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The Parameterisation of Turbulence in the Marine Environment

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Abstract

There are many problems in the fields of flow modelling around structures and tidal stream energy yield analysis which require a thorough understanding of the turbulent and time averaged flow speeds in marine environments. In this paper we examine the relationship between the turbulence intensity and mean tidal flow speed at a potential tidal stream power site.

We report data from the Humber Estuary wherein an Acoustic Doppler Current Meter (ADCP) was used to capture vertical profiles of the high frequency and mean tidal flow speeds throughout Spring and Neap, Flood and Ebb cycles.

We show not only that our results extend earlier work but also suggest that the turbulence intensity, I_T, can be described parametrically in terms of the mean flow, U, by an inverse power function

$$I_T = \alpha U^{\beta}$$

where the coefficient appears to be dependent upon the anisotropic nature of the turbulence. For the data reported here, the coefficient has value of about 17-18 and the eponent lies between -0.6 and -1.0. Confirmation of this relationship should not only improve engineering design work and energy yield analyses in turbulent tidal flows but also be applicable to other problems such as the prediction of sediment mass transport and pollution dispersal in estuarine management studies.

Keywords

Tidal Stream Power; Turbulence Intensity; ADCP; Estuary

1. Introduction

There are many problems in the fields of marine engineering, sediment transport, pollution dispersal, flow modelling and energy yield analysis which require a thorough understanding of the turbulent and time averaged flow speeds and directions in the marine environment. Computational or laboratory models are able to simulate the basic flows. However it is not possible, at present, to directly model the turbulence at all of the relevant scales. Rather, the turbulence must be estimated from field observations of the flow, which are inherently sparse and noisy (Thomson *et al.,* 2012).

In general, the instantaneous flow is taken as the sum of tidal and turbulent components and recent work has focussed on the identification of relationships between the turbulence intensity (the ratio of the velocity fluctuations to the mean velocity) and the mean tidal flow speed (e.g. Thomson *et al.* (2012), MacEnri *et al.* (2013) and McCaffrey *et al.* (2015)). The effects of turbulence on both the structure and the efficiency of tidal stream power devices have been studied and the analysis of field data is being used to identify general metrics which describe the relationship between the flow speed and the turbulence. In the analogous case of observations at wind energy sites, the key parameter is again identified as the turbulence intensity measured at turbine hub height and this has been shown to correlate with turbine performance and structural fatigue (Thomson *et al.* (2012), Mycek *et al.* (2014)).

Thomson *et al.* (2012) report data from sites off Admiralty Head and Nodule Point in Puget Sound, WA encompassing tidal flow speeds up to 3.25 and 1.75 ms^{-1} respectively. They show that the standard deviation of the instantaneous flow measurements (defined here as Eq.2) increases with the mean flow speed and that the turbulence intensity (defined here as Eq.3) is scattered below about 0.8 ms^{-1} and then steadies and decreases slowly to below about 10 % for higher flow speeds. The authors conclude that the results for the normalised turbulence intensity were consistent between their sites and different current meters, and provide useful values and value ranges for device fatigue and energy yield analyses.

MacEnri *et al.* (2013) argued that, since there is no currently accepted standard for the measurement of turbulence in tidal stream power applications, then it is right to adopt the corresponding wind turbine standard (IEC604-21, 2008) and utilise the turbulence intensity, I_T. Their data from the MCT Seagen site in Strangford Loch, Ireland shows I_T values that are scattered at low flow speeds but lie below 10 % for flow speeds above about 1 ms^{-1}, with indications that the values decrease at higher flow speeds.

McCaffrey *et al.* (2015) report data from the field deployment of an Acoustic Doppler Current Profiler (similar to the instrument used in the present project) in Puget Sound which confirms that the turbulence strength (as opposed to the turbulence intensity) increases with the mean tidal velocity. They introduce the idea of turbulent anisotropy where isotropic turbulence is defined as having uncorrelated orthogonal velocity fluctuations, whilst increasing anisotropy is represented by an increasing correlation between the orthogonal velocity fluctuations. They define the co-ordinate system invariant scalar magnitude of the anisotropy, A, as in Eq. 4 below and note that the anisotropy equals zero for uncorrelated turbulence and increases with the degree of correlation of the orthogonal velocity fluctuations. Filipot et al. (2016) report data from a proposed tidal stream power site located north-east of Brehat Island ibn the western English Channel, close to the coast of Brittany. The data again evidence the relationships between the mean tidal current speed and the turbulence strength described by McCaffrey et al. (2015)

Jeffcoate *et al*. (2015) report data from the testing of a SCHOTTEL tidal stream power turbine in Belfast Loch and also confirm the inverse power relationship between the turbulence intensity and the mean tidal flow speed.

