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# Coastal Shelf Model of Northern European waters to inform tidal power industry decisions

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***Abstract*—The Energy Technologies Institute has commissioned a Continental Shelf Model of Northern European waters. Its principal aims are to assess the tidal energy potential around the UK, to inform the design of energy harnessing schemes, to understand the interaction between different tidal range and tidal stream energy schemes, and to evaluate their impact on Northern European coasts. To that effect, coarse and detailed resolution versions of the model were developed.**

**Considerable effort was invested in identifying, obtaining and analysing suitable data for the model calibration and validation exercise. Good agreement was achieved overall, and in particular against discrete observed velocity data at two high energy sites in the Irish Sea/North Channel.**

**Computing time for a 15-day period is under 15 minutes on a 12-core desktop computer, and under 3 hours on a standard multi-core desktop computer for the coarser model. That for the detailed model is under 1.5 hours on an 8 x 12-core blade cluster. This allows simulations to be run efficiently and could open the way for parameter estimation and optimisation and ultimately for uncertainty analysis.**

**This makes the Continental Shelf Model a suitable tool for the tidal power industry to predict future tidal energy scheme scenarios, and the interaction between different energy schemes.**

## I. Introduction

Renewable energy extraction from tidal range and/or tidal current technologies in a particular area will affect the hydrodynamics of the local tidal system, impacting the tidal resource itself. There may also be a regional effect on the hydrodynamics, impacting other tidal energy extraction schemes' resource and potential energy yield. The impact of large scale and/or widespread tidal energy extraction on the tidal system is therefore important to understand in order to inform optimisation and management of the tidal resource.

This paper describes the development of coarse and detailed resolution versions of a Continental Shelf Model of Northern European waters (CCSM and DCSM respectively, CSM generically), and its anticipated use by the tidal power industry. [15] summarises the conclusions drawn from the CSM in terms of inter scheme interactions. The work was commissioned by the Energy Technologies Institute (The ETI) in 2011 with the aim of improving understanding of the possible interactions between proposed tidal energy extraction schemes. It was undertaken by Black & Veatch Ltd in partnership with HR Wallingford and the University of Edinburgh.

## II. The Continental Shelf Model setup

The open source, industry driven, TELEMAC system, and more specifically its two dimensional flow module, TELEMAC-2D, forms the underlying modelling tool for the development of the CSM.

### *A. Extent*

Recent publications [1, 4] have indicated that relatively small tidal power projects can affect very distant locations. In order to cater for long-range impacts and interactions between energy schemes, the CSM not only covers UK waters, but extends offshore slightly beyond the Northern European continental shelf (defined principally by the 300 m depth contour), and includes the coastlines of the United Kingdom, Ireland, the Channel Islands, France, Belgium, the Netherlands, Germany, Denmark, Sweden and Norway. It includes, amongst others, the Malin Sea, Irish Sea, Celtic Sea, English Channel and the North Sea. The Baltic Sea is not included in the model because of its very limited tidal range and minimal mean spring tidal current velocities [2]. An annual mean discharge is instead imposed as an inflow in the model. The extent of the CSM is shown in Figs. 3 and 4.

### *B. Resolution and exclusions*

Two versions of the CSM were developed as follows:

- The Coarse resolution of the CCSM starts from c. 1 km at the coastline, on islands and locations of selected tidal range and tidal current energy schemes, with a growth rate of 8%, to reach a maximum of c. 35 km in open water. The total number of nodes is c. 161,500; the number of elements is c. 301,000.
- The Detailed resolution of the DCSM starts from c. 200 m at the coastline, on islands and energy scheme sites, with a growth rate of 8%, to reach a maximum of c. 35 km. The total number of nodes is c. 1,625,000; the number of elements is c. 3,055,000.

While the resolution of the DCSM provides more detailed predictions than that of the CCSM, its purpose, like the CCSM, is primarily to provide preliminary impact assessment results for the entire Northern European continental shelf. It is not to be used in place of a refined local model when considering resources / impacts in specific areas.

In both versions of the CSM, the unstructured mesh used by TELEMAC-2D was fitted to predefined internal lines and refined locally to facilitate the inclusion of coastal sites of interest, or the geographical locations of anticipated tidal range and tidal current energy schemes at a later date. Particular attention was paid to coastal features such as small inlets, passages and islands, to ensure they were adequately represented in the models.

