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The influence of waves on morphodynamic impacts of energy extraction at a tidal stream turbine site in the Pentland Firth

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ABSTRACT

Extraction of energy from tidal streams has the potential to impact on the morphodynamics of areas such as sub-tidal sandbanks via alteration of hydrodynamics. Marine sediment transport is forced by both wave and tidal currents. Past work on tidal stream turbine impacts has largely ignored the contribution of waves. Here, a fully coupled hydrodynamic, spectral wave and sediment transport model is used to assess the importance of including waves in simulations of turbine impact on seabed morphodynamics. Assessment of this is important due to the additional expense of including waves in simulations. Focus is given to a sandbank in the Inner Sound of the Pentland Firth. It is found that inclusion of wave action alters hydrodynamics, although extent of alteration is dependant of wave direction. Magnitude of sediment transport is increased when waves are included in the simulations and this has implications for morphological and volumetric changes. Volumetric changes are substantially increased when wave action is included: the impact of including waves is greater than the impact of including tidal stream turbines. Therefore it is recommended that at tidal turbine array sites exposed to large swell or wind-seas, waves should be considered for inclusion in simulations of physical impact.

1. Introduction

Tidal stream turbines (TSTs) are maturing as a means of renewable energy generation: several demonstration devices have been deployed and the world's first array will be installed in the Inner Sound of the Pentland Firth with the aim of 386 MW of installed capacity by 2020 [1]; [2]. Presence of support structures and extraction of energy will impact a range of receptors, both physical [3–7] and biological [8–11]. This contribution simulates impact to the morphodynamics of sub-tidal sandbanks using a fully coupled wave – hydrodynamic - sediment transport model. This enables inclusion of wave driven sediment transport and wave-current interaction (WCI) in the computation. Attention is given to a sandbank in the Inner Sound of the Pentland Firth (Fig. 1), close to the Meygen Inner Sound array site [2].

Sub-tidal sandbanks must be considered in environmental impact assessments because they can be important ecological habitats, navigational hazards and sources of aggregates. A substantial amount of work has been conducted on the physical processes governing the morphology of sub-tidal sandbanks [12–16]. Sandbanks are often formed and maintained by residual current gyres which are caused by tidal asymmetry around headlands. Sub-tidal sandbanks can be found in the centre of these circulation patterns. The importance of the contribution of waves to sandbank morphodynamics and long term evolution is open to debate [17]. Dependant on environmental setting, the background stirring influence of low energy waves may be important [18] or episodic storm events may be more relevant [19,20]. Under storm conditions, tidal residuals may be reversed [21,22] both due to WCI and the dominance of wave driven currents.

The process of WCI is complex and highly studied phenomenon with both waves affecting currents and currents affecting waves (e.g. Refs. [23,24]). When waves propagate in a current field, various phenomena can occur, including: altered wind wave growth; current induced refraction; changes to wave steepness which alters rates of dissipation [25]; and wave blocking. Wave blocking is the prevention of wave energy transport caused when current velocity is equal and opposite to the wave group velocity [26,27]. The presence of waves can alter currents via two main