Here we review the relevant theoretical background to the turbulent components of the flow and then report results from experiments carried out in the Humber Estuary on the North Sea Coast of northern England. An Acoustic Doppler Current Profiler (ADCP) was used to capture vertical profiles of the high frequency (approximately 1 Hz) and five minute mean tidal flow speeds throughout Spring and Neap, Flood and Ebb cycles. The results extend the work, in particular, of Thompson *et al*., 2012, MacEnri *et al.* (2013) and McCaffrey *et al.* (2015).

These results suggest a simple parametric relationship may exist between the time-averaged tidal flow and the standard deviation of the turbulent components. Furthermore, the correlation coefficient appears to be dependent upon the anisotropic nature of the turbulence. Confirmation of this relationship should not only improve engineering and energy yield analyses in turbulent tidal flows but also be applicable to other problems such as the prediction of sediment mass transport and pollution dispersal in estuarine management work (*e.g.* Hardisty, 2007).

2 Theoretical Considerations

Flow Decomposition

Tidal flow velocities are complex as they accelerate, decelerate and reverse in direction over varying depths every tidal cycle. Tidal currents are, therefore, turbulent, unsteady and can exhibit conditions which vary from sub-critical through critical to supra-critical within a few hours (Lu, 2000; Hardisty, 2009). Thomson *et al.* (2012) decompose the time series of *u(t)* in a tidally dominant flow into three component variables:

$$u(t) = u_T(t) + u_w(t) + u'(t) \qquad \text{Eq.1}$$

Where *u(t)* is the resultant flow speed due to the superimposition of the tidal component, $u_T(t)$, the wave-induced component, $u_W(t)$, and *u'(t)* which is the component generated by turbulent eddies. The data reported here were collected in calm conditions, so that no further consideration is given to the wave-induced current term in this paper. In the following sections we present the theoretical derivation of the turbulent term.

Tidal Turbulence

Estuarine and coastal environments exhibit turbulent motion which is three dimensional and consists of a wide range of eddy sizes and fluctuation frequencies (Rodi, 1994). Controlled, in part, by the mean flow and the very high width to depth ratios which occur in estuaries (>100:1), the largest eddies are of the same order of magnitude as the flow domain and consist of two dimensional horizontal structures which are advected in a stream-wise direction during the tidal cycle. On a much smaller scale, three-dimensional turbulence is generated by bottom and wind shear, providing energy input at a different range of the spectrum.

The analysis of these turbulent eddies frequently involves the use of the turbulence strength, U_σ, which is defined by McCaffrey *et al.* (2015) as the standard deviation of the magnitude of the instantaneous flow measurements, U_i, compared with the mean flow in *N*:

$$U_\sigma = \sqrt{\sum_{i=1}^{N} \frac{(U_i - \overline{U})^2}{N}} \qquad Eq.2$$

The turbulent intensity, I_T, is then defined as

$$I_T = \frac{U_\sigma}{\overline{U}} \qquad Eq.3$$

Where U_σ is again the standard deviation of the individual flow measurements in a record (Eq.3) and $\overline{U}$ is the mean of all of the measurements in each sample. In the experiments described here, the sampling rate was approximately 1 Hz so that there were 323 measurements in each five minute record (N=323) using a 1200 kHz system and 577 measurements using a 600 kHz system.

Finally, McCaffrey *et al.* (2015) define the co-ordinate-system invariant scalar magnitude of the turbulent anisotropy, *A*, and note that the anisotropy equals zero for uncorrelated turbulence and increases with the degree of correlation of the orthogonal velocity fluctuations, which is itself indicative of different turbulent structures and regimes. These authors find that the anisotropy at their Puget Sound field site varies from close to 0 up to about 5 x 10^{-3} with units of energy/unit mass (m^2s^{-2}).

