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Programme Area: Marine

Project: Tidal Modelling

Title: Detailed Tidal Range Model and Documentation

Abstract:

This document describes the functional testing of the Detailed Tidal Range Model (DTRM). The DTRM extends to the mouth of the Bristol Channel, with a resolution of 50m at areas of interest and this resolution then grows at a rate of 8% up to the DCSM resolution at the interface. The DTRM operates in accord with tidal levels observed (and resynthesised) at Hinkley Point and Avonmouth.

Context:

Launched in October 2011 this project involved Black & Veatch, in collaboration with HR Wallingford and the University of Edinburgh to develop a model of the UK Continental Shelf and North European Waters, 100 times more accurate than existing marine data. This has been used to assess the tidal energy potential around the UK (tidal range and tidal streams), to inform the design of energy harnessing schemes, to assess their interactions, and to evaluate their impact on European coasts. It can also be used to renew and inform flood defences, coastal erosion and aggregate extraction. Now completed, the project has been launched to market under the brand of SMARTtide. This is available to the marine industry under licence from HR Wallingford.

Energy Technologies Institute

MA1009

Tidal Modelling

(Modelling Tidal Resource Interactions around the UK)

PM04.09

Detailed Tidal Range Model
Functional Summary and Testing Report

21st November 2012

Version 1.0

Participant Lead – HR Wallingford
Other Participants – Black & Veatch

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CONTENTS

1 EXECUTIVE SUMMARY

The *Energy Technologies Institute* (ETI) has proposed the development of a *Continental Shelf Model* (CSM) of the UK waters to assess the tidal energy potential around the UK, to inform the design of energy harnessing schemes and to evaluate their impact on European coasts. The CSM was delivered to, and signed off by, the ETI as part of Milestone 2 of this *Tidal Resource Modelling* (TRM) project. *Black & Veatch* (B&V), in collaboration with *HR Wallingford* (HRW) and the *University of Edinburgh* (UoE), is providing support with regard to the development of this model and subsequent use by the tidal power industry. This report has been led by HRW and is part of the TRM scope of work delivered by B&V as prime contractor.

B&V has been consulting on tidal energy since 1975 (B&V was previously Binnie & Partners in the UK until 1995). B&V has a very broad and in-depth experience of both tidal range and tidal current projects, including resource assessment and project development, technology development, due diligence, cost of energy and policy development. Through working on these projects, it has gained a deep technical and commercial understanding of tidal energy projects in addition to simply resource assessment.

HR Wallingford has vast experience of numerical modelling of free surface flows using the TELEMAC system and has been instrumental in its continued development. The TELEMAC system is a state-of-the-art free surface flow suite of solvers developed by a kernel of European organisations including HR Wallingford and other partners such as Electricité de France and the Federal Waterways Engineering and Research Institute of Germany (pertinent information related to the TELEMAC system and, in particular, to the 2D module used in this project is given in the D02 – CSM Requirements Specification document). HR Wallingford's expertise is acknowledged within the tidal modelling community as the principal entity in the UK with an in-depth experience of TELEMAC and its tailoring to specific problems.

The UoE is one of the largest and most successful universities in the UK with an international reputation as a centre of academic and research excellence. The Institute for Energy Systems (IES) is one of five multi-disciplinary research groupings within the School of Engineering at the University. In the most recent UK-wide Research Assessment Exercise (RAE 2008), the School was ranked third in the UK for combined research quality and quantity.

The aim of the TRM scope of work is to address the following fundamental questions:

- How will the impacts of tidal range and tidal current energy schemes positioned around the UK combine to form an overall effect?
- Will the extraction of tidal energy resources in one area affect the tidal energy resources at distant sites around the UK and Europe?
- What constraints might these interactions place on the design, development and location of future systems?

This is achieved through a series of work packages and, ultimately, 10 deliverables outlined below.

