Coupled flow-wave modelling for regional tidal site characterisation in the English Channel

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ABSTRACT: Numerical simulation is an essential tool to predict ocean conditions at tidal energy sites. Knowledge of flow velocity, water level and wave conditions are required for site selection, resource quantification and project planning. Studies for individual tidal energy sites have shown that wave effects can potentially reduce the average tidal energy potential by 8-15%. These studies have been performed for individual sites, rather than larger, regional models to inform the initial site identification.

Coupling of hydrodynamic flow and wave models is often undertaken to improve the accuracy of outputs from both models. Fully coupled simulations require considerable information to be passed between the individual flow and wave models at each computational time-step. This is considerably more computationally expensive and increases model run-times significantly. This work discusses the question of whether operating the flow and wave simulations in a fully coupled mode provides significant improvement over running the models separately.

A large regional coupled flow-wave model has been established covering the English Channel using the Delft3D Flexible Mesh hydrodynamic package coupled with SWAN (D-WAVE). This work presents a comparison study of the models when run as a fully coupled simulation and as a one-way offline simulation. Output is presented at several sites where the potential for tidal energy is considered. The statistical analysis of the differences is also discussed. This paper will be of interest to researchers and practitioners involved in tidal energy resource modelling and site identification and planning.

1 INTRODUCTION

1.1 *Tidal Energy*

Global effort to decarbonize the energy sector means that non-traditional forms of electricity generation are becoming increasingly more relevant. Tidal stream energy is a globally distributed sustainable energy resource that has the potential for significant contribution to the electricity sector. The UK alone has significant tidal stream resource, estimated at 95TWh/year (Crown Estate, 2013). Although there have been prominent demonstration projects and pilot plants, the industry has yet to develop into a commercial reality, readily available for installation and routinely contributing to renewable energy generation portfolio. The economic viability of large-scale deployments will be largely governed by aspects of tidal energy resource and technical plant availability, governing the energy yield.

1.2 *Tidal Resource Modelling*

Collecting in-situ measurements at tidal sites is an expensive and time-consuming process. Numerical simulations are able to provide flow speed, water level variation and other key resource parameters without the need for costly and risky offshore operations. Once calibrated against in-situ data, numerical simulations can also provide a long-term dataset, necessary for the assessment of the metocean climate at the site.

An accurate understanding of the expected power output from a tidal energy installation is essential for assessing its financial viability. Given that for tidal stream generation, power is proportional to the cube of the flow velocity, a small error in calculating the flow may result in a large error in power generation calculations and hence there would be a significant difference to the project LCOE.

Thus, commercial tidal energy projects critically require a good understanding and quantification of the energy yield. A significant project and hence investment risk component, affecting all tidal energy projects, is the uncertainty in the pre-construction resource and yield estimate. A robust understanding of those uncertainties will increase investor confidence (Cathain, 2013; Shah, 2016). Variations in energy yield directly translate to variations in revenue and thus the project viability. A detailed review (Livermore, 2015) identified and evaluated the main sources of uncertainty for tidal energy resource assessments:

1. Instrument measurement uncertainties are reasonably small and well-understood if best practice is followed during instrument deployment and data analysis.

2. Extrapolation procedures of tidal energy data are established, but the correct evaluation in site conditions with asymmetric tidal flows is challenging. Incorporating and quantifying wave-current interactions, when measuring and predicting the tidal resource is a key uncertainty factors for wave-exposed sites.

1.3 *Effect of Waves*

Wave-current interaction is regularly considered when investigating the wave climate, but studies of the tidal resource are often missing this key component. Previous research that has been conducted shows that the effect of waves is likely to be significant in calculating the tidal energy resource.

Lewis et. al. (2014) show that a decrease in tidal energy output of ~10% per meter of wave height is predicted. The study emphasizes the importance of including wave angle in the modelling. Hashemi et. al. (2015) have also looked at the tidal energy resource. The work looks at a tidal energy site off Anglesey, North Wales. It concludes that the wave stresses and increased bottom friction provide a reduction in tidal power of up to 20%.

Orbital velocities exist throughout the water column whenever waves are present. Simple linear wave theory provides the maximum horizontal component of the velocities to be:

$$u_0 = \frac{H}{T}\frac{\pi}{tanh\,kh}$$

Where H is the wave height, T is the wave period, $k = 2\pi/\lambda$ *is the wave number,* λ *is the wavelength and h is the water depth.*

Equation 1: Horizontal velocity component according to linear wave theory.

