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Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes

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ABSTRACT

Tidal Energy Converter (TEC) arrays are expected to reduce tidal current speeds locally, thus impacting sediment processes, even when positioned above bedrock, as well as having potential impacts to nearby offshore sand banks. Furthermore, the tidal dissipation at potential TEC sites can produce high suspended sediment concentrations (turbidity maxima) which are important for biological productivity. Yet few impact assessments of potential TEC sites have looked closely at sediment dynamics beyond local scouring issues. It is therefore important to understand to what extent exploitation of the tidal energy resource will affect sedimentary processes, and the scale of this impact is here assessed in relation to natural variability. At one such site in the Irish Sea that is highly attractive for the deployment of TEC arrays, we collect measurements of sediment type and bathymetry, apply a high resolution unstructured morphodynamic model, and a spectral wave model in order to quantify natural variability due to tidal and wave conditions. We then simulate the impacts of tidal-stream energy extraction using the morphodynamic model. Our results suggest that the sedimentary impacts of 'first generation' TEC arrays (i.e. less than 50 MW), at this site, are within the bounds of natural variability and are, therefore, not considered detrimental to the local environment. Yet we highlight potential environmental issues and demonstrate how impact assessments at other sites could be investigated.

1. Introduction

With growing interest in the exploitation of the tidal energy resource, the environmental impact of available technologies still requires detailed investigation [1–4]. Tidal-stream turbines, also referred to as Tidal Energy Converters (TECs), will reduce current speeds in the vicinity of the turbines and, therefore, impact sediment transport and morphodynamics, even in the absence of a local source of sediment supply [2]. Small changes in velocity (U) could potentially generate large changes in bed shear stress, which behaves as ~U^2. Further, sediment transport is a function of an even higher power of U, e.g. $U^{3.4}$ for total (bed load + suspended load) transport [5]. This will not only affect sediment transport in the near field, but also in the far field [2]. One way to ascertain whether these impacts, and their environmental consequences, are within the 'acceptable' range is to evaluate the natural variability of the system [6]. For instance, a TEC array may be considered as non-detrimental to the local environment if velocities and bed shear stress are affected by an amount less than the intra-seasonal and inter-annual variability due to natural tidal and wave motions [7]. Wave-induced variability will be greater during winter [8], when energy demand is high, than during summer when the sea is rich with biological productivity [9]. Therefore, it is important to consider natural intra-seasonal variability of oceanographic processes when determining the environmental impact of tidal energy extraction. To date, this approach has not been adopted in environmental impact assessments of energy extraction [1,10]. It is our aim, therefore, to investigate the natural variability of sedimentary processes as a means of quantifying the impacts of energy extraction.

Sedimentary processes are a nonlinear function of the current velocity and wave orbital motion, in conjunction with sediment properties such as grain size and bed features [11]. Sediment transport is typically subdivided into suspended load transport, which is carried by the water motion over large spatial and temporal scales, and bed load transport which takes place just above the bed and reacts instantaneously to the local conditions [11]. Suspended load transport consists of lighter sediment particles and organic particulate matter, such as detritus, zooplankton and fish early-life stages. Strong tidal dissipation can generate turbidity

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maxima which are regions of high concentrations of such suspended material [12]. Turbidity maxima are important as they enhance nutrient supply for marine species, thereby increasing secondary production, and serving as critical nursery areas for economically important species [13,14]. However, they can also have an ecological impact by reducing solar input. Turbidity maxima mediate marine population dynamics (e.g. Ref. [15]) and potentially species connectivity across shelf regions; hence, the effect of TEC arrays on the turbidity maxima is of obvious concern.

Bed load transport of heavier particles just above the bed mediates coastal morphology and sediment supply to beaches and offshore sand banks. Sandy deposits form as sand banks in the lee of strong flow past headlands and islands, maintained by recirculating tidal flows forming large eddy systems [16]. Sand banks are important for natural coastal protection during storm events as they cause waves to refract and dissipate their energy [1]. In relation to tidal-stream energy extraction, regions with strong tidal asymmetry can reduce the amount of bed level change and produce bed load transport effects up to 50 km away, though such far-field effects are reduced in regions of tidal symmetry [2]. It is important that the sedimentary processes described above are understood, and their natural variability quantified, if we are to assess the potential impact incurred by tidal-stream energy extraction.

1.1. *Case study: the Irish Sea*

The Irish Sea (Fig. 1) is a high-energy shelf sea region that is an ideal test site for investigating the impact of tidal-stream energy extraction on sediment transport processes. Model simulations of bed shear stress over the northwest European shelf seas [17] and sand transport pathways [18] indicate bed load separation in the south western Irish Sea and stresses directed into large bays in the east such as Liverpool Bay and Cardigan Bay, due to M_4-generated tidal asymmetries in these shallow regions. Consequently, provided the sediment carrying capacity of the currents is strong enough, sediment will be transported eastwards and deposited in English and Welsh coastal bays. Tidal ranges in the eastern Irish Sea are high, inducing high velocities where flow is constricted around headlands [19] and, hence, the opportunity for tidal energy extraction. Tidal-stream energy extraction is modelled here at a headland location off the northwest coast of Anglesey, Wales (Fig. 1), where strong velocities and tidal asymmetries exist [17]. This site has been highlighted as one of the seven specific regions of interest around the UK for 'first generation' tidal energy extraction, and has been leased by the Crown Estate for commercial development [20]. Tidal velocities here are relatively large (>2.5 m s^{-1}, during spring tidal flow), due to high tidal amplitudes and the flow being constricted between the mainland and a collection of small rocky islands known as the Skerries. Water depths in this region are approximately 30 m, which means that morphological features are potentially controlled by wave-induced bed shear stresses, which are estimated here using inter-annual predictions of the wave climate [8].