D01 – Tidal resource characterisation
D02 – Continental Shelf Model (CSM) requirements specification document
D03 – Scenarios modelling
D04 – Cost of Energy Model and supporting documentation
D05 – Interface specification for detailed tidal current model with CSM
D06 – CSM (coarse and detailed versions) with supporting documentation
D07 – Interactions (analysis and conclusions report)
D08 – Interface specification for detailed tidal range model and the CSM
D09 – Tidal Range model and supporting documentation
D10 – Project dissemination

This report forms part of the D09 deliverables, which comprise the *Detailed Tidal Range Model* (DTRM) itself, and supporting documentation – Function Summary and Testing report.

Explanation of the technical parameterisation for incorporation into the TELEMAC source code can be found in Deliverable D02 – CSM Requirements Specification document, as the same underlying code is used for the DTRM as for the CSM. General information about the TELEMAC system, upon which the CSM is based, can be found on the official website hosted and managed by HR Wallingford: http://www.opentelemac.org/.

If ETI members wish to use the models directly in house (having licensed and therefore purchased appropriate bathymetry data), HR Wallingford, as a primary distributor of the TELEMAC system for the last 20 years, strongly recommends that new (expert modelling) users still register for training courses if they are unfamiliar with TELEMAC suite of solvers - because this will enable ease of installation of the models and simpler user interfacing.

The DTRM has the capability to couple with the DCSM yielding a single combined model referred to as the MCSM to consider both site-specific and far-field effects. PM04.08 details the Interface Specifications for Tidal Range Models. With the capability to couple the DTRM to the DCSM as one combined MCSM, both site-specific and far-field effects can be considered together, although it is normally not recommended to use the MCSM for 'optioneering' studies, to avoid the slower run times inherent to the reduced time step in the DTRM, but rather to reuse the user inputs (structures' geographical and parametric characteristics) to the DTRM within the DCSM to predict the effect of the scenario outside of the area covered by the DTRM. Input files are common to all models developed through the TRM Project.

The site selected for the DTRM was the Bristol Channel; this was agreed with the ETI and ETI members (notably Rolls-Royce) prior to commencing the scope of work associated with this deliverable. The Bristol Channel was selected on the basis that it provides an array of barrage and lagoon options from smallest (Oxwich and Morte Bays) up to one of the largest options (the Severn Outer barrage). In addition, the Bristol Channel contains some of the most economically attractive tidal range sites in the UK, and is relatively well understood in terms of hydrodynamics. The DTRM extends to the mouth of the Bristol Channel, with a resolution of 50 m at areas of interest and this resolution then growing at a rate of 8% up to the DCSM resolution at the interface.

The objective of the DTRM is to provide predictions within a relatively short time period on a mid to high specification multi-core desktop computer. A guaranteed run time of 12 hrs has been set, for a single scenario (of 14 days) and for a c. 50,000 node mesh. It is noted that the inclusion of many more areas of refinement than originally envisaged, to anticipate future lagoons, barriers and barrages within the Bristol Channel, resulted in a final version of the DTRM with c. 82,000 nodes. Despite this, it is expected that the model will run in c. 4 hrs on a multi-core (6- or 8-) desktop computer.

It is apparent that the Bristol Channel DTRM agrees well overall with tidal levels observed (and re-synthesised) at Hinkley Point and Avonmouth. In all cases, the N-RMSE is 3% or less, which is comparable with the results obtained with the CCSM and with the DCSM, and well below the 10% target set in this study. This confirms calibration of the Bristol Channel DTRM is appropriate.

The scenarios have been designed with the aim of testing the sensitivity of the DTRM and providing observations about the performance of a combination of schemes in relation to their performance in the DCSM/other models. It should be highlighted that the tidal conditions imposed at the boundary of the DTRM come from the DCSM base case scenario rather than the DCSM with the equivalent scenario in place. Indeed, the principal purpose of the DTRM at this stage is to be used as a standalone model for faster investigation of structure alignments and operation.

