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Influence of Tidal Energy Converters on sediment dynamics in tidal channel

Christelle Auguste, Jean-Roch Nader, Philip Marsh, and Remo Cossu

Abstract—**Tidal stream turbines are one of the most advanced marine renewable energy technologies. Nonetheless, the application of the technology faces considerable challenges, as uncertainties exist about the potential impacts of these devices on the marine environment. For instance, sediment dynamics have important implications to local fauna as well as turbine foundations, design and longevity. As a result, understanding of local sediment dynamics and its impact on the environment is an important element for site assessments. However, full-scale environment surveys of tidal farms are sparse and limited, as it is at early stage of development. An alternative to study the potential impacts on the sediment transport is numerical modelling. Nevertheless, validation of these models remains challenging as it is difficult to acquire the necessary sediment data from these high-energy sites.**

Hydrodynamic case studies for tidal farms exist for modeller to compare their results and insuring their models behave accurately. However, no similar case study can be found for sediment transport around tidal farms. The aim of this work is to understand the general sediment behaviour around tidal farms as well as setting a benchmark study for future modelling analysis. A series of idealised simulations, using hydrodynamic and sediment transport of MIKE21 and MIKE3 flexible mesh, are developed to investigate processes and interaction of Tidal Energy Converters (TECs) in an artificial high energetic flow system under a range of conditions (two different grain sizes, two layouts of arrays).

Findings from this study show that the 3D depth averaged velocity (DAV) is very similar to the 2D velocity: resulting in little change in bed level, less than 3% regionally, when DAV is used for sediment transport rates. However, using the bottom velocity of the 3D model generates different sediment behaviour at the vicinity of tidal arrays.

Keywords—**Environmental impact, numerical modelling, sediment transport, tidal turbines.**

I. Introduction

To reduce reliance on fossil fuels and to ameliorate climate change, the focus must be on renewable-energy solutions. The economic potential of tidal resource is reliable when compared to the other types of renewable energy, as tides are highly predictable with regular flood and ebb cycles, and thus can become a great contributor to the global energy industry. The application of the technology, nonetheless, still faces considerable challenges, as uncertainties exist about the potential influence of tidal energy devices on the marine environment [1]. The placement of Tidal Energy Converters (TECs) modifies the hydrodynamics properties of its environment by introducing a blockage as well as removing energy from the system [2]. These changes in turn, can influence the sediment dynamic of the surrounding.

Sediment and Suspended Sediment Concentration (SSC) in coastal water columns play a crucial role in the functioning and structuring of coastal ecosystems. They are influenced by parameters such as the current speed, waves, grain size and bed features. Of these parameters bed shear stress is the principal parameter acting on sediment dynamics [3], and thus a good indicator of potential change for sediment transport. Sediments are transported by the basic processes of entrainment, transportation and deposition. Once the particles are in motion, two modes of transport are generally distinguished: suspended load transport and bed load transport. These processes drive the mechanism of potential morphological change. They are the most important and unknown parameters in the morphodynamics behaviour of a site and can therefore impact offshore structures foundations moorings with scour, as well as the dynamics of sandbanks [4], [5]. Increased anthropogenic pressure in the marine environment, such as marine renewable energy

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technologies, pushes scientific community and tidal projects developers to better understand these various natural phenomena, their interactions and the influence induced by human activities.

Some surveys are underway at full scale, but the likelihood to obtain actual data of TECs interactions is limited. One of the best approaches to study the potential influence on the hydrodynamics and the sediment transport is numerical modelling of both the initial state without turbines and a state which includes turbines. There have been considerable advances in numerical models in recent years, in assessing the influence of TECs on hydrodynamic at promising tidal sites, however only a few studies have focused on environmental concerns, such as sediment transport [6], [7], [8], [9], [10], [11], [12], [13]. According to [14] numerical modelling has shown that in most cases the deployment of small arrays (<10 devices) has minimal impacts on the physical environment. However, changes in bed shear stress can appear for larger arrays, with the reduction in flow velocities being greater [1]. These conclusions are site-specific and dependent on device design. On the other hand, laboratory studies investigating sediment transport around TECS are very scarce [15], [16]. All these studies highlight the important interactions between current flow, sediment and turbines properties.

The current study uses the numerical model MIKE21 Flexible Mesh (FM) and MIKE 3 FM to develop and tests numerical approaches to assess the hydrodynamic and sediment dynamics in an idealised dynamic channel and the impact of the introduction of TECs in the channel on sediment transport parameters. Using a high resolution model, changes in hydrodynamic and sediment transport processes under various conditions were investigated. The outcomes of this work will be helpful for future studies to compare the behaviour of different models. This work presents the modelling methodology applied to the theoretical channel in section 2, section 3 includes the results and section 4 consists of discussion.

II. THE MODEL

A. General Description

MIKE models are commercial numerical software packages that include various modules to simulate hydrodynamics, waves, sediment transport, and morphological changes. They have been widely used in the marine renewable energy field: tidal energy[9], [17], [18], wave energy [19] ,[20], [21], and in coastal processes [22],[23],[24]. The MIKE21 FM & MIKE3 FM hydrodynamic models are based on the cell-centred finite volume method, with unstructured mesh that allow accurate discretisation of the area. The model solves the Reynolds-averaged Navier-Stokes (RANS) equations in two/three dimensions, with the Boussinesq assumption as to the representation of turbulence by eddy viscosity and hydrostatic pressure. A detailed description of the models can be found in [25]. For sediment transport in this high energetic flow, the Sand Transport (ST) module quasi 3D (non-cohesive sediment) is used. The ST predictions are achieved using a mean horizontal velocity component, set to the depth averaged current velocity (2D/3D), or derived from the bottom stress value from the 3D hydrodynamic model. The ST model determines the transport of non-cohesive particle based on hydrodynamic conditions and sediment properties. Sediment motion is occurring in the model when the value of the dimensionless bed shear stress (Shields parameter) exceed the threshold value (critical Shields parameter). For this study, sediment transport is calculated applying commonly used van Rijn equations [26], which applies to total (bed load and suspended load) sediment transport. For the morphology the sediment continuity equations, Exner equations [26], are solved at each timestep, with the total bed level change (bed load + suspended load) calculated.

