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Programme Area: Marine

Project: PerAWAT

Title: Selection of Appropriate Example Sites and Acquisition of Necessary Data to define Site Characteristics

Abstract:
This deliverable sets out the choice of three locations to be studied as part of WG3 WP6 and the acquisition of the necessary data to model these. The three sites chosen have different characteristic geometries and are important examples of a strait, an estuary, and a headland. To model these sites data have been obtained from a number of sources. Bathymetric data have been purchased from Seazone, tidal forcing has been taken from Le Provost database (Le Provost et al. 1995), and measurements of current data have been obtained from the British Oceanographic Data Centre and from Admiralty's TotalTide software.

Context:
The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

Energy Technologies Institute

PerAWaT

WG3 WP6 D3: SELECTION OF APPROPRIATE EXAMPLE SITES AND ACQUISITION OF NECESSARY DATA TO DEFINE SITE CHARACTERISTICS

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0.1	11/8/2011	For review by GLGH
1.0	30/8/2011	For submission to ETI
2.0	20/9/2011	Updated following comments from GLGH

Executive summary

This deliverable sets out the choice of the three locations to be studied as part of WG3 WP6 and the acquisition of the necessary data to model these. The three sites chosen are the Pentland Firth, Bristol Channel and Anglesey Skerries. These sites have different characteristic geometries, being important examples of respectively: a strait, an estuary, and a headland.
To model these sites, data have been obtained from a number of sources. Bathymetric data have been purchased from Seazone. High quality bathymetry will be used in the immediate vicinity of the locations of the turbines with lower quality data used further away from the turbines. Tidal forcing at the boundary of the numerical model will be taken from the Le Provost database. Measurements of current data for tuning and validating the model have been obtained from the British Oceanographic Data Centre and from the Admiralty's TotalTide software.

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Acceptance criteria

The technology contract requires a "Report on selection of appropriate example sites and acquisition of necessary data to define site characteristics."

Acceptance criteria for this deliverable are set out in Table 1.

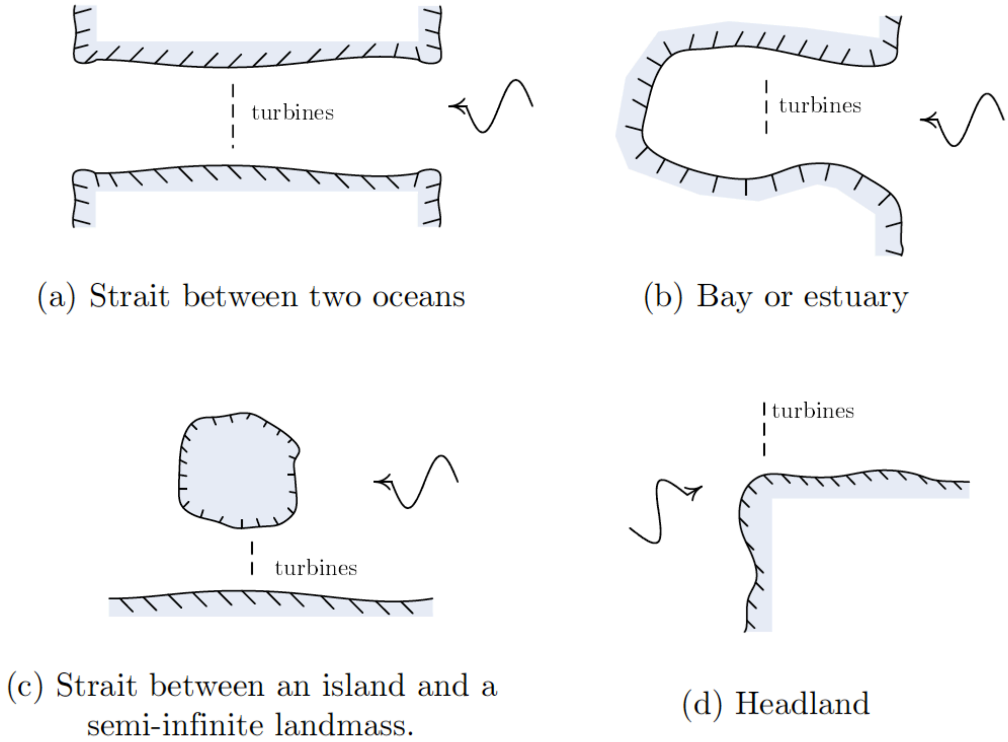
Acceptance criteria	Location in report
Justification / reasoning behind site selection and description of the differing characteristics being modelled.	Pages 4 -16
A description of the characteristics of each site selected	Pages 16-21

Table 1 Acceptance criteria

Choice of sites

The contract sets out that WG3 WP6 study three sites, and that one of these sites should be in common with WG3 WP3 (EDF) to allow for cross-comparison. The decisions on site selection were therefore taken in consultation with EDF.

A variety of site types should be considered with different characteristic geometries. Draper (2011) considers four generic site types illustrated in Figure 1. In each of these the cases, the geometry leads to fast currents and a relatively steep free surface, which may be suitable for tidal energy extraction. Real sites are obviously more complicated, and may be composites of different idealised sites. Nevertheless, the generic approach gives a guide to the different types of site that are to be studied. In WG3 WP6 we aim to study important examples which have features of each of these generic sites.



(a) Strait between two oceans

(b) Bay or estuary

(c) Strait between an island and a semi-infinite landmass.

(d) Headland

Figure 1 - Generic geometries from Draper (2011)

The three sites chosen for study in this work package are set out below:

Pentland Firth

The Pentland Firth is probably the most important location for tidal stream energy in Europe. Past studies have suggested that the strait has a large fraction of the available tidal stream energy of the United Kingdom. Hence, the magnitude of the energy the location can provide is key to assessing the total available energy of the United Kingdom. Despite this, the present authors are not aware of any in-depth study that has been made into how much energy may be extracted. Therefore, the Pentland Firth has been chosen as the site to be studied both by EDF and by the University of Oxford.

The location has elements of idealised geometries (a), (c) and (d).

Bristol Channel

The Bristol Channel is famous for having one of the largest tidal ranges in the world. Historically much interest has been shown in a barrage type scheme. However, there are also very strong tidal currents in the estuary which may allow energy to be extracted using tidal stream devices – either with or without a barrage. Some assessments have been made of the resource (Xia, et al. 2010) although the small domain size used in these studies could lead to highly inaccurate results (Adcock et al., 2011a).

The location is an estuary site and is similar to the idealised geometry (b). There is however no significant contraction then expansion of the channel (as occurs in certain locations) to form an enclosed bay (see Figure 13). Thus there is no area in which currents are enhanced as at, for example, Strangford Lough. Although there are several other candidate locations such as Strangford Lough, The Wash or the Mersey, the present study selected the Bristol Channel as it is likely to have the largest potential resource and thus is the most likely to be developed.

