Dynamic sandbanks in close proximity to sites of interest for tidal current power extraction

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***Abstract*— A validated numerical model of tidal flows and sediment transport around the Alderney South Banks was used to investigate the potential effects of large (300 MW) tidal turbine arrays at different locations in Alderney territorial waters. Two methods were used, firstly looking at hydrodynamic changes only and secondly modelling sediment transport over a non-erodible bed. The baseline hydrodynamic model was validated relative to ADCP velocity data collected in the immediate vicinity of the sandbank. Real-world sand transport rates were inferred from sand-wave migrations and agree favourably with sediment transport residuals calculated from model outputs. Outputs from the sediment model reproduced realistic morphological behaviours over the bank. Seventeen different locations were considered; most did not result in significant hydrodynamic changes over the South Banks, however three array locations were singled out as requiring extra caution if development were to occur. The results provide a means of optimizing**

***Keywords*— Tidal power, Resource assessment, Sandbanks**

I. INTRODUCTION

Fast tidal currents of interest for power generation often occur close to islands or headlands, where flow separation can occur and cause large areas of recirculation, extending over many kilometres. This is the case for a number of sites identified as having high potential for development, notably the Pentland Firth to the south of the island of Stroma [1]; at Portland [2] (a headland on the south coast of the UK) and Alderney [3] (an island in the Normandy-Brittany Gulf). In all these locations, large submerged sandbanks exist within a few hundred meters of flows that exceed 3 m/s at spring tides – flows that could easily remove the sandbanks, if diverted onto them. Often viewed on nautical and bathymetric charts as static entities, the sandbanks are revealed by repeated high-resolution swath bathymetry as highly dynamic places where large sand waves can propagate tens of meters in a day. Numerical modelling of these sandbanks in their natural state is a challenge due to the large range of temporal and spatial scales involved along with many uncertain parameters; extending such models to include large arrays of tidal turbines is even more challenging due to the uncertainties in tidal array parameterization.

Nevertheless, it is important to be able to assess the likely impacts on sandbanks of potential tidal power developments nearby. Sandbanks are of ecological significance and their precise location is important for safe navigation.

A. Sandbank development in fast tidal flows

The relevant type of sandbank here - Type 3 sandbanks [4] - are formed at headlands where sediment transported by long-shore drift (from one or both sides of the headland) is swept offshore where it accumulates to form a long, linear sandbank. Tidal flows around the headland are a key factor in the formation of Type 3 sandbanks. Strong currents are required to move sediment far offshore (along the length of the bank) and to form large eddies in the lee of the headland that play an important role in helping form and maintain the sandbank. Banner banks typically take the form of a straight line protruding from a coastal headland into deep water and are a consequence of the way in which tidal flows behave downstream from the headland.

Increases or decreases to the magnitudes of the residual sediment transport could modify the shape of the sandbank with newly created sediment convergence zones and subsequent modifications to the sandbank shape. Although modification of just the residual magnitudes could alter the sandbanks equilibrium profile it would seem that a reversal in the sediment transport residual direction at any point on the bank could have a very significant impact upon the morphology. If the sand circulation was reduced dramatically or even reversed at any point along either flank of the bank then the long-term equilibrium of the bank would be compromised.

A total reversal in the residual transport at a particular location would require a large change in the ambient hydrodynamics and is unlikely. Having said this, the important role of the propagating eddy shed by the headland tip is clear from the literature [5-7]. The strength, propagation direction and life-time of the eddy could be altered significantly by localised changes in the hydrodynamic regime in the region where the eddy forms. In this way, localized changes in the flow regime could have a wider impact upon sand movement around sandbanks.

