Analysis and Comparison of Tidal Datasets

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Abstract

Tidal resources are highly variable, spatially and temporally. For tidal current energy to be economically exploited, certain conditions need to be fulfilled. Principally the strength of the resource needs to be quantified before it can be effectively utilised. This paper will build on and expand the simplified tidal analysis methods adopted in [1] and other simplified regional and national scale resource assessments. High quality data collection for interesting sites is highly desirable but expensive, difficult to extrapolate over a larger area, and hence unsuitable for national scale resource analysis. Existing publicly available datasets have so far typically been used to examine the resource. A methodology to combine all of the available datasets to produce an improved resource assessment methodology is desirable.

Combining datasets will only be suitable if there is good correlation and consistency between them. The suitability of combining three UK wide datasets will be examined in this analysis. The data sources considered are:

- UK Moored Current Meter Data,
- UK Hydrographic Office publications, and the
- DTI Atlas of UK Marine Renewable Energy Resource.

The datasets do not generally coincide spatially or temporally. Analysis to enable direct comparison of these datasets for a case study region will be presented. This will inform whether the methodology of analysis and combining of datasets has potential for application at larger scales. If with additional processing, datasets can be combined, considerable improvement will potentially be realised in analysing the UK tidal energy resource. Future work is intended to combine outputs from this research with similar datasets for other intermittent renewable resources in order to examine their combined output and their potential integration into the existing electrical network infrastructure.

Keywords: Resource assessment, Tidal analysis, Harmonic tidal analysis, model skill.

Nomenclature

X = two dimension vector
Y = two dimension vector
$\overline{X}$ = mean of X
$\overline{Y}$ = mean of Y
Skill = Model Skill
CC = Cross Correlation Coefficient
x, y = Cartesian co-ordinate system
σ = Standard Deviation
N = Total number of observations
$v(z)$ = The velocity at some elevation in question z
$v(z_r)$ = The velocity at a unknown elevation z_r
P = Power
ρ = Density of sea water (1025 kg/m^3)
v = Velocity

1 Introduction

The UK has an excellent tidal current energy resource around its coastline. The development of these resources can potentially contribute to meeting future renewable energy requirements. Many studies have tried to quantify this resource with estimates including 18 TWh/yr [2], 13.3 TWh/yr [3], and 96.4 TWh/yr [4] to around 25 TWh/yr for Scotland alone [5]. The spread in the estimates is due to difficulties in evaluating the resource as a result of complex local tidal interaction as well as differences in use of resource information between the various studies. Simplified and often inaccurate assumptions can have a significant impact on the estimate arrived at within each study. With a range of tidal current devices in development, eventual deployment will be enhanced by reliable evidence about the resource, its characteristics, environmental impacts and costs.

The work described here is part of an effort to accurately model the UK tidal resource, both spatially and temporally. This will form part of a larger renewable resource model being developed by the Engineering and Physical Sciences Research Council's Supergen FlexNet consortium [6]. The aim is to develop a robust and repeatable method for generating resource related time series that reliably describes the available resource across the UK.

This paper provides a preliminary analysis and comparison of time series measurements from a case study region in the Irish Sea near the Island of Anglesey off the north Wales coast. The potential suitability of this location for tidal energy development is the reason for selecting this site for analysis. The water depth is about 40 metres and potentially offers a high tidal energy site, close to shore, conditions which suits first generation devices. Good landfall (beach, not cliffs) for bringing cables ashore, appropriate local harbour facilities for installation, operation and management activities are also important project development constraints potentially addressed at this location.

The datasets include current measurements from several buoys that were moored temporarily over relatively short periods but covering several spring-neap cycle tidal variations. The study is also re-evaluating the methodology used by Boehme *et al.* [1] to estimate the potential of the tidal resource in Scotland; the study used point source data from tidal diamonds obtained from Admiralty charts, to generate spatially consistent resource maps by means of Inverse Distance Weighting interpolation (IDW) [7]. The fidelity of this methodology will be considered.

The paper is structured as follows. Section 2 looks at the datasets available in the study area and explains the approach used. Details of the methodology used and the numerical experiments conducted are presented in section 3, discussion of the results obtained from the statistical analysis are also discussed here. Details of the comparison between the buoys, tidal diamonds and the effect of interpolation are also looked at followed by a summary and discussion in section 4.

2 Approach

Ongoing work at the University of Edinburgh is examining different datasets available for tidal resource assessment in UK. These include the UK moored current meter dataset made available through the British Oceanographic Data Centre (BODC), a national facility that archives marine data. One of the datasets available for academic purposes provides time series measurements of ocean currents from temporarily moored instruments deployed in the shelf seas around the British Isles [8, 9].

