Numerical investigation of tidal resource & far field effects of energy extraction in Lashy Sound, Orkney

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***Abstract*—Lashy Sound is a small channel in Orkney, Scotland, where a tidal stream energy development is planned. This study uses numerical modelling to investigate the energy resource of the Sound and the effects on the flow of removing this power. A new 3D regional-scale hydrodynamic model of the area was built using the MIKE software and was used to study Lashy Sound. A standard momentum sink approach was used to represent tidal energy converters. It is estimated that the maximum possible yield from this channel from the M2 tidal constituent alone is 23 MW mean and 61 MW peak power, although this would require an unrealistic and uneconomic arrangement of tidal turbines. The 30 MW capacity that is planned is predicted to be feasible, and the environmental effects of both large and small arrays are discussed.**

***Keywords*—MIKE, hydrodynamics, resource assessment, environmental impact**

I. Introduction

The Orkney archipelago in northern Scotland (Figure 1) contains a complex network of inter-island channels of which many, like the Pentland Firth to the south, experience rapid tidal flows and are hence of interest for tidal stream energy development. The strength of tidal activity in the region is due to the time taken for the M2 tidal wave to propagate around Scotland, and the resulting phase difference between the Atlantic and North Sea sides of Orkney [1].

Much research effort has been put into studying the Pentland Firth, which promises a great deal of tidal energy (e.g. [1]–[5]), and the large northern channel that includes the Fall of Warness, which is the location of the European Marine Energy Centre (EMEC) tidal test site (e.g. [6], [7]). Relatively little attention has been paid to the smaller channels within Orkney, what power may be available from them, and whether their exploitation could affect the major sites. In this work we use numerical modelling to examine one of these smaller channels, Lashy Sound, which has tidal energy development planned but has been largely uncovered in the academic literature.

In this paper we describe a new three-dimensional numerical hydrodynamic model of the Pentland Firth and Orkney Waters (PFOW) area that was developed to study Lashy Sound and its surroundings. We relate validation of this model, and describe early work on using the model to address two questions:

1) How much power is available from Lashy Sound?
2) What effect would exploitation of Lashy Sound have on other channels?

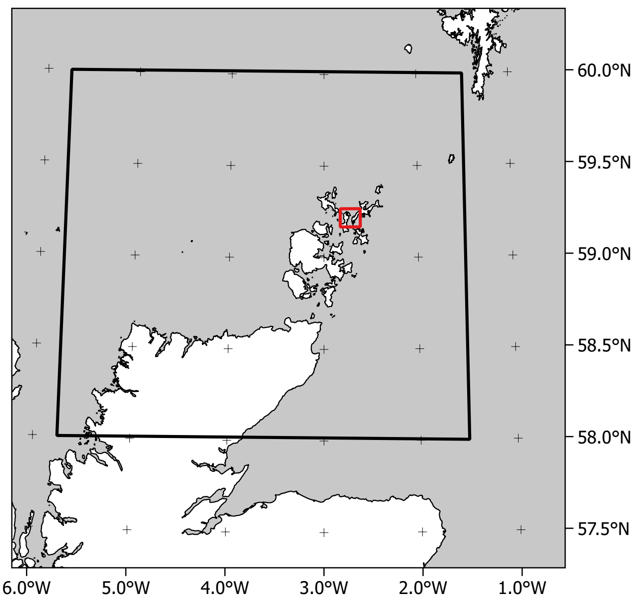


Fig. 1. Situation of Lashy Sound with respect to the Orkney archipeligo and the north of Scotland. The black box shows the extent of the model domain, and the red box highlights the location of Lashy Sound.

II. The channel

Lashy Sound lies in the northern part of the Orkney archipeligo, situated between the isles of Eday to the west and Sanday to the east. At the southern end it becomes Eday Sound, which links to the large channel through Orkney that includes the Fall of Warness. Eday Sound also has a shallow and partially-obstructed exit to the east which sustains rapid flows at some states of the tide. To the north, Lashy Sound opens into open sea. For a labelled map of these channels, see Figure 2.

It is notable that Lashy Sound has a north-south orientation, while the dominant tidal flow across the archipeligo as a whole is between east and west. Strong currents in Lashy Sound must, therefore, stem not directly from the hydraulic forcing between

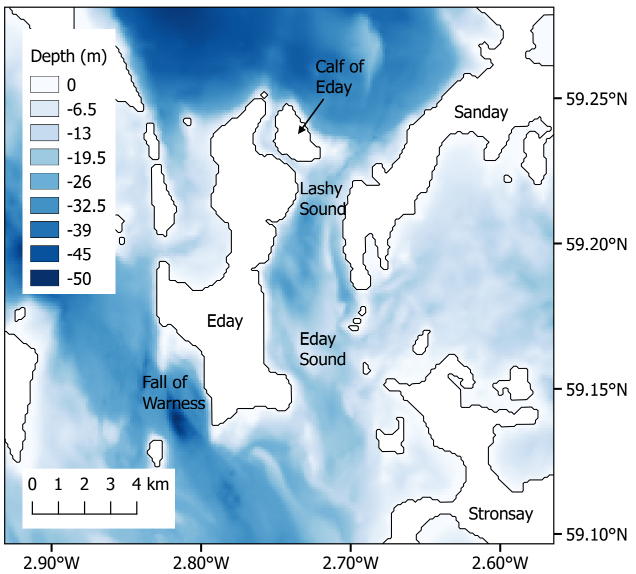


Fig. 2. Map showing the layout of Lashy Sound and the surrounding islands and channels. Colours show bathymetry with respect to mean sea level.

