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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,

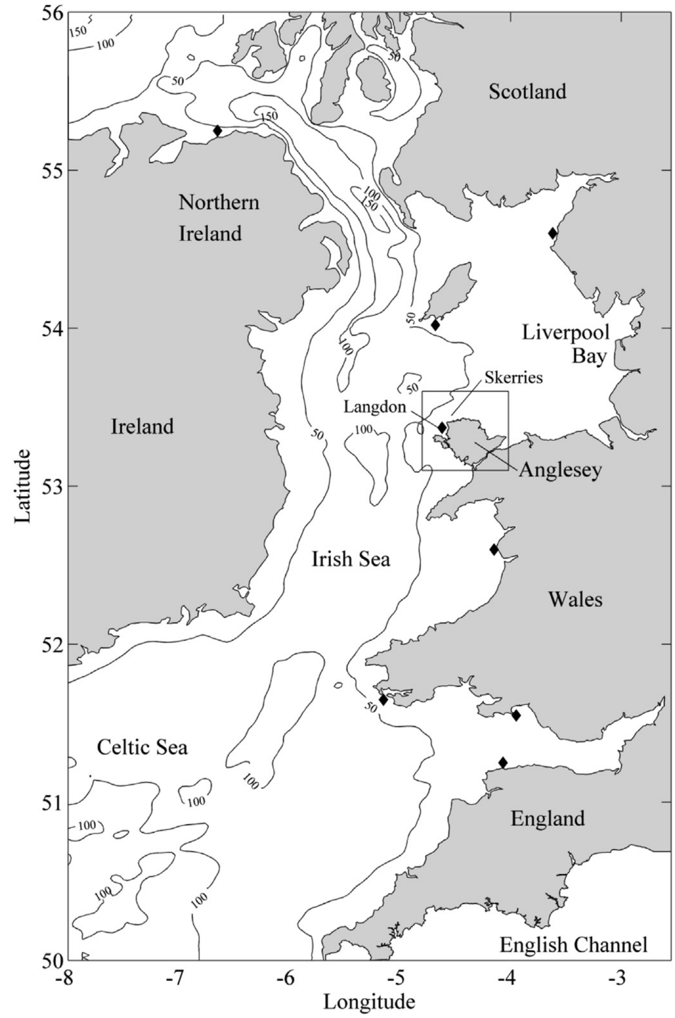

Fig. 1. Case study: The Irish Sea, showing water depths (m, relative to MSL). Our unstructured, finite-element morphodynamic Irish Sea Model simulated 2D hydrodynamics and sediment transport within this domain. Our model grid had variable resolution, being 2000 m at the offshore boundaries, increasing 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).

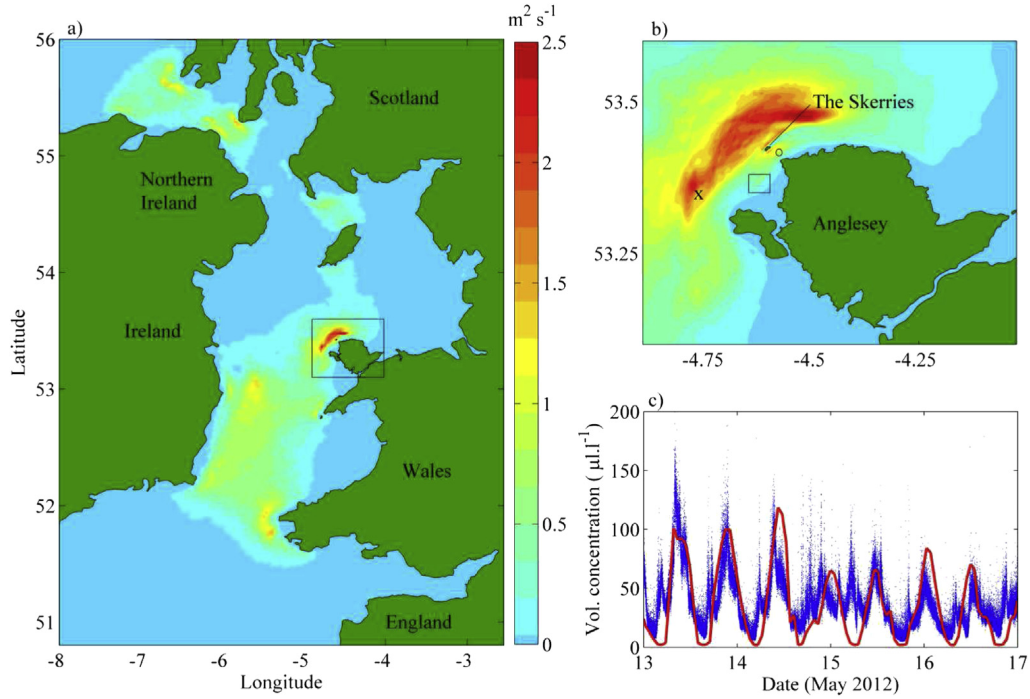

Fig. 2. Irish Sea Model (TELEMAC-2D + SISYPHE) output from our 'natural' simulation (RUN-1.1), showing (a) peak suspended sediment transport ($m^2\ s^{-1}$); the boxed area is enlarged in (b) to show the formation of the Anglesey Turbidity Maximum. The positions of the Skerries islands, the channel where energy extraction has been simulated (circle), and Langdon sand bank (rectangle), are also depicted in (b). Modelled, depth-averaged, volume concentrations of suspended sediment ($\mu l\ l^{-1}$) (red curve), during May 2012 at a location marked '*x*' in (b), are shown in (c), compared with LISST data (blue) measured at all depths and for all grain size classes. Peak spring flow occurred on 13 May 2012. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Data collection

The region off northwest Anglesey was surveyed twice for this study using the Research Vessel Prince Madog, once in May 2012 and again in November 2012. A Sequoia 100-X LISST (Laser In Situ Scattering and Transmissometry) instrument measured suspended sediment concentrations and distributions at a mooring within the Anglesey Turbidity Maximum (marked '*x*' in Fig. 2b). Sediment grab samples were also collected from the bed at the mooring. Volume concentrations within the ATM were tidally modulated, with maximum concentrations of 185 $\mu l\ l^{-1}$ (99th percentile) during spring tides, decreasing to below 100 $\mu l\ l^{-1}$ four days later (Fig. 2c). The spread of measured values in Fig. 2c occurs because all depths were recorded. The mean suspended sediment size was 85 μm, whilst the mean sediment size on the bed was 300 μm. In addition, 96 water samples (48 in the surface layer and 48 in the near-bed layer) were collected from different locations to calibrate the suspended sediment concentrations measured by the LISST.