Anglesey

A number of sites may be characterised as "headland" sites. Examples include Anglesey, Portland Bill, Mull of Kintyre, and Cromer. Any of these would have been suitable for studying in this work package. Anglesey was chosen for the following reasons:

- Permission has been granted for the installation of "10MW" of turbines in 2015. It will be the first headland site to be developed.
- There are adequate data available for model validation.
- Anglesey is relatively close to the Bristol Channel, and so both sites could be included in a single numerical model and interactions between the two sites examined.

Data

To model real sites it is necessary to apply boundary conditions to the model that are representative of the location. For tidal modelling using the standard shallow water equations we require:

1. Tidal forcing boundary conditions
2. Bathymetry
3. Eddy viscosity
4. Bed friction

Generally data are not available for (3) and (4) – although values may be estimated (Soulsby, 1998). These parameters are typically found by tuning their values in the numerical model so that the output is in agreement with field measurements. Thus field measurements are required.

Tidal forcing boundary conditions

Numerical models of tides must be "forced" at any open boundary by specifying the amplitude and flux. These are typically derived from a lower resolution model covering a larger area. The values must then be interpolated (both spatially and temporally) for input into the model.

A number of tidal databases exist – some of which are openly available whereas others are charged for. In this work package we have opted to use the Le Provost database (Le Provost et al. 1995). Figure 2 shows the coverage and resolution of this database. The choice of the Le Provost datatbase was motivated by the existing integration of this database into the meshing software SMS (Militello & Zundel, 1999) which will be used in this work package (as demonstrated in WG3 WP6 D2).

The Le Provost database gives the values of 13 principal tidal constituents (2N2, K1, K2, L2, M2, MU2, N2, NU2, O1, P1, Q1, S2, T2): see Militello & Zundel (1999) which are sufficient for modelling the tidal dynamics. It should be noted that high-harmonics (over-tides) are significant in areas of strong current such as the Pentland Firth, which has significant M4 and M6 components. These components are generated by the local bed friction and geometry and thus do not need to be fed in at the boundary.

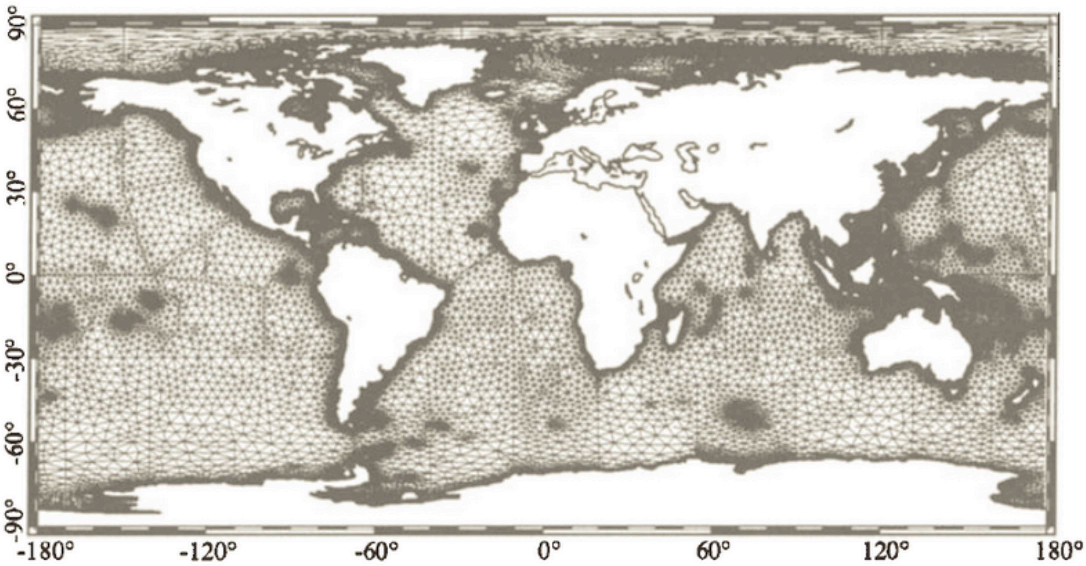


Figure 2 Coverage of Le Provost database

Bathymetry

Bathymetry is a crucial boundary condition in a tidal model. Modelling of the tidal dynamics of a site requires high quality bathymetry. If poor quality bathymetry is used it may still be possible to match measured data and apparently validate a tidal model. If only sparse data are available then it may be possible to tune a model to these data by using an inaccurate value of bed friction. This is particularly important when the only available data are tidal amplitudes and there are no current measurements available. The importance of accurately estimating the bed friction has been demonstrated by various authors (Garrett & Cummins, 2005; Draper et al., 2011).

There are two aspects which govern the quality of the bathymetry: the accuracy and the resolution. The latter is relatively easy to assess as this can be straightforwardly quantified. It is harder to determine the accuracy of bathymetric data. This has to be judged qualitatively based on the source. For instance, charted data used for shipping tends to make conservative assumption on the depth whereas data taken directly from surveys is assumed not to have this bias.

GEBCO data (Monahan, 2008) are freely available, and are used for modelling large scale ocean dynamics where a coarse, poor quality, bathymetry is acceptable (as the length scales are far larger and fine resolution of the dynamics is not needed). GEBCO is derived from navigational charts although the accuracy of the digitisation is not considered good. An example of this is shown in Figure 3 where a clear discontinuity can be seen in the bathymetry of the North Sea. In nearshore areas such as those where tidal turbines might be located, the resolution is deemed inadequate. As an example Figure 4 shows the GEBCO bathymetry for the Pentland Firth. Thus, we do not consider GEBCO as either accurate or highly resolved enough for this work.