The sediment dynamics off the northwest coast of Anglesey has been investigated in previous studies. Observations of seabed sediment type have been recorded as embedded boulders, cobbles and gravel, in fast-flowing areas (i.e. the Skerries), although regions of coarse and fine sands have been observed elsewhere [21]. Strong tidal dissipation in this region generates the Anglesey Turbidity Maximum (ATM). The ATM has been measured using optical instruments and remote sensing, and shown to be persistent throughout the year [12–14,22], although modulated by natural variability in the North Atlantic Oscillation (NAO), which correlates to the wind climate [23,24]. The ATM was simulated by Ellis et al. [14] using a two-dimensional aggregation–disaggregation model,

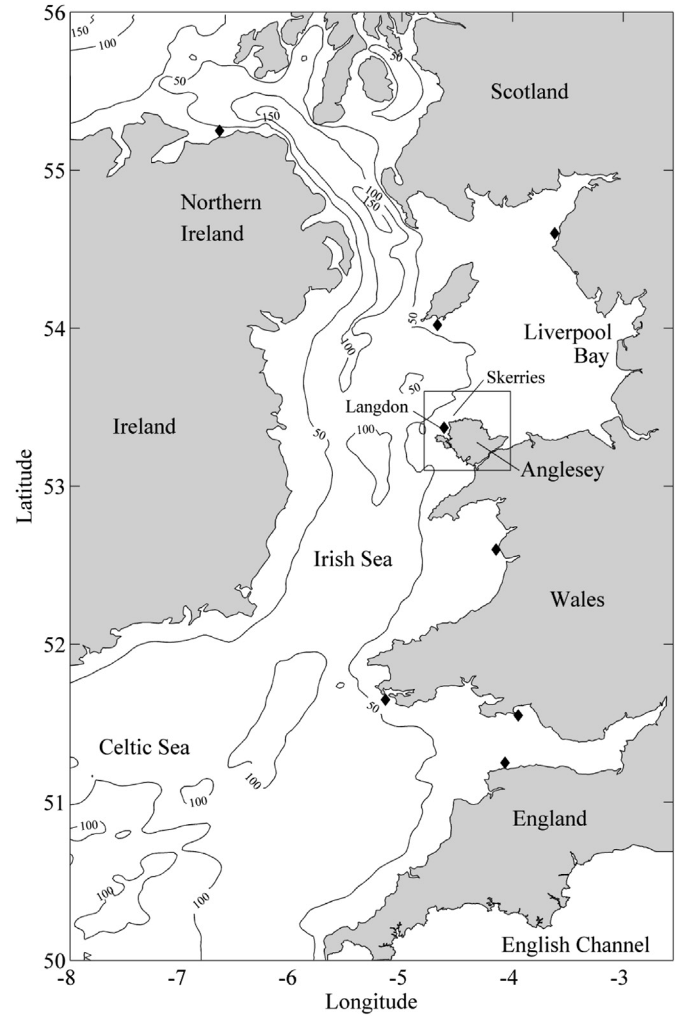

Fig. 1. Case study: The Irish Sea, showing water depths (m, relative to MSL). Our unstructured, finite-element morphodynamic Irish Sea Model simulated 2D hydrodynamics and sediment transport within this domain. Our model grid had variable resolution, being 2000 m at the offshore boundaries, increasing to 200–500 m in coastal areas and 15–50 m around northwest Anglesey. We focus on sedimentary processes around northwest Anglesey (boxed area), where we have conducted two in situ surveys (e.g. at Langdon sand bank) and also simulated tidal-stream energy extraction at 'the Skerries'. Our model was validated against tide gauge stations around the Irish Sea (marked with diamonds).

with two different sediment size classes, and maintained by the disaggregation of suspended flocs (~140 μm) into smaller particles (~70 μm). For the present study, we surveyed suspended sediment concentrations and particle size distributions in the region (described in Section 2). Langdon sand bank forms in the lee of the Skerries and Holy Island, approximately 10 km to the southwest of the Skerries (Fig. 2). Detailed bathymetric surveys and sediment measurements of the sand bank were therefore conducted for this study. We describe the application of morphodynamic and wave models in order to simulate the regional sedimentary and morphological processes, and to quantify natural variability. Next, we adapt our morphodynamic model to investigate whether tidal-stream energy extraction will significantly affect the sedimentary processes described above – whilst any impact induced by a tidal turbine array can affect the sedimentary environment, here we define 'significant change' as that which exceeds the natural levels of inter-seasonal and inter-annual variability of tidally-induced and wave-induced local bed shear stress (*see* Section 3).