Tidal energy resource assessment with TELEMAC-2D of the Churchill Barriers, Scotland

M. Yousef *, V. Venugopal, and L. Johanning

Abstract— **In order to tackle climate change challenges, various renewable energy sources are required to provide sufficient energy to phase out fossil fuel. Tidal energy is harnessing the power from tides to provide clean renewable energy, mainly in the form of electricity. The UK is the world leader in this newly emerging industry with the potential for tidal energy to provide 20% of the country's electricity needs. This paper presents a systematic approach to tidal energy resource assessment of the Churchill Barriers, the Orkney Islands, Scotland. The TELEMAC-2D model is employed in the study; the model set-up, calibration and validation are discussed herein. In the future, the approach will be used in the investigation of the potential for extracting tidal energy at the Churchill Barriers No.1 and No.2.**

Keywords – **Blue Kenue, Churchill Barrier, the Orkney Islands, TELEMAC-2D, Tidal energy resource assessment**

I. INTRODUCTION

Tidal energy concerns harnessing the power from tides to provide clean, renewable energy, mainly in the form of electricity. Tidal power generation can be divided into two main generating methods: tidal barrage, and tidal stream. The focus of this paper is on tidal stream power generation. The site identified for this study is the Churchill Barriers No.1 and No.2 in the Orkney Islands, Scotland.

Tidal barrages employ the difference in high and low tides to capture the energy from water moving in and out of an estuary or river to power turbines. The main advantages of tidal barrages are the high power density and efficiency, which are demonstrated in the renowned 240 MW EDF La Rance Barrage, Brittany, France. However, tidal barrages are large-scale structures, requiring high capital cost and can result in severe environmental impact [1].

Tidal stream power generation uses the kinetic energy from tidal currents to power turbines. Tidal stream devices, also known as Tidal Energy Converters (TEC), are based on well-understood concepts from the wind energy industry - since tidal turbines employ water in the same way that wind turbines use air to produce electricity. In contrast to wind and wave renewable energy resources, the tidal stream power generation has the advantage of being predictable and consistent. However, TECs require the current speed to be of no less than 4-5 knots (2–2.5 m/s) to achieve a cost-effective energy recovery [2]. Thus, TECs require site-specific conditions.

The unique geographical location of the United Kingdom and Scotland, in particular, provides an abundance of marine renewable resources. Consequently, the UK is currently regarded as a world leader in tidal energy research and development.

It is estimated that the potential energy from tidal streams worldwide is 100 GW [3] [4]. The UK's tidal energy resource represents approximately 50% of Europe's tidal energy capacity, with the potential to supply the country with 32 GW [3] [4] [5]. Furthermore, the tidal energy resource is projected to generate around 20% of the UK's requirement [6]. The UK Government is committed to source 15% of its energy from renewable resources by 2020 as well as 80% reduction of CO2 emissions 2050 [7].

For Scotland in particular, the tidal energy resource represents approximately 25% of Europe's tidal energy capacity, with the potential to provide 11 GW which can amount to more than 30% of Scotland's energy demands [8] [9]. The Scottish Government has set climate change and decarbonisation objectives, including supplying the country's electricity exclusively by renewable energy resources by 2020, as well as the reduction of greenhouse gas (CO2 emissions to 50 gCO2/kWh by 2030) [10] [11]. The region between the north-east of Midland Scotland and the south of the Orkney Islands is known as the Pentland Firth and Orkney Waters (PFOW). The PFOW is considered to have one of the strongest tidal streams in the world, with the potential to contribute to 6 GW [9] [11]. However, harvesting the energy from such highly energetic sites increases the challenges associated with it. Therefore, it is paramount to have an accurate and realistic resource assessment for the potential development site, not only considering the prospective of tidal energy yield but also, any associated risks, operation

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*Corresponding author - Mohammad Yousef: Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE), Edinburgh, EH9 3JL, United Kingdom (e-mail: M.Yousef@ed.ac.uk).

Professor Vengatesan Venugopal: University of Edinburgh, Edinburgh, EH9 3JL, United Kingdom (email: V.Venugopal@ed.ac.uk).

Professor Lars Johanning: University of Exeter, Cornwall, TR10 9FE, United Kingdom (email: L.Johanning@exeter.ac.uk).

