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Programme Area: Marine

Project: PerAWAT

Title: Comparison with EDF

Abstract:

This deliverable provides a comparison between the numerical model of the Pentland Firth developed by EDF and that developed by University of Oxford. The models show good agreement in the tidal dynamics outside of Pentland Firth. Each model uses different parameters for seabed coefficient resulting in small differences within the Pentland Firth. There are significant differences in the way the tides are modelled making it difficult to compare predicted power using different turbine configurations.

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 D6: COMPARISON WITH EDF

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1.0	16/9/2013	Submitted to GLGH
1.1	3/10/2013	Revised version submitted
1.2	23/10/2013	Revised version submitted

Executive summary

This report presents a comparison between the numerical model of the Pentland Firth developed by EDF and that developed by the University of Oxford. Both models have solved the depth-integrated shallow water equations but have used different methodologies to include tidal devices.

The models developed show good agreement in the tidal dynamics outside of the region of the Pentland Firth. Within the Pentland Firth there are significant differences in the modelled tidal dynamics. The differences in modelling the tidal dynamics within the Pentland Firth are due to the small differences in the models and different parameters being chosen for the bed friction coefficient. Such disagreements are inevitable when a very complicated tidal site is modelled by different organisations. There is insufficient field data available to determine which model is better reproducing the real tidal dynamics.

There appears to be general agreement as to the magnitude of the powers each of the models are producing. However, a detailed comparison of the differing methodologies for the implementation of tidal turbines is difficult because of the differences in the modelling of the tidal dynamics within the Pentland Firth.

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1. Acceptance criteria

Deliverable	Acceptance criteria	Location in report
WG3 WP6 D6 Report on Cross-verification of models including FDCs against EDF numerical code	Report on Cross-verification between UoO and EDF, provides clear description of methods of comparison and identification and explanation of any differences if they arise. Report provides an assessment of model performance based on validation exercises – including review of applications, sensitivities and limitations.	The applications, sensitivities and limitations are discussed in the introduction and the discussion. Comparison of the models is made in sections 3 and 4.

2. Introduction

This report presents a comparison of the numerical modelling of energy extraction from the Pentland Firth carried out by the University of Oxford and EDF.

Models of tidal dynamics

The two models in this study both solved the depth-integrated shallow water equations typically used for tidal modelling. The EDF simulations were carried out using TELEMAC which uses a continuous Galerkin numerical scheme. The Oxford simulations were carried out using ADCIRC, using a version which employs a discontinuous Galerkin scheme.

Whilst the basic equations for modelling tidal flows were the same in both cases, the mesh and the computational domain were different, as were some of the parameters such as the method used to model viscosity. Details of the verification and validation of the code and numerical model are given in WG3WP3D3 (EDF) and WG3WP6D3 and WG3WP6D4A.

Inclusion of tidal devices in depth averaged models

A further difference between the models is the method used to represent the presence of tidal turbines.

EDF use a very fine mesh and attempt to model individual turbines in the flow. The turbines are represented by drag imposed on individual elements. In this model the mixing between turbines is entirely simulated within the depth-integrated numerical model. The methodology is described in WG3WP3D2.

By contrast the Oxford code uses a sub-grid model to simulate the presence of turbines. Tidal turbines are represented in the model as a line discontinuity in elevation following the method of Draper et al. (2010) (see also Figure 1). This method relates the water level downstream of a homogeneous row of turbines (once local mixing in the wake of a turbine has taken place) to the water level upstream, and describes a momentum 'sink' representative of the force (equal and opposite) applied by the turbine to the flow. If this force per unit length along the fence is defined as *T,* it can be shown from continuity and conservation of momentum that the depth change Δh at any point along the fence is given by:

$$\frac{1}{2}\left(\frac{\Delta h}{h}\right)^3 - \frac{3}{2}\left(\frac{\Delta h}{h}\right)^2 + \left[1 - Fr^2\left(1 - \frac{T}{\rho h \bar{u}^2}\right)\right]\left(\frac{\Delta h}{h}\right) - Fr^2\frac{T}{\rho h \bar{u}^2} = 0$$

where Fr is the Froude number, and h and u are, respectively, the water depth and depth-averaged velocity normal to the fence at the location of the point.

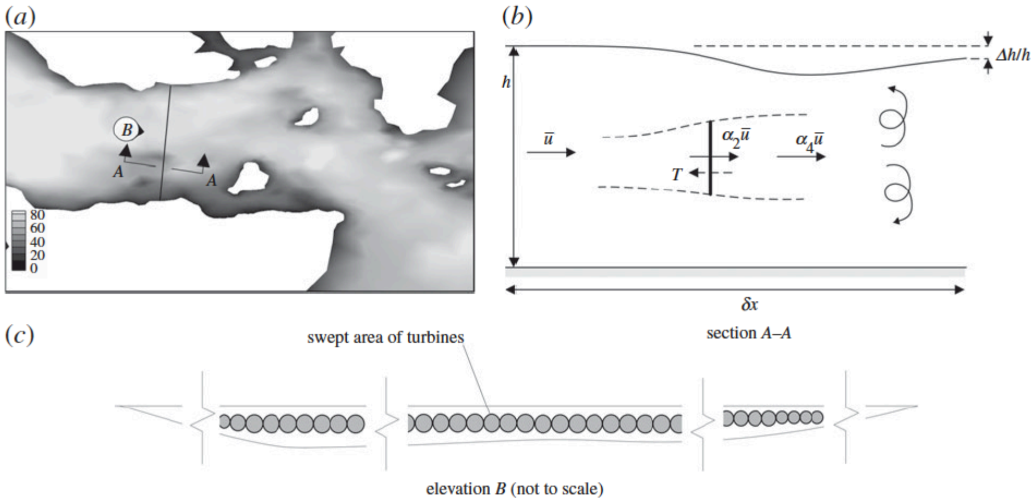

Figure 1 Schematic showing the inclusion of tidal turbines in the Oxford model.

The available power generated by the device producing this force is estimated using actuator disc theory (Houlsby *et al.* (2008)). Using this approach, the thrust per unit length of fence, T, and the total power extracted by the turbines per unit length of fence, P_e, are written as

$$T = \frac{C_T B}{2} \rho h \bar{u}^2$$

and

$$P_e = \rho g \bar{u} \left(\frac{\Delta h}{h}\right) h^2 \left(1 - Fr^2 \frac{1 - 1/2\left(\frac{\Delta h}{h}\right)}{\left(1 - \left(\frac{\Delta h}{h}\right)\right)^2} \right)$$

where the blockage ratio, B, is defined as the proportion of the cross section of the channel swept by turbines and C_T is a local thrust coefficient for the turbine. The local thrust coefficient can be written functionally as $C_T(Fr, B, \alpha_4)$, where α_4 is the wake velocity coefficient and is defined as the ratio of the velocity in the near wake of the turbine to that immediately upstream of the turbine.

The available power P_a is a fraction of the extracted power and is given to good approximation by:

$$P_a \approxeq \alpha_2 \left(1 - 1/2\frac{\Delta h}{h}\right) P_e$$

where α_2 is the ratio of the velocity of the fluid as it passes through the turbine to the velocity upstream.

A key contrast between the two models for including tidal turbines is the way the wakes behind a turbine array are treated. It is convenient to consider the scales of wake mixing: turbine mixing and array mixing. An example of these scales is shown in the CFD simulations shown in Figure 2. Two scales of wake are identifiable: the mixing behind the individual turbines which more or less takes place within the scale of the figure and he mixing with the flow around the turbine array which has a much longer scale.

