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Programme Area: Marine

Project: PerAWAT

Title: Tidal Farm Modelling: the Alderney Race, the Pentland Firth and the Paimpol-Bréhat Sites Modelled in Telemac Software

Abstract:

This report is the third deliverable of Work Group 3 Work Package 3 of this project (WG3 WP3 D3). In this work package, EDF R&D adapted the numerical tools developed internally; Telemac-2D and Telemac-3D, in order model the tidal farm performance and wake at large scales. This document presents the methodology used to model different tidal farm configurations on the three sites modelled in WG3 WP3 D1; Paimpol-Brehat, the Alderney Race, and the Pentland Firth. This methodology is then followed by descriptions of the tidal farm configurations chosen for each site as well as a description of the flow modelled. This deliverable also provides result for cross comparison and validation of WG3 WP6 and WG3 WP4.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

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PerAWAT WG3 WP3 D3

Tidal farm modelling: The Alderney Race, the Pentland Firth and the Paimpol-Bréhat sites modelled in Telemac software

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TABLE OF CONTENT

1 Introduction......4

1.1 Context of the report......4

1.2 Scope of this document......4

1.3 WG3 WP3 D3 Deliverables......4

1.4 WG3 WP3 D3 Acceptance criteria......4

2 Model Methodology......4

2.1 Modelling the flow around a selected site......5

2.2 Method chosen to model a TEC......5

2.3 Modelling a tidal energy converter farm in Telemac-2D......6

2.3.1 Refining the mesh around the TECs......6

2.3.2 Using the DRAGFO subroutine in Telemac-2D......7

2.4 Modelling large farms in Telemac-2D......8

2.5 Modelling a tidal energy converter farm in Telemac-3D......11

2.5.1 Refining the mesh around the TECs......11

2.5.2 Using the SOURCE subroutine in Telemac-3D......11

2.6 Additional outputs given by the subroutine DRAGFO and SOURCE......12

3 Description of the simulations for all the three sites......13

3.1 The Alderney Race......13

3.2 Numerical Modelling......13

3.2.1 The array configurations......14

3.2.2 Description of the simulations uploaded on the ftp site......16

3.2.2.1 Layout A......17

3.2.2.2 Layout B......18

3.2.2.3 Layout C......19

3.2.3 Illustrative example......20

3.2.4 References......22

3.3 The Pentland Firth......22

3.3.1 The array configurations......23

3.3.2 Description of the simulations uploaded on the ftp site......24

3.3.3 Illustrative example......25

3.4 Paimpol-Bréhat......28

3.4.1 The array configurations......28

3.4.2 Description of the simulations uploaded on the ftp site......29

3.4.3 Illustrative example......30

3.4.4 3D model......33

4 Path to the location of the files on the oxford SFTP site......34

5 Additional tools uploaded to the sftp site......35

5.1 conv_longlat2mercatortelemac.f......35

5.2 PowerFlume.f......35

5.3 GetPower.sh......35

5.4 DRAGFO......35

5.5 SOURCE......35

6 Appendix A1 – English Channel Model......36

7 Appendix A2 – English Channel Model – QUASI-BUBBLE DISCRETISATION IN SPACE FOR VELOCITY......38

8 Appendix A3 – Example of Telemac-2d steering file......40

1 INTRODUCTION

1.1 Context of the report

The present report fits within the PerAWaT (**Per**formance **A**ssessment of **Wa**ve and **T**idal Array Systems) project which has been commissioned and funded by the **E**nergy **T**echnologies **I**nstitute (ETI). The aim of the project is to establish and validate numerical models to predict hydrodynamic performance of wave and tidal energy converters, and therefore to provide tools which will help the decision on tidal and wave energy converters. This report is the third deliverable of Work Group 3 Work Package 3 of this project (WG3 WP3 D3). In this work package, EDF R&D adapted the numerical tools developed internally; Telemac-2D and Telemac-3D, in order model the tidal farm performance and wake at large scales.

1.2 Scope of this document

This document presents the methodology used to model different tidal farm configurations on the three sites modelled in WG3 WP3 D1; Paimpol-Brehat, the Alderney Race, and the Pentland Firth. This methodology is then followed by descriptions of the tidal farm configurations chosen for each site as well as a description of the flow modelled.

This deliverable also provides result for cross comparison and validation of WG3 WP6 and WG3 WP4.

1.3 WG3 WP3 D3 Deliverables

a) Input files for candidate sites
b) Report: model methodologies (and user manual), performance and validation (for 2D and 3D - 3D one site, and 2D for each different site)

1.4 WG3 WP3 D3 Acceptance criteria

a) Model needs to be capable of parametric characterisation of arrays implemented in Telemac software – 2D and 3D versions for sites as specified in WG0 D2. Input files to include:
    - The 3D meshes (spatial x and y coordinates with z bathymetry) used in the modelling but with bathymetries taken from open source lower quality data sources, e.g. GEDCOM.
    - Detailed instructions of how to obtain and utilise the higher quality proprietary Seazone bathymetry data.
    - All other input files and data for running the models. Such that the input files supplied can be run “out of the box”.
    - Software modules sufficiently commented/annotated such that can be logically followed by third party.

b) Report contains the following:
    - Description of model methodology (including user manual – guidance on input requirements, running the model and interpreting the results), assumptions and algorithms of the models
    - Provision of boundary conditions for the array scale models (WG3 WP2 UoE)

2 MODEL METHODOLOGY

The methodology used to model a tidal farm follows two steps. Firstly the flow without any tidal turbines is modelled, so that the hydrodynamic properties can be validated. The mesh constructed from this first step is then refined so that tidal energy converters can be modelled.

2.1 Modelling the flow around a selected site

To construct a hydrodynamic model the first step is to obtain bathymetric data. There are many different sources to obtain such data, but in this work package the GEBCO and Seazone data sets were used around the UK, and along the French coast bathymetric tiles were purchased from the SHOM[1]. It is recommended to convert this bathymetric data so that it is written in relation to the Mean Sea Level. Furthermore Telemac-2D and Telemac-3D require the coordinates to be written in a plane projection (e.g. the Mercator or Lambert projections). During the TELEMAC computation, the coordinates cannot be longitude/latitude. As a reminder the Mercator projection can be done using the two following equations:

$$X = R(\phi - \phi_0) \tag{1}$$

$$Y = R\left(\ln\left[\tan\left(\frac{\lambda}{2} + \frac{\pi}{4}\right)\right] - \ln\left[\tan\left(\frac{\lambda_0}{2} + \frac{\pi}{4}\right)\right]\right) \tag{2}$$

Where:

- X, Y are the horizontal and vertical coordinates in the Mercator projection
- ϕ, λ are the longitude and latitude respectively. These coordinates should be converted in radians
- ϕ_0, λ_0 are the coordinates in longitude and latitude of the point of origin used in the projection. These values also need to be converted in radians and it is recommended to place the origin in the center of the domain of interest.
- R is the radius of the earth

This bathymetric data is then used to construct a mesh. There are no definite rules on the element size when constructing a mesh, but it is recommended to refine it around the area of interest. Examples of mesh size can be found in WG3 WP3 D1.
To perform simulations of the flow using Telemac-2D or Telemac-3D the boundary conditions need to be imposed. In this work package the data from the NEA (North East Atlantic) model processed by NOVELTIS/LEGOS, the JMJ database from EDF/LNHE or the TPXO database are used to impose the tidal fluctuations at the boundaries.

Once this data has been obtained and a hydrodynamic model can be constructed in Telemac-2D or Telemac-3D. A detailed description of how the bathymetric and tidal data can be used to construct a model and the validation of the flow models for each candidate site can be found in WG3 WP3 D1.

2.2 Method chosen to model a TEC

The method chosen to model the influence of the turbines on the flow is to apply a drag force over a region representing a turbine to slow down the current. Therefore a force is applied on every node in opposition to the current:

$$F_{D,i} = -\frac{1}{2}\frac{NS}{A} C_D U_i |U_i| \tag{3}$$

Where F_D is the drag force of the turbines, N is the number of turbines modelled, S is the surface of the turbine ($s = \pi D^2/4$), D is the turbine diameter, A is the area over which the force is applied, and it is the area that represents the turbines defined the report for WG3 WP3 D2, C_D is the drag coefficient of the turbines and $\mathbf{U}$ is the flow velocity. Since the presence of a turbine will affect the flow velocities

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[1] "Service Hydrographique et Océanographique de la Marine", i.e. the French Navy Hydrographic and Oceanographic Service

locally, for each node affected by a TEC the flow velocity used to calculate the drag is taken at a distance $3.5D$ upstream.

The turbine is therefore modelled by a box of length L and width W, inside which a force resisting the flow is applied along the central axis of the turbine to all the nodes present in this region. The necessary quantities used therefore to apply properly this force are given in Figure 1

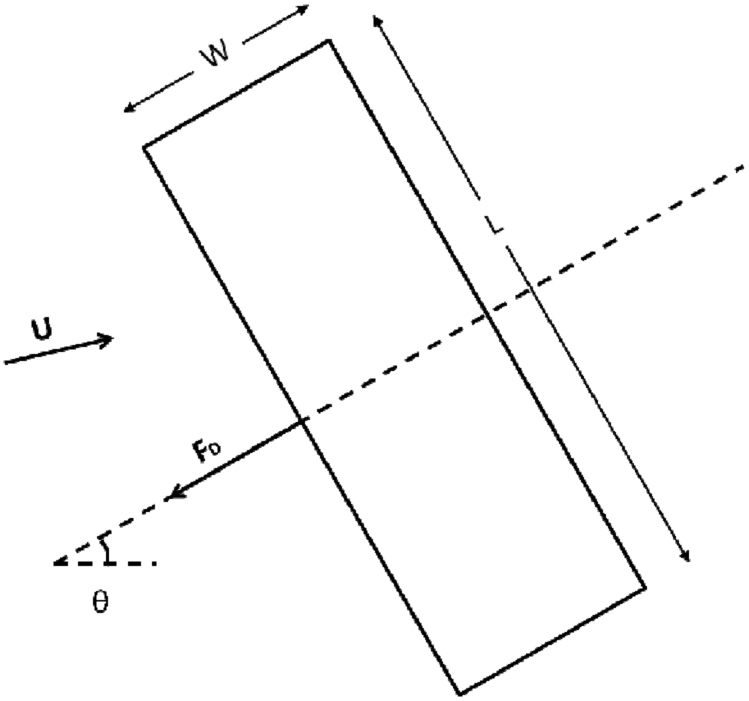

Figure 1: Representation of a TEC in Telemac.

To calculate the extracted power (P) of a TEC is given by the following equation:

$$P = \frac{1}{2} C_P S \rho U_i^2 |U_i| \tag{4}$$

With C_p is the power coefficient of a TEC and ρ is the water density

2.3 Modelling a tidal energy converter farm in Telemac-2D

Once a hydrodynamic model of the flow has been validated it is possible to model a tidal energy converter (TEC) farm within the flow. This is done by refining the mesh around the location of the TECs, then by imposing a drag force on the flow using the DRAGFO subroutine in Telemac-2D.

2.3.1 Refining the mesh around the TECs

The report WG3 WP3 D2 describes the development done to Telemac-2D to model TECs, as well as validation of this development. Furthermore tests were done in this report to calculate the mesh element size necessary to model accurately the flow around a turbine. This criterion, given in the following equation, governs the mesh size around the TEC farm configuration:

$$\frac{D}{8} < H_m < \frac{D}{4} \tag{5}$$

Where D represents the turbine diameter and H_m is the mesh element size.
This mesh element size needs to be applied on the zone covered by a TEC, as well as 25D before and after the turbines so that the wake can be captured. Furthermore a **growth rate of 1.2** needs to be applied afterwards

Figure 2 shows an example of a refined mesh near 2 rows of turbines.

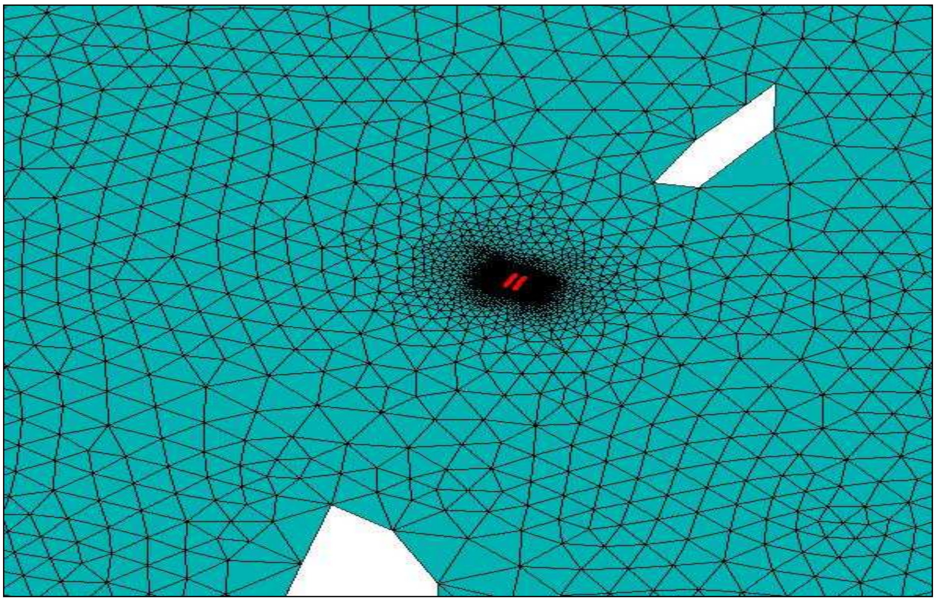

Figure 2: Mesh refined near 2 rows of turbines in the Pentland Firth.

For this work package the mesh is refined using the mesher Janet, which can deal with a large number of elements. The bathymetry of the new nodes is calculated using a linear interpolation within the original mesh.

2.3.2 Using the DRAGFO subroutine in Telemac-2D

Once a new mesh has been constructed, the subroutine DRAGFO is used in Telemac-2D to model the TEC farm. This subroutine imposes a drag coefficient on the nodes present within box representing the turbines. This box is defined so that it encompasses the TEC, i.e. since the flow is model in horizontal 2D the length of the box is equal to the diameter of the turbines and the width of the box to the width of the turbines. Therefore to model a farm of TEC each turbine is modelled individually and the parameters given in Table 1 need to be informed.

Table 1: Description of the parameters that need to be informed when using the subroutine DRAGFO in Telemac-2D to model tidal energy converters.

Variable name	Definition
HDL	Half length of a box representing one turbine
HDW	Half width of a box representing one turbine
CDTEC	Drag coefficient
CPTEC	Power coefficient
RTEC	Radius of the TEC
THETA	Angle between the axis of the TEC and the x-axis”
DD	Distance at which the far velocity is taken

In the steering file of a Telemac simulation, the keyword “FORMATTED DATA FILE 2” needs to be defined so that the path to the file containing the coordinates of the turbines centres is informed. This file needs to follow the format given in Figure 3.

```
N
X1, Y1
X2, Y2
...
XN, YN
```

Figure 3: The format necessary to inform the coordinates of the centre of each turbine. N is the number of turbines modelled and Xi, Yi are the coordinates of each turbine. These coordinates need to be in the same coordinate system as the mesh used in Telemac-2D.

Once the parameters used by DRAGFO are given the simulations need to be performed twice. Nevertheless, the first simulation is very short. The first run requires the variable DEJA to be set to .FALSE., so that the file “param_pos_hydro.TXT” will be written. The second run requires DEJA to be set to .TRUE. so that this new file can be used in the simulations.

The validations for using this subroutine to model a tidal energy converter can be found in the report for WG3 WP3 D2.

2.4 Modelling large farms in Telemac-2D

When large tidal farm configurations are chosen, following the method given in section 2.3 will produce meshes that are too large, which will increase the simulation times drastically. Therefore the method chosen to ease the calculation time is apply the DRAGFO routine on a larger box, which will include all of the TEC, but where the drag and power coefficient are modified to an equivalent value. This method will be referred as the Global Box method; whereas when each turbine is modelled individually the method will be referred to as the Individual Turbine method.