Bathymetry data were measured at Langdon sand bank, using a hull-mounted Reson SeaBat-7125 Multibeam (operating frequency: 400 kHz), giving horizontal resolution of 15 cm and vertical resolution of <5 cm, but with ~10 cm vertical error, due to real time kinematic post-processing. The area was surveyed once in May and again in November, this time collecting sediment grab samples as well. The areas of accreted sand (again with mean sediment size of 300 μm) comprise three distinct sandy 'ridges', 5–10 m in height, in water depths of ~13 m at the crests (Fig. 3a). The ridge crests are orientated approximately northwest–southeast, which is normal to the prevailing wave directions and, hence, it is thought that the features are modified by wave stress. Each ridge is approximately 200 m across the crest and approximately 1–2 km along the crest. Superimposed upon these sandy ridges are dune features with wavelengths of ~10 m (Fig. 3b and c). The two surveys of the sand bank, conducted six months apart, provide us with a direct assessment of some aspects of the natural variability of the sand bank. The crest height varied by up to 2 m over the summer period, mainly due to horizontal migration of the sand banks; i.e. the crest maintains its form but is transported horizontally (Fig. 3c). It is expected that variations in the sand bank will be more profound over the winter period, due to increased wave-induced bed shear stress (*see* Section 2.4).

2.2. Morphodynamic modelling

A finite-element morphodynamic model (TELEMAC Modelling System V6.1; [25]) was applied to the Irish Sea (Fig. 1), named hereafter Irish Sea Model. The model was used to predict at high resolution tidally-induced bed shear stress and sediment transport processes around northwest Anglesey. The hydrodynamic module (TELEMAC-2D) is based on the depth-averaged shallow water Saint–Venant equations of momentum and continuity, derived from the Navier–Stokes equations [25]. The hydrostatic assumption of the model is valid around Anglesey where bed slopes are small and vertical accelerations caused by the pressure are also small. The classical k–ε turbulence model has been adapted into vertically averaged form to include additional dispersion terms [26]; a constant internal friction coefficient of 3×10^{-2} m was implemented in Nikuradse's law of bottom friction [25]. Turbulent viscosity has been set constant with the overall viscosity (molecular + turbulent) coefficient equal to 10^{-2}. Coriolis effects have also been included. The unstructured model mesh, created using BlueKenue grid generation software, has variable resolution, being relatively fine (15–250 m) around Anglesey and coarser (500–2000 m) elsewhere. The mesh was mapped onto gridded Admiralty bathymetry data available at 200 m resolution [27].