3 Field Site

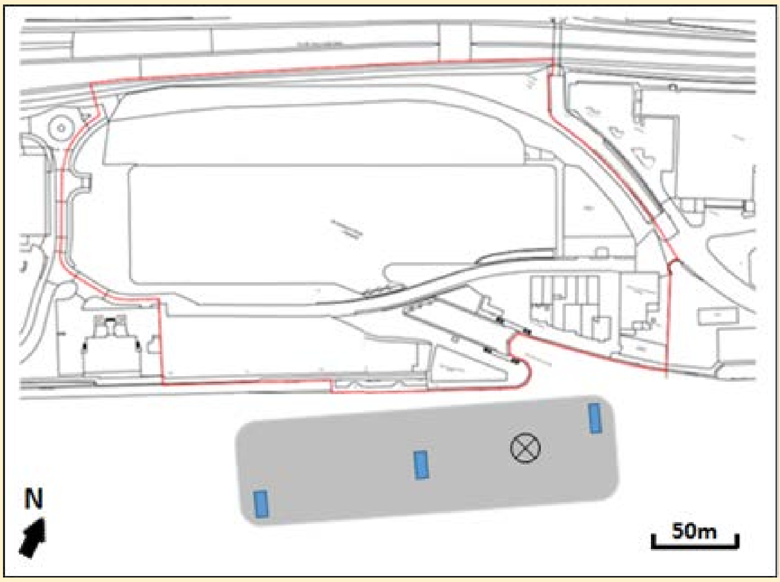

Figure 1 *Location of field survey site (53° 43.687' N 0°21.852' W) and the proposed 3 MW Humber Tidal Array on the north bank of the Humber Estuary and off the old St Andrew's Dock site.*

The experiments described here were designed as one element of the determination of the tidal resource at the proposed Humber Tidal Array Experimental Site on the north bank of the Humber Estuary and off the old St Andrew's Dock. The Humber is the largest estuarine system in the British Isles with a total catchment area of 26 000 km^2 and an annual average freshwater input of about 250 m^3s^{-1}.

The Humber is hyper-tidal (tidal range >6m, Hardisty, Rouse and Hughes, 1996) with tidal current velocities up to 2.5 ms^{-1}. The Humber tides are dominated by the M_2 amphidromic point in the eastern-central North Sea (Doodson and Warburg, 1941). In general the tidal wave progresses in a southerly direction down the coasts of Holderness and Lincolnshire (Hardisty, 1990 and Hardisty, Rouse and Hughes, 1996) and enters the estuary mouth some 6 hours before high water at Dover, taking about 3 hours to progress up the estuary to the Ouse-Trent confluence and higher order harmonics are generated during this progression.

The Humber Tidal Array experimental field site had been identified from earlier Energy Yield Analyses (Hardisty, 2014) as likely not only to demonstrate strong currents, but also to be closely located to shore side infrastructure and grid access. The location of the proposed tidal stream power installation made up of three individual 1 MW pods each of four twin turbine devices is shown in Figure 1. Each individual turbine is rated at 125 kW, but it is expected, from the results below, that peak output power of the individual turbines at the Humber Tidal Array site will be about 80-100 kW.

4 Methodology

Figure 2 *Mounting the Teledyne Workhorse ADCP*

600 kHz and 1200 kHz Teledyne Workhorse Acoustic Doppler Current Profilers (ADCPs) were used to measure flow speeds through depth and time for the Spring tide of 19th April 2015 and the Neap tide of 13th May 2015 at the Humber Tidal Array site (Figure 2). Measurements commenced at high water on the Spring tide and ran for four hours, followed by a two hour break and then for four hours during the following flood. A similar pattern was followed for the Neap tide.

The ADCP was bolted to a rigid inflatable boat and connected to a power supply and laptop running WinRiver II. The laptop was also connected to the boat's GPS for accurate VTG location referencing. The expected maximum water depth (15 m), maximum current velocity (3 ms^{-1}), boat speed (0 ms^{-1}) and transducer depth (0.5 m) were input so that the software calculated suitable measurements and displays of the data. Water profiling mode 12 was used during each transect which collected ensembles of data at 0.43 Hz with bin depths of 0.25 m with the 1200 kHz ADCP and 0.93 kHz with bin depths of 0.5 m with the 600 kHz ADCP. Mode 12 is calibrated for the highest accuracy measurements in strong flows up to 10 ms^{-1} and water depths up to 15 m.