The second data source examined here is analysis of Admiralty chart data and tidal stream atlases. These provide a series of descriptions of tidal current flows in terms of velocity magnitude and direction at hourly time intervals with respect to high water at a reference location. The data spans from 6 hours before high water through to 6 hours after high water for typical spring and neap tide conditions. The locations of these data are referred to as 'tidal diamonds', as their respective positions are indicated on Admiralty charts by diamond symbols. The UK Hydrographic Office (UKHO) TotalTide software package [10] contains fundamentally the same information as the Admiralty charts but provides a means of interrogating the tidal current data through time at the tidal diamond locations. The tidal current data in TotalTide would appear to only encapsulate variability of the available data prescribed by the two generally dominant tidal harmonic constituents, M_2 and S_2 [11].

The DTI Atlas of UK Marine Renewable Energy Resources also provides useful spatial information for offshore marine renewable technologies [12]. The information provided in the atlas is managed and maintained in a structured Geographic Information System (GIS) database and is available online [13].

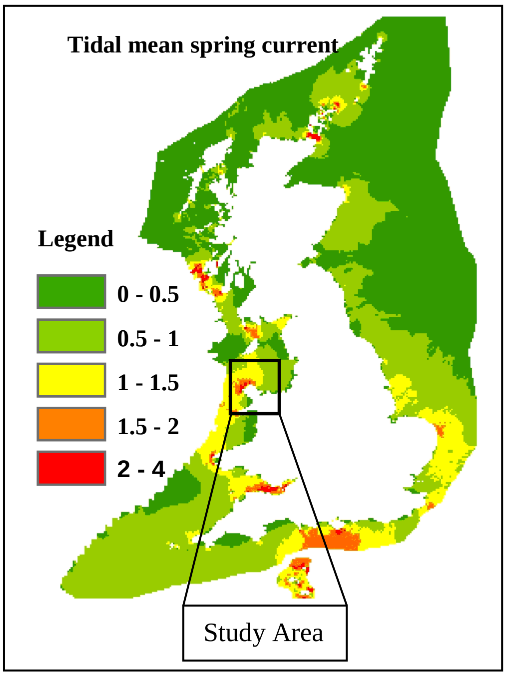

Figure 1: Figure showing mean spring peak current.

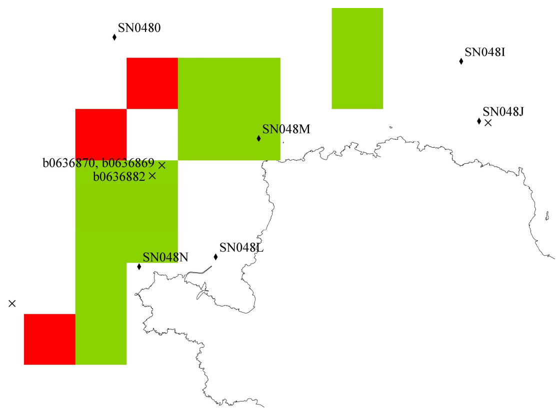

Figure 2. Location of tidal diamonds, mooring buoys and DTI Atlas identified tidal energy potential locations.

Figure 1 is an extract from the DTI Atlas showing the site of interest. The tidal current data presented in the DTI Atlas presents spatially averaged snapshots of mean spring and neap tides. It is based on data from continental shelf models developed by the Proudman Oceanographic Laboratory (POL). Times series data from the POL modelling effort have not been available for use in this analysis, only the output presented in the DTI Atlas is considered.

Figure 2 shows the location of the three buoy moorings and the eight tidal diamonds considered in this case study. The green (depth <40 metres) and red squares (depth > 40 metres) in figure 2 represent output from the DTI atlas where spring peak currents of greater than 2.0 m/s were predicted The minimum data length for the selected mooring buoys was 29 days in order to enable a detailed harmonic analysis to be conducted. Other buoy records in the area were rejected as they were of length less than 29 days. The tidal diamonds are all within a 50 km radius of the buoy locations. The location of the buoys and tidal diamonds along with their position in the water column is indicated in Table 1. Buoy records B1 and B2 were gathered simultaneously, on the same mooring. B1 was located 10 metres above the sea bed while B2 was positioned 37 meters above the sea bed (near surface). The water depth at this site is reported to be 40 metres [8].