The dimensions of the box are chosen so that they follow the following rules:

- If the rows are aligned:

$$W_{GB} = W_{row} + 1.18D \tag{6a}$$

$$L_{GB} = (p-1)\Delta d + 1.18D \tag{9b}$$

- If the rows are staggered:

$$W_{GB} = W_{row} + 0.12D \tag{7c}$$

$$L_{GB} = (p-1)\Delta d + 1.62D \tag{7d}$$

Where:

- W_{GB} and L_{GB} are the width and the length of the global box
- W_{row} is the width of rows of turbines
- p is the number of rows
- Δd is the distance between the row

In this method the mesh does not need to be refined as much as in the Individual Turbine method, and the following rule should be followed:

$$H_m \approx D \tag{8}$$

Furthermore, the surface of the Global Box is that of a single turbine multiplied by the number of turbines in the farm. This is done in Telemac-2D by modifying STEC.
In addition, to calculate the drag force of the global box one needs to calculate an equivalent value of the drag coefficient to correspond to the entire TEC farm. To do this all the turbines will be modelled individually in a canal whose dimensions are given by:

$$W_{ca} = 25D + W_{GB} + 25D \tag{9e}$$

$$L_{ca} = W_{add} + L_{GB} + W_{add} \tag{9f}$$

Where:

- W_{ca} and L_{ca} are the width and the length of this canal
- W_{add} is a distance that is sufficiently large that the edge do not affect the flow around the turbines

These dimensions are of course much larger than those of the Global Box. This is necessary so that the imposed boundary conditions of the flow do not affect the turbines wakes. For example, for a scenario over the Alderney Race, the numerical canal, shown in Figure 4, with one row of turbines was used.

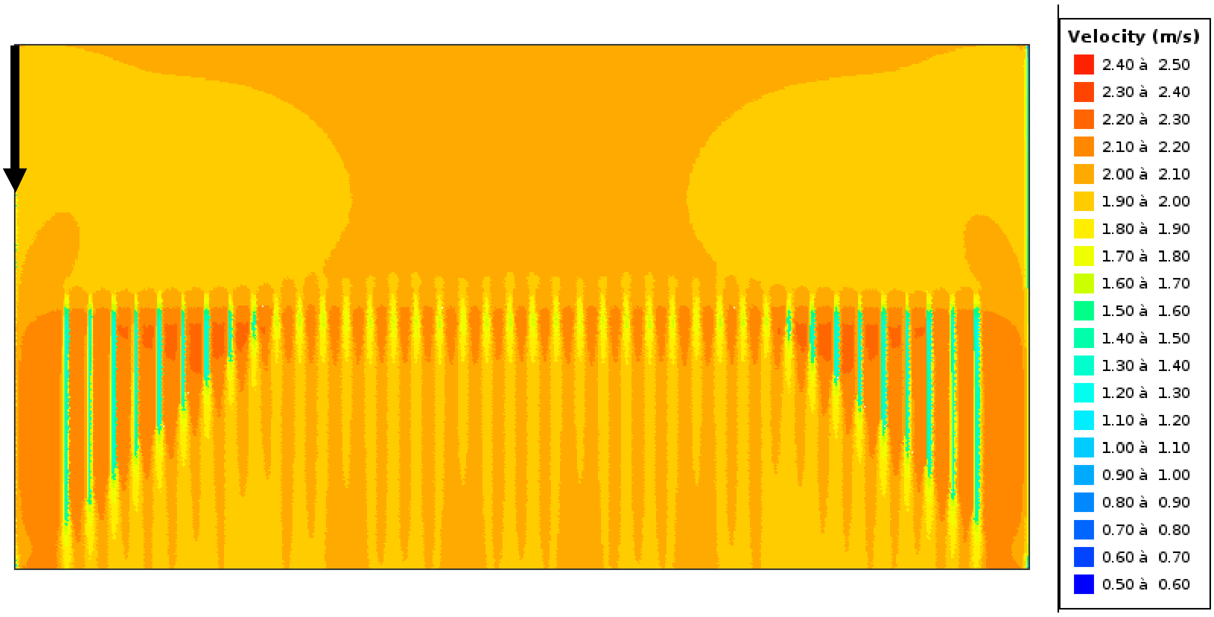

Figure 4: Example of canal used to simulate a row of turbines in order to get the equivalent drag force coefficient.

It should be noted that, the canal in Figure 4 contains 278386 mesh elements, and as such the simulation time, even with several processors, is quite long.

In this canal the bottom bathymetry corresponds to an idealised bathymetry that is homogeneously flat all over the canal extent and representative of typical depth over the study site. This allows a better understanding of the spatial variation of the fluid energy losses due solely to the working of the turbines. As the bathymetry highly influences the velocity pattern, the use of real bathymetry would be more realistic. But it would also make the analysis of the energy losses much more difficult as the entire velocity pattern would be modified by the integration of the turbines, and so energy losses due to bottom friction will be modified. The flow speed should correspond to the typical speed that turbines will experience in the flow. The mesh in this canal should follow the rules given in section 2.3, i.e. in the Individual Turbine method. The time simulation should be long enough to obtain a steady state solution. Once those simulations are done they can be used to calculate the drag coefficient, by calculating the energy lost because of the turbines in one time step using the “PowerFlume.f” fortran file. In this script, the energy is calculated along sections of the canal. Care should be taken when choosing the width along which the energy is calculated, and for the dimension that we are using a width of 3 m is recommended. This should give an energy profile similar to the one presented in Figure 5.

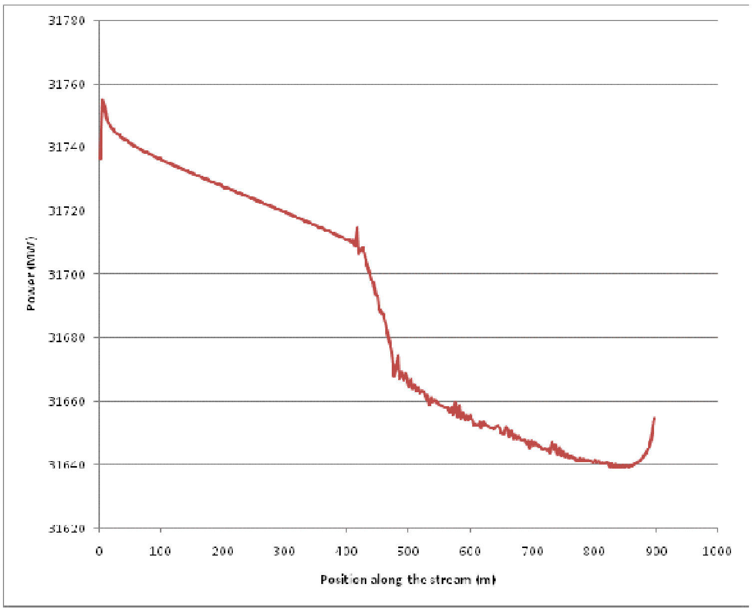

Figure 5: Spatial variation of the fluid energy along the stream

Since we use the real bathymetry it is recommended to calculate this energy lost by subtracting to this value the energy lost in the canal without TECs. The equivalent drag coefficient can be calculated using the following equation:

$$C_{D,GB}=\frac{\Delta E}{\Delta t}\frac{2}{\rho U_{ref}^{3}\sum A_{IT}} \tag{10}$$

Where:

- $C_{D,GB}$ is the equivalent drag coefficient of the Global Box
- $\Delta E/\Delta t$ is the energy lost over one time step
- ρ is the water density (1000 kg/m^3)
- U_{ref} is the reference velocity (upstream of the turbines)
- $\sum A_{IT}$ is the sum of the surface areas covered by each individual turbine covers

This drag coefficient therefore represents the entire farm, which can now be modelled in Telemac-2D by applying the equivalent drag force in the area of a global box using the routine DRAGFO, see section 2.3.2 for more details. Figure 6 shows how we build the mesh near the turbines area when we use the “Big Box” methodology presented in WG3 WP3 D2.

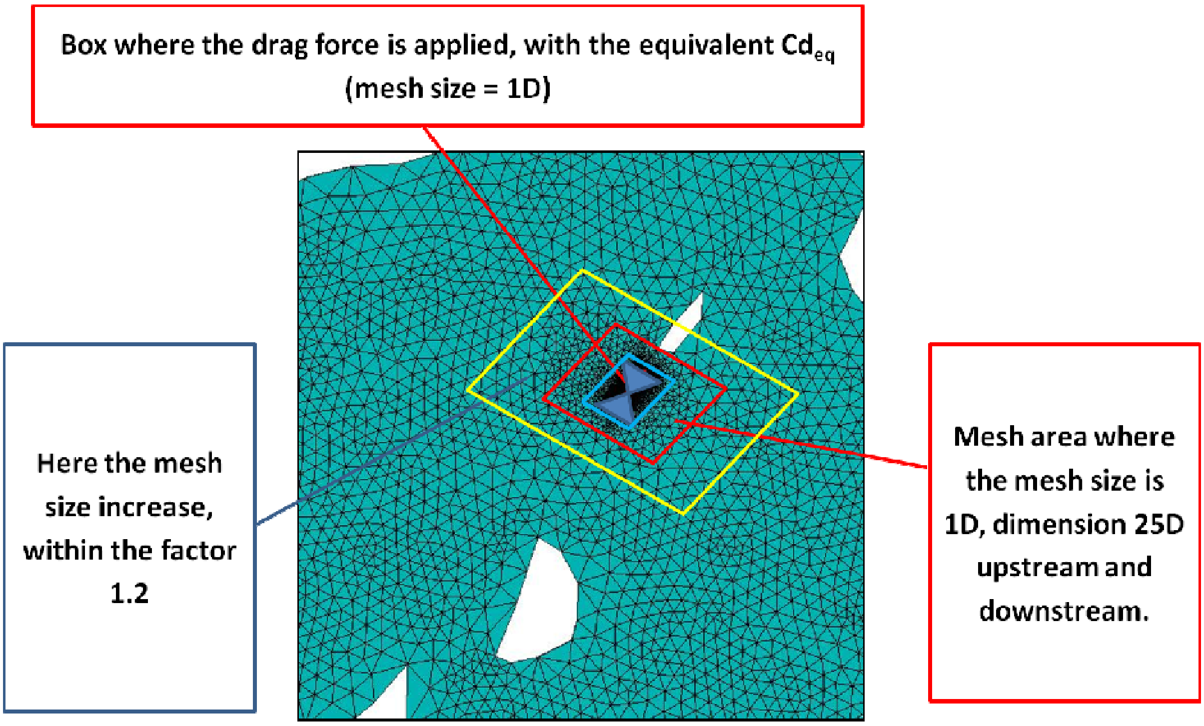

Figure 6: dimension of the mesh size in the area of the turbines.

Therefore, inside the "Big Box", the mesh size is 1D. Upstream and downstream, until 25D, the mesh size is also 1D, and after those limits, the mesh size increases with a factor of 1.2.

2.5 Modelling a tidal energy converter farm in Telemac-3D

Once a hydrodynamic model of the flow has been validated it is possible to model a tidal energy converter (TEC) farm within the flow. This is done by refining the mesh around the location of the TECs, then by imposing a drag force on the flow using the SOURCE subroutine in Telemac-3D. At the moment there are no methods equivalent to the "Big Box" method that are defined in three dimensions.

2.5.1 Refining the mesh around the TECs

The mesh refinement used in Telemac-3D follow the same conditions as in Telemac-2D. Therefore it is recommended to use the same mesh as the two-dimensional simulations, when possible. Then it is recommended to use at least 4 planes to cover the TEC in the vertical direction this will ensure that the turbines are modelled accurately

2.5.2 Using the SOURCE subroutine in Telemac-3D

Once a mesh has been constructed, the subroutine SOURCE is used in Telemac-3D to model the TEC farm. This subroutine works in the same fashion as the DRAGFO subroutine in Telemac-2D. Therefore to model a farm of TEC each turbine is modelled individually and the parameters given in Table 2 need to be informed.

Table 2: Description of the parameters that need to be informed when using the subroutine SOURCE in Telemac-3D to model tidal energy converters.

Variable name	Definition
HDW	Half width of a box representing one turbine
CDTEC	Drag coefficient
CPTEC	Power coefficient

RTEC	Radius of the TEC
THETA	Angle between the axis of the TEC and the x-axis”

In the steering file of a Telemac simulation, the keyword “FORMATTED DATA FILE 2” needs to be defined so that the path to the file containing the coordinates of the turbines centres is informed. This file needs to follow the format given in Figure 7.

```
N
X1, Y1, Z1
X2, Y2, Z2
…
XN, YN, ZN
```

Figure 7: The format necessary to inform the coordinates of the centre of each turbine. N is the number of turbines modelled and Xi, Yi, Zi are the coordinates of each turbine. These coordinates need to be in the same coordinate system as the mesh used in Telemac-3D.

2.6 Additional outputs given by the subroutine DRAGFO and SOURCE

The modifications given by DRAFO and SOURCE modify therefore the fluid velocities, which can then be compared to the original result files to model the wake. Furthermore the power extracted can be calculated using a simple AWK file “GetPower.sh” (see section 0).

3 DESCRIPTION OF THE SIMULATIONS FOR ALL THE THREE SITES

The three sites chosen were the Alderney Race, the Pentland Firth, and the Paimpol-Bréhat. The hydrodynamic models were given as part of WG3 WP3 D1 [A2].

3.1 The Alderney Race

The Alderney Race (also known as “Raz Blanchard” in French) is located off the western tip of the Cotentin peninsula in Normandy, France. As illustrated by Figure 8, it is a region where strong tidal currents are experienced. The characterisation of the tidal conditions over this area is described in [A2]. The Alderney Race has been acknowledged as being a site of particular interest for the possible deployment of industrial tidal turbine arrays.

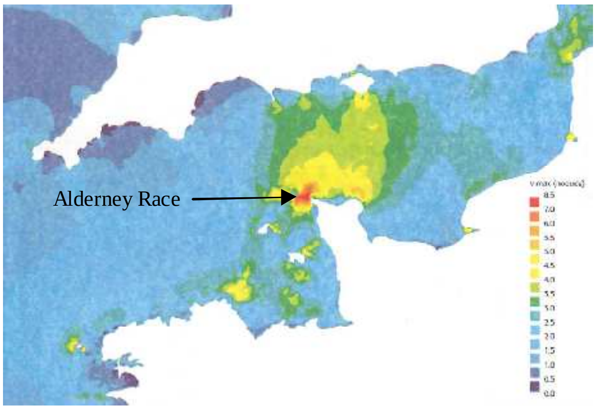

Figure 8: Maximal tidal velocities over the English Channel during a mean spring tide (in knots), source [A1].

3.2 Numerical Modelling

First results indicated that the extent of the Alderney local model built for WG3 WP3 D1 was not large enough to reliably assess the impact of the tidal farms as the wake induced by turbines was found very close to the boundaries of the local numerical model.

Therefore, the numerical model of the Pentland Firth developed in WG3 WP3 D1 was used to extract a model of the English Channel (see Figure 9). This ensures that the boundaries of the English Channel model will not interfere with any perturbation of the flow induced by the turbines.
The English Channel model is then used to model tidal farms around the Alderney Race for WG3 WP3 D3 and D4.

The TELEMAC-2D version 6.2 software (available in open source since summer 2012) is used in this study. As described in [A2] § 4.2., the model is forced at its liquid boundaries by TPXO database. The bathymetry is given by GEBCO_08 Grid (General Bathymetric Chart of the Oceans) that is freely available data which vertical datum is MSL [A2]. The bathymetry coordinates follow a Mercator projection, with a centre of origin given by 0 degrees in longitude and 51.5 degrees in latitude (m).

The validation of the English Channel model is described in Appendix A1 and Appendix A2, where it is shown that even though there is a slight loss of precision, compared to the validations presented in WG3 WP3 D1, the model is accurate enough to assess the effect of large TEC farms.