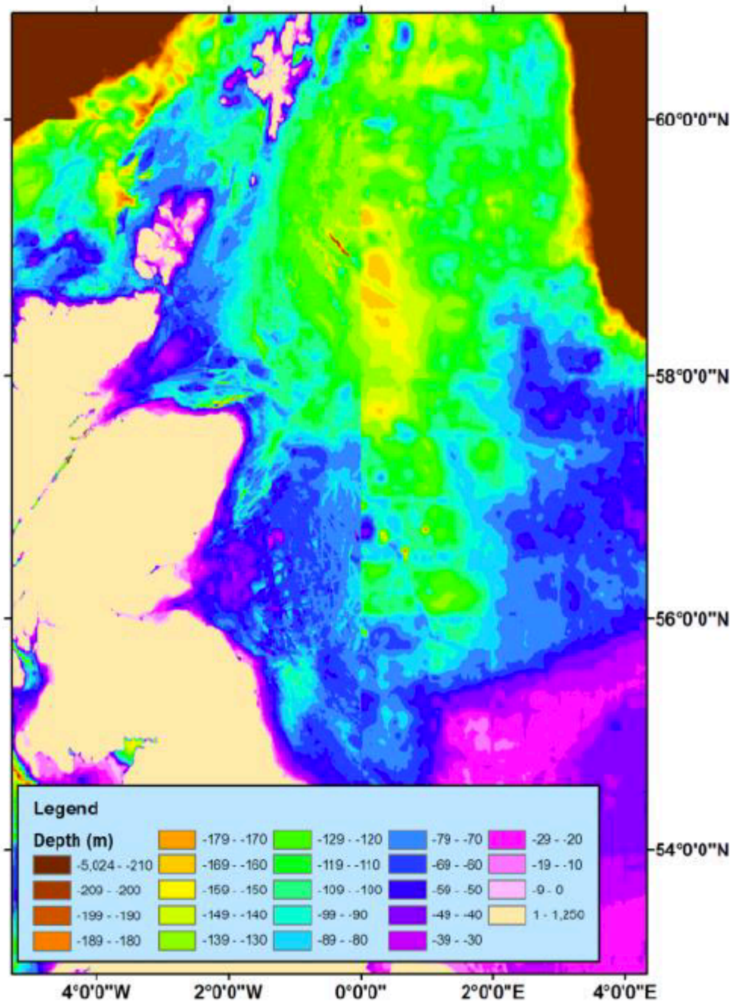


Figure 3 Example of GEDCOM data showing mismatch along the Greenwich Meridian

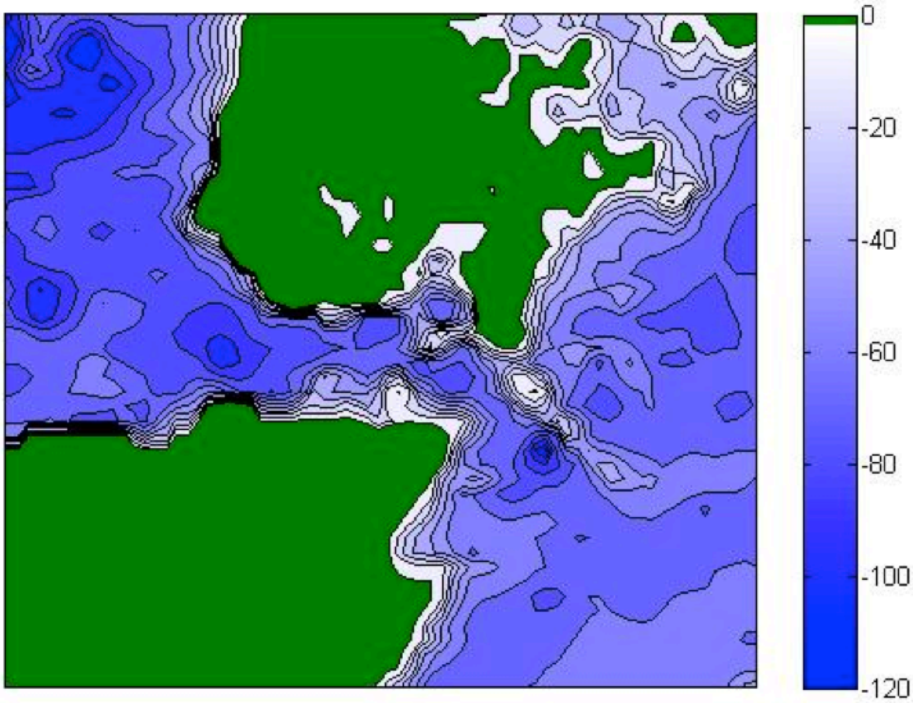


Figure 4 Bathymetry of the Pentland Firth from the GEBCO database. Depth is shown in m.

It was decided to purchase data from Seazone, who offer a range of bathymetry qualities. To model accurately the tidal dynamics close to the selected sites we will use the highest quality data derived and deconflicted from surveys. In areas distant from where turbines will be located it has been deemed acceptable to use lower quality data digitized by Seazone from nautical charts. This is higher resolution and experience suggests will be higher quality than GEBCO data. Figure 5 shows the areas which have been purchased. The extent of the data required is discussed by Adcock et al. (2011a) which is attached to WG3 WP6 D2.

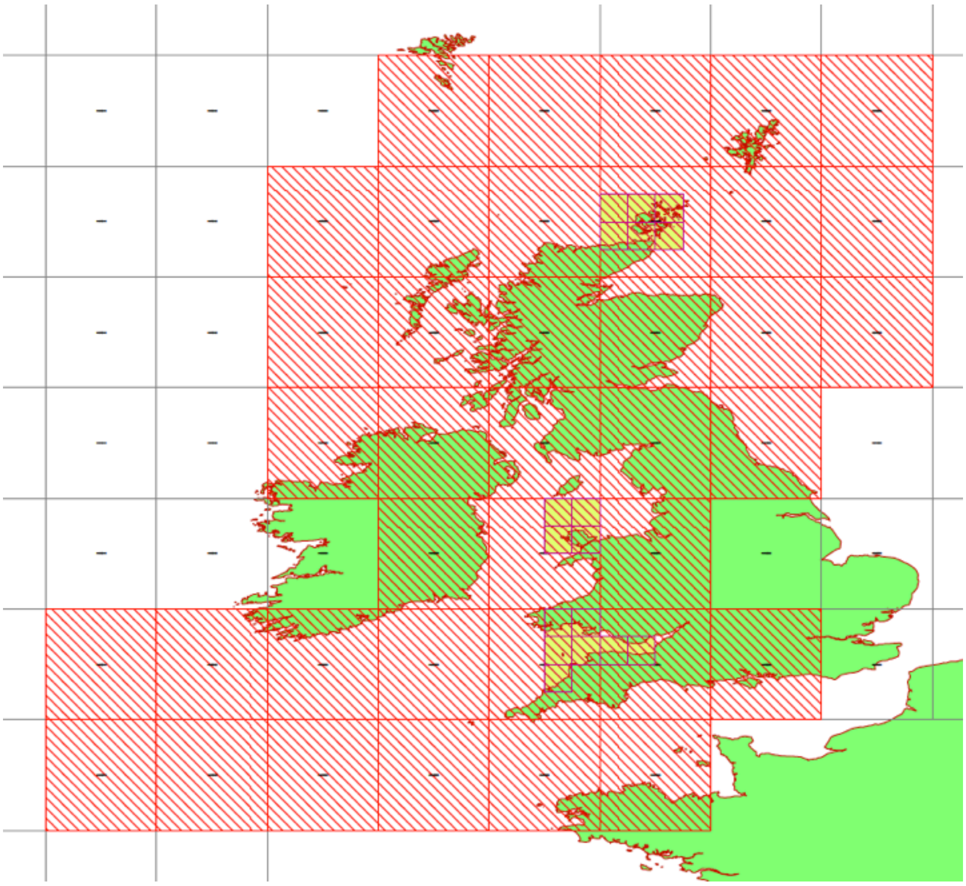


Figure 5 Map showing areas of data purchased from Seazone. Yellow boxes show high quality survey data. Red lines indicate lower quality data derived from charts.

