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A numerical study of wave and current fields around Ramsey Island - tidal energy resource assessment

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***Abstract*—In the Irish Sea, the best marine renewable energy sites are subjected to strong currents and exposed to relatively large waves (e.g. around Ramsey island and in the Bristol Channel). The objective of this research is to present the potential of the TELEMAC modelling system in various aspects of marine renewable energy studies such as multi-scale modelling, and wave-tide interaction. Firstly, an idealised triangular domain was modelled to study the impact of tides on quantifying the wave power resource. The overall dimensions of this case study resemble those of the Bristol Channel. The results of the idealised case study demonstrate that ignoring the tides when estimating wave power generates considerable errors, since wave power is related to significant wave height squared. Next, a multi-scale unstructured mesh model of the Irish Sea was developed using TELEMAC. Spatial and temporal variations of the currents around Ramsey Sound were captured using a relatively fine mesh (~40m). Despite the strong current field and complex bathymetry of this region, the multi-scale tidal model led to convincing results. Some recommendations for research and priorities for data collection have been identified.**

I. Introduction

A key step towards the successful deployment of marine energy devices is site selection. Assessment of the physical, environmental and socioeconomic constraints at a specific site is highly dependent on a proper understanding of the current (e.g. resource assessment for tidal energy devices) and wave (e.g. cost due to wave loads on tidal energy devices, or wave power estimation) fields. Due to consistently high current speeds, Ramsey Sound in the southern Irish Sea has attracted both academic and business interest as a suitable site for tidal energy extraction. Hence, companies are planning to install tidal energy devices here as pilot studies. Further, the Bristol Channel is one of the most energetic sites in the Irish Sea for tidal and wave energy devices. Numerical simulations of the hydrodynamics of these areas is a challenging task, as a result of the highly irregular bathymetry, strong tides and relatively energetic wave climate. Additionally, in most studies relating to marine renewable energy, waves and currents have been treated separately.

In the most recent version of TELEMAC (i.e. 6.1), it has been possible to develop current and wave models of a region based on the same mesh and boundary conditions, including one-way or two-way coupling of those models.

In the present research, the TELEMAC modelling system has been used to study tides, waves, and their interactions, in terms of estimating renewable energy resources. An idealised triangular case along with a multi-scale Irish Sea model has been developed and discussed to address this aim.

II. Study Area

The UK is located in a highly energetic environment in terms of marine renewable energy resources. In some areas like the Bristol Channel and around Ramsey Island, many studies have assessed the wave and tidal energy resources. The Bristol Channel is exposed to long fetch lengths from the Atlantic Ocean, potentially exceeding 1000 km. Hence, it is considered as one of the potential places for wave energy extraction in the UK. Further, with a mean spring tidal range of 12.2 m, and a mean neap range of 6.0 m at Avonmouth, the Bristol Channel has one of the highest tidal energy resources in the world. Depths in the approaches to the Bristol Channel are around 50 m. Ramsey Island is about 1 km off the coast of the St David's peninsula in Pembrokeshire in southwest Wales. Tidal currents are very strong particularly in the channel located at the east side of the island (i.e., Ramsey Sound).

III. TELEMAC-2D - TOMAWAC Modelling Approach

TELEMAC-2D and TOMAWAC were used to model tides, waves and their interaction [1]. TELEMAC-2D is a well-known and popular model which solves the 2-D shallow water equations using FEM. One of the attractive features of this model is its unstructured discretization. This makes it suitable for multi-scale problems without resort to nesting. As an example, to model the flow and waves around Ramsey Island a multi-scale Irish Sea model was developed in the present work. A mesh size of 7000 m was used around the southern boundary (Celtic Sea), while a much finer 40 m mesh was used to resolve the bathymetry and capture the flow field inside Ramsey Sound.

A. TOMAWAC

TOMAWAC is a third generation wave model which solves the evolution of the directional spectrum of wave action in Cartesian or spherical coordinates. It includes deep and shallow water physics such as refraction, white capping, bottom friction and wave breaking, as well as nonlinear wave-wave quadruplet and triad interactions. TOMAWAC can be applied to oceanic scales, to continental shelf seas, and to the coastal zone [1].