The level of detail with which sites of interest, the coastline and islands are represented in a model depends largely on the local resolution. For illustrative purposes, Fig. 1 shows representations of an hypothetical island, in a detailed- (top image) or coarse- (bottom image) resolution model. In Fig. 1, the colour contours show arbitrary elevations in the vicinity of the island. The unstructured mesh defined by the model resolution is shown in grey and a see-through surface is shown in blue that represents the still water level.

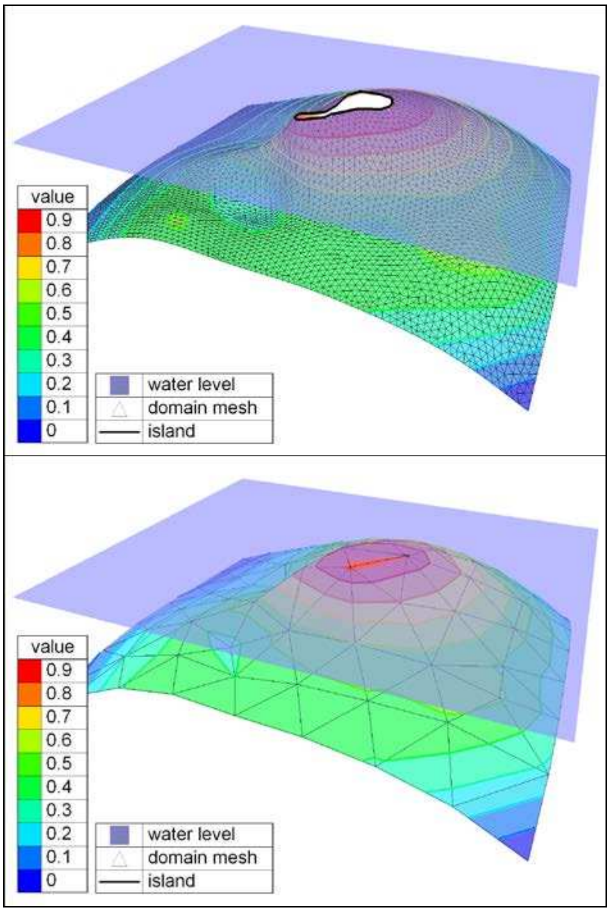


Figure 1. Representation of an island in different resolution models.

In the coarser model, the island is represented as a bathymetric feature; that is, all the elements are part of the unstructured mesh. As the water level goes down with the tide, dry cells will be introduced at the tip of the (under water) island (marked as a thin red patch). The cells will become wet again when the water level goes up.

In addition, significant effort was invested in this project to identify and group together clusters of small islands into larger land masses, in order to represent the hydrodynamics as closely as possible. Examples include the Isles of Scilly, the islands between Ile d'Ouessant and Ile de Molène off the coast of Brittany, or islands along the rugged coastline of Norway to name a few.

In the example illustrated in Fig. 2, the Isles of Scilly were individually contoured in the DCSM (purple contours) but clustered, to some extent, in the CCSM (orange contours). This was made necessary by the model resolution.

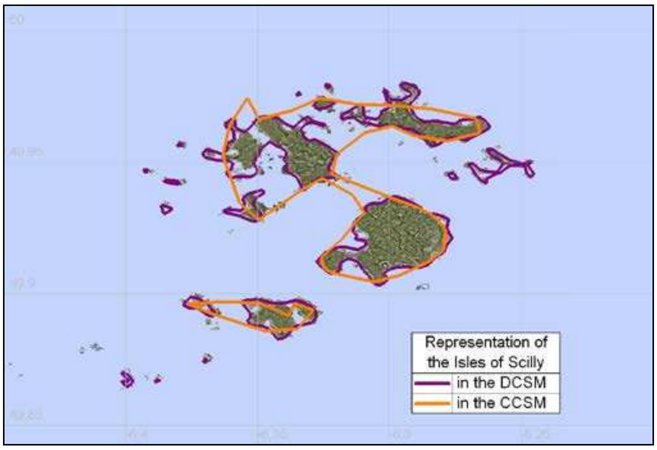


Figure 2. Representation of the Isles of Scilly in the CSM.

### C. *Seabed map*

The bathymetry in the CSM was developed from Admiralty Chart data processed and provided by SeaZone of HR Wallingford. Significant effort was invested in the pre-processing of the digitised bathymetric charts to ensure consistency across all regions as many of the charts overlapped. The level of detail included in the charts was deemed sufficient for the purpose of the CSM, given its resolution.