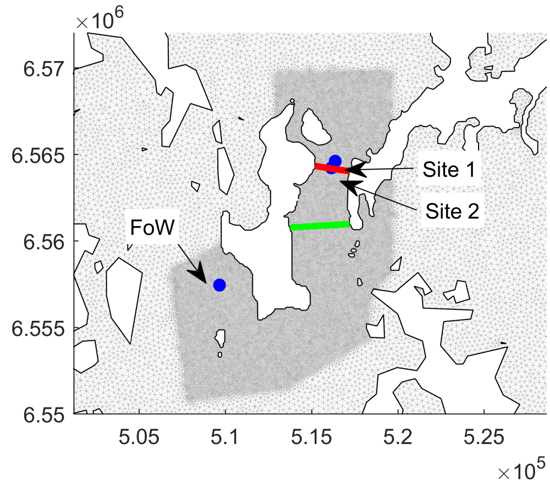


Fig. 3. Map showing the computational mesh for a part of the model. Blue points show the locations of ADCP surveys in the Fall of Warness (FoW) and Lashy Sound (Sites 1 & 2). The red line shows the transect used to place TECs, and the green line the transect used to measure transport through the channel. Spatial coordinates are in metres, referring to UTM Zone 30N.

the Atlantic and the North Sea, but from these links to other channels.

Lashy Sound itself is approximately $5\,\mathrm{km}$ long (measuring to the southern end of Sanday), between 3.5 and $1.5\,\mathrm{km}$ in width, and between 10 and $30\,\mathrm{m}$ deep. At the northern end a smaller subchannel of $<0.5\,\mathrm{km}$ width and approx. $10\,\mathrm{m}$ depth branches off the main stream and passes to the other side of a small island known as the Calf of Eday. Between the Calf of Eday and Sanday, which is the narrowest part of the main channel, is a narrow constriction in the deep channel with shallow water to either side.

Lashy Sound is of interest for commercial tidal energy generation, and developer Scotrenewables Ltd. has received an “agreement for lease” from The Crown Estate for a project of up to $30\,\mathrm{MW}$ capacity [8].

III. The model

A. Description

MIKE by DHI is a commercial hydrodynamic modelling suite commonly used in industry. For this work the 2012 version of the 3D Flexible Mesh Hydrodynamic Module (MIKE 3 FM HD) was used. This uses an element-centred finite volume approach to solve the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations under an assumption of hydrostatic pressure [9]. Turbulence is represented by eddy viscosity, which in this case was determined in the horizontal by the Smagorinsky formulation and in the vertical by a simple log law. Horizontal spatial discretization is on an unstructured mesh, while vertical discretization uses sigma layers. The simulation was run in barotropic mode without wind forcing.

Open boundaries were specified as clamped time-varying water levels, generated using the DHI global tidal model database [10]. This database is derived from TOPEX/POSEIDON altimetry and provides twelve tidal constituents at a spatial resolution of $0.125°$. Land boundaries were constrained to have zero velocity normal to the boundary, but permitted free slip along the shoreline. The seabed resistance was represented by a hydraulic roughness length, which was used as a calibration parameter.

The typical node spacing of the computational mesh was 80–$120\,\mathrm{m}$ in the area of interest around Lashy Sound and the Fall of Warness, increasing in stages to $8\,\mathrm{km}$ at the edges of the domain. Due to practical limits on computation time, finer meshes were not investigated. Bathymetric data within Lashy Sound was provided by Scotrenewables, while for the rest of the PFOW area a $20\,\mathrm{m}$ gridded dataset was provided by The Crown Estate (described in [11]). For the outer regions of the domain not covered by these sources, further bathymetry was supplied by SeaZone [12] on a grid of 6” resolution. The full extent of the model may be seen in Figure 1, and a part of the mesh in Figure 3.

B. Calibration & validation

The model was calibrated against ADCP records from the Fall of Warness, and validated against records from Lashy Sound. The choice was made to use different locations, rather than different times at the same locations, to ensure confidence in the validation as a measure of the model’s skill in the area of interest.

Calibration was conducted by adjusting the seabed roughness parameter k_s to achieve the best possible match of current speed between measurements and predictions. A value of $k_s = 0.1\mathrm{m}$ was chosen.

