2019 IMEKO TC-19 International Workshop on
Metrology for the Sea
Genoa, Italy, October 3-5, 2019

Turbulence changes due to a tidal stream turbine operation in the Pentland Firth (Scotland, UK)

Simone Zazzini[1], Michela De Dominicis[2], Agnese Pini[1], Giovanni Leuzzi[1], Paolo Monti[1], Rory O’Hara Murray[3], Xiaorong Li[4]

[1] *DICEA, University of Rome “La Sapienza”, via Eudossiana 18, Rome, Italy, simone.zazz@gmail.com, agnese.pini@uniroma1.it, giovanni.leuzzi@uniroma1.it, paolo.monti@uniroma1.it*
[2] *Marine System Modelling group, National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool, UK, micdom@noc.ac.uk*
[3] *Oceanography Group, Marine Scotland Science, Aberdeen, Scotland UK, r.murray@marlab.ac.uk*
[4] *Geography and Planning Department, University of Liverpool, Liverpool, UK, xiaorong.li@liverpool.ac.uk*

***Abstract* – The high tidal stream resource in the Pentland Firth (Scotland, UK) has encouraged the development of commercial scale tidal farms.**

This work is a modelling study primarily focused on how the layout of arrays determines the extractable power and may affect physical processes in the region. Furthermore, the study provides information about submarine turbine maintenance. Tidal dynamics in the Pentland Firth and Orkney Waters (PFOW) have been reproduced by a three-dimensional FVCOM model implementation. The tidal stream turbines were represented in the model as sub grid scale objects by using a momentum sink approach.

It has been explored how different turbine location, number and spacing can allow achieving very different amount of power resource, as well as degree of change to flow velocities. It has also been verified that turbulence changes can lead to an increase in bottom currents in the vicinity of the tidal turbines.

I. INTRODUCTION

During recent years, tidal stream energy sector is receiving significant attention as an alternative way to produce energy. Oceanic tides can be considered as a potential source of energy thanks to their consistent predictability and availability. A tidal stream power plant is structured by several turbines anchored to the sea bed which extract energy from the current flow. They are a stranger body in the marine environment and they represent a significant obstacle for the currents. In terms of hydrodynamics, energy extraction modifies the sea surface elevation and marine currents speed, consequently the transport of sediments, nutrients and microorganisms could be changed.

The domain analysed in this study is the Pentland Firth (UK), which is a channel suitable for tidal energy extraction thanks to high-speed tidal currents that flow between Scotland’s mainland and the Orkney Islands.

During recent years, many modelling studies on tidal energy extraction were carried out. In fact, hydrodynamic models help to understand how tidal stream turbine operation impacts the marine environment. The studies [1-3] looked at the changes on hydrodynamics induced by tidal energy extraction and at the effects of turbulence modifications by one turbine. This work is a modelling study which aims to investigate some aspects that were not explored in previous studies: how the layout of the array (location, number of turbines, spacing between turbines) influences the amount of power resource that could be extracted and the changes to current velocities and sea surface elevation; but in particular, the turbulence changes in the wake of the turbine.

II. METHODOLOGY

A. *Pentland Firth and Orkney Waters (PFOW) model*

In this study, a high spatial resolution three-dimensional FVCOM model [4] implementation for the Pentland Firth and Orkney Waters (PFOW), outlined in [2][5], was used. The model domain includes a portion of the Atlantic Ocean covering Orkney and Shetland Islands waters (north of Scotland) and a portion of the North Sea; latitude and longitude are from 57°N to 62°N and 6°W to 1°E. The resolution of the unstructured grid is typically in the PFOW region between 150 and 250 m, further away from the PFOW the resolution is 1-2 km. The model has 10 following-terrain vertical sigma layers. The PFOW bathymetry is originated from high resolution multibeam echo sounder data from the UK Hydrographic Office and Marine Scotland Science and from digitalised Admiralty Chart data. Further away from the Pentland Firth,

Table 1. Table of experiments.