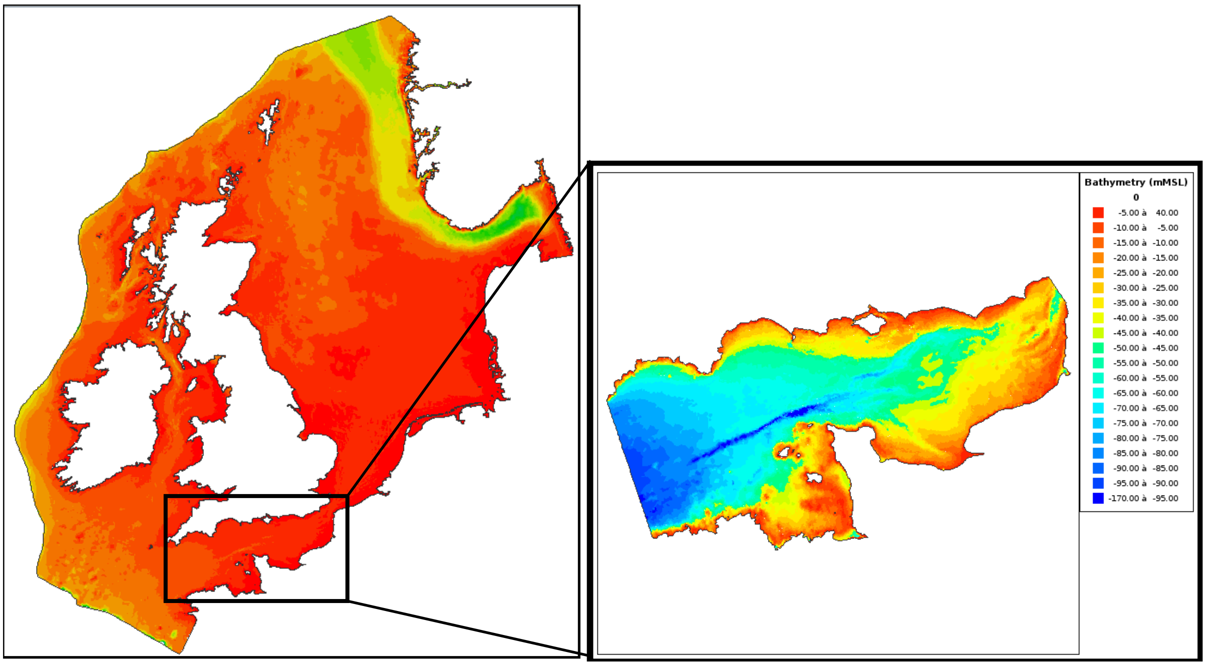

Figure 9: Extent of the Pentland Firth model [A2] (left panel). Extent of the English Channel model extracted from the Pentland Firth model (right panel).

3.2.1 The array configurations

Three tidal farm layouts were defined (see Figure 10 and Table 3). The first farm (layout A) is composed of three aligned 10-turbine arrays off the eastern coast of Alderney (see Figure 11). The second farm (layout B) consists in a single but larger array of 40 turbines on south of layout A (see Figure 11). The last configuration (layout C) consists in one significantly larger array of 150 turbines off the French coast (see Figure 12). The location of the arrays of each layout is given in the following table:

Layout / configuration	Number of turbines	X begin (m)	X end (m)	Y begin (m)	Y end (m)
A : first row	10	-236211.4	-235899.6	-312791.8	-312971.8
A : second row	10	-236121.4	-235809.6	-312635.9	-312815.9
A : third row	10	-236031.4	-235719.6	-312480.0	-312660.0
B : one row	40	-236631.4	-235280.4	-312594.9	-313374.9
C : one row	150	-228678.1	-223023.2	-311045.3	-312927.6

Table 3: Location of the tidal turbine arrays of each layout. The coordinates given here follow a Mercator projection, with a centre of origin given by 0 degrees in longitude and 51.5 degrees in latitude (m).

The transversal inter-device spacing (perpendicular to the main direction of the stream) is 40 m and the longitudinal inter-device spacing (streamwise) is 180 m (this only concerns layout A).
All turbines are assumed identical. Their diameter, D (m), their drag coefficient, C_d, and their power coefficient C_p, are supposed to be the same for each turbine and their values are D = 18 m, C_d = 0.86 and C_p = 0.53.

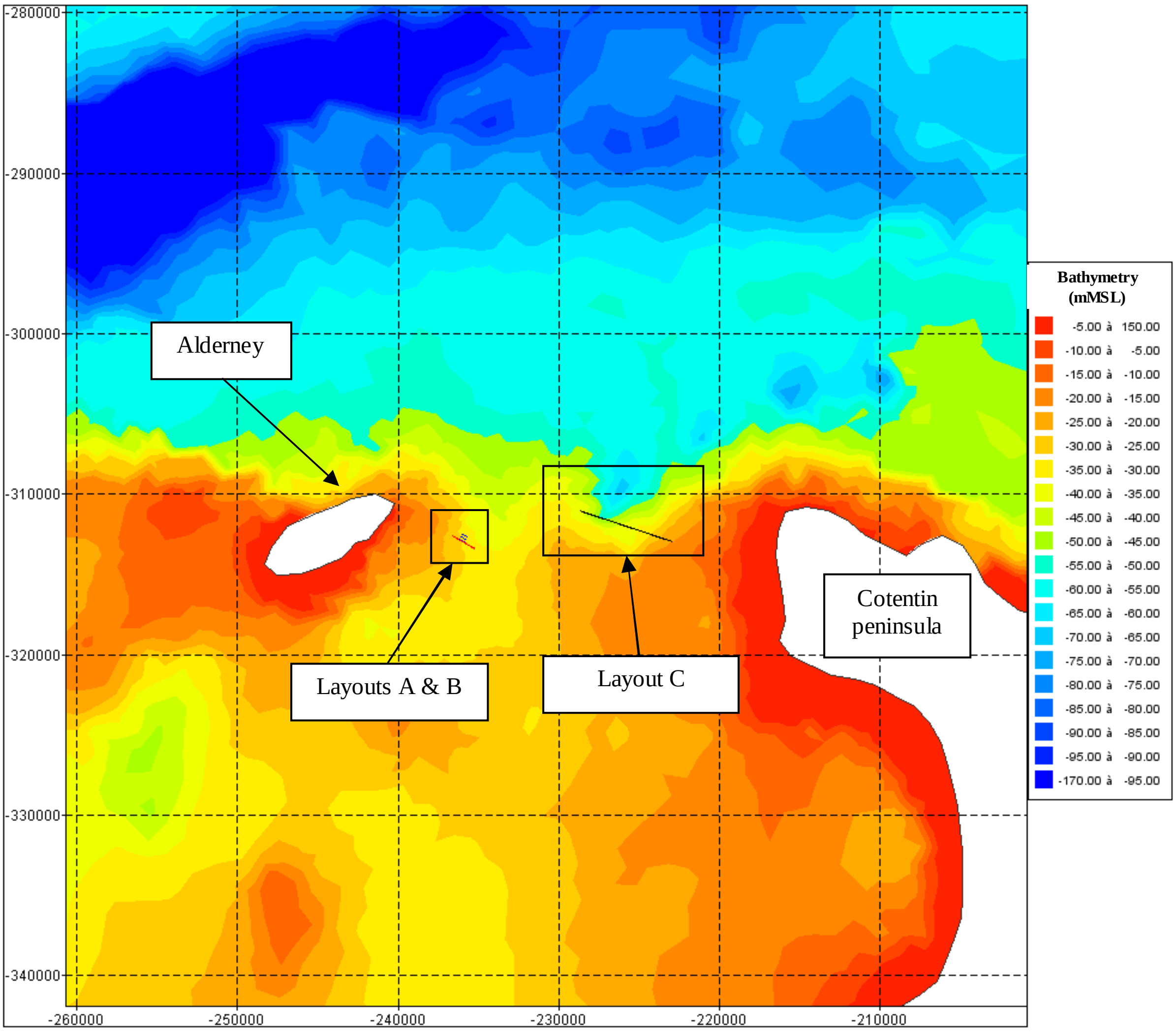

Figure 10: Location of the three tidal farm layouts over the study area, Mercator coordinates sytem (m)

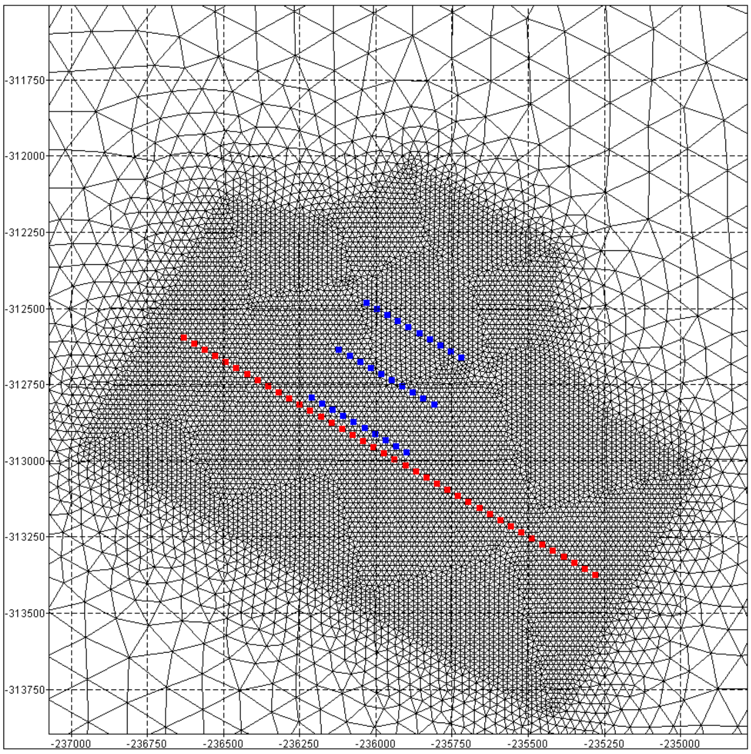

Figure 11: Focus of the numerical mesh on layout A tidal farm (blue points) and layout B tidal farm (red points), Mercator coordinates (m).

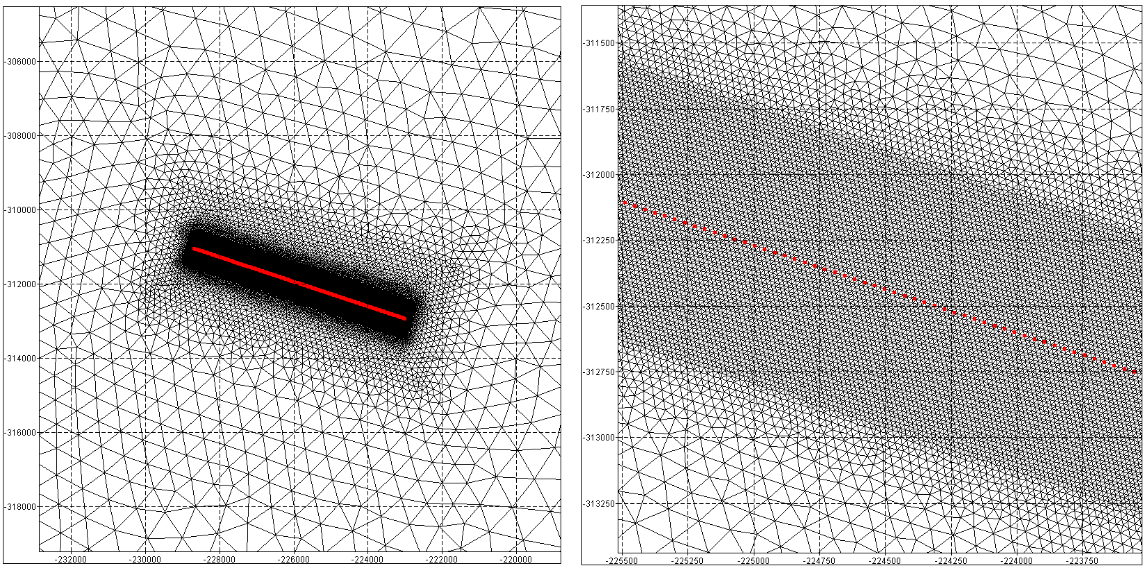

Figure 12: Focus of the numerical mesh on layout C tidal farm (red points), Mercator coordinate system (m). Left panel: tidal farm overview, right panel: detailed view.

3.2.2 Description of the simulations uploaded on the ftp site

All simulations cover a 16-day period, starting on the 14th of September 2001. A 2-day spin up period is first run to properly initialize the simulation without any turbine. Then, computation is continued for the next 14 days with and without representation of tidal farms. Indeed, TELEMAC-2D enables the user to carry out a computation using the last time step of a previous computation on the same mesh as initial state. To do so, two keywords are entered in the steering file: “COMPUTATION CONTINUED” and “PREVIOUS COMPUTATION FILE” (see example of steering file in Appendix A3).

The numerical parameters are almost identical to the one described as in WG3 WP3 D1 (see [A2] § 4.2.6). The main modification of the TELEMAC-2D steering file is on the change in the discretisations in space of the Saint-Venant equations. The corresponding TELEMAC-2D keyword is “DISCRETIZATIONS IN SPACE”. It was set to “12; 11”. This implies that the velocity is calculated over quasi-bubble triangles (4 nodes triangle, *i.e.* an additional node is located at the centre of the mesh element, see [A3-4]). This tuning avoids the development of free surface wiggles that would make uncertain the analysis of TEC-induced perturbations of the flow. It was also found that this setting of the discretisation modifies the tidal wave propagation (see Appendix A2), but consecutive changes were estimated acceptable for the purpose of the study (comparative study of the impact of a tidal farm on the marine flow).

Two additional minor modifications were brought in the steering file: the “CORIOLIS COEFFICIENT” is no longer specified and the “VELOCITY DIFFUSIVITY” is set to its default value (10^{-4} m²/s instead of 10^{-6} m²/s in WG3 WP3 D1). As spherical coordinates are employed, the Coriolis coefficient is automatically adjusted at each point of the domain. The change in velocity diffusivity will not modify the flow (see Paimpol-Bréhat sensitivity analysis §3.4) and is more in line with the theory as the turbulent viscosity (of the order of 10^{-4} m²/s) is predominant over the molecular viscosity of water (of the order of 10^{-6} m²/s).

When turbines are taken into account, the drag forces induced by the turbines are added in the momentum equation for the next 14 days using the DRAGFO subroutine (see § 2.3.2) following the “Global Box” methodology (see § 2.4).

The main numerical parameters of global box and English Channel models are summarized here in after.

3.2.2.1 Layout A

The numerical characteristics of the global box model are defined in Table 4. Figure 13 shows the mesh of the global box. The characteristics of the corresponding English Channel model are given by Table 5, Figure 10 and Figure 11.

Name of the TELEMAC-2D steering file	Big_box_ConfA_TEC_QBV_VC.cas
Time step	0.2 s
Listing printout period	6000
Number of mesh elements	121052
Number of mesh nodes	61027
Number of parallel processors	80
Mesh size	3.6 m

Table 4: Numerical characteristics of layout A global box.

	2-day spin up period	14-day period without turbines	14-day period with turbines
Name of the TELEMAC-2D steering file	D03_EC_AB_INI2J.cas	D03_EC_AB_IS_S1_14J.cas	D03_EC_AB_TECA_S1_14J.cas
Time step	0.5 s	0.5 s	0.2 s
Listing printout period	2400	2400	6000
Number of mesh elements	122425	122425	122425

Number of mesh nodes	62339	62339	62339
Number of parallel processors	128	128	128
Minimal mesh size	18 m	18 m	18 m

Table 5: Numerical characteristics of layout A English Channel model.

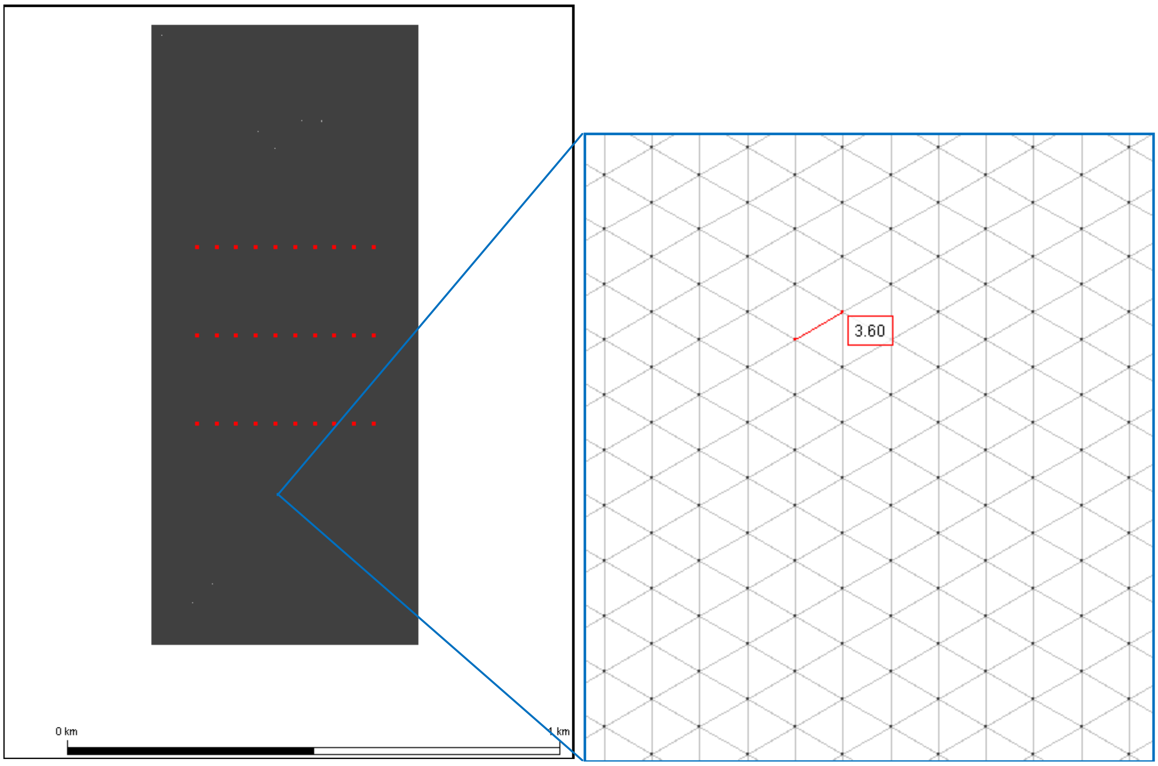

Figure 13: Mesh of the global box "Layout A" and tidal turbine locations (red points). Left panel: overview, right panel: detailed view and mesh size (m).