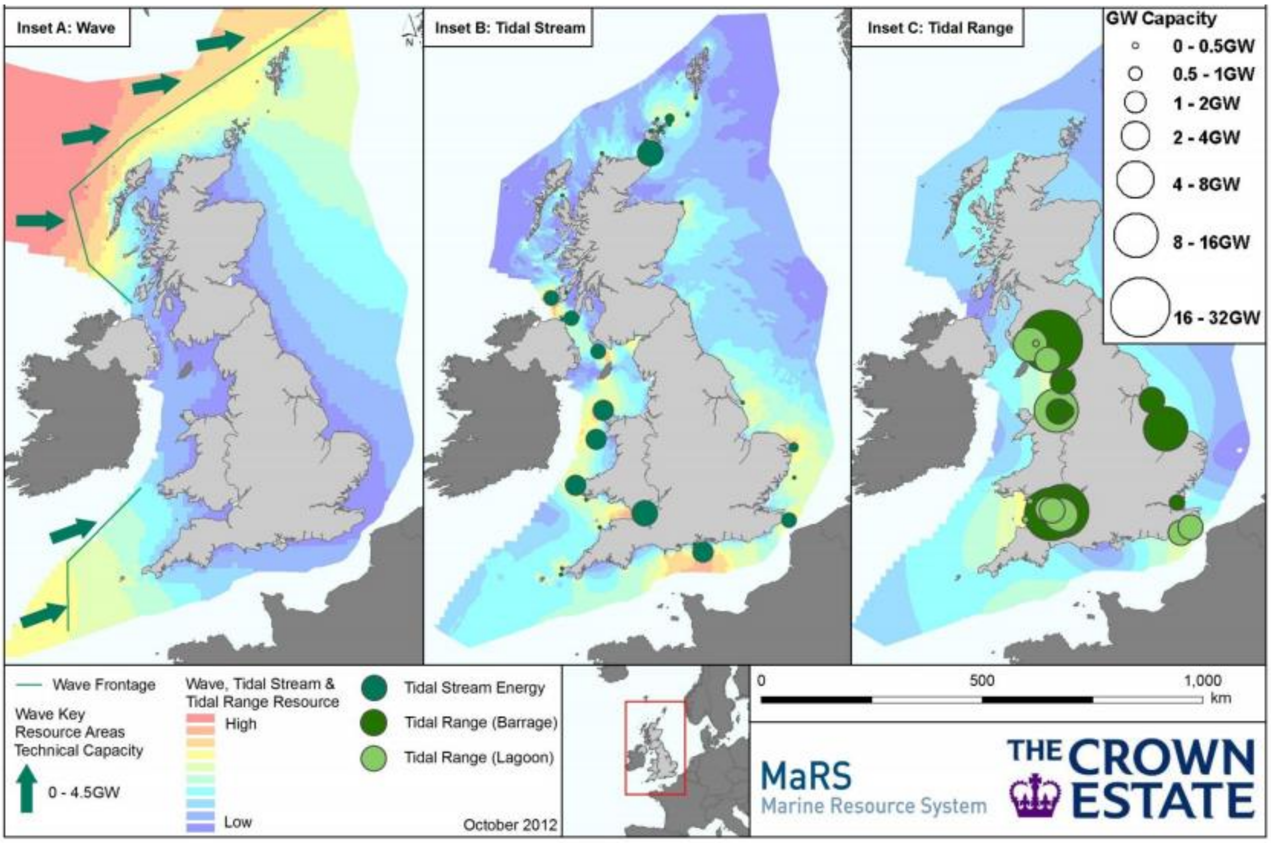

Fig. 1. Distribution of wave, tidal stream and tidal range energy resources in the UK [12]

and maintenance cost, logistics, survivability of TECs and economic viability of the overall project.

Furthermore, the physical tidal resource conditions, such as the current velocity ranges, water depths, and volumetric flow, are predominant factors in site selection. Also, it is important to consider environmental and social impacts of the development, in addition to access to the electrical grid. Hence, the process of resource assessment aims to increase the accuracy and reduce the uncertainty regarding the conditions of a prospective development site.

Presently, the following resources are employed in tidal energy resource assessment: Admiralty Tide Tables (Admiralty diamonds), tidal stream atlases, tide gauges, the British Oceanographic Data Centre (BODC) database, Acoustic Doppler Current Profiler (ADCP) devices and modelling (numerical or physical). Additionally, satellite altimetry, tide gauge, and ADCP devices measure the water elevations. ADCP devices also measure the current velocity in a water column. ADCP devices are widely used in field measurements due to the ease of deployment, the ability to sample throughout the water column, and high accuracy readings. Nevertheless, direct measurements using ADCP devices pose temporal and spatial limitations [13]. Temporal limitations of stand-alone ADCP devices include their finite battery life. The spatial limitation concerns the coverage of wide study area, which can be addressed by deploying a sufficient number of devices to cover the area of interest. Deploying a big number of ADCP devices can be challenging, very expensive and time consuming for large areas. The availability of bathymetric data for the study area enables the use of numerical models in the resource assessment study. Numerical models account for spatial and temporal variations, seabed roughness, and local meteorological conditions, such as wind and wave. Field data are still required for the calibration and validation of the numerical model.

Three types of numerical models can be employed in a resource assessment study: a) One-Dimensional (1D); b) Two-Dimensional (2D); and c) Three-Dimensional (3D). 1D models were not considered in this study as they cannot account for a variable bathymetry and geometry of channels [13]. On the other hand, 2D models can overcome the limitations of 1D models. 2D models use depth-average velocities, reducing the computational requirements. However, the simplified depth-average 2D models cannot accurately predict the current velocity across the water column [13] [14]. Lastly, 3D models have the advantage to provide additional insight on the flow characteristics by calculating the current velocity profile of the water column. On the other hand, this is computationally demanding, and thus, 3D models are usually used in small areas of study [13] [14].

This study presents a systematic approach to tidal energy resource assessment of the Churchill Barriers, the Orkney Islands, Scotland using a 2D model, the TELEMAC-2D.

II. RESOURCE ASSESSMENT STUDY AREA

THe site identified for this study is the Churchill Barriers No.1 and No.2 in the Orkney Islands, Scotland. The Churchill Barriers are located in the southern part of the islands connecting the Mainland to Burray and South Ronaldsay. Four barriers were built during the Second World War, two of which (barriers No.3 and No.4) are listed by the Historic Environment Scotland.

The Churchill Barriers have served a number of important roles over the years, from initially providing wartime defences for the Royal Naval anchorage in Scapa Flow during the Second World War, to currently providing vital road links between the Mainland and the islands; and now with the prospect of harnessing tidal resources, to providing electrical energy.