1) Numerical Domain

An idealised theoretical channel-bay system was created to represent a basic tidal channel with simplified bathymetry in first instance (Fig. 1). The domain is based on the test case developed by [27], [28] and expanded by [29], to enable validation of the hydrodynamic model. The tidal system is composed of a channel between a tidal bay and a shallow area of the open ocean (with dimensions in Table I) and with a tidal surface forcing of one meter applied on the open ocean boundary. To compare the model with the study from [29], the Coriolis force was not considered.

2) Implementation of turbines

To model tidal turbines, MIKE 21/3 provides an in-built tool structure called "Turbines". It represents a tidal turbine as a sub-grid object, and turbines are implemented as a momentum sink based on actuator disc theory. The effect to the flow due to the turbines is modelled by calculating the current induced drag and lift force on each individual layer [25].

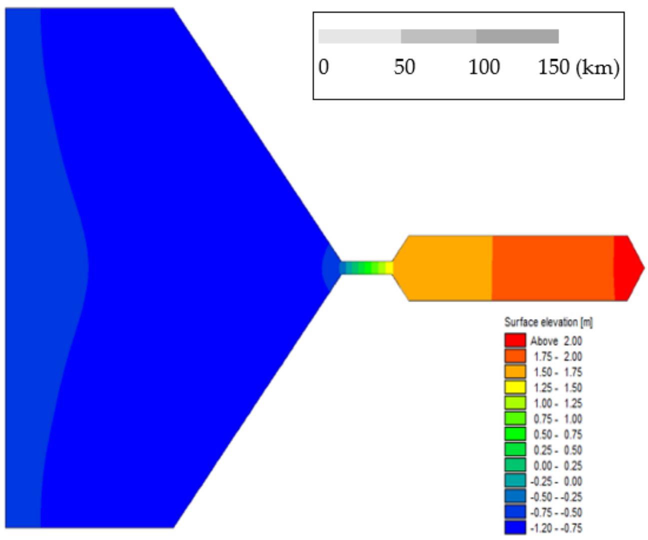


Fig. 1. Surface Elevation in the domain.

TABLE I
GEOMETRY OF THE DOMAIN

Domain	Length (km)	Width (km)	Depth (m)
Open ocean	200	240	200
Tidal Channel	30	6	60
Tidal Bay	150	30	100

The effective drag force, F_D and F_L are defined as:

$$F_D = \frac{1}{2}\rho\alpha C_D A_e U_0^2 \quad (1)$$

$$F_L = \frac{1}{2}\rho\alpha C_L A_e U_0^2 \quad (2)$$

where ρ is the density of water (equal to 1025 kg/m^3), α a correction factor (set to 1 in this study), C_D is the drag coefficient, $C_L$is the lift coefficient, A_e is the effective area of turbine exposed to current and U_0 is the upstream current speed. The power generated by the TECs can be calculated using:

$$P = \frac{1}{2}\rho C_T A_b \overline{U}^3 \quad (3)$$

where A_b is the turbine cross-sectional area and $\overline{U}$ is the average of tidal current speed over a tidal cycle. For this study it is considered that the turbines face the flow at all time and thus C_D = C_T (thrust coefficient) and C_L = 0. To implement the turbines in MIKE , the MATLAB scripts developed by [17] were used.

B. *Validation of the tidal energy extraction model*

The first step of this study was to validate the 2D MIKE model for tidal energy extraction by comparing it against a 2D Marine and HydroKinetic module in Finite Volume Coastal Ocean Model (MHK model) developed by [29]. They previously validated their model against a 1D analytical model [27].

In order to compare the simulations with the 2D MHK model, the same parameters for the TECs are used: C_T was set to 0.5, the diameter of the turbine was set to 10m given A_b equal to 78.54 m^2, and the hub height was set to 10m. The baseline condition was the simulation without the presence of TECs. Five cases with the presence of TECs were then conducted corresponding to: one, two, five, six and nine turbines implemented in each cell of the tidal channel (comprised of 10855 cells). Fig. 2 shows the extractable power as function of the total number of tidal turbines in the channel, and the comparison with the results from literature [29] (data were given in personal communication, 26/01/19). Model results closely matches the results of the MHK model [29] with a maximum difference of extractable power within 5%. Minor discrepancies can be explained by mesh differences between the numerical models, as the channel was here

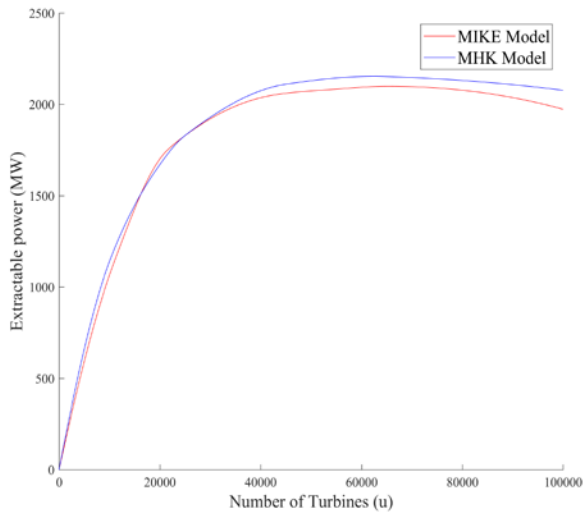


Fig. 2. Predicted extractable power as a function of number of turbines.

discretised with a finer unstructured mesh of 10 855 elements compared to the 1 140 elements MHK model [29].

Concern about the dependence of drag force on mesh size raised by [30] and [31] in the 2012 release of MIKE is corrected in the 2017 version, for more detail see [32]. To ensure this, tests cases were performed in the domain to check the application of the corrected drag force. Four meshes with different face length: 600m, 300m,100m and 50m were created.

The models were run for 7 days, first without turbines then with a single turbine in the middle of the tidal channel. The TECs was: 20m in diameter and had a thrust coefficient of 0.9. The difference between the predicted current speed with and without the turbine is within 1% as indicated by [30] and [31] in their correction.

C. *Building 2D scenarios for the influence of TECs on sediment dynamics*

A series of simulations with arrays of 50, 75, 100, 300 and 500 turbines was modelled. Two layouts were tested (see Fig. 3): (1) fences of turbines in the middle of the channel occupying the entire width of the channel with a monotonous spacing (although the spacing varied depending of the number of turbines) and, (2) a tidal farm in the middle of channel with a spacing about 10 diameters longitudinally, and with line (s) of 50 turbines each. The results of these were then compared with the baseline case where no TECs were installed.