3.2.2.2 Layout B

The global box numerical characteristics are defined in Table 6. Figure 14 shows the mesh of the global box. The same mesh is used to account for layouts A & B. The characteristics of the corresponding English Channel model are given by Table 7, Figure 10 and Figure 11.

Name of the TELEMAC-2D steering file	Big_box_ConfB_TEC_QBV_VC.cas
Time step	0.2 s
Listing printout period	6000
Number of mesh elements	278386
Number of mesh nodes	139927
Number of parallel processors	160
Mesh size	3.6 m

Table 6: Numerical characteristics of layout B global box.

	2-day spin up period	14-day period without turbines	14-day period with turbines
Name of the TELEMAC-2D steering file	D03_EC_AB_INI2J.cas	D03_EC_AB_IS_S1_14J.cas	D03_EC_AB_TECB_S1_14J.cas
Time step	0.5 s	0.5 s	0.1 s
Listing printout period	2400	2400	12000
Number of mesh elements	122425	122425	122425
Number of mesh nodes	62339	62339	62339
Number of parallel processors	128	128	128
Minimal mesh size	18 m	18 m	18 m

Table 7: Numerical characteristics of layout B English Channel model.

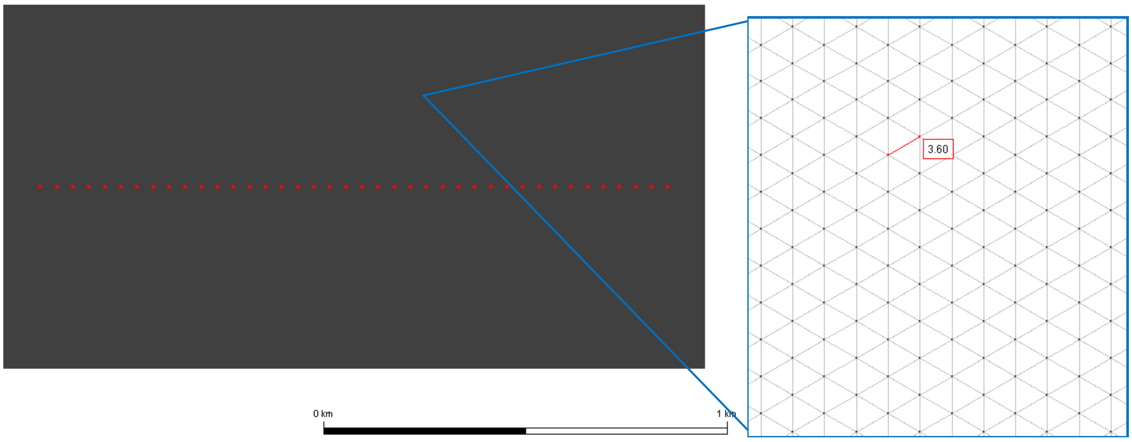

Figure 14: Mesh of the global box "Layout B" and tidal turbine locations (red points). Left panel: overview, right panel: detailed view and mesh size.

3.2.2.3 Layout C

The global box numerical characteristics are defined in Table 8. Figure 15 shows the mesh of the global box. The characteristics of the corresponding English Channel model are given by Table 9, Figure 10 and Figure 12.

Name of the TELEMAC-2D steering file	Big_box_ConfC_TEC_QBV_Ks30_VC.cas
Time step	0.2 s
Listing printout period	6000
Number of mesh elements	985584
Number of mesh nodes	494749

Number of parallel processors	640
Mesh size	3.6 m

Table 8: Numerical characteristics of layout C global box.

	2-day spin up period	14-day period without turbines	First 7-day period with turbines	Second 7-day period wi turbines
Name of the TELEMAC-2D steering file	D03_EC_C_INI2J.cas	D03_EC_C_IS_S1_14J.cas	D03_EC_C_TECC_S1_7J.cas	D03_EC_C_TECC_S2_7J.
Time step	0.5 s	0.5 s	0.05 s	0.05 s
Listing printout period	2400	2400	24000	24000
Number of mesh elements	159747	159747	159747	159747
Number of mesh nodes	80997	80997	80997	80997
Number of parallel processors	128	128	128	128
Minimal mesh size	18 m	18 m	18 m	18 m

Table 9: Numerical characteristics of layout C English Channel model.

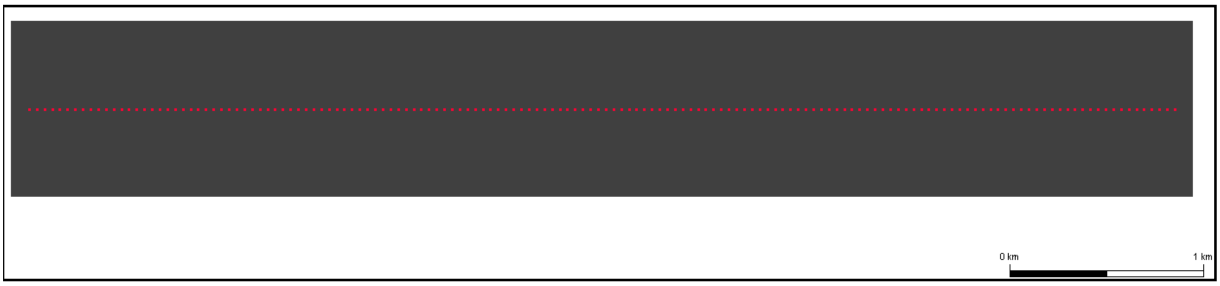

Figure 15: Overview of the mesh of the global box "Layout C" and tidal turbine locations (red points).

For every simulation, the time step, dt (s), respects the CFL condition, which, as a reminder, is given by the following equation:

$$\frac{dx}{u\,dt} < 1$$

Where dx is a mesh element size (m) and u the maximum velocity in this mesh element (m/s).

3.2.3 Illustrative example

An illustrative example of output results from layout B models is given in this section.

First, the global box results are examined to get an equivalent drag coefficient of the entire 40-turbine array (see § 2.4). Figure 16 shows the velocity field (m/s) over the global box.

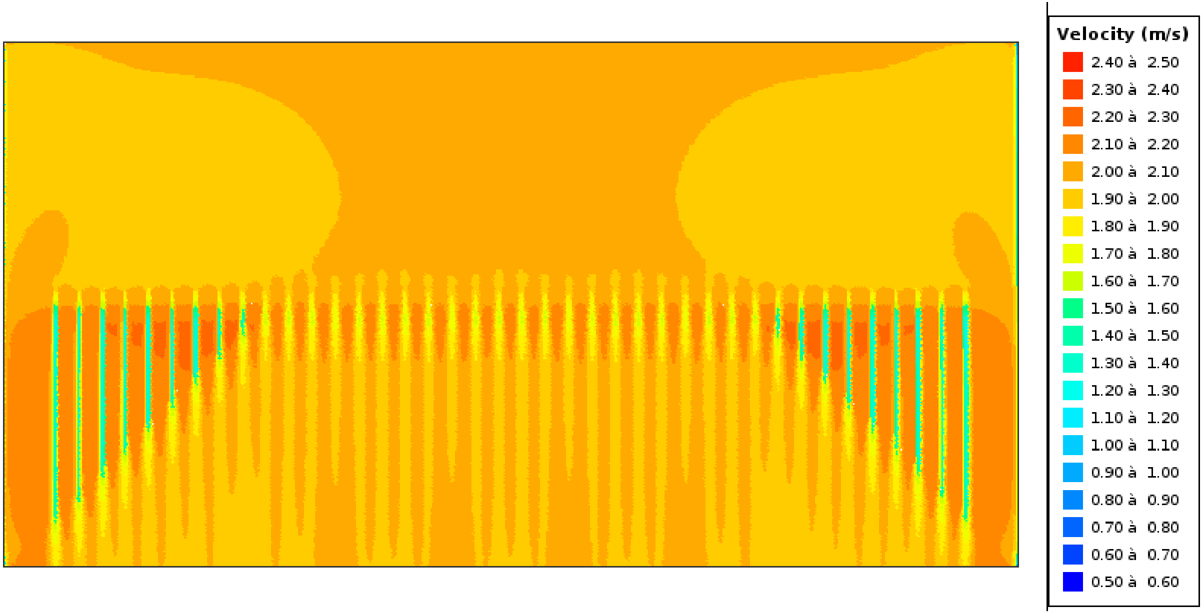

Figure 16: Velocity field (m/s) of layout B global box.

Then the equivalent drag coefficient is included in the English Channel model (see Figure 17). The tidal farm induced wake is clearly visible off the eastern coast of Alderney. The overall tidal farm power can be calculated (see Figure 18) to assess the energy yield of the farm over the chosen 14-day period.

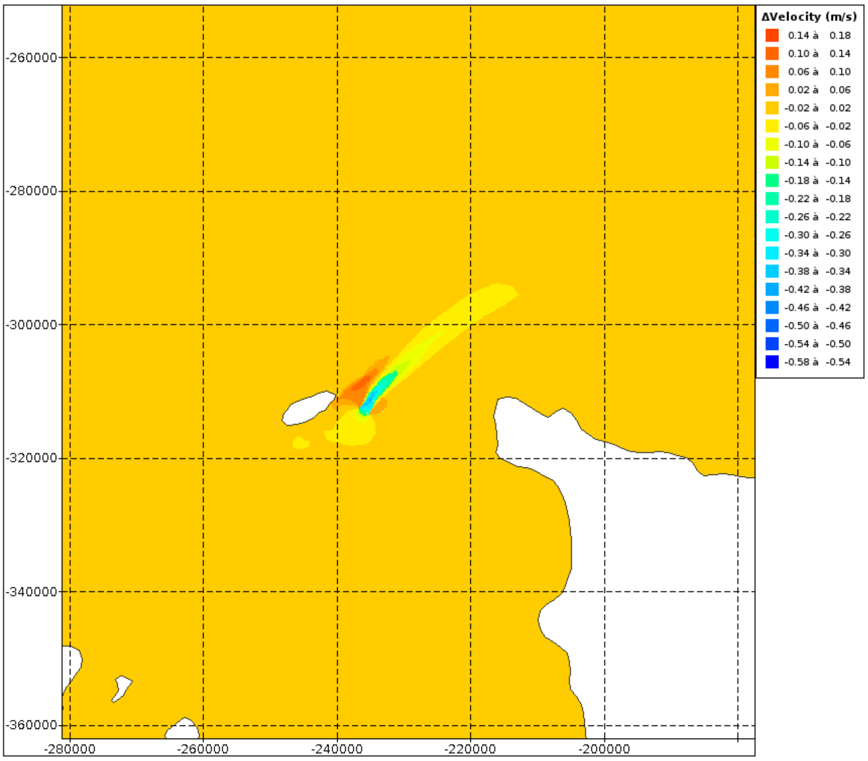

Figure 17: Field of velocity difference (m/s) from simulations with and without global box of the layout B English Channel model. The wake induced by the tidal farm is clearly visible off the eastern coast of Alderney.

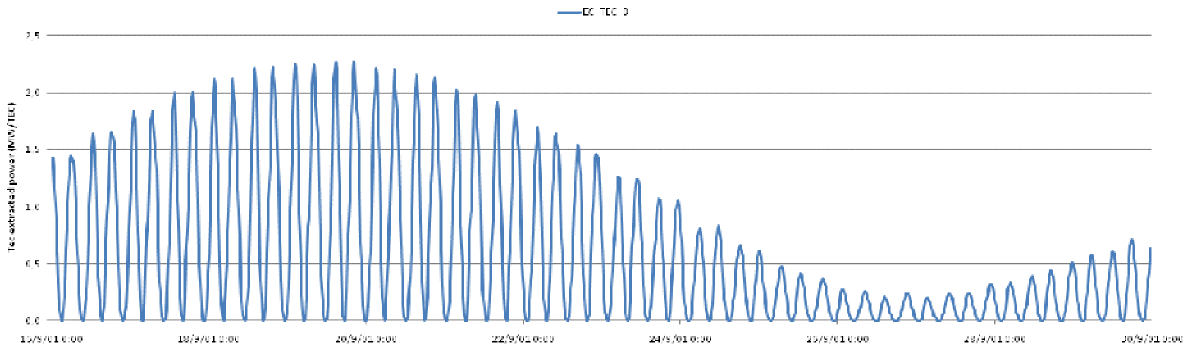

Figure 18: 14-day time-series of averaged TEC extracted power (MW/TEC) of layout B tidal farm.

3.2.4 References

[A1] Simon B. (2007). La marée océanique côtière. Institut océanographique éditeur, p. 280.
[A2] Martin V., Pham C.-T., Saviot S. (2012). PerAWAT WG3 WP3 D1 - Tidal basin modelling: The Alderney Race, the Pentland Firth and the Paimpol Bréhat sites modelled in Telemac software. PerAWAT report.
[A3] Telemac modelling system (2010). 2D Hydrodynamics. TELEMAC-2D Software. Version 6.0. Reference manual.
[A4] Telemac modelling system (2010). 2D Hydrodynamics. TELEMAC-2D Software. Version 6.0. User manual

3.3 The Pentland Firth

The Pentland Firth is a site with exceptionally fast tidal flow because the tide is forced through a constriction. Therefore, it is an interesting place for studying the energy that can be extracted with tidal turbines.

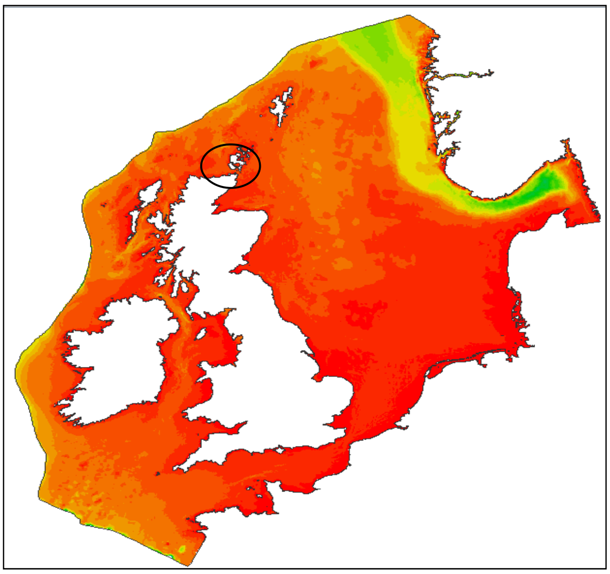

Figure 19: The Pentland Firth is the area inside the region surrounded by the black circle.

Furthermore the simulations in the Pentland Firth will be compared to those performed by the University of Oxford in WG3 WP6 D6.

3.3.1 The array configurations

Three test scenarios were chosen. Table 10 shows the start and end coordinates of each of the rows used to simulate the rows of turbines inside the Pentland Firth.

Table 10: Coordinates of the rows of turbines for all the three scenarios. The coordinates given here follow a Mercator projection, with a centre of origin given by 0 degrees in longitude and 51.5 degrees in latitude.

Scenario	X begin	X end	Y begin	Y end
1 : one row	-341979.99	-343224.38	1410993.41	1409515.34
2 : first row	-343836.95	-344003.75	1409515.34	1409215.47
2 : second row	-343681.28	-343836.95	1409429.66	1409129.80
3 : one row	-341979.99	-346312.08	1410993.41	1405852.22

In all three scenarios the interspacing is 1.5D, where D is the diameter equal to 18 m. In the first test scenario a row of 73 turbines were simulated, in the second scenario two rows of 14 turbines were simulated and for the third scenario a row of 250 turbines were simulated.

