Programme Area: Marine

Project: PerAWAT

Title: GH Inter-Array Scale Modelling Report

Abstract:

This document outlines the issues associated with array scale modelling within an energy yield analysis and array layout optimisation. The aim of the array scale modelling in the context of an energy yield assessment is to both evaluate the energy yield for each individual device within the array, and to predict the changes in the inter-array flow field due to the energy extraction process. A summary is provided of the standard guidelines for performance assessment of tidal energy devices and tidal energy resource assessments that have been written in recent years. This is followed by a review of existing methods for modelling an array of tidal turbines for the evaluation of energy yield. The GH array scale modelling approach is described and explained. This report provides an overview of the approach adopted by TidalFarmer for energy yield assessment, and a discussion of how the array scale models are implemented within the software.

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.

ETI MARINE PROGRAMME PROJECT
PERAWAT MA1003
WG3WP4 D6 GH INTER-ARRAY SCALE MODELLING REPORT

Client	Energy Technologies Institute
Contact	Geraldine Newton-Cross
Document No	104329/BR/06
Issue	2.0
Classification	Not to be disclosed other than in line with the terms of the Technology Contract
Date	3rd March 2011

Author:	M D Thomson/D McCowen
Checked by:	L Gill
Approved by:	R I Rawlinson-Smith

Garrad Hassan & Partners Ltd

St Vincent's Works, Silverthorne Lane, Bristol BS2 0QD, UK Tel: +44 (0)117 972 9900, Registered in England 1878456

IMPORTANT NOTICE AND DISCLAIMER

1. This report ("Report") is prepared and issued by Garrad Hassan & Partners Ltd ("GH" or "Garrad Hassan") for the sole use of the client named on its title page (the "Client") on whose instructions it has been prepared, and who has entered into a written agreement directly with Garrad Hassan. Garrad Hassan's liability to the Client is set out in that agreement. Garrad Hassan shall have no liability to third parties (being persons other than the Client) in connection with this Report or for any use whatsoever by third parties of this Report unless the subject of a written agreement between Garrad Hassan and such third party. The Report may only be reproduced and circulated in accordance with the Document Classification and associated conditions stipulated or referred to in this Report and/or in Garrad Hassan's written agreement with the Client. No part of this Report may be disclosed in any public offering memorandum, prospectus or stock exchange listing, circular or announcement without the express written consent of Garrad Hassan. A Document Classification permitting the Client to redistribute this Report shall not thereby imply that Garrad Hassan has any liability to any recipient other than the Client.
2. This report has been produced from information relating to dates and periods referred to in this report. The report does not imply that any information is not subject to change.

KEY TO DOCUMENT CLASSIFICATION

Strictly Confidential	:	For disclosure only to named individuals within the Client's organisation.
Private and Confidential	:	For disclosure only to individuals directly concerned with the subject matter of the Report within the Client's organisation.
Commercial in Confidence	:	Not to be disclosed outside the Client's organisation
GH only	:	Not to be disclosed to non GH staff
Client's Discretion	:	Distribution for information only at the discretion of the Client (subject to the above Important Notice and Disclaimer).
Published	:	Available for information only to the general public (subject to the above Important Notice and Disclaimer and Disclaimer).

REVISION HISTORY

Issue	Issue date	Summary
1.0	07/01/11	Original issue (electronic version only)
2.0	03/03/11	Second release, revised according to ETI feedback (electronic copy only)

CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This document outlines the issues associated with array scale modelling within an energy yield analysis and array layout optimisation. The aim of the array scale modelling in the context of an energy yield assessment is to both evaluate the energy yield for each individual device within the array, and to predict the changes in the inter-array flow field due to the energy extraction process.

A summary is provided of the standard guidelines for performance assessment of tidal energy devices and tidal energy resource assessments that have been written in recent years. This is followed by a review of existing methods for modelling an array of tidal turbines for the evaluation of energy yield.

The GH array scale modelling approach is described and explained. The GH array scale modelling approach incorporates many different aspects: the use of a rationalised flow field model to represent the tidal flow as a series of flow maps and a long term flow occurrence distribution; the use of an assimilation method to correct the numerical spatial flow model using site data, yielding 3-d array flow speed and turbulence intensity fields for each flow state; and the use of a perturbation method to allow the array influenced flow modelling to be imposed upon the tidal spatial flow model. This allows an efficient wake modelling approach, coupling a rationalised eddy viscosity model with wake interaction models.

This report provides an overview of the approach adopted by TidalFarmer for energy yield assessment, and a discussion of how the array scale models are implemented within the software. The next step for this work package is the issue of the Beta version of the TidalFarmer code (WG3WP4 D7).

SUMMARY OF NOTATION

P	Power
D	Rotor diameter
D_w	Area-averaged velocity deficit
A	Area
hh	Hub height
$\underline{u}$	Downstream velocity field
U(z)	Free stream axial flow speed (varying with depth)
U_i	Uniform upstream velocity
TI	Ambient turbulence intensity
Fx	Axial thrust upon rotor
x_H	Length of the near wake
$\mathbf{u}(x,y,z)$.	Velocity field
S	Sequence identifier

Indices

x	reference measurement point
s	representative flow state speed-up/slow down map.
i	device index
j	flow speed index
k	flow direction index
g	device grouping index
t	order of analysis per device grouping

Cartesian Co-ordinate systems

x	Axial co-ordinate
y	Transverse co-ordinate
z	Vertical co-ordinate
s	streamline co-ordinate

Abbreviations

1-d	one dimension (typically in the x-direction)
2-d	two dimensions
3-d	three dimensions
ADP	Acoustic Doppler Profiler
CFD	Computational fluid dynamics
RANS	Reynolds averaged Navier-Stokes

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 sixth deliverable (D6) 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). Garrad Hassan (GH) is the sole contributor to this work package. This document describes the theory behind and the method of implementation of the array scale modelling of a farm of tidal turbines and the interaction between devices for the purpose of energy yield and flow disturbance analysis.

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 WG3 WP4 D6 is to both document and provide a technical justification for the approach to array scale modelling adopted within the suite of models that make up the engineering tool 'TidalFarmer'.

1.3 Specific tasks associated with WG3 WP4 D6

WG3WP4 D6 comprises the following aspects:

- A definition of array modelling methodologies
- A description of the method of integration within the Tidal Farmer code.

1.4 WG3 WP4 D6 acceptance criteria

The acceptance criteria as stated in Schedule 5 of the PerAWaT technology contract are as follows:

D6: Overall inter-array[1] scale modelling report includes:

- A clear definition of resulting overall inter-array[1] scale modelling methodologies and model integration approach.
- Analysis covers both rationalised flow field and far wake models.

---

[1] The term inter-array scale modelling was used in the contract documentation to highlight that the focus of the modelling is within the array and not in the regions beyond the array. However, within this document the term "array scale" is synonymous with inter-array scale.

2 BACKGROUND AND THEORY

The purpose of the TidalFarmer design tool is to provide the tidal stream energy industry with a comprehensive and definitive detailed assessment of the potential energy capture of tidal arrays. The aim of the TidalFarmer software is to allow the user to design a tidal array to achieve the maximum energy production within the geometric and environmental constraints of the site. In order to obtain a prediction of energy yield for the tidal array under consideration, TidalFarmer requires as an input some form of description of the tidal energy device to be placed within the array, the resource at the site in terms of a temporal and spatial flow field, and other site characteristics which may impact on device interactions.

The figure below illustrates the inputs and outputs of the TidalFarmer tool at the three scales at which it operates, namely coastal basin, array and device scales. This figure is also shown in Section 5.2.

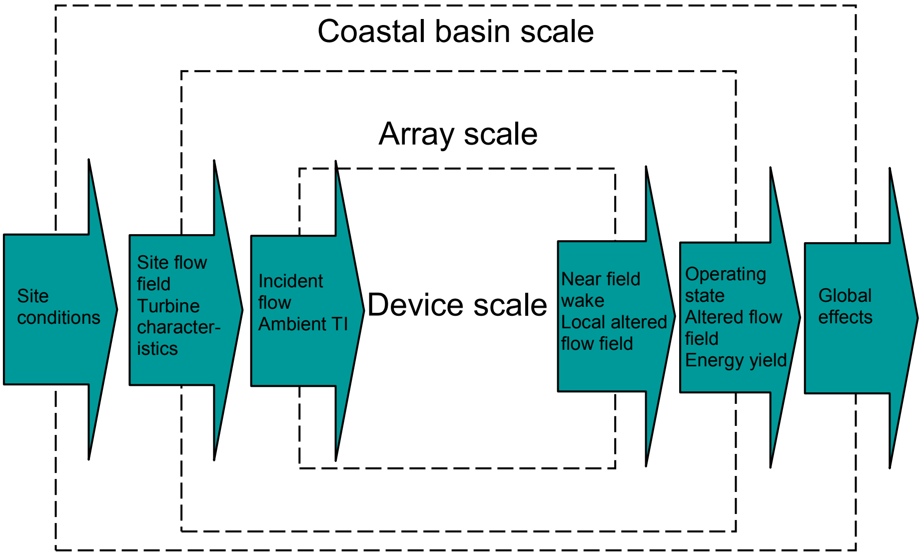

Figure 2-1: Hierarchy of modelling domains and scales

This section introduces the factors which affect array performance and which must therefore be considered when undertaking an energy yield analysis.

2.1 Tidal models

The driving force behind tidal flows is due to differential gravitational forces which are periodic in nature. Harmonic analysis for the prediction of tidal elevation and currents is a well established science, as described by Boon (2007). It assumes that tidal motion can be represented by the sum of a series of simple harmonic terms (tidal constituents) with each term being represented by an oscillation at a known frequency of astronomical origin. This phenomenon enables the prediction of the astronomically-driven part of tidal flow variations into the future. Typically astronomical effects are the main contribution to the time-varying aspect of tidal stream flows, but local meteorological forcing is also possible as the local geography can induce site-specific effects. To assess the effect of local phenomena, meteorological or otherwise, requires the measurement of site data for a sufficient period of time to allow for a statically robust analysis.

At potential tidal stream energy sites where the flow is strongly advective, the local geography can also have a significant impact on the spatial variation across a site. Thus to characterise the flow conditions at a site, a description of both the temporal and spatial variation is required. As discussed in the Rationalised flow field modelling report (WG3WP4 D4), there are various numerical modelling methods that can be employed to evaluate the spatial variations at a site given time-varying boundary conditions.