The model was validated against two ADCP surveys in the area of interest, (marked Site 1 & Site 2 in Figure 3), using a one-month period in February and March 2012. Comparisons

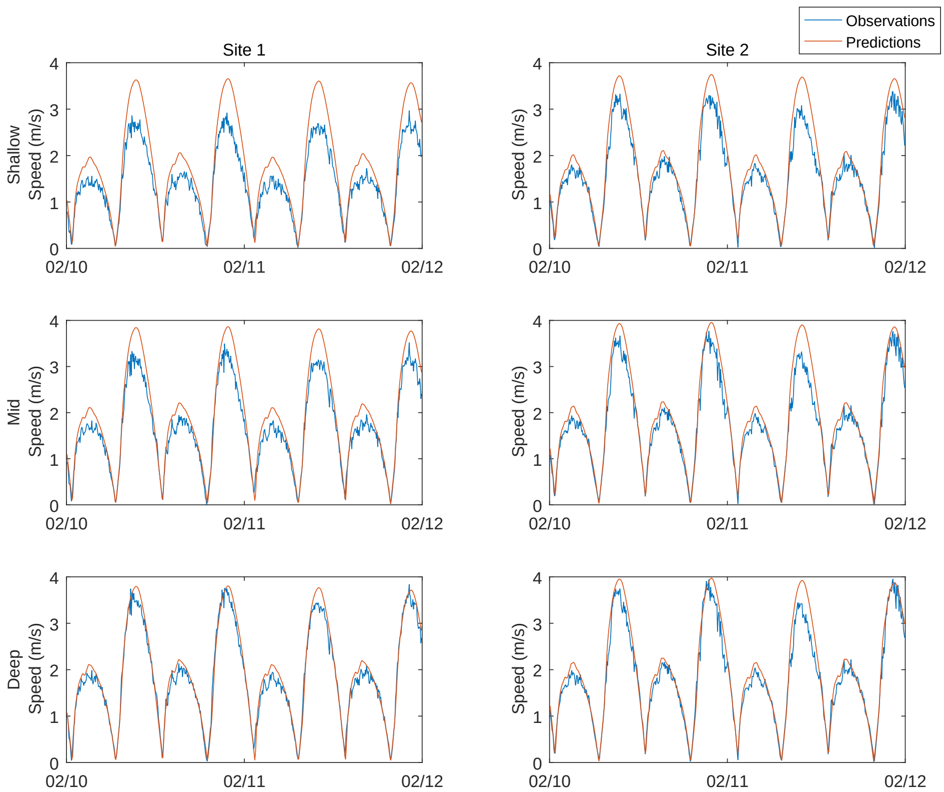


Fig. 4. Time series comparison of current speed between model and observations at three depths. For legibility, only 48 hours at spring tides are shown.

TABLE I
VALIDATION STATISTICS, COMPARING PREDICTIONS OF THE MIKE 3 MODEL TO OBSERVATIONS IN LASHY SOUND OVER A ONE MONTH PERIOD.

		Site 1		Site 2	
		u	v	u	v
RMSE (m/s)	Shallow	0.341	0.298	0.134	0.375
	Mid	0.162	0.294	0.166	0.426
	Deep	0.213	0.260	0.257	0.430
Scatter index	Shallow	0.577	0.304	0.175	0.372
	Mid	0.231	0.256	0.202	0.386
	Deep	0.278	0.206	0.302	0.375
R^2	Shallow	0.980	0.986	0.978	0.982
	Mid	0.983	0.988	0.979	0.983
	Deep	0.983	0.989	0.980	0.984
Bias (m/s)	Shallow	0.077	0.107	0.012	0.040
	Mid	−0.010	0.092	−0.043	0.057
	Deep	−0.117	0.074	−0.092	0.058

of u and v velocity components were made at three depths corresponding to approximately 20%, 50% and 80% of the water column. Statistical measures of agreement may be viewed in Table I, and visual comparisons in Figures 4–6.

In Lashy Sound the model provides accurate predictions at most states of the tide. However, it significantly overpredicts the highest current speeds near the surface, especially at Site 1. A "jet" of accelerated flow is predicted downstream of the constriction at the northern end of Lashy Sound, and it is possible that the model is incorrectly predicting the width or the strength of this jet. The overprediction may also relate to incorrect simulation of the flow through the subchannel to the west of the Calf of Eday, which meets the main channel close to ADCP Site 1. As this subchannel is shallower than the main channel, its effects would be most apparent near the surface. These hypotheses are presented as possible explanations for the difference seen, but neither can be tested with the available measurements.

The measured and predicted phases show a good match, and the asymmetry of the flow in the channel is reproduced well. At Site 1 the flow direction is predicted well, but at Site 2 there is a modest discrepancy.

Frequency-domain validation was conducted using the same predictions and measurements. For reasons of space it is only shown here in textual, depth-averaged, form (Table II). Phases and amplitudes of the major constituents, as given by `t_tide` [13], all match within 95% confidence intervals except for M2 amplitudes at Site 2. These M2 amplitudes are underpredicted in the u direction and overpredicted in the v direction, which matches the small discrepancy in flow direction seen in the time-domain analysis. It is interesting to note that harmonic analysis is not able to fully represent the flow in this area, with `t_tide` typically reporting that only 95% of the signal is explained by harmonic constituents. Since this aharmonic flow occurs in the model as well as the measurements, it cannot be attributed to weather effects. It probably relates to the jet of accelerated flow