The present arrangement and operation of the Churchill Barriers prevent water from flowing in either direction through Holm Sound. The flow characteristics would be different if the barriers were opened, with estimated velocity of 2-4m/s (with individual barrier No.1 at 2.9m/s and No.2 at 2.8m/s) [15]. Initial energy production is estimated to be between 18 MW at barrier No.1 and 7 MW at barrier No.2 [15]. Barrier No.1 is 610 meters long, while barrier No.2 is 570 meters (measured using Google Maps).

Fig. 2. Location of the Churchill Barrier No.1 and No.2 in the Orkney Islands, Scotland [15]

TABLE I
PREDICTIONS OF THE ENERGY POTENTIAL AT THE CHURCHILL BARRIERS [15]

Scenario	Barrier No.1		Barrier No.2	
	Channel Model (MW)	Delft3D Model (MW)	Channel Model (MW)	Delft3D Model (MW)
Barrier No.1 open	15.6	17.8	-	-
Barrier No.2 open	-	-	7.8	9.2
Both barriers open	15.4	15.8	7.3	7.7

III. TELEMAC MODEL OVERVIEW

TELEMAC-2D is an open source numerical model which was developed by the National Hydraulics and Environment Laboratory (Laboratoire National d'Hydraulique et Environnement - LNHE) of the Research and Development Directorate of the French Electricity Board (Électricité de France) EDF-R&D. TELEMAC-2D is now managed by a consortium of consultancies and research institutes such as HR-Wallingford in the UK [16]. TELEMAC-2D solves the second order partial differential equations for depth-averaged free surface flow in two dimensions of horizontal space and calculates the depth of water and the two velocity components at each node of the computational mesh [16] [17]. TELEMAC-2D solves the shallow water equations (Saint-Venant equations) using the finite-element method and a computation mesh of triangular elements [16] [17]. The model solves the following four hydrodynamic equations simultaneously:

Continuity:

$$\frac{\partial h}{\partial t} + u.\vec{\nabla}(h) + h\mathrm{div}(\vec{u}) = S_h \qquad (1)$$

Momentum along x:

$$\frac{\partial u}{\partial t} + \vec{u}.\vec{\nabla}(u) = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}\mathrm{div}\left(h v_t \vec{\nabla} u\right) \qquad (2)$$

Momentum along y:

$$\frac{\partial v}{\partial t} + \vec{u}.\vec{\nabla}(u) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\mathrm{div}\left(h v_t \vec{\nabla} v\right) \qquad (3)$$

Tracer conservation:

$$\frac{\partial T}{\partial t} + \vec{u}.\vec{\nabla}(T) = S_T + \frac{1}{h} div\left(h v_t \vec{\nabla} T\right) \qquad (4)$$

where

h	depth of water (m)
u, v	velocity components (m/s)
T	passive (non-buoyant) tracer (g/l or °C)
g	gravity acceleration (m/s^2)
vt, vT	momentum and tracer diffusion coefficients (m^2/s)
Z	free surface elevation (m)
t	time (s)
x, y	horizontal space coordinates (m)
Sh	source or sink of fluid (m/s)
Sx, Sy	source or sink terms in dynamic equations (m/s^2)
ST	source or sink of tracer (g/l/s)

h, u, v and T are the unknowns.

The TELEMAC-2D revision v7p2r3 is used in this study.

IV. TELEMAC-2D MODEL SET-UP

THe process of tidal modelling using TELEMAC-2D is illustrated in Fig. 1. The pre- and post-processing are carried out using the open source Blue Kenue software, which is developed by the National Research Council Canada [18]. Blue Kenue performs the data preparation, analysis, and visualisation for numerical modelling.

There are three mandatory input files for TELEMAC-2D: the geometry file, boundary conditions file, and the steering file.

The geometry file contains the mesh and the interpolated bathymetry and it is created in Blue Kenue. On the other hand, the boundary conditions file describes the type of each boundary of the computational domain which can be either closed (solid) or open (liquid) boundaries. Furthermore, the boundary conditions file is generated by Blue Kenue, which outlines the type and location of the boundaries. Finally, the steering file controls the simulation process. It is a text file which can be edited via a text editor (Notepad++ is used here). Keywords are used to define a run characteristics using the TELEMAC-2D dictionary. It includes several parameters that are required by TELEMAC-2D some of which are:

1. File names
2. General options
3. Boundary conditions
4. Initial conditions
5. Physical parameters; such as friction and turbulence
6. Numerical parameters; such solver specifications

It is important to note that both the geometry and boundary conditions files are required to be obtained before the creation of a new steering file.

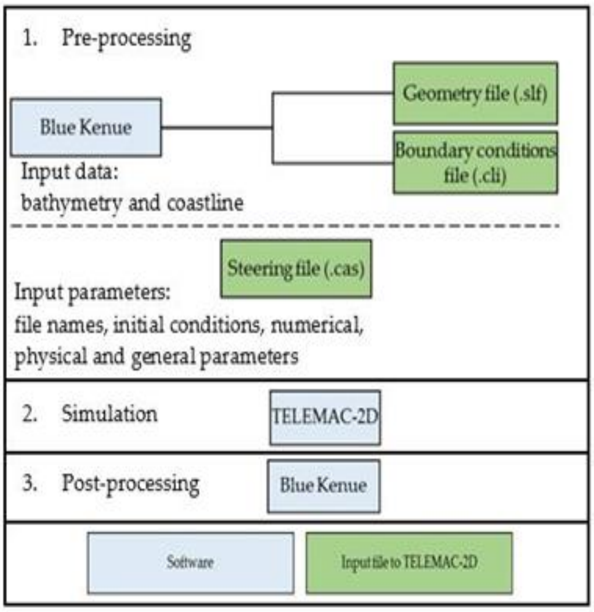

Fig. 3. Tidal modelling process using Blue Kenue and TELEMAC-2D.