	Name	Location	Depth below mean sea level (metres)
B1	b0636869	53.39°, -4.68°	30 m (near sea bed)
B2	b0636870	53.39°, -4.68°	3 m (near surface)
B3	b0636882	53.38°, -4.69°	3 m (near surface)
D1	SN0480	53.28°, -4.45°	5 m (near surface)
D2	SN048M	53.25°, -4.34°	5 m (near surface)
D3	SN048L	53.20°, -4.36°	5 m (near surface)
D4	SN048N	53.19°, -4.41°	5 m (near surface)
D5	SN048I	53.29°, -4.21°	5 m (near surface)
D6	SN048J	53.26°, -4.20°	5 m (near surface)
D7	SN048B	53.05°, -4.44°	5 m (near surface)
D8	SN062E	53.40°, -5.09°	5 m (near surface)

Table 1: List of buoys (B), tidal diamonds (D) and location.

3 Assessment

The analysis takes the form of a series of comparisons between:

1. the individual moored buoy records themselves,
2. the individual Admiralty tidal diamond data obtained from TotalTide
3. the individual moored buoy records and Admiralty tidal diamond data obtained from TotalTide.

Comparison of Buoys

The three individual moored buoy records do not coincide in time, although they were gathered during a coincident survey period. Direct comparison between the buoy data is therefore not possible. However, harmonic analysis and reconstruction can be used to generate accurate tidal predictions that are coincident.

The harmonic constituents of the tides contained within each of the three current meter datasets was determined using least-squared analysis. 23 principal constituents were obtained following the methodology advocated by National Oceanic and Atmospheric Administration (NOAA) Centre for Operational Oceanographic Products and Services (CO-OPS) in their Tidal Current Analysis Procedures and Associated Computer Programs documentation [14].

To verify how representative a prediction was generated through this analysis, the 23 constituent records were used to recreate the original time series and compared with the original current meter data. Fig 3 shows a scatter plot of the original current data and the data created using the 23 tidal constituents. It can be seen that while there is some scatter, the fit is good to excellent, and exhibits good homogeneity. The buoy data is a true in-situ record of sufficient length to allow confidence in its fidelity, therefore for this analysis it is reasonable to treat reconstructed moored buoy data as the 'gold standard' with which other datasets will be compared.

All comparisons are made for the common period of August 2009, with the harmonic constituents derived from the original data records used to create a pseudo-time series at 10-minute intervals for this period for each buoy location. Tidal current data are also obtained for the relevant Admiralty tidal diamond locations for the same time period using TotalTide.

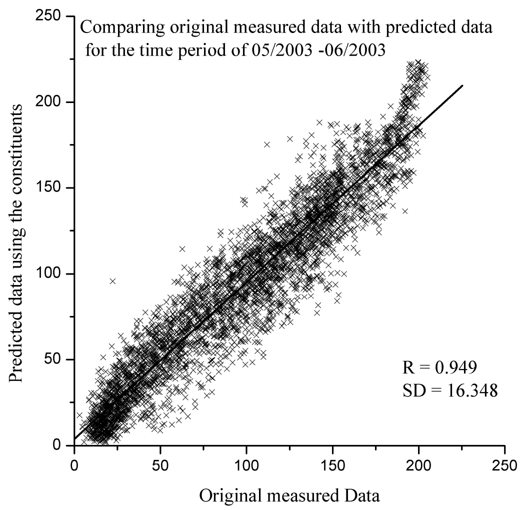

Figure 3: Scatter plot comparing between the original data record and the reconstructed data generated using 23 harmonic constituents.

The first comparison presented is between the individual moored buoy records. Given the location of the buoys (close physical proximity) the data would be expected to demonstrate good correlation. Figure 4 shows the velocity magnitude plot of all the three buoys for a randomly selected day in August 2009.

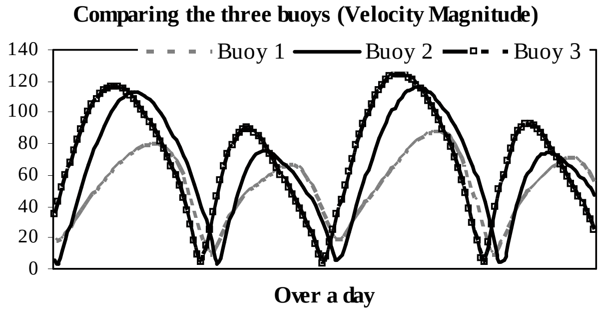

Figure 4: Figure showing currents at buoys B1, B2 and B3.