While detailed calculations can be applied from the wave spectra to obtain more accurate values for orbital velocities, this estimation shows that the wave induced velocities are proportional to wave height (Wiberg, 2008). The existence of these velocities has been shown to influence the tidal resource. (Hashemi et. al. 2015). Where these velocities propagate to the seabed, the wave motion will affect the forces and processes occurring in the flow (Gonzalez-Santamaria, 2011). Bottom friction and sediment transport rates are both increased in the presence of wave motions, both these parameters are important for the underlying calculations of the flow model.

Hydrodynamic flow models either do not account for wave effects or provide high level estimations of their effects. In order to fully capture wave influence on flow modelling output a separate spectral wave simulation is required.

This study presents an analysis of the differences in flow output when the influence of waves is introduced by comparing output generated from a standalone flow model with that of a fully (two-way) coupled flow-wave model. In Delft3D the following four process are impacted by the inclusion of wave data from a coupled wave model:

1. The bed friction is increased due to the enhancement of wave induced seabed shear stresses.
2. The wave action produces a mass flux in near-shore and shallow water areas.
3. Turbulence increases caused by wave breaking and white capping enhance vertical mixing.
4. Radiation stresses in the surf zone induce currents due to the momentum flux (e.g. rip currents).

For a detailed explanation of how wave-current is calculated in Delft3D the reader is directed to the Delft3D Technical Documentation (Deltares, 2020).

2 MODEL DESCRIPTION

2.1 *Overview of the model*

A hydrodynamic model of the English Channel has been built using the Delft3D-FM (flexible mesh) suite. Delft3D is a well-established and validated hydrodynamic modelling package developed by Deltares (2020). The code applies the hydrodynamic simulations to an unstructured grid. This enables to vary the grid resolution to vary throughout same mesh, areas of interest can benefit from high resolution output while areas of less interest can have lower resolution and improve the computational run time (Kernkamp et al., 2011; Martyr-Koller et al., 2017).

A model grid has been constructed with a combination of rectangular and triangular cells, as seen in Figure 1. The lower resolution offshore areas are composed of regular rectangular cells with a resolution of approximately 5 km. Coastal areas are covered by a triangular unstructured grid of varying resolution, at areas of interest the distance between cell centres ranges between 20-200 m. This resolution decreases until it links seamlessly with the rectangular sections.

A SWAN (called D-WAVE in the Deltares software parlance) wave model has been also set-up, covering the English Channel region. This model is meshed on a regular 2km grid.

The model was run from 1st September 2010 – 31st December 2010 (121 days). This period was chosen to capture multiple neap-spring cycles as well as a range of wave conditions.

2.2 *Inputs and boundary conditions*

The bathymetry for the model is provided by GEBCO via the Edina Digimap portal (EDINA, 2018) for UK waters and from the SHOM Geoportail (SHOM, 2016) for French waters. It is provided at 1 arcsecond resolution (approximately 20m) and has been interpolated onto the computational grids.

A water level boundary is provided at the four open boundaries on the model (South and West to the Atlantic, North in the Irish Sea and North into the North Sea). The water level variation is calculated by providing the harmonic constituents provided by the TPXO global harmonic model (Egbert et. al. 2002). The wave model is forced by wind and boundary wave parameters from the ECMWF ERA5 re-analysis dataset interpolated onto the grid cells and boundary points respectively. A JONSWAP spectrum was selected which is constructed by the software using the provided parameters.