Array	Number of turbines	C_T	Maximum extractable power [GW]	Mean extractable power [GW]
TeraWatt Pentland Firth	800	0.85	1.53	0.32
		variable	1.09	0.29
TeraWatt Brough Ness	100	0.85	0.38	0.05
		variable	0.23	0.05
TeraWatt Brims	200	0.85	0.51	0.09
		variable	0.27	0.08
TeraWatt Inner Sound	400	0.85	0.74	0.15
		variable	0.70	0.13
TeraWatt Ness of Duncansby	100	0.85	0.19	0.03
		variable	0.14	0.03

bathymetry data come from the European Marine Observation and Data Network (EMODnet). The data were converted to a common vertical datum and interpolated to the unstructured grid.

In order to simulate tidal dynamics, the model is forced at the boundaries by 8 tidal constituents (M_2, S_2, N_2, K_1, O_1, Q_1, P_1, K_2) computed by a tidal model based on the Oregon State University tidal inversion of TOPEX/POSEIDON altimeter data [5].

B. Turbine parameterisation

In the parameterisation implemented by [2], the tidal turbine is represented in the model adding a sink term in the momentum equation, as outlined in [6].

Similarly, in [3] turbines are modelled using the sub-grid scale momentum sink method outlined in [7]. In addition, [3] tidal stream turbine parameterisation considers also that the turbine perturbs turbulence in its wake. So, the TKE equations were modified, in the way suggested by [8], adding a turbine-induced turbulence generation term, a turbine-induced turbulence dissipation term and a term which considers the interference for the turbulence length-scale. TKE equations are closed physically and mathematically using the Mellor and Yamada level-2.5 (MY-2.5) turbulent closure [9] modified by Galperin [10]. Considering the purpose of this study, it is acceptable to model a generic tidal turbine with the following features: 20 m diameter rotor turbine anchored to the seabed, nominal capacity of 2.5 MW, rated speed of 2.5 m/s and cut-in and cut-out speed of 1 m/s and 4 m/s, respectively.

Turbines were modelled in PFOW model assuming that a yaw mechanism allows the turbine to be always in the flow direction. Furthermore, [2] parameterisation permits to consider that a turbine has usually cut-in and cut-out velocity, so, the turbine thrust coefficient C_T can be considered constant or varied as a function of the flow speed; while it is not accounted in [3].

C. Turbine arrays

Many different arrays of turbines in the Pentland Firth were simulated. Considering that the turbine hub height was fixed at 15 m above sea-bed and the blade diameter is about 20 m, turbines were not located in grid elements where water depth is less than 27.5 m. This allowed the turbines to remain submerged at all tidal states.

The location of the turbines of the TeraWatt Pentland array is shown in Fig. 1. The array is composed of 800 turbines, which are located in 4 different positions: 200 turbines are located south of the island of Hoy, 400 between the Scottish mainland and Swona, 100 between South Ronaldsay and the island of Muckle Sherry and 100 turbines at the end of Pentland Firth channel, i. e. where the Atlantic Ocean waters enter in the North Sea.

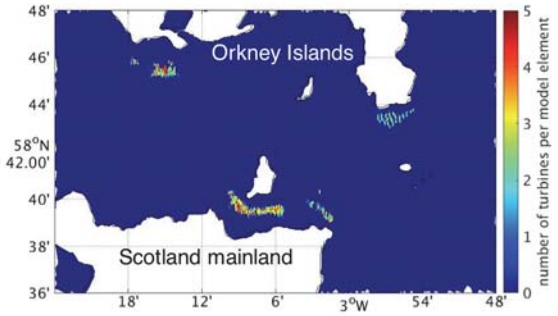

Fig. 1. TeraWatt Pentland turbine location

III. RESULTS

D. Tidal resource

The maximum average power density in the Pentland

Firth, estimated from a 30 days PFOW model run forced by the aforementioned tidal constituents without including any feedbacks of tidal array on the flow (undisturbed resource), is in the middle of the channel between Scotland and Orkney Islands; it could reach 10 kW/m^2 north of Stroma and it is related to the maximum currents speed.