The CSM was developed in a bespoke spherical coordinate system due to its large extent, true to distances in m. The vertical reference datum was Mean Sea Level (MSL).

### D. *Tidal forcing*

The CSM is driven by spatially varying time histories of water levels along the model offshore boundaries, combined with a radiative algorithm (Thompson boundary [8, 13]) that allows internal waves to leave the domain with little or no reflection. The time histories were synthesised at every computational point directly from TELEMAC [12], based on the 13 constituents available from the Northern European

TPXO dataset (8 primary, 2 long-period and 3 non-linear constituents).

The TPXO dataset is one of the most accurate global models of ocean tides [11]. It is based on a best-fit of tidal levels measured along remote sensing tracks from the TOPEX/POSEIDON satellite project in operation since 2002. The Northern European dataset was deemed adequate to define tidal levels in deep water, at the model boundary.

## III. THE CSM CALIBRATION, VALIDATION AND VERIFICATION

The CSM was first calibrated (against coastal observed tidal data), then validated (against offshore observed tidal data) and verified (against velocity data and atlases). Considerable effort was invested in identifying, obtaining and analysing suitable data from various organisations, metocean and hydrographic offices to that effect.

### *A. Calibration*

Calibration was carried out over a complete 15-day tidal cycle featuring above average spring conditions and below average neap conditions, to ensure that the CSM performs well for the entire range of expected tidal conditions. Calibration was achieved by tuning the CSM bed friction parameter, at a global level first and within 4 regions of the domain eventually, until good overall agreement was reached at 24 coastal tidal gauges [6, 9, 14].

These locations were selected such that (a) they cover the entire model area (this is particularly relevant since one of the principal aims of the CSM is to inform the impact of the implementation of tidal energy schemes upon other interests); (b) they represent the possible range of expected spatial variations in tidal amplitude throughout the model area; and (c) they are located close to key areas of interest (e.g. Hinkley Point – Avonmouth in the Bristol Channel, Portrush in the North Channel).

Agreement of the CSM results with observed data was primarily illustrated by comparison of the predicted and observed water level traces over the full 15-day tidal cycle, at all calibration locations. Examples for a subset of locations (marked in Fig. 4 and representative of the model area) are given in Fig. 5 for the DCSM. In these plots, the horizontal axis is time; the vertical axis is free surface elevation in m. To aid visualisation of the results, the vertical axis was coloured according to range (dark green for ±4 m, bright blue for ±8 m, and red for ±12 m).

While the time histories give an immediate visual impression of the agreement, the quality of the CSM calibration was assessed by computing the difference in tidal levels between the model predictions and the re-synthesised data at each time step throughout the 15-day tidal cycle. The result of this assessment was presented in terms of normalised Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) values for all the calibration locations. A target normalised RMSE value of 10% is often deemed to reflect a good calibration. This metrics was used for the CSM.

The analysis confirmed the suitability of both versions of the CSM. In the St George's Channel, Bristol Channel, Irish Sea and North Channel area, normalised RMSE values were generally well below the target value of 10%. The agreement was also strong around the Orkney and Shetland Islands although the calibration locations were not directly located in areas of significant tidal energy potential (due to lack of data at the time of the study).

In Fig. 3 and Fig. 4, the spots mark all the calibration locations considered in this project; the colour identifies the normalised RMSE value obtained from the calibrated CSM. For example, dark and light green spots indicate locations where the normalised RMSE value was below 5% and 10% respectively, that is, where the calibration target for the CSM was met or exceeded.

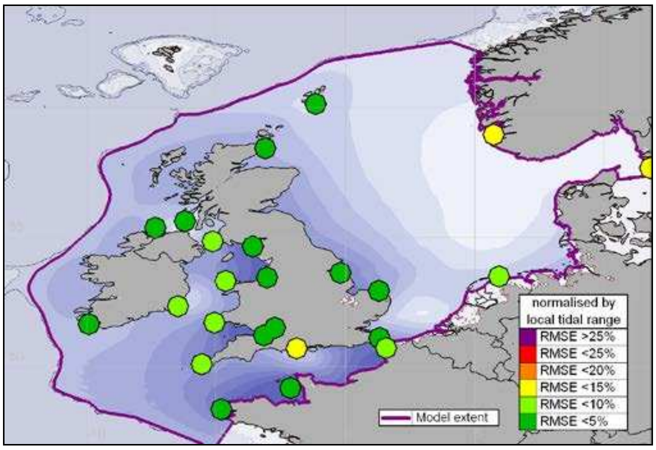


Figure 3. Quality of the CCSM calibration exercise measured in terms of normalised RMSE. The model extent is also shown.