II. SITE CHARACTERISTICS

The South Banks are collectively a 7.5 km long by 1.5 km wide submarine sandbank located to the South of the island of Alderney. The Alderney South Banks are a Type 3A 'banner' sandbank as determined using the classification system proposed by Dyer and Huntley [4]. The banks extend out from the littoral zone to depths of over 40m and exhibit maximum heights above the surrounding bedrock strata of around 25 m. The Race of Alderney has been the subject of interest for tidal power generation for many years [8-10] with estimates of power generation varying from GW to GW. It has also been the subject of a sediment transport modelling study [3] which did not have access to the high resolution bathymetry or flow data used in this study. As the ebb tidal flows pass to the South of Alderney large, clockwise eddies are shed by the island tip and propagate along the line of the sandbank. At the South Banks the circulation of sand represents a consistent clockwise pathway of the residual sediment transport around the bank. Fig. 1 shows the main sediment transport pathways around the South Banks, inferred from bedforms and sandwave migration between repeated swath surveys. There is a clockwise pattern of sediment circulation.

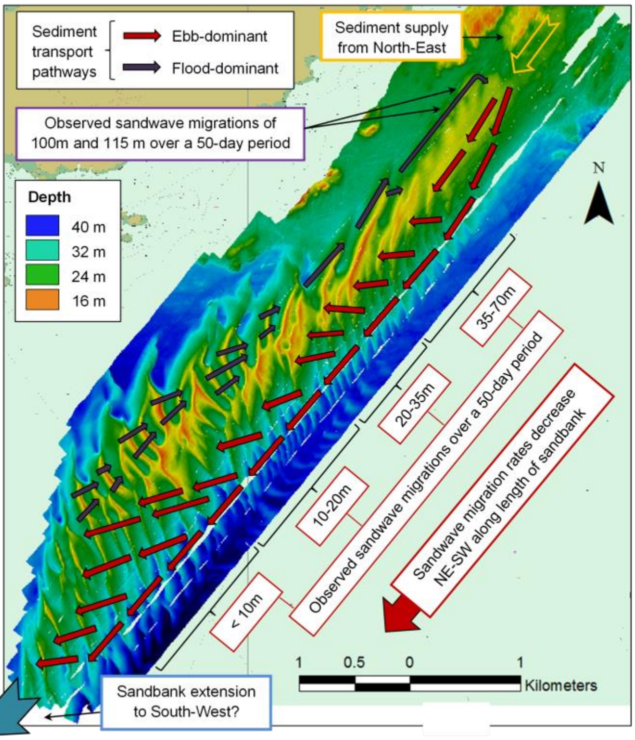


Fig. 1 Observed sandwave migration rates in the context of the bathymetry of Alderney South Banks

The South Banks possess a complex and extremely active morphology. Significant volumes of sand are circulated around the sandbank and very high sandwave migration rates of up to 70 m in a 50 day period were observed in one part of the Bank. It is possible that sand is supplied to the Banks from an active scour zone at the tip of the island, or from the wider sea-bed to the North-East of the island. To directly measure long term rates and directions of sediment transport within and around the Banks would require multiple bathymetric surveys over a period of months or years and this data is not presently available. Nevertheless, it is clear from depth soundings on historic charts that the Banks as a whole have been maintained in a quasi-equilibrium state for many decades. While it is not clear whether there is a sediment supply to the Banks, available survey data indicate net clockwise circulation of sediment around the centreline, which acts to maintain the Banks. Therefore changes to this important process caused by changes to the wider flow regime have the potential to affect the long-term stability of the Banks.

III. Methods

A. Baseline model

A 2-D numerical model was used to simulate the tidal flows in the vicinity of Alderney and across the wider English Channel. The model was driven by tidal elevations at its open boundaries using nine tidal constituents (M_2, S_2, K_1, O_1, P_1, N_2, K_2, Q_1 and M_4), derived from the OTPS software [11] and co-tidal charts [12]. The model was validated against tidal elevation records obtained from port tide-gauges and tidal currents derived from ADCP deployments.