Different arrays of turbines could extract different amount of power from the tidal flow depending on diverse location, number of turbines and spacing between turbines. For each array, the instantaneous tidal stream power extracted at any instant of time, has been calculated as:

$$P(t) = \frac{1}{2}\rho A_b C_T |\overrightarrow{u_T}|^3 \qquad (1)$$

where A_b is the flow facing area of a turbines, $\overrightarrow{u_T} = \sum_{\sigma=1}^{\sigma=k} K_\sigma \overrightarrow{u_\sigma}$ is the weighted average velocity vector over the diameter of the tidal turbine, $\overrightarrow{u_\sigma}$ is the flow velocity vector at the σ layer and k is the number of sigma layers. In Tab. 1 the amount of extracted power by different arrays are reported, considering that the turbine thrust coefficient C_T can be constant or varied as a function of the flow speed. The TeraWatt Pentland Firth array can provide 1.53 GW as maximum power and 0.32 GW on average with a constant C_T. On the other hand, with a variable C_T the maximum power and mean power are 1.09 GW and 0.29 GW, respectively.

E. Environmental effects

Different array layouts can cause different changes in current speed and surface elevation. In this work the maximum differences of velocities induced by energy extraction were analysed. Results presented in Fig. 2 (a)-(d) show that, in all the considered arrays, a deceleration occurs where turbines are located and in the wake of them and consequently, an acceleration arises at both sides of the array.

Furthermore, the changes to the high and low tide level were studied and shown in Fig. 3 (a)-(d) and Fig. 4 (a)-(d), respectively. It was found that, in general, tidal elevation increases upstream of the tidal array location (considering the direction of propagation of the tidal wave coming from the Atlantic Ocean) in the Pentland Firth. This effect is possibly generated by the blockage of the flow and by a consequent decrease of kinetic energy, which is transformed into potential energy upstream of the tidal array.

F. Turbulence effects

The turbine parameterization used in [3] allows to study the turbulence changes in the wake of the turbine. In Fig. 5 the changes induced by only one turbine are shown,