B. Wave-current interaction in TOMAWAC

Tides modulate the water depth and generate currents, both of which then affect the wave field. An extensive effort in the previous literature has been made to assess the interaction of waves and tides, and that is beyond the scope of the present research (e.g. [2,3]). Here, the mechanism of wave-current interaction in TELEMAC is briefly mentioned.

The dispersion equation can be expressed as,

$$\sigma^2 = gk \tanh kh \tag{1}$$

where σ is the relative wave angular frequency, which can be observed in a coordinate system moving with the same velocity as currents, k is the wave number, and h is the water depth. The relative wave frequency is dependent on the ambient current velocity and absolute wave frequency as follows,

$$\sigma = \omega - \vec{k}.\vec{U} \tag{2}$$

in which ω is the absolute wave angular frequency, which can be observed in a stationary coordinate system, and $\vec{U}$ is the vertically-integrated current velocity.

Referring to the dispersion equation, the refraction of waves in intermediate and shallow water is related to the water depth, and hence the wave field in the presence of a tide is modulated, even in the case of stationary steady wind. Further, the tidal currents modify the refractive wave propagation direction as well as the wave period through the Doppler Effect (Eq. (2)).

When waves encounter an opposing current, part of the wave energy is dissipated, because the group velocity of the highest frequencies might be lower than the opposite current velocity. Therefore, the wave height may also change depending on the current direction in relation to the wave field.

In TOMAWAC, it is possible to include variation of water level due to tide and/or currents (e.g. by reading the TELEMAC-2D results file). This is considered as one-way coupling.

From another perspective, waves possess momentum and generate radiation stresses. The radiation stresses can be expressed in terms of the wave energy as follows [4],

$$\begin{cases} S_{xx} = \sum \frac{E}{2} \left[2n\,(\cos\theta)^2 + (2n-1)\right]\Delta\sigma\Delta\theta \\ S_{xy} = S_{yx} = \sum En \sin\theta \cos\theta \Delta\sigma\Delta\theta \\ S_{yy} = \sum \frac{E}{2} \left[2n\,(\sin\theta)^2 + (2n-1)\right]\Delta\sigma\Delta\theta \end{cases} \tag{3}$$

where E is the wave energy, S is the radiation stress, θ is the angle of the wave propagation and,

$$n = \frac{c_g}{c} = \frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right) \tag{4}$$

Obviously, n is 1 in shallow water and ½ in deep water, which can lead to more simplified forms of Eq. (1). The wave induced forces are generated by the gradient of the radiation stresses,

$$\begin{cases} F_x = -\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) \\ F_y = -\left(\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{yx}}{\partial x}\right) \end{cases} \tag{5}$$

If these forces are significant, the current field, which is computed based on the momentum equation, is affected by wave radiation forces. Wave induced currents can be simulated in TELEMAC-2D. In a recent version of TELEMAC, it is possible to implement a two-way interaction of the wave and tidal models [3].

IV. Results and Discussion

To avoid complexities, particularly those related to bathymetry, a simplified idealised case was studied initially and is presented in subsection A. In this idealised case, different wave and current scenarios were modelled, and the results analysed in terms of estimating the wave power resource. The model of the Irish Sea, including Ramsey Sound and the Bristol Channel, is presented in subsection B.

A. Idealised triangular case

Fig. 1 shows a triangular channel, representing either an estuary, or a channel with a closed end. The dimensions and the bathymetry of this idealised case are parameterised on the Bristol Channel, with a length of 200 km and a width of 100km along the open boundary. The maximum water depth is 50 m at the centre of the open boundary, and the depth of channel gradually approaches zero toward the closed boundaries by a quadratic function.

The open boundary was forced with a harmonic semi-diurnal tide of amplitude 2 m and period of 12 h (for comparison, the M2 amplitude at the mouth of the Bristol Channel is about 2 m).