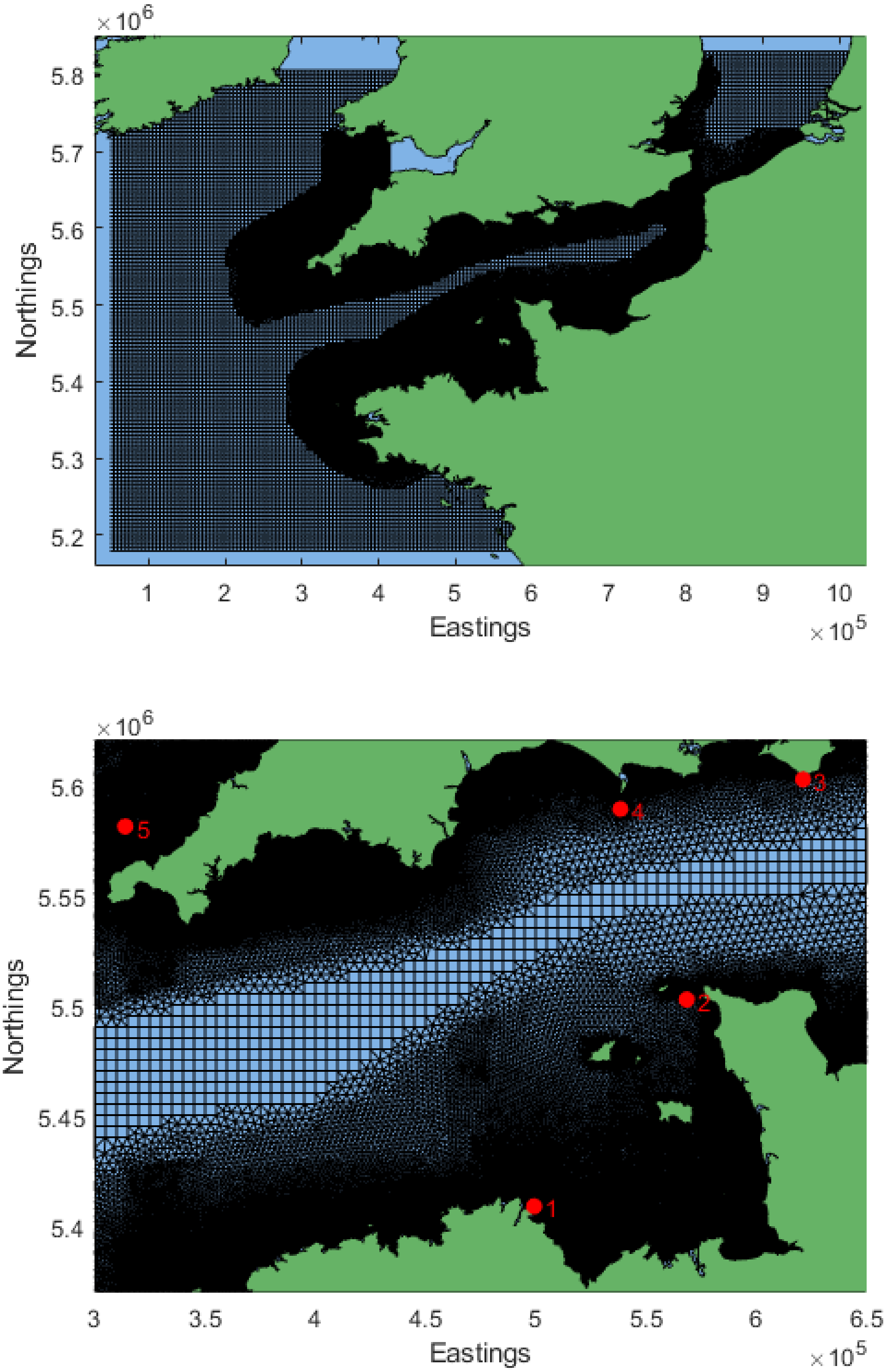


Figure 1 Complete model domain (top), Western part of English Channel (bottom) with sites of interest marked (see Table 1)

2.3 *Site characteristics*

The English Channel has multiple sites with the potential for tidal energy generation, where headlands, channels and islands create favourable conditions for fast flowing currents. Throughout the tidal cycle a considerable amount of water flows between the Atlantic Ocean and the North Sea. The complex topology and bathymetry around the English and French coastlines create a number of local flow variations and presents a challenging and interesting modelling problem.

The English Channel is also a highly energetic wave area. Atlantic swell combined with local wind waves subject the channel to significant wave energy exposure. The prevailing wave direction in most locations is from the West. However, there is significant variability and easterly winds regularly generate wave conditions in the opposite direction. All the potential tidal energy sites are subjected to waves under certain conditions which will have an impact on the energy generation output.

2.4 *Set-up of coupled vs. uncoupled models*

The models can be run as either fully (online) coupled or semi (offline) coupled. When run in fully coupled mode the two models exchange information regarding the sea state at each time-step, this enables the flow model to account for the present wave state and for the wave model to include the effects of currents. When the models are run in semi-coupled mode the flow model is run to completion without the inclusion of wave data. The wave model is then run with flow parameters taken as a time varying input. This is summarized in Figure 2. It is of course possible to reverse the order and run the wave model first to provide input to the flow model, but this has not been attempted in this study.