Figure 6 shows a comparison of the high quality bathymetry data for the Pentland Firth area with those derived from Seazone's poorer quality data derived from Admiralty charts. Clearly, some of the details of the bathymetry are not captured by the charted data.

The licensing conditions of the Seazone data prevent onwards transmission. Thus to fulfill WG3 WP6 D4, this data will be replaced with GEBCO data in the input files which are part of the D4 deliverable.

As part of this work package, we will be assessing the importance of high quality bathymetry by comparing the results derived using this to the low quality data from GEDCOM.

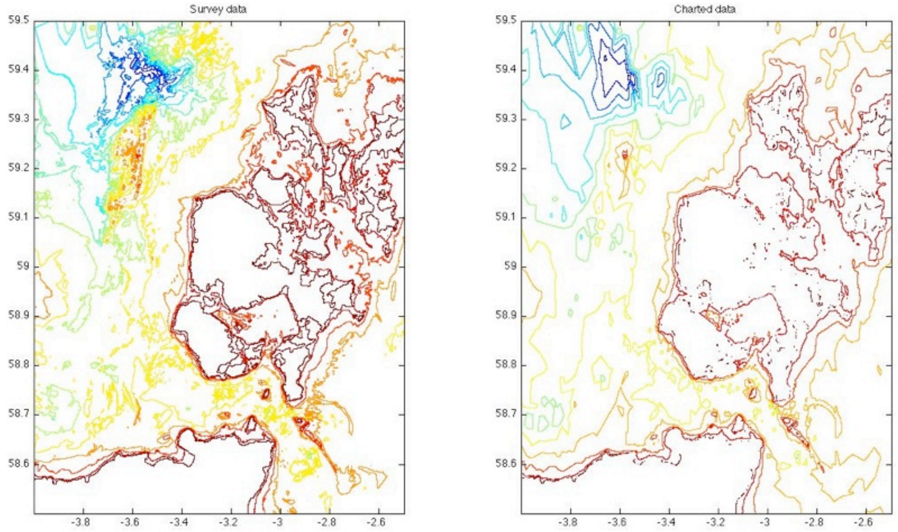


Figure 6 Bathymetry data from Seazone for the Pentland Firth. Axes are in longitude and latitude.

Tidal measurements

Amplitude and current measurements are vital for validating a numerical model of tidal dynamics and for tuning the bed friction and eddy viscosity terms.

Field measurements are available from the British Oceanographic Data Centre (BODC) who catalogue measurements from a number of sources. The data are available via the BODC website. Figure 7 shows the coverage for the Pentland Firth. Figure 8 and Figure 9 show the coverage for Anglesey and the Bristol Channel. There are no measurements available in the main strait. Coverage of the Bristol Channel is excellent. Coverage of the Anglesey Skerries is however rather poor.

An alternative source of data is provided by the Admiralty through its Total Tide software. This provides hindcasts, nowcasts and forecasts of tidal currents and amplitudes at various specified locations. The data on which these predictions are based is not generally known. Figure 10 shows the availability of data in the Pentland Firth. Some of the data points are common between the BODC measurements and the Admiralty predictions and presumably the latter are based on the former. A comparison of a common point is shown in Figure 8 for one location in the Pentland Firth which is highlighted in Figure 10. The field measurement is noisy when compared to the Admiralty data, due to non-tidal currents as listed in WG3WP6D2 and sensor noise. However, these data appear to be very similar and can be presumed to have the same source. The availability of tidal data for TotalTide for the Angelsey Skerries and Bristol Channel is shown in Figure 12 and Figure 13.

It is impossible to quantify the implications of poor data availability on the resource assessment. Qualitatively, the lack of data at the specific locations to be modelled will reduce the confidence that may be placed on the exact estimate of power output. Whether the uncertainties this causes are larger than the other uncertainties (discussed extensively in WG3 WP6 D2) cannot be estimated.