The waves were generated by a uniform steady westerly wind of 20 m/s. Further, it was assumed that the waves at the open boundary have a fetch length of 300 km. This can be approximately implemented in TOMAWAC by assuming a peak frequency of 0.091 and Phillips constant of 0.0107, using empirical JONSWAP formulae [5]. Alternatively, the open boundary can be forced with a specified significant wave height. A simplified wave estimation for the fetch limited seas can be written as [5],

$$H_{mo} = \frac{4.13\times10^{-2} C_D U_{10}^2}{g}\left(\frac{gX}{C_D U_{10}^2}\right)^{\frac{1}{2}} \qquad (6)$$

$$C_D = 0.001(1.1 + 0.035 U_{10}$$

where H_{mo} is the significant wave height, X is fetch length, and U_{10} is the wind velocity 10 m above MSL, all variables expressed in SI units. The estimated wave height at the boundary for the given wind speed is about 6.2 m based on this formulation.

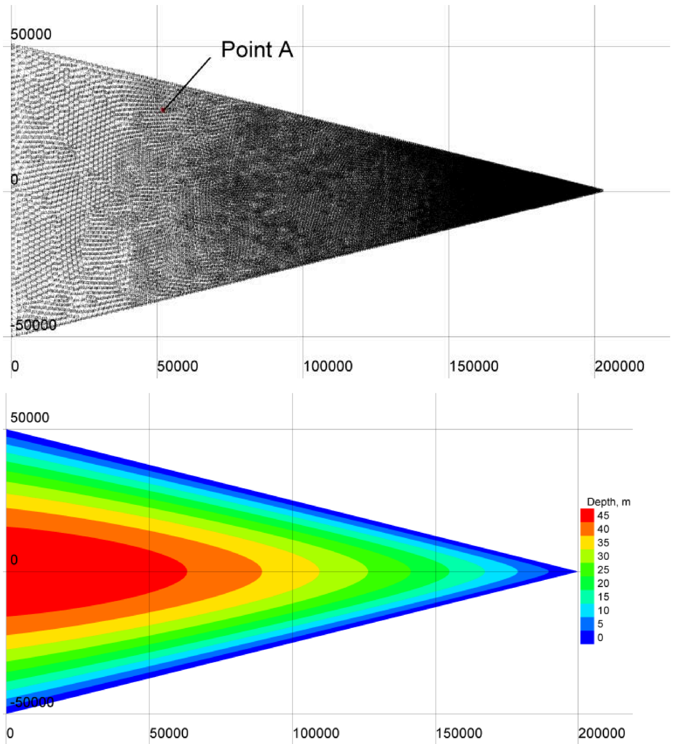

Figure 1. Geometry, mesh, and the bathymetry of the triangular idealised case. The only open boundary is on the west boundary.

Several scenarios for wave modelling were examined as follows:

- Ignoring tidal effects
- Considering only tidal water depth variations
- Inclusion of tidal water depth variations and currents
- Fully interactive wave-tidal model

Fig. 2 shows the wave field simulated by the wave model with no tidal effects. The wave height is about 6.3 m near the open boundary, and gradually approaches zero towards the closed boundary. The inclusion of tides leads to a modulation of the wave field according to the stage as the tide. Fig. 3 and Fig. 4 show the wave field at different times during the tidal cycle. Generally the wave heights are higher during flood but the times mentioned in these figures do not exactly correspond to the ebb and flood tide. As can be seen, the wave field is significantly affected by the tide.

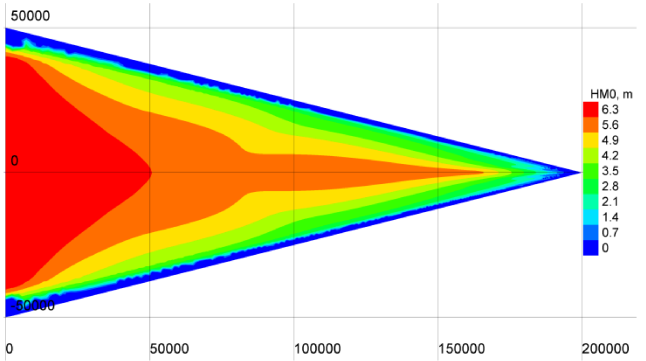

Figure 2. Modelled significant wave height for 20 m/s westerly wind when tidal effects are not included. H_{mo}=6.33 at x=50,000, y=0.