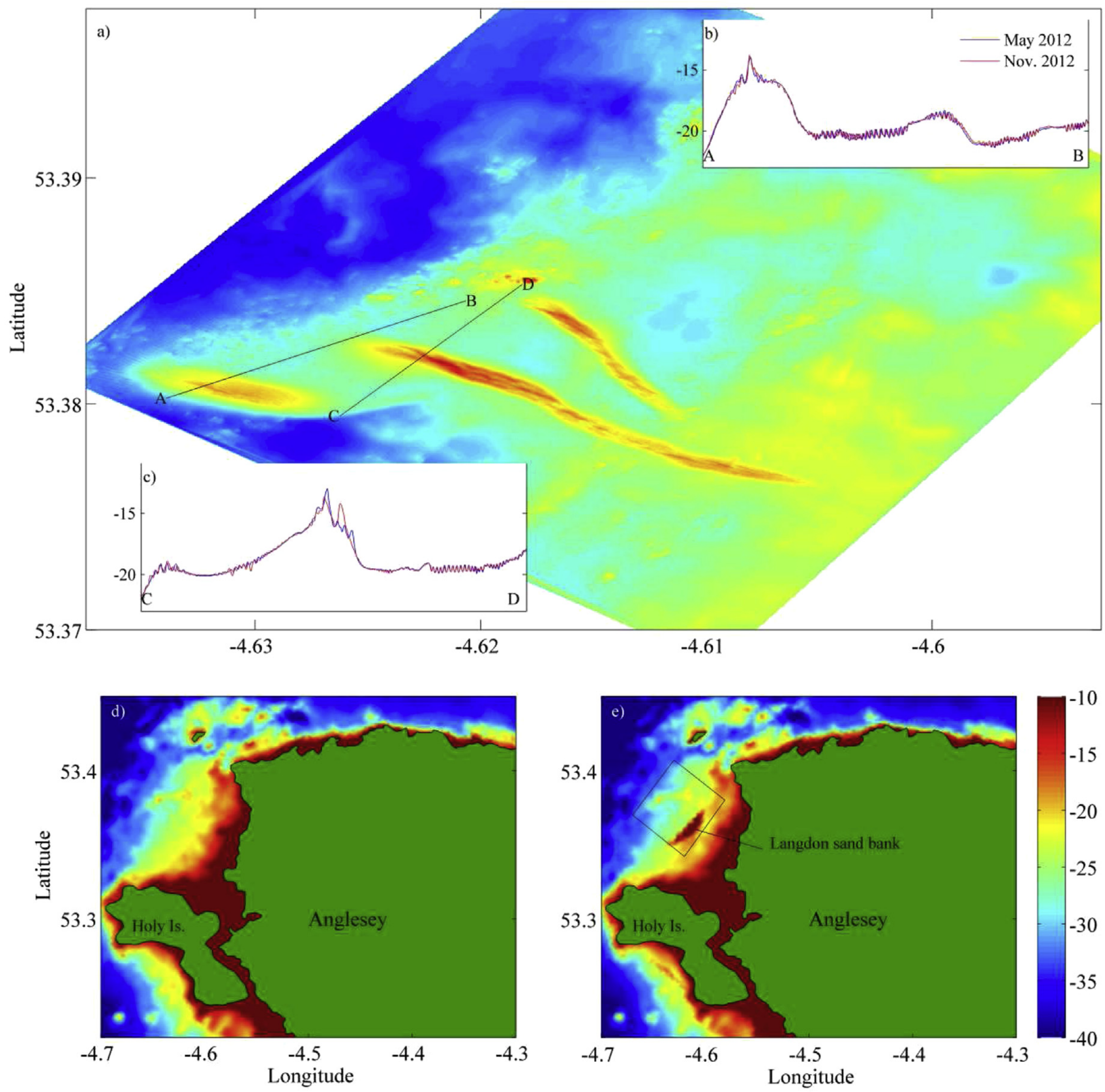

Fig. 3. (a) Multibeam data (surveyed during November 2012) showing Langdon sand bank, located 10 km to the southwest of the Skerries, in the lee of the mainland and Holy Island. Two transects are also marked in the figure (AB and CD), corresponding to Multibeam bed profiles in (b) and (c) (surveyed in May 2012 (blue curve) and November 2012 (red curve)). Our TELEMAC-2D + SISYPHE natural simulation (RUN-1.1) shows (d) initial bathymetry (where the seabed around Langdon sand bank was essentially flat, with ~25 m mean water depth, and comprised of both fine (85 μm) and coarse (300 μm) sands), and (e) bathymetry after a simulation of one lunar cycle (i.e. 14.75 days), after which the bed evolution was small due to an imposed maximum erodible bed. The approximate formation of Langdon sand bank is clearly shown, with ~15 m of mean water depth and comprised of coarse sand. All depths are in meters, referenced to mean sea level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The sediment transport module (SISYPHE) was internally coupled with the hydrodynamics (TELEMAC-2D) and was implemented here using the Soulsby–Van Rijn transport formula [5]. This formula applies to total (bed load + suspended load) sediment transport rate per width of the flow, and is intended for conditions in which the bed is rippled with a bed roughness length scale implicitly equal to 6 mm. While this condition is not strictly true for the entire Irish Sea (e.g. some areas contain bedrock or cobbles only), the Soulsby–Van Rijn transport formula [5] is appropriate in this case because we are primarily interested in suspended and bed load transport, as well as the formation and maintenance of sand banks. We also use bed shear stress as a proxy for sediment transport in regions where the formula is not appropriate. In this way, we are able to compare (and combine) tidally-induced and wave-induced contributions to net bed shear stress. In SISYPHE, we assumed that the entire seabed comprised equal proportions of both very fine (85 μm) and medium (300 μm) grained sands, based on mean values of suspended sediment concentrations measured at the Anglesey Turbidity Maximum and sediment grab samples collected at Langdon sand bank during the 2012 surveys. Elsewhere in the model domain, realistic sediment distributions have not been implemented and the simulated sediment transport is not thought to be accurate. Bed load transport is computed separately for each sediment size class, and corrected for sand grading effects [28]. The Exner equation is then solved for each size class, and bed evolutions are added to produce global evolution due to bed-load. Similarly, suspended load transport is solved for each size class and then resulting bed evolutions are added to give the global suspended load evolution. The concentration of each class of sediments is computed, with the corresponding settling velocity, erosion and deposition flux. Finally, at each time step, the total bed evolution (due to bed load and to suspended load) is used to update the sediment bed structure (composition and layer thickness) [28]. A maximum erodible layer thickness was calibrated to be 2 m throughout the domain, so that sediment transport and bed evolution corresponded to data collected in the region of northwest Anglesey. This condition ensured that there was a finite Irish Sea sediment supply, as would occur naturally over relatively short timescales [14]. Consequently, if the model bed erodes by 2 m, no further erosion can take place at that location; similar in effect to flow over bedrock.

A baseline simulation was performed (RUN-1.1, *see* Table 1) to model the 'natural' hydrodynamics and sediment transport processes observed around northwest Anglesey. The baseline simulation was forced by the principle semi-diurnal lunar (M_2) and solar (S_2) tidal constituents and, following a 24 h model spin-up, run for a period of two spring-neap tidal cycles (i.e. 29.5 days) which was sufficiently long to diminish any further spin-up artifacts. The modelled hydrodynamics were validated throughout the Irish Sea, against known tide gauge measurements, giving root mean square errors in M_2 amplitude and phase of 10 cm and 7°, respectively, which is comparable with other (3D) models of the region [29–33]. The simulation successfully reproduced a turbidity maximum in the region of northwest Anglesey, where suspended sediment concentrations were in good agreement with measurements collected during 2012 (Fig. 2). The simulation also reproduced the approximate formation of Langdon sand bank – from an initial 'flat-bed' case (Fig. 3d and e). While the model resolution was too coarse to accurately resolve individual dune formations, the modelled sand bank feature and position were realistic (Fig. 3a–c). Finally, the model has been used to illustrate northwest Anglesey as a region of tidal pumping, with residual and peak shear stresses being consistent with a net sediment transport pathway directed into Liverpool Bay (Fig. 4). Simulated residual bed shear stress around northwest Anglesey was of the order 0.25 N m^{-2}, which is comparable to other models of the region (e.g. Ref. [17]). Tidally-induced peak bed shear stresses exceeded 25 N m^{-2}.

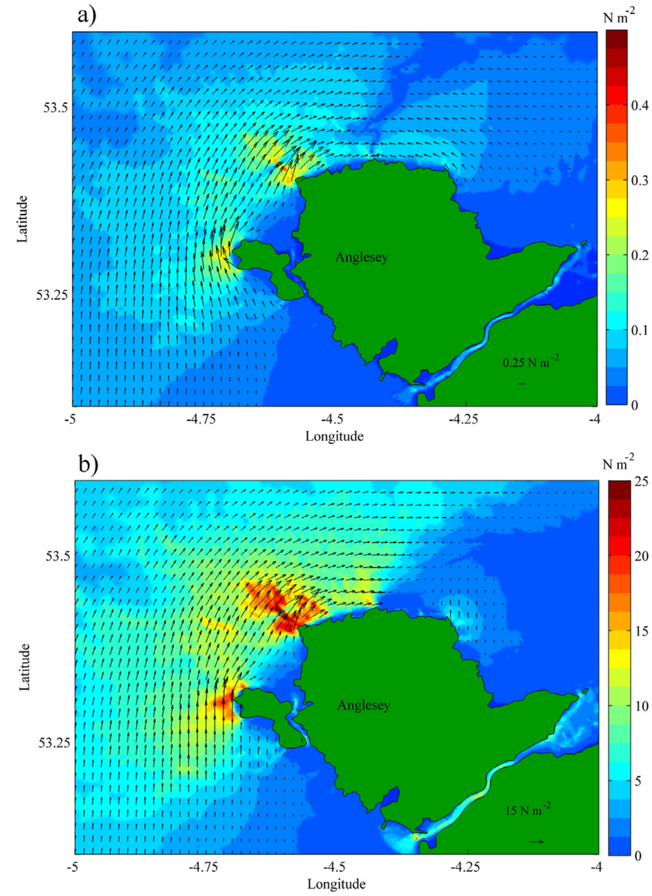

Fig. 4. Irish Sea Model (TELEMAC-2D + SISYPHE) output form the 'natural' simulation (RUN-1.1) showing (a) residual and (b) maximum bed shear stress around northwest Anglesey (calculated during two spring-neap tidal cycles with M_2 and S_2 tidal constituents only). Magnitudes are denoted by the colour scales and vector lengths, whereas vector orientation denotes direction. Modelled vectors (at unstructured nodal points) have been interpolated onto an orthogonal grid with resolution 1/60°, and only vectors greater than (a) 0.05 N m^{-1} and (b) 1.25 N m^{-1} are plotted (vectors within the Menai Strait are also omitted). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Wave modelling

Waves were modelled independently, using a validated spectral wave model (SWAN) of the northwest European shelf seas [8]. SWAN is a third-generation wave model which is spectrally discrete in frequencies and directions, and the kinematic behaviour of the waves is described by the linear theory of gravity waves [34]. SWAN accounts for wave generation by wind, non-linear wave–wave interactions, white-capping, and the shallow water effects of bottom friction, refraction, shoaling, and depth-induced wave breaking. The wave model was applied initially to a region which covered the entire North Atlantic at a grid resolution of 1/6° × 1/6°, extending from 60°W to 15°E, and from 40°N to 70°N. Nested within this model was a higher resolution model of the northwest European shelf seas. This inner nested region had a grid resolution of 1/24° × 1/24°, extending from 14°W to 11°E, and from 42°N to 62°N. After running the coarser outer model of the North Atlantic, this inner nested simulation was run without feedback to the outer nest, i.e. the nesting process was one-way. Gridded wind data was provided by Met Éireann (the Irish Meteorological Service) using their operational HIRLAM (High Resolution Limited Area Model) version 7.2 forecast model (www.hirlam.org). The grid resolution of this atmospheric model is 0.1° × 0.1°, with 60 vertical levels, and the resolution of the interpolated output wind data is 0.5° × 0.5°, extending from 60°W to 15°E, and from 40°N to 70°N at 3-hourly intervals. The inner nested model of the northwest European shelf seas was used to output an hourly time series of wave properties at Langdon Bank and the Skerries for a 7 year period (2005–2011).