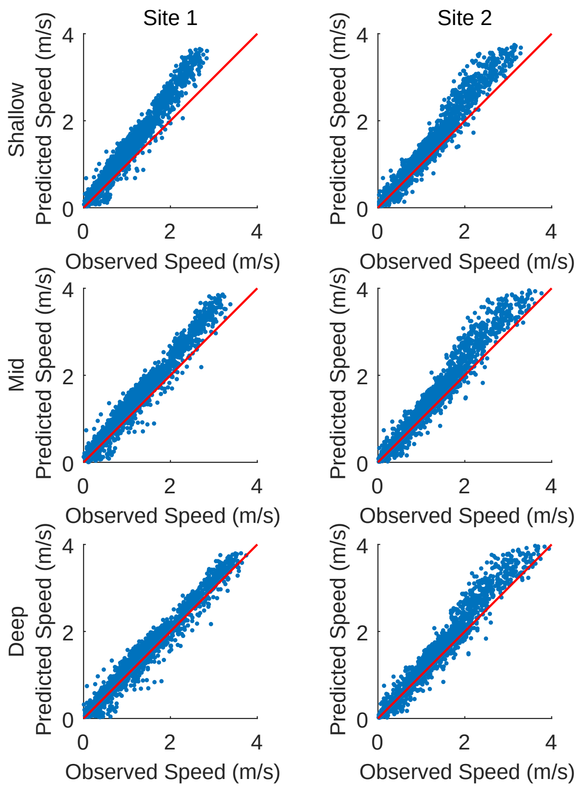


Fig. 5. Scatter plots comparing current speed between model and observations at three depths. For legibility, a regular sample of every fifth time step is shown. This results in a plotted time step of 25 minutes, and hence extreme values may be clipped slightly. The red lines represent 1:1 relationships.

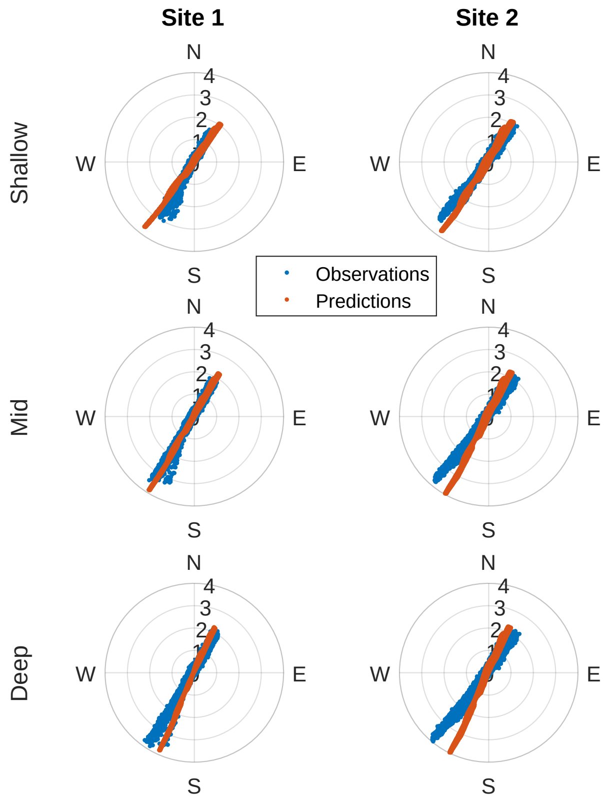


Fig. 6. Hodographs comparing measured and predicted velocities at three depths. Direction is that in which the flow is travelling. Radial axis indicates current speed in m/s.

TABLE II
COMPARISON OF DEPTH-AVERAGED PREDICTIONS AND OBSERVATIONS IN FREQUENCY DOMAIN AT TWO ADCP LOCATIONS IN LASHY SOUND.

		Amplitude (m)		Phase (°)	
		Model	ADCP	Model	ADCP
M2 u	Site 1	1.132	1.064	56.9	59.8
	Site 2	1.040	1.220	59.3	62.3
M2 v	Site 1	1.881	1.784	55.6	56.9
	Site 2	1.954	1.608	56.5	58.1
S2 u	Site 1	0.412	0.406	93.5	96.2
	Site 2	0.378	0.461	95.4	96.9
S2 v	Site 1	0.680	0.691	92.7	93.6
	Site 2	0.709	0.612	93.7	94.7

mentioned above, which introduces asymmetry that cannot be represented by sine waves at astronomical frequencies.

IV. ESTIMATING RESOURCE

A. Method

The approach taken in this work was not to consider realistic array layouts, but to arrive at a figure for the maximum power obtainable from this channel regardless of engineering or economic considerations. It is known that the most efficient way of extracting energy from a channel is to spread turbines evenly across its whole cross-sectional area to prevent any bypass flow [14], [15].

The MIKE software represents tidal energy convertors (TECs) as sub-grid momentum sinks based on actuator disc theory, and requires that they be specified in terms of hub location, diameter, and thrust coefficient. A transect was identified that crossed Lashy Sound at the narrowest point at which it remains a single channel (i.e. south of the split around the Calf of Eday; see Figure 3), and turbine locations were placed, evenly spaced, along this line.