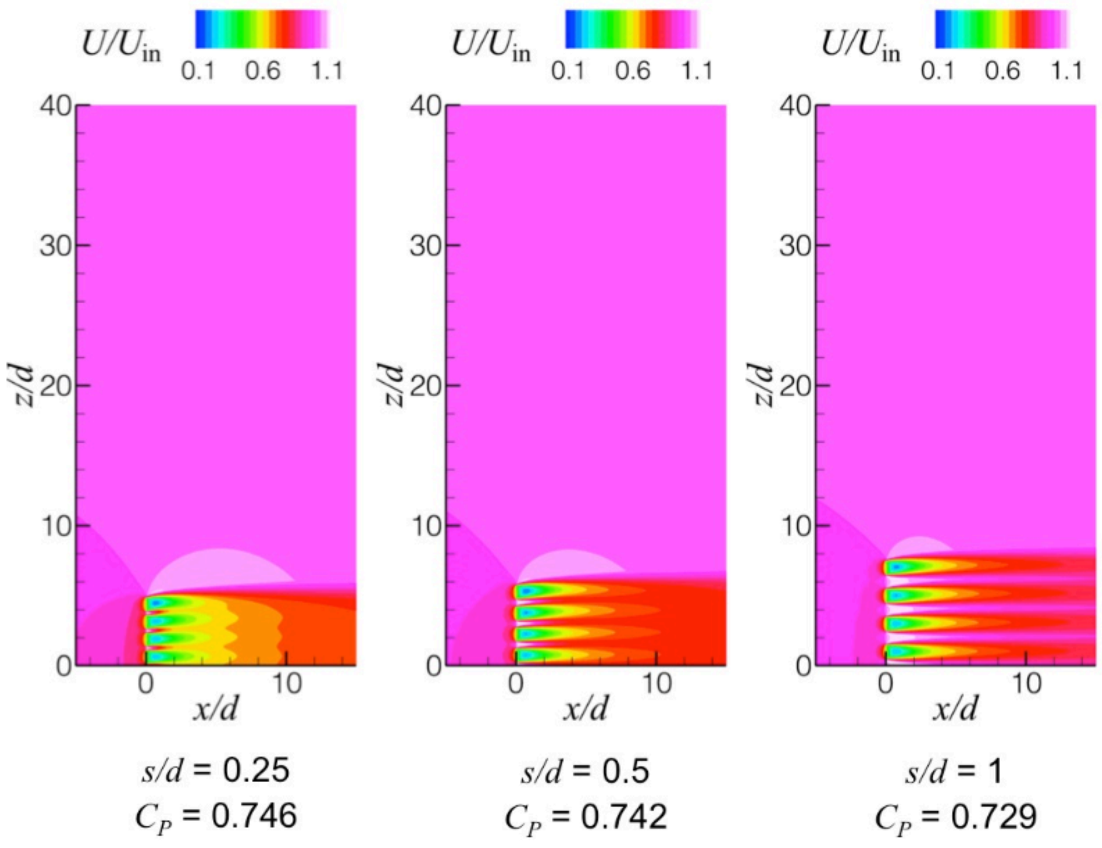

Figure 2 Example of different mixing scales in an array of tidal turbines

EDF's model tries to resolve both of the energy losses within the depth-integrated model. The practical difficulties of doing this are discussed at length in Vogel *et al.* (2013). The two key issues are

- A very fine mesh is required to resolve smaller than the size of an individual turbine. This has major implications for computation time.
- Imposing a large force on a single small area causes numerical instability.

We understand that both of these difficulties have been experienced by EDF in this project.

The methodology used by University of Oxford does not require a mesh which is resolved down to the turbine scale as the mixing between turbines is accounted for in the sub-grid scale model. The obvious disadvantage of the Oxford model is that it reduces the length scale of the mixing between the turbines to zero. However, it should also be noted that a depth averaged scheme which explicitly models the mixing between individual turbines will not be able to reproduce the complex three-dimensional physics of this mixing process. Thus the length scale of this mixing will not be modelled correctly with either approach.

Test period

Three different configurations of turbines were analysed by both groups. All simulations were for the same period. The start date of the simulations was set at 14 September 2001.

3. Comparison of flow before the inclusion of tidal turbines

Water levels

A number of locations in the vicinity of the Pentland Firth were selected for analysis. The location of these is given in Table 1 and are shown in Google Earth in Figure 3.

	Latitude	Longitude
A	58.8242N	3.7902W
B	58.5855N	2.6150W
C	58.4956N	1.7477W
D	59.2346N	4.6994W
E	58.7164N	3.0970W

Table 1 Locations of points used to compare water levels

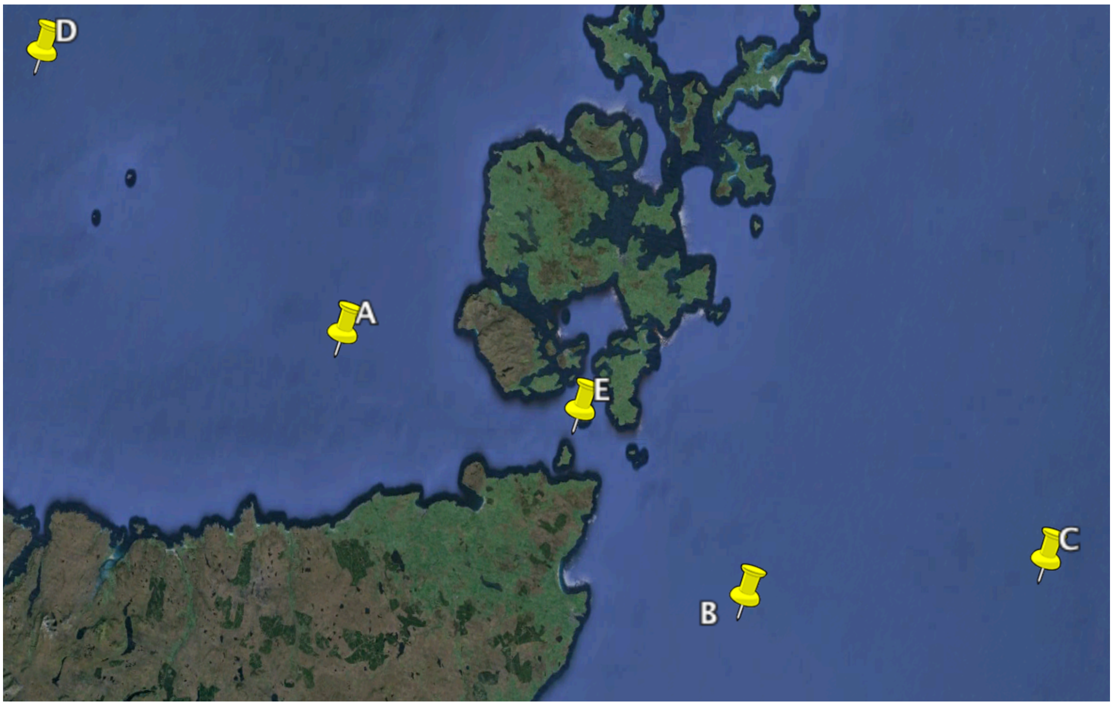

Figure 3 Locations of water level cross-comparisons

Timeseries showing a comparison between the two models are shown in Figures 2 to 6. For the locations outside the main channel (A, B, C and D) there is generally good agreement between the two models. The phases, both the spring/neap cycle and within the daily cycle, show good agreement. The amplitude of the water levels in excellent agreement for the cases not within the Pentland Firth. This is important as it implies the head across the Pentland Firth is close in both models. The work of Garrett & Cummins (2005) suggests that the extractable resource of the channel will be proportional to head loss and thus and difference in head loss will have a linear effect on the total extractable power. However, for the much smaller arrays described in this paper the power is much better predicted by the kinetic energy flux. This is proportional to velocity cubed. There is no simple relationship between velocity and head. However, we can examine limiting cases. If there is no friction in the channel then the velocity will be simply proportional to the head. Conversely if friction dominates the channel then the velocity will be proportional to the square root of the head. The Pentland Firth is in between these limiting cases.

There is significant discrepancy in the amplitude at point E in the middle of the Pentland Firth. Part of this may be explained by the difference in current (see below) that causes a change to the free surface elevation as predicted by Bernoulli's equation.