Four days were simulated (with an additional 12h spin up to avoid any start up transients) with a timestep of 600s. The element size of the mesh varied in the domain. Coarser elements of 3km typical size were used in the outer domain. A finer resolution was imposed in the channel with a mesh size of 180m and reaching down to the turbine diameter around the TEC arrays, for more accuracy in this area.

The MIKE turbines parameters were as follows: C_T was set to 0.85, the diameter of turbines to 20m and the hub

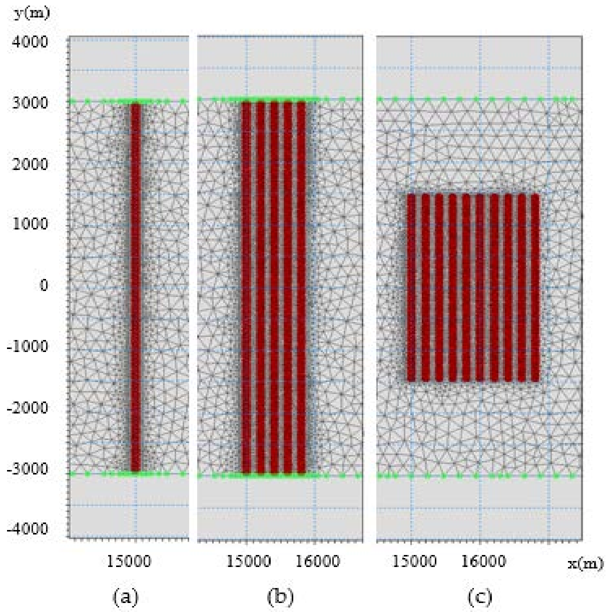


Fig. 3. Layouts of TECs in the tidal channel. (a): One fence for 50T/75T/100T cases, (b) 3 or 5 fences for 300T/500T cases and (c) the configuration for tidal farms.

height to 17m, values commonly used in the literature [9],[13]. Mannings number of 37.5 was used for the bed resistance. Following previous modelling studies in tidal energy sites [6,8] and preliminary insitu measurements in promising tidal energy site (Banks Strait, Tasmania), the grain size was set to 300mm (medium sand) for all the cases. Additionally, a 100mm grain size (very fine sand) was also applied for the tidal farm cases, in order to perform sensitivity test. The morphological boundary conditions were set to zero sediment flux gradient and the equilibrium conditions was chosen for sediment transport.

To evaluate the difference between 2D and 3D, three simulation was run on 3D using the same settings as in 2D, but with 12 layers on vertical profile. The only change to the 2D set up was for the bed resistance where the roughness height was used and calculated from the Manning's number.

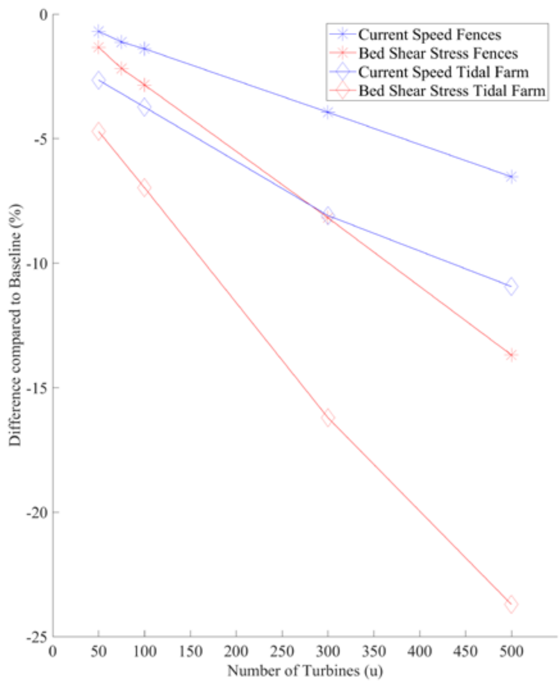


Fig. 5. Difference in percentage compared to baseline model for Fences and Tidal Farm at the profile Pr1.

III. RESULTS

D. Hydrodynamics

1) Two-Dimensional

Baseline models' velocities are strongest in the tidal channel, with a maximum of 4m/s whereas in open ocean and bay, velocities generally do not exceed 0.5m/s. The baseline comparison shows that mesh density does not significantly influence the results: less than 5%. For the profile Pr1 (14900/34000;0) shown in Fig.4 the mean velocity is 1.9m/s for fence configuration and 1.96m/s for tidal farm configuration. The average bed shear stress for fence configuration is 8.3 Pa and 8.7 Pa for tidal farm.

Fig. 5 shows the difference in percentage for both layouts compared to the baseline model for current speed and bed shear stress at profile Pr1. The depth averages

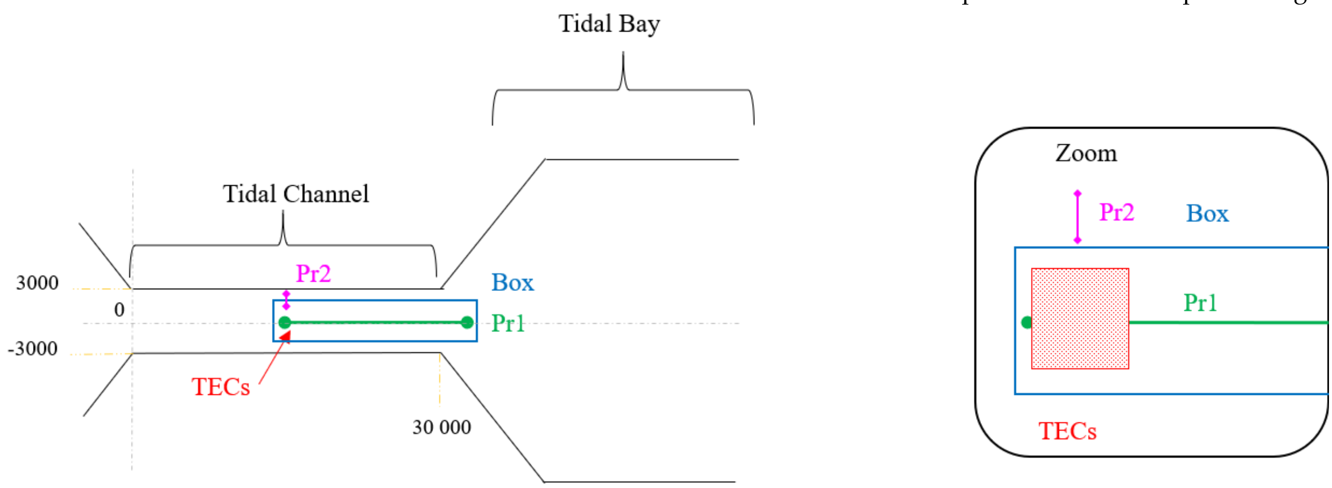


Fig. 4. Domain schematisation: (not to scale) Location of longitudinal profile Pr1, transversal Pr2 and the box.