The drag coefficient (C_d) and the power coefficient (C_p) are imposed to all the turbines as 0.86 and 0.53 respectively.

The following figures show the arrays configuration for the three cases:

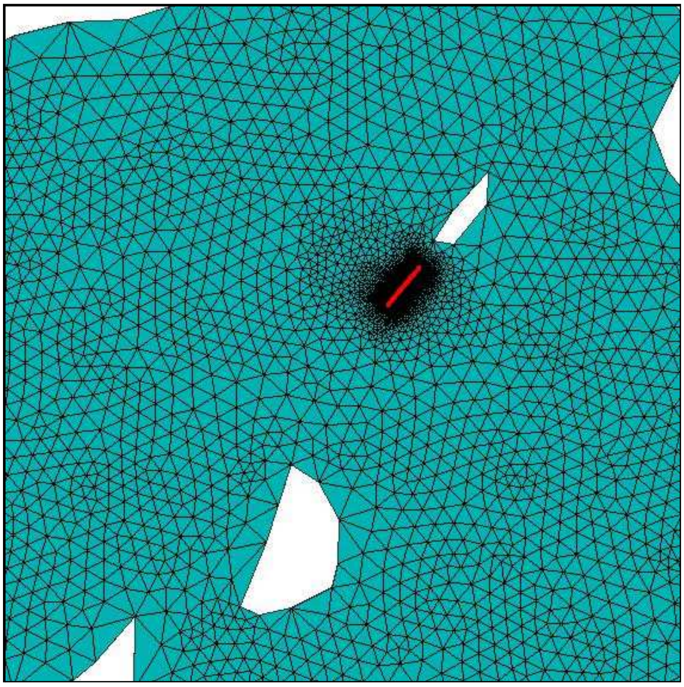

Figure 20: Array configuration for scenario 1.

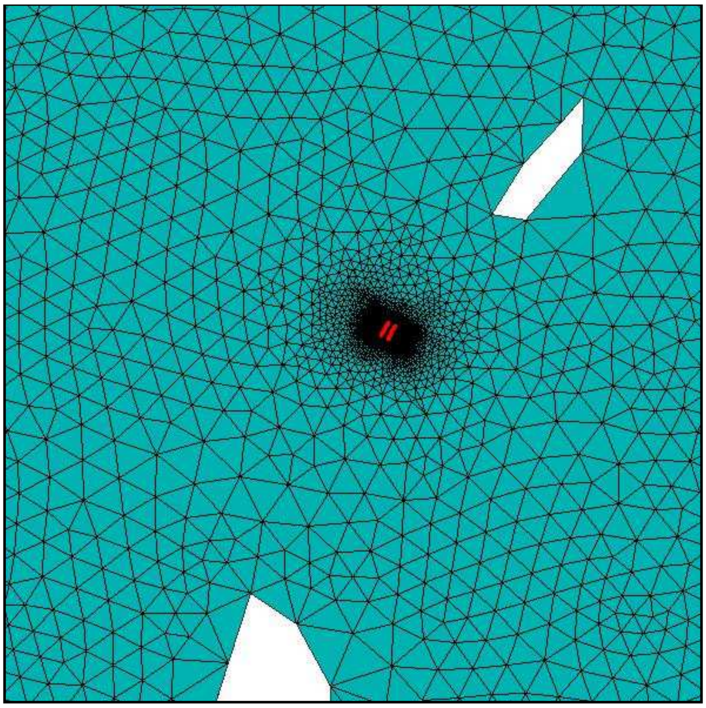

Figure 21: Array configuration for case 2 (2 rows are modelled).

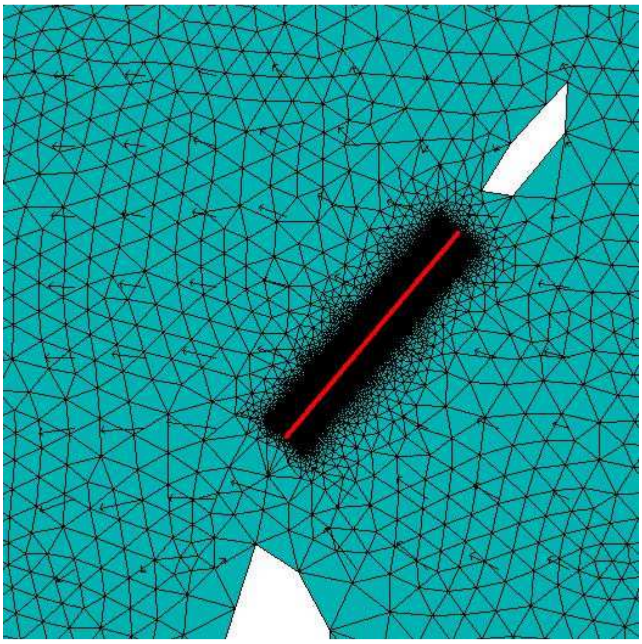

Figure 22: Array configuration for case 3.

As we can see in Figure 20, Figure 21 and Figure 22 the mesh is very refined near the TEC.

3.3.2 Description of the simulations uploaded on the ftp site

All simulations are modeled for 16 days, starting on the 14th of September 2001. The 2 first days are simulated without turbines in order to stabilize the flow. Then, the drag forces coming from the turbines are added in the momentum equation for the next 14 days. The flow is simulated using the same conditions as in WG3 WP3 D1.

The “Big Box” methodology is used for the scenarios 1 and 3 only. Turbines could be represented individually in the second scenario because there are only 28 turbines. However in this scenario the simulations were split in time in 7 parts, so that the simulation time was reduced. For each of those seven parts, two days were used systematically to establish the flow and then the rows of turbines were simulated during the two following days.

Further parameters of interest are summarized as follow:

Case 1:
Time step: 0.5 s
Listing printout period: 7200x0.5 = 3600 s
Number of mesh elements: 904182
Number of parallel processors used: 144

Case 2:
Time step: 0.05 s
Listing printout period: 36000x0.05 = 1800 s
Number of mesh elements: 976720
Number of parallel processors used: 288

Case 3:
Time step: 0.2 s
Listing printout period: 18000x0.2 = 3600 s
Number of mesh elements: 929950
Number of parallel processors used: 192

For all the cases, the time step dt has been reduced enough to respect the CFL conditions, which as a reminder is given by the following equation:

$$\frac{dx}{udt} < 1 \tag{11}$$

Where dt is the time step, dx is a mesh element size and u the maximum velocity in this mesh element. This condition needs to be true for all mesh elements.

3.3.3 Illustrative example

In this section the third scenario is used to illustrate the problem. Figure 23 shows the power evolution for 14 days:

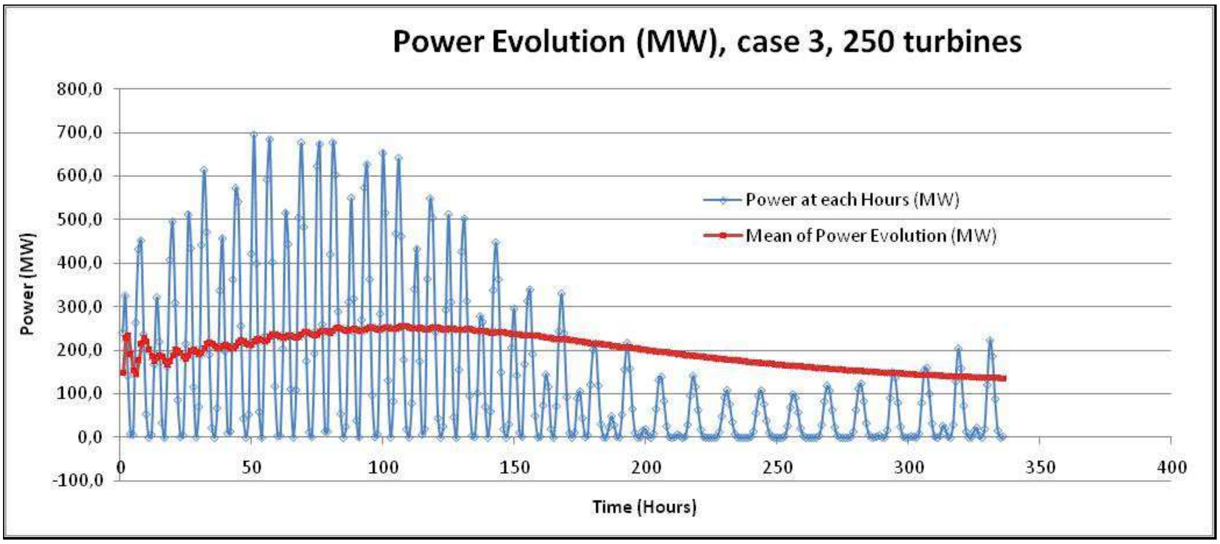

Figure 23: Power evolution for case 3.

This figure seems to show that the frequency is divided by 2 near the 250th hour of simulation. But in fact, the velocity becomes sometime very small and then, the extracted power becomes very small, and this explains the shape of the graph.

Note that for this case, the mean power is near 150 MW. For the case 1, we have 50 MW and for the case 2, 20 MW.

Figure 24 shows the location of a point within the Pentland Firth from which the velocity and the water level time series will be given Figure 25 and Figure 26. This point will be named point P for convenience.

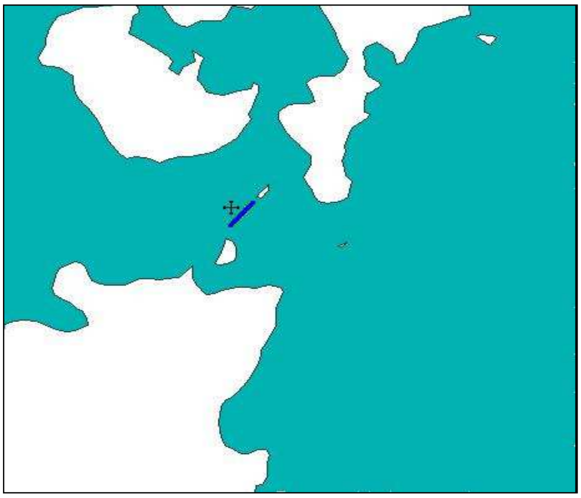

Figure 24: Location of point P within the Pentland Firth from which velocity and water level time series will be extracted (given by a cross).

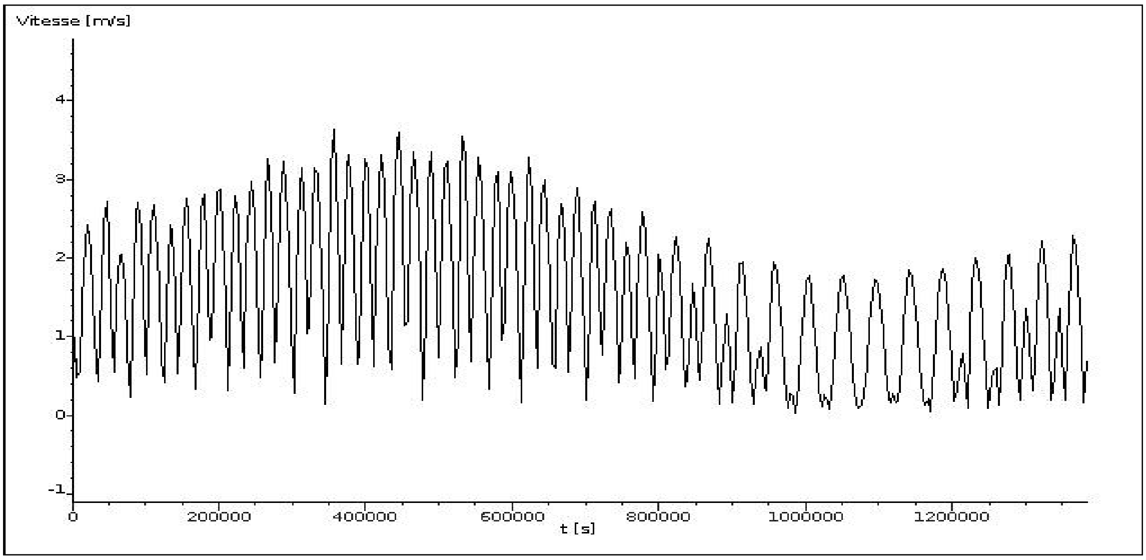

Figure 25: Velocity observed at the point P. As we can see, near the end of simulation, the velocity can become very small so that we could believe that the frequency is divided by 2.

As can be seen Figure 25, at the end of the simulation, the velocity can be very small, so that it could be believed (wrongly) that the frequency is divided by 2.

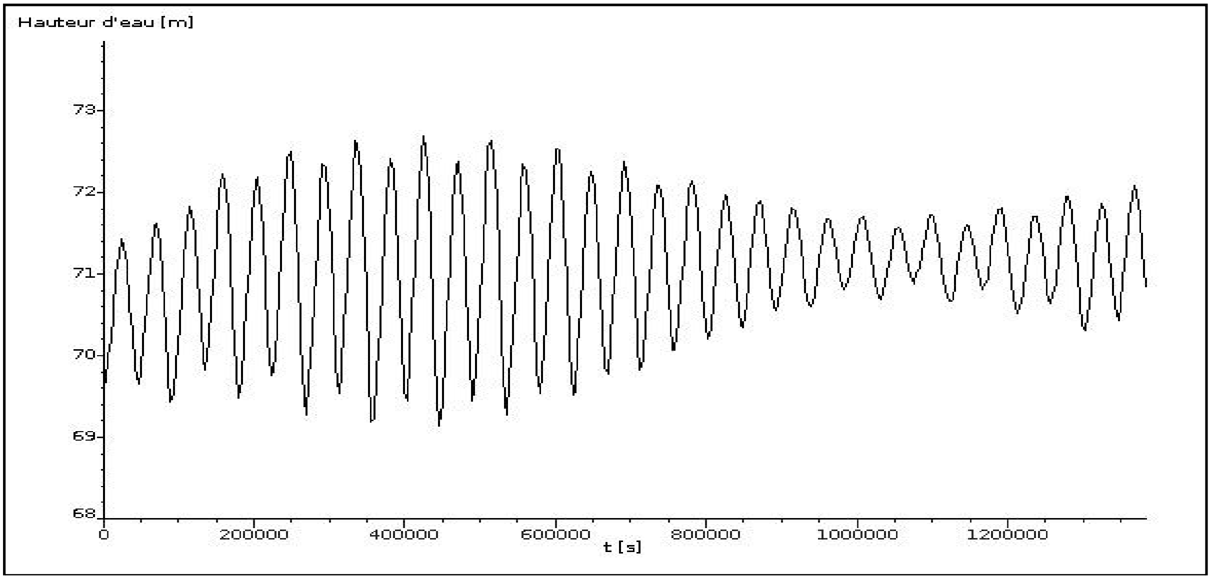

Figure 26: Water level observed at the point P.

For the water level, there are 32 minimums, which correspond to 16 days of simulation with 32 tides, therefore no tide has been removed by the presence of the TECs.

3.4 Paimpol-Bréhat

The Bréhat zone, also known as Paimpol region, is located in the Normandy-Brittany Gulf (English Channel) to the north-west of the Saint-Brieuc Gulf, in the French department of Côtes-d'Armor (22) in Brittany.

3.4.1 The array configurations

As the Paimpol-Bréhat site is not an area as powerful as the two other sites modeled with TELEMAC-2D (the Alderney Race and the Pentland Firth), it was decided to model only one farm of 30 turbines in one row, rather than modeling a huge farm. The only difference comes from the inter-device spacing (2*D*, 3*D*, and 4*D*, the distance measured between the centers of the devices with *D* the diameter of the turbine equal to 18 m), so that there are also three scenarios and that the effect of the lateral spacing can be investigated. In particular, the row is 1 to 2 km wide and perpendicular to the flood direction.
Table 11 shows the coordinates of the extremities of the rows of turbines.

Table 11: Coordinates of the extremities of the row of turbines for all the three scenarios (in meters). The coordinates given here follow a Lambert 1 North projection.

Scenario	X begin	Y begin	X end	Y end
2*D* spacing	217324.2	147668.6	217923.0	148523.8
3*D* spacing	217231.2	147535.9	218129.5	148818.7
4*D* spacing	217138.3	147403.2	218336.0	149113.6

The drag coefficient (C_d) and the power coefficient (C_p) are imposed to all the turbines as 0.86 and 0.53 respectively (like for the two other sites modeled with TELEMAC-2D).