A. *The geometry of the model*

Meshing is the process of discretisation of a continuous body into a finite number of elements. Finite-element models, such as TELEMAC-2D, require an unstructured computational mesh of triangles (variable sizes of triangles). The T3 Mesh Generator tool in Blue Kenue was used to produce 2D scalar triangular meshes that can be used in TELEMAC-2D. Blue Kenue employs an unconstrained Delaunay Triangulation [18]. Moreover, Blue Kenue requires the coastline and bathymetry data of the model domain as inputs to create the geometry file. As aforementioned, the geometry file includes the mesh and the interpolated bathymetry.

There are several publicly available sources for obtaining the coastline and bathymetry data. For instance, the coastline extractor tool by the National Oceanic and Atmospheric Administration (NOAA) can be utilised for coastline data, while the General Bathymetric Chart of the Oceans (GEBCO) provides bathymetry datasets. However, for the area of study, the publicly available data were deemed unsuitable due to poor resolution and would yield unsatisfactory results. Higher resolution data of 1 arc second which equated to 15mx30m per pixel/grid cell for the coastline and bathymetry were purchased from www.Findmaps.co.uk.

The coastline and bathymetry data were imported into Blue Kenue and converted into the Universal Transverse Mercator (UTM) coordinate system, UTM Zone 30 with WGS84 ellipsoid datum. The bathymetry data were relative to Chart Datum (CD). However, since TELEAMC-2D utilises Mean Sea Level (MSL), the bathymetry data were converted to MSL vertical datum (CD to MSL, Kirkwall 1.78m). At the site of interest, the Churchill Barriers, the mesh edge length was set to 15 m. The same mesh edge length was applied around the corners of the coast to allow the mesh to compute the flow between the islands with adequate resolution. Elsewhere in the model, the mesh resolution was coarser with a smoother transition between coarse and fine mesh (mesh edge length from 50m to 200m). Fig. 4 illustrates the geometry of the model domain with the mesh mapped to the bathymetry. The model domain contains 55661 nodes and 107640 elements.

Furthermore, the time step was selected to be 1 second to satisfy the Courant–Friedrichs–Lewy (CFL) stability condition. The CFL condition denotes the number of grid cells crossed by a water particle during a time step which considerably influences the quality of the results [16]. Time step value was calculated based on the smallest mesh edge value (15 m) and the highest current velocity (5 m/s) expected in the computational model domain. This maximum time step was calculated so that the flow should cross half of the element in one-time step; therefore the maximum time step 15 / 5 =3 s.

B. The boundary conditions of the model

Fig. 5 below illustrates the boundary conditions of the computational domain. The initial and boundary conditions that drive the model can be extracted from databases of harmonic constants available to use with TELEMAC-2D. TPXO satellite altimetry is a current version of a global model of ocean tides that includes regional and local tidal solutions, developed by Oregon State University (OSU). The European Shelf (ES) database was selected for this study [19]. The ES has 11 harmonic components and employs GEBCO 1′ database with a resolution of 1/30 of degree, 660x420 grid. The tidal harmonic database includes the following constituents: M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4. The solution provides amplitudes and phases for tidal elevation and transport from which the current velocity U and V can be deduced. Additionally, the Coriolis force and turbulence were accounted for, while other metrological phenomena such as wave and wind, were not included. Two open boundaries segments encompass the domain of the computational mesh. The open boundaries are represented in orange squares, while the closed boundary in grey (mainland Scotland). The current velocity U and V components along with water depth H were applied at the boundaries.

I. RESULTS AND DISCUSSION

THe calibration and validation of the model, sensitivity analysis and evaluation of performance indices are discussed in the following sections. The model results were assessed against observed (field measurement) data. The observed ADCP data are for a single location (deployment latitude 58º 53.061′N, longitude 002º 56.235′W) that is approximately 2 km to the west of barrier No.2 with a frequency of 10 minutes.

The ADCP data were provided by the Orkney Islands Council.