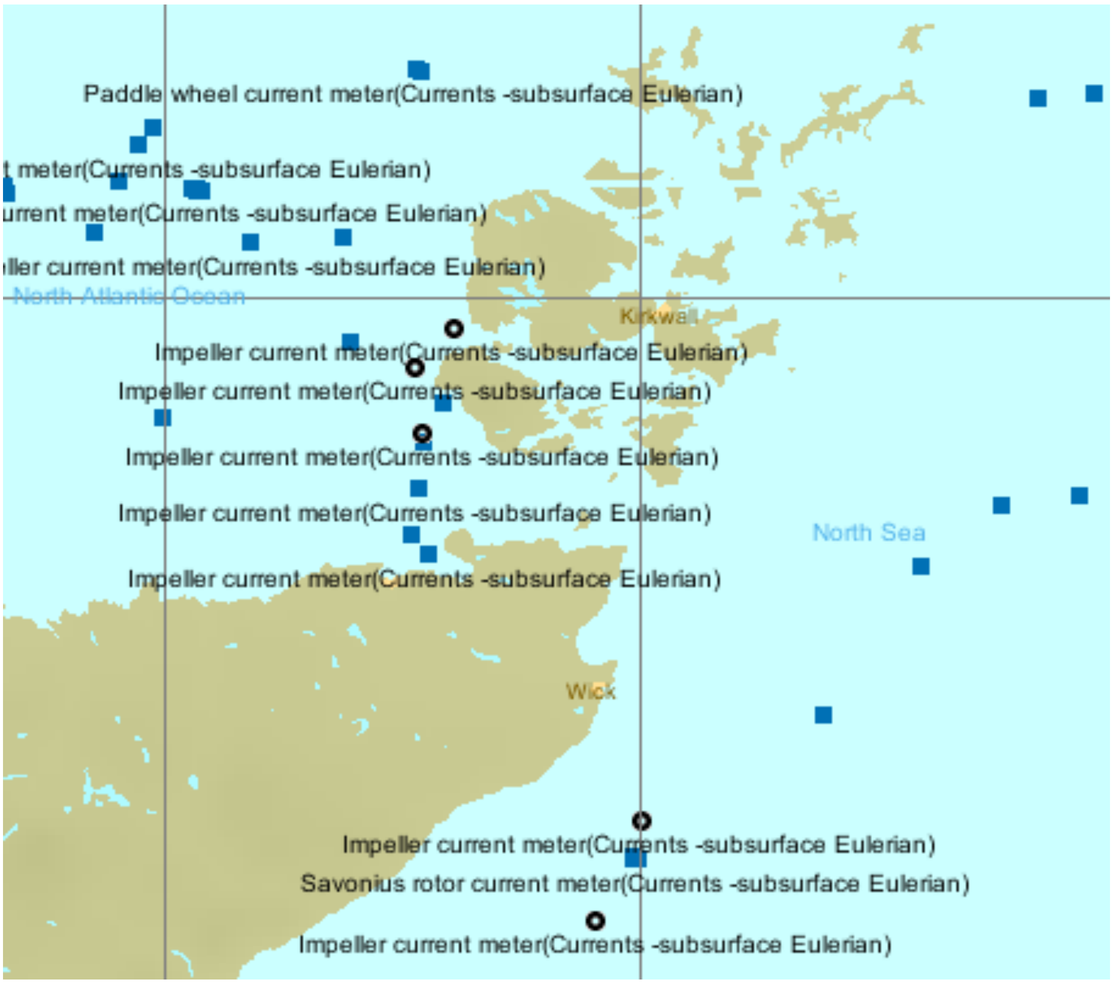


Figure 7 Available current measurements from BODC for the Pentland Firth

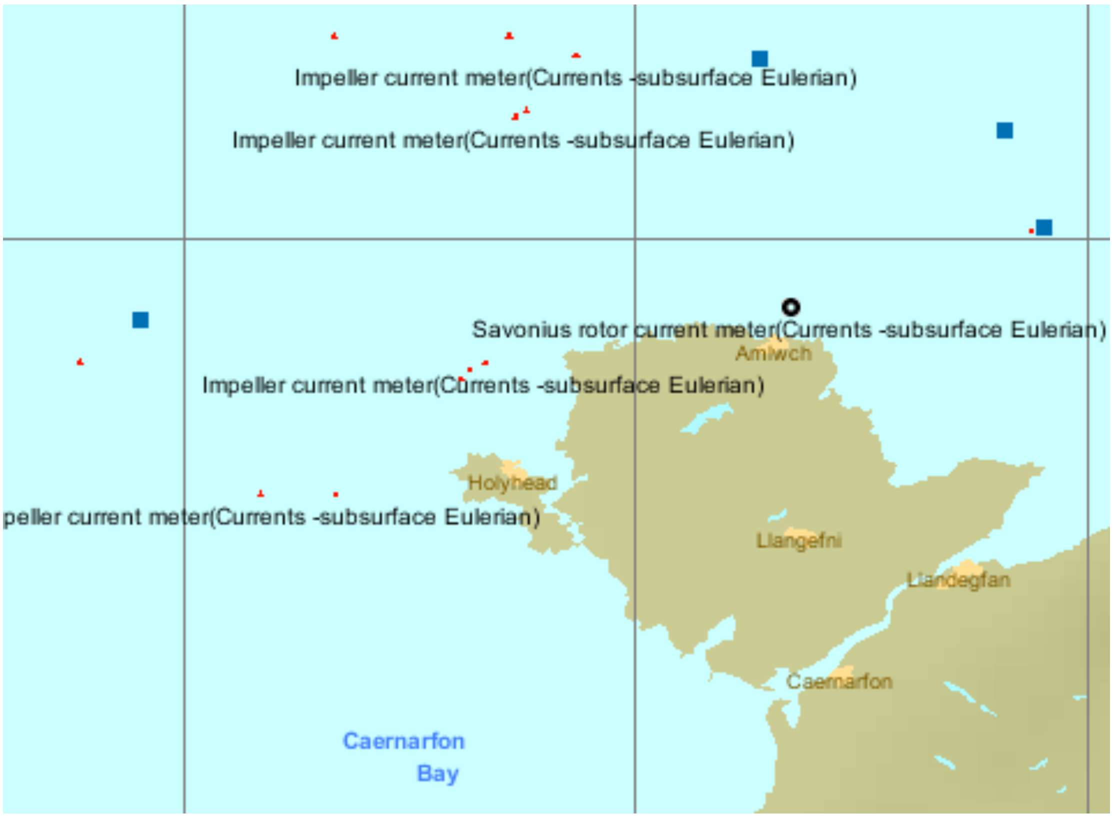


Figure 8 Available current measurements from BODC for Anglesey

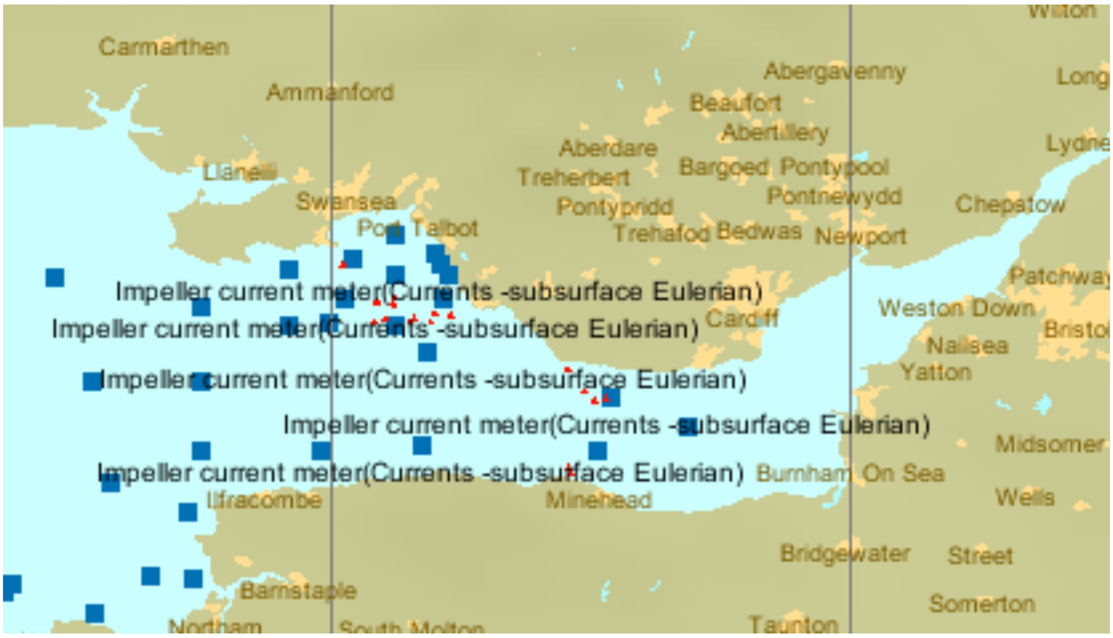


Figure 9 Available current measurements from BODC for the Bristol Channel

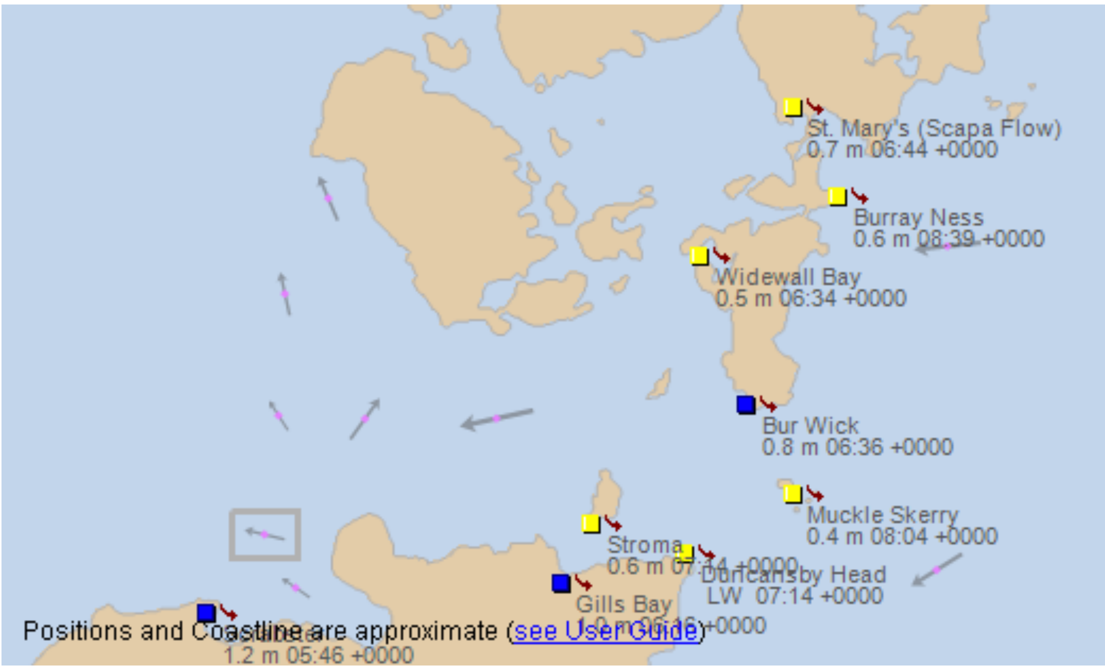