Buoy 1 and Buoy 2 are located on the same mooring, there is good phase agreement between the three records. Buoy 2 and buoy 3 are both located near surface and only 1.07 km apart, a slight phase lag is observed but the shape and size of the velocity magnitude plots compare well. To quantitatively compare these measurements statistical methods are adopted. First the mean absolute error (MAE) and relative mean absolute error (RMAE) are calculated. The data is converted from velocity magnitude and direction into two-dimensional vectors X(X_{1n}, X_{2n}) and Y(Y_{1n}, Y_{2n}). The MAE is calculated as [15]:

$$MAE = \frac{1}{N}\sum_{n=1}^{N}\sqrt{(Y_{1n}-X_{1n})^2+(Y_{2n}-X_{2n})^2}$$

This statistically incorporates both errors in velocity magnitude and direction. The relative mean absolute error is a better means of comparing between experiments as it incorporates the relative magnitude of the data considered.

$$RMAE = \frac{MAE}{\frac{1}{N}\sum_{n=1}^{N}\sqrt{(X_{1n}-X_{2n})^2}}$$

An RMAE value of zero indicates a perfect match. This will be a good indicator of how spatially variable tides in this site are. Table 2 has a summary of MAE and RMAE between the three records examined.

		B1	B2	B3
B1	MAE	-	31.16	51.86
	RMAE	-	0.49	0.82
B2	MAE	31.16	-	38.31
	RMAE	0.35	-	0.43
B3	MAE	51.86	38.31	-
	RMAE	0.54	0.40	-

Table 2: Comparing results from the buoys

Because B1 and B2 are co-located, good qualitative agreement is expected but with B2 having a much lower tidal velocity (due to its relative depth). A scaling factor would be required to account for the vertical velocity gradient between the sea-bed and the surface which skews the data in this case (e.g. $1/7^{th}$ power law).

B3 has better agreement with B2 than with B1 because B2 and B3 are both located close to the surface and except for a small phase lag have a very similar velocity magnitude.

Comparison of Tidal Diamonds

The next set of experiments compared all the tidal diamonds obtained from TotalTide. Tidal diamonds are a set of numbers that depict the tidal current behaviour at certain time relative to high water at a reference port [16].

A total of 8 tidal diamonds were used in this experiment - all those within 50 km radius of the buoys (see Figure 2). The MAE and RMAE are calculated for the four closest tidal diamonds, SN0480, SN048M, SN048L and SN048N. Table 3 has a summary of MAE and RMAE between the tidal diamonds. The error values are in general consistently bigger for the tidal diamonds compared with the buoy data. This is primarily because these data points are spatially more dispersed than the buoys. This gives us a good indication of how spatially variable tidal current velocity data can be even within a (relatively) short distance.

		D1	D2	D3	D4
D1	MAE	-	68.49	88.51	91.6
	RMAE	-	0.83	1.07	1.11
D2	MAE	68.41	-	122.52	67.8
	RMAE	0.53	-	0.95	0.53
D3	MAE	88.38	122.44	-	92.78
	RMAE	3.14	4.35	-	3.29
D4	MAE	91.48	67.7	92.82	-
	RMAE	0.84	0.62	0.85	-

Table 3: Comparing results from the tidal diamonds.

The RMAE and MAE values for D3 are exceptionally bad compared to the rest of the tidal diamonds because this particular tidal diamond is located just over the edge of the head land, therefore none of the strong tidal currents are observed at this location as it is shielded by the land mass.

Comparison of Buoys and Tidal Diamonds

To better understand the quantitative agreement between the buoys and the tidal diamonds, a model skills test [17] is conducted. The observed data considered are the measured buoys and the model data are the tidal diamonds. The skill is defined as:

$$Skill = \frac{\sum |X-Y|^2}{\sum \left(\left|X-\overline{Y}\right|+\left|X-\overline{Y}\right|\right)^2}$$

Where $\overline{Y}$ is the mean value of the observed data. A value of one indicates perfect agreement and a value of zero indicates total disagreement. All the three buoy records were compared against all eight tidal diamonds. The statistics are summarised in table 4. The values of least agreement within a 12 km radius and within the 50 km radii are shown in bold. Yet again, the model skill results for tidal diamond D3 which is 7.68 km away from buoy 1 and 2 compares even worse than the distant D7 and D8 diamonds, especially in the V direction. This has been explained earlier when the MAE and RMAE values were discussed. The effect is much more evident in the V direction as this is the stronger principal current direction.

		B1		B2		B3	
		U	V	U	V	U	V
Within 12 km	**D1**	0.91	0.88	0.94	0.90	0.81	0.77
	D2	0.87	0.82	0.92	0.96	0.91	0.94
	D3	**0.71**	**0.29**	**0.64**	**0.28**	**0.79**	**0.27**
	D4	0.78	0.84	0.79	0.93	0.90	0.97
Within 50 km	**D5**	0.90	0.10	0.94	0.14	0.86	0.15
	D6	0.90	**0.05**	0.94	**0.11**	0.85	**0.09**
	D7	**0.16**	0.91	**0.29**	0.93	**0.31**	0.82
	D8	0.87	0.94	0.80	0.86	0.69	0.78

Table 4: Comparing 'model skill' results from the buoys and tidal diamonds.

