IMPACTS OF TIDAL ENERGY EXTRACTION ON SEA BED MORPHOLOGY

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In this paper, the application of a 3D numerical model covering the area of Pentland Firth channel (Scotland, UK) to investigate the hydrodynamics related to tidal energy extraction is presented in detail. A full validation analysis is carried out so that the fully operational 3D hydrodynamic model could be applied with confidence in order to explore possible impacts of tidal devices on the ambient marine environment. Following that, a higher resolution hydrodynamic and morphodynamic model covering the area of Inner Sound channel, between the Island of Stroma and Scottish Mainland, favoured for tidal energy extraction inside Pentland Firth, is set up. Preliminary results indicate that the existing morphodynamics of the observed sandbank areas inside Inner Sound Channel are very dynamic. In such a dynamic environment, results imply that possible alterations in tidal currents due to energy extraction may have some implications on the existing morphodynamic regime.

Keywords: tidal hydrodynamics; morphodynamics; Delft3D; renewable energy; Pentland Firth; numerical modelling; tidal energy extraction

INTRODUCTION

UK is ideally located to exploit marine renewable energy resources. Tidal energy generation is an option favoured by the UK Government (Bryden, 2006). Since industry is now moving to large array installations, it is vital that the local and regional environmental impacts of tidal energy extraction are well understood (Robins, 2013). Particular concerns are the extent to which the altered tidal environment as a result of energy extraction will change the natural sediment transport regime and hence the sea bottom morphodynamics, which may have some implications on beach stability, coastal ecology and flooding (Neill, Jordan & Couch, 2012). Prior to exploring the environmental effects of tidal energy extraction it is essential that the natural environment is modelled in detail and understood. In consistence with the above statement a 3D hydrodynamic and morphodynamic model is set up and validated in the present work. The validated model will afterwards provide a powerful tool to investigate possible impacts of tidal stream turbines in the sediment transport regime. Pentland Firth (PF) channel between Scottish Mainland (UK) and Orkney Islands, joining Atlantic Ocean with the Northern Sea, is used as the test site. Due to different tidal ranges and phases at the ends of the channel, hydraulic tidal currents of up to 8 m/s are generated in places in response to 2.5 m head drop (Bowyer & Marchi, 2011), providing a substantial energy resource for turbines deployment (Baston & Harris, 2011) (Figure 1).

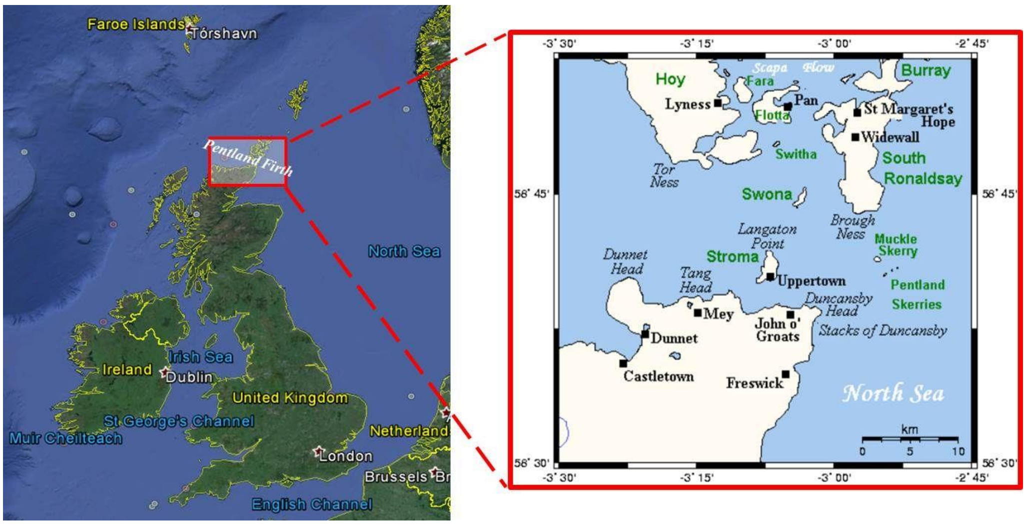

Figure 1. Field Site

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NUMERICAL MODEL

To investigate the sediment and morphodynamic environment in Pentland Firth, open source Delft3D flow model, developed by Delft Hydraulics (Lesser et al., 2004) is used. Delft3D is a finite difference code which solves the Navier-Stokes equations under the Boussinesq and shallow water assumptions, in two (2D) or three (3D) dimensions. The numerical scheme solves a system of a continuity equation, horizontal momentum equations, a turbulence closure model and the advection-diffusion transport equation. In the vertical direction momentum equation reduces to a hydrostatic pressure assumption (Lesser et al., 2004). In the horizontal direction a regular or curvilinear grid can be applied and the modelled quantities in the vertical profile can be defined in z or σ –coordinates. For a 3D flow simulation the system of equations then reads:

$$\frac{\partial(\zeta)}{\partial t}+\frac{\partial\left[(\zeta+d)\overline{U}\right]}{\partial x}+\frac{\partial\left[(\zeta+d)\overline{V}\right]}{\partial y}=S \tag{1}$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+\frac{\omega}{h}\frac{\partial U}{\partial\sigma}-fV=-\frac{1}{\rho_0}P_x+F_x+M_x+\frac{1}{h^2}\frac{\partial}{\partial\sigma}\left(\nu_V\frac{\partial u}{\partial\sigma}\right) \tag{2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+\frac{\omega}{h}\frac{\partial V}{\partial\sigma}-fU=-\frac{1}{\rho_0}P_y+F_y+M_y+\frac{1}{h^2}\frac{\partial}{\partial\sigma}\left(\nu_V\frac{\partial v}{\partial\sigma}\right) \tag{3}$$