The use of a single design of TEC would result either in large regions of horizontal bypass flow, at the sides of the channel where the depth was insufficient for the rotor, or — if smaller diameter turbines were used — a great deal of vertical bypass in the middle as flow diverted over and under the rotors. To avoid this bypass flow, the diameter of each turbine was calculated to fit the depth at that location subject to maximum and minimum diameters of $20\,\mathrm{m}$ and $4\,\mathrm{m}$ respectively, and with a $3\,\mathrm{m}$ allowance for bottom clearance and tidal range. However, this change in rotor diameters would have led to evenly spaced turbines having unequal gaps between them, which would have caused changes in local blockage across the channel. To address this, additional rotors were added to each location as necessary to normalise the local blockage ratio to the same as that of the largest turbine. Although clearly not physically realistic at a sub-grid level, at the resolution of the model this is equivalent, in all but the sparsest layouts, to placing the smaller rotors closer together.

A realistic turbine would be expected to have a thrust coefficient that varied as a function of the flow speed. However, when exploring the maximum potential of a channel this can be problematic, because if the turbines have a cut-in speed they are unable to reduce the flow in the channel below this speed. For this work, therefore, the turbines were given a fixed thrust coefficient of 0.85. For simplicity, no supporting structures were included in the model.

A range of levels of exploitation were simulated, from 10 to 2400 TEC locations. In the more heavily exploited scenarios a single row of turbines is unrealistic, but should be considered as representing a two-dimensional array. Because this single-row layout is unlikely to be optimal, the actual number of TECs should be used only for comparative purposes, and it is not intended that capacity factors or matters of economic viability should be considered.

In order to allow a large number of scenarios to be explored in limited computation time, only the M2 tidal constituent was used. This allows the use of just 12.4 hours of output — a single M2 cycle — as a representative time period. It was determined empirically that the model required 3 days of spinup time before its predictions in Lashy Sound became fully periodic, so each scenario was run for 4 days of model time and the output data taken from the first 12.4 hours of the fourth day.

Rotor thrust is reported by the MIKE software on a per-turbine basis by

$$F = \frac{1}{2}\rho C_T A|\boldsymbol{u}|\boldsymbol{u} \tag{1}$$

where F is thrust, ρ is the density of the water, C_T is the thrust coefficient, A is the area of the rotor and $\boldsymbol{u}$ is the flow velocity. In this work it was assumed that all rotors face into the flow at all times. Power produced was estimated as a post-processing step using

$$P = C_C F|\boldsymbol{u}| \tag{2}$$

where C_C is a coefficient that represents the conversion losses between kinetic energy in the flow and electricity. A value of 0.5 was assigned to C_C based on experimental results reported by Jeffcoate *et al.* [16]. The chosen values of $C_T = 0.85$ and $C_C = 0.5$ are equivalent to a power coefficient of $C_P = 0.425$.

It is acknowledged that some inaccuracy is inherent in using the same value of $|\boldsymbol{u}|$, representing an entire mesh element, in both of the equations above. More correctly, the velocity in (1) should be the free-stream velocity and that in (2) should be the velocity at the turbine, neither of which is known to the model [17], [18]. We plan to address this discrepancy in future work.

Transport through the channel was recorded for each scenario. This was calculated by taking 200 sample points along a straight line from coast to coast (Figure 3), extracting mean depths and depth-averaged velocities normal to this line at each point, and using simple trapezoidal integration.

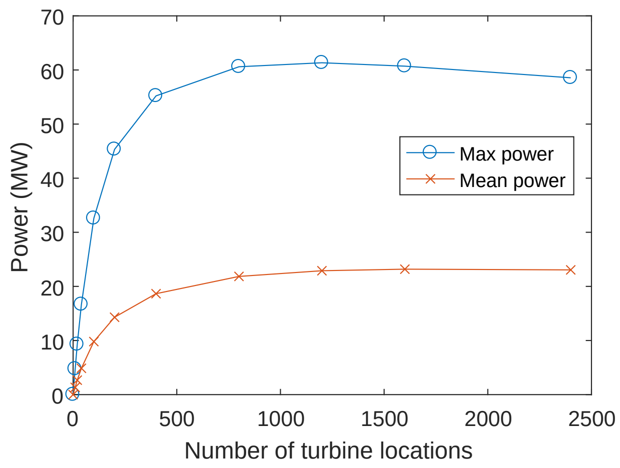


Fig. 7. Mean and maximum output over a M2 tidal cycle, with respect to the number of TEC locations.

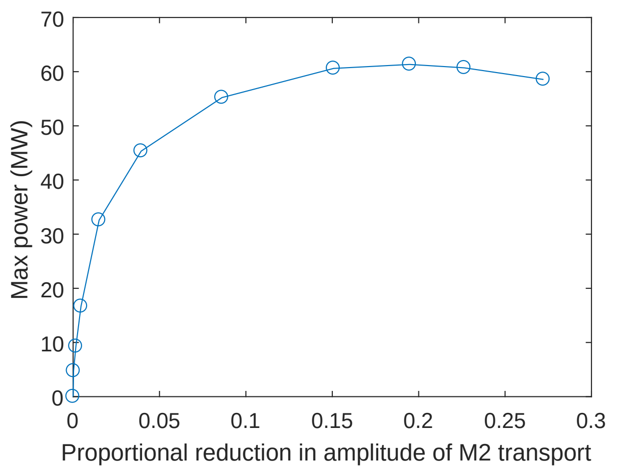


Fig. 8. Maximum output over a M2 tidal cycle, with respect to proportional reduction in volume transport through the channel.