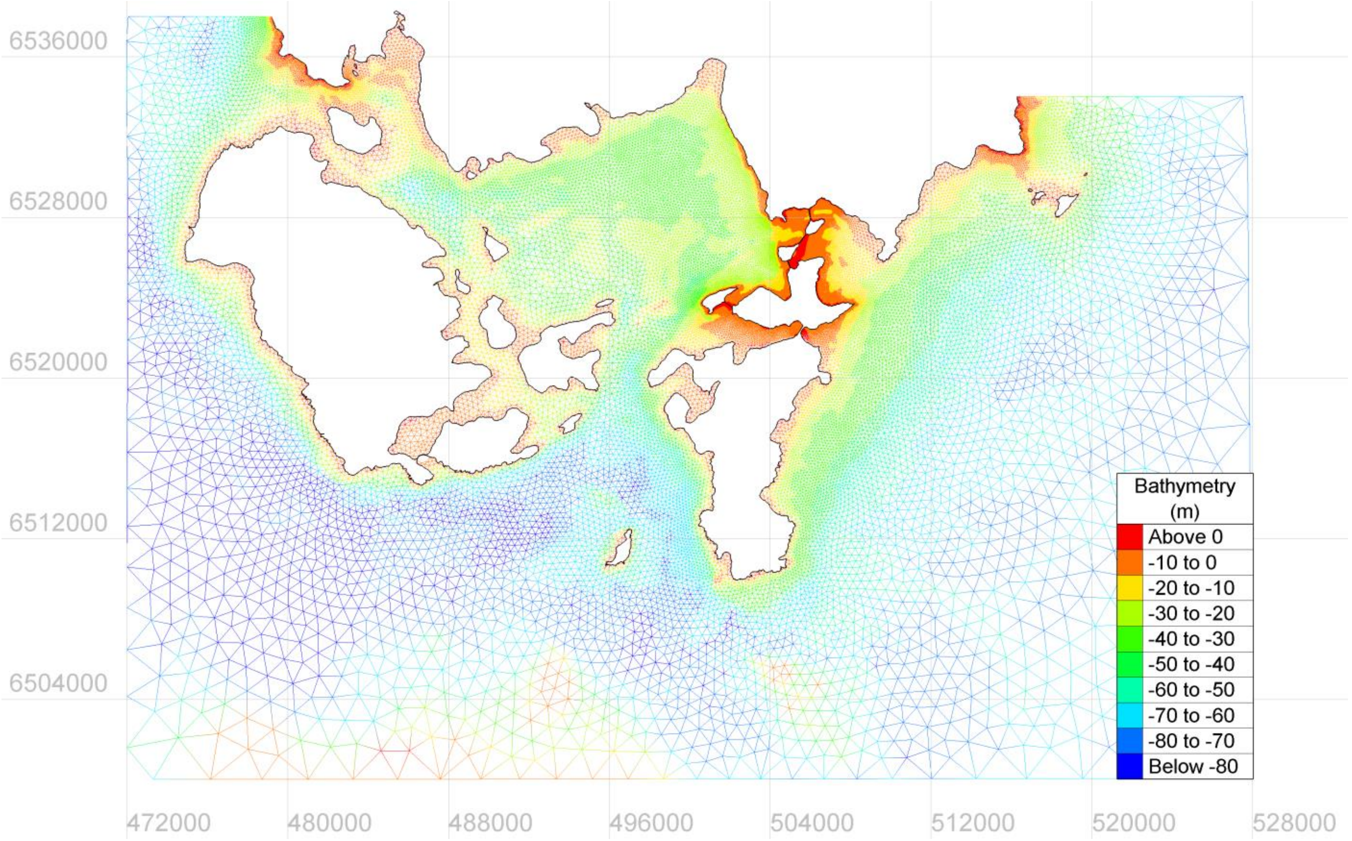

Fig. 4. Computational domain of the model with the mesh and the interpolated data