B. Energy extraction approach

An existing, area-averaged roughness method for parameterising the effects of energy extraction for tidal arrays was incorporated into the model [13]. A numerical sediment model was set up to be coupled and run in parallel with the hydrodynamic computation. The modelling phase consisted of two distinct stages: a hydrodynamics-only model (TELEMAC-2D) and a sedimentary model (TELEMAC-2D coupled with SISYPHE) [14]. Baseline and energy-extraction models are setup identically (i.e. model-run time, tidal boundary forcing, format of results) with the exception of the added drag force representing the arrays. Extraction outputs are then subtracted from the baseline outputs (velocity for the hydrodynamic model, bed-level evolution for the sedimentary model) to quantify the spatial and time-varying impact of each extraction scenario. These velocity differences are then used to assess the likely impact of each energy extraction scenario upon the South Banks' morphology.

C. Static bed hydrodynamic model

An identical 300 MW tidal array parameterisation was applied to the model in 17 different locations to simulate different energy extraction scenarios. The hydrodynamics-only model was setup to run for one spring-neap cycle (14.8 days). The spring-neap cycle chosen was from 14 August 2009 to 28 August 2009 with the spring tide occurring in the middle of the model run. This period was chosen because the model was primarily validated using ADCP data collected during 2009 and the cycle is one of the largest cycles of the year. The model is therefore conservative in that it represents the impacts of energy extraction during a period of higher-than-average tidal velocities. Residual sediment transport rates across the South Banks were calculated using the

D. Coupled sediment transport model

A set of sedimentary model-runs were also performed for a longer 90-day period with the sediment module activated. A non-erodible bed was used to limit potential erosion depths within the sediment model and to ensure realistic sediment supply, in contrast to [3]. The sediment model was set up to run for a longer time-period than the hydrodynamics-only model to help investigate cumulative impacts on a larger time scale. A model run of 90 days (3 months) was chosen and was situated symmetrically in time around the hydrodynamic-only modelling period (i.e. July-September 2009). The model run encompasses six spring-neap cycles with the principal output consisting of bed evolution time-series for each node of the model mesh.

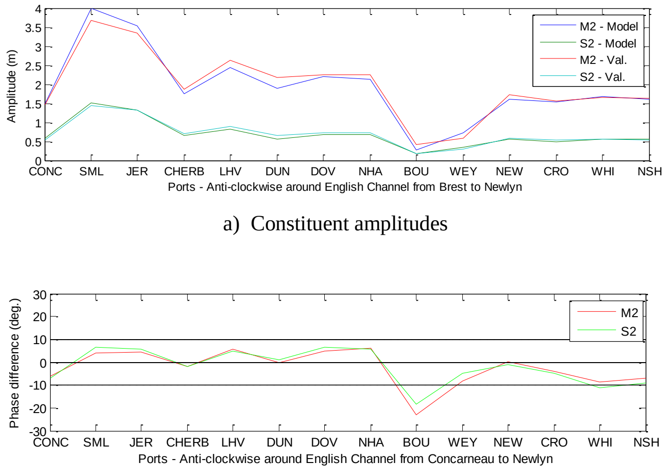
TABLE I
ERRORS IN TIDAL ELEVATION CONSTITUENTS AT TIDE GAUGES IN THE MODEL DOMAIN (MODELLED VERSUS ACTUAL)

	M_2			S_2		
	Amp.		Phase	Amp.		Phase
Location	**(m)**	**(%)**	**(deg)**	**(m)**	**(%)**	**(deg)**
Concarneau	0.03	1.7	-6.3	0.04	7.3	-7.0
Saint-Malo	0.33	8.9	4.0	0.07	4.8	6.4
Jersey	0.19	5.7	4.3	0.01	0.4	5.5
Cherbourg	-0.13	-7.0	-1.8	-0.05	-7.3	-1.9
Le Havre	-0.18	-6.9	5.5	-0.08	-8.6	5.0
Dunkirk	-0.29	-13.4	-0.1	-0.11	-16.3	1.1
Dover	-0.06	-2.8	4.9	-0.04	-5.8	6.4
Newhaven	-0.12	-5.3	6.3	-0.06	-8.6	5.9
Bournemouth	-0.13	-32.4	-23.1	-0.01	-5.3	-18.6
Weymouth	0.15	25.0	-8.1	0.04	14.6	-5.0
Newlyn	-0.10	-6.1	0.4	-0.02	-4.3	-1.0
Cromer	-0.01	-0.8	-4.2	-0.05	-9.4	-5.0
Whitby	0.03	2.0	-8.7	0.01	1.6	-11.0
North Shields	-0.01	-0.9	-6.9	0.00	0.7	-9.1