The chosen sampling frequency and duration is a compromise between collecting sufficient data to calculate a reasonable ensemble average and the need to ensure stationarity of the tidal flow which may itself be accelerating and decelerating. The rates used here are similar to those used by Thomson *et al.* (2012) and Jeffcoate *et al.* (2015) and were judged sufficient to acquire converged statistics.

Data were post-processed using WinRiver II, Matlab and Excel which involved calculating 5 minute averages and standard deviations from individual ensembles and then depth averaged means and standard deviations. These values were then used to calculate the turbulence intensity as discussed above.

5. Results

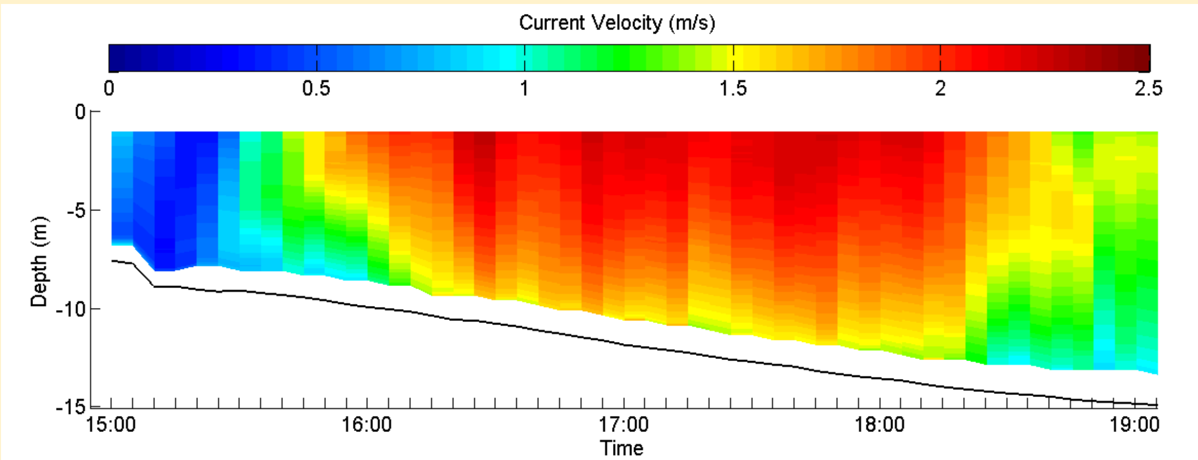

Figure 3 *Acoustic Doppler Current Profile of tidal flow for the Spring flood tide on Sunday 19th April 2015 at the Humber Tidal Array Experimental Field site.*

The results for the Spring Flood tide on April 19th 2015 are shown in Figure 3 as time (GMT) versus depth from the surface downwards, contoured against the corresponding flow speed. The results are discussed in detail below but it is noted here that flows >2 ms^{-1} persist for more than 2 hrs on this Spring Flood with a peak of about 2.35 ms^{-1}. There is evidence of faster surging at about 16:20, 16:40, 17:00 and 17:30 which may be represent the submergence of 'barrier sand bars' further upstream in the estuary. It is estimated that the Flood flow on a larger Spring tide is potentially 2.5 ms^{-1}. The data for the Spring Ebb on April 19th 2015 showed that flows >1.75 ms^{-1} persist for more than 2 hrs with a peak of about 1.85 ms^{-1}. There was no evidence of faster surging during the ebb which also accords with the idea that the flood surges may be evidence of the submergence of 'barrier sand bars' further upstream in the estuary.

The data for the Neap Flood on 13th May showed that flows >1.5 ms^{-1} persist for more about 2 hrs on the Neap Flood with a peak of about 1.75 ms^{-1}. There was evidence of faster surging at about 12:00, 12:20 and 12:40 which may be evidence of the submergence of 'barrier sand bars' further upstream in the estuary, as discussed above. The data for the Neap Ebb on 13th May 2015 showed that flows >1.00 ms^{-1} persist for more than 2 hrs on this Neap Ebb with a peak of about 1.5 m/s. The result suggests that a tentative estimate of the flow harmonics from this data is U_{M2} max = 2.0 ms^{-1} and U_{S2} max = 0.5 ms^{-1}.