The DTRM slightly under predicts energy yield for the Severn Cardiff-Weston in ebb only mode in comparison to the range of results presented from DECC SEA Options Definition report. The reason for this is likely to be the less detailed bathymetry in the DTRM. Pumping has successfully been incorporated into the model; however, as expected it requires optimisation in order to be able to draw firm conclusions about its net economic benefit.

2 INTRODUCTION

In accordance with the acceptance criteria for Deliverable D09 – Tidal Range model and supporting documentation, a Detailed Tidal Range Model (DTRM) has been set up, based on the open source, industry-driven TELEMAC system. The site selected for the DTRM was the Bristol Channel; this was agreed with the ETI and ETI members prior to commencing the scope of work.

The DTRM is a stand-alone local model, which can either be accessed and run via the web interface (fee for service through the TELEMAC website (http://www.opentelemac.org/) following a registration process specific to the CSM/DTRM), or be run by the ETI or its members on a mid to high specification desktop computer (provided the appropriate bathymetry licences are purchased).

Should far-field effects also be of interest, it is recommended to normally reuse the same scenario inputs to the DTRM, but run the inputs through either the CCSM or the DCSM to predict the effect of the scenario outside of the area covered by the DTRM. Whilst the DTRM has the capability to couple with the DCSM, yielding a single combined model referred to as the *Modified CSM* (MCSM), because the MCSM includes the DCSM with more than a million calculation points, it should be run on a super computer. In addition, because the MCSM includes the Bristol Channel DTRM with a time step 6 times smaller than the DCSM, simulations of the MCSM would be expected to take 5 to 10 times longer (or utilise 5 to 10 times more of the super computing resources) than the DCSM on its own.

The testing and use of the MCSM is not part of the scope of this project, although the interface specification to allow coupling of the DTRM with the CSM is covered in Deliverable D08.

This report assumes that the user has suitable experience in the underlying tidal modelling and tidal technology. HR Wallingford, as a primary distributor of the TELEMAC system for the last 20 years, strongly recommends that new users register for training courses. Interaction with an expert in the system is invaluable and is something that a technical report does not replace.

3 PROJECT DESIGN/METHODOLOGY

3.1 The Detailed Tidal Range Model

3.1.1 Objectives

The DTRM provides a tool for more detailed site investigation at a specified tidal range site. For any project or site-specific consideration of potential tidal range options, it is expected that a refined model, as per the Bristol Channel DTRM developed for this deliverable, be generated for the testing of different technology types and other options such as turbine operational characteristics.

With the capability to couple the DTRM to the DCSM as one combined MCSM, both site-specific and far-field effects can be considered together, although it is normally not recommended to use the MCSM for 'optioneering' studies, to avoid the slower run times inherent to the reduced time step in the DTRM, but rather to reuse the inputs to the DTRM within the DCSM to predict the effect of the scenario outside of the area covered by the DTRM. Input files are common to all models developed through the TRM Project

The objective of the DTRM is to provide predictions within a relatively short time period on a mid to high specification multi-core desktop computer. A guaranteed run time of 12 hrs has been set, for a single scenario (of 14 days) and for a c. 50,000 node mesh. It is noted that the inclusion of many more areas of refinement than originally envisaged, to anticipate future lagoons, barriers and barrages within the Bristol Channel, resulted in a final version of the DTRM with c. 82,000 nodes. Despite this, it is expected that the model will run in c. 4 hrs on a multi-core (6- or 8-) desktop computer.

The DTRM is accessible to registered users through the protected ETI area of the TELEMAC website (http://www.opentelemac.org/) and is run from the web interface, following a similar procedure/fee structure as those set out for the CSM. The ETI and the ETI members are able to run the model on their own desktop computers subject to purchasing appropriate licensing of the bathymetry data used to develop the model.