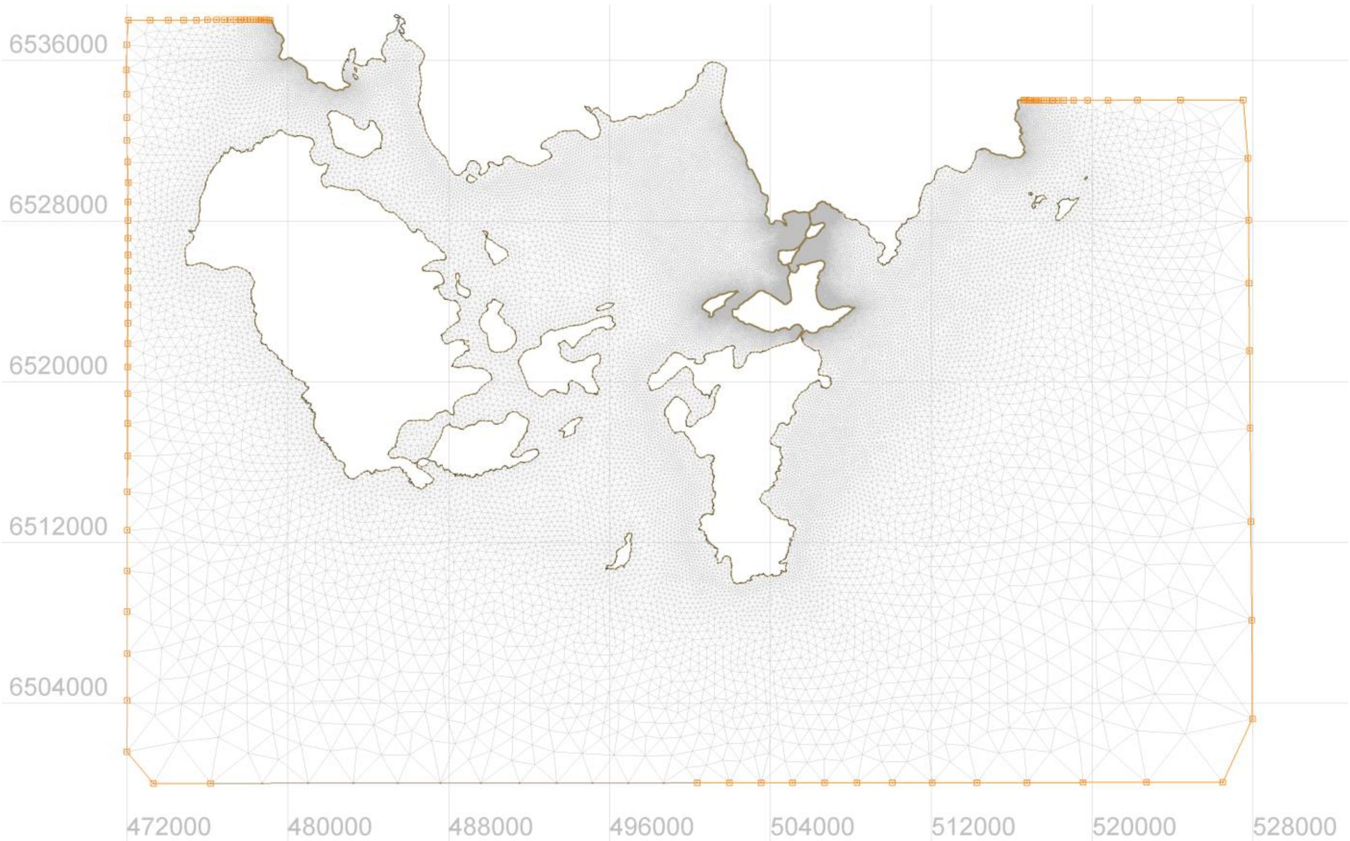

Fig. 5. Computational domain of the model with boundary condition segments

I. CALIBRATION OF THE TIDAL MODEL

The simulation period started at 00:00 on the 28th September 2013 until 00:00 on the 1st November 2013. The model initiating period can take up to 3 days to reach fully developed sea conditions [8]. Thus, the initial time period between the 28th and 30th of September 2013 was not considered in the analysis; this is to allow for the model to achieve numerical stability. The simulation period output from the 1st to 31st of October 2013 was used for the analysis and calibration of the model. It is worth mentioning that HR-Wallingford advised that the newer versions of TELEMAC-2D (post revision v5) require only 24 hours to achieve numerical stability. Therefore, a 15 day simulation period (covering a spring and a neap cycle) is sufficient for model calibration and validation purposes.

The model calibration process aims to achieve the best fit of the model results in comparison to field observations by tuning the model input parameters. Such input parameters include the coefficients of seabed friction, tidal range, sea level and metrological factors. However, as there is no standard procedure for model calibration in the literature, a trial and error approach was adopted during this stage [20]. Initially, the model was run using the default values as recommended in the TELELAMC-2D Manual; later, a series of cases with various combinations of input parameter values was run.

Several statistical representations were used in comparing the observed data and the predicted model output to assess the predictive capability of the TELEMAC-2D model. The equations (5)-(10) define the quality indices utilised in the calibration and sensitivity analysis of the model [8]. The Root Mean Square Error (RMSE) evaluates the difference between the observed and predicted data, where a smaller RMSE value is desired. The strength of linear correlation between the observed and predicted data is evaluated with the Pearson’s correlation coefficient R, where the closer the value to 1, the stronger correlation between the two data sets.

$$\mathrm{Bias} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x}_{\mathrm{oi}} - \mathrm{x}_{\mathrm{mi}}) \tag{5}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x}_{\mathrm{mi}} - \mathrm{x}_{\mathrm{oi}})^2} \tag{6}$$

$$\overline{x_o} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x}_{\mathrm{oi}}) \tag{7}$$

$$\overline{x_m} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x}_{\mathrm{mi}}) \tag{8}$$

$$\mathrm{SI} = \frac{RMSE}{\overline{x_o}} \tag{9}$$

$$\mathrm{R} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x}_{\mathrm{oi}} - \overline{x_o})(\mathrm{x}_{\mathrm{mi}} - \overline{x_m})}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x}_{\mathrm{oi}} - \overline{x_o})^2 (\mathrm{x}_{\mathrm{mi}} - \overline{x_m})^2}} \tag{10}$$

where x_{o} and x_{m} are the observed and model data respectively.

Water depths from ADCP observed data were used in the comparison. The sensitivity analysis concluded that the TELEMAC-2D default input parameter values yield the highest accuracy when assessed against the statistical quality indices, as shown in Table II. Fig. 7 below illustrates a comparison of water depths between the measured and predicted data for October 2013. There is a slight discrepancy between the two datasets of 3%.