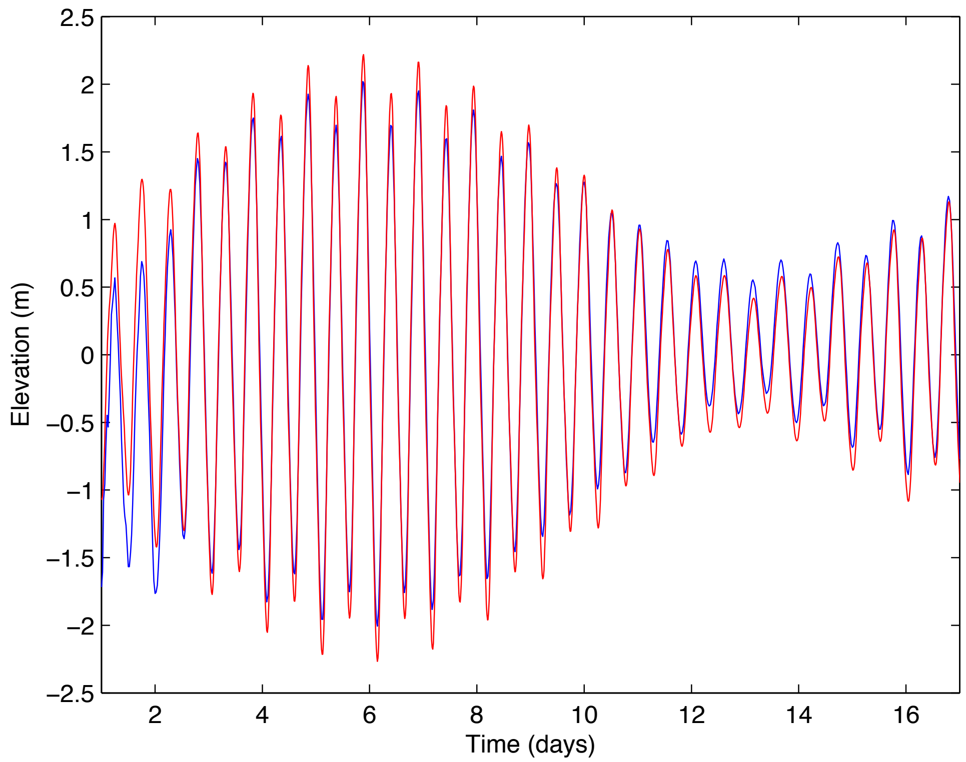

Figure 4 Comparison of water levels at location A. EDF blue; Oxford red

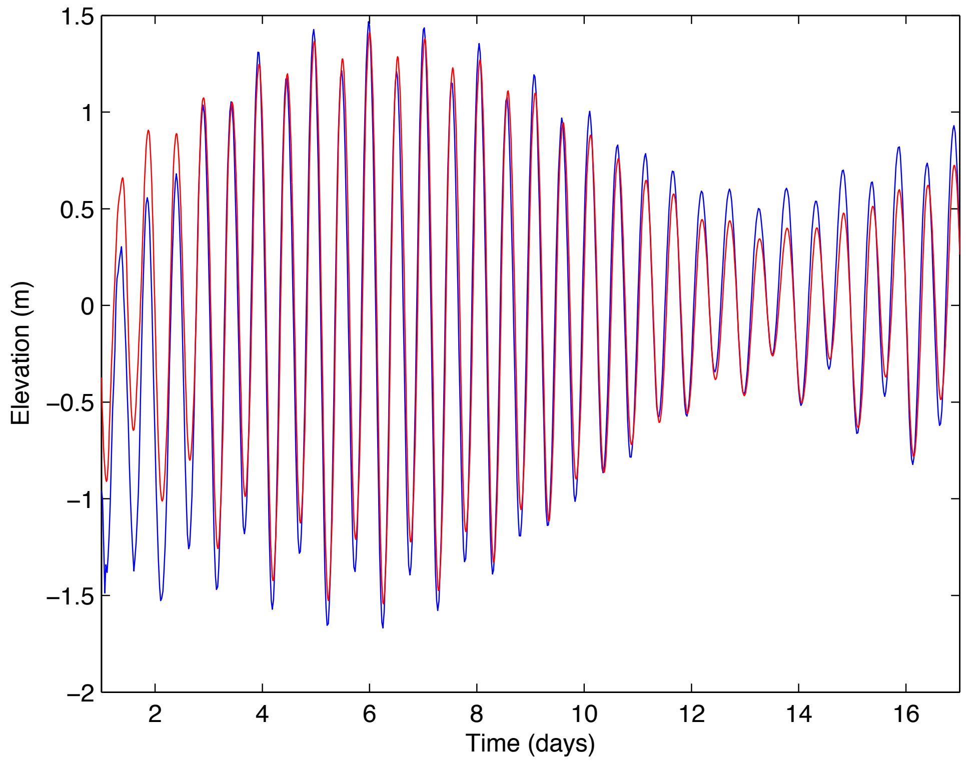

Figure 5 Comparison of water levels at location B. EDF blue; Oxford red

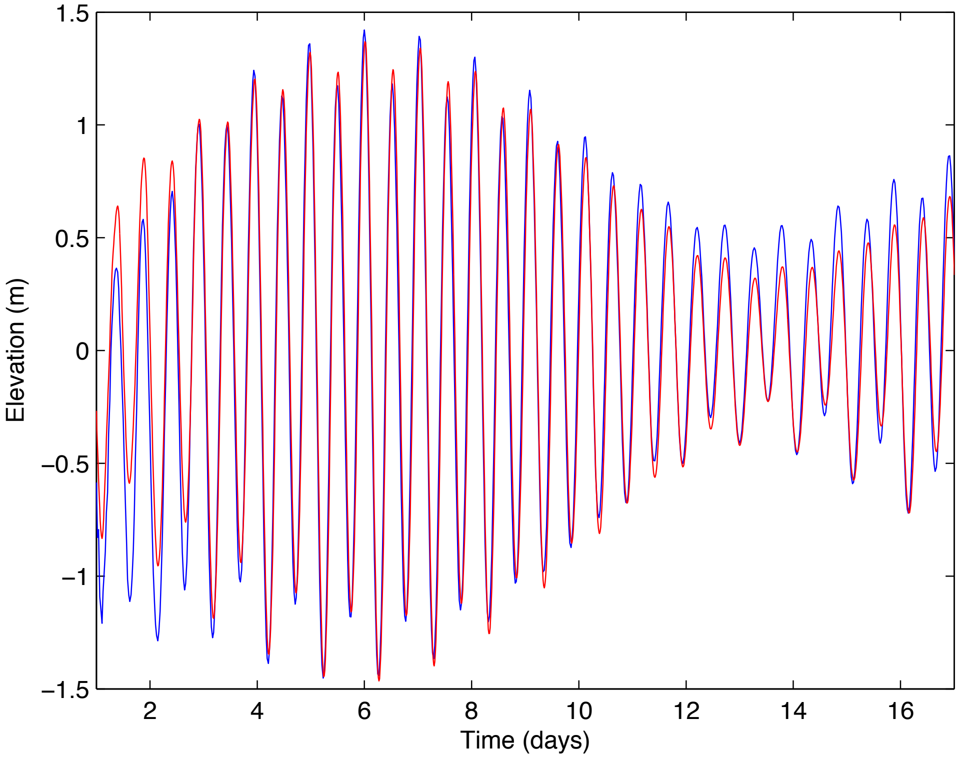

Figure 6 Comparison of water levels at location C. EDF blue; Oxford red

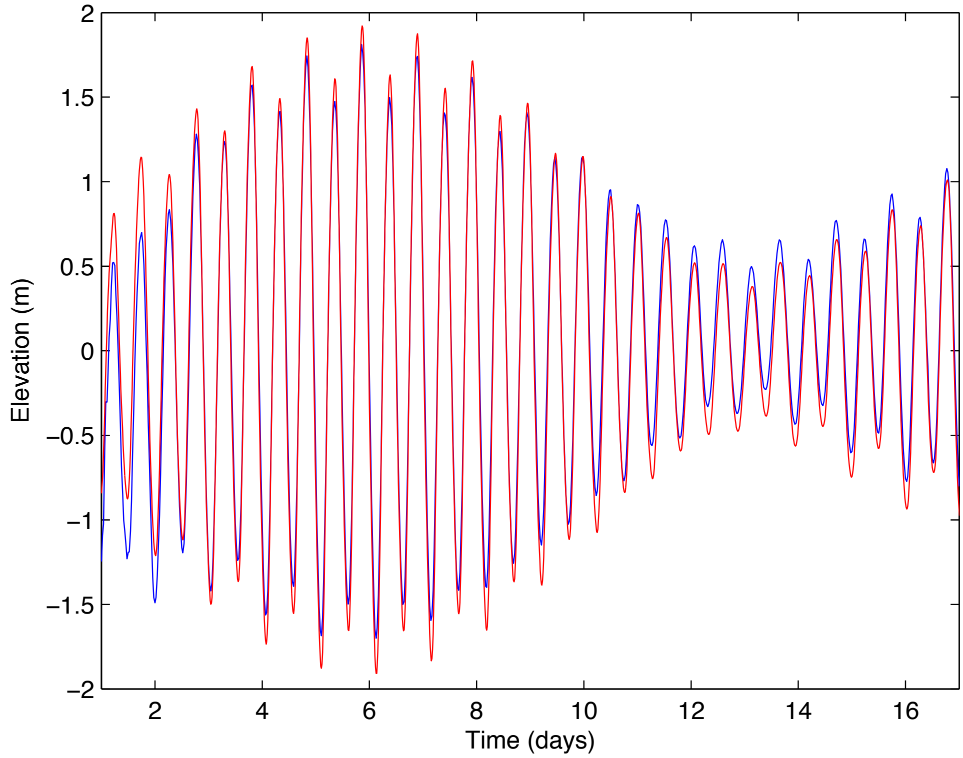

Figure 7 Comparison of water levels at location D. EDF blue; Oxford red

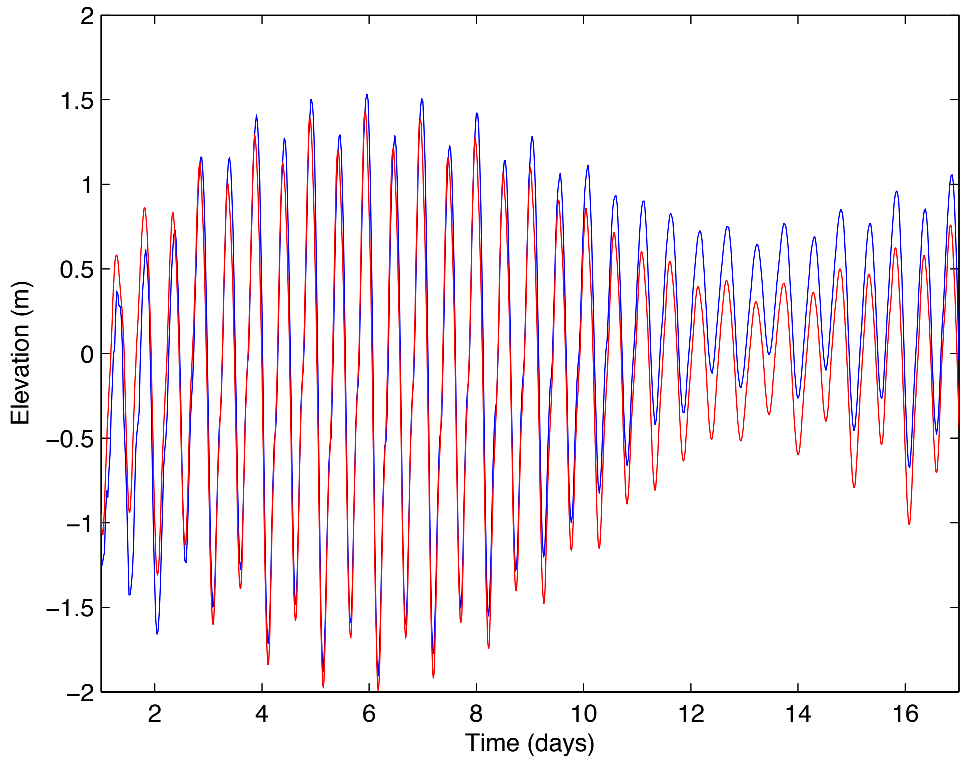

Figure 8 Comparison of water levels at location E. EDF blue; Oxford red

Current comparison

Comparisons of the naturally occurring modelled current within the Pentland Firth has been made at four locations (F to I). These are given in Table 2 and shown in Figure 9.

	Latitude	Longitude
F	58.7164N	3.0970W
G	58.7583N	3.0005W
H	58.6638N	2.9661W
I	58.6566N	3.1242W

Table 2 Locations used in current comparison

Figure 9 Location used for the current comparisons in Google Earth

A comparison of the currents are shown in Figure 10 to Figure 13.