Figure 10 Data available from Admiralty TotalTide for Pentland Firth. Map is indicative only. Squares indicate water level data and arrows are current measurements

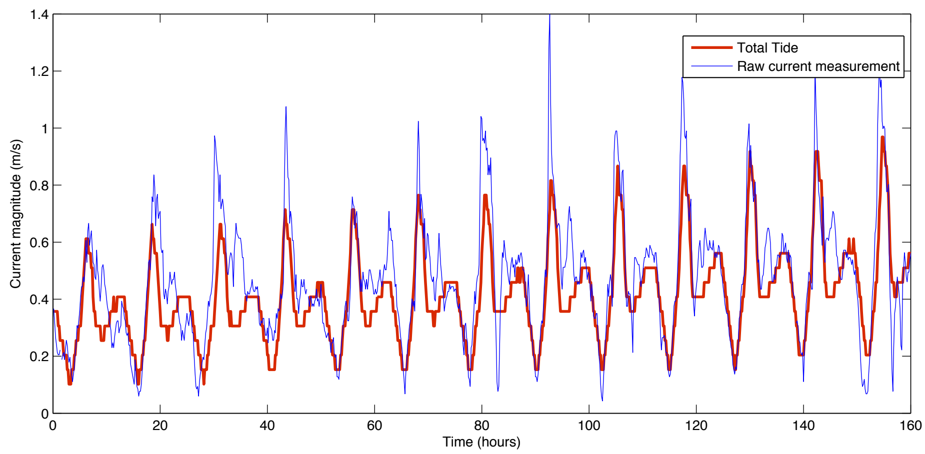


Figure 11 Comparison of field measurement and Total Tide Prediction for 58°3867N 3°29.21W

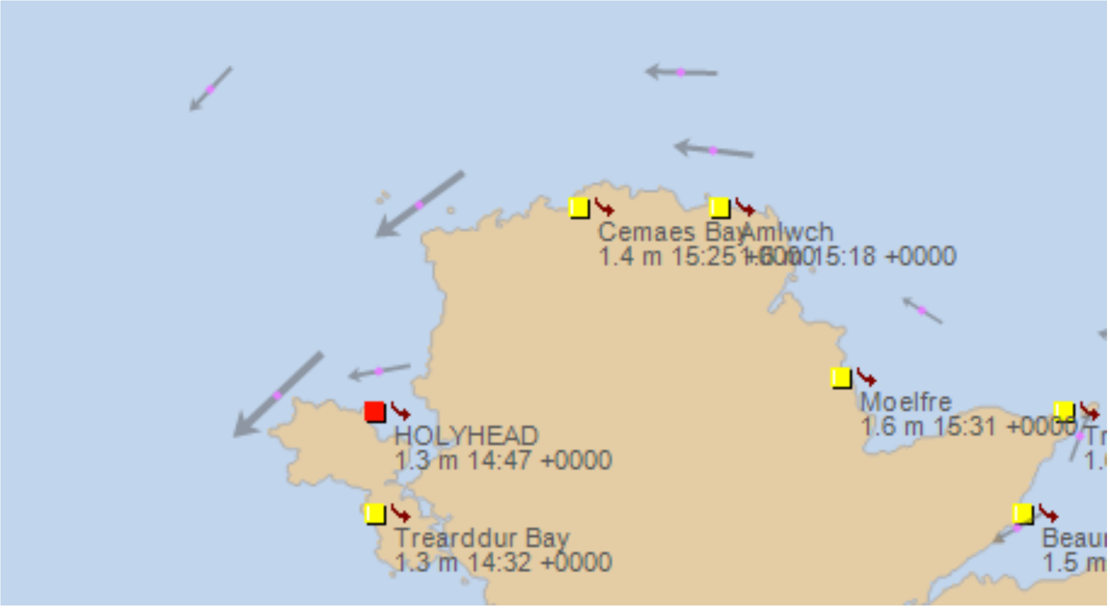


Figure 12 Tidal data available from TotalTide for Anglesey. Squares indicate water level data and arrows are current measurements