Standard deviation σ was also calculated to get a measure of the statistical spread of the values.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Where N is the total number of observations and x_i is the ith value. Standard deviation can also be used to calculate the cross correlation coefficient (CC) between the buoy and the tidal diamond data:

$$CC = \sigma_x^{-1}\sigma_y^{-1}\frac{1}{N}\sum_{1}^{N}(x_i - \bar{x})(y_i - \bar{y})$$

CC has been calculated for all the buoys and the four closest tidal diamonds (D1-D4). These values have been plotted and can be seen in Figure 5.

Perfect correlation is indicated by a value of 1 and -1 indicates negative correlation.

Effect of Interpolation

The inverse distance weighting (IDW) interpolation methodology advocated by Shepard [7] was applied to the tidal diamond records.

$$u(x) = \frac{\sum_{k=0}^{N} w_k(x)u_k}{\sum_{k=0}^{N} w_k(x)}$$

Where:

$$w_k = \frac{1}{d(x, x_k)^p}$$

Here $p = 2$ is adopted as recommended by Shepard. Selection of the value of p enables the user to prescribe how sharp a peak the function exhibits by giving greater influence to nearby data points. A low value of p provides a smoother solution, with more 'smearing' of peaks. IDW is used in this instance to create 'pseudo' diamonds from the tidal diamonds available in the location. To test the fidelity of these 'pseudo' diamonds, the interpolation locations are mapped onto existing buoy record locations. The further away a tidal diamond is from a specific location, the less weighting it will have in the calculation. Similarly, tidal diamonds located close to the buoy will have a higher weighting therefore having a more significant influence on the pseudo diamond.

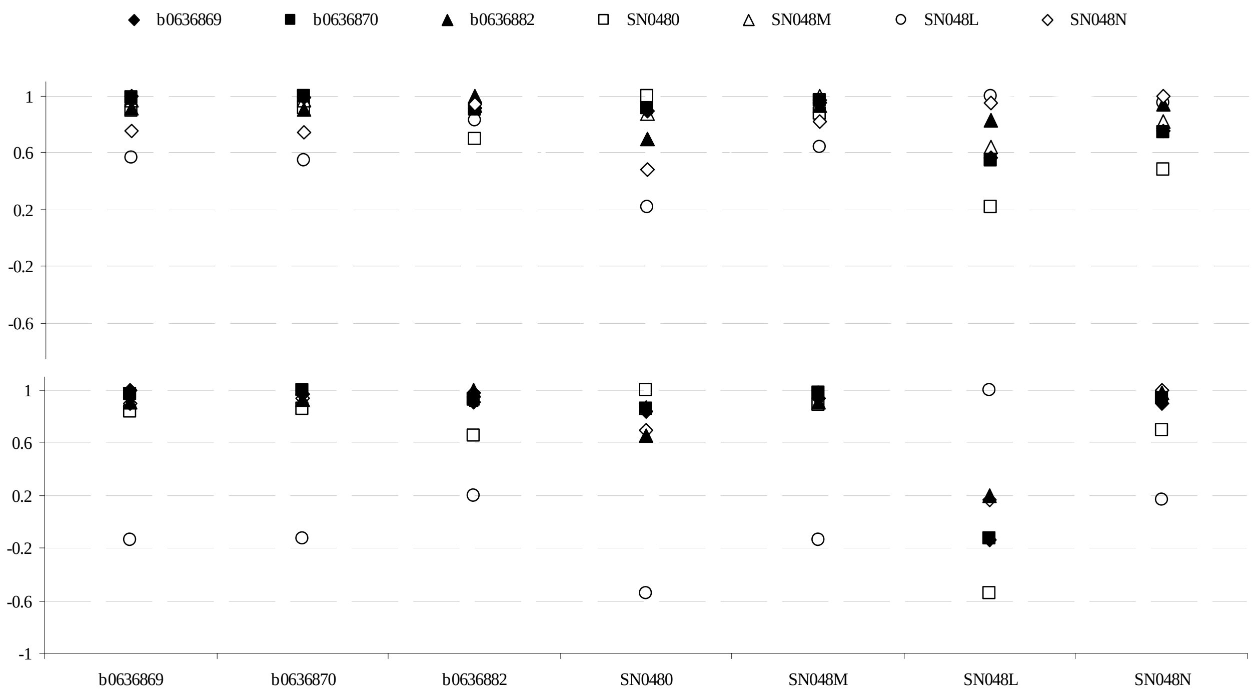

Figure 5: Comparing CC between buoys and tidal diamonds n directions (top) West-East, (bottom) South-North.