Table 1
Summary of energy extraction simulations, showing rated capacity and simulated power output.

Model simulation	Number of devices	Rated capacity of array	Mean power output of array	Maximum capacity of array
RUN-1.1	0	0	0	0
RUN-2.1	5	10 MW	7 MW (70%)	10 MW (100%)
RUN-2.2	25	50 MW	33 MW (66%)	50 MW (100%)
RUN-2.3	50	100 MW	60 MW (60%)	100 MW (100%)
RUN-2.4	150	300 MW	141 MW (47%)	298 MW (99%)

2.4. Natural variability

Natural variability of suspended sediment concentrations at the Anglesey Turbidity Maximum was calculated by Ellis et al. [14]

using a 2D aggregation–disaggregation model, with two different sediment size classes, and maintained by the disaggregation of suspended flocs (~140 μm) into smaller particles (~70 μm). High suspended sediment volume concentrations (35 μl l^{-1}) were simulated during winter, with seasonal variability of the order 19 μl l^{-1}, which was comparable to visible-band satellite observations [12]; however, this was a surface-only comparison. Based upon the entire water depth (and potentially at a different location within the ATM to that measured by Ellis et al. [14]), our simulation produced mean volume concentrations during spring tide of 30 μl l^{-1} which correspond well with our LISST measurements (Fig. 2c). These conclusions were adopted for our study, and no further calculations were performed.

Natural variability of bed load transport has been calculated by evaluating tidally-induced bed shear stress and wave-induced bed shear stress separately, then combining these stresses through successive years to produce the mean bed shear stress and also intra-seasonal and inter-annual levels of variability. Values were calculated at two locations: in the Skerries channel, and at Langdon sand bank. Firstly, tidally-induced bed shear stress (τ_{tide}) was output from our morphodynamic model (RUN-1.1) and extrapolated over 7 years (2005–2011) to coincide with the wave model simulation (this is possible since only M_2 and S_2 tidal constituents were modelled, which are in-phase over a spring-neap cycle). Secondly, wave-induced bed shear stress (τ_{wave}) has been calculated based upon the wave climate output from our wave model simulation.

The SWAN simulated root-mean square wave orbital velocity (UW_{RMS}) at the Skerries (~30 m water depth at mean sea level) and also at Langdon sand bank (~13 m water depth at mean sea level), based on the discretised wave spectrum and using linear wave theory [5], were used to calculate wave-induced bed shear stress as follows:

$$\tau_{\text{wave}} = \frac{1}{2}\rho f_{\text{w}} UW_{\text{RMS}}^2 \tag{1}$$

We have assumed no wave–tide interaction (e.g. Refs. [35,36]), a time-varying water depth, and a water density $\rho = 1027$ kg m^{-3}. The friction factor, f_w, is dependent on the ratio of the semi-orbital excursion near the bed ($UW_{RMS}T/2\pi$, for wave period T) and the sand grain roughness (k_s), and has been set to 0.02 at the Skerries (rough turbulent flow) and 0.05 at Langdon sand bank (rippled sandy bed) [5]. Finally, due to the non-linear interaction of the wave and current boundary layers, the combined time-mean bed shear stress (from tides and waves) was calculated using Soulsby's [5] expression:

$$\tau_{\text{total}} = \tau_{\text{tide}}\left[1 + 1.2\left(\frac{\tau_{\text{wave}}}{\tau_{\text{tide}} + \tau_{\text{wave}}}\right)^{3.2}\right] \tag{2}$$

The non-linear interaction of tidally-induced and wave-induced bed shear stresses cannot be accounted for by simple linear addition (Soulsby 1997) because, considering bed shear stress as a time-series, the frequency of wave stress is small compared with the much longer period oscillation of the tidally induced bed shear stress. Hence, when considering the combined bed shear stress over a tidal cycle, the contribution of high frequency wind/swell waves must be much less than the tidal contribution, resulting in a reduced bed shear stress overall. We then applied Equation (2) over the 7-year time series to calculate the annual mean bed shear stress; thus inter-annual and intra-seasonal variability can be estimated.

2.5. Tidal energy extraction

Tidal-stream energy extraction was implemented in the Irish Sea Model by introducing an additional drag force in the east and north directions, F_x and F_y, respectively, on the flow at the locations (nodes) of energy extraction as follows [1]:

$$F_x = -C_p \frac{P}{\rho UAD}\cos(\theta), \tag{3a}$$

$$F_y = -C_p \frac{P}{\rho UAD}\sin(\theta), \tag{3b}$$

where ρ is the water density, A is the 'plan' area of seabed which each individual turbine affects, D is the water depth, and θ is the direction of the depth-averaged current, U. We assumed a typical power curve [2,37] to parameterise extracted power, P (in Watts)