The most important location is location F in the center of the channel. The overall trend is the same in both sets of data. However, the Oxford simulations predict a significantly lower velocity than the EDF simulations. The most obvious reason is that different bed frictions are used within the models, and indeed a rather higher velocity was found in the Oxford model when a lower friction was used (see Adcock *et al* (2013)). We do have measured data from this channel although only in harmonically analysed form. The reason for the bed friction chosen by Oxford is discussed at length in Adcock *et al* (2013). However, given the uncertainties in the data and modelling it is difficult to say whether the EDF or the Oxford model is better reproducing reality.

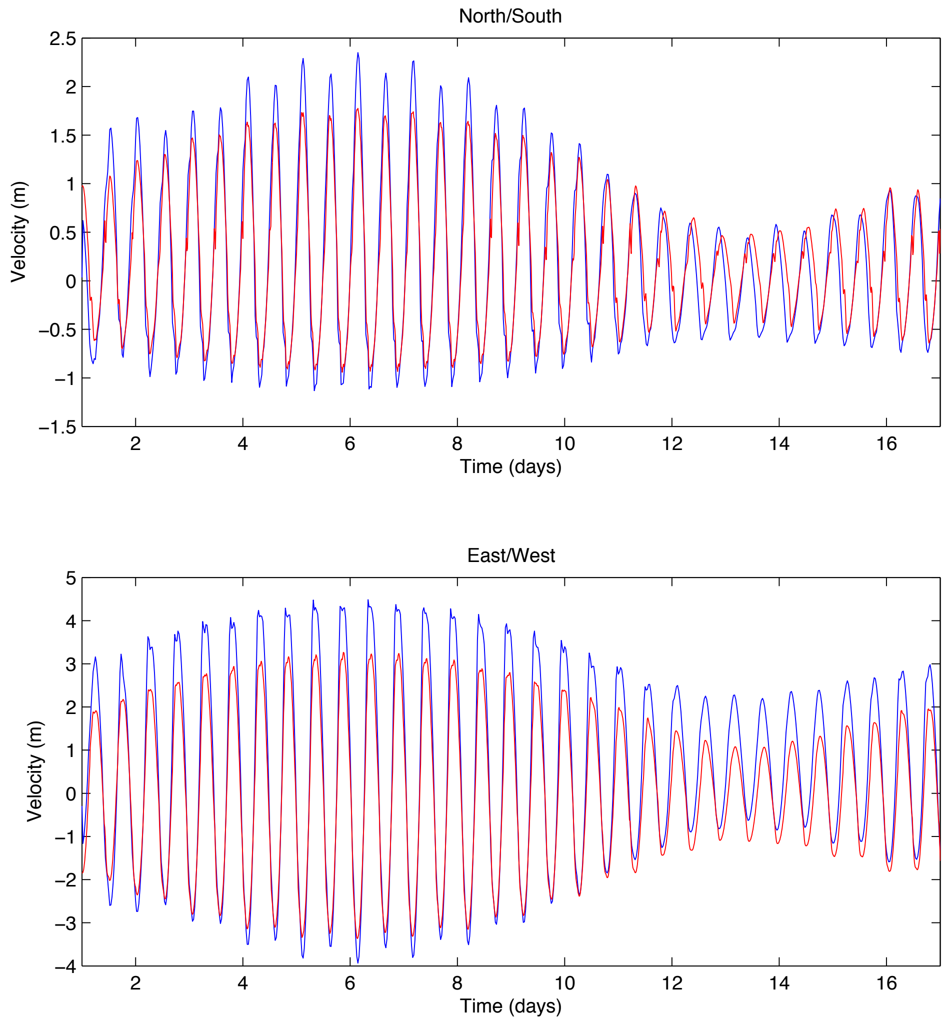

Figure 10 Comparison of currents at location F. EDF blue; Oxford red.

There is a very significant discrepancy in the currents at G. In part this is assumed to be due to the proximity of the coastline. The coastline has been derived slightly differently in each model. However, the strong east/west current shown in the EDF simulation does seem surprising high given the location (see Figure 9).