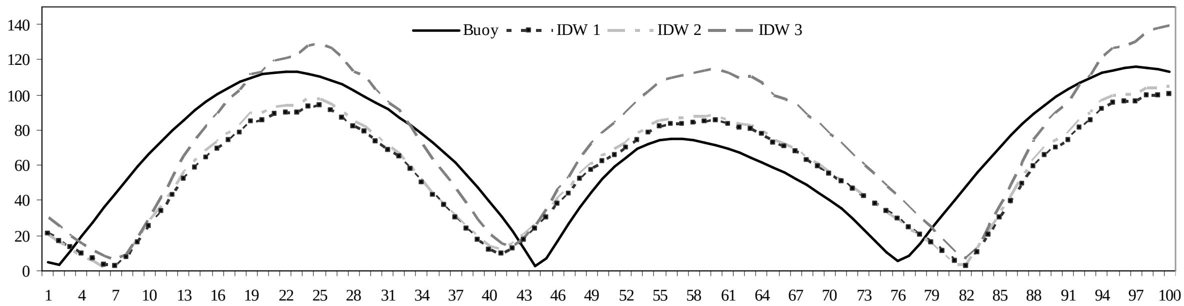

Figure 6: Velocity magnitude comparison of buoy with IDW 1, IDW 2 and IDW 3.

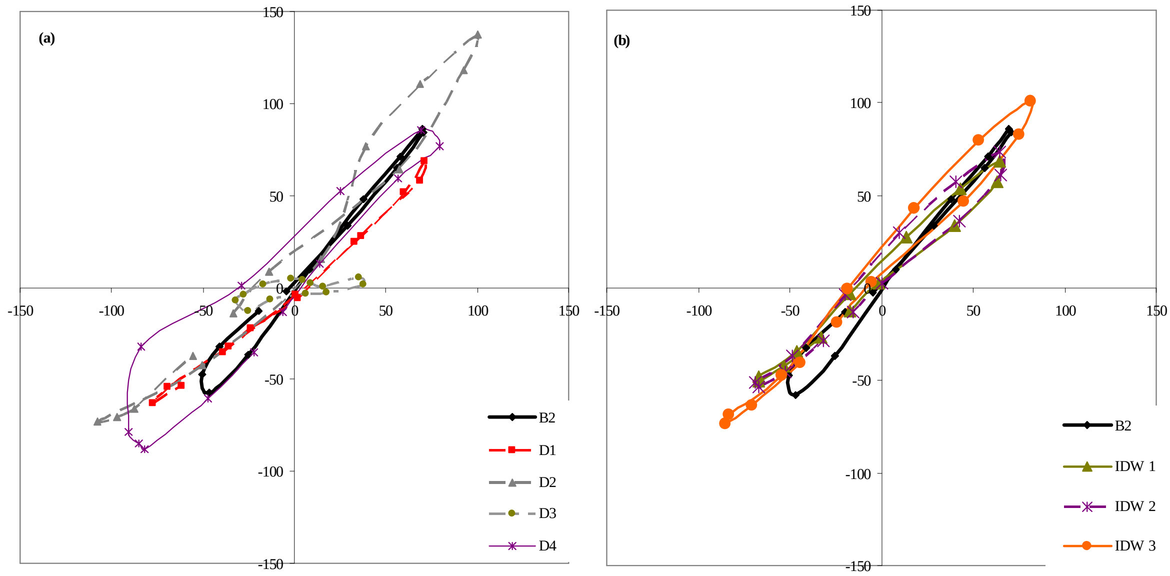

Figure 7: Tidal ellipse hodographs (a) comparing buoy data with tidal diamond data and (b) comparing buoy data with IDW data constructed from tidal diamond records.

Three sets of IDW's are created. IDW 1 indiscriminately includes all the tidal diamonds within 50 km radii of B2. IDW 2 only includes the four tidal diamonds within 12 km of B2 and IDW 3 is a 'selected' variation of IDW 2 where tidal diamonds are selected based upon their statistical correlation. Table 5 summarises the distance between all the tidal diamonds and B.

	Distance (km)
D 1	10.45
D 2	8.42
D 3	6.98
D 4	7.68
D 5	24.49
D 6	33.23
D 7	33.23
D 8	44.09

Table 5: Distance between each tidal diamond and B2

Statistical analysis has been carried out to better understand the correlation between IDW 1, IDW 2 and IDW 3 and see how theses representations compare with the individual buoy record.