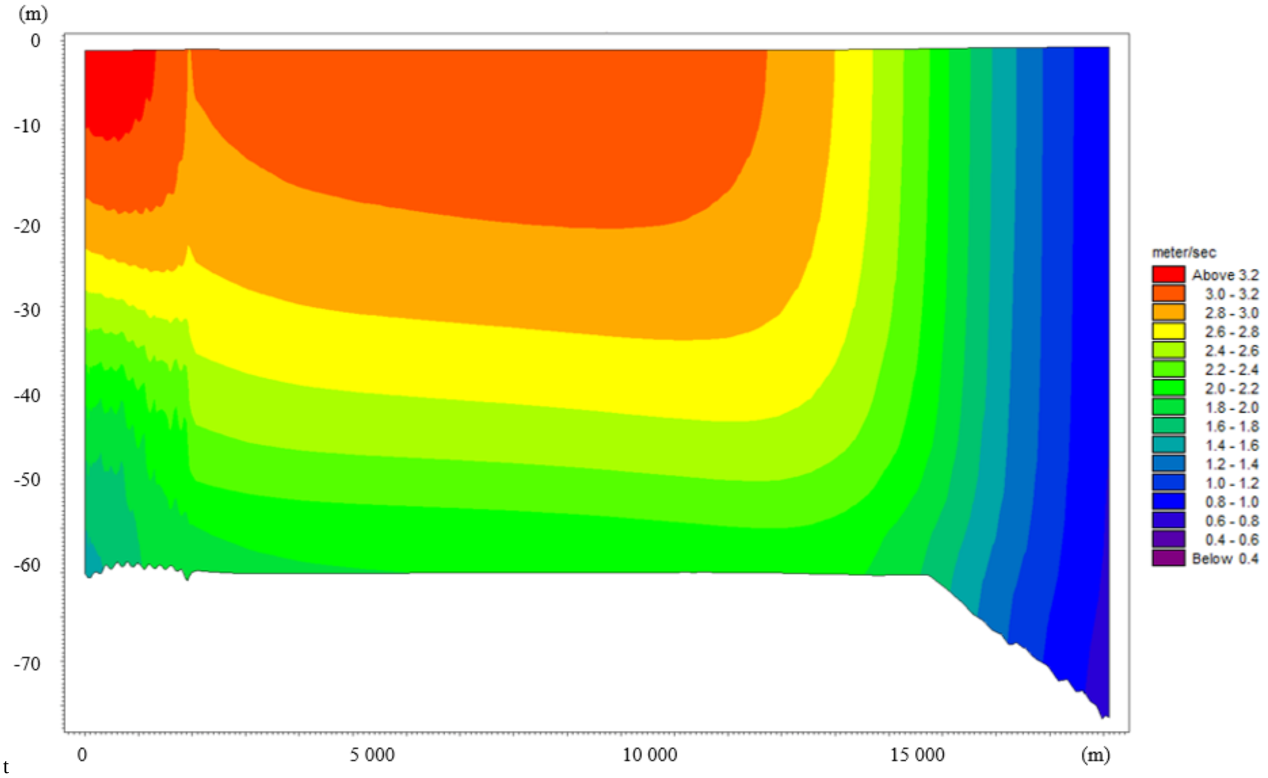


Fig. 6. Current Speed at Pr1 for the simulation of tidal farm with 500TECs in 3D (T=92h).

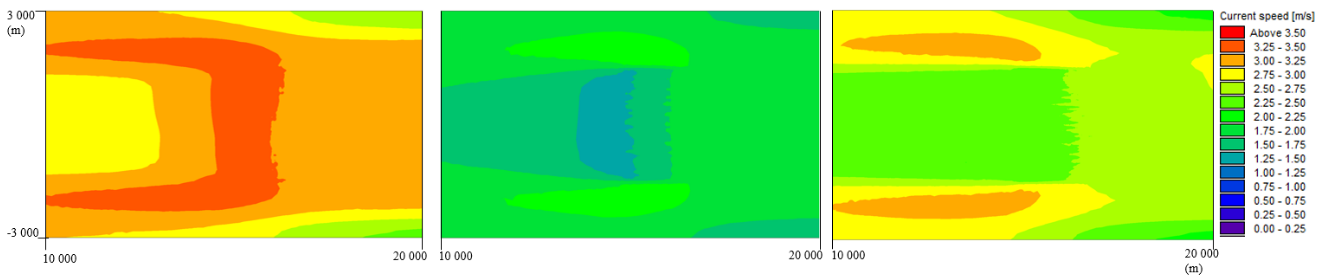
velocities in the tidal channel were reduced by only a few percent (less than 1.4%) under the 100 TECs condition and reached 6.5% for 500 TECs for the fence layout. The changes in current speeds for the implementation of a tidal farm is greater than for the fence layout: a deficit of 2.65% compared to 10.94%. The reduction in current speed is larger for layout tidal farm: a decrease of 7% between 100 and 500 turbines, instead of 5% for the case of the fences. The fence layout has less impact on the reduction of bed shear stress: it still acts as a barrier but with smaller far field effects than seen in with the tidal farm configuration. Reduction in current speed implies that there is accretion: maximum reduction of 8Pa for a tidal farm of 500 TECs, at the vicinity of the array.

While there is mainly reduction in the domain, on either side of the tidal farm, as expected, bed shear stresses increase locally (not shown). Between the boundaries and the tidal farm, the flow is accelerated by constriction. In the cross-stream profile Pr2 (16000;3000/1500) bed shear stress increase is 0.040 Pa on average (corresponding to a 0.40% increase of the undisturbed flow), with a maximum value of 0.25 Pa.

2) Three-Dimensional

Simulation was performed in 3D for the tidal farm of 500 TECs, with results shown in Fig. 6 for current speed along profile Pr1. Changes in the bathymetry can also be observed, with erosion before and after the tidal farm and accretion with the maximum value of 1.2m in the tidal farm. Compared to the 3D baseline, there is a reduction of velocities of 10% in the vicinity of the tidal farm, and an average of 6.81% for the entire profile.