There is no measured data available for this channel with which to compare the results of the model. However, the tidal stream atlas (Admiralty, 1986) suggests that the Oxford model underestimates the current through this channel (as noted in Adcock *et al.* (2013)). We are unable to account for why the Oxford model might under-predict velocities in this channel.

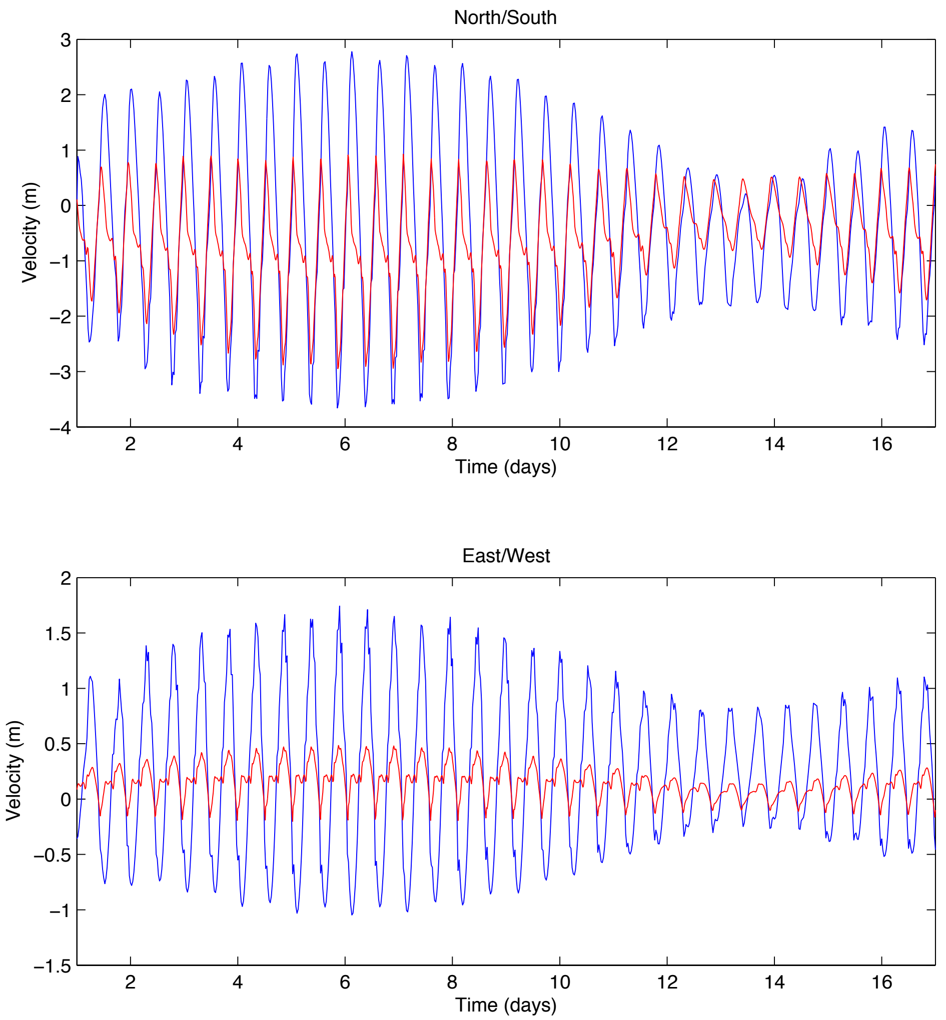

Figure 11 Comparison of currents at location G. EDF blue; Oxford red.

Location H is on the east side of the Pentland Firth. In general the magnitude of the current shows very good agreement between the two models, but there is a significant difference in the direction of the peak flow. There appears to be no obvious explanation for this difference.

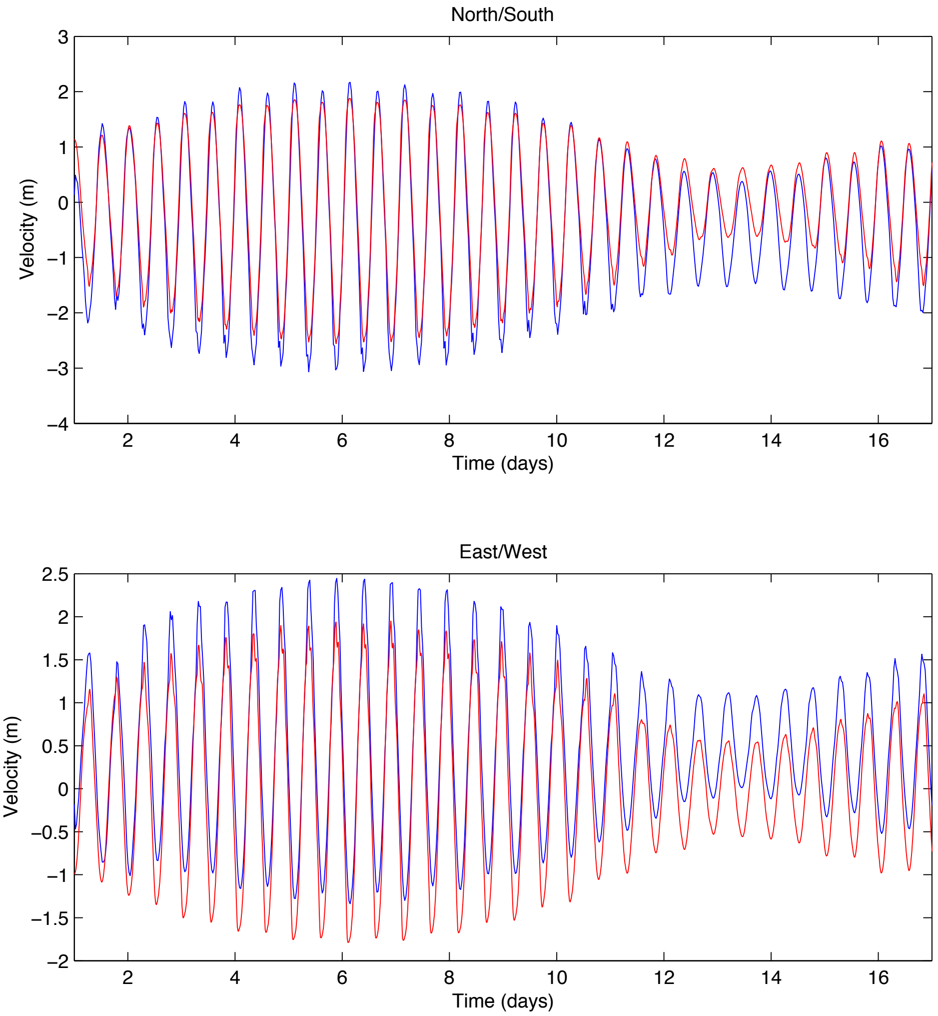

Figure 12 Comparison of currents at location H. EDF blue; Oxford red.

Location I is in the Inner Sound. The Oxford model predicts a much lower current than the EDF model. In the absence of field data it is impossible to know which model is closer to reality.