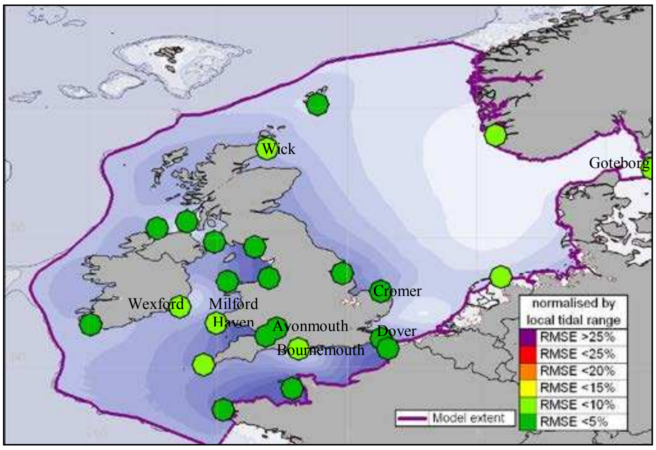


Figure 4. Quality of the DCSM calibration exercise.

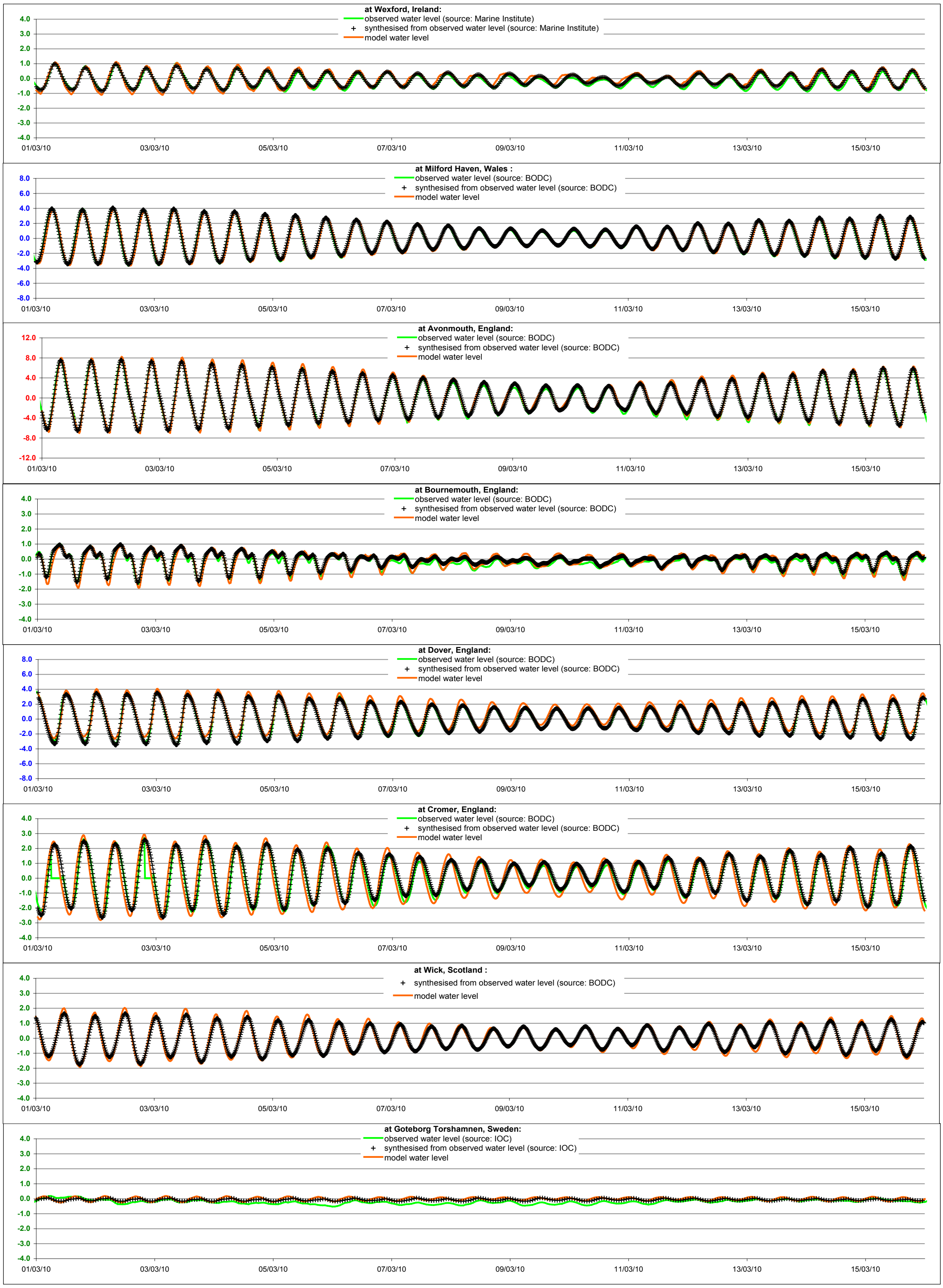


Figure 5. Tidal range time histories. The tidal levels predicted by the DCSM are indicated as a thick orange line, the levels obtained by tidal re-synthesis are shown as black crosses. When available concurrently to the calibration period, the observations [6, 9, 14] are represented by a thick light green line.

### B. Validation

Validation of the CSM was performed against independent sets of observed offshore tidal gauge and bottom pressure data (at 11 stations). Comparison against these data sets confirmed the suitability of the CSM in high energy key areas.

### C. Verification

The data used to verify the CSM comprised velocity data and atlases of tidal range and peak current speed. Although the agreement of the CCSM with velocity data was mixed (principally because of its coarse resolution), the DCSM velocity predictions compared very favourably with measurements available at the time of the study. The results of this analysis cannot be shown in this paper to protect the copyright attached to the measured velocity data.

Verification against the MAFF Atlas [10] was successful with the amphidromic points (e.g. off Wexford) and the areas of high tidal range (e.g. Morecambe Bay) qualitatively very well reproduced in both versions of the CSM.

Verification against the UK Marine Renewable Energy Resources Atlas [5] was also positive for known energetic areas. It is noted that the finer resolution of the CSM (compared to that used in the UK Atlas [5]) allows a far better discretisation of the velocity field in key areas. As such, the DCSM (and to a lesser extent the CCSM) identified strong current areas (e.g. at the Falls of Warness, or in the North Channel off Larne) that had been previously misrepresented in the UK Atlas.

These comparisons against atlases, as opposed to the spot checks performed in the calibration/validation exercise, enhance the overall CSM credibility.

### D. Discussion

It is noted that the CCSM and the DCSM have similar tidal level behaviour. Overall, the predicted tidal ranges are higher with the DCSM than with the CCSM. Differences are not unexpected. The DCSM understandably provides far superior resolution everywhere. This is most apparent on current velocity maps.