For the purposes of an energy yield analysis the flow field needs to be represented to a reasonable resolution. This is because the relationship between flow speed and power output is typically cubic in the region below rated flow speed, and thus there is a need to ensure that the prediction of the incident flow speed is accurate to avoid the magnification of errors when calculating power output. Laterally, a minimum resolution of 0.5 – 2 rotor diameters is considered by GH to be the minimum required to sufficiently represent the flow conditions through the array. Vertically, a minimum resolution of 0.1 rotor diameters is considered sensible.

A resolution of 2 turbine diameters will provide a reasonable indication of the flow conditions across the array, however this assumes a linear gradient across the rotor swept area and thus may not be an accurate representation the flow conditions. 2 turbine diameters is therefore considered by GH to be the minimum acceptable resolution. A resolution of 0.5 turbine diameters is considered to be the ideal situation, providing greater resolution across the rotor to enable a more accurate calculation to be made of the current speeds, and hence the energy yield, across the rotor swept area.

The fine vertical resolution of 0.1 turbine diameters is considered to be of particular importance due to the presence of the wake. A reasonable vertical resolution is necessary due to the shear profile through the water column (although this can be approximated by a shear function where necessary), but a fine resolution is critical in order to accurately characterise the wake of the devices.

2.2 Interactions within an array of tidal turbines

The main factors which will affect the flow field within a farm of tidal stream turbine are:

- The ambient flow field across the site (both velocity and turbulence intensity)
- The operating state of each turbine
- The proximity to bounding surfaces such as the free-surface or seabed.
- The proximity to other devices (lateral and longitudinal)

A detailed discussion of the background and theory behind the development of a 3-d ambient spatial flow field for use in the energy yield analysis is presented in the Rationalised flow field modelling report (WG3WP4 D4). The impact of the operating state of a single device upon the energy yield analysis is described in the Device scale modelling report (WG3WP4 D3), and the Far wake modelling report (WG3WP4 D5) discusses the detail of the wake development through the array flow field. However, to provide the reader with a brief overview the flowing figure and text cover the salient aspects.

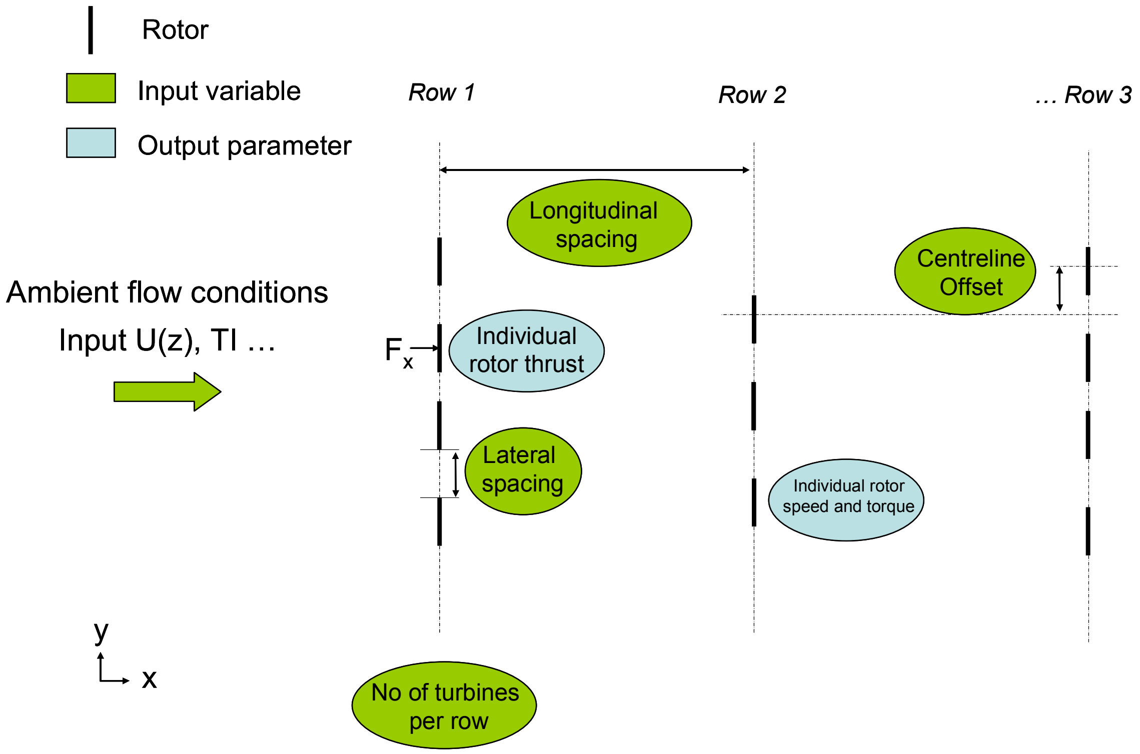

Figure 2-2 Variables affecting device performance and wake structure

The ambient flow conditions can vary significantly across a site leading to different incident inflow conditions. In addition, the presence of a variation in flow velocity with depth (shear profile) at tidal energy sites can be significant, such that the mean incident flow onto the rotor is not uniform or is even non-linear. Operating in the lower region of the boundary layer may lead to a significant asymmetry in the flow above and below the wake, altering the velocity profile and the wake recovery.

As the wake propagates downstream, momentum is transferred into the wake through turbulent mixing with the ambient flow, reducing the velocity deficit until it approaches that of the free stream. Once into the far wake region, this recovery process is driven primarily by the ambient turbulence, which can significantly enhance the mixing process and hence accelerate the re-energising of the wake. Ambient turbulence intensity is prominently governed by the seabed roughness, but can also be affected by free-surface waves. Certain wave states and operating depths may therefore significantly impact on the entire wake recovery process.

The development of the wake is influenced by the free stream conditions as well as the interaction and merging with other turbine wakes within the flow field.

2.3 Parameterisation of a tidal energy device when operating in an array

The parameterisation of a tidal energy device for an energy yield analysis is required for computational efficiency. As outlined in the Device scale modelling report WG3WP4 D3, the adopted method to describe a tidal energy device is in the form of power and thrust curves. Figure 2-3 below shows a generic power curve (steady power produced against flow speed) and generic steady thrust curve (rotor thrust against flow speed).

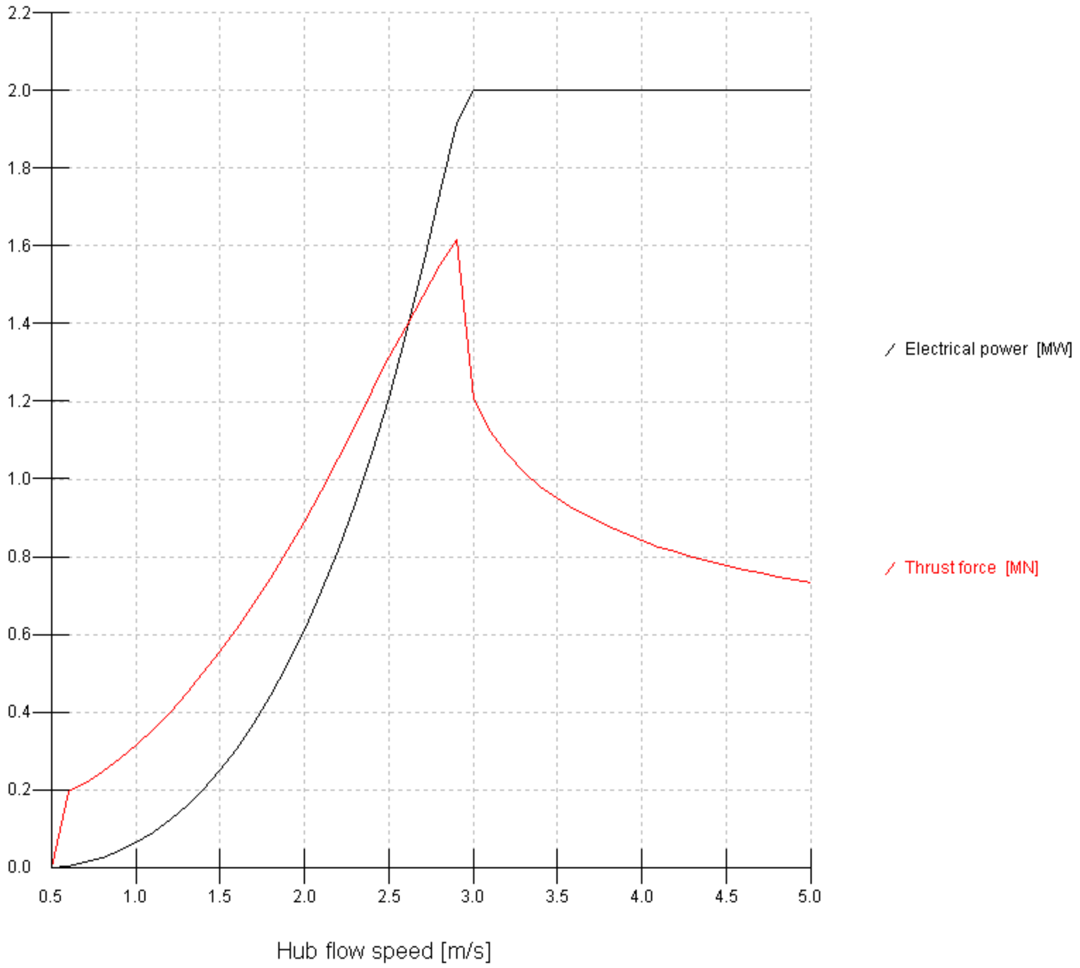

Figure 2-3: Power and thrust curves for a generic pitch regulated rotor

The power curve provides a relationship between the incident rotor flow speed at each device location within a tidal farm and the expected power output. The issue of unsteady effects can be addressed with the use of a dynamic power curve which has been measured/certified by independent 3rd parties. The thrust curve, when coupled with information regarding the ambient inflow conditions (both velocity and turbulence intensity), can be used to evaluate the near wake profile behind a single device. Corrections to both the power and thrust curves can be made to account for the presence of bounding surfaces.

3 TIDAL STREAM ENERGY STANDARD GUIDELINES AND METHODS FOR ARRAY ENERGY YIELD ANALYSIS

The tidal turbine industry has not yet reached the stage of commercial maturity demanding of a finalised international standard on the energy yield assessment of a tidal stream energy array. EMEC were commissioned by BERR to produce a number of guidelines to support the development of the marine renewable energy industry, resulting in guidelines for the assessment of device performance (EMEC 2009a) and tidal energy resource (EMEC 2009b). Although these two documents do not completely outline the requirements for an energy yield assessment of an array of tidal stream energy converters, they do contain relevant information, the salient aspects of which are summarised below. The International Electrotechnical Commission's (IEC) Technical Committee 114 (Marine Energy – Wave and Tidal Energy Converters) is currently in the process of developing the EMEC guidelines into international technical specifications.