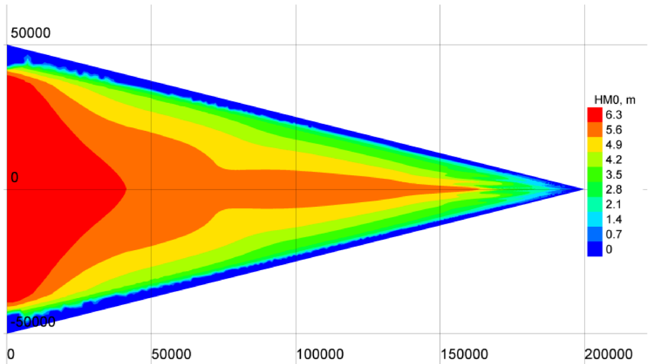

Figure 3. Modelled significant wave height for 20 m/s westerly wind when tidal effects are included. H_{mo}=6.08 at x=50,000, y=0 and, t=13h40.

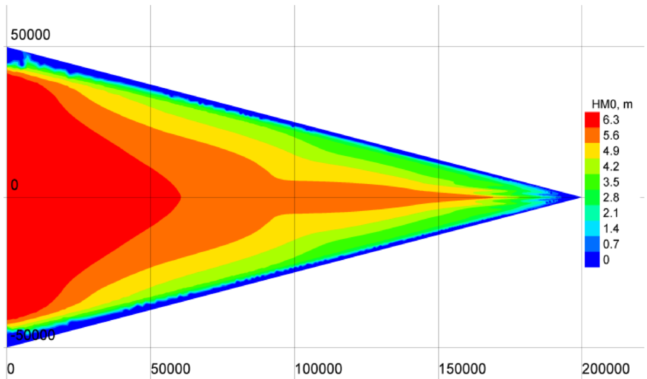

Figure 4. Modelled significant wave height for 20 m/s westerly wind when tidal effects are included. H_{mo}=6.54 at x=50,000, y=0 and, t=7h20.

Referring to Fig. 1, the hydrodynamic variables at a typical point A (x=52191 m, y=27993 m and d =19.9 m) were extracted for more detailed analysis. Point A is relatively near the coast and will be affected by the refraction and shallow water wave physics. Fig. 5 shows the variation of the water depth along with computed significant height for various modelling scenarios. The estimated H_{mo} based on a pure wave model is 4.77 m. If the tidal variations in water depth are included, H_{mo} fluctuates in the range 4.56 - 4.95 m. For the case of fully interactive wave tide model, H_{mo} can reach 5.08 m. Therefore, ignoring the tide could lead to a maximum 12% error in estimating the wave height. Further analysis showed that as the amplitude of the tide increases, this error grows. Hence, tidal effects are more important towards the end of the channel which has a higher tidal range.

Similar results were observed for the other wave parameters such as the mean wave direction and mean wave period. As Fig. 6 demonstrates, water depth fluctuation and tidal currents both have a distinct effect on modulating wave direction and period.

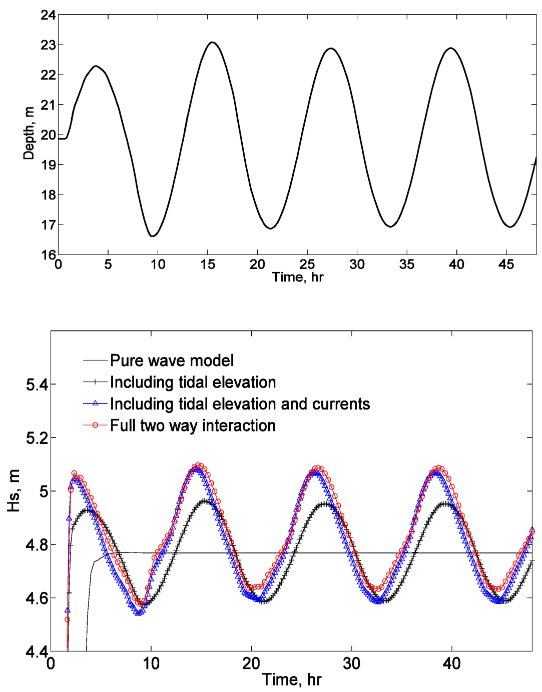

Figure 5. The variation of water depth and significant wave height at Point A (Fig. 1), assuming various wave modelling scenarios.