IV. RESULTS AND DISCUSSION

A. Validation of baseline numerical model

The modelled tidal elevations were analyzed harmonically using T_TIDE [15] and constituents compared with those derived from tide gauge records at eleven ports in the English Channel (Concarneau, Saint Malo, Jersey, Cherbourg, Le Havre, Dunkirk, Dover, Newhaven, Bournemouth, Weymouth and Newlyn) and a further three ports in the North Sea (Cromer, Whitby and North Shields). Figure 2 shows the comparison for the two main constituents, M_2 and S_2. It can be seen that amplitude agreement is excellent and phase error is within 10 degrees with the exception of Bournemouth where M_2 and S_2 amplitudes are small and non-linear tides dominate. Current profiles from five ADCP deployments were analyzed and compared with the depth-averaged currents from the model; the differences are tabulated in Table 1. The agreement for M_2 tidal ellipse parameters (major axis, phase and inclination) was very good, less so for S_2. However the M_2 constituent typically accounts for 80% of tidal dissipation in this part of the continental shelf [16] and therefore overall the currents were reproduced well by the model.



a) Constituent amplitudes

b) Constituent phases

Fig. 2 Comparison of modelled and actual M_2 and S_2 constituents at tide gauges in the model domain (see Table 1 for full names)

TABLE II
ERRORS IN DEPTH-AVERAGED TIDAL CURRENT ELLIPSE PARAMETERS

	M_2				S_2			
	Maj. axis		Phas.	Incl.	Maj. axis		Phas.	Incl.
ADCP	**(m/s)**	**(%)**	**(deg)**	**(deg)**	**(m/s)**	**(%)**	**(deg)**	**(deg)**
T61[a]	0.08	2.9	3.9	-0.9	0.58	138.1	0.5	2.0
T61[b]	-0.06	-2.3	0.2	-7.36	0.47	97.9	-3.2	-9.5
T75[a]	0.06	2.7	2.9	-0.3	0.40	94.6	5.3	-1.4
T75[b]	0.14	6.4	2.9	13.05	0.41	100.0	0.3	13.1
T74[b]	-0.11	-6.7	-0.1	3.7	-0.13	21.2	29.0	2.6

B. Energy extraction areas

The results of the baseline model were used to select a subset of Alderney waters of interest for tidal current power generation, using the cube-root-mean-cube flow speed as a threshold. While this is not a reliable metric for the available resource [17,18], it nevertheless highlights areas where a single large array would generate high power. The selected areas are indicated in Figure 4 as rectangles aligned to the major axis of the M_2 ellipse. Note the high velocity area on the right of the image lies outside of Alderney territorial waters.