The mean difference between 2D and 3D model in velocity for Pr1 is only of 0.75% for the entire profile but reaches 3.45% for the area of the tidal farm. The acceleration of the flow due to barrier effects is better reproduced in the 3D model. Fig. 7 shows the comparison of current speed at the location of the tidal farm for 2D and 3D models. As a 2D model can only provide depth averaged velocities, the complex flow at the vicinity of the tidal farm cannot be identified. Results from the 3D simulation however, show considerable difference between the bottom and surface velocity distribution. In the 3D model the flow is not uniform with depth and does



(a) 3D Surface layer (b) 3D Bottom layer (c) 2D

Fig. 7. Comparison of current speed at Pr1 for 2D and 3D models for a tidal farm of 500 TECs (T=92h).

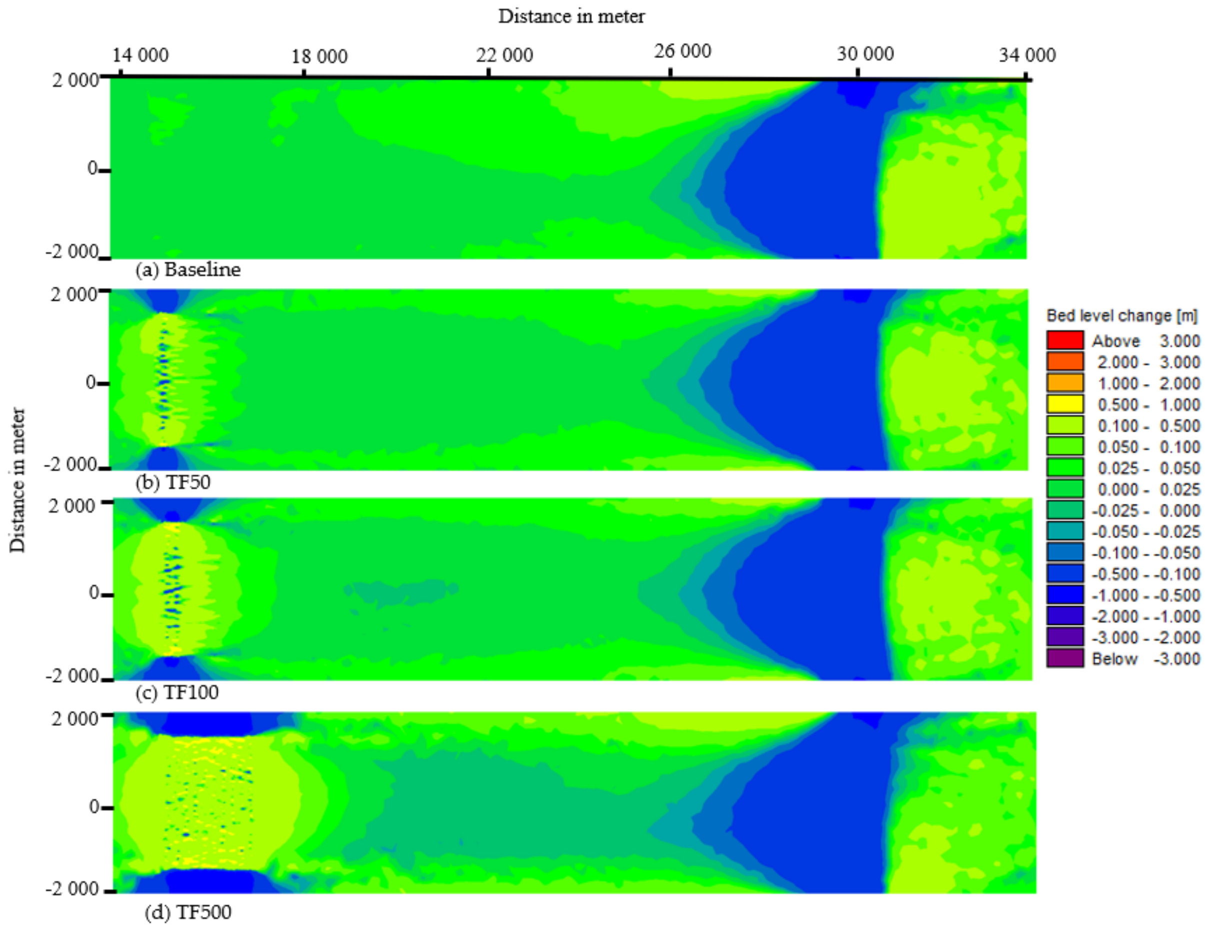


Fig. 8. Bed Level Change for Tidal Farms at the location of the box (see Fig. 4).

not follow a power law vertical profile.

E. *Sediment dynamics*

1) *Grain size= 300 microns/ Two-dimensional*

Fig. 8 shows the bed level change in the middle of the channel between the baseline model and various configurations of tidal farms. Due to strong flows between the tidal farm and the boundaries, the bed is eroded at either side of the channel (depicted by blue shaded areas). Where strong flows occur (above 3m/s), the total load transport is greater allowing less deposition. The bed level change in this area is significant as it reaches -0.37m locally corresponding to a 0.36m increasing of the bed level change baseline.

Erosion can also be observed at the transition between the tidal channel and the tidal bay. The tidal range is limited in this area, which due to the principles of mass

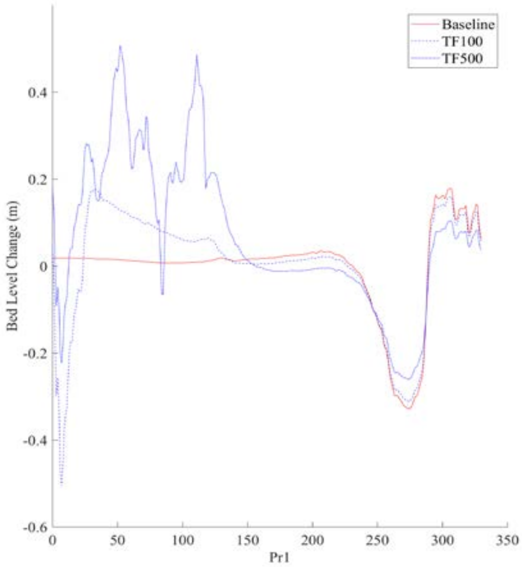


Fig. 9. Bed Level Change at Pr1 for tidal farms and baseline (T=92h).