TABLE II
QUALITY INDICES FOR OCTOBER 2013

Mean	Bias	RMSE	Bias/Mean	SI	R
26.31	0.20	0.26	0.01	0.01	0.98

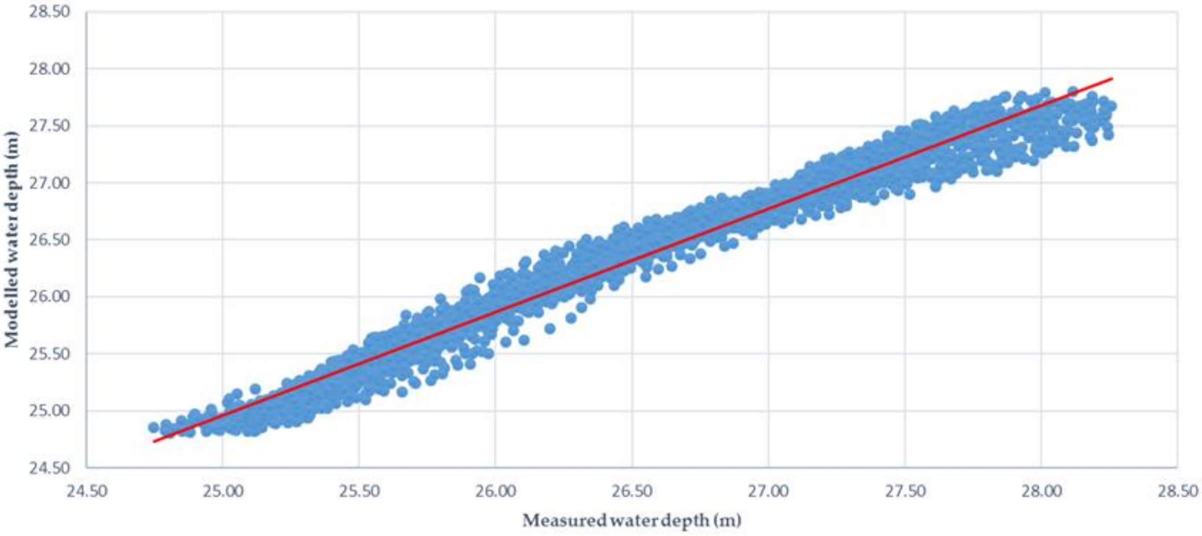

Fig. 6. Correlation plot of the water depths for October 2013.

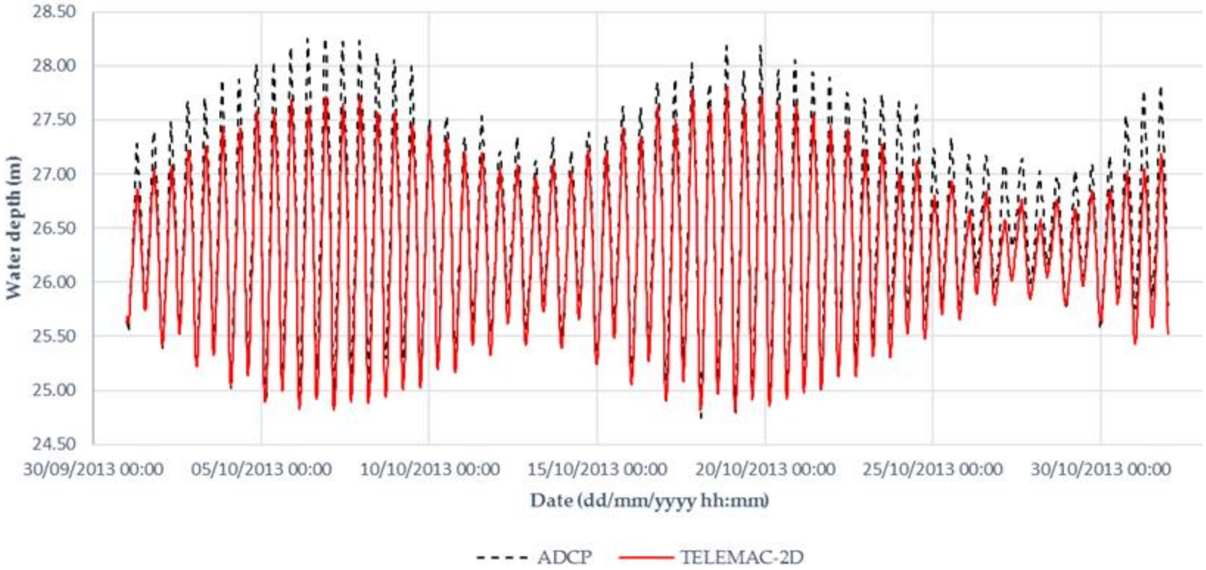

Fig. 7. Comparison of the water depths between the measured and predicted for October 2013.

II. VALIDATION OF THE TIDAL MODEL

During the validation process, the model was introduced to a new dataset with a different time period. The statistical quality indices were calculated and used in comparing the observed data against the predicted model output. This process is to ensure that the model is sufficiently accurate for future use. Due to the limited ADCP data for the study area, the validation dataset is for only 20 days. The simulation period was set to start at 00:00 on the 8th September 2013 until 00:00 on the 28th September 2013. The initial 24 hour period was not considered in the analysis. Table III shows the quality parameters for the validation dataset which indicates excellent matching between the observed and predicted water depths, with a 2.6% discrepancy between the two datasets.