6. Turbulence

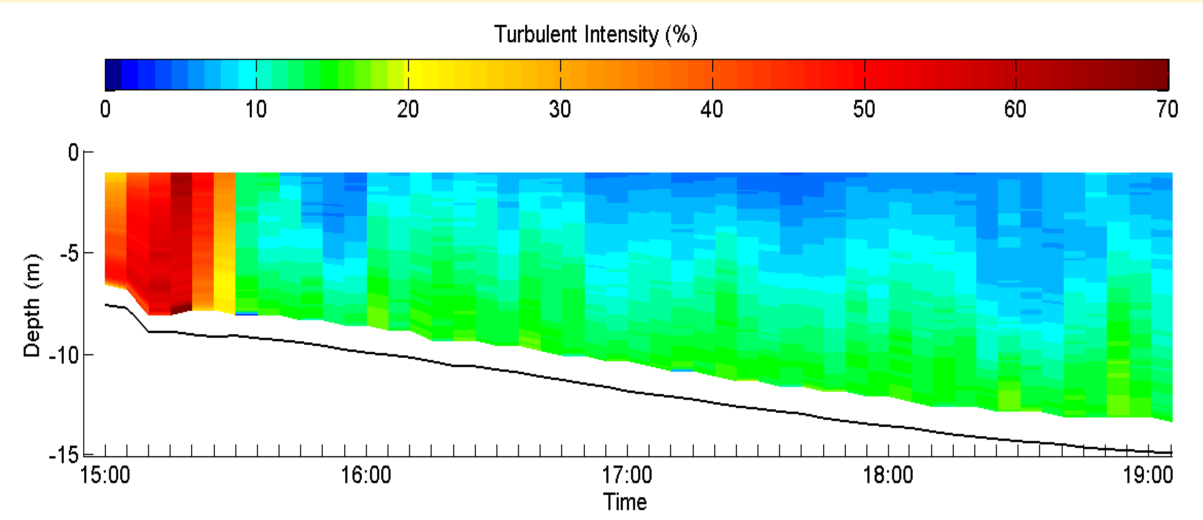

Figure 4 *Turbulence intensities (Eq.3) for the Spring flood tide of Sunday 19th April 2015.*

Qualitative observations indicated the presence of turbulence at the field site. The level of turbulence was quantitatively analysed using the turbulence intensity introduced earlier. The flow speed increases to a maximum and then decreases towards high water as discussed earlier (Figure 3) and decreases towards the bed. The turbulence intensity (Figure 4) is high at low water, remains constant at around 10 % for the most of the flood and increases towards the bed as discussed below. These observations of a relatively high turbulence intensity at slack water are similar to those reported by, *e.g.,* Thomson *et al*. (2012), MacEnri *et al*. (2013), Gunawan *et al*. (2014) and McCaffrey *et al*. (2015), but, in so far as we are aware, the observations that the turbulent intensity increases towards the bed have not yet been explicitly published elsewhere. There is clearly an increase in the turbulence intensity around low water relative to the mean tidal current and it may be postulated that this represents the advection of large but slow moving parcels of water and perhaps eddies. It is also not unreasonable to p[rop;ose that the increase in turbulence intensity towards the bed marks the generation of turbulence by the bed roughness in accordance with the Von-Karman boundary layer model.

It is interesting to note that the flow speed at about 17:00 on the Spring Flood is about 1.2 ms^{-1} at the bed and 2.4 ms^{-1} at the surface. Since the hydraulic power density increases with the cube of the flow speed (*e.g*. Hardisty, 2009) then there is perhaps eight times more power available for floating tidal stream power turbines than for a comparable, sea-bed mounted generator.