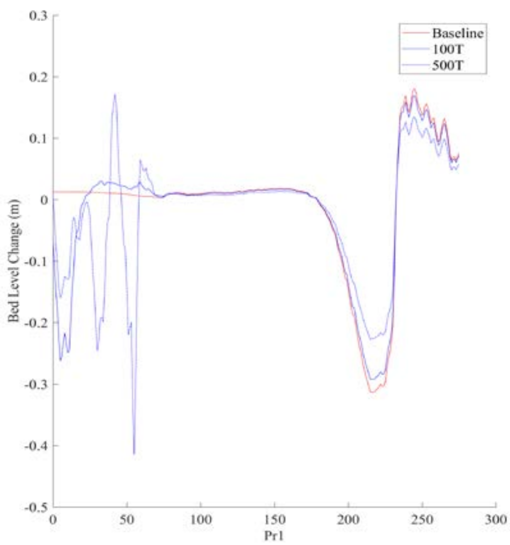


Fig. 10. Bed Level Change at Pr1 for a fences and baseline (T=92h).

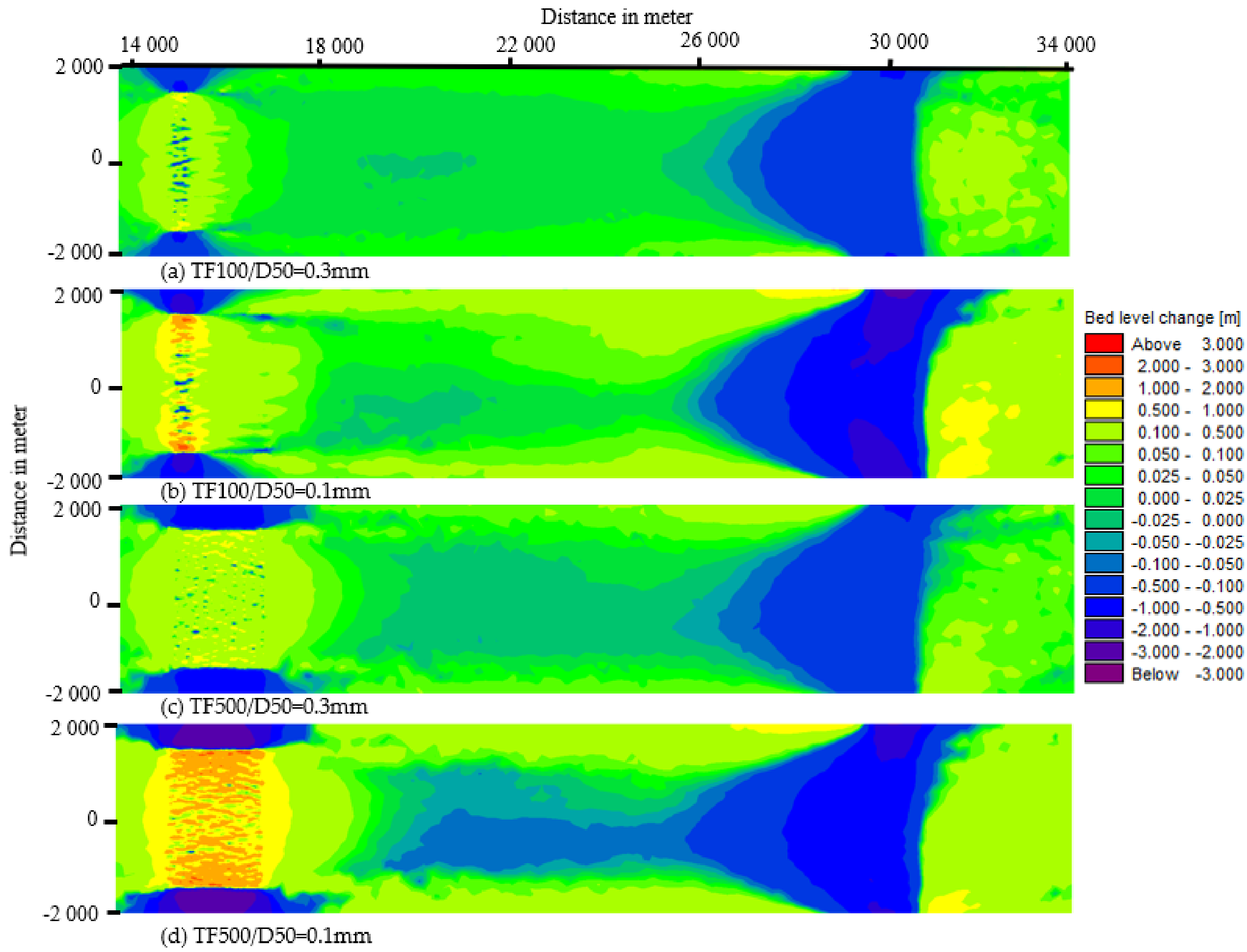


Fig. 11. Comparison of Bed Level Change for different grain size for Tidal Farms (T=92h) at the location of the box (see Fig. 4).

conservation is driving the acceleration of the flow. The bed level change is insignificant compared to baseline variability in this area, as shown in Fig. 8 and 9.

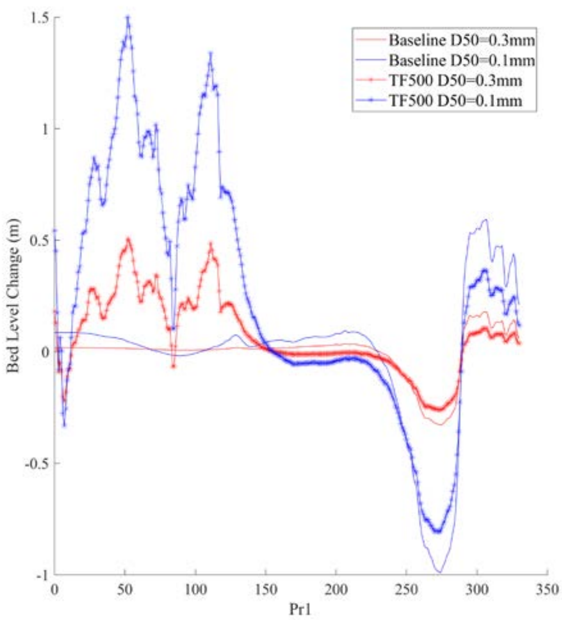


Fig. 12. Comparison of bed level change at Pr1 for two different grain size for baseline and tidal farm of 500 TECs (T=92h).