where f is the Coriolis parameter; U and V are the horizontal velocities in x and y direction; ω is the vertical velocity in relation to σ –coordinates; F_x, F_y are the horizontal Reynold's stresses; ν_V is the vertical eddy viscosity; P_x, P_y are the horizontal pressure terms approximated by the Boussinesq assumptions; M_x, M_y are external forces added as source or sink terms in the momentum equations (2), (3); ρ_0 is the reference density; S represents the contributions per unit area due to the discharge or withdrawal of water, evaporation and precipitation; ζ is the water level; d is the water depth in relation to a reference level and h is the total water depth ($h=\zeta+d$).

MODEL VALIDATION ANALYSIS OF RESULTS

A full validation analysis was carried out so that an appropriate combination of Delft3D flow parameters could be applied to the area of interest. A 2D formulation of Delft3D Flow model was run for a shelf-scale domain (2Km*2Km) in a fully coupled mode with a 3D higher resolution nested model (200m*200m) covering the whole area of Pentland Firth Channel (Figure 2). Model bathymetry data were provided by the Crown Estate, UK at a 20m*20m grid resolution, thus allowing for a detailed representation of the complex bathymetry in the model domain. The modelled hydrodynamics over a full neap-spring cycle (26/09/2001- 4/10/2001) was compared against observations at 4 tidal gauges located in the shelf - scale model (2Km*2Km) and 3 ADCP record sites inside Pentland Firth (PF) Channel (200m*200m) (Figure 3).

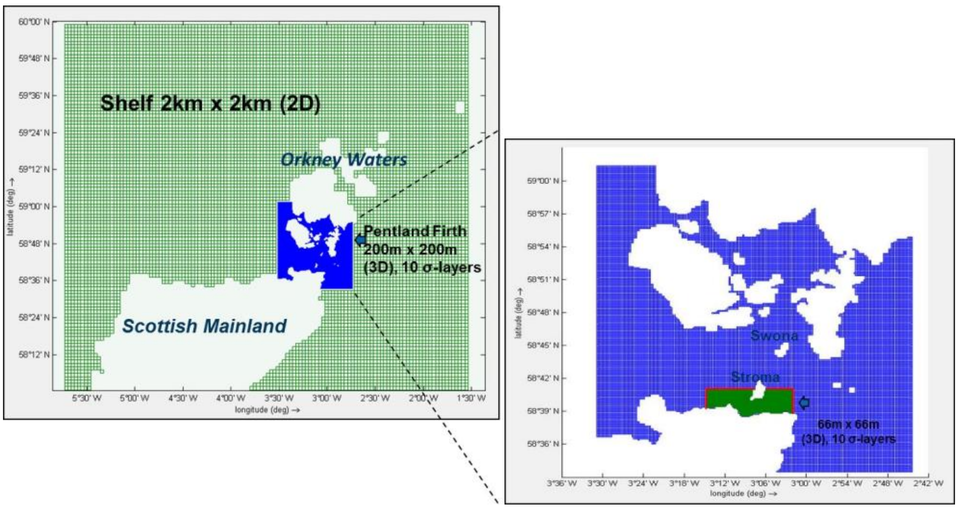

Figure 2. Computational Domain Set up

The details of the ADCP measurements can be found in Baston et al. (2013). Hydrodynamics of the regional (PF) model provided the appropriate boundary conditions for a nested, higher resolution local scale model (66m* 66m) which covers the Inner Sound sub channel between the Island of Stroma and Mainland Scotland, favoured for tidal turbines deployment (Goddijn-Murphy et al. 2013).

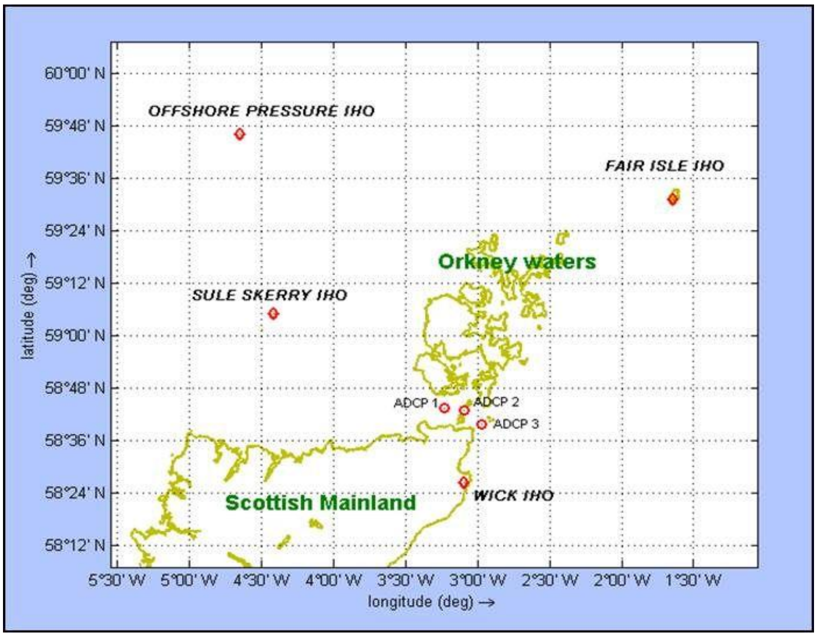

Figure 3. Study area with the location of 4 tidal gauges and ADCP Sites

One of the principal tunable parameters in Delft3D flow model, which was involved in validation process is the bed friction coefficient. Frictional losses occurred as a result of the interaction of tidal currents with the rough sea bed along with energized turbulent flows result in a significant amount of naturally energy dissipation per square meter of the ocean. It is essential that a hydrodynamic model is able to accurately reproduce important flow characteristics.