The CCSM and the DCSM also have similar levels of performance, with the DCSM, generally, only marginally more accurate than the CCSM in terms of normalised RMSE (the principal measure chosen to evaluate performance).

This gives confidence in the CSM predictions, and in the model robustness.

Verification against existing models was successful and enhances the CSM credibility. It is noted that the DCSM is two orders of magnitude finer (at sites of interest) than the existing UK Marine Renewable Energy Resources Atlas.

### E. Sensitivity

A sensitivity analysis was subsequently performed in an effort to assess the response of the CSM to tuneable parameters such as bed friction, turbulence and numerical schemes. Sensitivity to freshwater discharges was also considered.

The main conclusions are:

- Based on experience with hydrodynamic models, the parameter with the most impact on model results is the bathymetry.
- The good level of agreement between the CCSM and the DCSM (obtained with very different model resolutions) demonstrates grid insensitivity, although the DCSM results will be more resolved.
- It has been shown that the formulation employed to represent bed friction is not of particular importance.
- However, the selection of the bed friction parameter has a significant effect on the CSM predictions (water levels and current speeds), hence on the performance against observations. In general terms, the highest impact in terms of levels is observed in the English Channel, in the Severn Estuary, and in the Irish Sea east of the Isle of Man.
- Turbulence has a noticeable effect on the predicted current speeds in some specific areas. However, in the absence of observed velocity data available globally around the UK to calibrate against, it is difficult to discard (or favour) one turbulence formulation over the other. While the constant viscosity and Smagorinski models were tested, the Elder model was eventually retained based on HR Wallingford experience.
- The other parameters tested - “free surface gradient compatibility criteria”, discharge rate applied in the Thames and/or the Baltic Sea, and tidal force (calculating the astronomical terms required in the tidal forcing terms) - all have a limited impact on the CSM water level and velocity predictions.