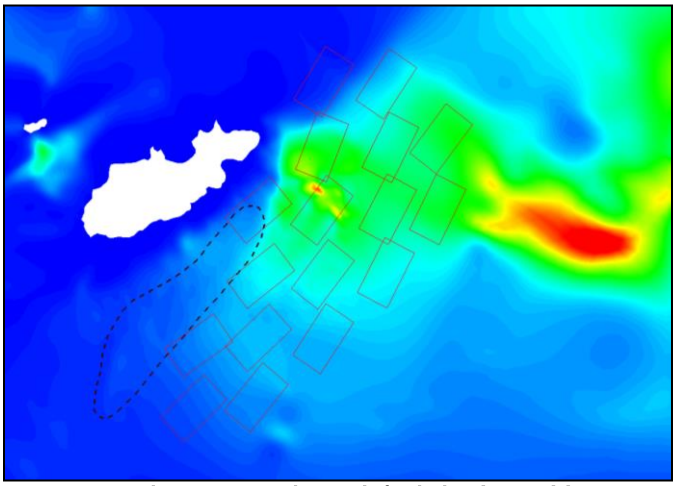
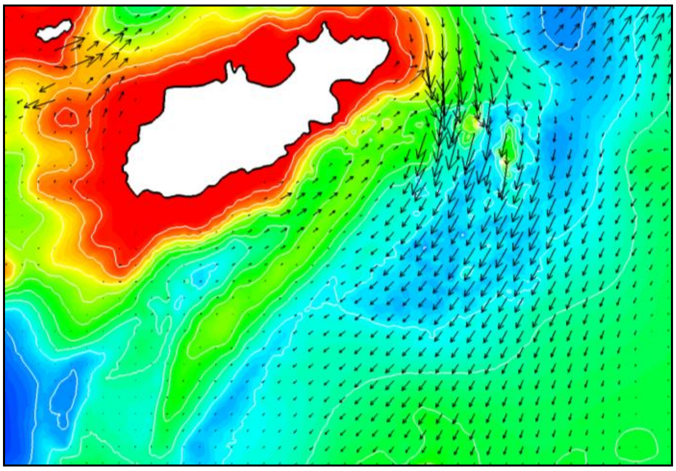


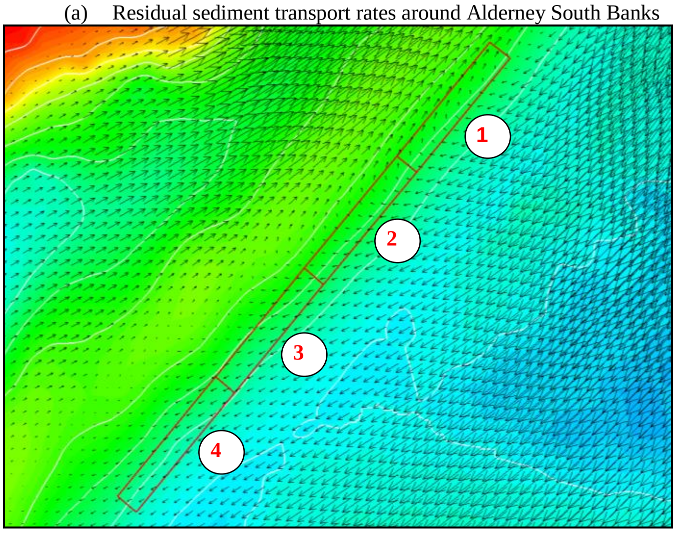
Figure 4. Cube-root-mean-cube speeds for the baseline model. Array footprints included for reference and the South Banks limits marked by the dashed line.

C. *Static bed model*

The residual sediment transport rates calculated using Equation 1 were compared with those calculated from observed sandwave migration over a 50-day period. Figure 5 illustrates the baseline residual sediment transport vectors as calculated from the model; the clockwise rotation of the vectors around the South Banks can be clearly seen. Figure 5(b) zooms in on four areas where repeated survey occurred and Table III gives a comparison between the sediment transport rates as estimated from observed sandwave migration and that calculated from the model. Note that sandwave migration tends to underestimate bedload sediment transport (q_b), as sand grains may roll over more than one sandwave, or be carried into suspension. Soulsby [19] suggests that the underestimate may be up to a factor of around two. Additionally, total load (q_t; bedload plus suspended load) can be estimated from the bedload given the water depth and sediment properties. Sediment transport rates for our model match those inferred from the sandwave migrations very well for analysis region number 4 with almost identical residual direction and very similar total-load values observed. Differences in region 3 are also fairly small. In analysis region 2 the directionality of the residual is wrong by around 30° and the magnitudes an under prediction by ~30%. Discrepancies are at a maximum in region 1 where the directionality is almost 100° out and the magnitudes an underestimate by ~40%. The increasing disparity towards the North-East of the bank appears to be due to the effects of the residual eddy and its specific location relative to the bank crest (see below). There are a number of problems with such a comparison (likely difference of directionality between q_b and q_s residuals, varying proportions of q_s and q_b) but we feel that the method represents the only means we have for checking the realism of the model transport rates.