It can be stated that overall model output seems to be significantly sensitive to bed friction where a constant Chezy value of 50 m $^{(1/2)}$/sec is eventually selected. Higher Chezy values represent a smoother bed whereas lower values represent a rougher bed. In essence, the prescribed value of a constant Chezy coefficient C_{3D} (m $^{(1/2)}$/sec) is inserted into a quadratic friction formulation (Eq. 4) which results in the bottom friction coefficient in accordance to the $c=g/C^2_{3D}$ relation:

$$\overrightarrow{\tau_{b3D}} = \frac{g\rho_0 \left|\overrightarrow{u_b}\right| \overrightarrow{u_b}}{C_{3D}^2} \qquad (4)$$

in which $|u_b|$ (m/sec) is the horizontal velocity component which is assigned to the first computational layer above the seabed It can be stressed that observed deviations between measured and simulated flow fields may be attributed to wave–current interactions and stratification effects which were not included in the current modelling procedure. It can be assumed that considering the excessively high tidal velocities prevailing in the study area, flow stratification may be small. However, it should be noted that no measurements are available to investigate this further.

The ability of the model to efficiently reproduce the large-scale hydrodynamics of Pentland Firth channel can be demonstrated by comparing the measured water surface elevations with the predicted elevations at four tidal gauges; SULE SKERRY IHO, OFFSHORE PRESSURE IHO, FAIR ISLE IHO and WICK IHO (Figure 3) The comparisons cover a full neap (26/09/2001) - spring (04/10/2001) tidal cycle and the results are shown in Figure 4. A good agreement is found between the measured and predicted water levels both in phase and amplitude at all four tidal gauges as can be seen in Figure 4 below.

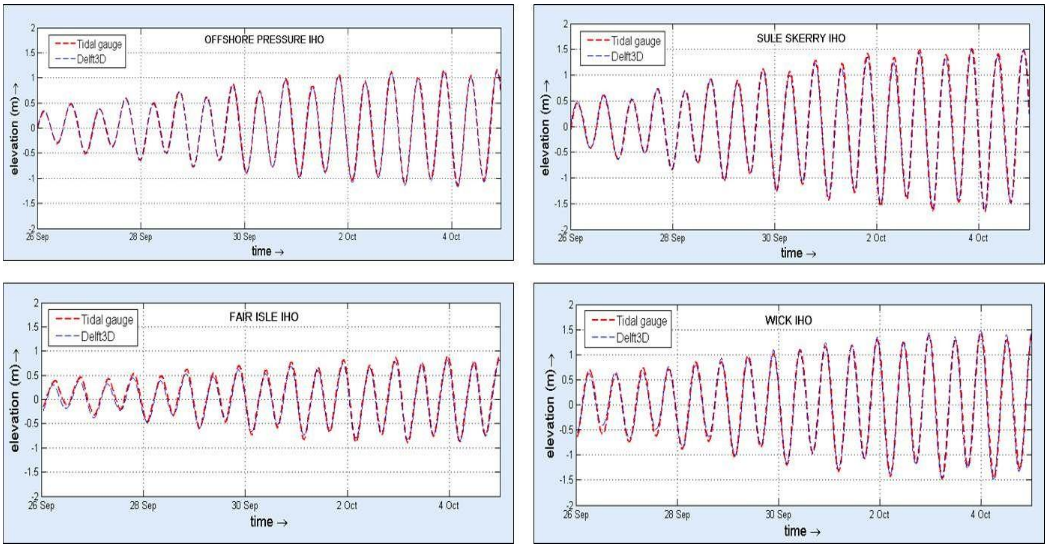

Figure 4. Comparisons between modelled and measured surface elevations at 4 tidal gauges

Mapped tidal ellipses at 3 ADCP sites inside PF provide information on the principal direction of the current flows (Figure 5). A thin ellipse indicates that during a tidal cycle currents flow mostly in the direction similar to their main axis (Site 3). In a wider ellipse changes in direction occur more gradually (Site 1) (Flather et al., 1990).

In figure 5 the direction of measured and simulated ebb and flood currents at spring tide is compared for all three sites, at three depths below mean water surface. A good agreement was observed between the measured and predicted flow direction in the vertical column. Higher angles correspond to ebb phase whereas smaller angles to flood phase.

