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Programme Area: Marine

Project: PerAWAT

Title: Regional Scale Plug-In Protocol

Abstract:

The purpose of WG3WP4 is to develop, validate and document an engineering tool that allows a rapid assessment of the energy yield potential of a tidal turbine array on non-specialist hardware. The specific objective of WG3WP4 D10 is to document the method by which TidalFarmer interfaces with regional scale numerical models. This report includes some background on the requirements for communicating with regional scale numerical models, a description of the interface protocol for communicating with the regional scale numerical modelling software Telemac and a description and discussion around the parameterisations of an array within regional scale numerical models.

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.

GL Garrad Hassan

ETI Marine Programme Project
PerAWaT MA1003
WG3WP4 D10 REGIONAL SCALE PLUG-IN PROTOCOL

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EXECUTIVE SUMMARY

The purpose of WG3WP4 is to develop, validate and document an engineering tool that allows a rapid assessment of the energy yield potential of a tidal turbine array on non-specialist hardware. The specific objective of WG3WP4 D10 is to document the method by which TidalFarmer interfaces with regional scale numerical models. This report includes some background on the requirements for communicating with regional scale numerical models, a description of the interface protocol for communicating with the regional scale numerical modelling software Telemac and a description and discussion around the parameterisations of an array within regional scale numerical models.

The specific acceptance criteria associated with this report is the definition of a communication protocol and this is covered in Section 3.1 of this report and the specific methodology for interfacing with Telemac is discussed in Section 3.2 and Section 4. Overall the PerAWaT project has produced two different methods by which to represent arrays of tidal devices within a regional scale model. WG3 WP6 D6 aims to assess the relative merits and limitations of each of the approaches. In the meantime, the selected approach uses the EDF Telemac code developments and the outputs of TidalFarmer to develop an array scale representation.

SUMMARY OF NOTATION

Turbine characteristics

D	Rotor diameter (m)

Abbreviations

2-d	two dimensions
3-d	three dimensions
ADCIRC	ADvanced CIRCulation model
CFD	Computational fluid dynamics
DHI	Danish Hydraulic Institute
GNU	A recursive acronym for “GNU's Not Unix!”
GPL	GNU General Public Licence
LGPL	GNU Lesser General Public License.
RANS	Reynolds Averaged Navier Stokes
ROMS	Regional Ocean Model System
SW	Shallow Water

A general glossary on tidal energy terms was provided as part of WG0 D2 – “Glossary of PerAWaT terms”. This is a working document which will be revised as the project progresses.

1 INTRODUCTION

1.1 Scope of this document

This document constitutes the fourth deliverable (D4) of working group 3, work package 4 (WG3WP4) of the PerAWaT (Performance Assessment of Wave and Tidal Arrays) project funded by the Energy Technologies Institute (ETI). GL Garrad Hassan (GH) is the sole contributor to this work package. This document describes the theory behind and the method of implementation of the mathematical models used to evaluate the flow field in the proposed location of a tidal stream turbine or array of tidal stream turbines.

1.2 Purpose of this document

The purpose of WG3WP4 is to develop, validate and document an engineering tool that allows a rapid assessment of the energy yield potential of a tidal turbine array on non-specialist hardware. The specific objective of WG3WP4 D10 is to document the method by which TidalFarmer interfaces with regional scale numerical models.

1.3 Specific tasks associated with WG3 WP4 D4

WG3WP4 D10 comprises the following aspects:

- Some background texts contextualising the requirements for communicating with regional scale numerical models
- A description of the method by which TidalFarmer interfaces with regional scale numerical models
- A description and discussion upon the selection and us of array parameterisations within regional scale numerical models and the linkage to TidalFarmer.

1.4 WG3 WP4 D4 acceptance criteria

The following table repeats the acceptance criteria for the D10: Regional scale plug-in protocol report deliverable, as stated in Schedule 7 of the PerAWaT technology contract, and describes how they have been achieved.