Both significant wave height and wave period contribute to the estimation of the wave power.

1) Effect of tide on wave power estimation: It is possible to extract wave power from the results of TOMAWAC directly (*POW* output variable).

There are several formulations for the estimation of the wave power. For instance [6],

$$P = \frac{1}{64}\frac{\rho g^2}{\pi}\left(H_{mo}{}^2 T^2\right) \quad (7)$$

where, T is the wave period. According to the above equation, any error in estimating wave height and wave period could be magnified when estimating wave power. Fig. 7 shows the time series of the estimated wave power at Point A (Fig. 1).

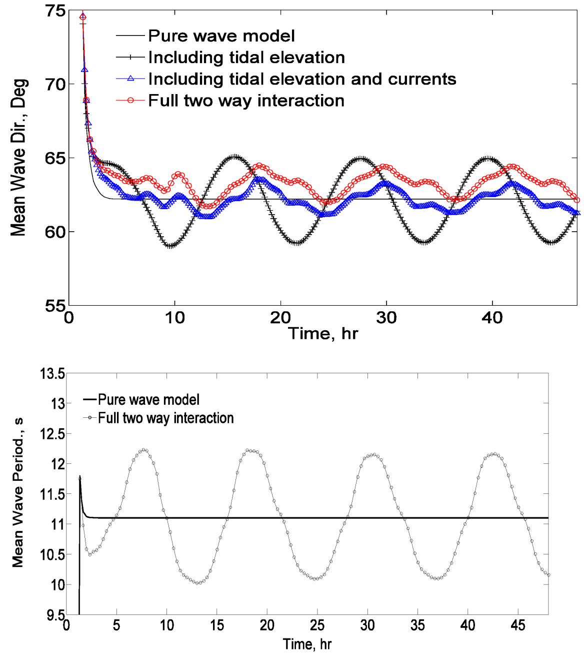

Figure 6. Time series of wave parameters at Point A (Fig. 1), assuming various scenarios for wave modelling.

As this figure shows, not only the estimated wave power varies with the tide, but there is an error associated with net power estimated over a tidal period. In Table I, the estimated errors at this typical point have been summarised. The results show that the estimated error in the predicted power (6%) is about twice that in the significant wave height (3%). Further, the error increases as tidal amplitude increases. For instance, if the west boundary is forced by a tidal amplitude of 3 m, the error in estimating the mean wave power increases from 6.0% to 9.2%.

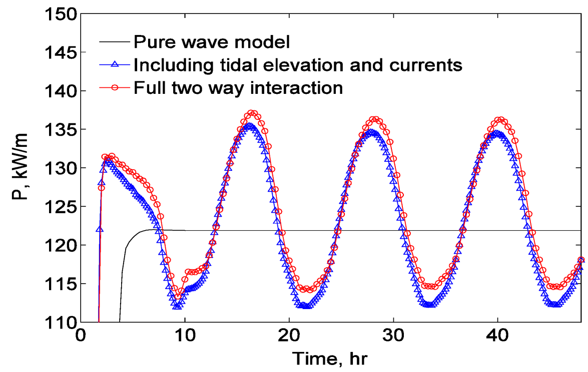

Figure 7. The fluctuation of the wave power as a result of the tide at point A (Fig. 1).

TABLE I. ESTIMATED ERROR IN THE WAVE POWER ESTIMATION DUE TO THE TIDE AT POINT A FOR FULLY COUPLED MODELS (FIG. 1)

	Percentage error			
	a*=2		**a=3**	
	H_{mo}	*Wave Power*	H_{mo}	*Wave Power*
Average	3.0	6.0	4.7	9.2
Max.	6.7	11.9	9.8	16.2

* The tidal amplitude at the left open boundary

2) Other considerations: Apart from estimating wave power, other parameters which have a primary role in the design of marine renewable energy schemes can be affected by wave-tidal interactions. Accordingly, the extreme wave loads have traditionally been used for the structural design of nearshore or offshore structures. Hence, underestimating wave height due to ignoring wave-tidal effects can increase the risk of damage to a tidal energy device.