The following figure shows the arrays configuration for the three cases. The domain covers an area that is almost square, extending approximately 60 km from North to South and from West to East. The same mesh was used for the three layouts. It is made of 171,512 nodes and 342,191 triangular elements (compared to 14,129 nodes and 27,425 elements for the previous mesh when modeling the area without any turbines). The mesh is particularly refined around these layouts with a maximum size of elements of 3.6 m, which is equal to *D*/5 with *D* the diameter of the turbine equal to 18 m, around the turbine, on an area covering 25*D* in front of and behind the row of turbines.

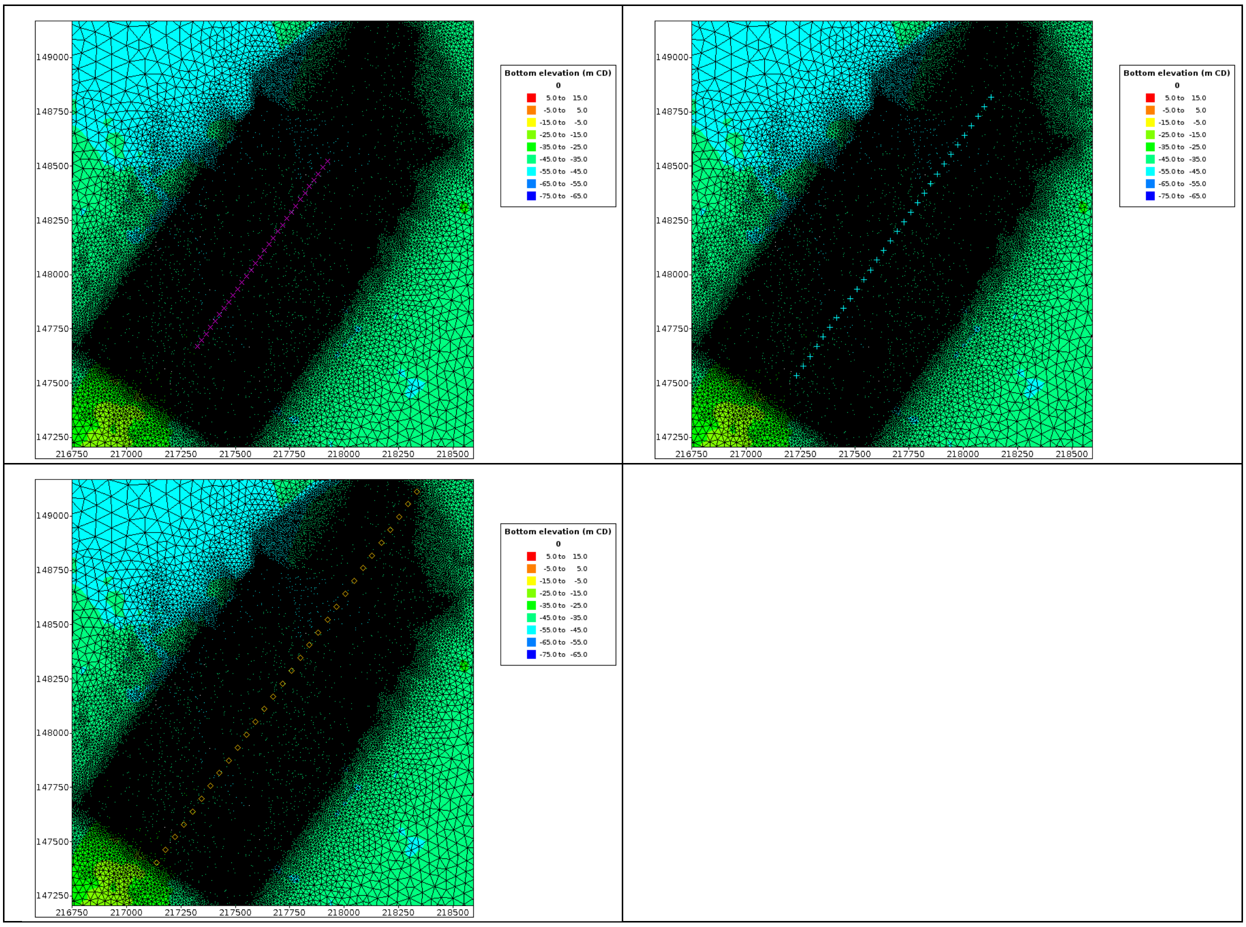

Figure 27: Array configurations with different spacings (top left = 2*D*, top right = 3*D*, bottom left = 4*D*).

3.4.2 Description of the simulations uploaded on the ftp site

All simulations are modeled for 16 days in 2001. The first two days are simulated without turbines in order to stabilize the flow. Then, the drag forces coming from the turbines are added in the momentum equation for the next 14 days. The flow is simulated using the same conditions as in WG3 WP3 D1.

Turbines are represented individually in every scenario because the number of turbines is not big ("Individual Turbine method"). In particular, the "Big Box" methodology is not used contrary to some scenarios for the Pentland Firth or the Alderney Race.

Further parameters of interest are summarized as follow. The time step used for all simulations with turbines in the Paimpol-Bréhat area is the same for every layouts: 0.5 s (compared to 20 s for the model without any turbines). 256 cores on the BlueGene Q owned by EDF are used to run the computations. Results are written every 10 minutes.

The version of TELEMAC-2D used for this study is the version 6.2 for all these computations for a few reasons, amongst:
- the Thompson-type boundary conditions can be calculated in parallel (but you have to use a smaller coefficient for the keyword FREE SURFACE GRADIENT COMPATIBILITY, e.g. 0.5 rather than 0.9, to avoid spurious oscillations),
- the boundary conditions when prescribing tidal values (water depth and/or horizontal components of velocities) are automatically calculated because they are implemented in the standard version,

- the initial conditions can be calculated from the harmonic constants solutions coming from the Oregon State University (with the option ‘TPXO SATELLITE ALTIMETRY”) that provide elevation of the free surface and horizontal velocity components.

For every scenario, three computations are run with three choices to model turbulence:

- constant viscosity (VELOCITY DIFFUSIVITY = 10^{-4} m^2/s, that is the default value),
- constant viscosity (VELOCITY DIFFUSIVITY = 10^{-6} m^2/s),
- k-ε model.

3.4.3 Illustrative example

Results of power time series (instantaneous and mean powers) are rather the same for different values of VELOCITY DIFFUSIVITY and are close between a constant viscosity and the k-ε model.
Please note that the figures are relative to results starting on 14th of September 2001. In WG3WP3D4, the results will be given for a period of time between January 30th to February 14th 2010.

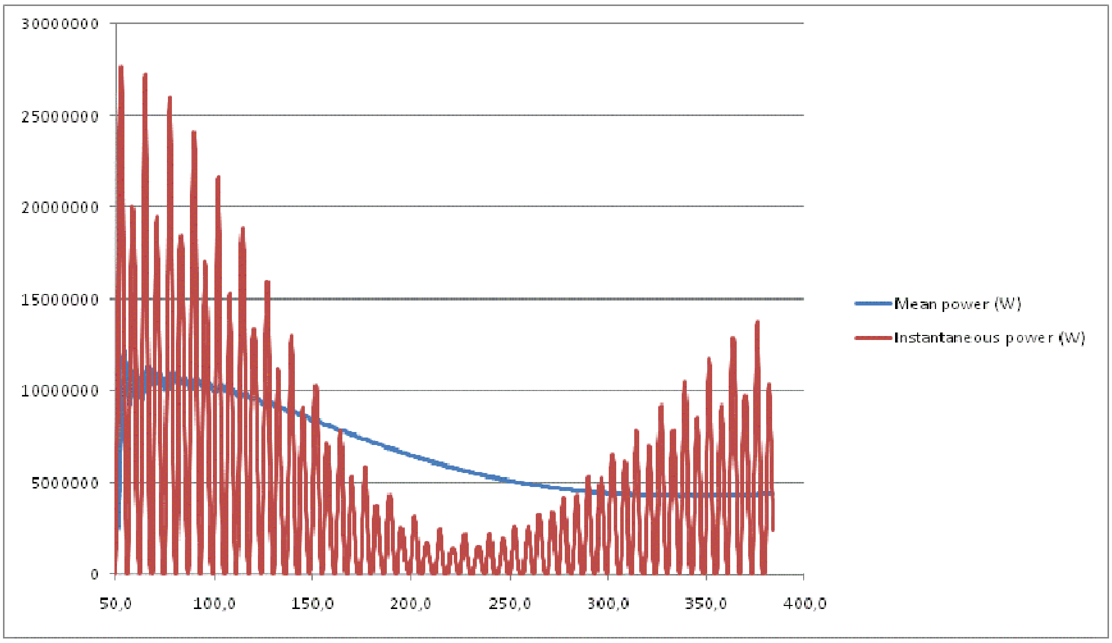

Figure 28: Power generation (over 14 days). 1 example. Spacing: 2D, turbulence model: constant viscosity = 10^{-4} m^2/s.

P_{mean} (MW)	$\upsilon_t = 10^{-4}\ m^2/s$	$\upsilon_t = 10^{-6}\ m^2/s$	k-ε
2D	4,386	4,386	4,388
3D	4,341	4,341	4,343
4D	4,373	4,373	4,374

Table 12: Mean power generation (in MW) for a 30 TEC layout (over 14 days). 3 layouts, 3 turbulence models.

Table 12 shows that the power results are rather the same for the same layout (same spacing) when changing the turbulence model (error less than 0.1 %) and that with these scenarios (different spacings), the power results are not too different for the same turbulence model (error less than 1 %).

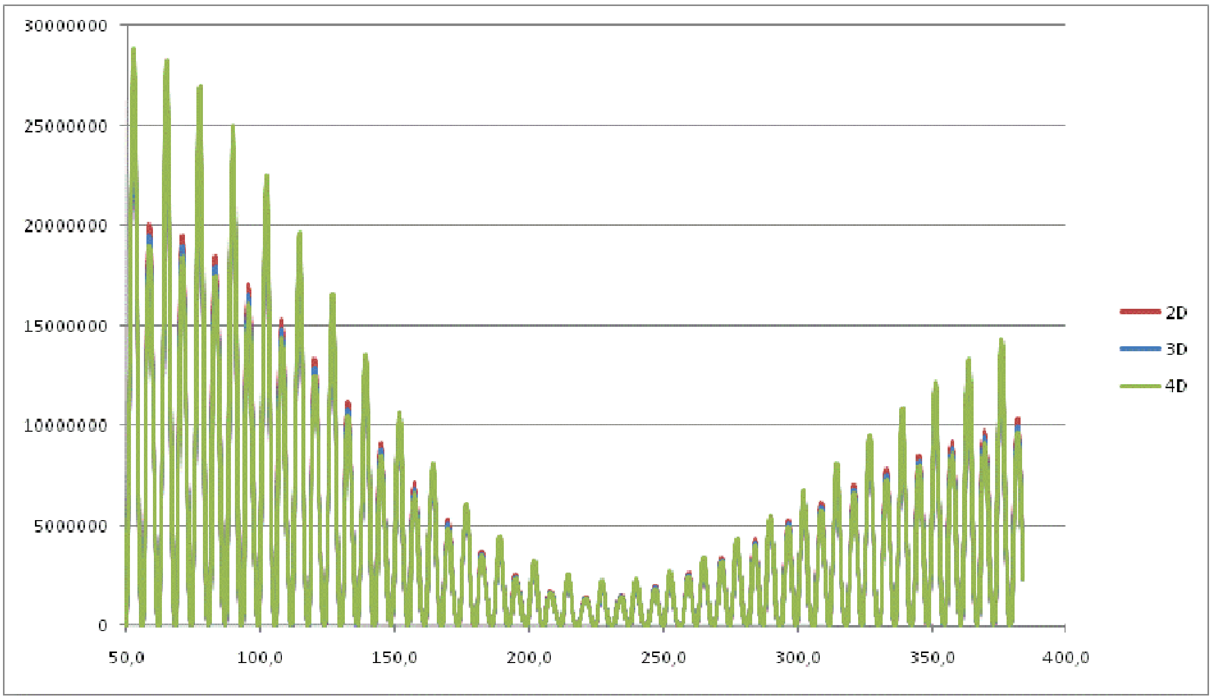

Figure 29: Mean power generation (in MW) for a 30 TEC layout (over 14 days). Comparison for the 3 layouts with the same turbulence model (constant viscosity = 10^{-4} m^2/s).

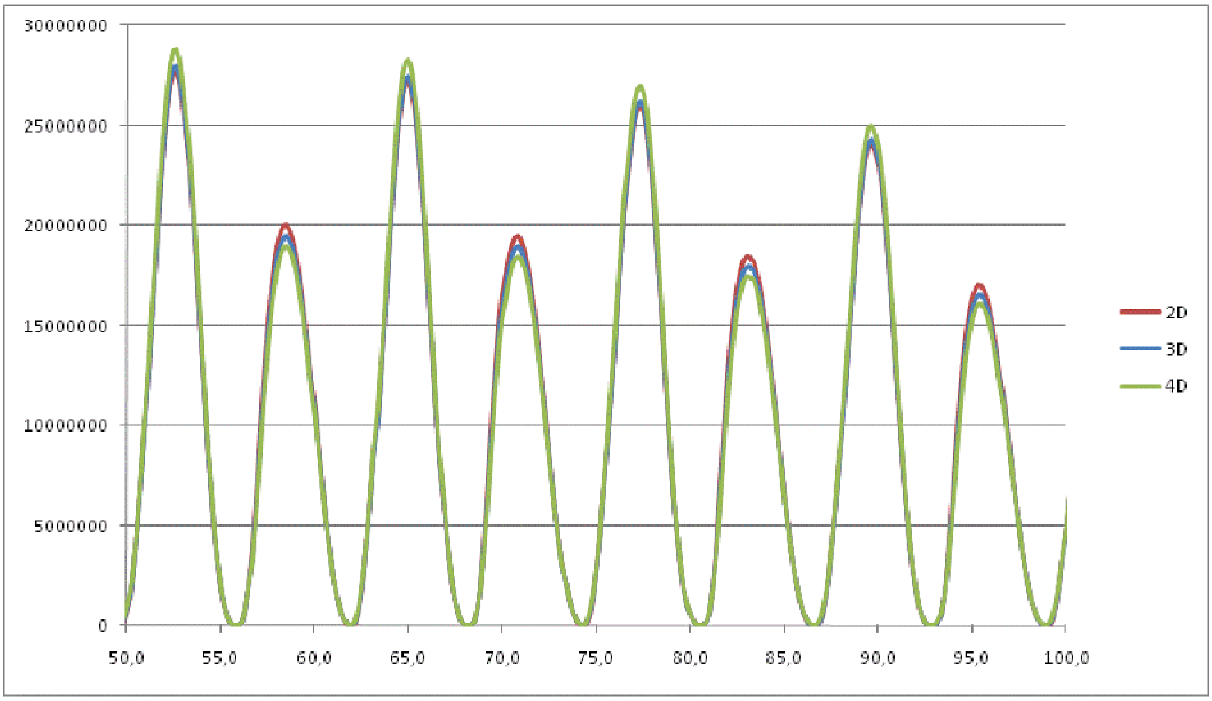

Figure 30: Mean power generation (in MW) for a 30 TEC layout (over 14 days). Comparison for the 3 layouts with the same turbulence model (constant viscosity = 10^{-4} m^2/s).

Figures 29 and 30 show that the power results are not too different for these scenarios. Figure 30 is a zoom of Figure 29 over a 50 h period of time.