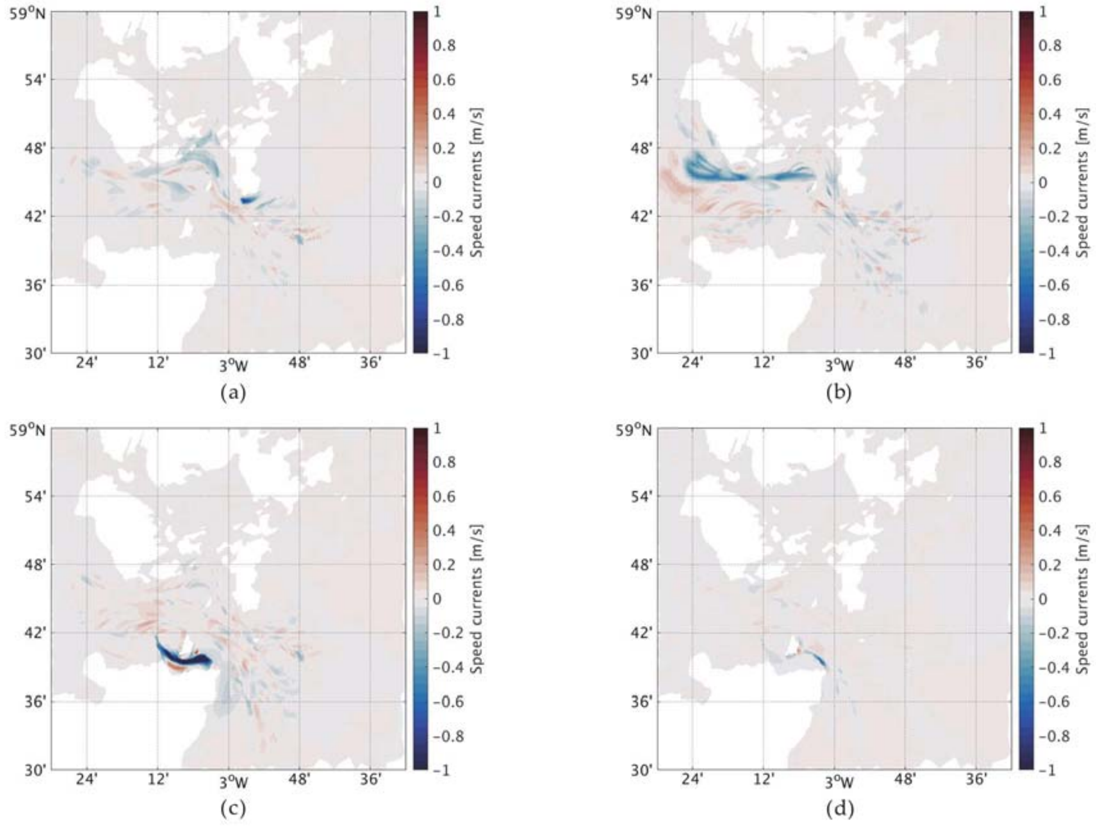

Fig. 2. Maximum changes in speed currents due to tidal stream energy extraction in the Pentland Firth: TeraWatt Brought Ness array (a), TeraWatt Brims array (b) and TeraWatt Inner Sound array (c), TeraWatt Ness of Duncansby (d).

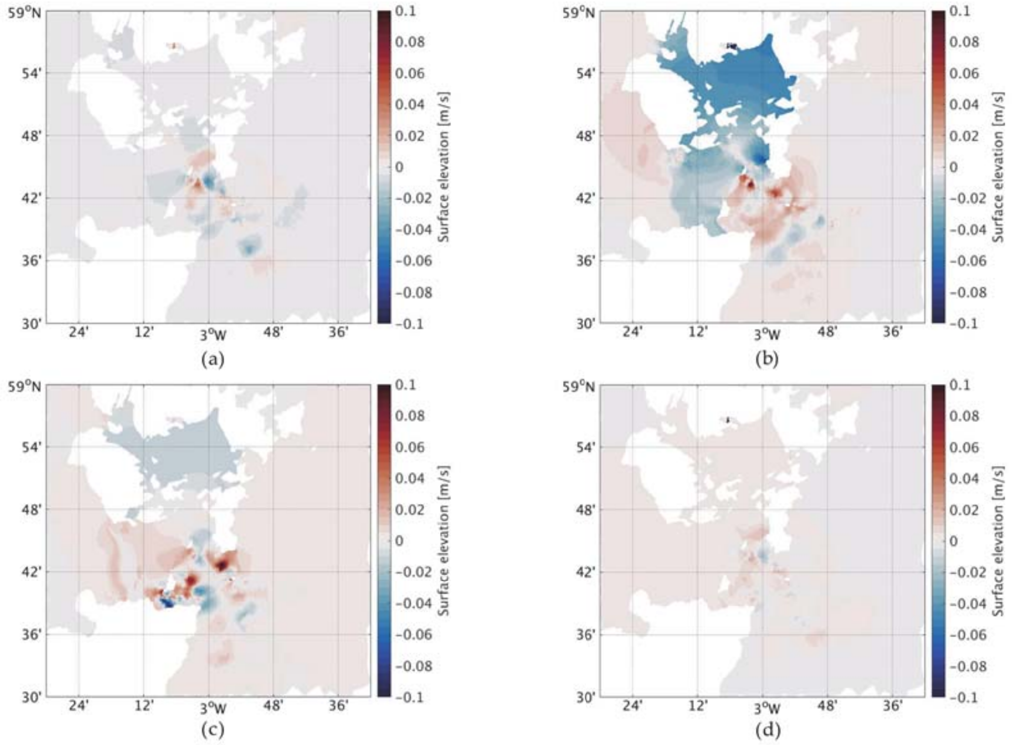

Fig. 3. Changes in maximum (high tide) surface elevation due to tidal stream energy extraction in the Pentland Firth: TeraWatt Brought Ness array (a), TeraWatt Brims array (b) and TeraWatt Inner Sound array (c), TeraWatt Ness of Duncansby (d).