Acceptance criteria	Location in report
Regional scale plug-in software built in with multiple communication platform so capable of communicating with Telemac, ROMS, etc (portability).	Section 3.1 of Interfacing with regional scale numerical models: Communicating with regional scale numerical model results.
Report describes the methodology for interfacing with telemac/ROMS software.	Section 3.1 of Interfacing with regional scale numerical models: 3.2 Protocol for interfacing with Telemac. And Section 4 – Parameterisation within a regional scale numerical model

2 BACKGROUND

Better understanding the complexities surrounding the modelling of tidal turbine energy extraction is a fundamental objective of the PerAWaT project. From the outset it has been known that it is simply not possible to model the details of a tidal turbine blade within a regional scale model of a realistic tidal flow. Hence the focus of PerAWaT has been to develop parameterisations of the hydrodynamic performance and operation of devices at different physical scales, namely device, array and regional (or coastal basin) scale. Understanding the limitations of the modelling and how one can interact with another is essential for an accurate energy yield prediction. The following text summaries some of the benefits and limitations of the various modelling methods.

2.1 CFD models - RANS (Reynolds Averaged Navier Stokes) solvers

Within PerAWaT there have been several studies using commercial or open source RANS solvers. Whilst these codes offer the most complete solver i.e. incorporating the more physics in to the fundamental equations, it is simply not possible to run simulations on a required regional flow scale. RANS solvers could be used for specific site analysis of the flow field (either for a single tidal cycle or at a set mean flow speeds), but care must be taken to properly model the highly turbulent flows. Representation of the device within the solver is possible via a number of approaches: blade resolved model (as per WG3WP1), embedded BEM (as per WG3WP1) or actuator disc (as per WG3WP2D5a). The first two approaches should yield accurate predictions of mean power performance of a device. The third is used for wake modelling purposes only and should be developed from understanding the device performance. In principle all three methods can be used to get predictions of the turbine wake and its recovery. However, by its nature RANS solvers use a parameterisation of the Reynolds Stresses to predict the behaviour of the mixing process and hence requires model tuning. The embedded actuator disc approach has been used for modelling arrays of wind turbines, however, the computational effort is vast and requires expert set-up. For this reason GH believes that at the array design stage (rather than verification) a quicker solver is required and hence has adopted to decouple the solution of the flow field from the wake mixing problem. In addition, by rationalising the formulation of the RANS equations the computational time is much reduced and also reduces the output sensitivity to user set-up.

2.2 Regional scale numerical models - Shallow water solvers

Regional scale numerical models further rationalise the RANS equations by depth averaging the vertical flow. This yields a set of equations known as the Shallow water equations. The base assumption behind the shallow water equations is that the flow geometry of the fluid layer is thin and that the sea surface is modelled using a free-surface which can be deformed [Salmon 1998, Gill 1982]. Once the equations are depth-integrated the model considers any variation in the vertical in the depth-averaged sense. However, the accurate representation of the operation and wake flow of a device cannot be depth-averaged as this does not capture the wake flow or the flow onto the rotor plane accurately. These models are typically compared to tidal height and flow current data to calibrate and validate against as discussed in Draper *et al*, (2013). One of the first limitations of these models is that the flow speeds are not necessarily accurately reproduced, [WG3 WP3 D5].

Developed to model 2-d regional scale dynamics of tidal and estuarine flows, shallow water solvers offer an advantage over full 3-d CFD codes in terms of a tailored application of loading and managing boundary conditions as well as the obvious computational saving by only modelling the depth-averaged flow. There have been several studies on how to represent tidal stream devices in shallow water models. These include models where drag is smeared over an area, to the embedding of an energy yield model based on actuator disc theory to understand the potential energy for extraction. The primary failing of the shallow water models is the inability to capture wake recovery due to resolution and assumptions of the models. This often means that downstream, the inflow to further arrays will be poorly predicted.

Hence although shallow water solvers offer an effective solution to the flow field, they have limitations in representing turbine scale energy extraction and wake mixing which mean that a project specific energy yield assessment is problematic. There are several possible approaches for this parameterisation and they are discussed in Section 4.

2.3 TidalFarmer – linking RANS and Shallow water solvers

GH's involvement in the PerAWaT project has been the development of tidal energy extraction method that can calculate energy yield with a quantifiable level of certainty for an array of tidal stream devices. The TidalFarmer method adopts a rationalised modelling approach where various modelling methods, including the development of a three-dimensional flow field, change in device performance due to blockage and the wake recovery downstream of operational devices are coupled together. This allows an engineering solution to be evaluated very quickly and enable the software user to rapidly assess the impact of design changes to an array of tidal turbines. In addition simplified modelling techniques are better understood and can be quantified Goldstein *et al* (2013).