3.1 Device performance assessment guidelines

As discussed in the Device scale modelling report (WG3WP4 D3), the EMEC 'Assessment of Performance of Tidal Energy Conversion Systems' guideline (EMEC 2009a) outlines a methodology to produce a power curve for a tidal energy device. The approach uses the method of bins to construct a measured power curve. The specific relevant guidelines for measuring the flow at the device are as follows:

- Flow speed measurement
    - Flow speed (mean, standard deviation, min and max) is to be recorded every 10 minutes or less.
    - The flow speed measurements should be taken throughout the water column at a maximum vertical spatial increment of 1m, allowing the flow velocity over the area of the rotor to be evaluated.
    - The current measurement device(s) (e.g. an Acoustic Doppler Profiler (ADP)) must be positioned close to the turbine, but sufficiently separated from it that the currents measures are not appreciably affected by the presence of the turbine.
    - The location of the current measurement device (ADP) must be placed where the water depth is within +/- 10% of the depth at the turbine location, and it should be bottom-mounted.
- The measurements of power are grouped by flow speed bin increments of 0.1m/s
- The mean value of the measured electrical power per flow speed bin should be used.

The requirements above allow for the development of a device specific measured power curve which can then be used in an energy yield analysis. Although not explicitly prescribed in the guidelines, site specific affects on power generation such as waves and blockage should also be considered.

3.2 Resource assessment guidelines

The guidance provided by the EMEC 'Assessment of Tidal Energy Resource' document (EMEC 2009b) covers four levels of analysis ranging from preliminary site screening to a detailed final assessment. The following table summarises the stages involved in the resource assessment and is taken from the above-mentioned document.

Table 3-1 Resource assessment stages (EMEC 2009b)

Stage	Category	Aim	Area	Constraints	Permit
1	Regional assessment	Site screening	Region/ country	Limited constraints identified	No
2a	Site assessment	Pre-feasibility	Whole estuary / channel, etc	Major constraints identified	No
2b	Site assessment	Full feasibility	Local area within channel or estuary	All constraints identified	Applied for
3	Site assessment	Design development	Local area within channel or estuary	All constraints identified	Obtained

Flow measurement - The guidelines require that the resource assessment is conducted by using a minimum period ADP measurement campaign and a robust harmonic analysis procedure, namely:

- Transects (vessel-mounted ADP surveys) to be carried out during Stage 2a.
- Surveys using bottom-fixed ADP(s) to be done during the latter stages:
  - Stage 2b (1 month minimum)
  - Stage 3 (3 months minimum)

For the latter stages of the site assessment (stages 2b and 3), a minimum of 20 tidal constituents should be used in the harmonic analysis and prediction. A frequency distribution of velocity at the site over the duration of one year is the required output from the resource assessment.

Bathymetry – the resolution of bathymetry required depends on which stage of the assessment is being performed. The required resolutions are:

Table 3-2 Bathymetry resolution requirements (EMEC 2009b)

Assessment stage	Resolution required (min grid size)
1	1-2 km
2a	100 m
2b	20 m
3	5 m

If adequate bathymetry data is not available from other sources at a given stage in the process, a bathymetry survey should be carried out (preferably using a multi-beam echo sounder).

Selection of modelling software – the EMEC guideline contains a (non-exhaustive) list of commercial shallow water modelling software packages which may be suitable for use in the resource assessment. Some overlap is seen with the packages covered in Table 3-1 of the Rationalised flow field modelling report (WG3WP4 D4). The guideline acknowledges that the best choice of code will of course depend on individual circumstances. 2-d modelling is acceptable up to and including Stage 2, but at Stage 3 the vertical component of flow should be included in the model, although it is noted that this does not necessarily mean that a full 3-d model is needed.

Converting the resource assessment into an energy yield assessment is briefly covered in the EMEC document. It suggests two options: either the Farm or the Flux methods. The Farm method assumes a ‘generic’ array layout where the inter-array effects are assumed to be negligible and where ‘generic’ lateral and longitudinal spacings are suggested. The Flux method applies a factor to the kinetic energy flux flowing through the site, limiting the extractable energy to a fraction of the total kinetic energy. In both cases the effect of devices upon the flow is not modelled directly. Developments to better model the inter-array effects are discussed in Section 3.3 below.

3.3 Energy yield and layout optimisation analysis

As mentioned previously, the EMEC device performance assessment document (EMEC 2009a) provides a methodology to yield a device specific measured power curve, and the EMEC resource document (EMEC 2009b) provides detailed guidance on how to model the raw tidal flow resource. Coupling the power curve and the raw resource allows for an initial assessment of energy yield. However, without taking into consideration the effect of the devices upon the flow, inter-array effects associated with the specific array configuration will not be accounted for.

During the project financing and design phase of project development, it is considered important to be able to investigate the impact of varying array layouts on project viability. Ideally a project is designed to optimise the balance between energy yield and project capital cost, essentially optimising the project cost of energy. In order to understand the impact of a specific array layout upon the energy yield potential, inter-array modelling must be undertaken. In addition, to provide the required confidence at these stages of project development it is considered necessary to have data similar or superior to the level associated with Stage 3 in the EMEC resource guideline (EMEC 2009b) (see Section 3.2). The requirement to resolve the vertical profile is seen as critical to the evaluation of the mean power at each location, and the need to model the extraction of momentum from the flow and the subsequent recovery is also seen as essential in order to evaluate the 3-d flow field within the array.

To date several methods have been proposed to incorporate device/flow interactions within shallow water models. The first method adopted was the added drag term which models the turbine as an addition to the seabed drag coefficient. This has been applied in simple 1-d channel models (Bryden, 2005) and within commercial shallow water flow solvers such as Telemac (Peyrard, 2006). The latest research published by EDF (Pham, C-T, 2010) includes wake modelling using the added drag method. However, without a closed loop iteration method the drag approach does not incorporate any local blockage effects and will not take into account the effect of the devices upon the flow. An alterative approach has been developed by Draper et al (2009), which embeds 2-d linear momentum actuator disc theory into a 2-d numerical flow solver. If the amount of momentum extracted from the site is small in comparison with the mechanism driving the tidal flow, then modelling the impact of the devices upon the flow may be neglected. Weather this upstream effect is significant or not, modelling the recovery of and interaction of individual wakes will be required and this can only be achieved through the specific tuning of the employed turbulence close models.

The most refined approach is the 2.5-d[1] modelling of a single device which includes both a momentum sink term and an added turbulence term by Roc (2010). As described by Roc, matching numerical models to experimental data requires tuning of the shallow water turbulence closure model. Figure 3-1 below shows the effect of changing the ambient turbulence parameter on the velocity deficit along the hub centreline. Velocity deficit is defined as:

$$D_w = 1 - \frac{u}{U_i}$$

---

[1] These 2.5-d models are the common reference for models which solve multiple layers of 2-d flows coupled by the 3-d continuity equation.

Where D_w is the area-averaged velocity deficit, U_i is the uniform upstream velocity and $\underline{u}$ is the downstream velocity field.

To address the near-to-far wake transition, a method to delay the onset of recovery is proposed using injected turbulence. This method will be calibrated against experimental data in WG4WP2 and against CFD results in WG3WP1. The tuning of global parameters to calibrate the model to wake recovery may induce errors at the basin scale and this is definitely an area for further investigation.

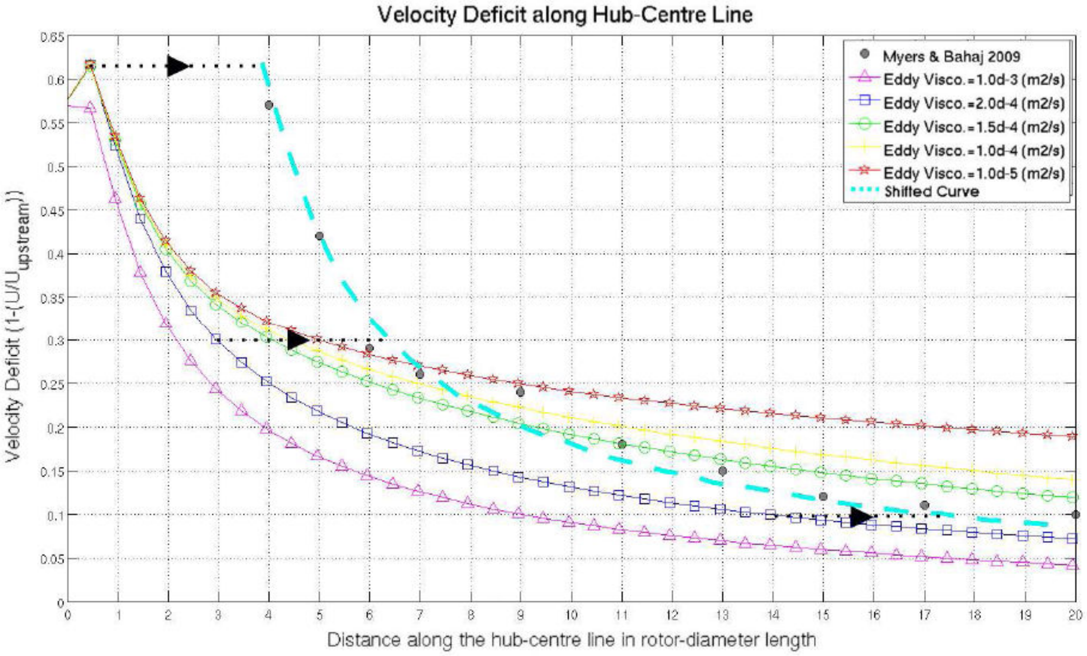

Figure 3-1 Tuning ROMS to experimental wake data via turbulence parameters (Roc, 2010)

4 GH APPROACH TO ARRAY SCALE MODELLING

The purpose of the TidalFarmer software is to allow for a detailed analysis of the energy yield potential of an array layout during the project financing and detailed design phase of project development. In order to provide a design tool that allows for numerous iterations, the GH approach to energy yield prediction is to use an efficient means of evaluating array scale interactions and the potential effect which the array layout has on energy yield. This means reducing the extremely complex interactions between tidal turbines and the surrounding flow field via simplified means.