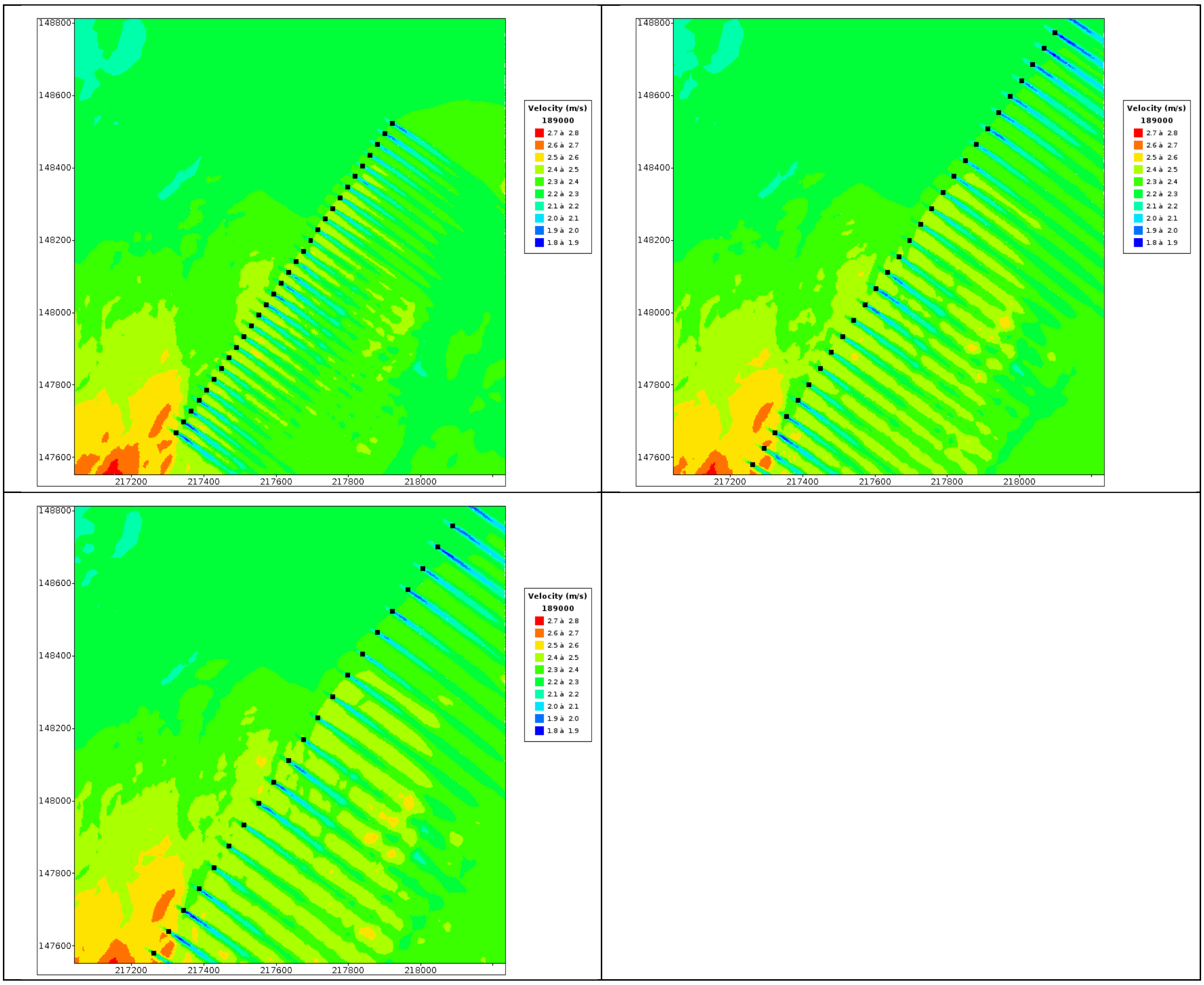

Figure 31: Wake effects. Influence of the spacing for a 30 TEC layout. Comparison for the 3 layouts with the same turbulence model (constant viscosity = 10^{-4} m^2/s) on February 1st during flood. Top left: 2*D*, top right: 3*D*, bottom left: 4*D*.

Figure 31 shows that the spacing influences the shape of the wake.

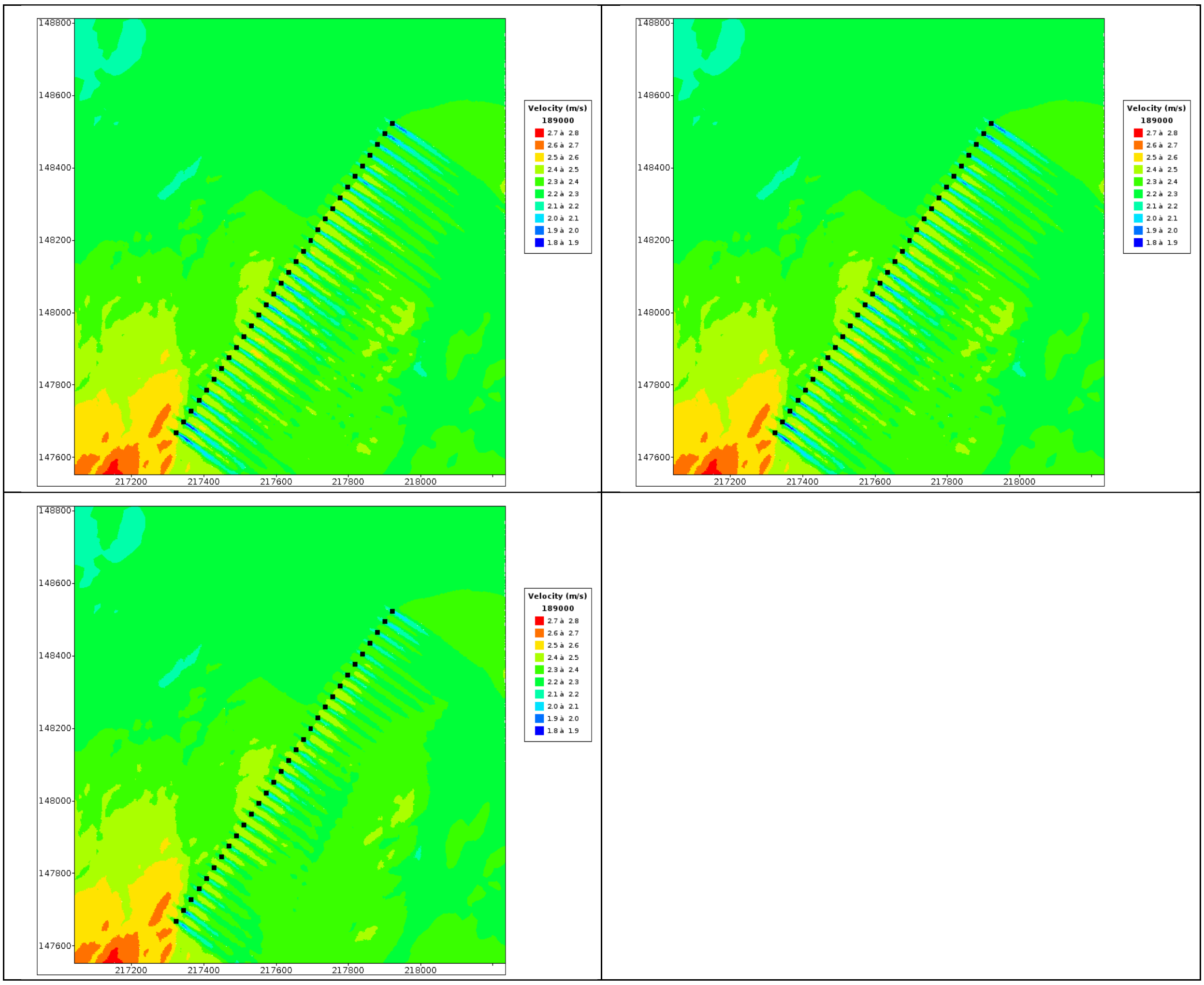

Figure 32: Wake effects. Influence of the turbulence choice for a 30 TEC layout. Comparison for the 3 choices, with the same spacing (2*D*) on February 1st during flood. Top left: constant viscosity with $\upsilon_t = 10^{-4}$ m^2/s, top right: constant viscosity with $\upsilon_t = 10^{-6}$ m^2/s, bottom left: *k*-ε model.

Figure 32 shows that there are close to no differences on the shape of the wakes when using different turbulence choices (turbulence models or the value of the viscosity).

3.4.4 3D model

The same extent, three array configurations, drag and power coefficients are used for the 3D model of the Paimpol-Bréhat area (see 3.4.1). The file containing the coordinates of the TEC has to be changed from the ones used in the 2D model. Indeed, the user has to give the elevation of the centers of every TEC in addition to the horizontal coordinates.

The mesh is the same as for the 2D model for its horizontal part (in particular for the refinement). 21 planes are used for the 3D model, mixing σ-layers (2 layers above to the bottom including it and 5 layers below the free surface including it) and Z-layers (from 65 m to 26 m every 3 meters, thus 14 planes, with prescribed elevation) so that a TEC is covered by 5 to 6 planes over the vertical (4 to 5 layers). The 3D mesh is then made of 3,601,752 nodes and 6,843,820 elements.

The Individual Turbine method is used to model the TEC.

The time step used for all simulations with turbines is about 0.1 to 0.2 s. 2,048 cores on the BlueGene Q owned by EDF are used to run the computations.

CPU time are very long due to the number of 3D elements, and the CPU time is coarsely equal to the physical time you want to model.

The version of TELEMAC-3D used for this study is the version 6.2 for all these computations for a few reasons, amongst:
- the boundary conditions when prescribing tidal values (water depth and/or horizontal components of velocities) are automatically calculated because they are implemented in the standard version,
- the initial conditions can be calculated from the harmonic constants solutions coming from the Oregon State University (with the option ‘TPXO SATELLITE ALTIMETRY”) that provide elevation of the free surface and horizontal velocity components.

To decrease the CPU time, the Thompson-type method to calculate the boundary conditions is not used and either the horizontal velocities or the water depth are prescribed on the open boundaries (see WG3WP3D1).

For every scenario, the computations are run with only a constant viscosity equal to 10^{-6} m^2/s that is the default value (keyword VELOCITY DIFFUSIVITY).

4 PATH TO THE LOCATION OF THE FILES ON THE OXFORD SFTP SITE

All the input files have been placed on the Oxford sftp site under the directory:

/home/PerAWaT/WorkGroups/WG3/WP3/D3/Data

Under this directory there are three folders (one for each site): ALDERNEY, PAIMPOL and PENTLAND_FIRTH.

5 ADDITIONAL TOOLS UPLOADED TO THE SFTP SITE

Additional tools, which can be useful when modeling TECs, are also uploaded to the oxford sftp site.

5.1 conv_longlat2mercatortelemac.f

Only available to PerAWaT participants.

5.2 PowerFlume.f

Only available to PerAWaT participants.

5.3 GetPower.sh

Only available to PerAWaT participants.

5.4 DRAGFO

Only available to PerAWaT participants.

5.5 SOURCE

Only available to PerAWaT participants.

6 APPENDIX A1 – ENGLISH CHANNEL MODEL

Prior to any representation of tidal farms (mesh refinement, use of DRAGFO subroutine), tidal range, resp. tidal currents, are compared to SHOM data at Braye and Goury, resp. two ADCP measurement points (cf. [A2] § 3.5.9.) in order to check the validity of the use of the English Channel model (see. § 3.1). Comparison results show that the English Channel model is acceptable for the purpose of WG3 WP3 D3 & D4 despite the fact that the local model developed for WG3 WP3 D1 was more accurate.

The validation is performed with a model of the English Channel model whose mesh is relatively coarse (of the order of 1 km in the study area) as no turbines are to be integrated. It corresponds to a portion of the WG3 WP3 D1 Pentland Firth model limited to the English Channel domain. The mesh is made of 52724 nodes and 103201 elements (see Figure hereafter).

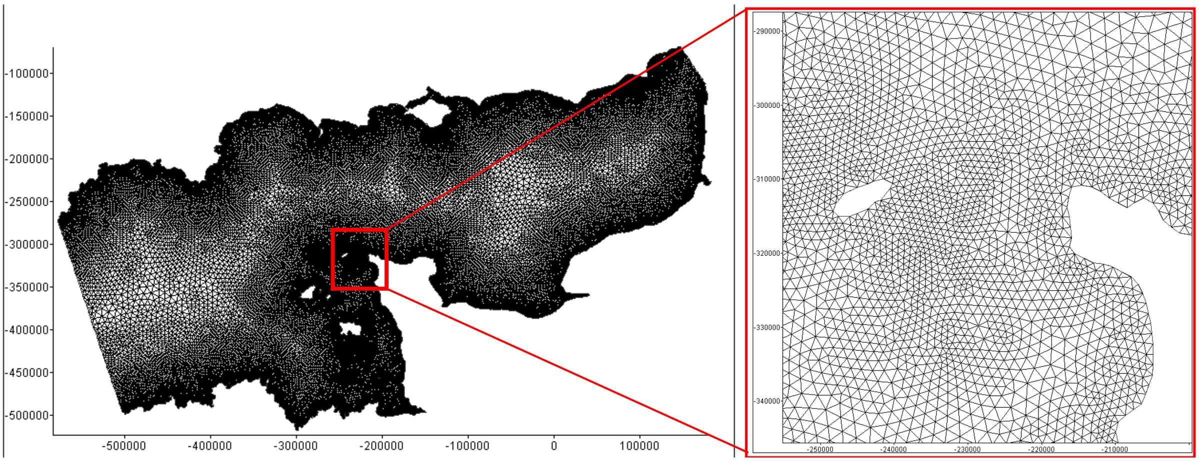

Figure 33: English Channel model mesh used for validation, Mercator projection (m)

This model is run throughout the month of July 2010, after a 2-day spin up period, in order to compare the simulated tidal range to SHOM predictions (cf. [A2] § 3.5.9.2.).

Results are displayed in Figure 34 to Figure 39. The overall agreement is acceptable with a good fit for tidal range and an acceptable fit for tidal current speeds despite a clear over-estimation by nearly 1m/s at the peak of the flood at ADCP1 location. Numerical quality indexes were not calculated for tidal current speed as the length of the validation period does not cover a sufficient length to be statistically relevant.

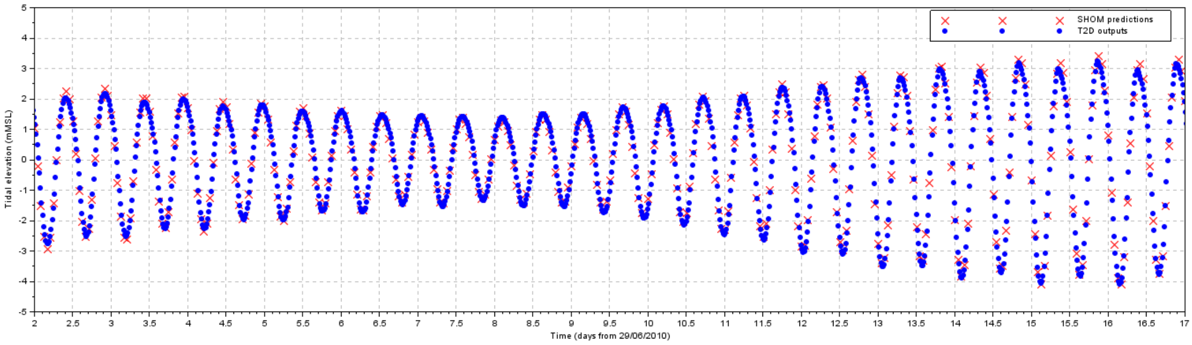

Figure 34: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Goury, time is given in days from 29/06/2010.

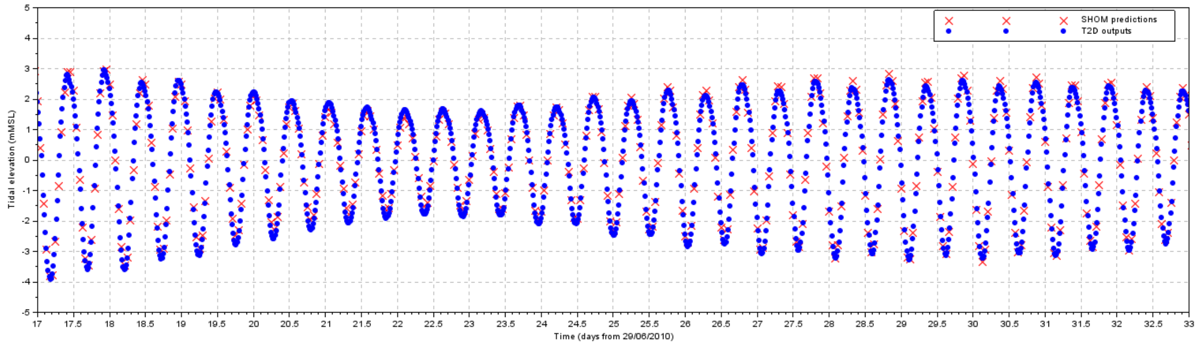

Figure 35: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Goury, time is given in days from 29/06/2010.