Vector magnitude plots of B2 along with IDW 1, IDW 2 and IDW 3 are plotted in Figure 6. There is good quantitative agreement between IDW 1, which includes all the tidal diamond current data within the 50 km radii, and IDW 2 which only includes the 4 closest buoys. The minimal difference between IDW1 and IDW 2 (they nearly overlap in figure 6) is due to the inverse distance weighting ensuring that the distant buoys provide a limited impact in this particular case (see table 5).

As the buoy data encapsulates 23 constituents where as the Total Tide diamond data generally has only 2 constituents, [11] there is a surprisingly good qualitative agreement and correlation. The shape and the general envelope of the spring-neap cycle are also well captured (not shown).

Velocity magnitude peaks and phasing in figure 6 indicate reasonable qualitative agreement between the different records, certainly offering improvement over the comparison with individual TotalTide sourced tidal diamond records are presented in the preceding section.

Comparing tidal ellipses hodographs

Tidal ellipse comparisons have been plotted in figure 7, where the local individual tidal diamond ellipses (left) are compared with all the IDW ellipses (right). The IDW ellipses show a good qualitative agreement and the IDW presents substantially graphically reduced errors, suggesting that this methodology does in fact improve the representation of some of the tidal characteristics. The bi-directionality of the tides makes this location very desirable and this is shown well by the IDW's.

Comparison with the DTI Atlas data

It is estimated that only 0.15% (1269 km^2 Area) in the UK continental shelf has a peak flow of 3 m/s or greater [18]. These are the very high energy sites that can make tidal energy extraction economically viable. Before devices are deployed into the water, it is important to precisely identify these locations and study the individual site characteristics.

Depth-averaged data is often used during calculations; in this study we have buoy data near surface, at 37 metres and near bed at 10 metres. TotalTide data is near surface, approximately 35 metres. Current velocity data can be obtained at specific depth by using a scaling value. A $1/7^{th}$ power law is often considered appropriate in fluid flows [19].

The POL (CS3) model used to construct the DTI Atlas [11] uses a depth-variation profile.

Alternatively, [2] uses a variable power law:

$$\frac{v(z)}{v(z_r)} = \left(\frac{z}{z_r}\right)^{\frac{1}{x}}$$

Where $v(z)$ is a known velocity at a known elevation z , and $v(z_r)$ is the unknown velocity at the elevation of interest, z_r, and x = 7 in case of $1/7^{th}$ power law or 10 in case of $1/10^{th}$ power law (these values are typically applied in the fluids community, and carry over into the wind industry).This formula can be used to estimate the tidal velocity at a specific height in the water column. This would enable the calculation of velocity at the height intended for installation of a selected tidal turbine from data records elsewhere in the water column.

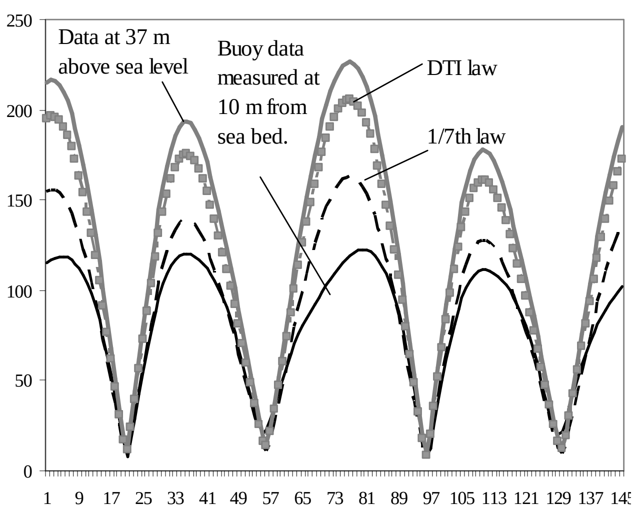

Figure 8: B2 scaled down using the $1/7^{th}$ and DTI scaling factors.

Figure 8 shows spring peak measurements for B2 which is located at 37 metres (near surface), scaled to 10 metres using the scaling factor as suggested by the DTI (Dept. of Energy). Also plotted is the actual measured data obtained at 30 metre in the same location.

The scaling factor used by DTI is about 0.9. However figure 8 indicates that the current velocity is nearly half at 10 metres depth, suggesting that a scaling factor of approximately 0.5 would be more appropriate in this particular case. The DTI Marine Atlas uses layers obtained from the HRCS model and this scaling factor to obtain their depth averaged current velocity and power. For this particular site this scaling factor overestimates the current velocity significantly. When then manipulate to produce an estimate of the energy that can be harvested at this location, this overestimation would then be compounded.