TABLE III
QUALITY INDICES FOR 9TH -27TH SEPTEMBER 2013

Mean	Bias	RMSE	Bias/Mean	SI	R
26.31	0.12	0.19	4.72E-03	0.01	0.99

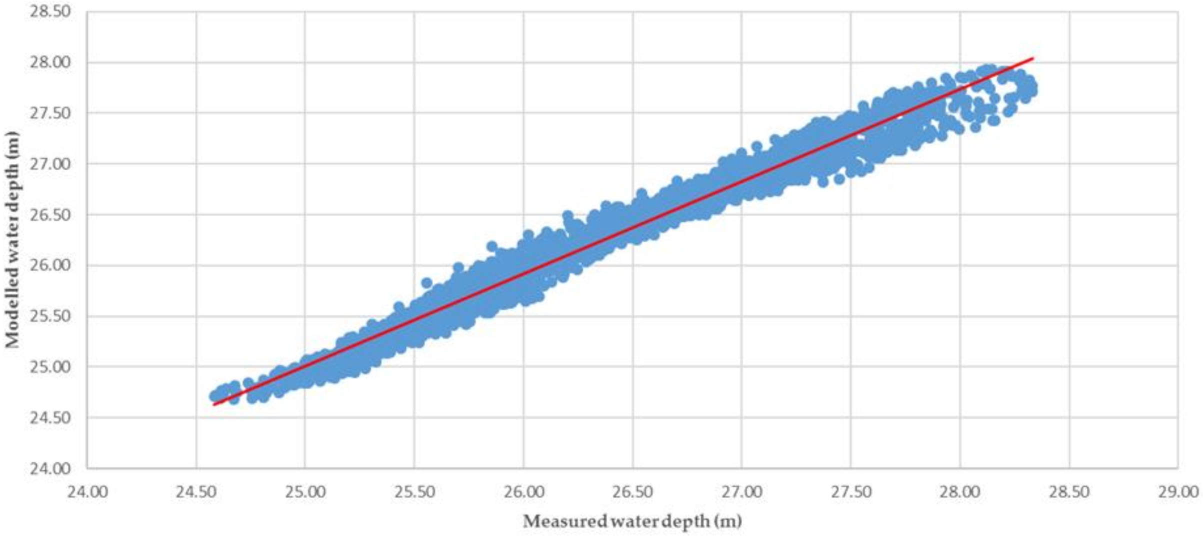

Fig. 8. Correlation plot of the water depths for 9th – 27th September 2013.

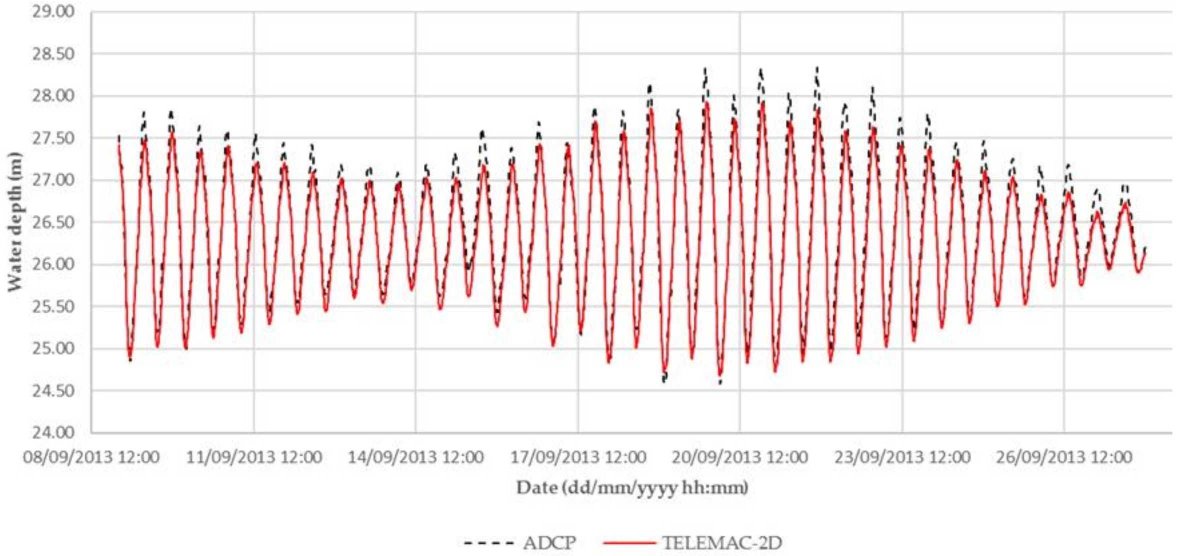

Fig. 9. Comparison of the water depth the measured and predicted 9th – 27th September 2013.

III. UNCERTAINTY ASSESSMENT

It is demonstrated that the calibration and validation of the model provided excellent results when assessed against the ADCP water depths data. However, there are uncertainties present in the study that are discussed herein.

Assuming that the ADCP data was acquired correctly, there is still, a lack of observed data in the area of study as the data employed in the study are for a single location and not covering several months or years. Having more field measurements at various locations and for longer periods would allow for a more robust calibration and validation of the model. However, ADCP data collection can be a costly and lengthy process. Furthermore, only water depth data acquired by ADCP devices are considered here; current velocities in the study area are very low due to the presence of the barriers. The maximum current velocity recorded by the ADCP is 0.16 m/s. Moreover, ADCP devices are not accurate in measuring very low current velocities below 1 m/s, and hence, the current velocity was not included in the calibration and validation of the model. Also, time of measurements can have a significant impact on the quality of measurements; if the deployment is in winter, the cold water increases the visibility which will reduce the accuracy of the ADCP measurements as a result of not measuring enough suspended particles in the water column [21] [22].

The bathymetry data describe the topography of the seabed including the depths and shapes of the underwater terrain. Thus, the quality and accuracy of the bathymetry data have a significant impact on the simulation results. The areas in the vicinity of the barriers have a low-resolution bathymetry details which should be taken into account when evaluating the model performance.

Finally, meteorological inputs such as waves are not included in the simulation, as access to data is unavailable. The barriers experience different waves from the east and the west, and consequently, the waves can impact the quality of the predicted results. It is observed that the inclusion of wind in the model does not impact the simulation results.

II. CONCLUSION

THe paper presents a systematic approach to tidal energy resource assessment of the Churchill Barriers No.1 and No.2, Orkney Islands, Scotland using TELEMAC-2D. The TELEMAC-2D model set-up, calibration and validation along with uncertainty assessment are discussed. The model is successfully calibrated and validated to the current site conditions. This approach can aid developers in site selection and preliminary tidal farm design including potential energy available for extraction at the study site. In the future, the approach will be used in the investigation of the potential for extracting tidal energy at the Churchill Barriers by incorporating TECs. A series of scenarios will be explored in evaluating the viability of tidal energy extraction at the site either in the existing barriers' infrastructure or in a channel formed by opening up a proportion of the barriers.

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