Fig. 9 illustrates the bed level change along Pr1 at T=92h for the baseline, 100 and 500 TECs tidal farm models. In the turbines arrays the difference is important up to 0.5m of accumulation of sediment. The flow reduction in the tidal farm allows deposition within the turbine's arrays. Fig. 10 shows the same comparison but for the fence configuration.

The change due to the TECs is different at the location of the arrays, erosion occurs compared to the layout tidal farm. The reduction of velocities in the configuration of fence is lower, allowing particles to be transported beyond the array.

2) *Grain size= 100 microns/Two-dimensional*

The bed level change predicted for two different grain size is presented in Fig. 11 and 12. As expected the variations in bed level for a grain size of 0.1mm is bigger than for 0.3mm over 4 days of simulation as the critical bed shear stress for the entrainment of particles is lower for finer particles [33], see Table II.

For Pr1 the mean difference of bed level change between the two grain sizes for a tidal farm of 500 TECs is 0.17m and reaches 1m in the area of the tidal farm.

3) *Three-dimensional*

For 3D simulations, the mean horizontal velocity component used for sediment transport calculation is

TABLE II
CRITICAL SHEAR STRESS FOR DIFFERENT GRAIN SIZE (FROM [33])

Sediment Class	Diameter(mm)	Critical bed shear stress (Pa)
Coarse Sand	0.5-1	0.27-0.47
Medium Sand	0.25-0.5	0.194-0.27
Fine Sand	0.125-0.25	0.145-0.194
Very fine Sand	0.0625-0.125	0.110-0.145

derived from the bottom stress value from the hydrodynamic module in the first simulation (3D-BS) , and by the depth-averaged velocity in simulation 2 (3D-DAV). For the first one, the mean velocity component is given by:

$$\bar{V} = \sqrt{\frac{\tau_b}{\rho c_f}} \quad (4)$$

where τ_b is the bottom stress value and c_f is the drag coefficient. Fig. 13 illustrates the comparison of bed level change at Pr1 for the 2D and 3D models. The mean difference all along the profile Pr1 is not significant: around 0,06m. But when the focus is on the area of tidal farm the mean difference is 0.34m with a maximum of 1.24m.

Fig. 14 highlights the difference between the 3 models: the 3D-BS model captures more accurately the flow around the tidal arrays than the models based on depth averaged velocity. The accumulation of sediment in the tidal farm is bigger in 3D-BS model and new zone of erosion also appears at the vicinity of the arrays, which can also be observed in Fig. 14. The 3D-BS model captures the acceleration caused by the constriction of the flow near the sea bed under the TECs. The maximum value of bed level change is 1.20m in the array. Compared to the 2D value (0.48m) it is an increase of 0.7m. The difference between 3D-DAV and 2D model for Pr1 is not considerable, less than 3%.

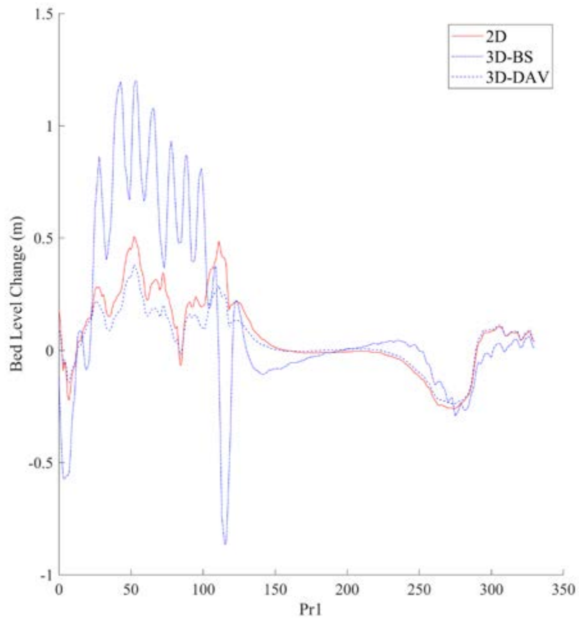


Fig. 13. Bed Level Change for a tidal farm of 500 TECs for simulation in 2D and 3D (BS=Bottom Stress; DAV=Depth Average Velocities)(T=92h).

Fig. 15 shows the difference of bed level change between the 3D-BS and 2D model. The major difference is in the tidal farm (+/- 1m), then gradually reduce to reach a 0.01m difference at 6km from the array.