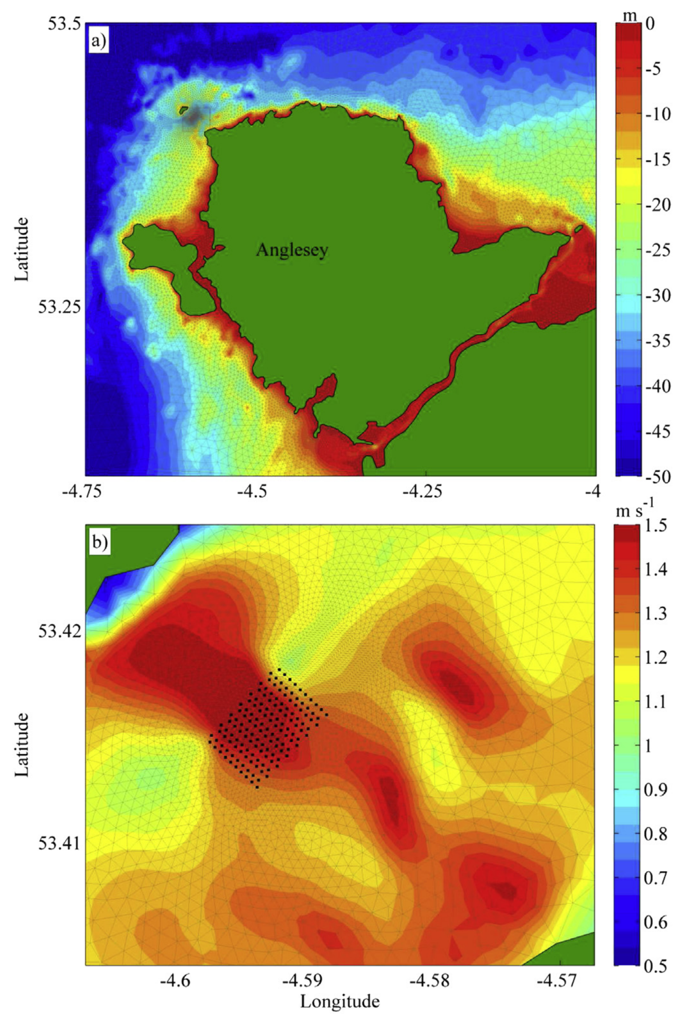

Fig. 5. Sub-sections of the Irish Sea Model grid: (a) Anglesey and (b) the Skerries Channel. Colour contours in denote (a) water depth at mean sea level (m) and (b) mean depth-averaged velocities (m s^{-1}). The finite-element grid has variable resolution and edge lengths which connect nodes where parameters are calculated. The region of the TEC array in the Skerries Channel is shown in (b) – the location chosen based on both bathymetry and velocities; each highlighted (black) node represents one turbine (i.e. 2 MW of extractable power) where tidal-stream energy extraction takes place. In the figure, 150 highlighted nodes represent a rated capacity array of 300 MW which, for our array configuration, generated 141 MW over a spring-neap cycle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for each turbine, with a cut-in velocity of 0.7 m s^{-1} and rated velocity of 2.7 m s^{-1} which produced 2 MW (assuming two drive-trains per device). We assumed a constant power coefficient (C_p) at the location of extraction of 0.35. Support structure (drag) losses have been assumed negligible.

Several tidal-stream energy extraction scenarios have been modelled for our prospective TEC array in the Skerries, positioned and mid-way between northwest Anglesey and the Skerries Islands (Fig. 5a); where water depths were appropriate (i.e. approximately 30 m) and simulated mean velocities were greatest (Fig. 5b). Specifically, simulations approximated rated energy extraction amounting to 10, 50, 100, and 300 MW (RUN-2.1–RUN-2.4, respectively; *see* Table 1). Therefore, 5 TEC devices were needed for the 10 MW rated power case and 50 devices for 100 MW rated power case. It must be noted that energy extraction will be variable below rated velocity and, given the oscillatory nature of the tidal currents and spring-neap cycle, the actual energy extracted is likely to be much less than the rated values. As such, we have calculated the mean power output of each TEC array, averaged over a spring-neap cycle (*see* Table 1). Each individual turbine was assigned a typical device width, L, of 45 m [2] and was represented by a separate node within the TEC array. Therefore, the area of seabed, A, upon which each turbine acts is L^2 (i.e. 2025 m^2). Each turbine was separated laterally by one device width and by 5 L in the up/downstream flow direction (i.e. southwest–northeast), and staggered in the configuration shown in Fig. 5b [38]. All other aspects of RUN-1.1 remained unchanged. The impact of the device support structure has been neglected.

3. Results

3.1. Natural variability in bed shear stress

Annual and monthly-averaged wave-induced bed shear stress statistics were calculated for sites in the Skerries (water depth ~30 m) and at Langdon sand bank (water depth ~13 m), based on a 7 year time series (2005–2011) of wave model simulations (Fig. 6). Wave climate variability, over the 7 year period, altered mean annual bed shear stress at the Skerries by 0.012 ± 0.005 N m^{-2}, where variability denotes the 90% confidence interval (Fig. 6a). Intra-seasonal variance in bed shear stress at the Skerries was greater; considering summer months only (i.e. April to September), wave-induced bed shear stress was 0.004 ± 0.002 N m^{-2}, which was an order of magnitude less than during winter (0.03 ± 0.01 N m^{-2}) (Fig. 6b). At Langdon sand bank, wave-induced annual bed shear stress and inter-annual variability were 0.45 ± 0.05 N m^{-2}, which was greater than at the Skerries, since water depths are reduced (Fig. 6c). Bed shear stress was reduced during summer months (0.15 ± 0.06 N m^{-2}), compared with winter (0.72 ± 0.2 N m^{-2}; Fig. 6d). Again, variabilities denotes the 90% confidence interval either side of the mean.

Total bed shear stress was dominated by the tidal forcing in this region; averaged tidally-induced bed shear stress was 5.24 N m^{-2} (at the Skerries) and 3.39 N m^{-2} (at Langdon sand bank), when only M_2 and S_2 constituents were considered. By combining tide- and wave-induced bed shear stresses (Eq. (2) [5]; e.g. Fig. 7) for the 7-year period, the root mean square (RMS) bed shear stress at the

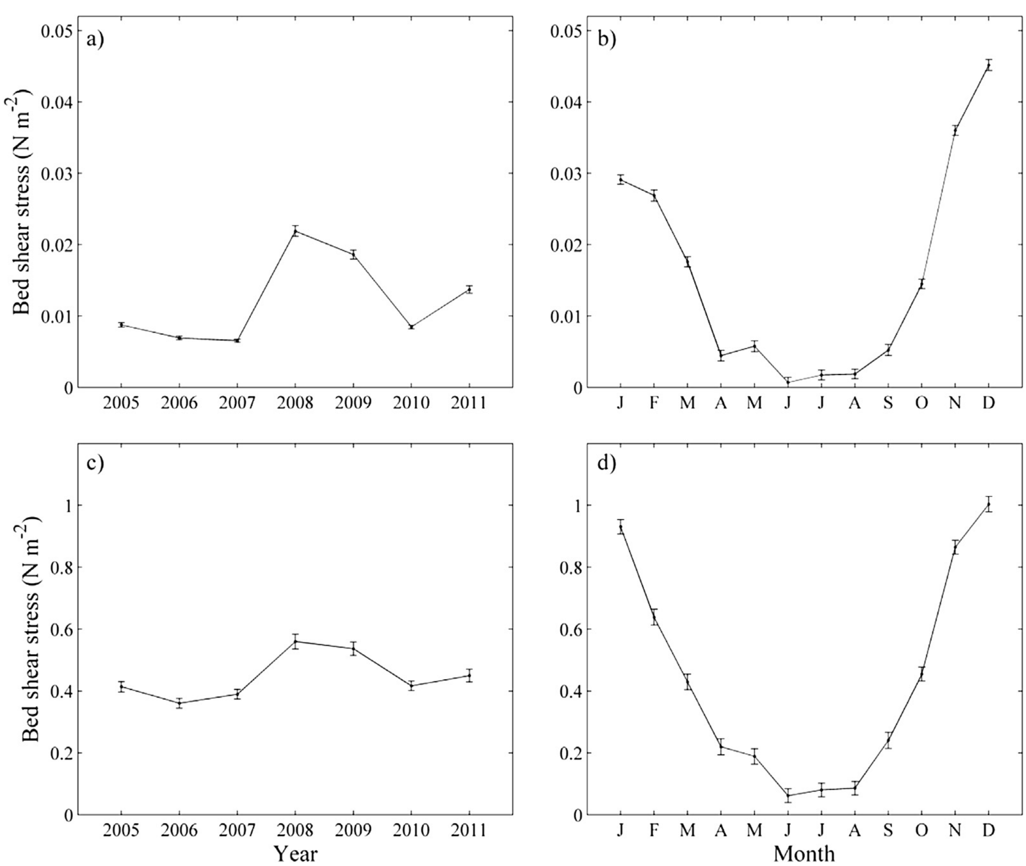

Fig. 6. Natural variability in wave-induced bed shear stress: at the Skerries (a, b) and at Langdon sand bank (c, d). Bed shear stress has been calculated, using linear wave theory [5], from our SWAN wave model for the years 2005–2011. Inter-annual (a, c) and intra-seasonal (b, d) variabilities of the wave climate are shown, where error bars denote 95% confidence intervals either side of the mean.