This paper examines the differences in the flow model output between model runs utilizing wave parameters in fully-coupled mode and model runs without wave parameters. When considering flow parameters, the semi-coupled mode is identical to running the flow simulation as a standalone model. All other inputs and the time-period for both sets of data are identical.

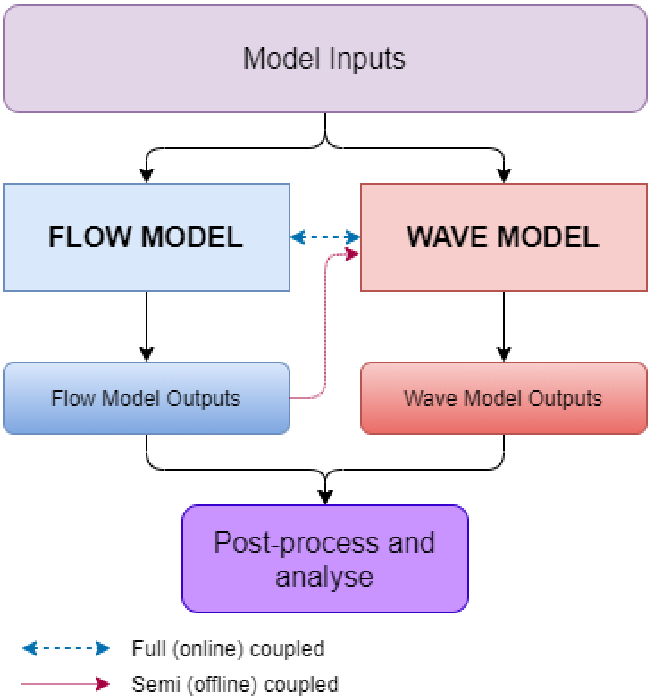


Figure 2 Flow of data in coupled models

3 OUTPUT AND ANALYSIS

3.1 *Select model output*

Two sites have been selected to evaluate the model sensitivity with regards to the wave coupling. Le Raz Blanchard in the channel between the French Normandy coast and the island of Alderney is a highly energetic site identified for tidal energy development. A lower flow site with greater wave activity has been chosen at Wave Hub off the North Coast of Cornwall, UK in order to provide a comparison. An example of the depth averaged flow speed from both the coupled and uncoupled models for the two sites is shown in Figure 3. The plots show a fourteen-day sample of the model output covering a full spring-neap cycle. A sample of the wave conditions at the sites covering the same period is shown in Figure 4.

*Table 1 Tidal energy sites in the English Channel. *Wave Hub is included as a low flow site for comparison.*

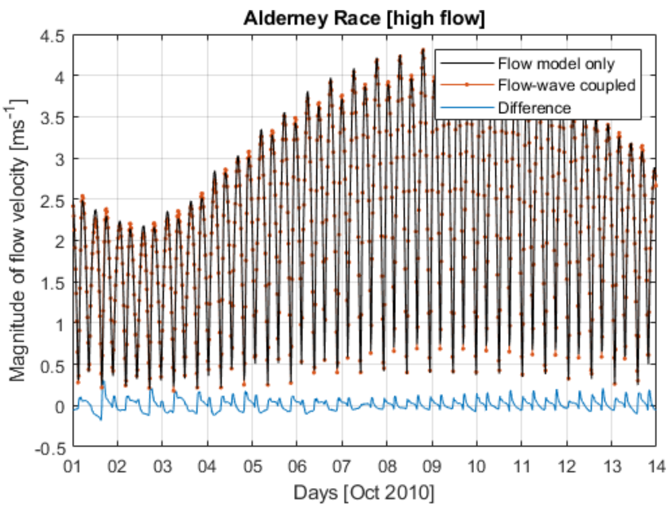
	Site Name	Position	Max Flow	Reference
1	Paimpol-Brehat	48.83°N, 3.01°W	3.0ms^{-1}	Pham & Martin (2009)
2	Le Raz Blanchard	49.67°N, 2.05°W	5.0ms^{-1}	Bahaj & Myers (2004)
3	PTEC, Isle of White	50.56°N, 1.29°W	2.9 ms^{-1}	Perpetus (2014)
4	Portland Bill	50.05°N, 2.46°W	3.2ms^{-1}	Blunden & Bahaj (2006)
5	Wave Hub*	50.19°N, 5.43°W	0.8ms^{-1}	Smith et. al. (2011)

The results show that the flow model output is affected by the influence of wave data with the absolute difference shown on the plots. Given by:

$$d = v_{co} - v_{un}$$

Where v_{co} and v_{un} are the magnitudes of the flow velocity from the coupled and uncoupled model runs respectively.