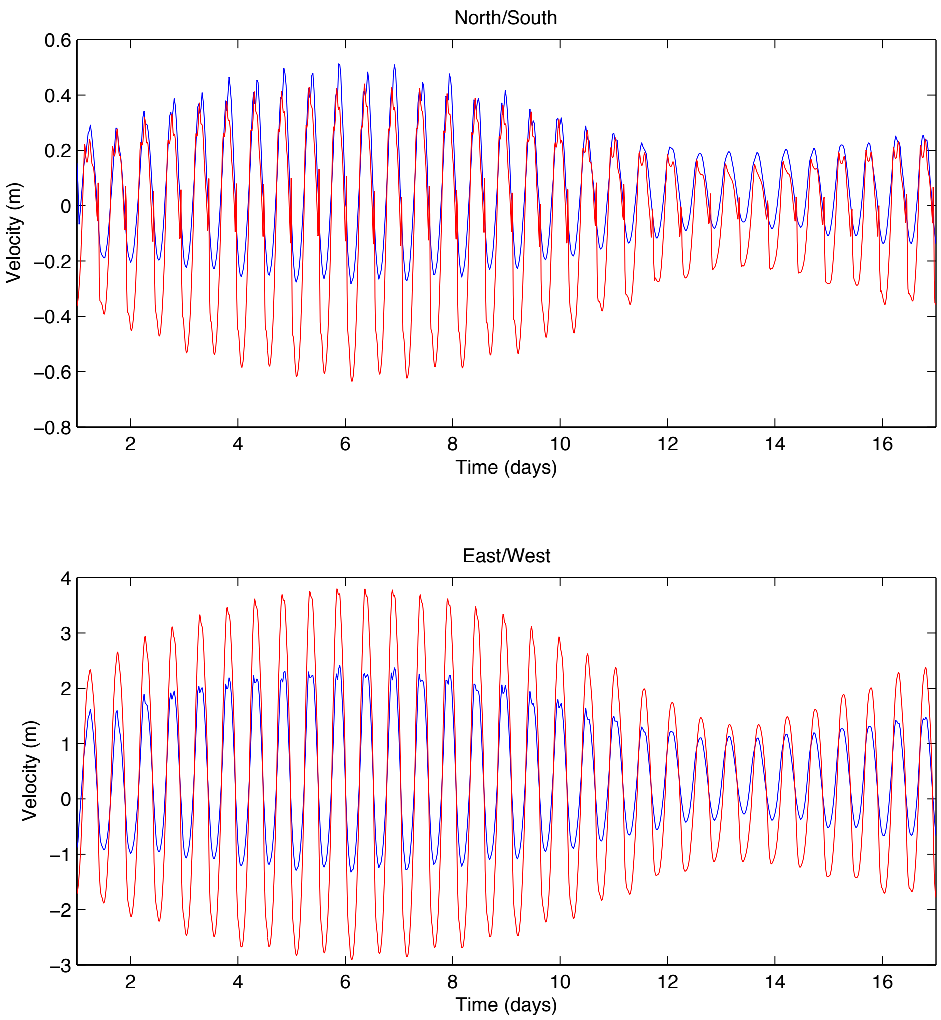

Figure 13 Comparison of currents at location I. EDF blue; Oxford red.

Kinetic energy flux

The overall resource of a site is poorly predicted by the kinetic energy flux (Garrett & Cummins, 2005). However, for small installations such as those analysed in this deliverable, the available power is strongly related to the naturally occurring kinetic energy flux.

In the present report we consider turbines placed between Swona and Stroma, and between Stroma and mainland Scotland. Thus it is of interest to consider the kinetic energy flux passing through these areas. As representative we consider the kinetic energy flux, per meter squared, at F and I. These are shown in Figure 14 and Figure 15. It can be seen that there is a significant mismatch.

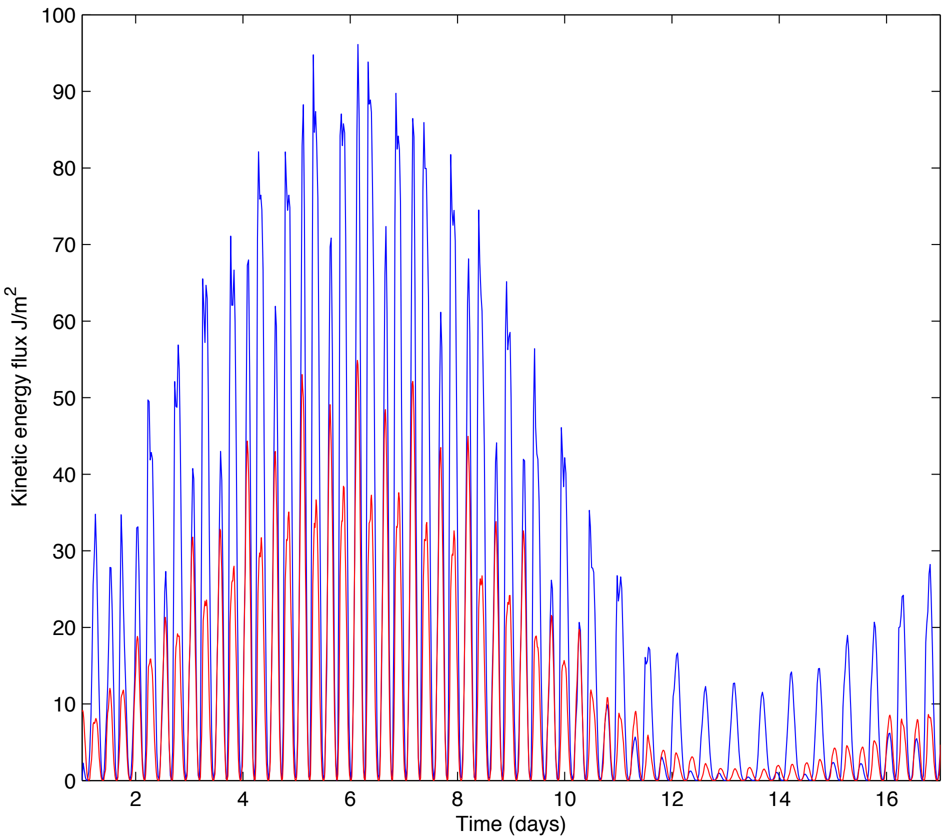

Figure 14 Kinetic energy flux at point F. EDF blue; Oxford red

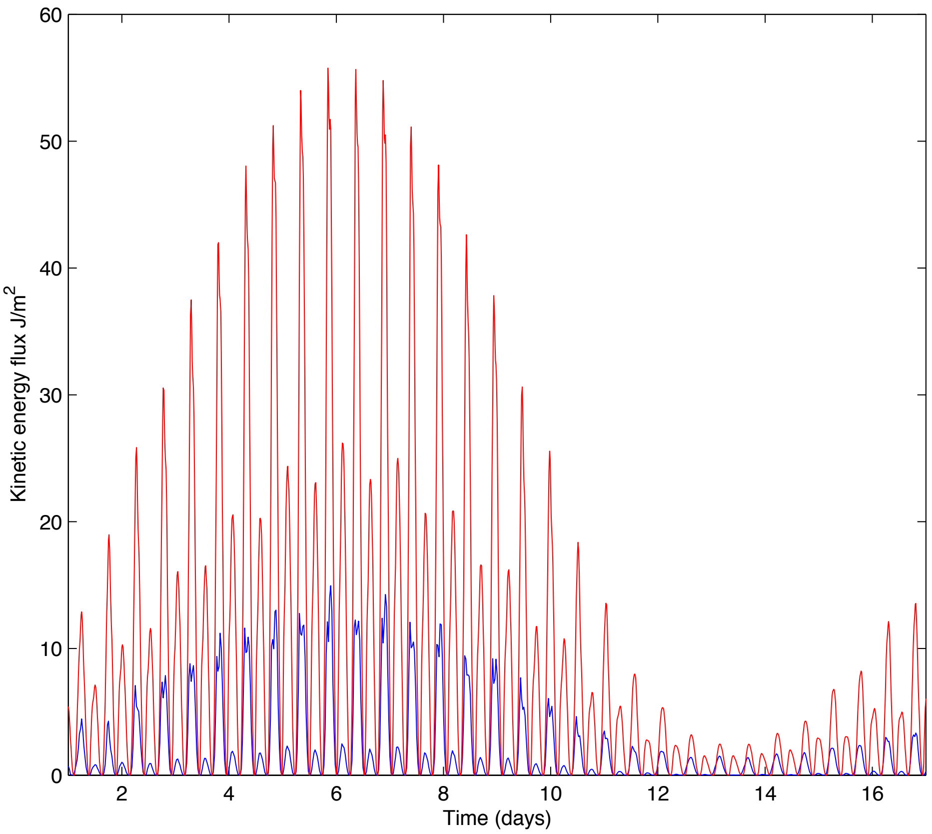

Figure 15 Kinetic energy flux at point I. EDF blue; Oxford red

4. Modelled power output

The data provided by EDF was averaged at hourly intervals. For comparison the University of Oxford data has also been presented this way.

Case 1

The location of the rows of turbines used in this case are shown in Figure 16. The turbines extend from (3.1085W,58.7150N) to (3.0936W,58.7276N). The turbines modelled had a nominal diameter of 18m and were spaced at 1.5 diameters.

Figure 16 Location of turbines for Case 1 in Google maps.

The power output from both models is shown in Figure 17. An alternative view is shown in Figure 18, where we present a low pass filtered version of the data to show the variation over the spring/neap cycle.