Skerries remained at 5.24 N m^{-2}. At Langdon sand bank, wave contributions were more significant; RMS bed shear stress being 3.43 N m^{-2}. Therefore, bed shear stress is dominated by tidal motions, except perhaps during extreme storm wave events which last for a few hours (e.g. Fig. 7). Such events are rare (i.e. >99th percentile of the wave time series), but contribute to the majority of the variability in bed load transport. To appreciate the effects of bed shear stress on bed load transport, the annual percentage of time that total bed shear stress exceeded 0.2 N m^{-2} was calculated. This threshold corresponds approximately to the incipient motion of medium sands (i.e. 300 μm; [39]) that are ubiquitous of northwest Anglesey. At the Skerries, bed shear stress exceeded 0.2 N m^{-2} for 94.7% of the year, whereas at Langdon sand bank, bed shear stress exceeded the threshold 92.5% of the time.

3.2. Tidal-stream energy extraction

Simulated tidal-stream energy extraction for each scenario (RUN-2.1–RUN-2.4) has been calculated and compared with the rated capacities (*see* Table 1). Averaged over each array and over a spring-neap tidal cycle, simulated energy extraction was between 70% (10 MW rated array) and 47% (300 MW rated array) of the rated capacity; the 'energy loss' mainly caused by the oscillatory nature of the tidal velocities (i.e. long periods of sub-rated velocities around slack water and neap tides) and tidal asymmetries (i.e. sub-rated ebb velocities vs. super-rated flood velocities). Yet wake damping of velocities and blockage effects associated with dense turbine arrays are also contributing factors (e.g. the larger arrays simulated a lower proportion of the rated capacity). Maximum capacities largely reached the rated capacity, but only for a small percentage of the time during peak spring flow (*see* Table 1). It must be noted that the mean power output of each TEC array may vary according to different array configurations; actual arrays installed are expected to be fully optimised for their specific resource which would increase their efficiency.

Our model results (RUN-2.1–RUN-2.4) suggest that tidal-stream energy extraction at the Skerries will have a non-linear impact on velocities, bed shear stress and sediment dynamics (Fig. 8). Considering model output averaged over the TEC array, depth-averaged velocities in the near field were reduced by only a few percent, even with large amounts of simulated energy extraction (i.e. greater than 100 MW, or a rated array capacity of 300 MW) (Fig. 8a). Tidally-induced bed shear stress was affected by energy extraction to a greater extent than velocities, since bed shear stress is a function of U^2. For example, power extraction of 141 MW (300 MW rated capacity array) reduced local bed shear stress by 5% (Fig. 8a). As expected, bed load transport was impacted most by the simulated TEC arrays, being a still higher power of U [5]. It is interesting to note that suspended transport, which forms the Anglesey Turbidity Maximum, was least impacted upon, possibly because TEC array operation led to increased turbulence, which in some ways counteracts the effect of reduced velocities. Most importantly, we predict that the impact of first-generation TEC arrays (i.e. <50 MW) on local bed shear stress and sediment transport was minimal (i.e. less than a few percent). The above results refer only to the location of energy extraction; the impact of our simulated TEC arrays was even less further afield. For example, at Langdon sand bank which is 10 km away from of the TEC array, energy extraction affected velocities, bed shear stress and bed load transport, though only marginally (i.e. by less than 2% for a 141 MW TEC array (300 MW rated capacity array); Fig. 8b).

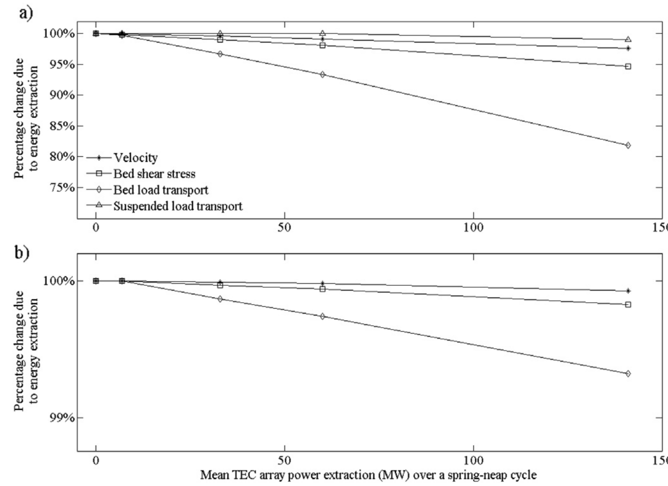

Fig. 8. Impact of tidal-stream energy extraction on: depth-averaged velocities, tidally-induced bed shear stress, bed load sediment transport, and suspended sediment transport. Comparisons are made at (a) the point of energy extraction (the Skerries) and (b) 10 km to the southwest (Langdon sand bank). The horizontal axis denotes the simulated mean TEC array power extraction over a spring-neap tidal cycle (the corresponding rated capacity of each simulation is shown in Table 1).

In order to assess the scale of the impacts described above, we have considered natural intra-seasonal and inter-annual variability of bed shear stress at the Skerries, and at Langdon sand bank (Fig. 9). Total seasonally-averaged (for 'summer' and 'winter' seasons) bed shear stress, due to combined tidal and wave motions, is plotted for the present-day natural case and for different energy extraction scenarios (i.e. RUN-2.1–RUN-2.4). The maximum seasonal variance has enabled us to calculate the threshold of energy extraction that reduces bed shear stress significantly. Our results show that, during winter months, up to 87 MW (or a 165 MW rated capacity array) can be extracted by the TEC array before local impact on bed shear stress exceeds natural variability (Fig. 9a). During summer, this threshold is reduced to 52 MW (or 85 MW rated capacity array) (Fig. 9b). The regional impact of energy extraction is likely to be insignificant with regard to natural variability. For example, 10 km upstream/downstream at Langdon sand bank, the impact of extracting over 100 MW on bed shear stress was an order of magnitude less (~0.014 N m^{-2}) than that caused by natural variability (~0.14 N m^{-2}) (Fig. 9c and d). However, this could be due to local-scale effects, such as spatial variability to the exposure of waves.