A key input to the energy extraction analysis is the resource or flow field prediction. This provides information of how the flow varies spatially across a site. As explained in WG3WP4D5, there are numerous flow field modelling packages are available, from open-source code to commercial packages. With a wide variety of modelling options available, there is little merit in GH developing its own in-house spatial flow field model. So instead TidalFarmer interfaces with a suitable shallow water or CFD solver.

As outlined in Section 2.1 and detailed in WG3WP4D3&D4, the wake modelling in TidalFarmer uses a simplified form of the RANS equations and a solution is sought only after the wake has become self-similar (i.e. beyond the highly complex flow region just behind the rotor). Test data obtained through the PerAWaT project corroborates that the wake become self-similar at around 2D downstream. The theory surrounding this implies that the momentum, at the point at which the wake becomes self-preserving becomes conserved (Tennekes & Lumley, page 111). Again, from studies undertaken within the PerAWaT project it appears that the flow is self-similar such that once the wake develops it conserves momentum. Therefore, if we can predict the momentum extracted by each rotor in TidalFarmer, it is then possible to obtain an upper bound for this quantity and inform a shallow water model to analyse the global scale impacts of the array's energy extraction.

In subcritical flows information propagates both upstream and downstream, Patterson (1983). A basic example is a free-surface flow over a small bump which can be solved analytically. In the super-critical flow regime, where the Froude number is greater than unity, information propagates solely downstream such that the free-surface has no time to react to the upcoming bump and an increase in surface elevation is observed. If the Froude number is smaller than unity the flow has prior knowledge of the obstacle due to the upstream propagation of information. Hence all structures that present an obstacle to an oncoming subcritical flow radiate an upstream pressure field such that the flow foresees the obstacle causing the flow to alter it path. If an array of tidal energy devices causes too greater impedance upon the flow and local regional scale topography is such that the flow could divert elsewhere, then a "global blockage affect" may act to diverted the kinetic energy flux away from the array limiting the amount of energy that is extractable from a site. For densely packed arrays the global blockage effect is readily observed, such as in the regional (coastal basin) scale experiments in WG4WP4.

As reported in Garrett & Cummins (2005), and Draper et al (2013), extracting large amounts of the energy across a channel via a tidal fence or a highly blockage row of devices, causes a significant wake and bypass flow alterations. However, tidal fences look to exploit the driving head of the tide via large scale blockage and in such cases careful analysis of the global blockage effect is required. Horizontal axis turbines look to avoid the large scale impact and cost (of the structure) that barrages and fences have. For this reason as well as the practical issues around device installation (as outlined in WG3WP4D6) the packing density and hence global blockage affects maybe limited. Nevertheless the shallow nature of tidal channels means that the flow blockage is higher than for wind farms as the presence of bounding surfaces (i.e. the seabed and free surface) disturbs the natural expansion of the streamtube that bounds the rotor and can act to enhance individual device performance (but note the device loadings also increase). Forcing more flow through the rotor can only be achieved if there is sufficient upstream head and thus as the number of individual turbines increases, there will become a point when the required driving head is insufficient to force the flow through the array and it diverts elsewhere. For arrays where the local blockage ratio is high (although the absolute value with be site specific a general rule of thumb is where the lateral spacing is less than 2D centre to centre) there will need to be a mechanism by which to assess the point at which additional devices actually extract too much head from the flow causing flow diversion and essentially offering diminishing returns to the project.

In addition to the global upstream effect, modelling of recovery of the downstream array wake will be of interest from the perspective of environmental constraints and surrounding projects. In a similar way to assessing the global impact, intra array modelling is not directly required provide the overall array affect is captured and then represented within a regional scale numerical model.

In summary, TidalFarmer’s focus is on modelling the energy extraction at array scale. To do this in a practical manner regional scale flow field modelling is decoupled from the intra array wake modelling. This has two key limitations which need to be address via a loose coupled modelling methodology.

Firstly, in order to deal with the issue of upstream global blockage a suitable array energy extraction parameterisation within a regional scale numerical model is required. Such a method would allow the regional scale modelling to assess the potential impact of the array upon the global flow. If the global flow near the array is significantly affected then two causes of action are available. Firstly the total energy extraction is reduced until the upstream impact is minimised. Alternatively the altered flow field could then be fed into the array scale modelling. With this approach there will be an iteration in modelling until the optimum energy extraction is found. Section 4 of this document further examines the method by which array energy extraction can be represented within a regional scale model.