(a) Residual sediment transport rates around Alderney South Banks



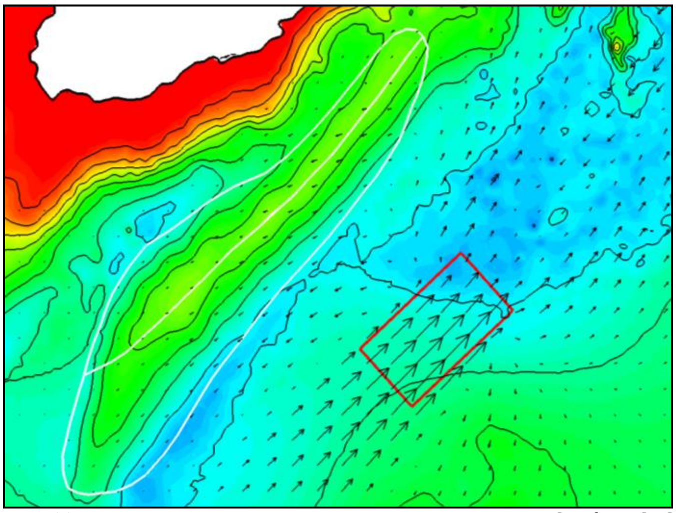
(b) Zoomed in view of analysis regions 1-4 where repeated bathymetric survey indicated sandwave migration rates.

Fig 5. Residual sediment transport for the static bed baseline model. Velocity vectors were combined with the Soulsby-Van Rijn total-load transport formula [19] to produce instantaneous sediment transport rate vectors for each time-step. Rates were then vector-averaged across the 14.8 day run-period to produce the residual. Values mapped onto a rectilinear mesh (i.e. arrows do not imply mesh resolution).

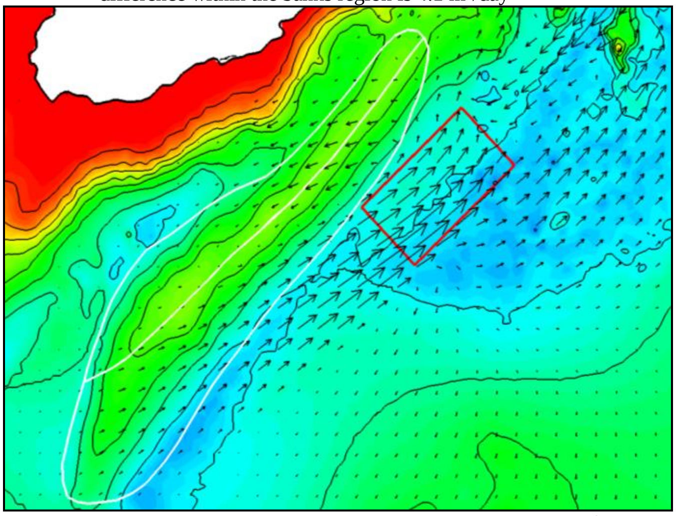
TABLE III

ESTIMATED BED AND TOTAL LOAD MAGNITUDE AND DIRECTION FOR ANALYSIS REGIONS IN FIGURE 5

	Sandwave migration analysis (observed)			**Sediment transport residual (model)**	
	q_b	Approx. q_t	Dir.	q_t	Dir.
	m^2/day	(5.6q_b)	(deg.)	m^2/day	(deg.)
1	0.99	5.49	251.6	3.22	344.0
2	0.77	4.28	256.4	2.97	284.8
3	0.64	3.55	257.6	4.00	250.8
4	0.78	4.32	241.3	4.15	241.5



(a) T86 energy extraction scenario. Maximum magnitude of residual difference within the banks region is 4.1 m^2/day