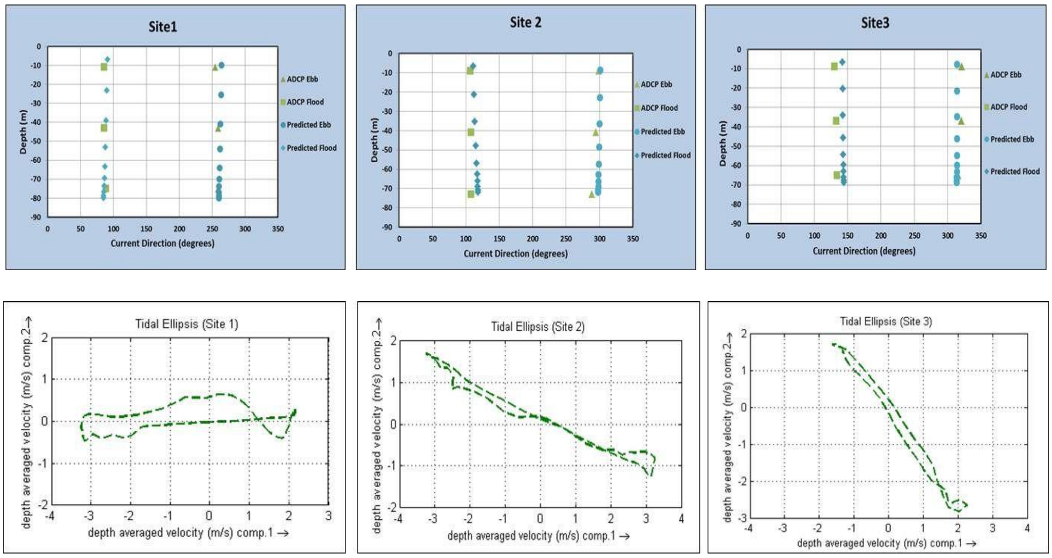

Figure 5. Mapped tidal ellipses and corresponding current directions in the vertical column at 3 ADCP sites over a full spring tidal cycle (04/10/2001)

Mapped depth averaged velocity field (m/sec) effectively reproduces the fast moving tidal jet developed by the islands of Swona and Stroma constriction (Figure 1). The tidal jet travels north –

westwards during ebb phase whereas it travels south-south eastwards during flood phase (Figure 6). Spatially varying transient eddies are apparent closer to the islands of Swona and Stroma.

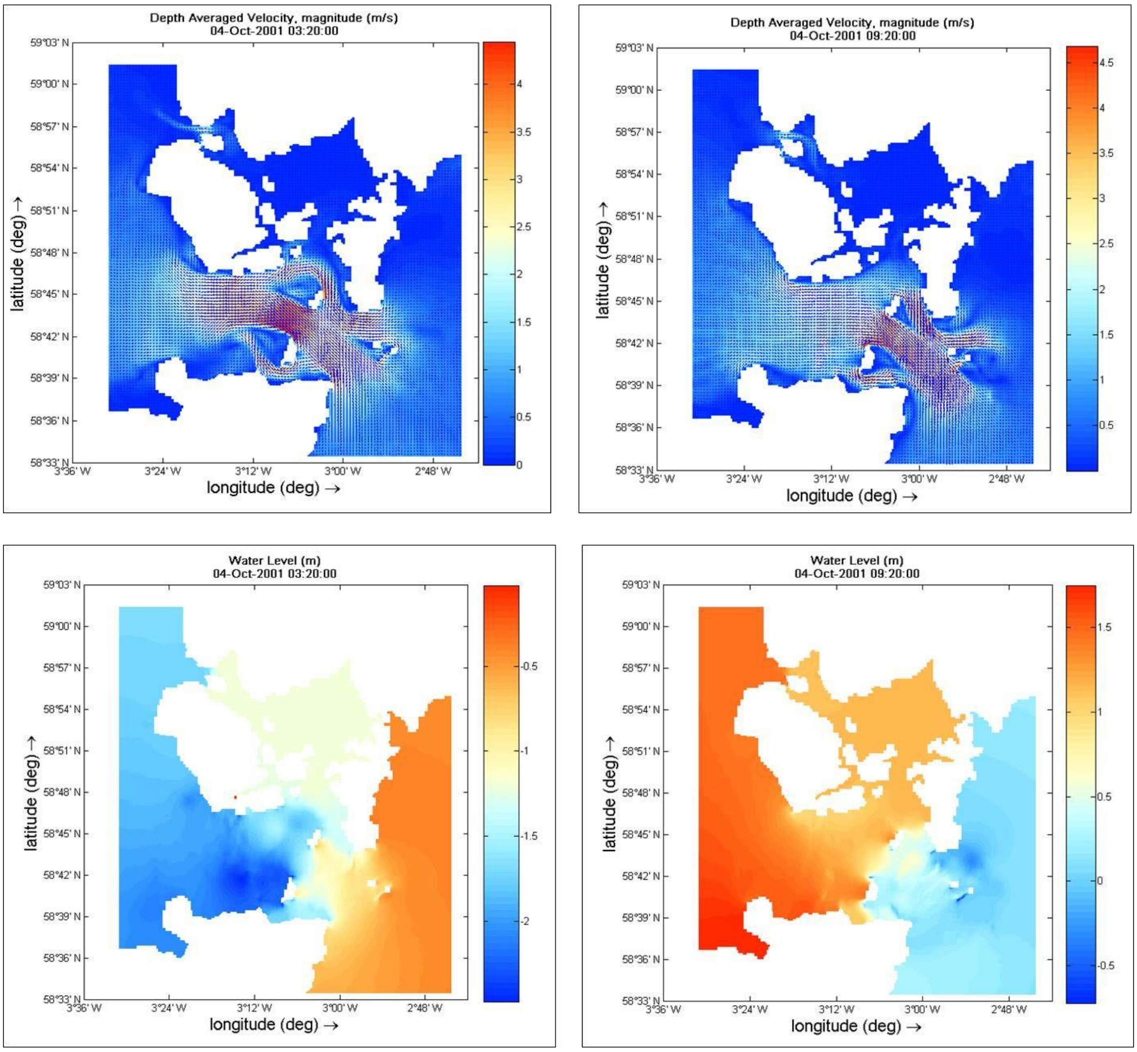

Figure 6. Snapshots of depth averaged velocity field and water elevation at spring ebb (3:20) and flood (09:20) tide on 04 October 2001