As a final discussion point for this idealised case, the effect of waves on tidal currents is briefly demonstrated. The predicted current fields with and without inclusion of the wave forces have been subtracted and plotted in Fig. 8 to represent a typical time snapshot. Also, the corresponding wave forces are presented in Fig. 9. As expected, the wave-generated currents are more noticeable in the nearshore zone. This can lead to 0.40 m/s error, which is about 20% in

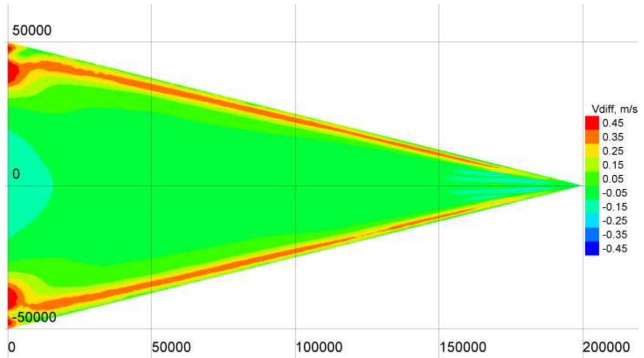

Figure 8. The difference of current speed with and without the inclusion of wave forces at t=14h00.

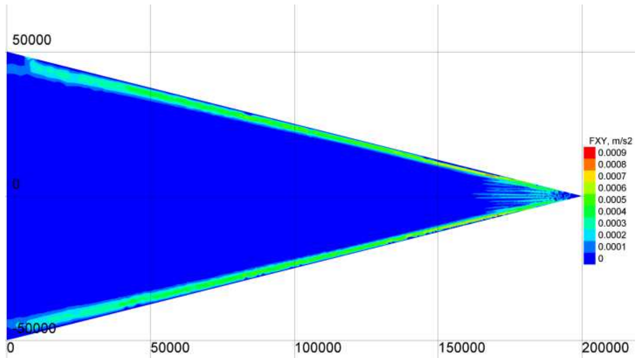

Figure 9. Wave forces at t=14h00.

the prediction of tidal currents. There is a clear association between this difference and wave generated forces.

B. *Irish Sea/Ramsey Sound Model*

The FEM mesh of the Irish Sea model is presented in Fig. 10. The mesh size is about 7 km near the southern boundary in the Celtic Sea, and gradually approaches 40 m around Ramsey Sound (Figs. 11 and 12).

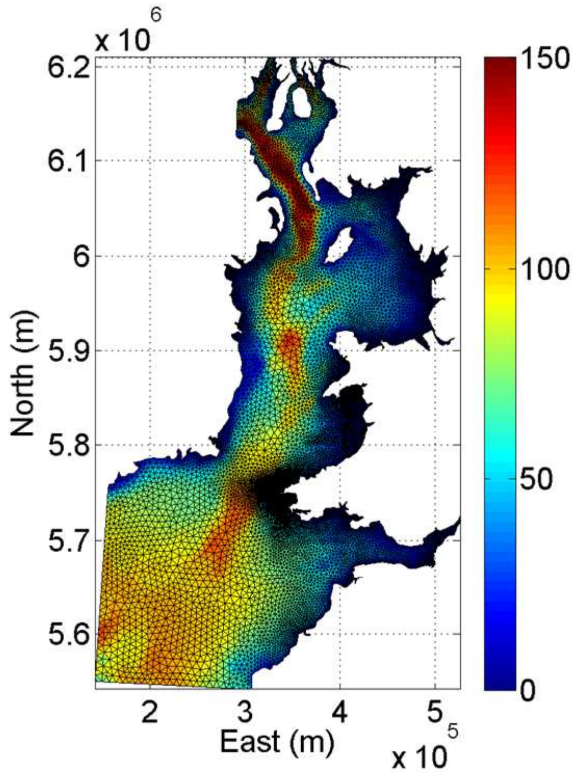

Figure 10. Bathymetry and FEM mesh of the Irish sea TELEMAC model.