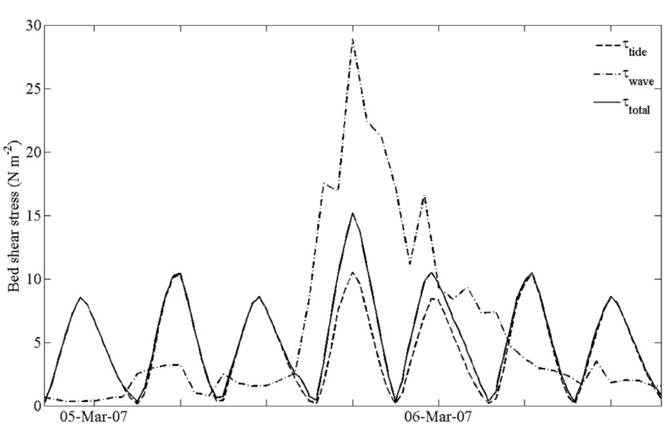

Fig. 7. Bed shear stress at Langdon sand bank, during a storm wave event in March 2007. Tidally-induced stress was calculated from our morphodynamic model (TELEMAC-2D + SISYPHE; RUN-1.1) and extrapolated over the period 2005–2011, to coincide with wave-induced stress, which was output from our wave model (SWAN) of the northwest European shelf. Total bed shear stress is calculated using Eq. (2) [5].

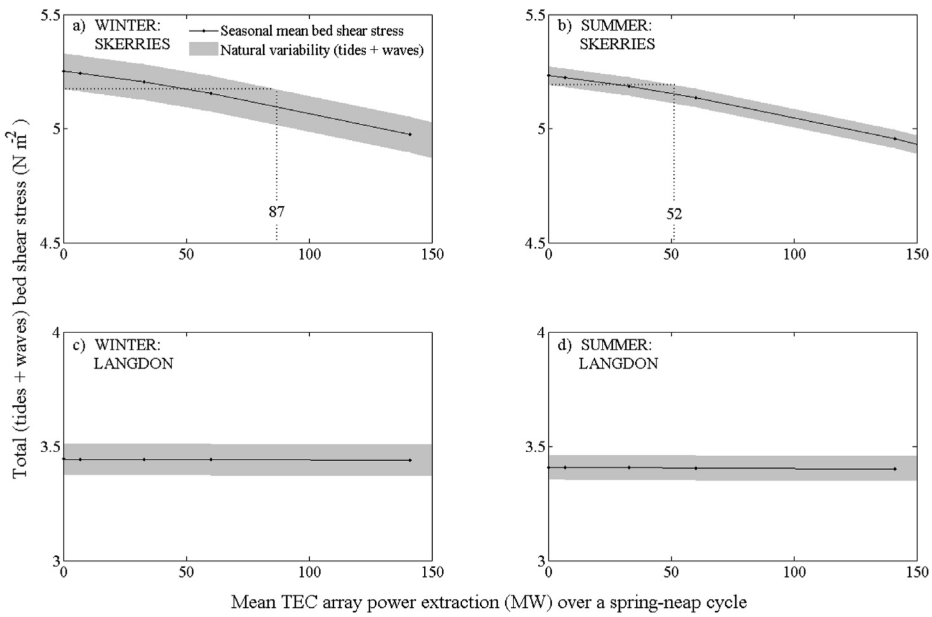

Fig. 9. Impact of tidal-stream energy extraction, from hypothetical TEC arrays positioned in the Skerries Channel (RUN-2.1–RUN-2.4), on total (tides + waves) bed shear stress. Results are shown at the point of energy extraction in the Skerries (a and b) and 10 km upstream/downstream at Langdon sand bank (c and d). Averaged bed shear stress during winter months (October–March; a and c) has been plotted separately to summer months (April–September; b and d). Natural variance in total bed shear stress (shaded areas) denote one standard deviation either side of the seasonal mean. Dotted lines (in a and b only) show the threshold of energy extraction where impact of the TEC arrays exceeds natural variability. The horizontal axis denotes the simulated mean TEC array power extraction over a spring-neap tidal cycle (the corresponding rated capacity of each simulation is shown in Table 1).

4. Discussion

The marine renewable industry is looking towards high velocity coastal regions, ideally close to locations where demand for electricity is large, as a low carbon source of energy to convert to electricity and sell commercially. We have examined how tidal-stream energy extraction affects sediment transport, being a nonlinear function of the current velocity and wave orbital motion, and also the sediment properties such as grain size and bed morphology. Suspended load transport, where lighter particles and less dense organic matter are transported in the water column, affects water quality and nutrient supply for marine species. Bed load transport of heavier particles just above the bed mediates coastal morphology and sediment supply to beaches and off-shore sand banks which protect the coast from wave impacts during storm events. These are important coastal processes which are not being routinely investigated as part of environmental impact assessments of marine renewable energy projects.

The impact of energy extraction on sediment dynamics has been assessed here in relation to natural variability of bed shear stress and sediment dynamics, caused primarily by intra-seasonal and inter-annual variations in the wave climate, since tidal energy dissipation largely remains constant over a year (in fact, we only simulate M_2 and S_2 tidal constituents which means natural variability in our study, beyond the spring-neap fortnightly cycle, is solely derived from the wave climate). Neill and Hashemi [8] predicted large variability in the wave energy resource over the northwest European shelf seas, particularly during winter months (i.e. 48 ± 7.3 kW/m which equates to approximately 30% variability), and they predicted similarities between wave energy patterns and the North Atlantic Oscillation (NAO). We estimate natural variabilities in bed shear stress of approximately 2% (5.24 ± 0.05 N m^{-2}) at the location of energy extraction (note that variabilities in bed shear stress cannot be directly related to variabilities in wave energy), which is substantially more than our simulated stress-impact due to first-generation energy extraction schemes (i.e. <50 MW arrays).

Like many tidally-dominated basins around the world, tidal asymmetry in the Irish Sea generates regions of bed load parting and convergence [19,40]. It was predicted by Neill et al. [2] that energy exploitation in a tidal channel (i.e. flow constrained laterally) with strong tidal asymmetry can produce sediment transport effects up to 50 km away. Indeed, sediment transport at the Skerries will be significantly affected by energy extraction of the order 52–87 MW (averaged over a spring-neap cycle), or a rated capacity of the order 85–165 MW, depending on the time of year. We define 'significant' here as the impact that exceeds levels of natural variability – winter months experiencing higher variability. Impacts further afield will be less, and the overall impact on the sediment flux through the Skerries has not been quantified. It is also worth noting that the proposed development at the Skerries will potentially involve a shut-down of production during extreme wave conditions (which coincides with the most dynamic sedimentary processes) in order to manage the loading acting on the turbines (S. Couch *pers. comm.*). This action would further reduce the impact of TEC devices on sediment dynamics (other than the contribution of the support structure).