The second impact of not modelling the flow field directly within the waking modelling solver is the impact wake mixing has on the local flow field. It has been shown in WG3WP4D3 that the impact of energy extraction on the free surface elevation is small, however, there may be local affects due to additional shear in the flow. The blockage modelling with the TidalFarmer code looks to predict changes in local flow field that may occur due to local blockage (as outlined in WG3WP4D1).

3 INTERFACING WITH REGIONAL SCALE NUMERICAL MODELS

In directly addressing the acceptance criteria for this report, the following section outlines the method by which TidalFarmer can communicate with multiple shallow water software packages.

3.1 Communicating with regional scale numerical model results

All the models reported here were discussed in WG3 WP4 D5 and therefore the reader is directed towards this report for further details. The following discussion relates to how files, generated using external flow modelling software tools, can be opened and read by the base module of the TidalFarmer tool. TidalFarmer requires a spatial flow field of the site within which the tidal devices are to be located. The resolution of the flow modelling results will vary both in time and space and hence TidalFarmer needs to have a robust pre-processing method for converting the time series or static data into the TidalFarmer modelling domain. The approach can vary depending on the flow modelling software. The specific interface for a number of the leading regional scale numerical modelling software packages are detailed below. In lieu of a bespoke interface and support software, then a standard format is used. This format allows for any number of time steps and the use of an unstructured grid.

This adopted approach was verified during the tool beta testing in (WG3WP4 D7). Although there were several coding issues (i.e. bugs), the method was proven. The identified issues have since been addressed and resolved.

The following text further describes some of the leading regional scale numerical modelling shallow water solvers and details their interface options:

3.1.1 Telemac

Telemac is an open-source code[1] and available for download[2]. Telemac is an integrated suite of solvers and has been developed as part of a consortium of organisations including HR Wallingford and EDF. The validity of the models for practical problems in free-surface flow has been demonstrated.

Our primary interest concerns the telemac 2-d and 3-d modules although there are various libraries that can be coupled with the base hydrodynamic solvers

The format of the output file for Telemac simulations is a serafin file (*.slf). This is a binary file, the form of which is documented in the appendix of the user manual that can be found on the open telemac website (Telemac, 2013). A selafin file can output information concerning the depth-averaged current velocity, free-surface height as well as the bottom friction and bathymetry at each mesh node.

The matlab file exchange contains pre-written code (*.m scripts) in order to perform computations or complete tasks. One series of files that can be downloaded are the Telemac tools. This set of files includes an example selafin output file from a Telemac simulation along with code that can be used to read these binary files[3]. Telemac tools can be found at the following web address

[1] See http://www.telemacsystem.com/images/licence/Licence_Telemac.pdf

[2] See http://www.opentelemac.org/

[3] These scripts should only be incorporated at the users risk and the author is absolved of any responsibility for any issues that arise from the use of these scripts.

http://www.mathworks.co.uk/matlabcentral/fileexchange/25021-telemac-tools

Using this suite of tools TidalFarmer can read in both Telemac2d and Telemac3d model results. This makes it possible to exchange information between Telemac and TidalFarmer.

3.1.2 DHI Mike

The Mike 21 & Mike 3 software have been developed by the DHI (Danish Hydraulic Institute[4]). This software has been widely used within the sector, due to its advanced and easy to use user interface. It is therefore important that TidalFarmer can read in files outputted form these simulations.

DFSU files that have been outputted from a simulation can be exported to .xyz files. These files, contain the variable, time and date of the simulation output in the file name along with positional and magnitude of the associated variable. At present, TidalFarmer can read in *.xyz files in order to run a resource analysis or energy yield assessment. The reading in of data was proven as part of the beta testing that took place at the end of 2011 and finished in April 2012.

3.1.3 ADCIRC

The Advanced CIRCulation model (ADCIRC)[5] is an open-source code that can be used to undertake tidal flow simulations. This model was discussed in the WG3 WP4 D4 report and has been used extensively as part of the PerAWaT project to report on the large scale hydrodynamic effect of energy extraction. Therefore, it is important that we can communicate with this software in order to be able to obtain energy yield in TidalFarmer.

In order to read output files from an ADCIRC simulation the grid and boundary information file must be read (fort.14 file) and then to obtain information about the flow field the fort.63 contains information concerning the elevation time series at all nodes and fort.64 gives the depth-averaged velocity time series at all nodes. It is reported on the website how these text files can be read.