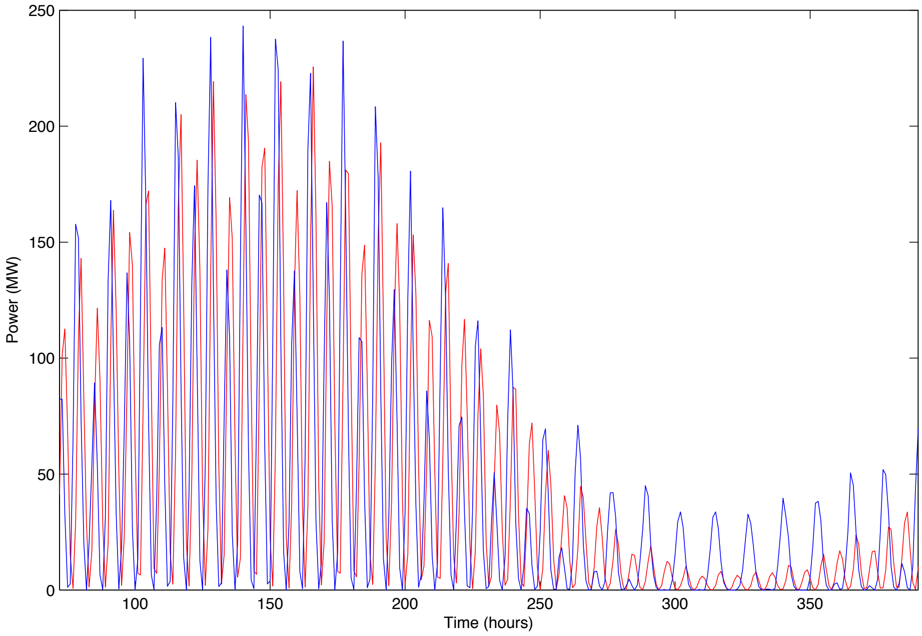

Figure 17 Comparison of power output on case 1. Powers are averaged over 1 hour. EDF blue; Oxford red.

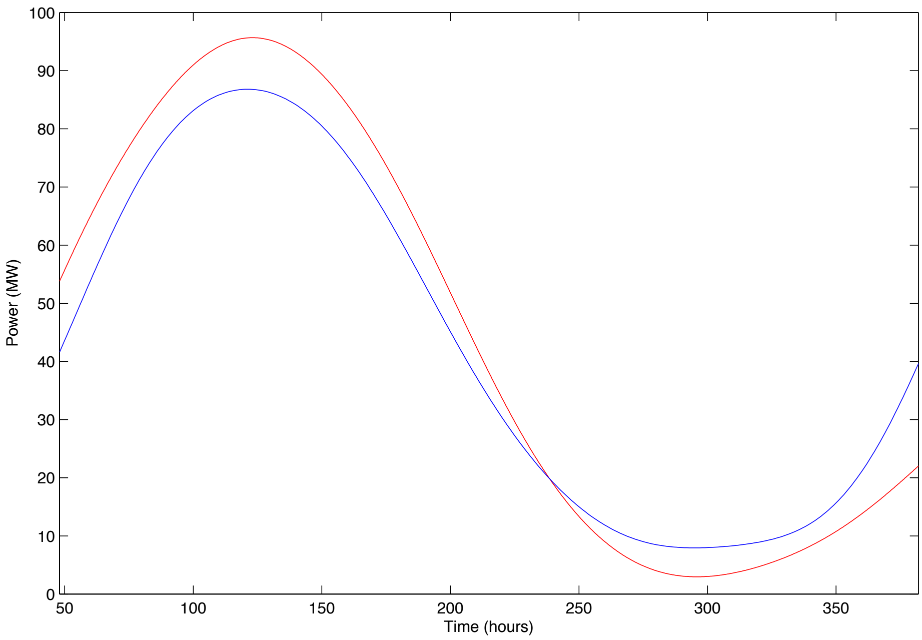

Figure 18 Comparison of power output on case 1. Powers are low pass filtered to remove the daily variation. EDF blue; Oxford red.

Both models are showing the same general trend across the spring/neap tidal cycle and both are of similar magnitude.

Although the agreement between the data sets are satisfactory, there are a number of other differences between the two timeseries. One is the difference in the magnitude of the power at spring tide (Oxford higher) and neap tide (Oxford lower). The second is the larger asymmetry between the flood and ebb tide in the EDF model compared to the Oxford model.

Case 2

Case two simulates two short rows of turbines of size 18m at 1.5 diameter spacing. The locations of the two rows are (3.0922W, 58.7256N) to (3.0937344W, 58.7241679N) and (3.0908W, 58.7252N) to (3.0922545W, 58.7237456N). These are shown in Figure 19.

Figure 19 Location of turbines in Case 2 in Google maps.

The power output from both models is shown in Figure 20. Initially there is general agreement on the magnitude and phase of the power between the models. However, after about 100 hours the pattern of the EDF model changes which the magnitude of the power output no longer follows the regular spring neap cycle observed in the Oxford data and in other graphs. This is attributable to a numerical instability in the EDF code.

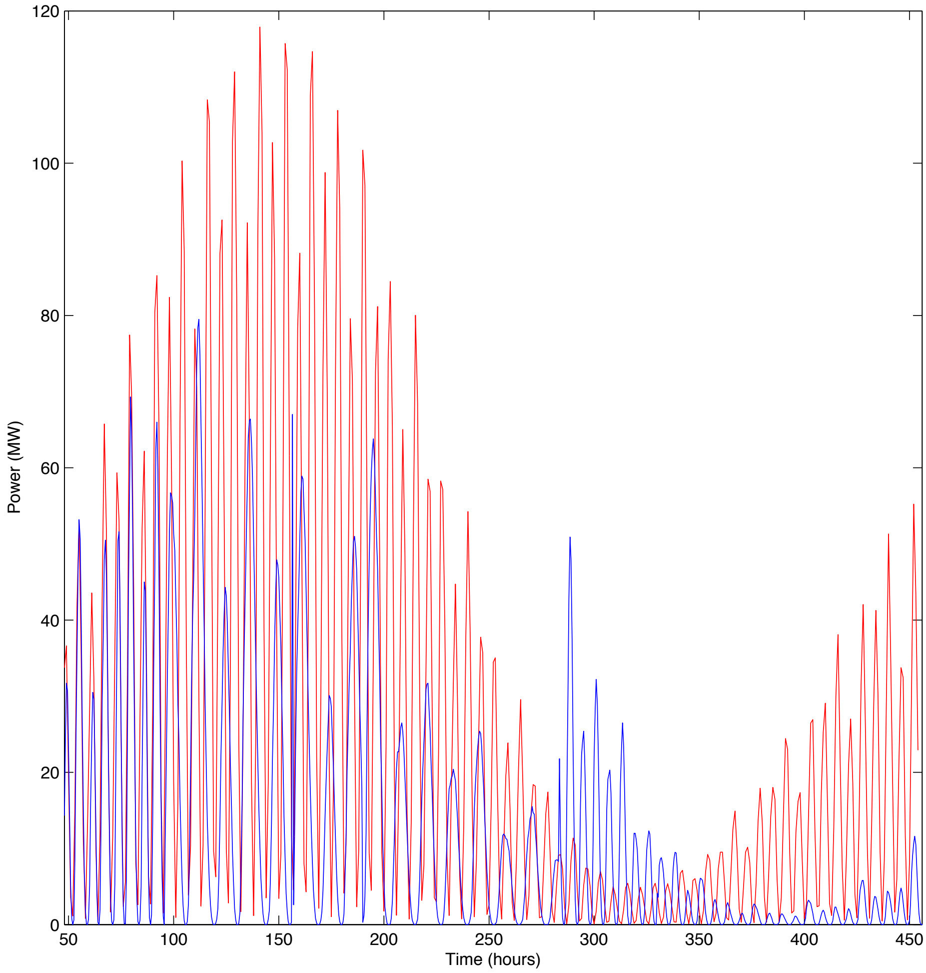

Figure 20 Power output for case 2. EDF — blue; Oxford — red.

Case 3

In case 3 we considered a row of turbines extending across the Inner Sound of the Pentland Firth. This is one of the first areas to be developed. As part of the PerAWaT project the available power and extractable power have been analysed (and published) in respectively Adcock *et al.* (2013) and Draper *et al.* (2013a).