Regions of high tidal dissipation can produce suspended sediment concentrations which generate turbidity maxima [13]. Strong tidal dissipation to the northwest of Anglesey generates a turbidity maximum which is vital to the summer biological productivity of the entire Irish Sea [14]. We have simulated suspended sediment volume concentrations in the region that correspond with observations collected during spring and autumn in 2012, and also with previous optical and satellite measurements [2,13]. Moreover, our modelled suspended sediment concentrations were maintained throughout a lunar cycle; a process that some other models have difficulty reproducing (e.g. Ref. [41]). Although we have shown that TEC arrays sited in such regions will impact upon suspended sediment volume concentrations, the impact is localised and relatively small, since seasonal variability is large (i.e. 35 ± 19 μl l^{-1} [11]). On reflection, therefore, even large-scale energy extraction at the Skerries is likely to have minimal impact on suspended sediment concentrations and the maintenance of the Anglesey Turbidity Maximum.

We have demonstrated that tidal-stream energy extraction can reduce regional velocities, away from the TEC array, where currents are usually weaker and sand accumulates, thereby altering the structure and maintenance of any offshore sand bank in such areas. Yet in our case study, it is unlikely that even a large TEC array will affect sand banks 10 km away, with regard to natural levels of variability in bed shear stress. This is a positive result for developers who are planning first-generation TEC arrays extracting less than 50 MW. However, we have also shown here that the impacts of TEC arrays will be site-specific and dependent on natural processes such as the incident wave climate and the occurrence of storm events. In regions and times of large variability in the wave climate (e.g. in northern Europe during winter months, when demand for energy is high), it may be the case that a large amount of energy can be extracted before local sand banks change above the level of natural variability. However, during more quiescent periods (e.g. in northern Europe during summer when demand for energy is lower and biological productivity is high), sediment processes are more sensitive to energy extraction. To further alleviate the sedimentary effects of TEC arrays, it has been postulated [1,42] that siting TEC arrays further off-shore from headlands, islands, and sand banks would reduce the impacts on coastal erosion, but at the price of increased installation and maintenance costs, and also reduced energy yield.

4.1. Assumptions and future recommendations

Computer models of coastal processes are formalised representations of reality; they contain ideas about hydrodynamics, waves, and sediment transport that are captured in formulations, but should not be viewed as actual representations [11]. In particular, sediment dynamics is complex and not fully understood. Nevertheless, we can advance our understanding about some procedures without understanding every detail in the process. It must be stressed that we have investigated only one geographic region in this study. The scale of natural variability varies spatially (e.g. Ref. [8]). We have assumed linear wave theory [5], which is not the case if waves become steep or breaking in shallow water. Hence this is a significant assumption, considering we also assume no wave–tide interactions, i.e. the tide modifying wave parameters [35], and wave–tide interactions near the bed [36,43,44]. As a consequence, there is uncertainty in our bed shear stress calculations; yet since we capture the observed storm events and predict the relative differences of bed shear stress, we can assume our results are reasonably accurate. Our simulated energy reduction in the system (Eq. (3)) only accounts for the energy production by the turbines (regarding one type of array configuration), it does not account for: machine efficiency losses (which are thought to be relatively small), support structure (drag) losses (which can be significant, particularly above rated power conditions), wake mixing losses downstream of the devices (also thought to be relatively small unless the array device density is high), and other more optimised array configurations (S. Couch *pers. comm.*). Hence our modelled flow reduction is not a complete representation and our simulation of environmental impact might be understated.

We show that waves and natural variability of wave induced bed shear stress is important. Hence future studies would be advised to improve on the above assumptions, and invest in more computational expensive schemes such as dynamically coupled wave–tide hydrodynamic models. Given sufficient computer power, high resolution three-dimensional models (e.g. Ref. [40]) can resolve wake effects from individual turbines and numerous array configurations. Simulated energy extraction coefficients should be parameterised to account for both the power extracted by the turbines and the power lost in the wake (i.e. capturing the total power dissipation, rather than just extraction). Based on the array density and assumed extraction coefficient, mixing losses will likely be on the order of 20–30% of total dissipation [45], although there will be significant uncertainty associated with this estimate since extraction will be variable below rated speed. Such models, run on high powered computing systems, could simulate decades of climate variability (e.g. Ref. [35]).

Our method for calculating total bed shear stress, τ_{total}, (Eq. (2)) produces mean total stress which relate to the sediment flux once particles are ‘in motion’ [5]. However, future studies may wish to also consider methods for calculating maximum total bed shear stress which induces bed stirring and the onset on sediment transport [5]. Considering maximum total bed shear stress is likely to increase levels of natural variability in the analysis. Finally, potential future changes to ‘storminess’ (e.g. Ref. [46]) could be assessed. In this context, Mitchell et al. [47] stated concerns about a future increase in storm events. In contrast, Lewis et al. [48] predicted that there will be no increase in storm events above levels of natural variability, considering climate projections such as UKCP09 [49].

5. Conclusions

A 2D, finite-element morphodynamic model of the Irish Sea has been used to simulate complex sedimentary processes in a region which is desirable for tidal-stream energy extraction, the Skerries (northwest Anglesey, UK). Simulated suspended sediment concentrations correspond to a turbidity maximum which is present in the region throughout the year and is important for the biological productivity of the Irish Sea. Simulations of bed shear stress and bed load transport reproduced established residual transport pathways and areas of sediment accretion where offshore sand banks form, which act as a natural form of coastal protection during storm events.

Our case study of energy extraction off northwest Anglesey has shown that first generation TEC arrays (of the order 10–50 MW) reduce velocities locally by only a few percent, and reduce bed shear stress and bed load transport by slightly more (suspended load transport is relatively unchanged, since TEC arrays induce locally increased turbidity). However, these changes were small compared to the range of natural variability and could therefore be considered negligible. It is only when a considerable proportion of energy was extracted from the system (e.g. greater than 50 MW) that sedimentary processes became significantly affected. Further afield (e.g. 10 km from the TEC array), it is unlikely that the impact of energy extraction on bed shear stress will ever exceed natural levels of variability, in all but the most quiescent wave periods, and most energetic (spring) tidal periods.

Our results reflect positively for the marine energy industry, and clarify the environmental implications that tidal-stream energy extraction may have in terms of sediment dynamics. For example, in northern Europe, wave-induced natural variability in bed shear stress is higher during winter months (when energy demand is high), enabling more energy to be extracted at low environmental cost than during summer months when energy demand is low and biological productivity is high.

However, since sedimentary processes and natural variability are controlled by waves, tides, sediment type, and morphology, the impact of energy extraction will always be site-specific. If we are to exploit the large tidal energy resource of the UK, and help reduce carbon emissions at low environmental cost, the sedimentary and morphological impacts of energy extraction should be considered at the site selection stage. This could mean compromising energy production and increasing maintenance costs in order to prevent issues arising from coastal erosion and sediment supply, and secondary effects on marine biodiversity.

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