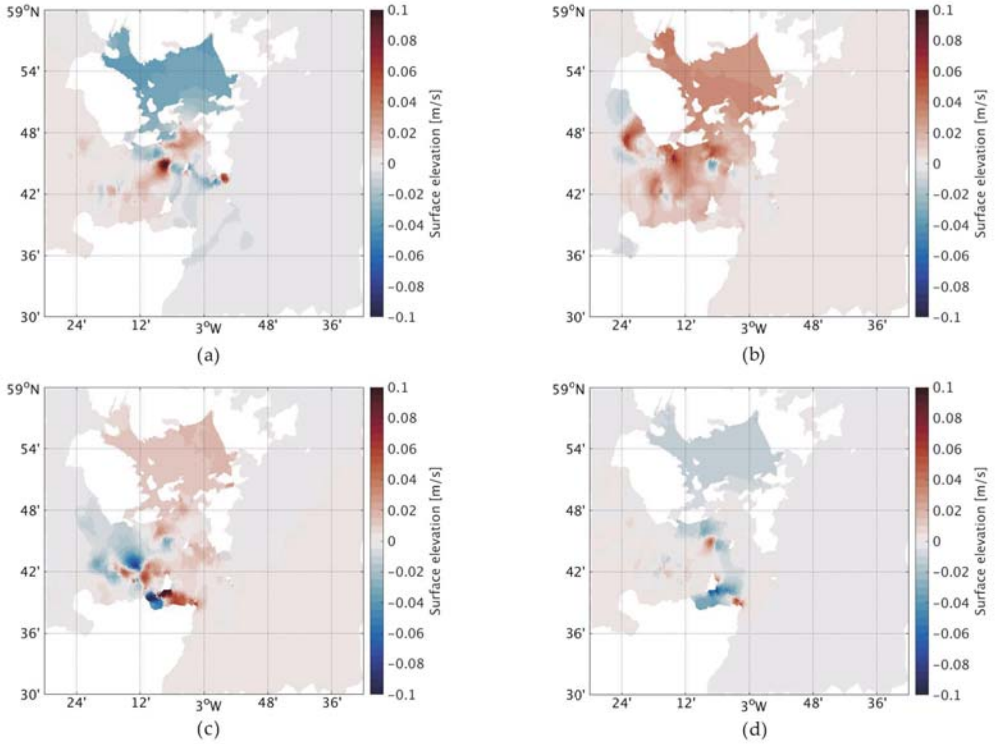

Fig. 4. Changes in minimum surface elevation (low tides) due to tidal stream energy extraction in the Pentland Firth: TeraWatt Brought Ness array (a), TeraWatt Brims array (b) and TeraWatt Inner Sound array (c), TeraWatt Ness of Duncansby (d).

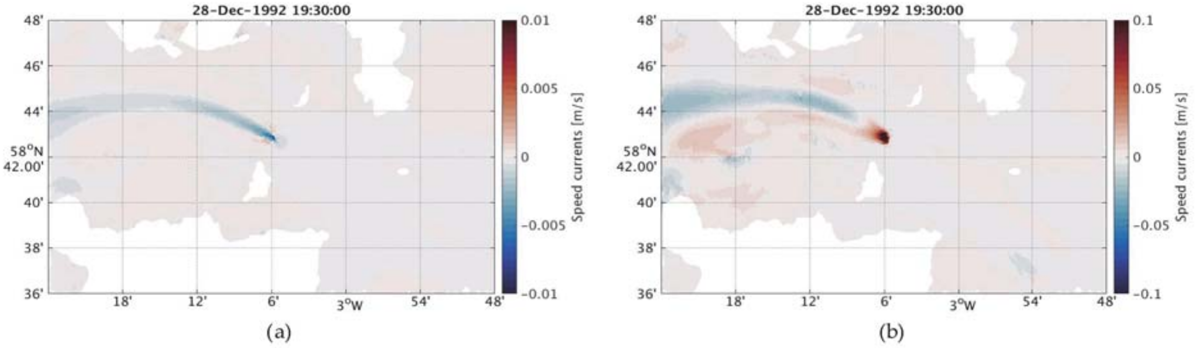

Fig. 5. Changes on current speeds at bottom layer induced by 1 turbine (a) and considering the effects of turbulence on current speed in the wake of turbine (b).