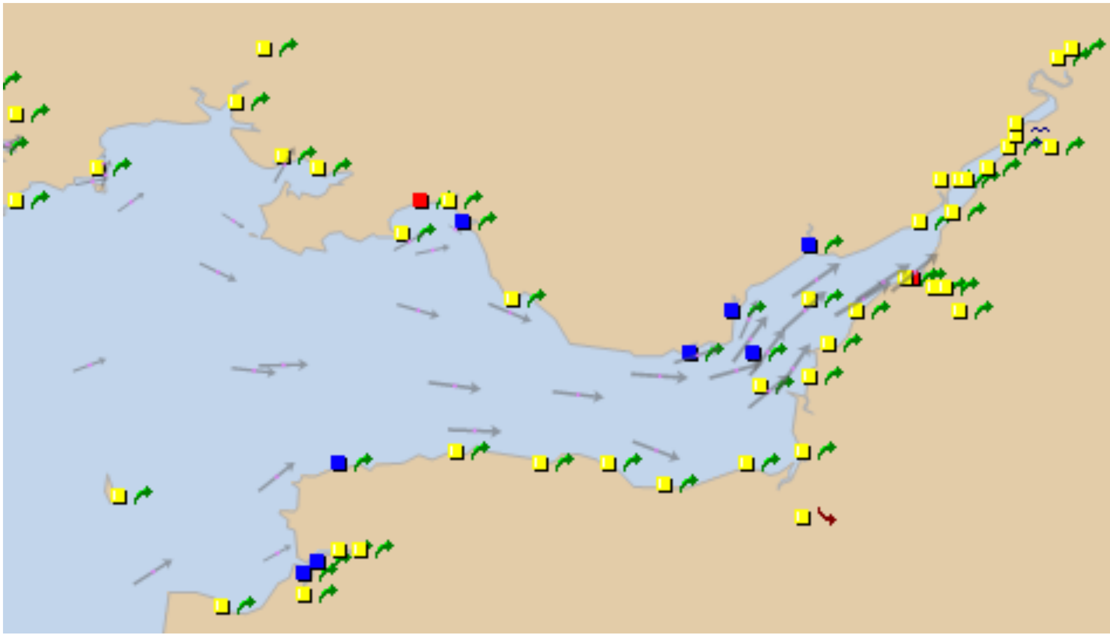


Figure 13 Tidal data available from TotalTide for Bristol Channel. Squares indicate water level data and arrows are current measurements

Characterisation of sites

Pentland Firth

As mentioned above the Pentland Firth is one of the most promising sites for tidal stream energy extraction in the world. The Strait connects the Atlantic to the North Sea and the strong currents are caused as the tidal wave passes around the top of Scotland between Orkney and the mainland. Thus the site could be thought of as a composite between locations (a) (c) and (d) in Figure 1.

The authors are not aware of any study estimates of the tidal energy resource of the Pentland Firth (other than several which base their analysis on kinetic flux, e.g. Black & Veatch (2005)). A useful analysis has been made of a small section (the Inner Sound of Stroma) of the strait by Easton et al. (2010).

Figure 14 shows the bathymetry of the strait.

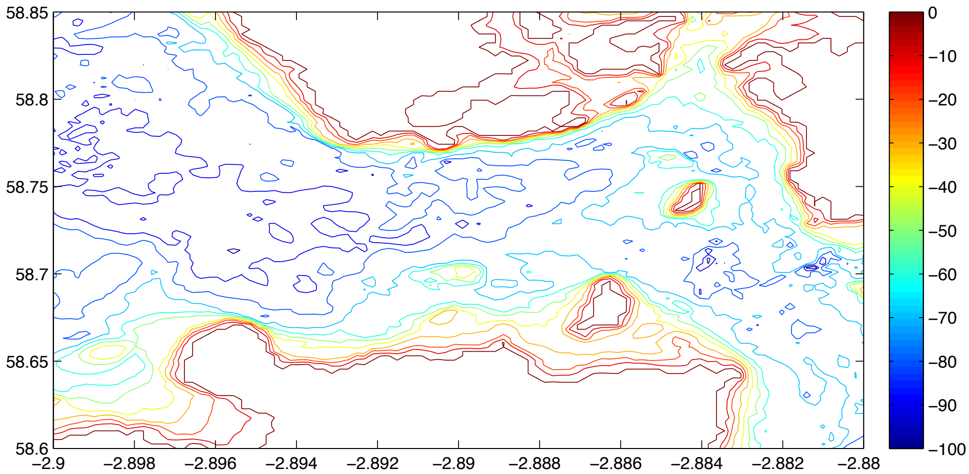


Figure 14 Bathymetry of the Pentland Firth. Axes are in latitude and longitude. Depth relative to mean sea level in m. Data from Seazone.

As a first approximation the site may be considered as a strait of constant cross-section linking two oceans whose tidal amplitudes are unaffected by changes within the channel. The situation of a strait linking two oceans is considered by Garrett & Cummins (2005) in their classic paper. They found that the amount of energy which may be extracted is surprisingly insensitive to the friction in a channel and is given by $\sim 0.2\rho g \Delta h Q$ where ρ is the density of water, g gravitational acceleration, Δh the amplitude of the change in water level across the channel, and Q the natural flow rate. This formula can be crudely applied to the Pentland Firth by taking amplitude and current data from TotalTide. The results suggest that the maximum power which may be extracted from the flow is 4.7GW averaged over the tidal cycle.

With a finite number of rows of turbines, and a blockage ratio <1, it is impossible to extract this much energy as there will be energy lost as the wakes mix. Vennell

(2010) used the actuator disc model of Garrett & Cummins (2007) to tune actuator disc models of turbines to calculate the maximum useful power that may be extracted, given the energy which will be lost in mixing in the turbine wake. The actuator disc model, sometimes referred to as a porous disc model, of a turbine is an idealization of the behaviour of a real turbine whereby a force is applied to the fluid as it passes through the disc. This is, of course, a gross simplification of the behaviour of real turbines but it is useful for understanding the basic physics and establishing an upper limit on the power which might be extracted.

We have applied this approach to the idealised Pentland Firth channel. Figure 15 shows the power which may be extracted with different blockage and number of rows, N. Use of a large number of rows is likely to prove prohibitively expensive as the additional power available reduces rapidly as extra rows are added. Physical limitations due to the geometry of the channel, and the requirement for shipping lanes make a blockage ratio of greater than 0.5 unlikely. Thus the actual power available is likely to be about 1/3 of the power predicted by the Garrett & Cummins limit. This gives a new estimate of ~1.5GW when averaged over a tidal cycle.

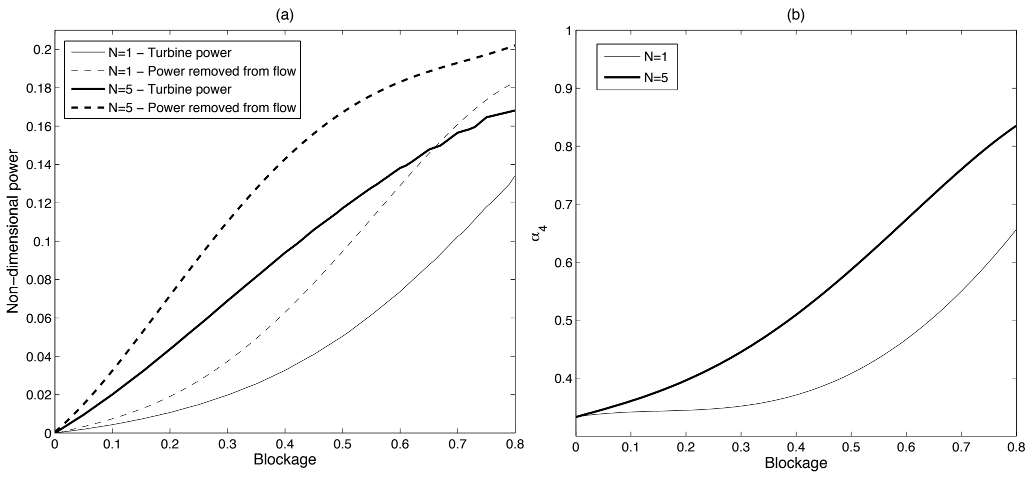


Figure 15 Shaft power available for different blockage ratios. (a) Turbine power and total power extracted (b) Turbine wake induction factor, α_4 which maximizes power take off. Power is non-dimensionalised by $\rho g \Delta h Q$

We have also verified the results Adcock et al. (2011b) using the finite Froude model of a turbine derived by Houlsby et al. (2008). We find that the results are virtually identical to those found using the small Froude number model of Garrett & Cummins (2007).