## IV. THE CSM AS A TOOL TO INVESTIGATE TIDAL POWER PROJECTS AROUND THE UK

From the outset, it was the intention that the CSM would become publicly available for the tidal power industry to understand the possible interactions between proposed tidal energy schemes across Northern European waters. With that in mind, the CSM was designed to be versatile. Each tidal scheme, in the CSM, is defined by:

- a geographical extent and location. The geographic extent and location are stored within binary geospatial files, commonly called shape files. The format of these files is the standard ESRI format, produced by many geographic information systems (GIS) and by analysis and visualisation software such as Blue Kenue.
- parameters informing how the CSM should respond to the presence of the tidal range and/or tidal current

schemes. Implementation of various energy schemes by the end-user is done through generic parameterised formulations representing schemes at the scale and resolution of the CSM, and catering for all types of technology, current and future. These formulations rely on the existing functionalities of the TELEMAC system.

### *A. TELEMAC-2D*

TELEMAC-2D solves the 2D depth-averaged shallow water equations, also called the St Venant equations ([7]). These comprise three equations: one equation for the conservation of the volume of water and two equations representing the conservation of the water momentum, as follows:

continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = Srce \qquad (1)$$

where *Srce* is a variation of the volume of water within the water column (including rain, evaporation and other intakes and outlets such as those found around hydraulic structures). This makes the continuity equation well suited to represent flows through tidal range schemes.

x-momentum equation:

$$\begin{aligned} &\rho h\frac{\partial u}{\partial t} + \rho hu\frac{\partial u}{\partial x} + \rho hv\frac{\partial u}{\partial y} = \\ &\quad -\rho gh\frac{\partial (h+b)}{\partial x} + \frac{\partial}{\partial x}\left[\rho h \nu_e \frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[\rho h \nu_e \frac{\partial u}{\partial y}\right] + hF_x \end{aligned} \qquad (2)$$

y-momentum equation:

$$\begin{aligned} &\rho h\frac{\partial v}{\partial t} + \rho hu\frac{\partial v}{\partial x} + \rho hv\frac{\partial v}{\partial y} = \\ &\quad -\rho gh\frac{\partial (h+b)}{\partial y} + \frac{\partial}{\partial x}\left[\rho h \nu_e \frac{\partial v}{\partial x}\right] + \frac{\partial}{\partial y}\left[\rho h \nu_e \frac{\partial v}{\partial y}\right] + hF_y \end{aligned} \qquad (3)$$

where $F_x$ and $F_y$ are source terms and body forces acting on the water momentum (including seabed friction, Coriolis, drag, and possible energy extraction devices). This makes the momentum equations well suited to represent drag and energy extraction at tidal current schemes.

### *B. Tidal range scheme implementation in the CSM*

#### *1) Identification*

The location of a tidal range scheme is defined by a polyline representing the barrage or lagoon alignment along which embankment, turbines and sluices lie. The mesh elements which this polyline crosses are automatically identified and masked to represent the blockage; the corresponding nodes are listed for source and sink terms to be applied.

To facilitate the process, a convention on the orientation of the polyline determines which nodes are upstream and which are downstream of the structure. This is particularly relevant to schemes operating only during ebb tides or flood tides. This methodology also allows barrages to be defined between islands for example, where the coastline cannot be used to identify the upstream and downstream of the works.

The turbines and sluices are then sited along the line of the structure using their specified width, starting from the deepest regions.

#### *2) Parameterisation*

As introduced earlier, a tidal range scheme is represented in the continuity equation (1) through the source/sink term *Srce* (subroutine PROSOU). The discharge (by extension the power generated) is a function of the head and energy difference across the control structure as follows:

$$\begin{aligned} Q = \ & D_1 + D_2\, \Delta h + D_3\, \Delta h^2 + D_4\, \Delta h^3 + D_5\, h\sqrt{\Delta h} \\ & + D_6 \sqrt{\Delta h} + D_7\, \Delta u^2 \end{aligned} \qquad (4)$$

where $Q$ is the discharge in $m^3/s$, $\Delta h$ is the head difference in m, $h$ is the average water depth in m, $\Delta u^2$ relates to the energy difference and can be used to represent other energy losses, and where $D_1$ to $D_7$ are constants defined by the technology type, the operational procedures, the turbine capacity, the size, submergence and types of the openings and other key turbine parameters.