B. Results

Figure 7 shows the maximum and mean power output of the various scenarios over a single M2 cycle. Figure 8 relates the maximum output to the maximum reduction in volume transport through the channel. There is a near-linear relationship between TEC numbers and output at low levels of exploitation, beyond which the marginal gain in power for each new turbine location decreases as the flow speed through the channel is reduced. At approximately 1200 TEC locations the marginal gain from additional turbines turns negative, as the reduction in power from the loss of flow speed outweighs the effect of adding more generating capacity. This point therefore represents the maximum yield available from the channel, and corresponds to mean and maximum outputs of 23 MW and 61 MW respectively. This is achieved with a reduction in transport of approximately 20%.

V. Far field effects

Two scenarios were studied: The first is that identified above with 1200 TEC locations and a peak output of 61 MW which, since it is the most energy that can be extracted, should be the "worst case" for environmental impacts. The second is one with 100 TEC locations and a peak output of 33 MW, which is close to the 30 MW that is planned for Lashy Sound. In each case the flow was compared to that with no TECs, and the effects on mean depth-averaged current speed are shown in Figure 9.

The 61 MW scenario results in a large reduction in mean current speed through the TEC array itself, for the length of Lashy and Eday Sounds, and for some kilometres beyond. Some flow acceleration around the array is also visible, which has arisen because of the lower limit that was placed on the size of a rotor and hence the absence of simulated turbines from water shallower than 7 m.

Outside the immediate flow of Lashy Sound, effects are small but extant. There is a very small increase in speeds in the Fall of Warness, of up to $5\,\mathrm{cm\,s^{-1}}$. There are more significant increases in flow along the south coast of Eday (up to $0.2\,\mathrm{m\,s^{-1}}$) and through the channel between Sanday and Stronsay (up to $0.5\,\mathrm{m\,s^{-1}}$) at certain stages of the tidal cycle. These changes are not visible in the figure as this only shows a temporal average.

Figure 10 shows changes in the maximum and minimum water level in each cell in the 61 MW scenario. The line of turbines is very clear in these maps because a 15 cm increase in the amplitude of M2 is produced north of them. This increase in range is not replicated south of the tidal fence; instead, the southern part of Lashy and Eday Sounds show a small increase in both minimum and maximum sea level, with the maximum increasing by up to 7 cm on the coast of Sanday.

Effects on water levels beyond Lashy and Eday sounds are small, but reductions in tidal range of the order of 1–2 cm are predicted along substantial parts of the Sanday and Stronsay coasts, as well as the south coast of Eday and even parts of Shapinsay, Rousay and the West Mainland (not shown in figure). Mid-channel water levels in the Fall of Warness are affected by a similar amount.

In the 33 MW scenario the magnitude of the effects is lower and impacts beyond Lashy and Eday Sounds, including those on other tidal sites, are predicted to be negligible. Within Lashy Sound an increase in maximum sea level at the coasts of up to 2 cm may be expected (not shown), and the reduction in mean current speed in line with the array is approximately $0.3\,\mathrm{m\,s^{-1}}$ in mid-channel (see Figure 9b).

VI. Discussion

In these simulations, the maximum power obtainable from the channel is achieved with a reduction in transport of 20%. This is well outside the range of 29–42% that is given by the simple analytic model of Garrett and Cummins [19] (hereafter GC05), and substantially below figures that have been identified for the Pentland Firth by numerical modelling [4], [5].

Part of this discrepancy is due to the presence of bypass flow around the ends of the simulated TEC array where the water is too shallow for the minimum rotor diameter that was specified. Part may also be due to the GC05 model not being fully applicable.