3.1.4 ROMS

The Regional Ocean Modelling System[6] solves the primitive equations in order to simulate free-surface flow. The output format of these files can be in *.mat file format. This is a binary file that can be opened, either using MATLAB specific routines or using available documentation to read the format. Therefore, if necessary, the reading of ROMS output files could easily be achieved.

3.2 Protocol for interfacing with Telemac

The secondary aim of this report was to establish a protocol for interfacing with an existing shallow water solver. Telemac has been selected as the shallow water solver to develop a dynamic interface with. The primary reasons for selecting Telemac are: the heritage of the solver; the open source nature of the code; and, the application within the sector, both in terms of EDF's use of Telemac in PerAWaT (WG3WP3D1) and in the TRM modelling project Bourban *et al*. (2012).

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[4] See http://www.mikebydhi.com/Products/CoastAndSea.aspx

[5] See http://adcirc.org/

[6] See www.myroms.org

Within WG3WP3 EDF has developed a method to model tidal turbine energy extraction within the Telemac software and this method has been tested and validated against both single device and array-scale test data. Within the RANS shallow water equations a drag term has been included in the conservation of momentum equation to represent an object which impedes the flow. In the Telemac source code there is a subroutine, called DRAGFO.F that can be altered such that bridge piers or piles can be represented in a shallow water model. A text file with the number of devices and the device coordinates can be read into the subroutine and the drag for these devices is automatically generated.

Currently TidalFarmer is able to supply input files, such as device positions and drag values derived from the thrust coefficients of the array, for the Telemac subroutine DRAGFO.f to read. This file has been developed by EDF to model pier structures and has been recently developed by EDF to model tidal arrays.

In addition to the current interfacing method, further modifications are proposed. This would enable the Telemac code to be compiled as a stand-alone executable. All communication between TidalFarmer and Telemac would be done via data saved standard open file formats, with the Telemac executable triggered from within TidalFarmer via a command line statement.

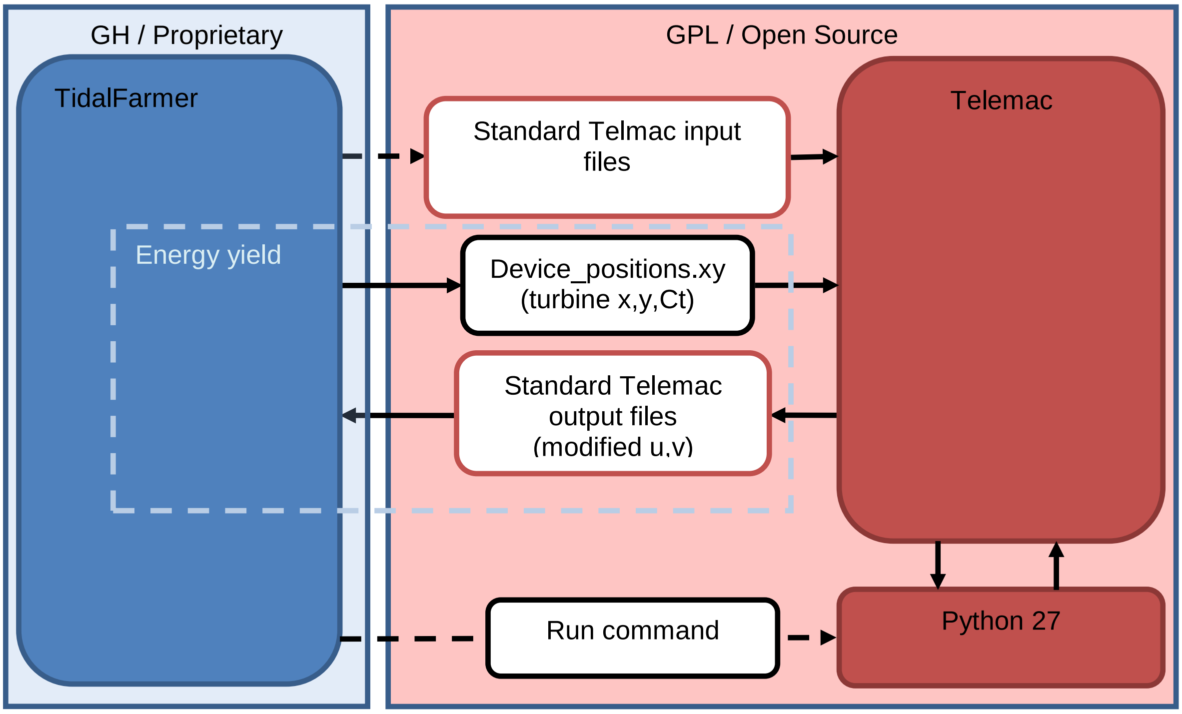

Figure 3-1 Interfacing with Telemac

The TELEMAC suite of software is owned and was created by EDF R&D. It is now open source and covered mostly by a "GPL" license (GNU General Public License), with one central component covered by a less restrictive "LGPL" license (GNU Lesser General Public License).