Equation 2: Difference in flow velocity output between coupled and uncoupled runs.



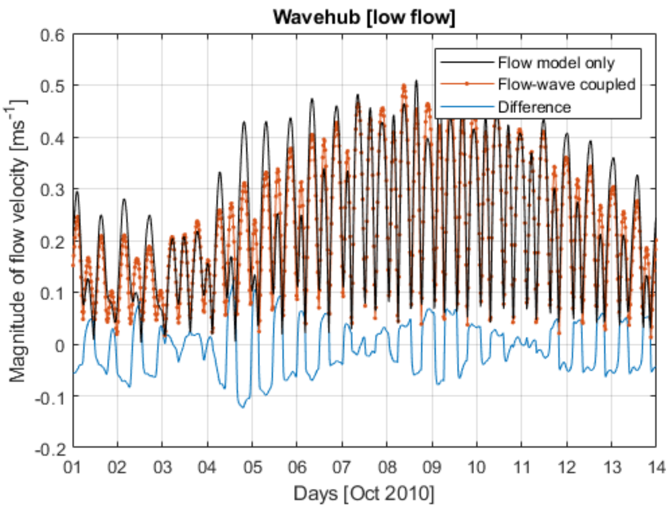


Figure 3 Depth averaged flow speed at Alderney (top), and Wave-hub (bottom).

3.2 *Analysis of coupled vs. uncoupled*

The wave and flow model output is analysed at difference phases of the tide and under different wave conditions to identify whether the model discrepancies are increased and/or dependent during characteristic conditions.

Table 2 shows the data separated by wave state. The objective is to identify whether the flow speed output was sensitive to specific wave conditions.

Table 2 Variation in the maximum and mean values of |d| grouped by wave conditions. A represents Aldernay Race and W representws Wave Hub.

Wave	Max $\|d\|$		Mean $\|d\|$		# points	
Dir	**A**	**W**	**A**	**W**	**A**	**W**
N	0.46	0.28	0.07	0.06	3165	4326
S	0.32	0.23	0.06	0.07	1197	564
E	0.24	0.14	0.05	0.05	915	603
W	0.55	0.22	0.07	0.05	3351	3120
Hs [m]	**A**	**W**	**A**	**W**	**A**	**W**
< 1	0.33	0.27	0.06	0.05	7032	1599
1-2	0.37	0.28	0.08	0.05	1500	6132
2-3	0.55	0.30	0.19	0.09	81	672
3-4	-	0.30	-	0.15	0	201
>4	-	0.20	-	0.14	0	9
Tm [s]	**A**	**W**	**A**	**W**	**A**	**W**
<3	0.30	0.28	0.06	0.07	3792	840
3-5	0.55	0.30	0.07	0.05	3309	7371
5-7	0.55	0.21	0.06	0.11	987	402
7-9	0.13	-	0.06	-	321	0
>9	0.08	-	0.05	-	204	0

The results suggest that average and maximum difference between coupled and uncoupled models is greater for occurrences with larger wave heights. The wave direction does not appear to have a significant impact on the flow speed output. The directions at which the maximum values of *d* occur are the prevailing wave directions and include the largest waves.

The data were also examined from the opposite perspective. By separating the series by flow conditions, it was possible to explore whether the model output was impacted by wave data at different parts of the tidal cycle. The data have been separated into flood and ebb cycles and by flow velocity, the results are shown in Table 3.

At both sites the maximum wave impact is shown during the flood tidal period, this suggests that flow direction is a factor in predicting the effects of waves on the flow. When these data are examined in greater detail (see Figure 5) there is a clear separation between the impacts at each tidal phase. In the model output the impact of wave interaction provides an increase in current speed during one phase of the tide and a decrease in current speed when the flow is in the opposing direction.