MORPHODYNAMIC REGIME INSIDE INNER SOUND

To investigate the naturally occurring sediment transport regime inside the Inner Sound Channel, which is highly favoured for tidal energy extraction inside PF channel, a nested hydrodynamic and morphodynamic model is set up. The complex patterns of sediment distribution are encapsulated by considering varying sediment grain size and mobile seabed thickness. Sand coverage within the selected computational grid was reproduced via data interrogation accessed by Marine Scotland (MS) video trawls, British Geological Survey (BGS) particle size processed data and mapped geological conditions available by Meygen EIA Quality Mark Report (Meygen Ltd, n.d.). The collocated sediment data revealed mainly rocky areas although extensive sand and gravel deposits are abundant in some places.

A large scale, pear shaped sandbank (sandbank A) lying eastwards and a smaller scale shelf bank area (sandbank B) located westwards in NW-SE direction, at maximum depth of ~ 33m, in the lee of the Island of Stroma are of particular importance (Figure 7). In the enlarged sandbank (A) area, highly mobile gravels form large sandy ripples, superimposed on small sand waves. The east sandbank (A) lies in SW-NE direction, with a maximum height of ~15m above a surrounding maximum depth of ~35m of scoured bedrock. In the lee side of Stroma a less expanded bedform of finer sand at the inner side and coarser sand at the outer side (sandbank C) can be also observed (Figure 7).

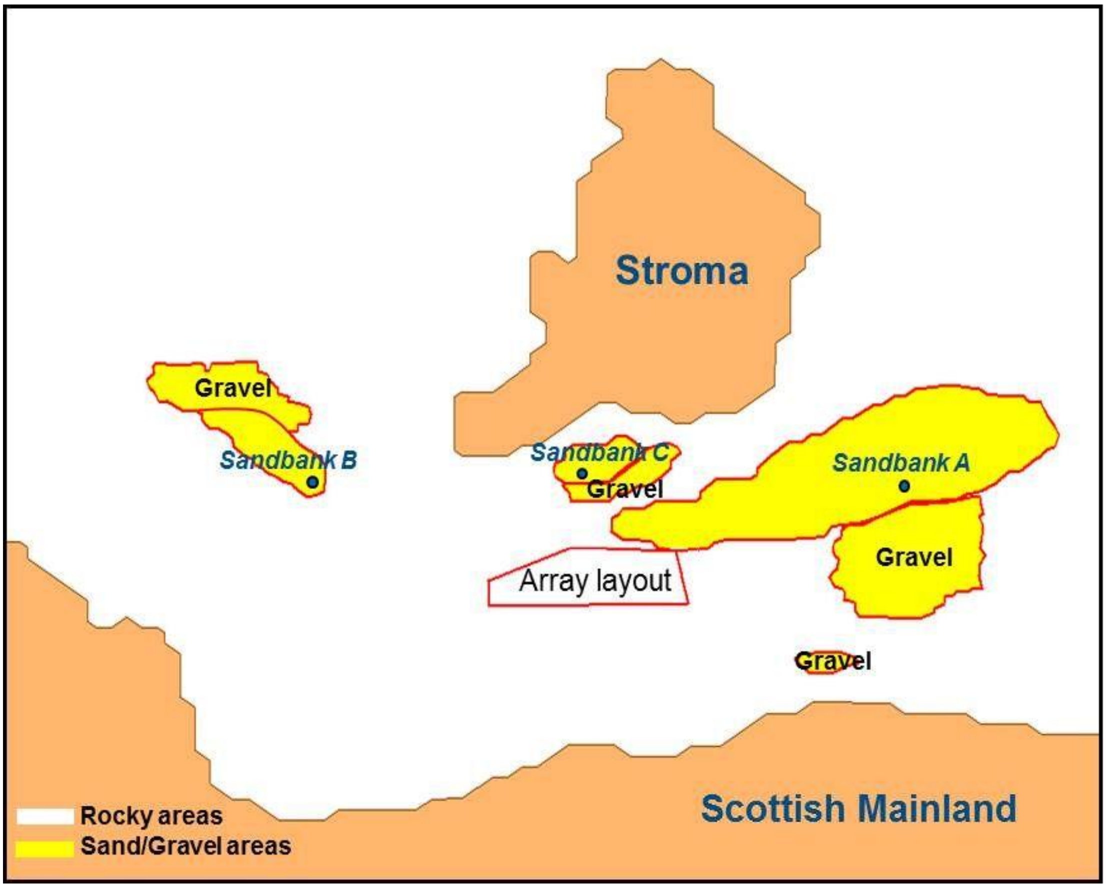

Figure 7. Sediment availability in Inner Sound channel inside PF

It is to be noted that in many places, sub tidal banks which lie few kilometers away from the coastline, are proved to be of significant economic importance (Dyer & Huntley, 1999). The presence of shelf sandbanks enhances the wave dissipation and refraction and provides natural coastal protection against shoreline erosion. The banks can serve as an important feeding ground for fish populations and their presence is associated with the existence of ecologically important benthic communities. Locations favoured for tidal energy extraction lie also in cases, in proximity to these sandbank areas (Figure 7). It is thus important that the natural dynamics of those banks are fully modelled and understood prior to installing tidal turbines.