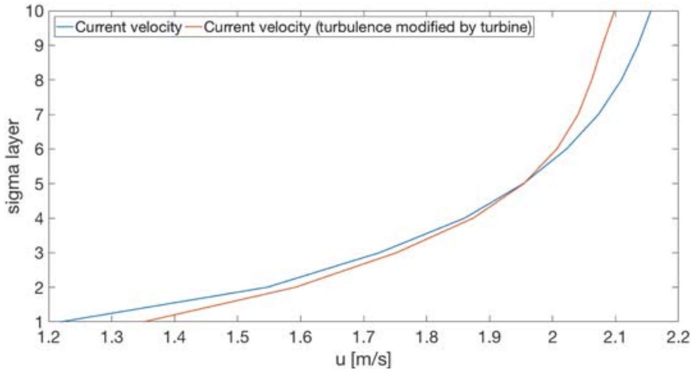

Fig. 6. Current velocity profile (blue line) and current velocity profile considering turbulence modified by turbine (orange line) in correspondence of the turbine location, i.e. in the middle of the Pentland Firth

studied as a simple idealized case. It is possible to see that, at the bottom layer, the changes in turbulence produce a velocity increase of 0.1 m/s both at the turbine location and at the side of the deceleration area, in the wake of the turbine (Fig. 2b). On the contrary, current speed is only decelerated by the presence of the turbine (Fig. 2a) when changes in turbulence are not considered.

Physically, the turbine work enhances the turbulence in its wake. In detail, looking at Fig. 3, the cross section velocity profile shows that turbulence produces a mixing of momentum on the water depth; so there is a transfer of momentum from the upper layers to the bottom layers. That means that water at bottom layers gains more energy and is accelerated.

IV. DISCUSSION/CONCLUSION

In this study, different tidal stream array operations in the Pentland Firth were studied. The comparison of the turbine array was carried out to understand the amount of energy which could be extracted and far-field impacts. A high spatial resolution, unstructured grid, three-dimensional FVCOM hydrodynamic model implementation for the Pentland Firth and Orkney Waters was employed. The tidal stream turbines were represented as sub grid scale objects by using a momentum sink approach. Different tidal stream arrays were simulated to estimate tidal resource available in the Pentland Firth and to understand how the layout of the arrays of turbines could modify current speeds, water elevations and turbulence. Energy extraction by the tested turbine arrays induced a deceleration where the turbines are located and in their wake. On the contrary an acceleration on both sides of the array occurs. The common pattern for the maximum change in currents is an averaged deceleration of 0.2 m/s, but each array changes the currents differently. The modification of current velocities could alter the transport of sediments, nutrients and microorganisms, with consequent sea-bed changes. Moreover, tidal elevation increases upstream of the tidal array location in the Pentland Firth and decreases downstream. It is possibly due to the presence of the turbines anchored to the sea bed, because they represent an obstacle for the flow, which decelerates. The consequent decrease of kinetic energy could mean an increase of potential energy. In the basin surrounded by the Orkney Islands, called Scapa Flow, it is mostly located a decrease of the water levels, during high tide, and it could reach 0.1 m. During low tide each array changes the currents differently. Furthermore, it was found that the turbine enhances the turbulence in its wake. Due to the momentum balance, the mean velocity increases at the bottom layer behind the turbine. This has to be considered for turbine maintenances. In the future, higher resolution hydrodynamic model at bottom layer at the turbine location, for example with a grid resolution of the scale of turbulence structures, will enable to better investigate the momentum mixing in the wake of a tidal turbine. Furthermore, it could be taken into account the wind stress as boundary condition allows to consider the contribution of the wind setup (meteorological tide) and to assess the extent of its contribution.

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