An example array is described below as a means of illustrating the number of calculations which are required to optimise the array layout for energy yield. At the array scale, the flow domain will be of the order of hundreds of rotor diameters square for a medium to large array. Using a parametric description of each device significantly reduces the modelling effort, but to model the flow at the required resolution still means a computational domain of tens of thousands of grid nodes. As an example, an array of forty devices in three rotor diameters (3D) of water depth with a longitudinal spacing of 20D requires approximately fifty thousand nodes within the array domain. Although grid efficiency can be achieved via the use of unstructured grids, the model will additionally need to incorporate significant area around the site.

To model the effect of energy extraction requires an iterative process where the calculation at each grid node must converge to a solution. This may be in the order of tens of iterations, but it is dependant on the flow solver and the ability of the solver to address discontinuities such as those introduced by the parametric description of the device. Traditionally shallow water models are run in the time domain to incorporate unsteady effects such as large eddy motion. The time step used in tidal flow modelling is typically between ten and fifteen minutes, further increasing the number of computations. Assuming a single representative lunar month is used to capture the temporal variations in tidal flow, then the number of computations multiples by at least 2800 (29.53 days in a lunar month). If, however, several single tidal cycles can be shown to be more representative, then this number could be reduced to less than a hundred. Thus for the example array described above, the requirements for a single time-domain analysis is of the order of 30-3000 million calculations. To optimise the array layout for energy yield may require several tens if not hundreds of location alterations to be investigated, leading to a very high computational requirement.

The GH approach requires the development of rationalised modelling methods to allow a computationally efficient energy yield and optimisation analysis. As described in the Device scale modelling report (WG3WP4 D3) the GH approach reduces the energy yield analysis from the time domain to the frequency domain. The method of bins reduces the number of computations by an order of magnitude and allows site specific data to be coupled with long term wind and wave effects in order to develop a representative range of wind, wave, turbulence and current conditions. The method of bins is a data reduction procedure that groups test data for a certain parameter into subsets typified by an independent underlying variable or variables. Such a “binning” method reduces a full simulation of a representative lunar month or the complete astronomical tidal cycle (a year) to a number of flow state simulations.

The method is widely adopted in the wind industry, where there are many different incident flow directions and velocity distributions possible, and it is recommended in the IEC-61400-12-1 ‘Power performance measurements of electricity producing wind turbines’ standard (IEC 2005). The impact of adopting this approach means that the device scale modelling is simplified to a quasi-steady analysis. It assumes that the time varying effects average out and that the acceleration effects are small. Provided that the flow speed bin width is sufficiently small (i.e. ~0.1 m/s) then the acceleration terms will be negligible and at the inter-array scale will not have any discernable effect.

However, at the basin scale it will be important to model time varying interactions to assess the impact the array has on tidal wave propagation. It is GH's intention to model the impact of the array on the global/basin scale flow using a link to an external basin scale modelling package. Pre and post optimisation checks will be used to confirm any variation in global flow. This is further discussed in the Rationalised flow field modelling report (WG3WP4 D4).

Another key assumption in the GH approach is the decoupling of the seabed driven flow field calculation from the flow field generated during energy extraction (i.e. blockage and wake modelling). Instead of modelling the process of extraction of energy within the shallow water model, which requires an extension to the fundamental flow solver and specific tuning to represent the wake recovery process, a perturbation approach is taken. This approach avoids using flow solvers which have not been designed to accurately model tidal energy devices and the recovery of their wakes. Instead of altering a single model, two models are combined externally.

Allowing the tidal cycle to be represented as a number of discrete 'flow states' (direction sectors and flow speed bins) enables the mean power of each device per flow state to be converted in to an energy yield. Using a device scale parametric model which adequately describes the device performance for a given flow state (i.e. a dynamic power curve) the power output of the device can be calculated. For each flow state the local operating conditions for each device location are found and coupled with the device model to evaluate a mean power output. An energy calculation then combines mean power at each flow state with the occurrence distribution of that flow state, resulting in the expected energy yield.

In summary, the aim of array scale modelling in the context of an energy yield assessment is to:

- Develop an array spatial flow field of the required accuracy
- Predict the interactions between devices
- Calculate the energy production of an array of devices for a given layout at a specific site

Section 4.1 defines the development of an array flow field, Section 4.2 discusses the inter-array models and Section 4.3 outlines how an array energy yield prediction is developed.

4.1 Spatial tidal flow modelling

The purpose of the flow field modelling is to provide the spatial variation of flow speed and direction across the site at each flow speed bin and direction sector i.e. localised speed-ups/slow-downs relative to a reference point for each flow state. In addition, modelling the vertical variations in flow speed, due to flow shear, will be important if the rotor takes up a significant proportion of the water column and hence experiences a non-linear variation in flow speed between the top and bottom of the rotor.

The flow field modelling requirements and approaches for TidalFarmer are discussed in more detail in WG3WP4 D4. In essence the adopted approach utilises developed and sophisticated external shallow water flow solvers to provide the undisturbed flow field. Code developments under PerAWaT will develop the interface with shallow water flow solvers to provide an integrated link and then undertake the required analysis to convert these typically time-domain models in to spatial flow fields for each flow state. Post processing methods are used in order to satisfy the requirements for a 3-d flow field for each flow state and also to better match the numerical prediction with available site data.

In the vicinity of the array, interpolation methods will be employed if sufficient resolution (0.5 – 2 rotor diameters) has not been achieved with the flow field model. Typically resource models are run in 2-d, but can be extended to run in 3-d in areas of interest. However, the computational effort increases by 30-60 times (depending on the layer resolution) and typically site data at the model boundaries is required. GH's approach will be to generate a 3-d flow field by extrapolating the depth-averaged 2-d flow through the water column using shear profiles determined from the site data. GH are currently sponsoring PhD work (Parkinson, in press) to develop an analytical model to predict the evolution of the shear layer across the site due to bathymetric changes. It is hoped that this method may yield a much more computationally efficient solution than running the model in 3-d, however these developments are not part of the PerAWaT project. If thought beneficial, the findings from the PhD may be incorporated into the first commercial versions of the GH tool, post the PerAWaT project.

Where site data of reasonable accuracy exists, the modelled flow fields will be calibrated to better match measured and modelled results. Typically much effort is required to match shallow water solvers with numerous site data points. Complex and involved iteration algorithms are required to converge a solution around a sparse data set of measurements. Instead, GH propose a correction approach to incorporate as much of the available site survey data as possible. Corrections are applied to the modelled data via a post processing assimilation method. For each flow state the spatial flow field is normalised relative to a single or multiple Long Term Reference Point(s) (LTRP(s)). At the LTRP location(s) a long term prediction of the tidal flow will have been made through harmonic analysis, yielding a flow speed occurrence distribution representative of the flow at that point for the project duration (further discussion of the development of the LTRP is given is Section 5). If multiple LTRPs are available, the methods described below are applied to an area of the site defined within a locus of the nearest LTRP.

Normalising the spatial flow fields to the LTRP for each flow state yields *N* speed-ups/slow-down maps, where *N* is the multiple of the number of flow speed bins and flow directions. To reduce the analysis a review of all the speed-up/slow-down maps is undertaken in order to assess the minimum number of representative speed-up/slow-down maps needed to capture the major variations in the spatial flow field across the site during a tidal cycle. This can be achieved by reviewing the distribution of speed-up/slow down values across the flow states at each point in the flow field.

To compare modelled results with the available measured data set, including bottom-mounted ADP data and/or vessel-mounted transect data, requires the whole site to be normalised to the LTRP. This can be done in a number of ways and is dependant on the spatial domain and temporal period of measurement. If data is not concurrent with the LTRP data then the flow root-mean-cubed value of the data may be used to relate the measurement data to the LTRP. The normalised measured data reference points can then be used to evaluate model/measurement errors, using the following equation:

$$\text{Error}_{x\,s} = \frac{\text{Measured}_{xs} - \text{Model}_{xs}}{\text{Measured}_{xs}}$$

Where the index x represents the reference measurement point and s represents the representative speed-up/slow down map. Model refers to the value of the model speed-up/slow down map at the reference measurement point and Measured is the normalised measurement value.

To correct the model maps beyond the specific reference measurement point location, spatial weightings for each measurement point are derived. The magnitude and coverage of the weighting is influenced by the associated quality of the measured data and the likely extent of the area of applicability (based on a review of the local bathymetry). This yields weighing maps for each representative flow state and each measurement point. Correction maps are then developed using the following equation:

$$\text{Correction map}_{\,s} = \sum_{Nx} (1 - \text{Error}_{x\,s}).\text{Weighting map}_{x\,s}.\text{Model}_{s}$$

As before, the index *x* represents the reference measurement point and *s* represent the representative flow state speed-up/slow down map.

4.2 Interactions within an array

As stated at the beginning of this section, the GH approach assumes that the flow field governed by variations in seabed bathymetry and roughness can be decoupled from the inter-array governed flow field, and hence that a perturbation approach is sufficient for the purpose of a design tool. This approach is only valid if the order of magnitude of the perturbation is small in comparison with the momentum in the surrounding flow, and hence that the flow within the array is sufficiently unaltered such that the hydrodynamic interaction with the seabed does not change significantly. The manner in which energy is extracted means that the larger local flow changes are often away from the seabed and thus seabed shear stress changes are negligible. However, once the wakes have fully expanded and start interacting with the seabed there will be some change in the overall flow momentum. Typically the momentum deficit within a single device wake is equivalent to <5% of the momentum in an area of four times the rotor swept area. It is unlikely that practical deployment configurations will exceed the ratio of four. As an example, it would mean that for a long row of devices in a water depth of 2D, the average lateral spacing between rotor centres should be no less than 1.5D i.e. a 0.75D tip clearance. Given the practical constraints of marine operations during array installation, this is considered acceptable. However, even if the flow speed changes are discernible and result in differential seabed drag effects, changes to the spatial relationship due to varying seabed drag will be a secondary effect to the wake effects. Note that typically shallow water solvers use a single drag coefficient across the basin scale as small changes in the seabed drag have little effect on the overall spatial flow field.

The assumption that the overall extracted momentum is small in comparison with the surrounding momentum implicitly implies that there is sufficient driving head behind the flow to allow the flow to recover from the extraction of energy. A detailed analysis of this is given in the Device scale modelling report (WG3WP4 D3). As stated in WG3WP4 D3 it will be important to assess the driving force and total energy in the system via basin scale models to confirm this assumption, prior to undertaking inter-array modelling.

The purpose of the inter-array modelling is to predict the effect of the hydrodynamic interaction, between adjacent devices and the bounding surfaces of the channel (blockage modelling); and between multiple device wakes and the ambient flow conditions; such that the impact upon downstream devices can be evaluated. The array influenced flow field prediction incorporates changes to the local operating conditions of the flow field incident on a device. Changes to the flow field include:

- changes in the local flow field due to blockage;
- changes in the flow field due to the wake of upstream devices; and,
- changes in the ambient turbulence intensity due to upstream devices.