The model was forced by tidal water elevations at the open boundaries. The tidal constituents at the open boundaries were interpolated from an analysis of POLCOMS shelf scale model output. Model results at different tidal gauge locations in the Bristol Channel and Liverpool bay compared well with observed data (not presented here). ADCP data collected during the spring tide of May-2011 (14-20 May 2011) were used to evaluate the simulated currents around Ramsey Island. As an example, Fig. 12 and Fig. 13 demonstrate the flow pattern on 15-May-2011 at 11:30, along with measured ADCP data. As can be seen, the spatial variations of the currents in this region are extensive, and the model and observations have a convincing agreement. The current speed approaches 3.5 m/s inside Ramsey sound during this period.

A TOMAWAC wave model of the same area was developed. Since the majority of waves in the Irish Sea are generated by winds emanating from the southwest [7], the distribution of the significant wave height for a typical southwesterly wind speed of 20 m/s is plotted in Fig. 14.

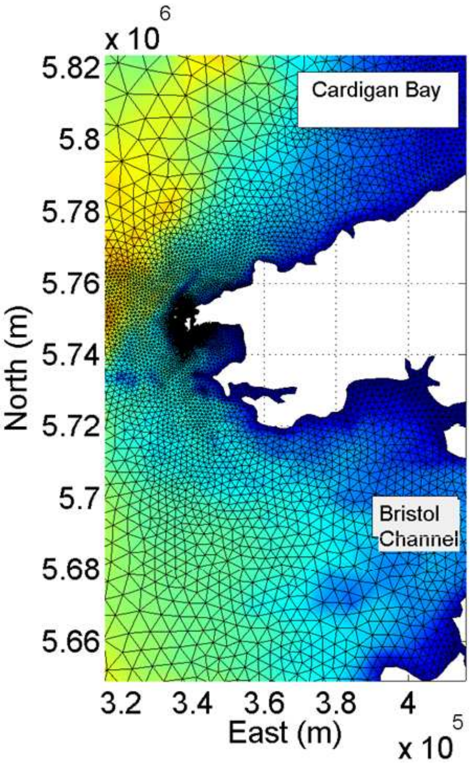

Figure 11. A closer view of the variable mesh density with very fine mesh around Ramsey Island.

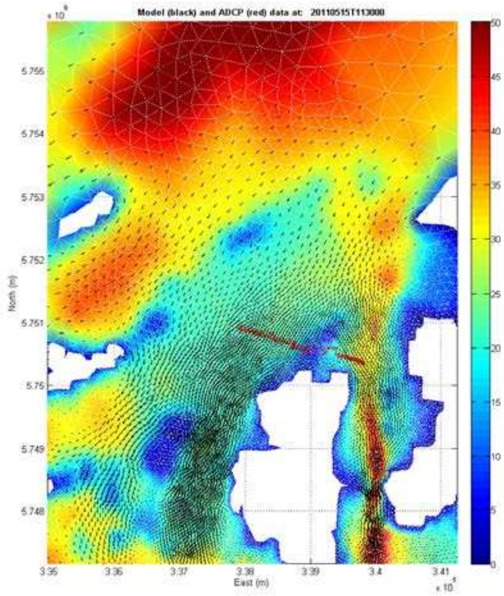

Figure 12. A typical flow pattern in the vicinity of Ramsey Island at 15-May-2011 11:30 PM compared with ADCP data (measured data were collected by Cardiff University).

It is clear that Ramsey Sound is sheltered from this typical southwesterly wind event. However, the wave heights to the west of Ramsey Island reach up to 7 m for this event. This suggests that running a coupled wave current model is more essential to the west of the island, while the wave energy inside Ramsey sound is not that significant. Further, the model results could be improved, particularly by improving the bathymetry near the coastline and intertidal zone.

To the best of our knowledge, no wave buoy data are available around Ramsey Island. However, wave data exist for Scarweather WaveNet Site, which is located at the middle of the Bristol Channel. The effect of the inclusion of tides on estimated wave heights during an event in October-2005 is depicted in Fig. 15. Fluctuations of the wave height due to the tide are present in both the measurement and the coupled wave current model. However, a pure wave model cannot capture these fluctuations. Further work is underway to improve the wave-current model and assessment of wave energy resources using this coupled model.

V. Conclusions and Recommendations

Our study of wave-tidal interactions in an idealised triangular domain suggest that assessment of the wave energy resource, without considering the effect of tides, could lead to errors of up to 10% in high tidal range areas like the Bristol Channel. Further research is underway to investigate this for the actual bathymetry of the Irish Sea. The errors associated with estimating wave power are almost twice those errors in simulating the significant wave height. Additionally, for the safe design of offshore or nearshore tidal energy devices, the effect of tides on modulating the wave heights should be considered.