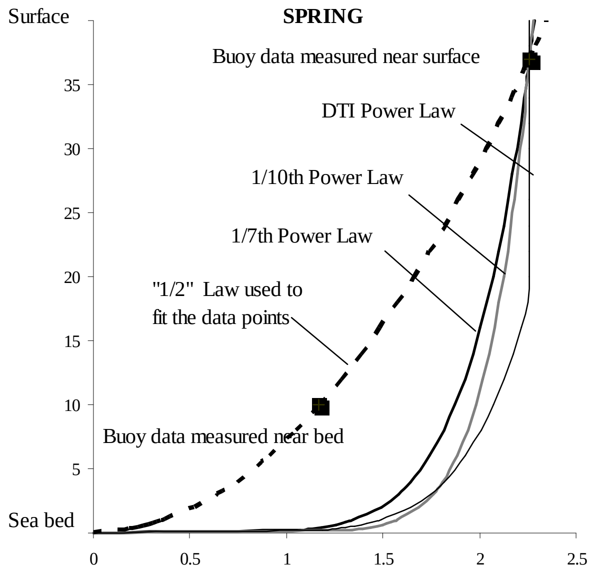

Figure 9: Tidal current velocity profile.

Figure 9 shows current vertical velocity profiles in a water depth of 40 metres. The figure compares various commonly applied power law plots with two data points obtained from the buoys. The power law cures have been derived from the near surface buoy data. As suggested earlier, a scaling factor of 0.5 is appropriate for fitting a power curve to the data. Similarly calculations for neap tide data were best fitted using a similar scaling factor. It remains unclear weather overestimation of the resource in this case by the $1/7^{th}$, $1/10^{th}$ and DTI power law would be replicated at other locations without further evidence. However it is of significant interest that the extreme tidal velocities of interest for tidal energy development are potentially not well represented by traditional vertical velocity variation assumptions.

Comparing Power outputs for B2 buoy and IDW's

Power output for all the three IDW's and B2 have been calculated for the month considered for case study analysis. Power was calculated using:

$$P = \frac{1}{2}\rho A v^3$$

Where

$\rho = 1025$ kg/m^3 and A is taken as 1m^2

Similarly, the power output from the DTI Atlas for this region is also obtained, the mean annual kw/m^2 was extracted from the atlas and multiplied by the number of hours in a year (8760 hours) to obtain the annual energy output. Table 6 summarises the output resource assuming that the simulated month is representative of the entire year. B2 is used as the base value here for comparison and the annual energy yield is compared with the three IDW outputs and the DTI Atlas.

	Annual energy resource available per square metre (kWh)
B2	6395
IDW 1	4038
IDW 2	4538
IDW 3	9875
DTI Atlas	10319

Table 6: Power output for B2, IDW1, IDW2 & IDW3

From the preceding analysis, the error margin between the velocity magnitudes were substantially reduced between the IDW representations of the tidal diamond data over consideration of the individual tidal diamond data when compared with the moored buoy derived data record. However, when these datasets are used to conduct a long-term monthly, or annual energy yield assessment, even the IDW representation of the tidal diamond data show poor agreement. As prediction of long-term energy yield is at the heart of any sensible economic appraisal of a particular development project, the application of the IDW methodology for use in tidal energy resource assessment must be questioned.

These error margins make a significant impact on site selection and lifetime production costs. If this was to be considered over 25 years, the typical intended lifecycle of tidal energy development projects, these error margins would be unacceptable.

4 Conclusion

The spatial variability of tides is governed by complex non-linear physics, topography, the bathymetry and the fluid interaction at the site. For this reason, interpolating spatially diffuse tidal data records is always going to lead to inaccuracies. These complex phenomena cannot be well represented by simple interpolation. This is particularly true when the current velocity derived will inevitably be manipulated to conduct tidal energy generation calculations and scenarios analysis. Even though statistical analysis shows the MAE and RMAE of velocity records to be relatively small, the error is magnified when the power output is estimated for a site. The significant variations in the available energy in the water column derived using even the improved IDW representations demonstrates that this methodology is not robust for serious resource or development project economic assessment.

The most important issue the authors wish to highlight is that it is essential for developers before committing to a site for development to conduct an appropriate survey of the available resource. Gathering multiple Acoustic Doppler Current Profiler (ADCP) records across the intended site at a minimum temporal resolution of 29 days is recommended to enable an appropriate spatial and temporal representation of the tidal currents to be determined. This will also assist in making assessments of the future energy yield through appropriate harmonic predictions that can feed into power production calculations and economic assessment models. Ultimately this type of data will enable project developers to better estimate future revenue generation, or conversely be able to pre-determine that a site is in fact uneconomic for development.

Additional case studies are necessary to support the various conclusions reached here. Further analysis is ongoing to support and expand upon the current work.

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