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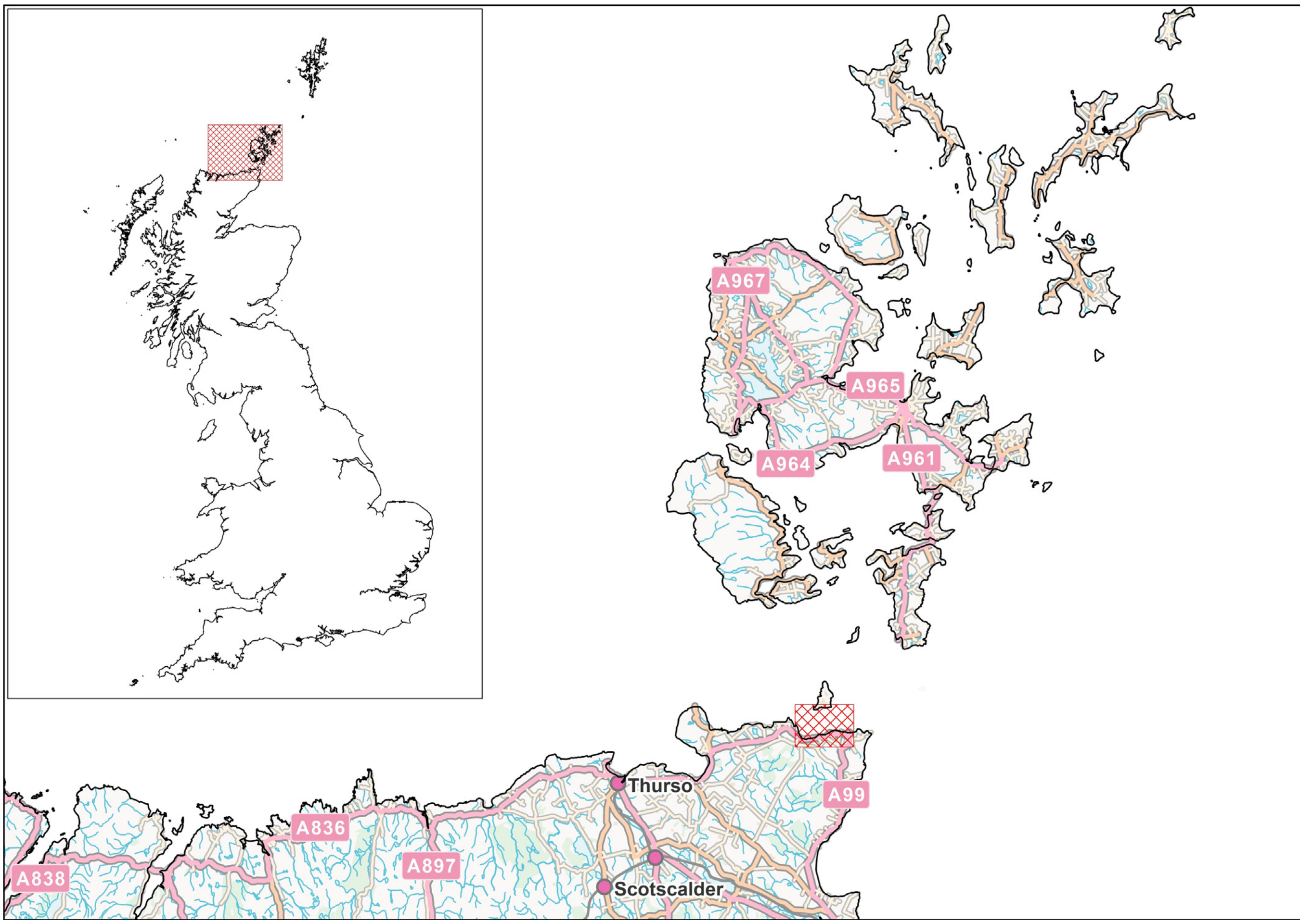

Fig. 1. (Inset) a map of the UK with the Pentland Firth and Orkney Waters marked with red hatching; (main) a map of the Orkney Islands and northern Scotland. The Pentland Firth is the channel between mainland Scotland and the Orkney Islands. The inner sound is marked by the red hatched area.

processes: firstly, additional currents can be induced via gradients in wave radiation stress and secondly the presence of waves increases turbulence at the bed, effectively increasing the friction felt by the current field. Inclusion of WCI in tidal resource estimation studies can lead to alteration in the predicted available resource [28,29]. Previous work looking at tidal range schemes has shown that changes to currents forced by energy extraction can alter tidal modulation of wave heights [30].

The impact of TSTs on sandbank morphodynamics been considered by various authors [16,31–39]. This work has shown that energy extraction at various locations can disrupt residual current gyres. Research has focussed on sediment transport by tidal currents alone with little consideration given to the relevance of including wave effects in the simulation. Purely simulating tide-driven processes may ignore key physical processes, Robins et al. [37], assessed the contribution of waves to bed sheer stress and concluded that wave-driven processes may be important. Fairley and Karunarathna [40] demonstrate, for the same sandbank as tested here, that wave action can magnify the impact of TSTs on bed level changes by considering short term simulations of characteristic storm processes. A 24 h period is simulated for storms from opposing directions (east and west) and tide only conditions, with and without turbines. The same model set up as presented here is used. Residual current magnitudes are altered by up to 10% when waves are included. Patterns of impact to bed level change are similar with and without wave action and are dictated by the presence of sand waves. The short time period and constant wave action used in that study means that more detailed simulations are required to better assess the importance of wave action for TST environmental impact studies.

Here, the analysis of Fairley and Karunarathna [40] is extended to consider morphodynamics over a spring-neap cycle with summer and winter wave conditions. Both baseline and extraction scenarios are considered. The aim of this paper is to both provide realistic simulations of morphological changes in the region and to assess if inclusion of wave processes makes a material difference to prediction of impacts.

2. Capabilities of MIKE3 regarding wave-current interaction

The MIKE3 2012 release was used in this analysis. Two key factors are involved with the alteration of currents by waves. Firstly wave radiation stress can induce a current. The hydrodynamic module takes radiation stresses (S_{xx}, S_{yy}, S_{xy}) from the wave module every time step. A uniform variation in radiation stress with depth is used for the vertical variation. Secondly, waves can increase the apparent bed roughness felt by a current. This is caused by increased turbulence intensity and shear stresses in the boundary layer forced by oscillatory wave motion (e.g. Ref. [41]).

The impact of tidal conditions on waves can be split between the variation in water depth and the presence of currents. Variation in