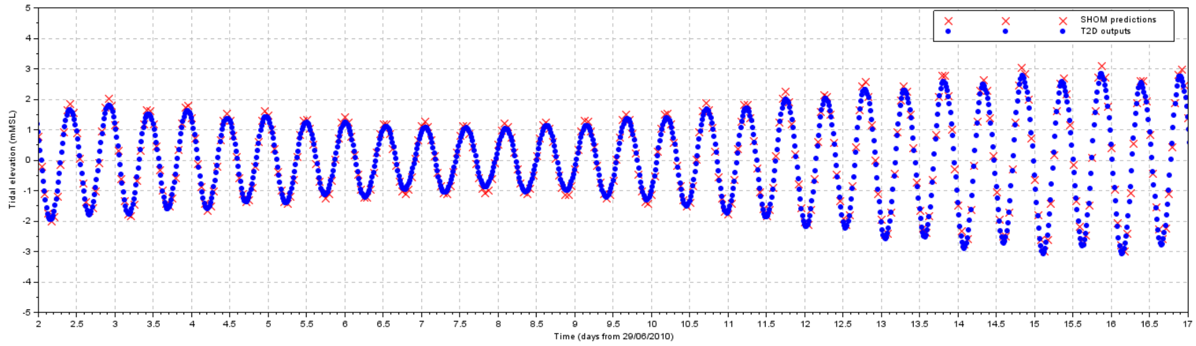

Figure 36: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Braye, time is given in days from 29/06/2010.

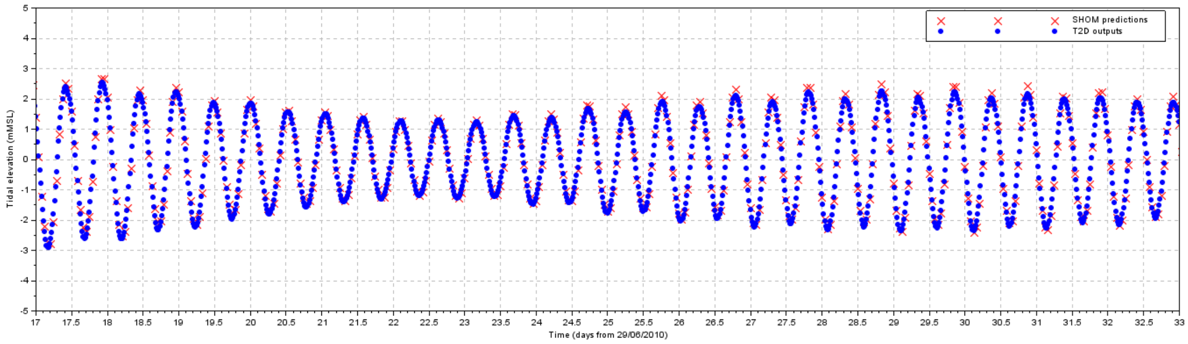

Figure 37: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Braye, time is given in days from 29/06/2010.

Location	Bias	Bias absolute	RMSE	Adim bias	SI	CC
Braye	0.00	0.11	0.13	0.00	0.02	0.99
Goury	0.02	0.20	0.25	0.00	0.04	0.99

Table 13: Numerical quality indexes of water level time-series at Braye and Goury harbours.

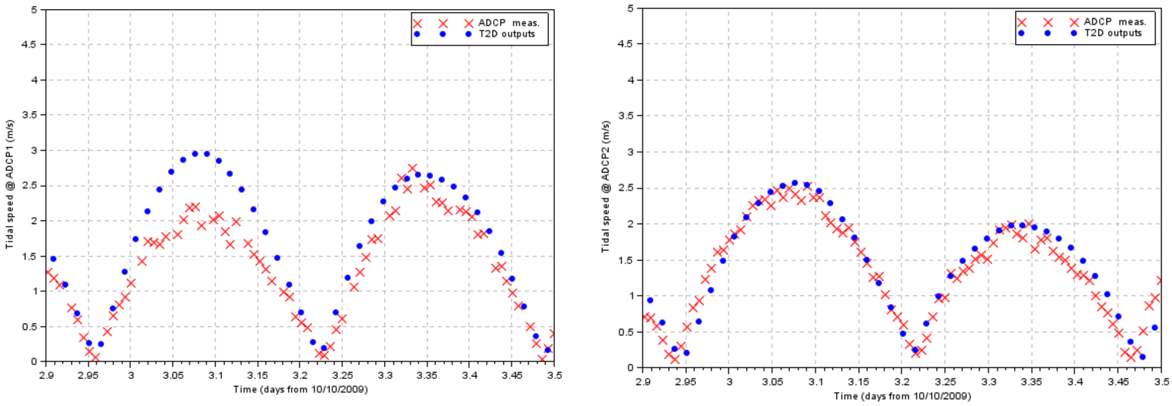

Figure 38: Depth-averaged tidal current speed (m/s) from model outputs (blue dots) and ADCP measurements (red crosses) during a mean neap tide at ADCP1 (left panel) and ADCP2 (right panel) locations, time is given in days from 10/10/2009.

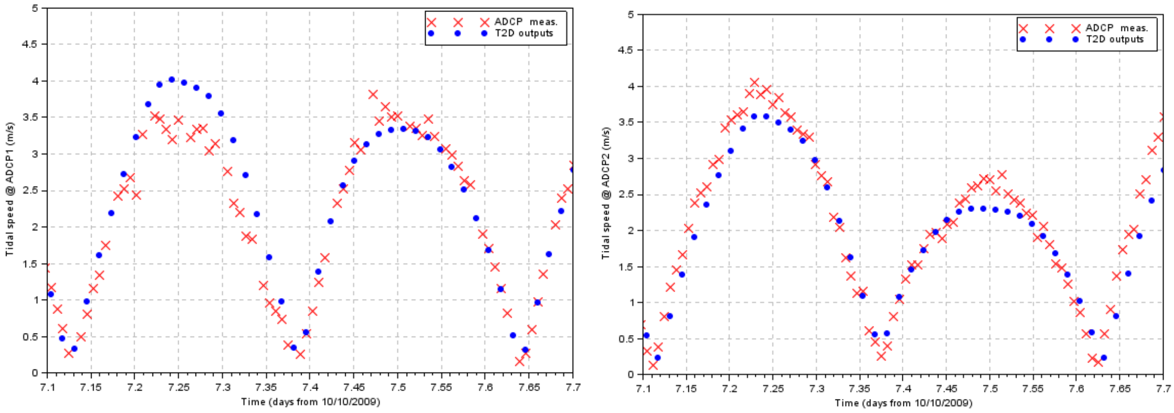

Figure 39: Depth-averaged tidal current speed (m/s) from model outputs (blue dots) and ADCP measurements (red crosses) during a mean spring tide at ADCP1 (left panel) and ADCP2 (right panel) locations, time is given in days from 10/10/2009.

7 APPENDIX A2 – ENGLISH CHANNEL MODEL – QUASI-BUBBLE DISCRETISATION IN SPACE FOR VELOCITY

The validation carried out in Appendix A1 is performed again in order to check the validity of the English Channel model with the change in spatial discretisation of velocity (see. § 3.2.2). Tidal range, resp. tidal currents, are compared to SHOM data at Braye and Goury, resp. two ADCP measurement points (cf. [A2] § 3.5.9.). The validation is performed with the English Channel model described in Appendix A1.

Results show that tidal range is now clearly underestimated at Braye and especially at Goury. However, tidal velocities at ADCP 1 & 2 locations are less sensitive. Results remain similar in terms of velocity. Given that the present study is a comparative study (with and without TECs) and that the wake is main feature of the TEC induced perturbation of the flow, the model results are considered acceptable.

Location	Bias	Bias absolute	RMSE	Adim bias	SI	CC
Braye	0.00	0.18	0.21	0.00	0.04	0.99
Goury	0.02	0.28	0.34	0.00	0.05	0.98

Table 14: Numerical quality indexes of water level time-series at Braye and Goury harbours.

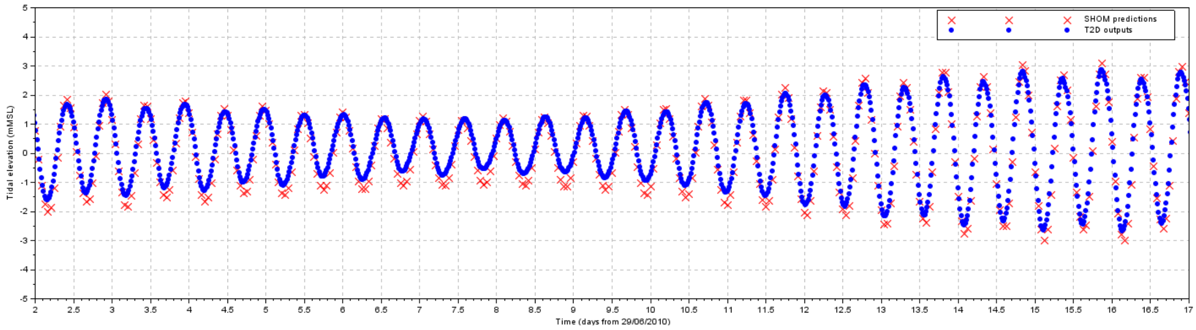

Figure 40: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Braye, time is given in days from 29/06/2010.

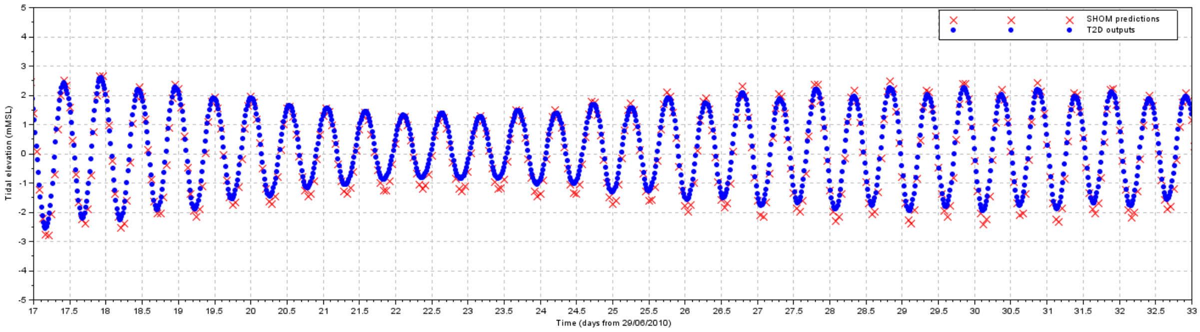

Figure 41: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Braye, time is given in days from 29/06/2010.

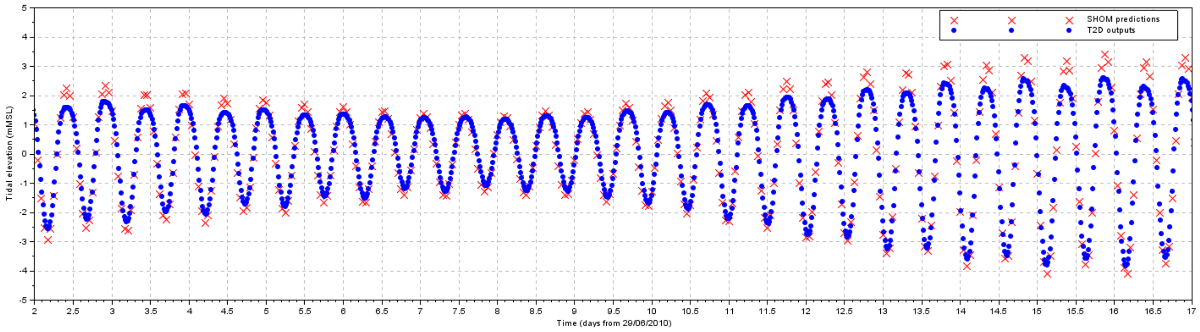

Figure 42: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Goury, time is given in days from 29/06/2010.

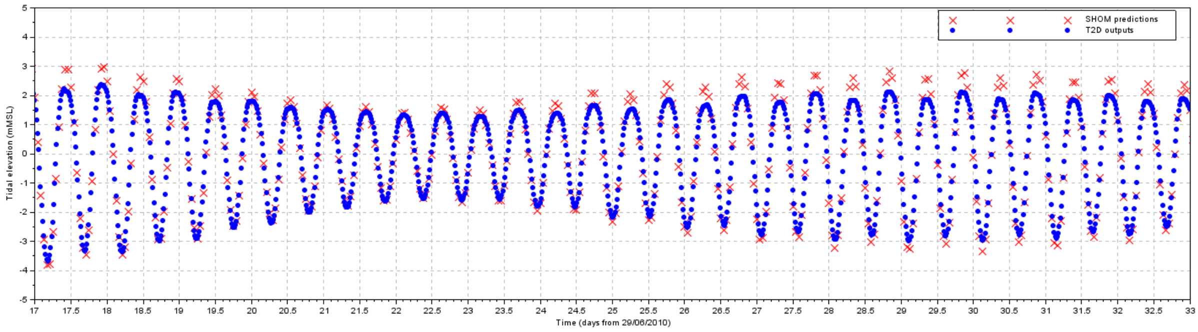

Figure 43: Water level time-series (mMSL) from model outputs (blue dots) and SHOM predictions (red crosses) at Goury, time is given in days from 29/06/2010.

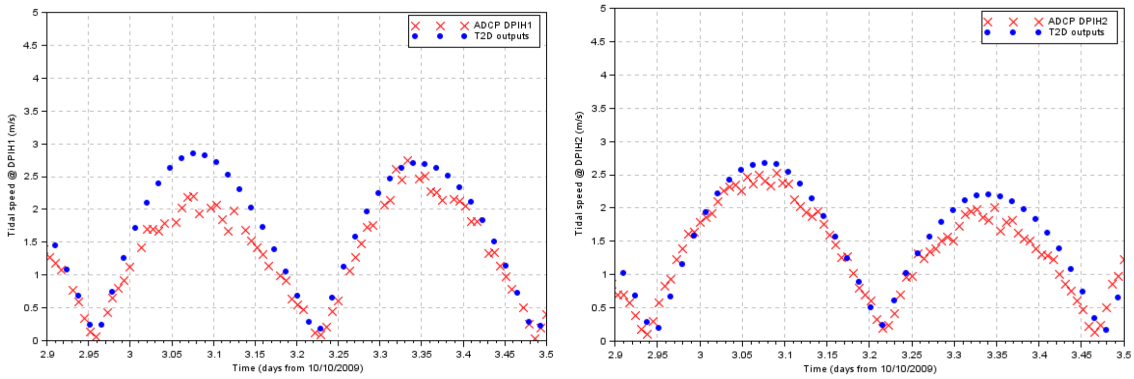

Figure 44: Depth-averaged tidal current speed (m/s) from model outputs (blue dots) and ADCP measurements (red crosses) during a mean neap tide at ADCP1 (left panel) and ADCP2 (right panel) locations, time is given in days from 10/10/2009.

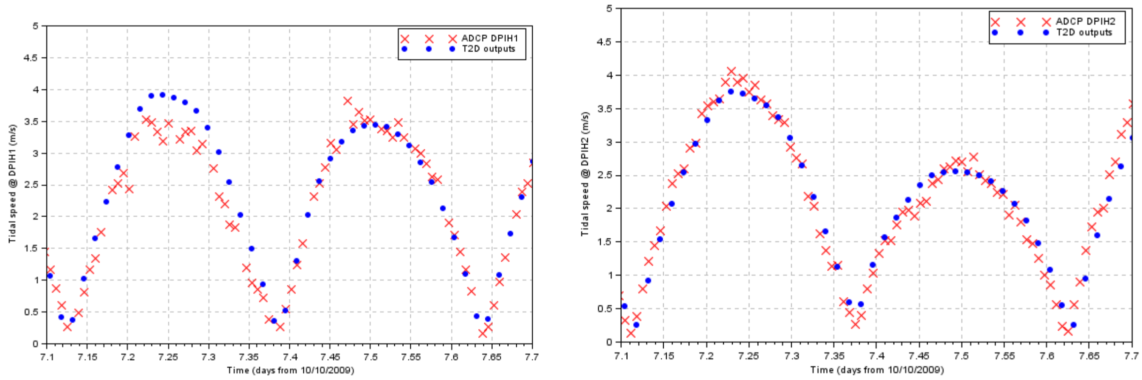

Figure 45: Depth-averaged tidal current speed (m/s) from model outputs (blue dots) and ADCP measurements (red crosses) during a mean spring tide at ADCP1 (left panel) and ADCP2 (right panel) locations, time is given in days from 10/10/2009.

8 APPENDIX A3 – EXAMPLE OF TELEMAC-2D STEERING FILE

Only available to PerAWaT participants.