As stated above, perturbation approaches are used to incorporate the inter-array effect and seabed driven flow field. Further details are given below.

The models used to predict changes to the inter-array flow field include both the device scale blockage model and far wake modelling. The blockage model predicts local changes to the velocity field which may impact on adjacent devices. Further details of the GH Blockage model are presented in the report WG3WP4 D1. Typically the local flow changes are of the order of <10%, and hence these changes can be applied as a perturbation to the spatial flow field. The alterations to the flow field are used within the near field and far field models, in both cases to evaluate the surrounding momentum in order to ensure that the effects of the surrounding boundaries are accounted for.

The far wake models alter both the velocity and turbulence fields within the array due to the effects of upstream devices. The far wake modelling requirements and approach are discussed in more detail in WG3WP4 D5. The use of a rationalised CFD method (eddy viscosity technique) allows an efficient method to obtain a solution for the disturbance of the flow field wake recovery in the far wake region. The eddy viscosity wake model is a calculation of the velocity deficit field using a finite-difference solution to the thin shear layer equation of the Navier-Stokes equations in axi-symmetric co-ordinates. The details of the empirical added turbulence intensity are also detailed in the Far wake report (WG3WP4 D5).

The far wake model is applied to each turbine within a grouping. Prior to undertaking far wake modelling upon each device, the 2-d spatial flow field (per flow state map) is used to evaluate the streamlines which propagate from each device location. These streamlines are used to evaluate the path (or trajectory) the wake centreline will take. A streamline is a curve upon which every point is tangent to the velocity field. Streamlines coincide with the paths of a fluid particle when the flow is steady and **u**(x,y,z). The corresponding streamline equations are:

$$\frac{dx}{ds} = u \quad \frac{dy}{ds} = v \quad \frac{dz}{ds} = w \qquad\qquad ds^2 = dx^2 + dy^2 + dz^2$$

Tying the wake centreline to the streamline requires the transformation of a regular grid upon a curvilinear line, such that at regular distances along the streamline the surrounding momentum is evaluated to inform the far wake model. The far wake model is evaluated upon a regular grid, but then transformed upon the streamline and the flow state map via a perturbation approach. The conservation of momentum is observed via corrections at each downstream location. Once all of the wakes within a turbine grouping have been evaluated and added to the flow state map, wake merging models are used to incorporate the effect of wake interactions.

On completion of blockage and wake modelling upon the first grouping of turbines and the update of the inter-array flow field, the analysis moves on to the second grouping of turbines and a similar analysis is undertaken.

In addition to the development of the inter-array velocity field, the turbulence intensity field is also updated via a perturbation approach. The method by which the wake-generated added turbulence intensity decay is evaluated at downstream locations is detailed in the Far wake report (WG3WP4 D5). For each single device the wake generated turbulence intensity is added to the ambient turbulence field, however in areas where the spatial flow speed changes, the added turbulence intensity is scaled accordingly.

4.3 Energy calculation

As discussed in the Device scale modelling report (WG3WP4 D3) the GH turbine model utilises an evaluated incident flow speed and power curve to calculate the mean power output for each turbine at each defined ‘flow state’. The mean powers of each device for each state are then combined with the occurrence distribution to yield an overall energy yield for each device in the array and hence an overall array energy yield. The total array energy extraction is the sum of all the individual devices and can be described by the equation below:

$$\text{Total array energy yield} = \sum_{Nk} \sum_{Nj} \sum_{Ni} P^{i}_{jk}.O_{jk}$$

Where:

- P is the mean power output and O is the percentage of occurrence;
- i is the device index which provides a reference number of the device in the array, and Ni is the total number of devices in the array;
- j is the flow speed index related to the speed bin (e.g. 1.95-2.05m/s) under consideration, and Nj is the total number of flow speeds in the long term flow speed distribution for each flow direction; and,
- k is the index for flow direction, with Nk being the total number of flow speed directions.

The method above shows no preference to the sequencing of turbines. Clearly this is important when considering the inter-array effects. To address this issue a logic-based approach is adopted. A sequence identifier is introduced to order the calculation sequence and hence allow the inter-array flow field to be updated prior to subsequent energy yield calculations.

$$\text{Sequence identifer} = S_{grk}.$$

Where:

- S is the device index
- g is the device grouping index (typically groupings are in rows)
- t is the order of analysis per device grouping
- k is the index for flow direction,

The calculation sequence (Sequence identifier) is derived from a review of the geometric layout of the array and the flow field through the array. For each flow direction devices are grouped by downstream distance from a boundary normal to the flow direction located on the edge of the site and coupled with close lateral spacing. The sequence of devices within a grouping is ordered by upstream location within the group.

5 INTEGRATION AND IMPLEMENTATION OF ARRAY MODELLING WITHIN TIDALFARMER

This section describes how GH inter-array models are incorporated into the TidalFarmer software tool.

5.1 Description of TidalFarmer

The purpose of the TidalFarmer design tool is to provide the industry with a comprehensive and definitive tool that can optimise the energy capture of tidal stream turbine arrays.

To assess and optimise the energy capture of an array at a specific site, four distinct steps are required:

1. Site specific tidal flow field prediction
2. Array influenced flow field prediction
3. Energy calculation for the life time of the project
4. Energy optimisation by altering array layout

To assess the energy capture capability of a specific site the tool shall be required to evaluate the flow field within and around the array and incorporate the effect which the turbines have on each other and on the flow.

5.2 An overview of the TidalFarmer approach

The overall concept of the TidalFarmer modelling method is to reduce the extremely complex interactions between tidal turbines and the surrounding flow field into a series of distinct physical processes which can be simplified and modelled.

The underlying analysis simplifies the physical processes under investigation via the selection of an appropriate scale. The three appropriate scales of interest here are: Coastal basin, Array and Device scale.

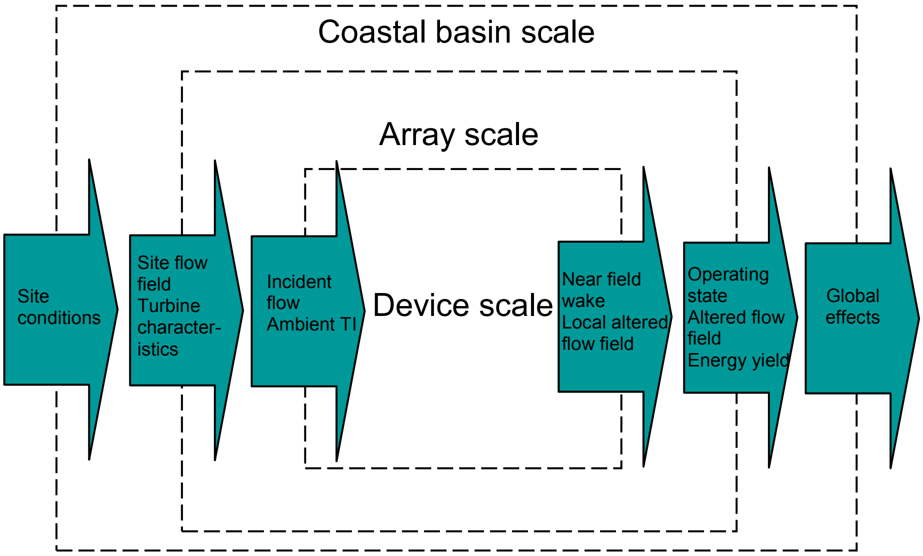

Figure 5-1 Hierarchy of modelling domains and scales

The TidalFarmer tool uses a collection of models to undertake an energy resource analysis and layout optimisation of a proposed tidal stream array. The present conceptual layout of TidalFarmer is outlined in Figure 5-2.

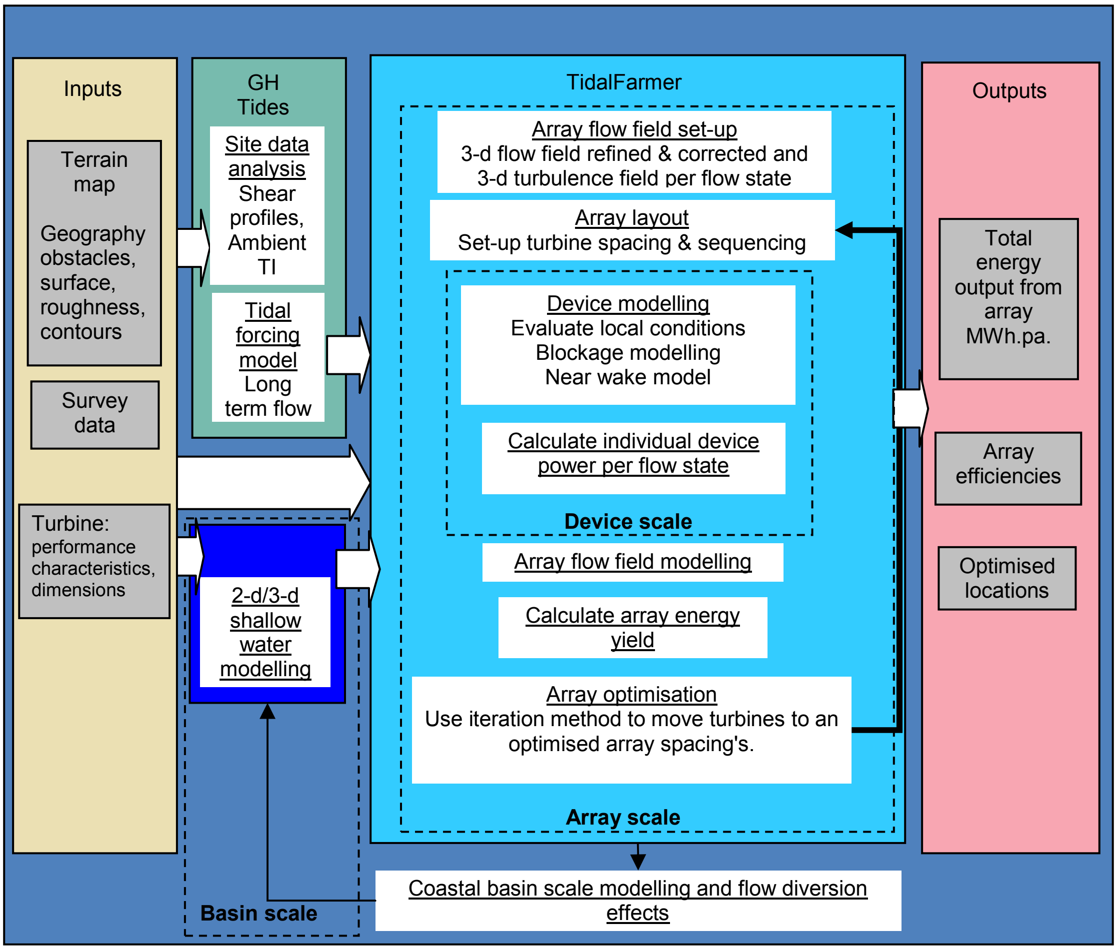

Figure 5-2 Overview of TidalFarmer software architecture

In the context of the four key aspects of an energy yield and optimisation tool, TidalFarmer undertakes analysis at each step:

1. Site specific tidal flow field prediction

Utilising the method of bins allows the tidal flow modelling problem to be split into two parts. First is the evaluation of a long term prediction of flow speed occurrence at specific locations within the site (referred to as LTRP(s)). Secondly a 3-d spatial flow field model is developed utilising numerical models and site measurement data.