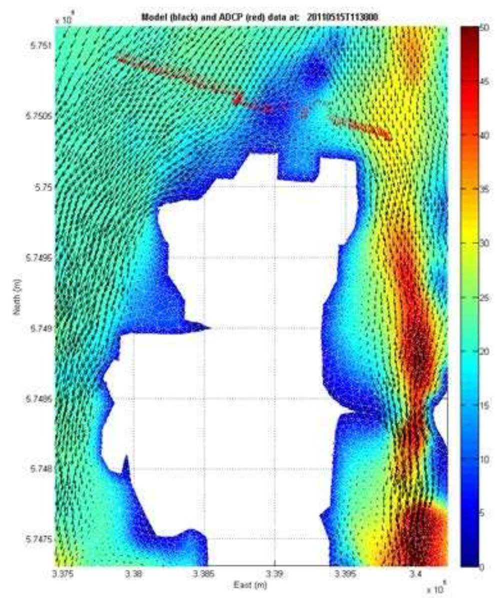

Figure 13. A closer view of flow around Ramsey Island (see also Fig. 12).

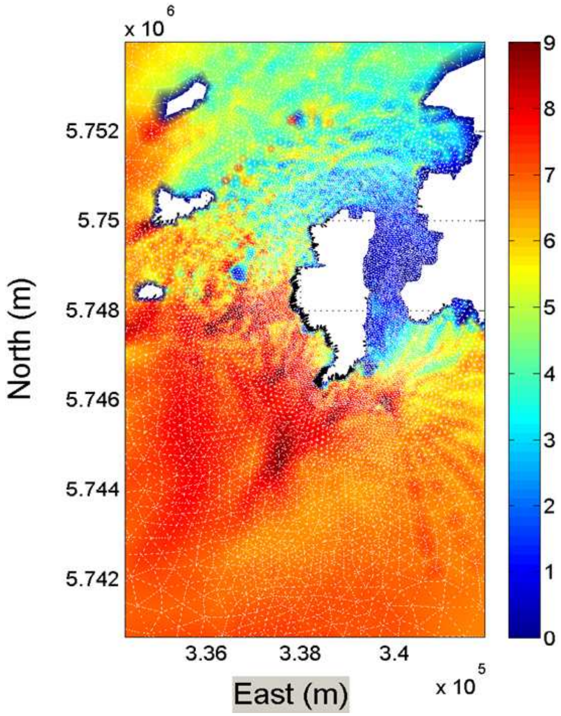

Figure 14. The distribution of the significant wave height around Ramsey Island for a typical southwesterly wind of 20 m/s simulated by TOMAWAC.

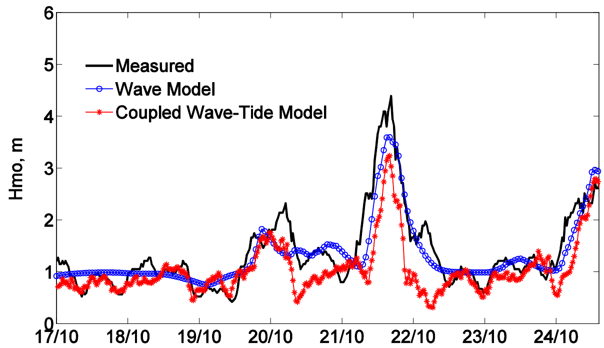

Figure 15. Effect of including the tide on wave prediction at a Scarweather WaveNet Site, Bristol Channel (51°26'.00N and 003°55'.99W), 17-24 October 2005.

The primary hydrodynamic model of Ramsey Sound demonstrated the suitability of TELEMAC for multi-scale modelling of waves and currents in highly energetic environments with complex bathymetry. The resolution of the bathymetry, especially near coasts and in the intertidal zone, is the key factor for improving the model results.

Ramsey Sound is sheltered from southwesterly wind waves, while the interaction of waves and tides to the west and southwest of Ramsey Island is important, and can be simulated by models like TELEMAC.

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