In addition to the parameters representing head-discharge-power characteristics, a tidal range scheme is characterised by a mode (Ebb, Flood, Dual or Wall) and an extensive list of numerical parameters. They include various turbine characteristics and operating rules for three different types of turbines. Thus, while the number of parameters (79 in total) is significant, not all the parameters are required to define a particular scheme.

### *C. Tidal current scheme implementation in the CSM*

#### *1) Identification*

The extent of a tidal current scheme is defined by a closed polygon representing the area within which the turbines are to be sited. The additional momentum forces are applied to all the nodes automatically listed with the closed polygon.

It is noted that a methodology was developed as part of this project to delineate the regions of most interest for tidal current device deployment. These regions are constrained by a number of pre-defined criteria, such as geographic constraints (e.g. distance from shore, political boundaries), technology constraints (e.g. turbine operational depth, minimum operational resource), environmental constraints (e.g. reduction in mean velocity) or targeted installed capacity. The regions respecting the search criteria and with the highest kinetic power density are delineated first.

This methodology is illustrated in Fig. 6 for the incremental development, with different decades, of the available resource at a proposed tidal current scheme site[1].

In Fig. 6, the x and y axes are easting and northing, and the colour of the polygons identifies different decades. For example, light blue identifies the region developed during the 1st period because of the proximity to shore. The other deployments (dark blue to deep pink) were delineated incrementally from the 1st time period, and therefore a given decade deployment has fed into the next decade. It is clear from Fig. 6 that the deployments follow the (extent and shape of the) resource.

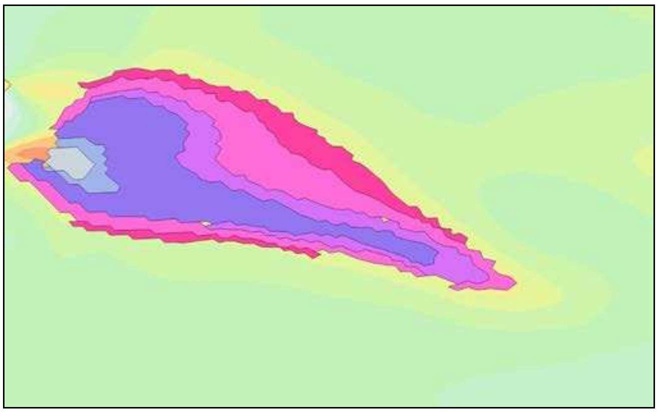

Figure 6. Identification of the “best” available resource corresponding to different decades (search criteria). Underlying map shows maximum current speed as predicted by the DCSM.

*2) Parameterisation*

When tidal current devices are introduced in the hydrodynamic system, the system loses energy, whether the energy is extracted or whether drag forces are introduced. The various contributions for the loss of energy are represented as additional terms (subroutine DRAGFO), the sum of which will be $F_x$ and $F_y$ in the momentum equations (2) and (3).

These additional momentum terms are a means of parameterising physical processes that occur at higher resolution than is used within the model. The parameterised terms replace small-scale physical processes (from the point of view of model resolution) with a continuous property applied across computational cell.

A tidal current scheme is, therefore, characterised by: (a) a number of devices per km$^2$ (or a device footprint in m$^2$, whichever is readily known); (b) a structural drag coefficient and associated support structure area, which both depend on the technology; and (c) a power/thrust curve for extracted energy, which also depends on the technology. It is noted that the power/thrust curve relates to mechanical power (that which is removed from the system in the CSM), as opposed to electrical power delivered to the grid. An efficiency factor of 0.8 was assumed to that effect since the electrical power curve is that typically known.

Should the user not know the power/thrust curve for a particular device, it is possible to estimate it based on the device characteristics (e.g. turbine diameter, cut-in and rated velocity). In that case, the estimate would be based on a 5th order polynomial function of the rated velocity.

*D. Example applications*

Not detailed in this paper, but the subject of [15], the CSM was employed in this project to investigate a number of viable options, introduced in [3] and corresponding to a real interest in terms of tidal power resource.

Fig. 7 and Fig. 8 present examples of such tidal range and tidal current scheme implementations in the DCSM. In these figures, the schemes are identified as black dashed lines; the impact is expressed in terms of tidal range difference in % for tidal range schemes, and in terms of kinetic power density changes in % for tidal current schemes, relative to the no-scheme scenario. Unfortunately the scales cannot be shown to protect the value of the CSM results, prior to its official release, but the effect of the schemes is clear.