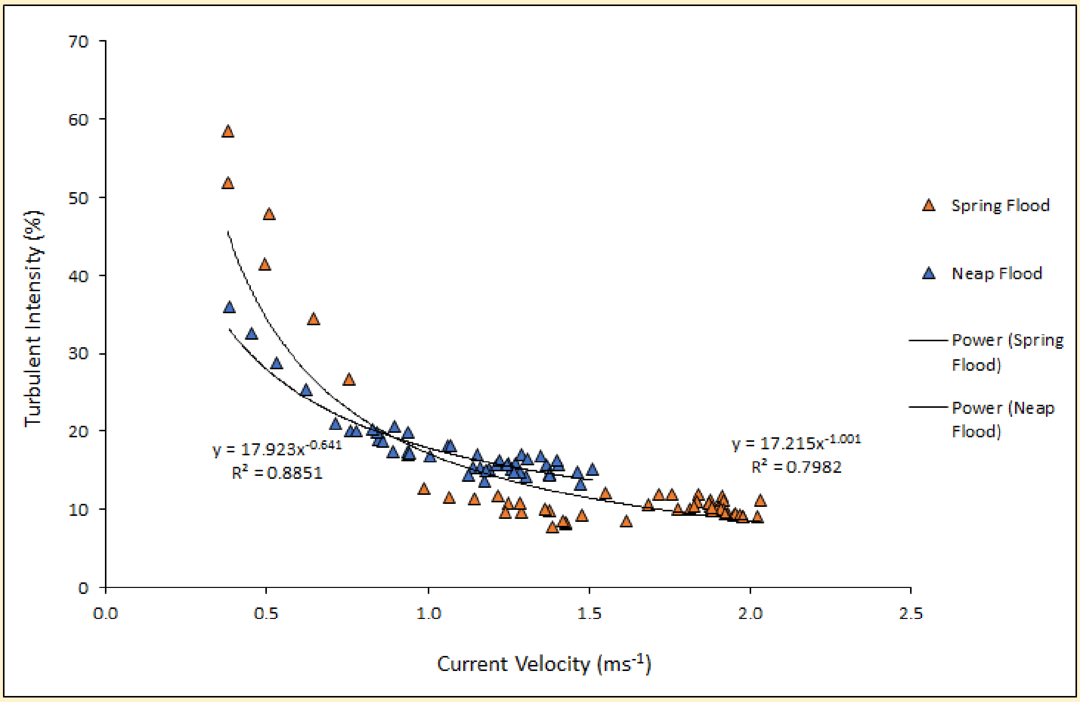

Figure 5 *The turbulence intensity as a function of the tidal current velocity through the Spring flood tide of 19th April and the Neap flood tide of 13th May 2015 at the Humber Tidal Array Experimental Site.*

Figure 5 shows the depth and time averaged tidal current velocity and the turbulence intensity for the Spring Flood tide on 19th April and the Neap Flood tide of 13th May 2015 as described earlier. We note that, as in other recent research papers, these data are beginning to define a pattern for the turbulent structure in tidal flows (Thomson *et al.* (2012); MacEnri *et al.* (2013), McCaffrey *et al.* (2015)), Jeffcoate *et al*. (2015) and Filipot et al. (2016)). The turbulence intensities appear to be high at low flow speeds, corresponding to high water and low water, which may be largely because the flow is less structured and weak. The intensity decreases as flow speeds increase to values of about 0.8 ms^{-1} above which I_T decreases slowly with the tidal current speed and is below 10 %.

We suggest here that the turbulent intensity can be described parametrically by the simple relationship

$$I_T = \alpha\, U^{\beta} \qquad \textit{Eq.4}$$

where the coefficient, α, appears to be dependent upon the anisotropic nature of the turbulence (McCaffrey *et al.,* 2015). For the data reported here and shown in Figure 5, α has a value of about 17-18 for both tides. β is very close to minus unity (-1.001) with a correlation coefficient of 0.80 and about -0.64 with a correlation coefficient of 0.89 for the Spring and Neap floods respectively.

5. Discussion and Conclusions

The review of the recent literature from Puget Sound and Strangford Loch and the new field results from the Humber Tidal Array experimental site suggest that the turbulence intensity in tidal flows has high values at low water and high water and that the value decreases to <10 % with flows above about 0.8 ms^{-1}.

We suggest here that the turbulence intensity can be described parametrically by the simple relationship $I_T = \alpha\, U^{\beta}$ and we note that the value of the coefficient, α, may be a function of the co-ordinate system invariant scalar magnitude of the turbulent anisotropy. Such anisotropy will relate to local turbulent forcing due, for example, to the bathymetry of the site and the effects of changing water depth and bed roughness. For the data reported here and shown in Figure 5, α has values of 17 to 18 and β has values of -0.6 to -1.0.

Confirmation of this relationship should not only improve engineering and energy yield analyses in turbulent tidal flows but also be applicable to other problems such as the prediction of sediment mass transport and pollution dispersal for estuarine management work.

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