GH Tides is the name given to the code that has been developed by GH outside of the PerAWaT project to post-process ADP and tidal gauge site data and can be used to produce a long term prediction of the flow at reference locations across the site. Typical project lifetimes will be between 20 and 30 years and hence long term predictions need to incorporate the effects of both the astronomical tidal forcing (the longest significant tidal variation being the 18.6 year cycle) and local meteorological phenomena at the site. Standard tidal forcing models based on tidal harmonic constituents are common practise for the analysis and prediction of tidal flows at specific locations.

The use of harmonic analysis upon the flow speed and surface elevation data can be used to derive the local flow and tidal elevation harmonic constituents' magnitude and phase. These harmonic constituents are then used to predict the tides or tidal currents at any point in the future at that location, e.g. yielding a 25 year prediction

The long term prediction should include long term meteorological effects. GH Tides allows for a review of the available Met data and local tidal gauge data in or around the site to check for any significant meteorological effects during the measurement period which could impact on the harmonic analysis. Correlations to the data might be required to remove meteorological effects prior to harmonic analysis. However, a prediction of long term meteorological effects will need to be assessed and supplemented to the long term prediction harmonic (or astronomical) prediction.

2-d/3-d shallow water modelling& Array flow field set-up

In order to develop a computationally efficient method for producing a 3-d spatial flow field of the required resolution and one which utilises as much site data as possible, a combined approach is used. The use of existing shallow water model results is seen as preferential to the set-up and execution of a new flow model and hence the method revolves around utilising, extending and improving the results of existing models. Tidal flow shallow water models are run in the time domain to ensure the flow driving dynamics are captured. However, for the purposes of an array energy yield analysis a quasi-steady approach is adopted. This method of utilising a reduced number of discrete simulations is considered to be more computationally efficient than a single time domain simulation. However, in some cases more detailed shallow water modelling will be required. An assimilation method is used to improve the numerical prediction and calibrate it to available site data.

Coupling the long term distribution of flow speed occurrence with the spatial flow maps provides the required description of the specific tidal flow conditions at the site of interest.

2. Array influenced flow field prediction

The purpose of the array influenced flow field prediction is to evaluate any changes in the local operating conditions incident upon a device due to the presence of other devices. This is achieved through the combination of different models which independently evaluate the interaction of a device with both the near and far field and which are then incorporated into the spatial flow field. Changes to the inter-array flow field include:

- changes in the local flow field due to blockage;
- changes in the flow field due to the wake of upstream devices; and,
- changes in the ambient turbulence intensity due to upstream devices.

Device scale modelling& Array flow field modelling

The models used to predict changes to the inter-array flow field include both the device scale blockage model and far wake modelling. The blockage model predicts local changes to the velocity field which may impact on adjacent devices. The far wake models alter both the velocity and turbulence fields within the array due to the effect of upstream devices.

Sequencing

The use of a perturbation approach requires that the order of analysis be sequenced logically. A sequencing method is used to group devices within the array and then evaluate the order of analysis based on the flow state under consideration.

3. Energy calculation for the life time of the project

The energy yield calculation uses the mean power prediction for each device at each flow state coupled with a long term distribution of flow speeds to calculate a mean annual energy yield representative of the project lifetime.

In analysing the array energy yield production, several energy calculations are performed to allow assessment of the efficiency of the proposed array layout design and to thus aid layout optimisation. These are:

A. Basic model: All devices experience the same flow regime as at the reference location, at the hub height, without any allowance for losses. .

B. All turbines experience the bathymetry induced local speed changes.

C. Calculation B including calculation of wake losses.

D. All turbines with the bathymetry induced local speed changes, calculation of wake losses, and local blockage effects modelled.

To indicate the performance of the array layout the following efficiencies are evaluated:

- Spatial efficiency = Calculation B / Calculation A (also referred to as Gross efficiency)
- Wake efficiency = Calculation C / Calculation B
- Blockage efficiency = Calculation D / Calculation C
- Array efficiency = Calculation D / Calculation B

The program calculates the net energy output, array and bathymetry efficiency for each individual turbine and the tidal array as a whole. To calculate the net energy production of each tidal turbine calculation C or D is required. Calculations A and B are used to estimate the wake and bathymetry effects experienced by each turbine.

4. Energy optimisation by altering array layout

The present GH optimiser for wind turbine arrays is based on a hill-climbing algorithm. This approach is also applicable to tidal turbine array layouts. To enable an optimisation based around constraints, an interface with a GIS system is envisaged. Such systems would be used to identify exclusion zones due to any number of constraints, e.g. geotechnics, wrecks, etc. Prior to interfacing with such a GIS system some basic constraint limitation are included within the existing GH optimiser; these include user defined exclusion zones and limits on slope angle.

Although the industry standard for designing a renewable energy project uses optimisation of energy yield, in recent years the focus has shifted to the optimisation of the cost of energy of a specific project. This is to better capture the impact of inter-array cabling as well as incorporating the potential increase in capital costs because of the increased fatigue loading resulting from upstream devices. Within the current TidalFarmer code the impact of energy optimisation is not directly coupled to the standard GH cost of energy model. This link has been achieved with GH WindFarmer and it is envisaged that future developments will realise this link for TidalFarmer.

5.3 Array scale modelling inputs

The inputs required by the TidalFarmer tool consist of:

- Turbine characteristics, including a power curve (and the corresponding ambient turbulence level) and thrust curve. In addition the rotor diameter and hub height dimensions are also required.
- Site flow field maps (typically a 2-d flow field will be provided).
- Site measured data
    - Depth profile flow data
    - Tidal elevation data
- A long term flow state occurrence distribution at specified location(s) i.e. LTRP(s)
- Site bathymetry
- A definition of any site constraints

To clarify the links between different software used in the energy yield analysis (i.e. those highlighted in Figure 5-2), the table below summarises the external inputs and outputs of each software.

Table 5-1 External inputs and outputs

	GH Tides	Flow solver	TidalFarmer
Bathymetry: 3-d terrain map	-	input	input
ADP or equivalent flow time series	input	(possibly)	input
Long term flow distribution per ebb and flood direction	output	input	input
Depth profiles per direction and speed bin	output	(input if 3-d)	input
2-d flow field	-	output	input (interpolation to a finer grid resolution if required)
3-d flow field	-	output if 3-d	input /output
Turbine characteristics	-	-	input
Array constraints	-	-	input
Array layout	-	input	output
Device operating state	-	input	output
Global flow field blockage	-	output	input
Energy yield per turbine per speed bin, per direction	-	-	output

Specifically within the TidalFarmer code the following inputs are evaluated for use in inter-array modelling:

- Time series from a 2-d or 3-d flow solver
- Site measured data
    - Depth profile flow data (velocity and turbulence intensity)
- A long term flow state occurrence distribution at specified location(s)
- Site bathymetry yielding the proximity of the seabed and free surface at any point in the flow
- The proximity of near field objects, such as adjacent turbines and channel walls
- The required accuracy for the calculation (i.e. the grid size and modelling method) based on the iteration point in the optimisation loop.

5.4 Array scale modelling procedures

The main steps within the inter-array modelling code include:

Rationalised flow field modelling

- Interfacing with a flow solver to import flow solver model results
- Reduction of time domain numerical model flow field result in to a series of discrete flow states
- Processing of the flow field model results and site data to yield array flow and turbulence intensity fields
- Read in/load site measured data of the right form and quality
- Read in/load long term flow state distributions (alterations to align flow speed binning may be required)
- Pre-processing of data, including:
    - Spatial flow field binning and checking for minimum required representative flow state maps.
    - Interpolation of the flow data onto the TidalFarmer regular grid
    - Extrapolation of 2-d flow fields into 3-d using site data and roughness models or comparison of 3-d numerical model with depth profile measured data.
    - Correction of flow field via assimilation method
        - Evaluate numerical model errors
- Presentation of 3-d array flow maps for each required flow state

Array layout and set-up

- Define array layout via optimiser or user defined
- For each device
    - Evaluate proximities of surrounding objects, such as adjacent turbines and channel walls
    - Evaluate blockage modelling requirement (based on proximities)
    - Evaluate wake modelling requirements (based on downstream turbines – per flow direction)
- Sequence analysis
    - For each turbine evaluate the sequence identifier i.e. evaluate the turbine groupings and the sequence per flow direction
- Evaluate wake trajectories (streamlines originating from turbine locations) for each representative flow state.

```
Influenced array flow field - main calculation loop
    For each turbine group (in sequence)
      • Evaluate local flow changes due to blockage (GH Blockage modelling)
        For each turbine in the calculation sequence (requiring wake modelling)
          • Call wake set-up model (near wake modelling)
          • Call Eddy viscosity model
              • At each downstream grid location
                  o For each of the split models solve the finite difference scheme
                  o Combine the centreline velocity deficit solutions
                  o Momentum Integral model
                      ▪ Using the proximity to boundaries (including adjacent wakes) at each
                        downstream grid location evaluate the local wake widths given the
                        centreline deficit and predict the wake form at each downstream
                        location.
                  o Assess the surrounding available momentum and correction centreline deficit
                    as required.
                  o Adjust Momentum Integral model if required
              • Store altered local flow field
          • Call turbulence intensity wake model
              • The centreline added turbulence intensity at each downstream location
              • Use the same elliptical wake form as the velocity deficit
  End of turbine loop
End of the turbine group (in sequence)
      • Wake interaction models
          o Evaluate the wake merging from multiple turbines at each downstream grid location.
      • Adjust array flow field (velocity and turbulence intensity) before looping on next turbine
        grouping
```

The resulting output from the array scale modelling is the mean power output for each turbine for each flow state, as well as any alterations for the inter-array flow field.