In compliance with the license, any modifications to the Telemac source code should be made available publically available.

Telemac and TidalFarmer would remain separate programmes and would be described as such in the TidalFarmer user interface and documentation. Telemac would constitute only one plug-in option and TidalFarmer could function without Telemac entirely. Furthermore, a third party could prepare and analyse inputs / outputs to the modified Telemac code independently. The two programmes would be distributed as an “aggregate” on the installation CD / download site.

4 PARAMETERISATION WITHIN A REGIONAL SCALE NUMERICAL MODELS

The fundamental purpose of a parameterisation of tidal energy devices within a regional scale hydrodynamic model is to represent the energy extraction of the array of turbines in order to evaluate the total energy extraction potential and impact the array has on the flow. A range of methodologies are discussed below, all of which have been compared/validated against experimental measurements. They start with the most highly resolved representation of a turbine and subsequently exchange resolution for a broader representation of the overall array.

- **Semi-empirical (Roc *et al*, 2013)**: A velocity deficit is created via a momentum sink approach which is derived from actuator disc theory with empirical corrections. It uses the reference flow speed at the turbine location, but applies the momentum deficit 2D downstream where the far wake begins

- **Applied drag force per turbine (EDF WG3WP3)**: An applied drag force term is derived for each turbine within the array. The force is then applied over an area (determined by empirical observations) within the momentum equations. The velocity used to evaluate the drag force is a local velocity.

- **Induction factor (Stansby, 1996)**: In a similar way to the applied drag force method above, each turbine is represented by a drag term, however, the reference velocity used is an upstream reference flow speed which is linked to the applied force via the induction factor which is defined in actuator disc theory. The force is applied over a mesh via an addition to the seabed roughness coefficient.

- **Linear momentum actuator disc theory (Draper *et al*, 2008, UoO WG3WP6)**: Using a general form of actuator disc theory and incorporating local blockage and wake recovery, local conditions are used to predict the head drop across a row of devices. A momentum sink is then used to apply the head drop (applied force).

- **Applied drag force per array (EDF WG3WP3)**: In the case of a large area EDF have developed a method by which the an applied drag force term is smeared over the total array area in order to invesgiate the overall effect of the array upon the global flow field.

4.1 Semi-empirical

The most evolved method for representing a turbine within a flow solver is the use of an empirically corrected actuator disc model and Roc *et al*, (2013) adopted this method for use in the open source regional scale shallow water code ROMS. An empirically adjusted actuator disc model is used to predict a magnitude and shape of the sink of momentum and, in addition, an added turbulence source term is placed in the turbulent kinetic energy transport equation in order to better represent the single turbine wake mixing recovery in the far wake.

This method has the most refined representation of a turbine wake, however, in order to capture the wake mixing, the coastal basin scale turbulence closure parameterisation was de-tuned, resulting is a less effective regional scale modelling solver.

4.2 Applied drag force per turbine (EDF WG3WP3)

As part of WG3WP3, EDF has explored representing individual turbines as point drag forces. This is realised by the use of a per turbine drag coefficient. The corresponding drag force is evaluated using the reference velocity (in WG3 WP3 D2 it is stated that the 2D upstream reference velocity could not be used and thus the local velocity - at the point of force application was is used) and a turbine thrust coefficient (Ct) and is applied over a seabed area of roughly the length of 4D and 2D wide. At present the value for the drag coefficient is fixed at 3*Ct in order to match the wake characteristics observed in the UoM experiments (WG4WP2). Even then the flow will often only match well with the results when the wake transitions from an axisymmetric wake to a shallow-water wake i.e. vertically mixed with the wake solely in the horizontal and hence 2-d in nature. This is typically quite far downstream (~12D) which means that the inflow to a second row of turbines might not be correctly predicted. To better model the wake mixing some additional terms can be introduced into the kepsil.f subroutines in the source code for telemac2d. If using the k-epsilon closure model then additional terms can be incorporated to represent the increase in turbulence kinetic energy production due to the operation of multiple devices. These terms are reported in WG3 WP3 D2. Also reported in WG3 WP3 D2 is the development of the SOURCE sub-routine which can be used in Telemac-3D to represent turbines in a similar manner to the DRAGFO sub-routine.