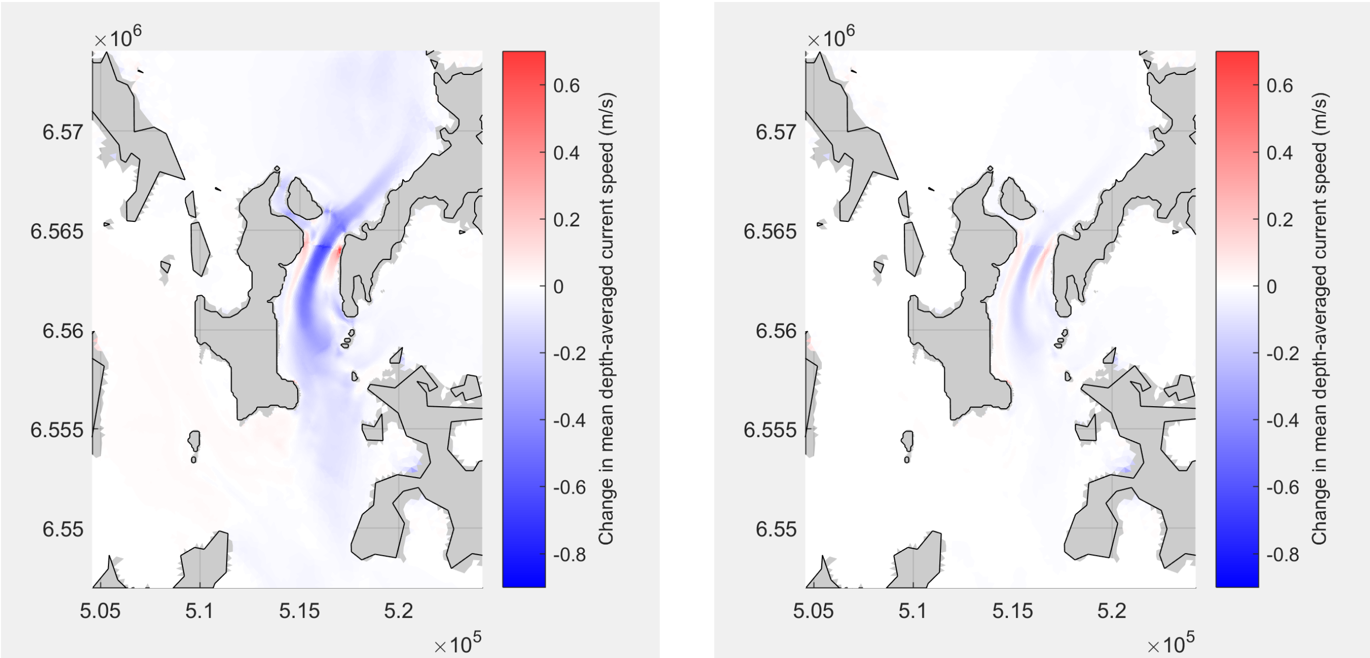
A limitation that Garret and Cummins noted in their model was that it did not allow for the driving head across a channel to change as a result of energy extraction. This is a valid assumption for their scenario of a single channel connecting two large basins, but does not hold for the more complex situation studied here. In fact surface elevations near to the northern mouth of Lashy Sound, and within the southern part of Eday Sound, are predicted to change by 2–8 cm at some stages of the tide in the maximum yield scenario. The complexity of the surrounding archipeligo may also mean that, even when the model is driven with only the M2 tidal constituent, Lashy Sound itself experiences more complex forcing. Further study of the dynamics of this channel, with and without energy extraction, is planned for the future.

The agreement to lease that has been granted by The Crown Estate for this area permits development of a tidal array with output capacity of 30 MW. Our work indicates that this is feasible from a physical perspective. Since 30 MW of maximum power is reached in the near-linear part of Figure 7 it is likely to be attainable with a modest number of TECs, contributing to a high capacity factor, which is a favourable contribution to any study of the economic viability of the site. However, the asymmetry of current velocities in this channel leads to a relatively low ratio of mean to maximum power output, even with M2 only, of around 30%, and this will act to reduce the capacity factor. A more detailed study, using realistic array layouts and more tidal constituents, would of course be required to establish an accurate figure.

In the simulation with maximum yield, hence that with the greatest environmental impacts, energy extraction results in changes to the flow over a moderate area, including the waters south of Eday and those between Sanday and Stronsay. It appears that this path acts as an alternate route into which a proportion of the flow diverts when Lashy Sound is obstructed. In this "worst case" scenario maximum water levels on the Eday and Sanday coasts are increased by up to 15 cm. This change could have implications for intertidal habitats and perhaps for human activities, but such effects are outside the scope of this study. Smaller effects, unlikely to be of any importance, are predicted as far afield as the West Mainland of Orkney.

In the more realistic scenario approximating the planned 30 MW of peak power, the increase in maximum water level is reduced to 2 cm along the coasts of the northern part Lashy Sound, and no significant effects are predicted beyond this area. As with any tidal stream development, changes to the flow pattern within the Sound would have modest effects on bed stress, and hence potentially on benthic ecology. These effects on bed stress would need to be investigated as part of the environmental impact assessment for any development.

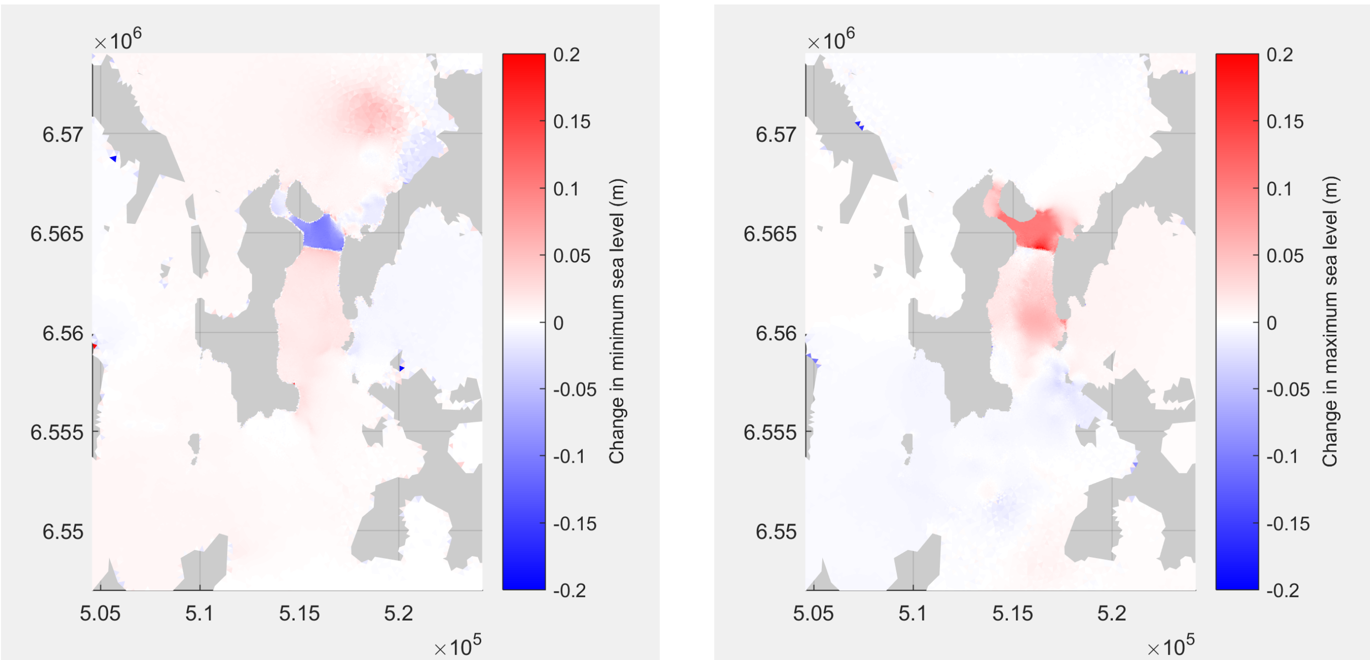
It is important to note that roughly doubling the power extracted from 33 MW to 61 MW involves a 12-fold increase