Figure 5-3 illustrates the array scale modelling process. Further details on both the Rationalised flow field modelling and the Far field wake modelling can be found in WG3WP4 D4 and WG3WP4 D5 respectively.

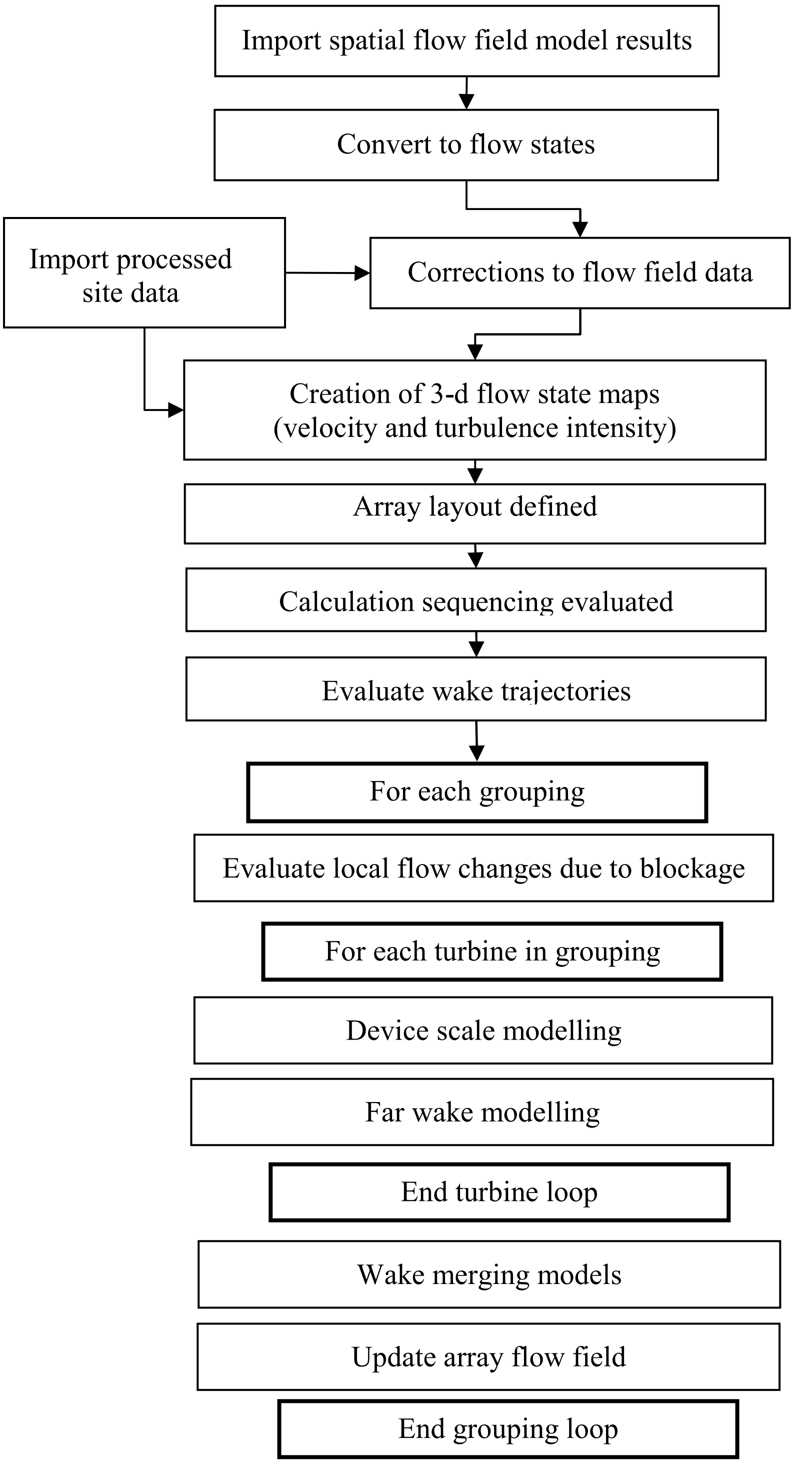

Figure 5-3 Flow diagram of the Array scale modelling

5.5 Implementation

Figure 5-4 below represents the envisaged structure of the TidalFarmer tool. Under PerAWaT the core functionality of the tool will be further developed, together with interfaces to external software including GH Tides, the flow solver, and the shared modules (the optimiser, graphics and mapping components).

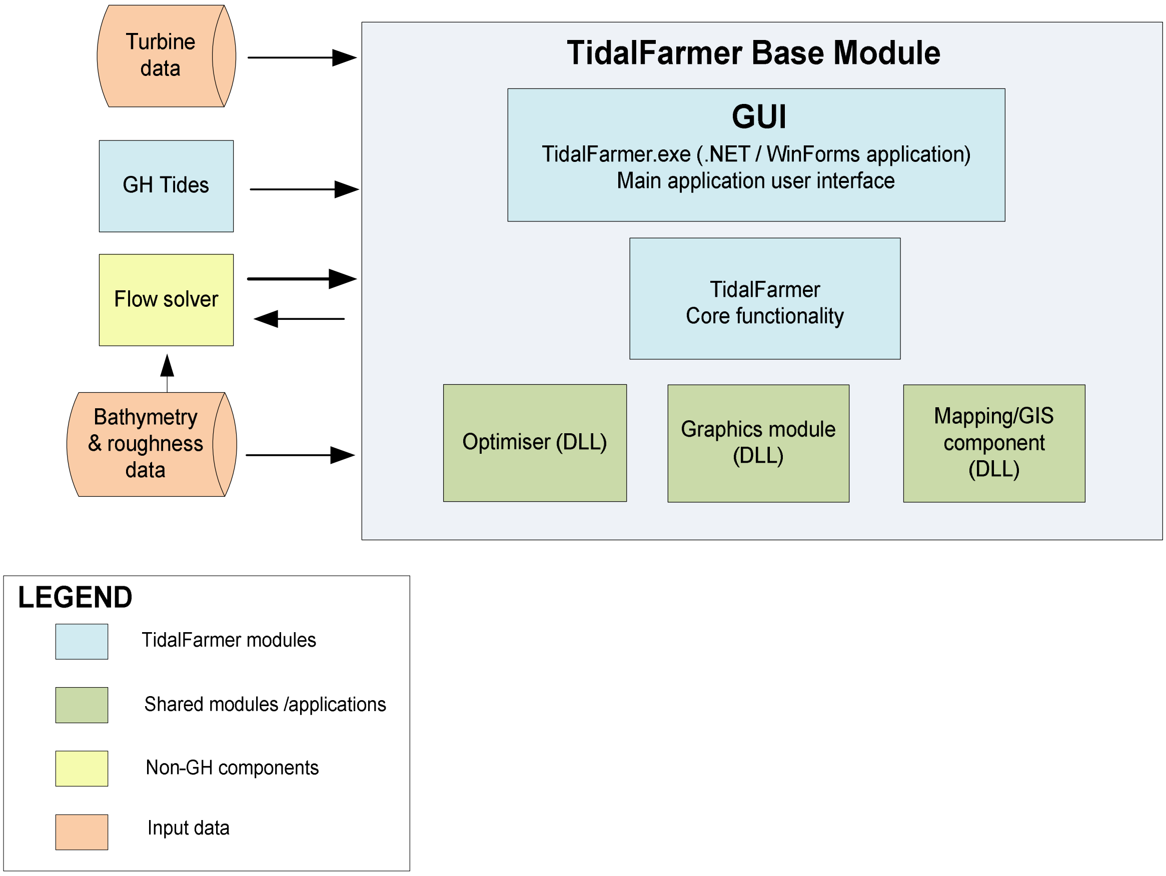

Figure 5-4 Summary of the TidalFarmer envisaged structure

The TidalFarmer software tool will consist of a single executable file (including a user interface) with which the user will interact, as well as a number of calculation modules which will be implemented as dynamic-link libraries (DLLs). Tidal calculations will be controlled and coordinated by a top-level “core functionality” module.

Choosing the most appropriate programming language depends on the method of investigation and how the results will be analysed. Currently the code is written as a Matlab script, which allows for easy interrogation and analysis.

The user interface is likely to be written in a .NET language such as C#, while the modules which do the actual calculations will either remain in Matlab or migrate to another language, such as Fortran or C++. For the Beta releases a generic basic user interface will be provided to allow the user to input key data and query the calculation outputs.

The diagram above illustrates the present structure of the TidalFarmer code. Tables 5-2 and 5-3 provide a functional description of the GH array scale modelling.