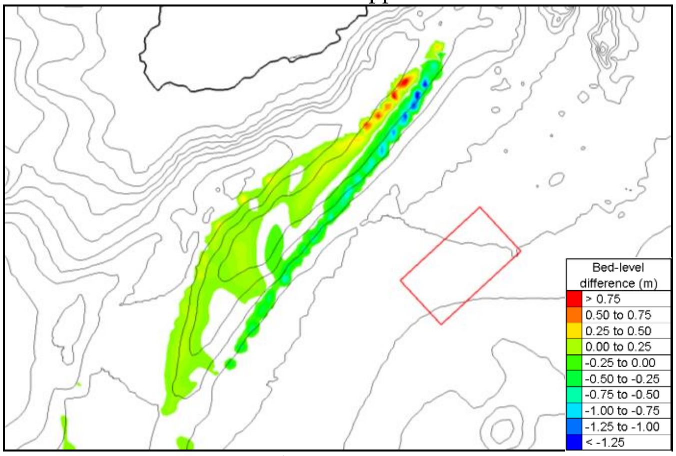
(b) T74 energy extraction scenario. Maximum magnitude of residual difference within the banks region is 10.0 m^2/day.

Figure 6. Vector-difference in residual sediment transport between the baseline and energy extraction scenarios. The regions of ebb and flood dominance over the South Banks are outlined and divided. Array footprint highlighted in red.

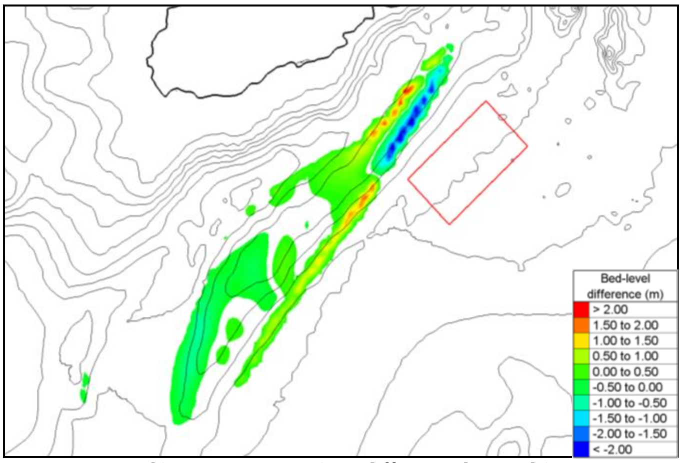
D. Coupled sediment transport model

A steady state was not reached during the 90-day baseline simulation period, so the coupled sediment transport model results could only give qualitative indications of short term changes that would occur under different energy extraction scenarios.

Differences in bed level change relative to the baseline scenario, over the 90-day simulation period, are plotted in Figure 7 for two of the seventeen cases. It can be seen that the patterns of erosion rates are very sensitive to the proximity of the array to the banks. Energy extraction in T74 leads to much larger bed-level differences relative to the baseline case. In contrast to the T86 scenario the large deposition zone at the South-West of the sandbank sees less deposition than baseline case. The region immediately downstream of the T74 array on the ebb-tide sees a reduction in erosion rates (due to flow deceleration) and a subsequent relative increase in bed-levels. Flow acceleration around the North-Western side of the array (ebb-tide) leads to increased erosion on the near-side of the bank and reduced erosion on the opposite side.



a) T86 scenario



b) T74 scenario (note different colour scale)

Fig. 7 Differences in bed elevation after 90-day model run under energy extraction scenarios (location of simulated array indicated by red rectangle)

V. CONCLUSIONS

Within the context of energy extraction, the simulations suggest that the potential for asymmetrical modifications to the flow regime, and hence to the sedimentary regime, is high. Areas of flow-deceleration downstream from tidal device arrays will only occur on one phase of the tidal cycle (either flood or ebb). From this study the South Banks will experience relative flow deceleration from the modelled arrays on the ebb-tide predominantly. Flow acceleration around arrays may also have an important impact. Although acceleration effects around arrays are typically smaller than deceleration effects downstream of arrays, they may be induced in the region of the South Banks on both the ebb and flood tides thereby increasing the impact of such acceleration effects.

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