For example, in Fig. 7, a significant reduction in maximum tidal range (pink areas) was observed upstream of the longest barrage following its construction. The smaller barrage yielded a lesser, yet noticeable, reduction (deep blue areas). This configuration did not conform to the expressed requirement to maintain at least 80% of the natural tidal range in the basin, and alternative options were considered.

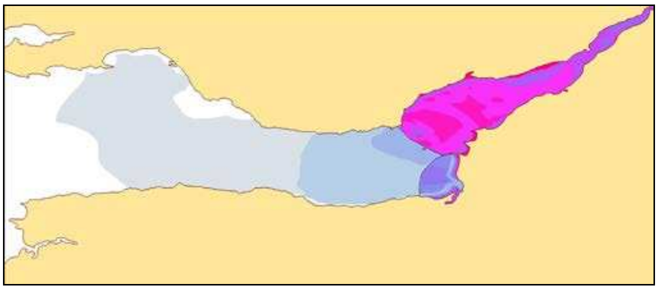

Figure 7. Example impact of two tidal range schemes implemented in the DCSM. Expressed in terms of maximum range difference (%).

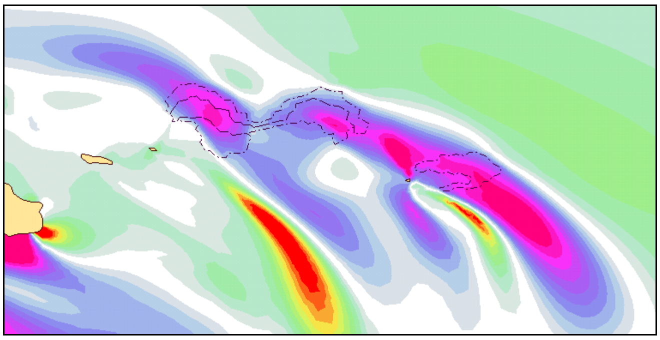

Figure 8. Example impact of a tidal current scheme implemented in the DCSM. Expressed in terms of mean kinetic power density change (%).

[1] Its location has been purposefully disguised in this figure, to protect the ETI, prior to the official release of the CSM.

In Fig. 8, it is apparent that the resource is redistributed as a result of the tidal scheme implementation with a deficit in mean kinetic power density in the lee of the devices, and a pocket of higher energy further south. This case highlighted problematic intra-scheme interactions with some of the devices in the wake of others.

## V. WHAT NEXT?

The CSM has proven, as expected, to be an extremely useful modelling tool for the analysis of tidal characteristics on the Northern European continental shelf and, most importantly for this project, of the interactions resulting from the development of schemes to harness these tidal characteristics, be they tidal range or tidal current schemes. A paper is being presented at the ICOE 2012 conference [15] summarising the conclusions drawn from this work in terms of inter scheme interactions.

From the outset, the ETI had decided to make the CSM publicly available, through a fee-for-service arrangement[2]. A Web User Interface has, therefore, been put in place, which principal goal is to provide users with a simple functional tool to operate the CSM irrespective of the chosen resolution. Users will be able to upload tidal energy schemes, automatically triggering submission on the appropriate high performance computers.

The CCSM computes a 15-day period within 3 hours on a standard multi-core desktop computer. If used in parallel on one 12-core workstation, the CCSM only takes 15 minutes for the same predicted period. The DCSM computes a 15-day period within 15 hours on one 12-core workstation and in less than 2 hours on one 8-blade 12-core high performance computer. These times do not include pre- and post-processing of data and transfer of files to and from the targeted computers.

The CSM will provide the industry with a UK scale tool for assessing likely interactions between schemes. It is generally recommended that the CCSM be used for high level tidal range and broad tidal current investigations. However, the DCSM should generally be used in preference to the CCSM for investigation of tidal current schemes, as the greater resolution predicts tidal currents (and spatial variability thereof) more accurately. For detailed site specific investigations, more detailed analysis is required.

Building on the experience gained with the CCSM and the DCSM, it could now be envisaged to further refine the CSM, within a couple of years, to include more resolved bathymetry data (e.g. TruDepth from SeaZone). This Refined CSM (RCSM) would aim at solving different problems and would require a minimum resolution of c. 50m at the sites of interest and at the coastline if not smaller to match up with bathymetry resolution.

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[2] Fees will be re-invested to maintain and develop the CSM.