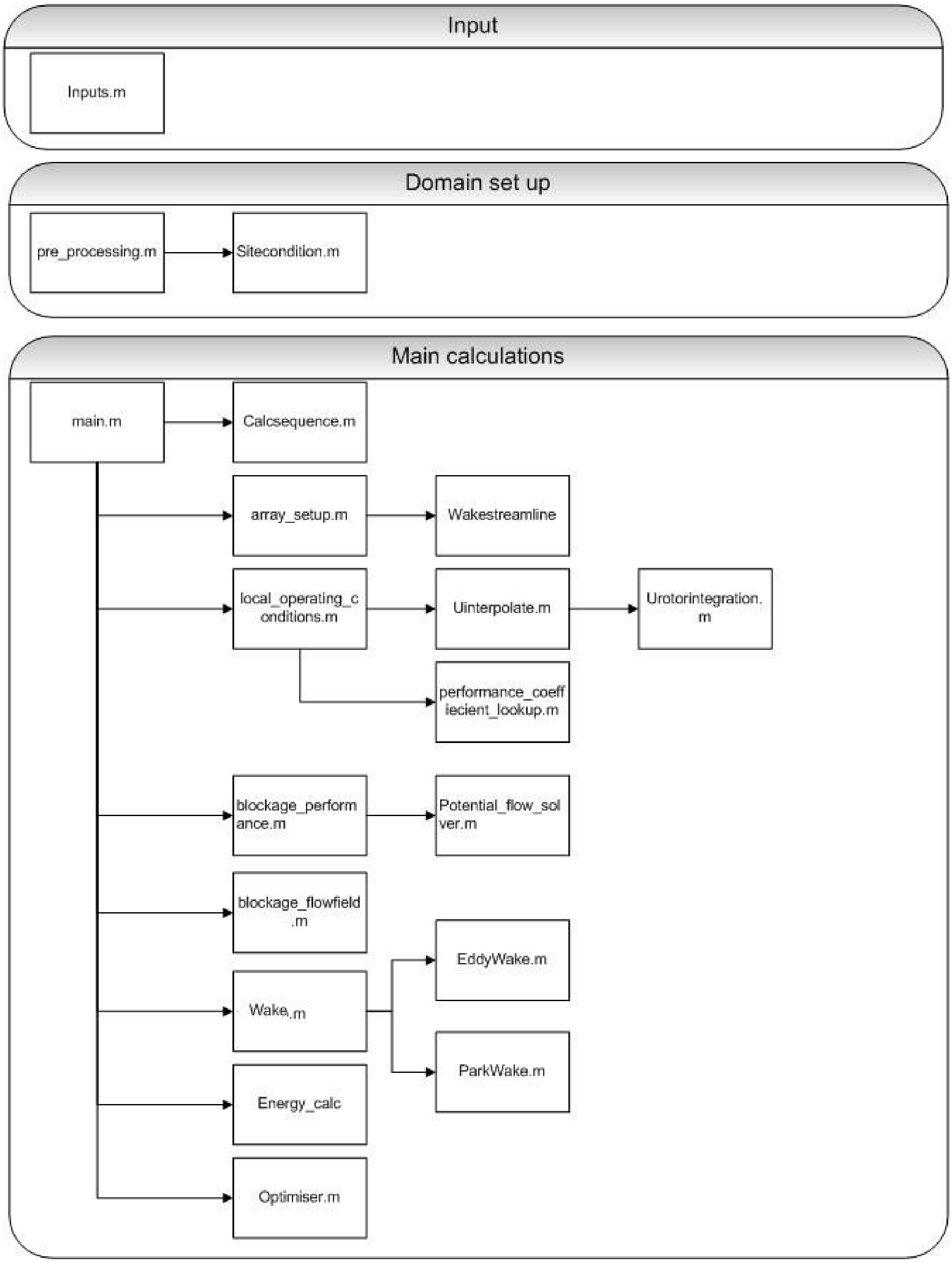

Figure 5-5 Current TidalFarmer (MATLAB) code

Table 5-2 Summary functional description of the array scale modelling

Model	**Inputs**	**Outputs**	**Method used**
Rationalised flow field model	Flow solver model results (time series), Measured site flow and turbulence data	Corrected 3-d flow field maps for each flow state	Binning method, 2-d flow field models extended to 3-d by means of depth profile models, Assimilation method
Array layout and set-up procedures	Turbine locations, Site bathymetry,	Proximities between objects, Wake trajectories, Calculation sequence	Geometric and proximity logic, Streamlines
Array influenced model			
Device scale modelling	Power and thrust curve, Incident 3-d flow field	Power output per turbine, Near wake form	Device scale models
Far wake model	Near wake form per device, ambient and altered TI (ambient plus upstream wakes if any), turbine spacing	3-d velocity deficit profile	Eddy viscosity model, Momentum integral model
Inter-array flow alteration	Alterations to flow field, Spatial flow fields	Updated flow field	Wake merging models, flow combination methods

Table 5-3 Detailed functional description of the array scale modelling

Matlab file reference	Task	Input	Output	Method
	Rationalised flow field modelling			
-	Interface with external flow solver model results	Input file description	Time series from flow solver	Interface protocols.
input.m	Reads in spatial flow field time series	Input file description	Time series from flow solver in useful format for computations	Data structure protocols
	Reads in site bathymetry	Input file description	Site bathymetry in useful format	Data structure protocols
	Reads in site measurement data	Input file description	Range of available site data (Bottom mounted and transect data) in useful format	Data structure protocols
pre-processing.m	Spatial flow field binning	Spatial model time series results LTRP Direction sector & flow speed bins (flow states)	Flow speed up/slow down map per flow state	Binning method
	Selection of minimum required representative flow state maps	Flow speed up/slow down map per flow state	Statical parameters describing the relative spatial variations in time	Comparison analysis (user defined)
	Interpolation of the flow data onto the TidalFarmer regular grid	Representative flow state maps (rel. flow maps)	representative flow state maps on TidalFarmer grid	Interpolation method
	Extrapolation of 2-d flow maps into 3-d	Site roughness and site measured depth profiles Or 3-d numerical model	3-d rel. flow maps	Depth profile models (WG3WP4D4).
	Correction of flow field maps	2-d & 3-d rel. flow maps	numerical model errors corrected 3-d rel. flow maps	Assimilation method (Section 4.1)
	Visualises input data	Flow maps	Plots in a selection of formats (e.g. screen, jpeg, eps etc.)	Selection of visualisation methods (surface plot, velocity vector plot etc)
Siteconditions.m	Sets up the modelling grid domain: Converts coordinates into non-dimensional space Rotates site to align with principle flow axis	Site boundaries Coordinate system(s) in use	Non-dimensionalised site coordinates	Transformation procedures (coordination transformations)

Matlab file reference	Task	Input	Output	Method
	Array layout and set-up procedures			
main.m	Define array layout via optimiser or user defined	Turbine locations	Turbine locations (local coordinates)	Coordinate transformation method
Wakestreamline.m	Evaluate wake trajectories	Turbine locations 2-d flow field per flow state	Wake trajectories per turbine per flow state	Streamlines (Section 4)
Array set-up.m	For each device evaluate: proximities of surrounds objects, blockage modelling requirement, wake modelling requirements	Turbine locations 3-d bathymetry Wake trajectories per turbine per flow state	Modelling requires for each turbine for each flow state	Geometric and proximity logic
Calcsequence.m	Evaluate group sequence	Turbine locations Criteria for proximity (radial distance apart)	Sequence identifier	Geometric and proximity logic (Section 4.3)
For each flow state				
Loop for group of turbines				
	Device scale modelling			
blockage_flowfield.m	Local flow changes caused by the group of turbines	Local operating conditions per turbine	Local flow changes	GH Blockage model (WG3WP4 D1)
Loop for turbines(in group)				
Wake.m	Initialise far wake model	Operating state of turbine, local surround flow field	Far wake model inputs	GH Near wake model (WG3WP4 D2).
	Far wake model			
Eddywake.m	Flow deficit and turbulence intensity models	Near wake flow field Array flow field	3-d wake velocity deficit profile at each downstream location	GH Eddy viscosity model (WG3WP4 D5).
wakestreamline.m	Evaluate available surrounding momentum	Surrounding flow field	Equivalent free stream velocity.	Momentum integral model Limiting expanding check algorithm (WG3WP4 D5)
End loop for turbines(in group)				
	Inter-array flow alteration			
Wake.m	Evaluate wake merging	Multiple far wakes	Altered inter-array flow field (incorporating effects from group of devices)	Wake interaction models
Main.m	Combine wake influenced flow field (inter-array) to the array flow field	Inter-array flow field Array flow field	Updated array flow field	Combination method (Section 4.2)
End loop for group of turbines				

6 SUMMARY

This report describes the GH array scale modelling method for the purpose of both energy yield analysis and including the impact which devices within the array have upon each other. A discussion of key effects which impact on the inter-array flow field is given along with a review of the present industry guidelines.

The GH approach simplifies the modelling requirement in two key ways. Firstly, removing the need to model the process of energy extraction in the time domain reduces the analysis to a number of discrete flow states, which can then be coupled to a long term flow prediction. Secondly, a perturbation approach allows the inter-array device/flow interactions to be modelled separately to the effect of the seabed/flow interaction. Together, this allows for a much reduced modelling and hence computational effort, which is required of an array layout design tool.

The methodology of the GH array scale modelling approach has been detailed and an account of how the approach is implemented within the Beta code is provided.

The GH array scale modelling incorporates the following key aspects:

- Use of a rationalised flow field model to represent the tidal flow as a series of flow maps and a long term flow occurrence distribution (at a specific point). The use of an assimilation method corrects the numerical spatial flow model using site data, yielding 3-d array flow fields for each flow state.
- Array set-up procedures are used to establish the requirements for inter-array modelling and the calculation sequence.
- Array influenced flow modelling, which incorporates:
  - The use of a far wake model to predict the change in wake form as the wake changes at different downstream locations
  - Wake interaction models to combine the wakes from a group of devices
  - Inter-array flow alteration which combines the array influenced flow field with the flow field across the array

The next steps for this work package in relation to array scale modelling are:

- To issue and support the Beta testing of the TidalFarmer code
- Testing of a working method through tool Beta testing (WG3WP4 D7)
- To analyse the experimental results provided from WG4WP1, WG4WP2 & WG4WP3 and further compare the single far wake model with the numerical modelling results provided from WG3WP1 & WG3WP5 to:
  - compare the results to the existing model and adjust as required
  - evaluate the modelling uncertainties associated with the array scale models and report in WG3WP4 D14 & D15.
- The development of a protocol for interfacing with an existing shallow water solver (WG3WP4 D10)

7 BIBLIOGRAPHY

Boon, J.D. (2007). *Secrets of the Tide*, Horwood.

Bryden, I. G., Melville, G. (2004). *Choosing and evaluating sites for tidal current development*, Proc. Instn Mech. Engrs Part A: J. Power and Energy 218, 567–577

Draper, S., Houlsby, G.T., Oldfield, M.L.G., Borthwick, A.G.L. (2009). *Modelling Tidal Energy Extraction in a Depth-Averaged Coastal Domain* Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 2009

EMEC. (2009a). Marine Renewable Energy Guide, *Assessment of performance of tidal energy conversion systems*.

EMEC. (2009b). Marine Renewable Energy Guide, *Assessment of tidal energy resource*.

IEC 61400-12-1 Wind turbines - Part 12-1. (2005). *Power performance measurements of electricity producing wind turbines.* First Edition 2005 -12.

Parkinson, S., Hogan, S.J. Hogg, A., Champneys, A., Thomson, M. (2010). *Effect of bathymetry variation on two-dimensional tidal flow: a Galerkin approach.* JFM-10-S-0838, under review.

Peyrard, C., Buvat, C., Lafon, F., Abonnel, C. (2006). *Investigations of the wake effects in marine current farms, through numerical modelling with the TELEMAC system*. ICOE 2006 Proceedings, Bremerhaven, Germany.

Pham, C-T. Pinte, K. (2010). *Paimpol-Bréhat tidal turbine demonstration farm (Brittany): optimisation of the layout, wake effects and energy yield evaluation using Telemac* 3rd International Conference on Ocean Energy, 6 October, Bilbao

Roc, T., Conley, D.C., Greaves, D. (2010). *Accounting for Turbulence in a Regional Numerical Model for Tidal Current Turbine Farm Planning* 3rd International Conference on Ocean Energy, 6 October, Bilbao