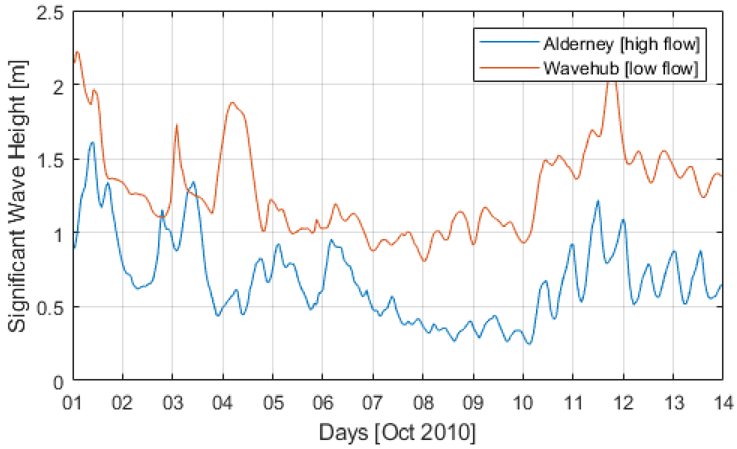


Figure 4 Sample of significant wave height at the two sites.

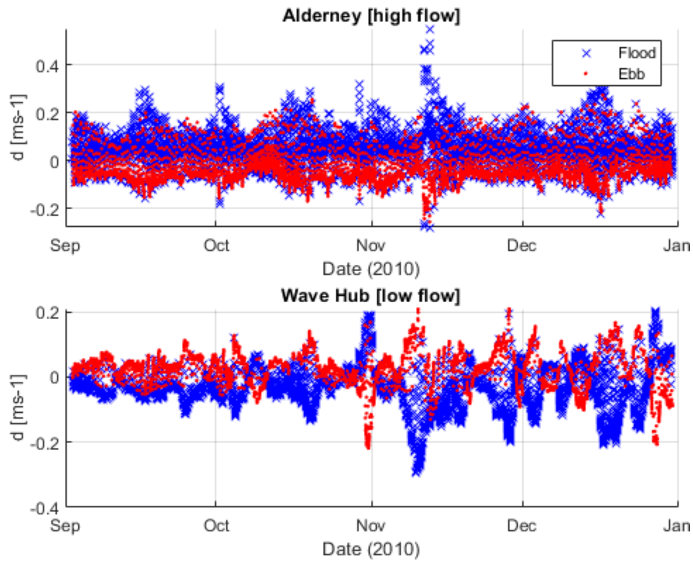


Figure 5 Difference in model output given the phase of the tide.

Table 3 Variation of maximum and mean values of |d| grouped by tidal flow conditions. A represents Alderney Race;W represents Wave Hub.

Flow	Max $\|d\|$		Mean $\|d\|$		# points	
	A	W	A	W	A	W
Flood	0.55	0.30	0.07	0.06	4717	5381
Ebb	0.27	0.22	0.07	0.05	3896	3232
v [ms^{-1}]	A	W	A	W	A	W
< 20%	0.56	0.21	0.08	0.05	1377	2610
20-40%	0.55	0.21	0.08	0.06	1957	2955
40-60%	0.49	0.30	0.07	0.06	2508	2044
60-80%	0.21	0.31	0.05	0.08	2153	877
>80%	0.14	0.29	0.05	0.16	618	127

4 DISCUSSION AND CONCLUSION

This study has shown that flow-speeds from a stand-alone Delft3D model can differ significantly compared with a coupled flow-wave model.

Tidal energy projects relying on modelled data to estimate their generation predictions and LCOE could result in significant uncertainties if wave effects are not properly included. The results also indicate that if there are significant wave effects on currents at a site, then using a fully-coupled flow-wave model could improve the accuracy of long-term energy yield predictions compared with extrapolations from harmonic predictions which neglect meteorological effects.

The presented results focus on the output of numerical modelling and will require detailed validation against field ocean data at relevant sites. This is subject of ongoing future work

While this study has not shown a significant impact from the wave direction this has been shown to be a key parameter when modelling wave-current interaction. The limited scope of this work means that the relationship is an indication of the interactions, and a more detailed coupled flow study will be considered.

The next steps will include a validation and sensitivity exercise on the model output to ascertain the accuracy of the modelled parameters in relation to measured data. The sensitivity of key parameters will be investigated with the aim of improving the reliability of the model and quantifying the sources of uncertainty.

In conclusion, a fully-coupled flow-wave model is capable to improve the energy yield predictions for potential commercial tidal energy sites in the English Channel and beyond, for tidal sites with complex wave exposure.

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