(a) 1200 TEC locations, max 61 MW.

(b) 100 TEC locations, max 33 MW.

Fig. 9. Map showing the mean effect on depth-averaged current speed, over a single M2 cycle, of extracting the (a) maximum available power, and (b) approximately the planned power, from Lashy Sound. Speed differences are calculated on a per-timestep basis before the temporal mean is taken. Spatial coordinates are in metres, referring to UTM Zone 30N.



(a)

(b)

Fig. 10. Maps showing the change in the (a) minimum and (b) maximum surface elevation of each cell at any time during an M2 cycle as a result of extracting the maximum available power (peak 61 MW) from Lashy Sound. Spatial coordinates are in metres, referring to UTM Zone 30N. Note that both of these plots correspond to the scenario shown in Fig. 9a; the effects on elevation of the second scenario, which are small, are not shown for space reasons.

in the area of turbines and a similarly disproportionate increase in environmental impacts. Although this study was not intended to address economic matters, it is clear that reaching the higher level of exploitation — the maximum physically possible in the channel — would be economically prohibitive and hence is extremely unlikely to ever occur.

Since a realistic array would spread its thrust less evenly across the channel than the continuous fence arrangement modelled here, it would lose more power to wake mixing [15]. This means that the total power lost from the channel, and hence the resulting environmental effects, might be greater than those shown here for the same electrical output. However, since the effect on maximum transport predicted here for a $33\,\mathrm{MW}$ output is less than 1.5%, the far-field effects of a well-designed array are still likely to be small.

VII. Conclusions

In this work a new 3D hydrodynamic model of the Pentland Firth and Orkney Waters area was developed to study the area around Lashy Sound. Validation showed good general performance, although there was an unexplained overprediction of the highest flow speeds.

Simulations using only the M2 tidal constituent indicate that the maximum yield available from Lashy Sound, using unrealistically large numbers of turbines that form a nearly complete fence, is a mean power of $23\,\mathrm{MW}$ with a peak of $61\,\mathrm{MW}$. This is achieved with a reduction in volume transport of 20%. A mean power of $10\,\mathrm{MW}$ and peak of $33\,\mathrm{MW}$, similar to the array that is planned in the strait, can be achieved with a 1.5% reduction in transport.

These powers will be underestimates of the true values, because only the M2 tidal constituent was simulated and because some bypass flow was permitted in shallow water at the sides of the channel. A realistic $30\,\mathrm{MW}$ array would lose more energy to wake mixing than the continuous fence arrangement modelled here, and would hence cause a slightly greater reduction in transport for the same power output.

In the $61\,\mathrm{MW}$ scenario very small environmental impacts are predicted over a wide area, and increases in maximum sea level of up to $15\,\mathrm{cm}$ within Lashy Sound are estimated. We emphasise that this scenario is a hypothetical one which is very unlikely to be realised.

In the $33\,\mathrm{MW}$ scenario significant effects do not extend beyond Lashy and Eday Sounds. Changes to the flow patterns within Lashy Sound would have modest effects on bed stress in the area, and an increase in maximum sea level of up to $2\,\mathrm{cm}$ is predicted on the coasts of Eday and Sanday close to the development site.

Acknowledgments

We are grateful to Scotrenewables Ltd. for bathymetry and coastline data for Lashy Sound and for the ADCP records used for validation. Neither the specification of turbines nor any of the layouts used herein are intended to represent Scotrenewables' technology or their plans for the area. We thank The Crown Estate for access to their gridded bathymetry for the region, and the UK Hydrographic Office for access to the VORF dataset. Support was provided by the EPSRC-funded TeraWatt and EcoWatt2050 UKCMER Grand Challenge projects (grant numbers EP/J010170/1 & EP/K012851/1 respectively).

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