In the present work Van Rijn (1993) sediment transport formula is used in Delft3D to calculate the bed load transport rates ($m^3/s/m$). Due to the limited availability of measured suspended sediment concentrations inside the Inner Sound channel, and also due to the prevailing sediment size in the sandbanks concerned, the transport formula is tuned to exclude the suspended load sediment transport.

At maximum ebb phase a tidal jet is formed and travels offshore from the western side of the Island of Stroma. At spring flood phase, strong currents (> 2.8 m/s) occur offshore of the southern flank of the east sandbank (A) area. In similar manner to ebb phase, a tidal jet is formed and flows in a constrained path located in the middle part of Inner Sound channel during flood phase.Mapped residual sediment transport patterns over a spring tidal cycle (04/10/2001 00:00 -04/10/2001 12:00) reveal an inner zone where sediments move towards the crest/centre of the east sandbank (A). Mean sediment transport regime results in an anticlockwise circulation over the enlarged sandbank (A) area as can be observed in Figure 8. It is particularly interesting to note that the computed sediment transport rates decrease steadily in magnitude towards the centre of the sandbank.

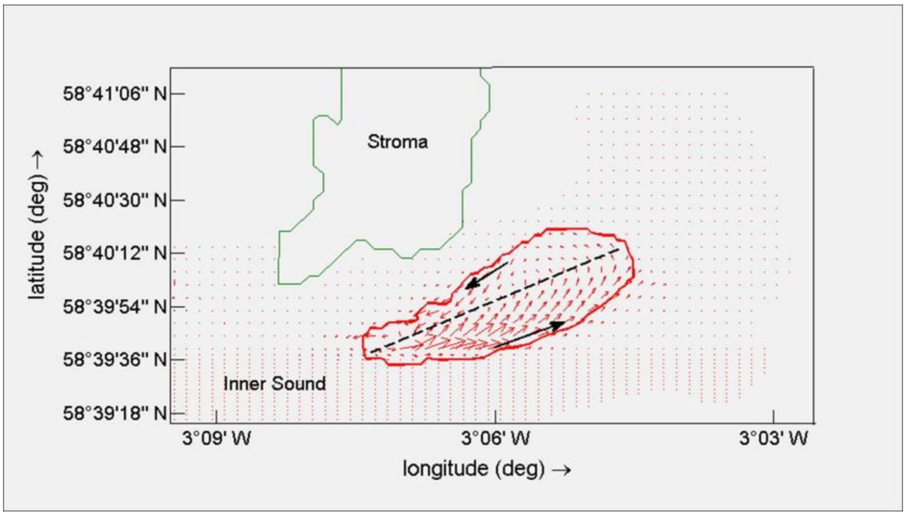

Figure 8. Residual sediment transport regime over the East sandbank (A) area for a full spring tidal cycle at 04/10/2001

During the spring tidal cycle, Eulerian monitoring points located in the inner side of the east shelf bank (A) reveal a longer in duration and stronger ebb phase in contrast to a less significant flood phase. Following that, excess shear stresses tend to move sediments in the ebb direction. In contrast, at the outer side, a stronger flood phase moves the sediments in the direction of the flood current (Figure 9). Observed residual ebb currents towards the tip of the island of Stroma and residual flood currents away from the island form a distinct anticlockwise flow circulation pattern.

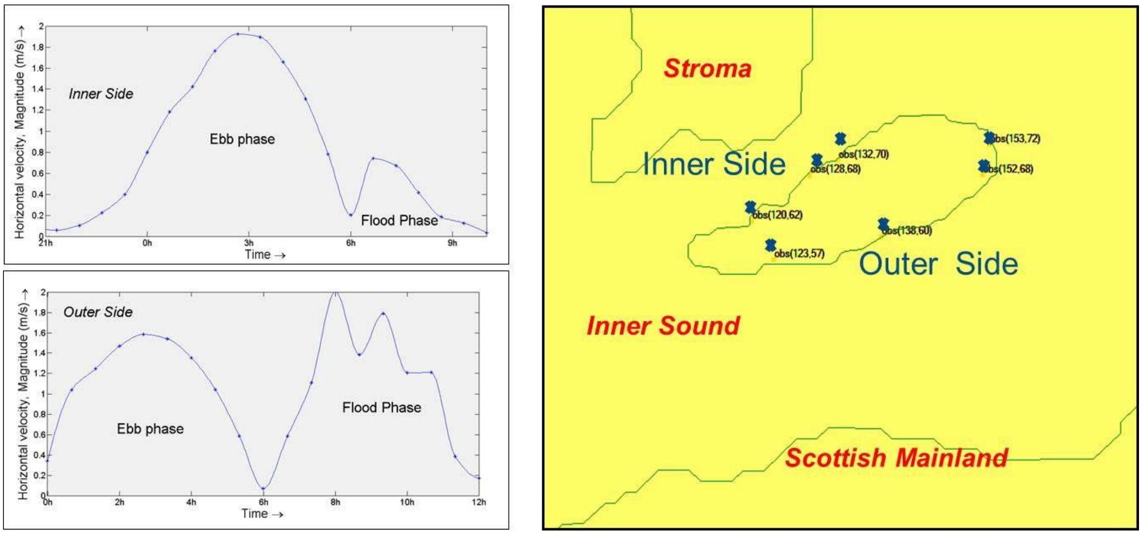

Figure 9. Marked asymmetry in strength and duration of the ebb and flood currents on the East sandbank (A) area over a spring tidal cycle at 04/10/2001

It was found that the interactions between the hydrodynamics and the east shelf bank (A) result in a near equilibrium condition after a two – month simulation period as can be seen in Figure 10.

