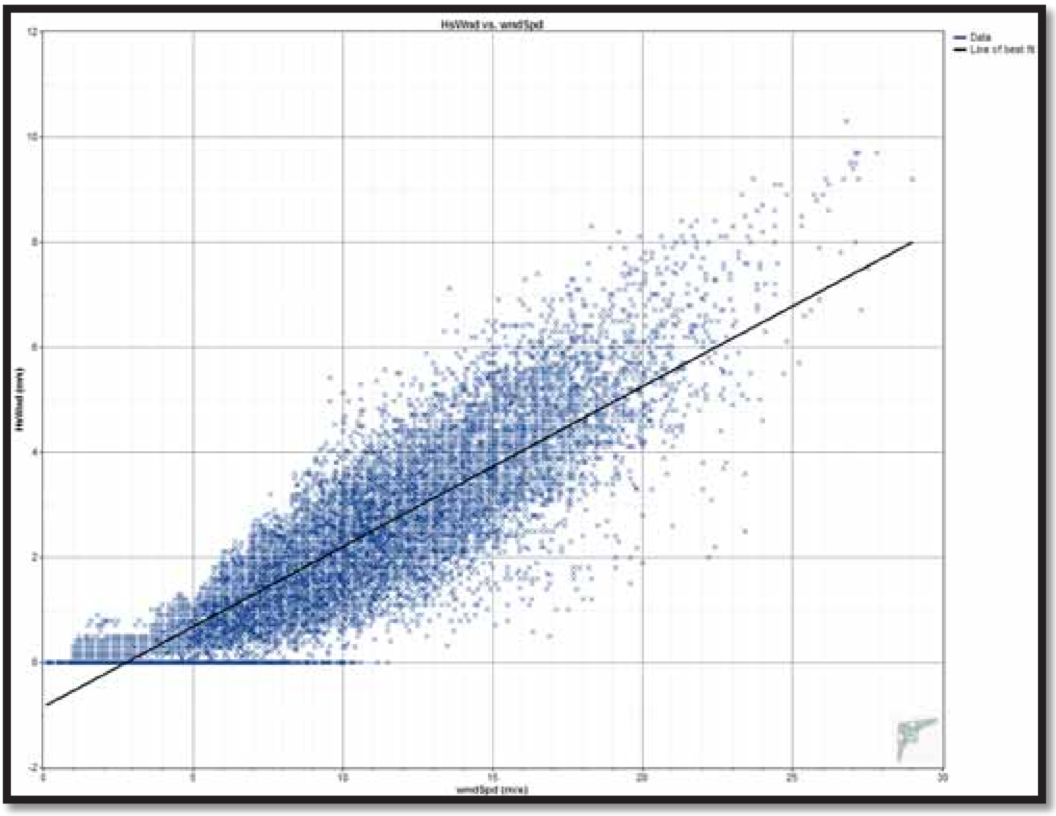


Figure 88: Plot of Wind Speed vs wind sea wave height

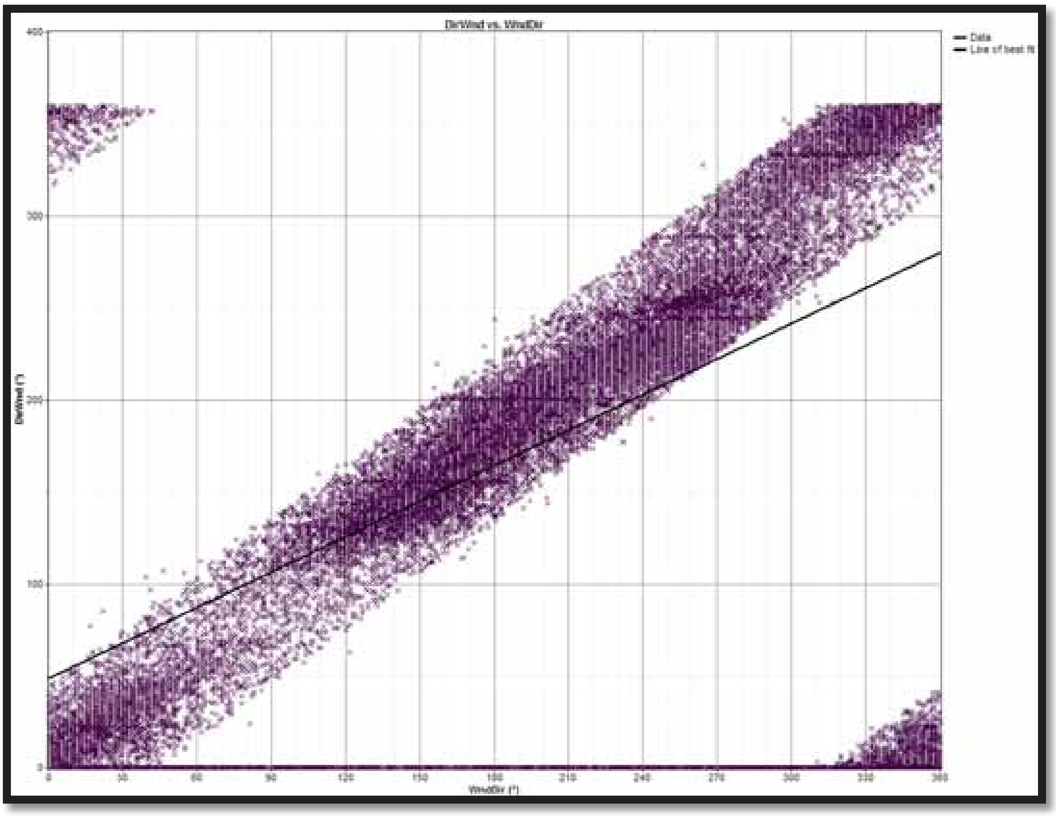


Figure 89: Plot of Wind Direction vs the direction of travel of wind sea