For large arrays the drag force per turbine approach can be computationally demanding as it requires a mesh with sufficient resolution around the device locations. For the simulation to represent individual devices a mesh resolution of D/4 is required and for large arrays this requires a very large number of mesh points.

Generally speaking discontinuities in flow field variables can cause numerical methods to fail. In the case of shallow fluid flow, representing devices individually means that large velocity gradients between each device can occur in close proximity resulting in numerical stability issues and EDF reported such issues in WG3WP3D3 when modelling the devices is this matter. This is discussed by UoO in WG3WP6D1.

4.3 Induction factor

Even before the interest in tidal energy extraction, studies have been undertaken to understand the effect of structures, such as piles, on the flow. In Stansby *et al* (1996) groups of submerged piles were modelled in a series of experiments. The results were compared to a CFD solution of the RANS equations where drag terms was used to represent the pile group. The study showed that the code was able to model the interaction of the structures with the global flow field.

Understanding that the structures have an effect of the flow approaching the structure, Stansby used Actuator disc theory Betz (1920) to include an induction factor to predict the applied force. Once the drag force is estimated, it is converted to an added roughness term and then applied through the seabed friction applied force term smeared over several cells local to the structure's location.

At present this method assumes a fixed induction factor and as such is only applicable to certain turbine operating states. It also does not correct for the effect of flow blockage. The advantage of this approach is that the inclusion of drag terms in a flow solver is relatively straightforward and, as demonstrated by Stansby *et al* (1996) can lead to a good representation for array of submerged structures.

4.4 Linear momentum actuator disc theory (Draper *et al* 2008, UoO WG3WP6)

This method is described fully in WG3WP6. In essence, a generalised 1-d linear momentum actuator disc theory is used to predict the performance of a row of devices and the impact on the downstream flow. This LMADT model is embedded within the ADCIRC shallow water solver and is applied via a momentum sink.

The LMADT model incorporates the blockage effect for an infinite row of turbines and for free-surface flows can be used to predict a head drop across the system. As well as providing an analysis of the wake and bypass flow, estimates of the power lost during the wake merging process downstream of the array is also provided. Within ADCIRC the application of the LMADT the local grid water depth and flow speed are used to inform the calculation of the head drop along with an assumption about the turbine wake flow (which is informed via the turbine thrust coefficient). The shallow water solver model represents energy extraction as a momentum sink discontinuity. The discontinuous Galerkin version of ADCIRC is used to enable appropriate handling of the discontinuous jump in the height of the free-surface

The advantage of using this method is that a distinction is made between the power available to the row of turbines (or fence) and the power extracted by the fence. The theoretical model captures the physics of energy extraction and can be used to describe the changes in the free-surface elevation and therefore the impact on the resource. In particular the parameter for the turbine wake flow (alpha) can be related to a thrust curve such that the changes in energy extraction can be modelled. The major disadvantage with adopting such an approach is that only the upstream effects and forces on the emulator are captured as reported in Draper *et al*, (2013) the wake flow is not well reproduced and this will have an impact on the power production results for downstream rows. In addition, this model only works for arrays of tidal energy converters where devices are arranged in tightly packed (~<1D lateral spacing) rows.

4.5 Applied drag force per array (EDF WG3WP3)

Instead of modelling the devices individually, EDF investigated applying a drag force over the total area covered by the array instead of at each turbine location. In this scenario, the global/box drag term is informed via empirical formula developed by tuning simulations at devices scale to match the UoM experiments (WG4WP2). The global drag coefficient is related to a reference flow speed which is specified as a “representative flow speeds in that location” and can be derived from the mean flow speed of the site. The size of the bounding box is dictated by the scaling parameters found in the WG3 WP3 D2.

Within WG3 WP3 D3 EDF report a detailed investigation to arrive at a number of key tuning parameters. The main benefit of this approach is that the need for a highly resolved mesh is removed. The main drawback is in the selection of the reference flow speed.

4.6 Summary of approaches

The table below summaries the parameterisations discussed in the above sections.