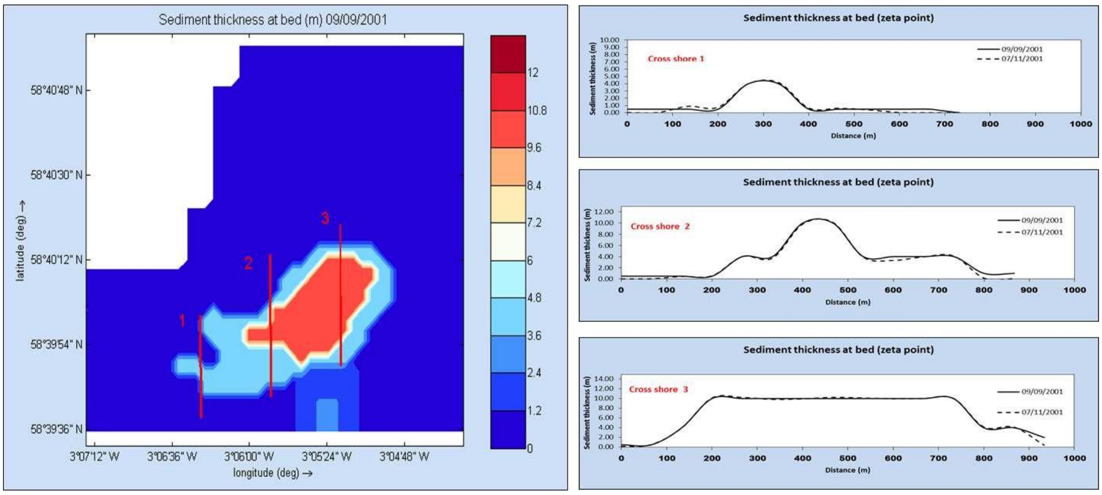

Figure 10. Evolution of the topographic profile of the East Sandbank (A) (after 2 months simulations)

The evolution of the topographic profile of the West sandbank (B) at four cross sections is also mapped after a two-month simulation period (09/09/2001-07/11/2001). The results are shown in Figure 11. The sandy deposit on the bank erodes southwards whereas sediments mostly move and accumulate at the northern part of the shelf bank area (B) in a similar manner to the residual sediment transport over the east sandbank (A).

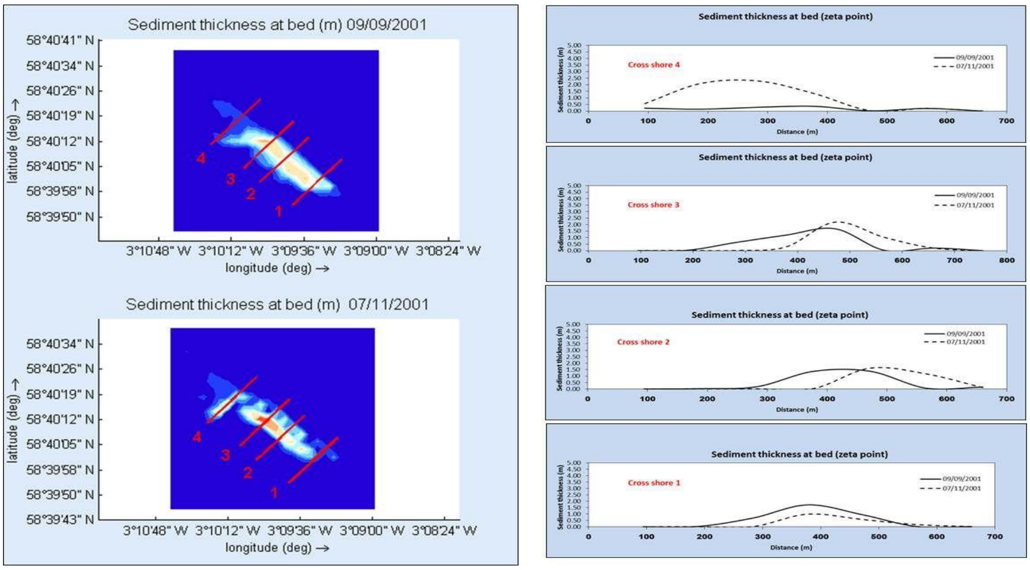

Figure 11. Evolution of the topographic profile of The West Sandbank (B) (2 months simulations)

A small scale residual eddy is formed directly in the lee of the Island of Stroma, which coincides with the location of the sandbank C (Figure 7, 12). As the currents pass over the tip of a coastal irregularity such as the tip of the Island of Stroma, there is a possibility that the flow will separate (Robinson, 1983 cited in Dyer & Huntley 1999). The above process in action is apparently true for currents flowing in Inner Sound channel in the lee of Stroma. Following that, the existence of the less expanded bedform can be linked to insignificant flow separation patterns which occur in the leeward side of the Island of Stroma (Belderson et al, 1982 cited in Dyer & Huntley 1999).