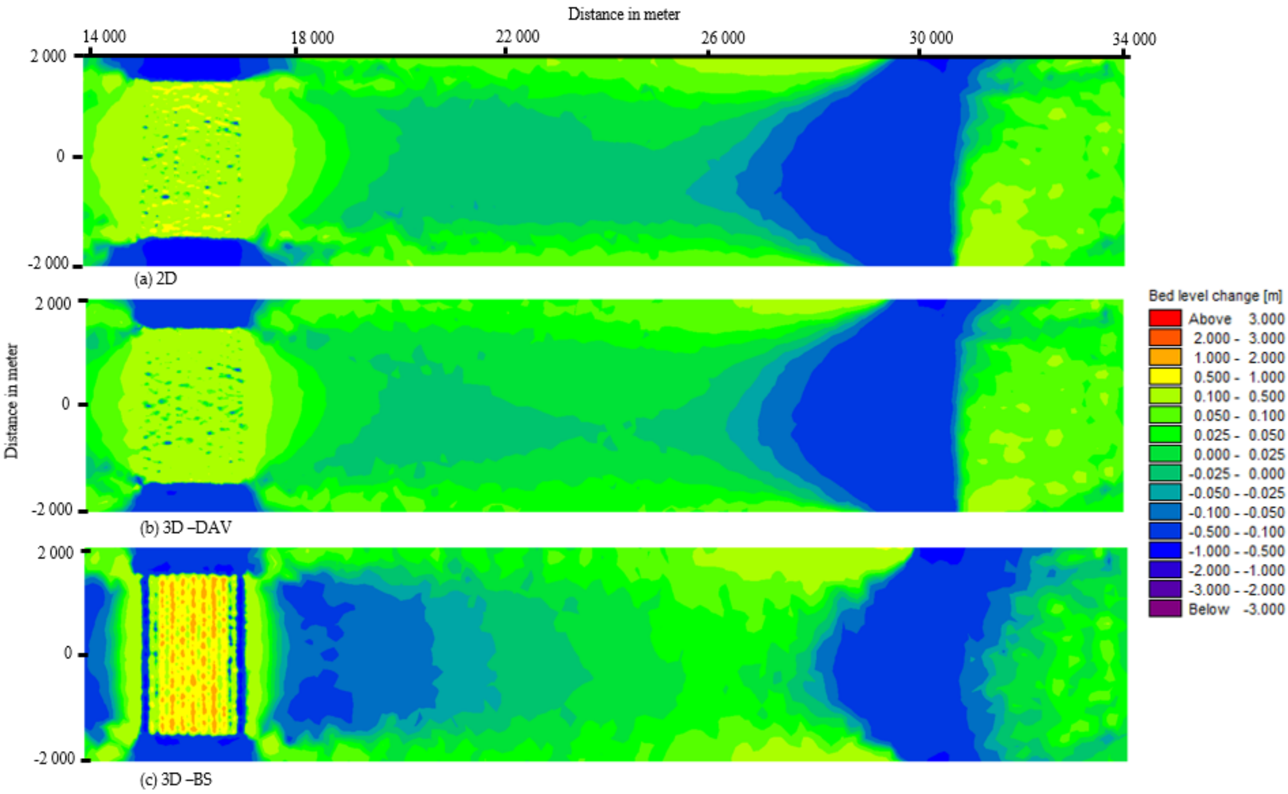


Fig. 14. Comparison of 2D and 3D simulations for bed level change for a tidal farm of 500TECs (T=92h) at the location of the box (see Fig. 4).

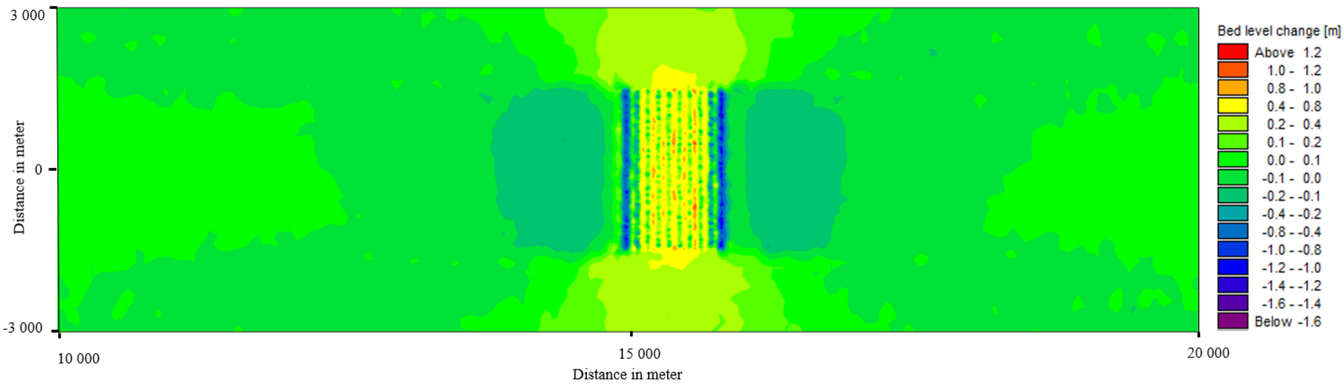


Fig. 15. Difference of bed level change between 3D-BS and 2D in the middle of the channel for a tidal farm of 500 TECs (T=92h).

IV. Discussion

The modelling results in the theoretical channel closely matches some others modelling studies of real sites. The reduction of the current speed is significant (7-11%) which is in agreement to others studies [7], [10]. This study confirms that placement of large arrays of TECs could alter erosion on either side of the array and could lead to an accumulation of sediment in the TECs arrays, increasing maintenance costs. In each layout the impact on sediment dynamics under 100 turbines was minimal, such as in [1]. This reflects positive outcome for the tidal energy industry for deployment of tidal farms at smaller scale.

From hydrodynamic analysis, 2D model gives an accurate representation of the depth-averaged velocity, in and around the tidal farm. However, when applied to sediment transport analysis, large discrepancies are found between the 2D and 3D models. These differences emerged from the methods in which the bed shear stress is derived from these models. Because TECs strongly impact on the velocity profile, the later does not follow the typical power law and large differences are expected to be found between the bottom shear stress derived from the mean velocity as in the 2D or the 3D-DAV as that from the one obtained with the 3D-BS model. The 3D-BS model is more accurate and realistic in the vicinity of the arrays, but at higher computational cost. The 2D model were computationally more efficient: 9 times faster than the simulation in 3D. Although a two-dimensional hydrodynamic model is useful in many situations and are still commonly applied for sediment transport model, it is also limited to its depth-averaged equations and thereby unable to resolve the vertical flow structure and the mixing in the wake of turbine. A three-dimensional model, though more complex and CPU intensive, can determine the vertical distribution of currents in the water column needed for the dynamics of sediment and for underwater structures [34].

This paper shows that 3D model is powerful tool to capture the depth varied velocities around structure and have accurate results on the change of sediment dynamics of the near field or at the location of the array with the 3D-BS method. It follows that, in order to study the sediment dynamic around a tidal farm, a full 3D model is strongly recommended. The spatial extend from which the tidal farm impacts on the sediment dynamic is still to be investigated.

There are several limitations and caution should be applied to these results. Firstly, the channel is not realistic: constant bathymetry in the tidal channel and uniform grain size without rock area. The domain is not perfectly symmetric due to the unstructured mesh. No validation exists for a theoretical channel, only comparison before/after are possible. In addition, only model tidal currents have been studied, further investigations need to be performed with the impact of wind and waves. This will be part of the next step of the project.

V. Conclusion

To the knowledge of the authors, this study defines, for the first time, a benchmark for interactions of TECs on sediment transport. This would serve for future studies to test the sensitivity of their models and will be the base to better understand the potential impacts of TECs on the sediment dynamics in real sites.

This study shows: (1) MIKE 21/3 FM can be used for tidal energy extraction modelling, (2) Beyond 100 turbines, the impact of TECs arrays become significant, (3) 2D model gives accurate results for the sediment dynamics away from the tidal farm, but 3D model using the bottom velocity for sediment transport rates is needed for more accurate result in the tidal farm.

This is the first step of a larger project whose ultimate aim is to use multiples test cases to improve the prediction of the effects of TECs on sediment transport in Banks Strait, Tasmania, a promising tidal energy site, identified as part of the ARENA "Tidal Energy in Australia – Assessing Resource and Feasibility to Australia's Future Energy Mix" project.

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