Table 4-1 Summary of array parameterisations with a regional scale numerical model

Author	SW solver	Turbine or Array	Turbine/Array model	Reference conditions	Area of application	Grid resolution	Wake mixing
Roc	ROMS 2.5-d	Per turbine	Inflow U gives semi-empirical momentum deficit (from wind)	Local grid point (at turbine) U	A grid point 2D downstream	High resolution in wake (0.5D)	Additional terms are included in the second order turbulence closure terms and there are applied at grid cells near to the device rotor plane.
EDF	Telemac2-d &3-d	Per turbine	Thrust force from Ct	Local U	Area ~ 4D long and 2D wide.	Highly refined in around turbine and in wake (<1D)	Mixing model tuned to improve wake recovery modelling
Stansby	Stansby code - SW RANS	Per turbine or array representation	Static actuator disc i.e. assume constant induction factor	Local U	Over multiple grid cells ~ $4D^2$	same as for regional scale	Via mixing model of 2-d flow (regional scale)
Draper	Oxtides & ADCIRC 2-d (Dis-continuous)	Array (row of turbines)	LMADT to give head drop which is realised as momentum deficit.	Local grid point Fr (U and H)	Line of grid points along row	Same as for regional scale	Turbine scale mixing accounted for within LMADT i.e. mixing sub grid. Subsequent mixing via SW mixing model.
EDF	Telemac2-d	Per array	Drag force empirically derived	"Representative" flow speed	Over array area	As per regional scale modeling	None

4.7 TidalFarmer approach

Section 3.2 outlines a process by which TidalFarmer and Telemac can exchange information about the flow field and any changes which might be expected due to the presence of the array.

As indicated by EDF the computational complexity to run numerous simulations of multiple turbines at a turbine scale grid resolution is onerous. Hence the approach to use a single array parameter to represent the global energy extraction seems a more practical solution. At present the preferred method is to relate the overall momentum defect within the array to a drag value for the array in a shallow water model.

Given the assumptions of self-similarity, the momentum deficit for the flow is constant with respect to downstream distance [Tennekes 1972]. Therefore, we can calculate the momentum extraction by the array using TidalFarmer. It is already possible to use TidalFarmer to predict the total energy extraction by the turbines as well as using the intra 3-d wake modelling to produce more accurate prediction of the total momentum deficit within the array. These outputs can then be used to inform the a look-up table of drag coefficients in the DRAGFO routine as per the EDF drag force per array methodology or similarly in another shallow water code (they have been applied to represent an array within the Stansby code). An iteration is required to check that the impact of the array on the global field isn't such that the flow into the array is altered. If it is altered, this new flow field would then be feed into TidalFarmer.

The focus of WG3WP6 D6 is to compare the drag and LMADT approaches. At the time of writing this work is still on going. However, it is proposed that the propose that the LMADT should also be implement within in the Telemac source code. This has already been considered and will require development of the prosou.f subroutine as discussed in Bourban *et al* (2012). The code modifications have already been implemented to represent the drop in height for a tidal range scheme and so this should be readily translated to the approach adopted in this report.

5 SUMMARY

It is not possible to fully represent a tidal turbine within a regional scale model of a realistic tidal flow and hence the focus of the TidalFarmer software is to develop a suitable parameterisation of the hydrodynamic performance and operation of an array of devices for regional scale numerical modelling. TidalFarmer is an array-scale tool that can predict the energy yield given a flow field input. Decoupling the flow field solver and the intra array wake solver enables a fast (and hence practical) computation of the energy yield for a chosen layout. However, a suitable interface with a regional scale model is required. To address this point TidalFarmer has been developed to allow a common interface with the majority of leading regional scale numerical modelling software packages and has specifically created a link with EDF Telemac software.

This report outlines a number of strategies that could be used for the representation of tidal devices within a regional scale numerical model, all of which have been compared against experimental measurement data. At this stage it is unclear which parameterisation best represents both the upstream and downstream effects of an array of devices. Experiments performed in WG4 WP4 D3 and reported in the Draper *et al* (2013) suggests that the LMADT theory predict the correct upstream effects and is also able to account for some of the downstream wake mixing. It also avoids the necessity of having to use an upstream reference velocity. However, there are draw backs to using depth integrated models to capture the intra-array wake mixing and hence GH propose to avoid this step by simply replacing the whole array with a parameterisation. In this case it would involve modelling the total momentum extraction via a head drop across the array.

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