Residual tidal currents inside Inner Sound

The residual currents over a spring tidal cycle are mapped (Figure 12) following Bastos et al. (2003). Residual tidal flows are indicative of resultant flow patterns covering a period of few tidal cycles. It is essential to explore the naturally occurring residual circulation since it is proved to play an important role in ocean productivity in some localities (Sanchez et al., 2014). Following that, the effects of tidal farms on residual patterns may in turn have some ecological implications. It has been proved that the inclusion of tidal energy turbines in open shallow sea may result in changes in residual circulation patterns up to 100Km further away from the point of energy extraction (Shapiro, 2011). Averaged currents over a spring tidal cycle (04/10/2001 00:00 -04/10/2001 12:00) confirm the presence of a large anti-clockwise cyclonic residual eddy eastwards and a smaller scale clockwise anti-cyclonic eddy westwards. The residual eddies are mainly attributed to the observed tidal asymmetry between the ebb and the flood phase both in magnitude and direction. The smallest velocities are observed in the centre of those residual vortices (<0.2 m/sec). It can be stated that the tidal asymmetry along with the less significant secondary flows due to the curvature of the flow mainly contribute to the maintenance mechanisms of the shelf bank areas (Easton et al., 2010). The residual eddies introduce secondary flows which converge to the centre of the eddy at the seabed and diverge at the surface, as explained by the tidal stirring concept proposed by Pingree (1978). However it should be noted that the secondary flows contribute only 5-15% to the main flow and that the residual flow patterns are apparently weaker than the observed transient currents.

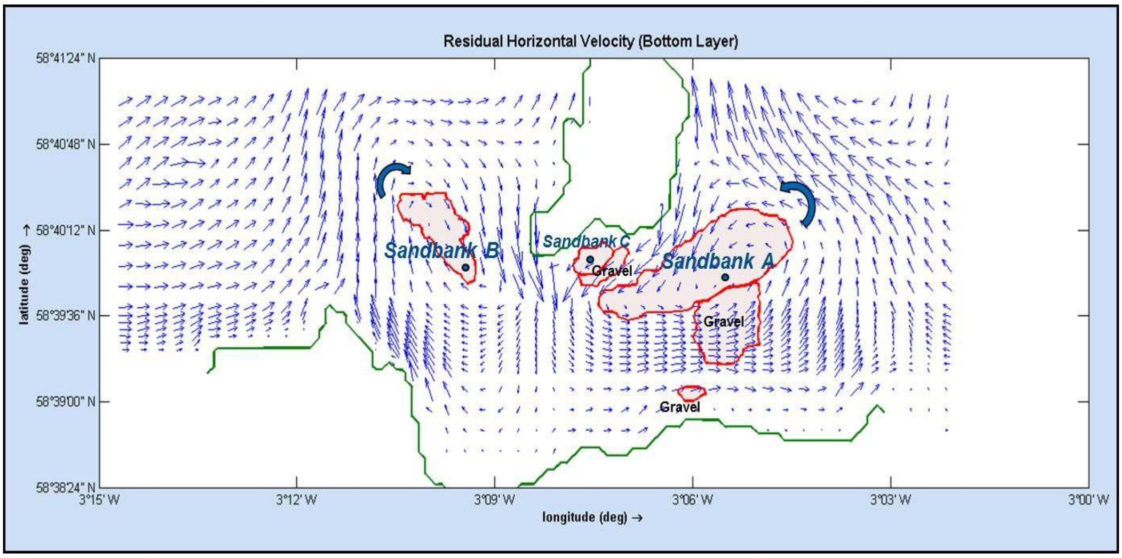

Figure 12. Residual flow patterns inside Inner Sound Channel (blue arrows indicate the rotational direction of residual eddies – red patches denote sediment availability in the sub -channel)

CONCLUSIONS AND WORK IN PROGRESS

A 3D hydrodynamic model DELFT3D is set up for the Pentland Firth Channel (Scotland, UK) to investigate the hydrodynamic and morphodynamic regime relevant to tidal energy generation. The complex tidal current regime inside Inner Sound channel was effectively reproduced. Sea bed morphology of sandy areas in PF proved to be sensitive to hydrodynamics. Locations favoured for tidal energy extraction lie in proximity to highly sensitive sand/gravel deposits. It is thus considered important to investigate the impacts of tidal energy extraction on the hydrodynamics and the morphodynamics of this area. Numerical modelling study is still underway to investigate the linkage between the complex current patterns and the existing sediment transport regime. Following that, the models will be used to investigate the impacts of tidal current turbines on sea bed sediment dynamics.

Tidal current turbines will be implemented in Delft3D as porous discs (Jang & Hoang, 2013). In essence the effects of tidal devices on the flow will be generally added as sink terms in the momentum equation (Houlsby et al., 2008; Sun et al., 2008). A range of energy extraction scenarios, array configurations and turbine locations in the water column will be selected. The selected scenarios will be modelled to investigate and quantify the potential changes to the existing morphodynamic regime at the test site. In subsequent, resulting morphodynamic changes could be effectively correlated with the current field in order to map notable relationships between altered currents and seabed change.

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