The figure of 1.5GW neglects losses due to the behavior of real turbines as compared to actuator discs (Belloni & Willden, 2011; Fleming et al., 2011), generator losses, transmission losses etc. It should be stressed that the analysis quoted here uses a very crude representation of the Pentland Firth, and so there will be a large error in this estimate. The analysis to be carried out in subsequent work packages will give a much better estimate.

Anglesey

The Anglesey Skerries are a headland site on the north west coast of Wales. A fast current occurs as the tidal wave propagates in and out of the Irish Sea.

Extensive analysis of generic headland sites is given by Draper et al. (2011). The results of this study are somewhat difficult to apply directly to a realistic location so an analysis similar to that carried out from the Pentland Firth cannot be undertaken. However, this work does give a valuable insight into the important parameters in the problem. The theoretical work of Draper highlights the importance of accurately modelling the *in situ* tidal dynamics.

The Anglesey site is being developed by MCT through SeaGen Wales. The proposed installation would have a maximum capacity of 10MW. Investigations have gone on into the location including a detailed model carried out by HR Wallingford. Unfortunately the results of this study are confidential and not available to the present authors. However, a useful scoping report is available (PMSS, 2006).

Figure 16 shows that the bathymetry of the area is quite complex. The work of Draper shows that an important factor in the resource is the resistance to flow diverting away from the turbine farm. In Anglesey the water gets rapidly deeper as one moves away from the coastline, which will reduce the resistance to flow diversion. However, this can only be fully assessed with a numerical model.

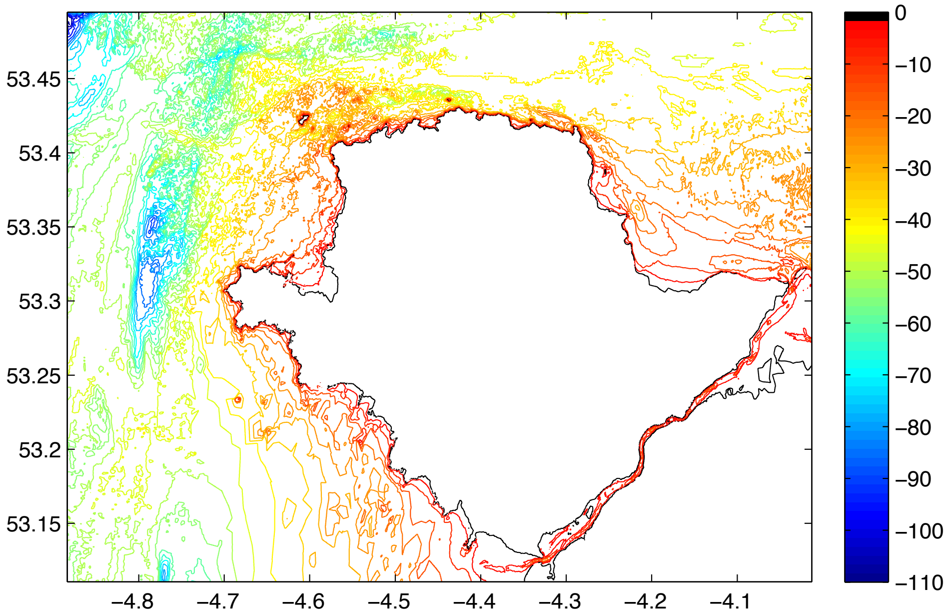


Figure 16 Bathymetry around Anglesey. Depth relative to MSL in m. Axes are longitude and latitude

Bristol Channel

The Bristol Channel has one of the largest tidal ranges in the world. This is due to a combination of factors, including the resonance between the continental shelf and the estuary and the funneling effect of the estuary shape. This large tidal range has led to considerable interest in constructing a tidal barrage. However, there is considerable opposition to this scheme due to its cost and perceived environmental impact (HM Government, 2010). A proposed alternative is to use tidal stream turbines to capture the energy. As pointed out by Blanchfield et al. (2008) such a scheme is theoretically capable of extracting a similar order of magnitude of energy, particularly once the losses due to the finite time to empty a basin are accounted for (Prandle, 2009). A "low-head" barrage will behave nearly identically to a highly blocked tidal turbine farm. Even so, using tidal turbines to extract energy from the Bristol Channel appears to be a more attractive option than using a barrage as there will be less disturbance to the sediment dynamics and the installation may be carried out in stages.

A major study of the barrage plan was carried out by Bondi (1980). This analysis was based on various different numerical models. Various other studies have taken place such as by Xia et al. (2010). As pointed out by Adcock et al. (2011) selection of the correct boundary condition is crucial to the analysis of this location.

Taylor's analytical model (Taylor, 1921) of the tidal hydrodynamics was used by Rainey (2009) to investigate the available energy. This work inevitably simplifies the system but does allow the basic characteristics of the tidal dynamics in the estuary to be understood. This analytical model will be applied in this work package, alongside a detailed numerical model, to analyse the tidal energy extraction from the channel.

Conclusions

The present report sets out our reasons for selecting the three sites for further study in WG3 WP6. These are the Pentland Firth, Anglesey and the Bristol Channel. These sites are representative of different types of geometry which may be suitable for energy extraction and represent some of the most promising sites in the world.

Data have been gathered which will provide the boundary conditions for the numerical model. High quality bathymetry data have been purchased from Seazone for the areas where tidal turbines will be located, with data derived from Admiralty charts used for other areas. Tidal forcing boundary conditions will be derived from the Le Provost model. Tidal measurements have been acquired for the three sites. However, it has not been practical to obtain high quality measurements in the areas where turbines will be located for the Pentland Firth and Anglesey. This will limit the confidence we have in our numerical model. None-the-less we have sufficient data to carry out the analysis of the three locations of interest.

Next steps

The next steps in WG3 WP6 are to set up numerical models of the naturally occurring tidal dynamics. This will be done for two regions – the North of Scotland and the Irish Sea/Celtic Sea. Work will also proceed to include a turbine model in the ADCIRC DG code.

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