The row of turbines studies extends from (3.1363W, 58.665N) to (3.1376W, 58.646N). The turbines are nominally 10m in diameter with 1.5 diameter spacing. The location of the turbines is shown in Figure 21.

Figure 21 Location of turbines for Case 3 in Google maps.

The power calculated by the two models is shown in Figure 22. There is clearly a significant mismatch between the power outputs from the two models. Possible reasons for the discrepancy are presented in Section 5. However, it is not possible to identify for certain the reason for the differences observed.

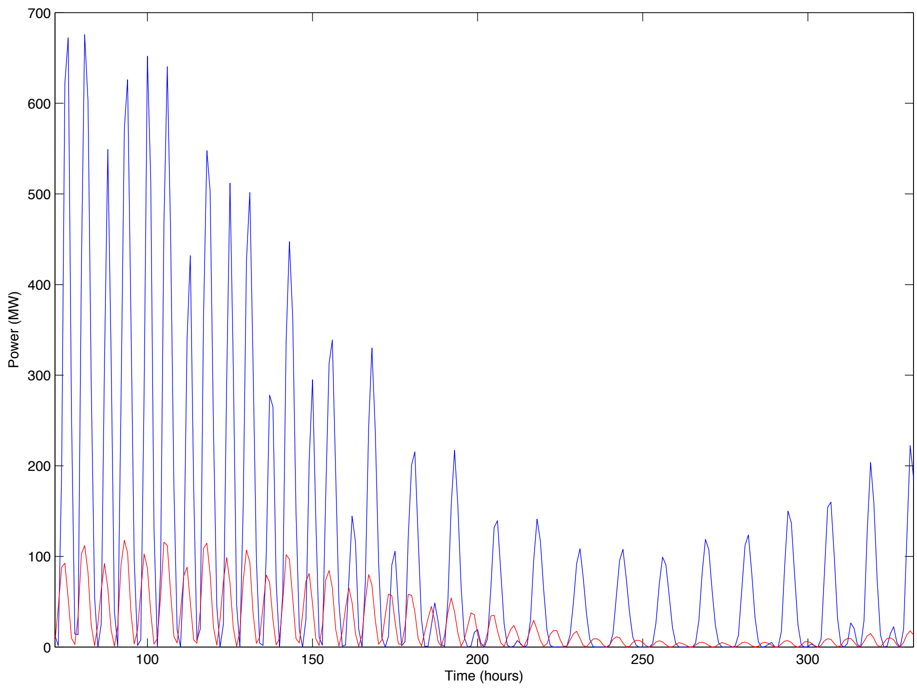

Figure 22 Power variations for case 3. EDF blue; Oxford red.

5. Discussion

There is clearly a significant mismatch between some of the powers predicted by the EDF and Oxford models. Some of this is due to the differences in the method used to model the tidal turbines. However, even if an identical methodology was used there would still be major discrepancies for the cases chosen due to the differences in modelling the natural environment.

For a small array[1] of turbines the disruption to the naturally occurring flow is small and the power available to the turbines will be close to a proportion of the naturally occurring kinetic energy flux. This flux is proportional to velocity cubed and thus is very sensitive to small differences in modelling and particularly the bed friction. This deliverable demonstrates that this makes it very difficult to

[1] Indeed, it may be convenient to define a "small array" as one which makes no significant change to the natural hydrodynamics away from the immediate vicinity of the turbine.

make accurate predictions of energy yield of small arrays using the methodologies developed in this work.

However, larger deployments of tidal turbines are far less dependent on the naturally occurring kinetic energy flux and are more dependent on the head across the channel. As shown in this report, this form of modelling satisfactorily predicts the head across the channel.

This point has been demonstrated in this project by Adcock et al. (2013) where peak available power is calculated when different bed frictions are used in the Pentland Firth model. For small deployments, changing the bed friction causes a large change in the available power. However, for large deployments the results are far less sensitive to the bed friction parameter.

Thus, a key outcome is that it is possible to make a robust estimate of the upper limit of the tidal resource of a site using the methodology developed in this report, as the upper limit will require a large number of turbines. However, doing a detailed assessment of smaller arrays of turbines requires a more refined analysis than has been carried out in this work. Indeed, to accurately evaluate the power from arrays of the size studied in this deliverable would require far more field data than was available in this project so as to have confidence that the model was reproducing the real dynamics of a site. Given the complexity of the physical processes, it is likely that a full 3D modelling of the hydrodynamics would be required for the results to be accurate.

There remains a question as to the mismatch in the powers predicted by the different models. Estimates using kinetic energy do not predict mismatches shown in the power calculations.

Consider a "back-of-the-envelope" calculation for case 3. The turbines are relatively small and so it is likely the natural kinetic energy flux passing through the turbines (multiplied by some efficiency) will be in the same ballpark as a correct estimate of the power output. The total area of turbines deployed approximately $10^4 m^2$. We take the density of sea-water to b $1000 kg/m^3$. Further let us assume that the velocity is constant across the cross-section. This allows us to calculate the velocity required to give the peak power output shown in Figure

22 using the equation $P=\eta\rho A u^3$. In this equation η is the efficiency of the turbine which we take crudely as 0.6 (close to the Betz limit). For the EDF simulation the required velocity is

$$u = \sqrt[3]{\frac{700\times10^6}{0.6\times1000\times10^4}} = 4.9\text{m/s}$$

and for Oxford's simulations

$$u = \sqrt[3]{\frac{100\times10^6}{0.6\times1000\times10^4}} = 2.6 \text{ m/s}$$

Whilst very high velocities close to 5 m/s have been recorded in the Pentland Firth, these are in the shallow areas around Islands and would not be expected to extend across an entire channel. Further, the currents shown in Figure 13 are not of this magnitude in either of the models. By contrast, the figure of 2.6 m/s appears to be in the right ballpark given this very rough calculation. The Oxford code has been thoroughly tested in WG3WP6D5 and shows excellent agreement with alternative energy extraction approaches such as using enhanced bed-friction. Further, the methodology used by Oxford has been shown to be consistent with physical model measurements (WG4 WP4 and Draper et al. (2013c)). We therefore suggest that the discrepancies between the models is likely to be caused by the instabilities in the EDF code.

6. Recommendations

In order to properly assess the energy extraction methodologies, and their implementation into the code, a comparison could be carried out on idealised case studies. For example, comparison could be made with the simple channel analysed in WG3 WP6 D2 and WG3 WP6 D5. The channel could either be driven by a set head difference or by a fixed flow rate. Analysis of this simple scenario has two main benefits

- It should be possible to establish identical flows in both models before tidal turbines are included.

- The energy extraction from simple channels is reasonably well understood so that it would be more straightforward to analyse the behaviour of energy extraction in the models.

A further benefit of an idealised test is that it can be compared with experimental results such as those in WG4 WP4. This would be unlikely to be useful in identifying minor differences but would allow for the identification of any large problems in the methodology.

Analysis of idealised cases is not, of course, sufficient to full test the models. In models of real sites there are features that are not present in idealised cases such as variable bathymetry and eddies passing through the turbine array (although cases could be created to analyse these individually).

In this project it was decided at an early stage that Oxford and EDF would carry out the modelling individually — i.e. they would build different meshes. Identical bathymetry data was used by each group but the imposed water levels on the boundary were taken from different sources (although this latter would not be expected to give a significant error). However, it would be possible to compare models with near identical meshes (although given the differences in the implementation of tidal turbines these could not be identical close to the turbines). There would still be differences since the models solve the governing equations used different methods that would require different time steps. Because of these differences it was decided not to share a mesh but to set up the domain in the best way for each model. However, identical meshes could be used in any future comparisons.

7. Conclusions

This report presents a comparison between the numerical modelling of the Pentland Firth undertaken by the University of Oxford and EDF. The simulations of the tides before the presence of tidal turbines show good agreement for the head difference across the Pentland Firth. However, there are significant differences between the way the tides are modelled within the Pentland Firth. Unfortunately, these difference make it difficult to compare the power predicted from the models when different configurations of turbines are employed. However, when simple hand calculations are used there appear to be some issues, possibly connected with numerical instability, in the EDF code.

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