3.1.2 Coupling mechanism between the DCSM and the DTRM

As introduced in Section 3.1.1, the DTRM has the capability to couple with the DCSM yielding a single combined model referred to as the MCSM to consider both site-specific and far-field effects. This follows essentially the same methodology and coupling mechanism developed and presented as part of Deliverable D05 – Interface specification for detailed tidal current model with CSM (PM01.05). This methodology was originally developed in the context of tidal current schemes to enable interfacing between the DCSM and other detailed tidal current models. As the DTRM was built using matching nodes from the DCSM this makes the DTRM a plug-in / plug-out a part of the DCSM domain. As long as there is a common strip where model resolutions and node locations are the same for both a detailed model and the DCSM this plug-in/plug-out capability exists. If a detailed model does not have matching nodes (it could have been developed entirely separately) then an adjoining mesh is required. With this methodology, bi-directional coupling is ensured as there is a single combined model to be run, the MCSM. Due to the selection of the TELEMAC system, the approach to transpose the parameterised tidal range formulation and parameterisation between the MCSM and the DTRM is straightforward.

PM04.08 details the Interface Specifications for Tidal Range Models. .

3.2 Description of the Bristol Channel DTRM

3.2.1 Site selection – Bristol Channel

This deliverable is intended not only to describe the DTRM for a specific site, Bristol Channel, but also to act as a 'proof of concept' for other detailed models around the UK coast.

The Bristol Channel was selected on the basis that it provides an array of barrage and lagoon options from smallest (Oxwich and Morte Bays) up to one of the largest options (the Severn Outer barrage). In addition, the Bristol Channel contains some of the most economically attractive tidal range sites in the UK, and is relatively well understood in terms of hydrodynamics.

3.2.2 Extent and resolution of the Bristol Channel DTRM

The Bristol Channel DTRM extends to the mouth of the Bristol Channel, from Milford Haven in Wales to Padstow in England, as illustrated in Figure 1 (inset map). In order for the DTRM to interface with the DCSM (following the interface procedure established in PM04.08), the tidal boundary follows the element orientation (and exact node locations) of the DCSM. The node-to-node boundary fitting is evident in Figure 1, where the DCSM mesh (up to the interface) is displayed in orange and the DTRM mesh in blue.

The Bristol Channel DTRM resolution is also shown in inset to Figure 1, in comparison to that of the DCSM. It is apparent that the mesh resolution varies smoothly (without shocks) at the interface between the two models. This also complies with the methodology established in PM04.08.

Areas of interest are well resolved, with the resolution in these areas being c. 50 m. These areas were defined in agreement with Rolls-Royce (a member of the ETI), corresponding to the three strategic regions, which early studies identified as the most promising options for tidal range scheme locations:

- A-Region (Lower Severn) – Severn Outer or Minehead-Aberthaw
- B-Region (Mid Severn) – Cardiff-Weston, Hinkley Point-Lavernock Point, Brean Down-Lavernock Point
- C-Region (Upper Severn) –Shoots and Beachley Barrages

Particular emphasis was placed on the B-Region to ensure that a number of proposals in this region, which vary in geometry (curved, kinked or straight), location and whether they go in front of, behind, or though the islands, can be incorporated in the Bristol Channel DTRM.

Bridgwater lagoon was also defined as an area of interest (resolution of c. 50m).

A resolution of c. 200m was used for the coastlines, as was the case in the DCSM. From there, the mesh size grows at a rate of 8% up to the DCSM resolution at the interface.

Overall, the model area was represented using approximately 82,000 nodes (160,000 elements). With a time step of 5s, the Bristol Channel DTRM performs a 14 day simulation in c. 6 hours on 3 cores. This compares very favourably to the 12 hrs guaranteed run time on a multi-core desktop computer.

The underlying bathymetry data are mostly Level 3 Seazone Charted Bathymetry data, as per the scope of works, but it is noted that the use of Levels 4, 5 and 6 data was necessary to resolve parts of the Severn Estuary.

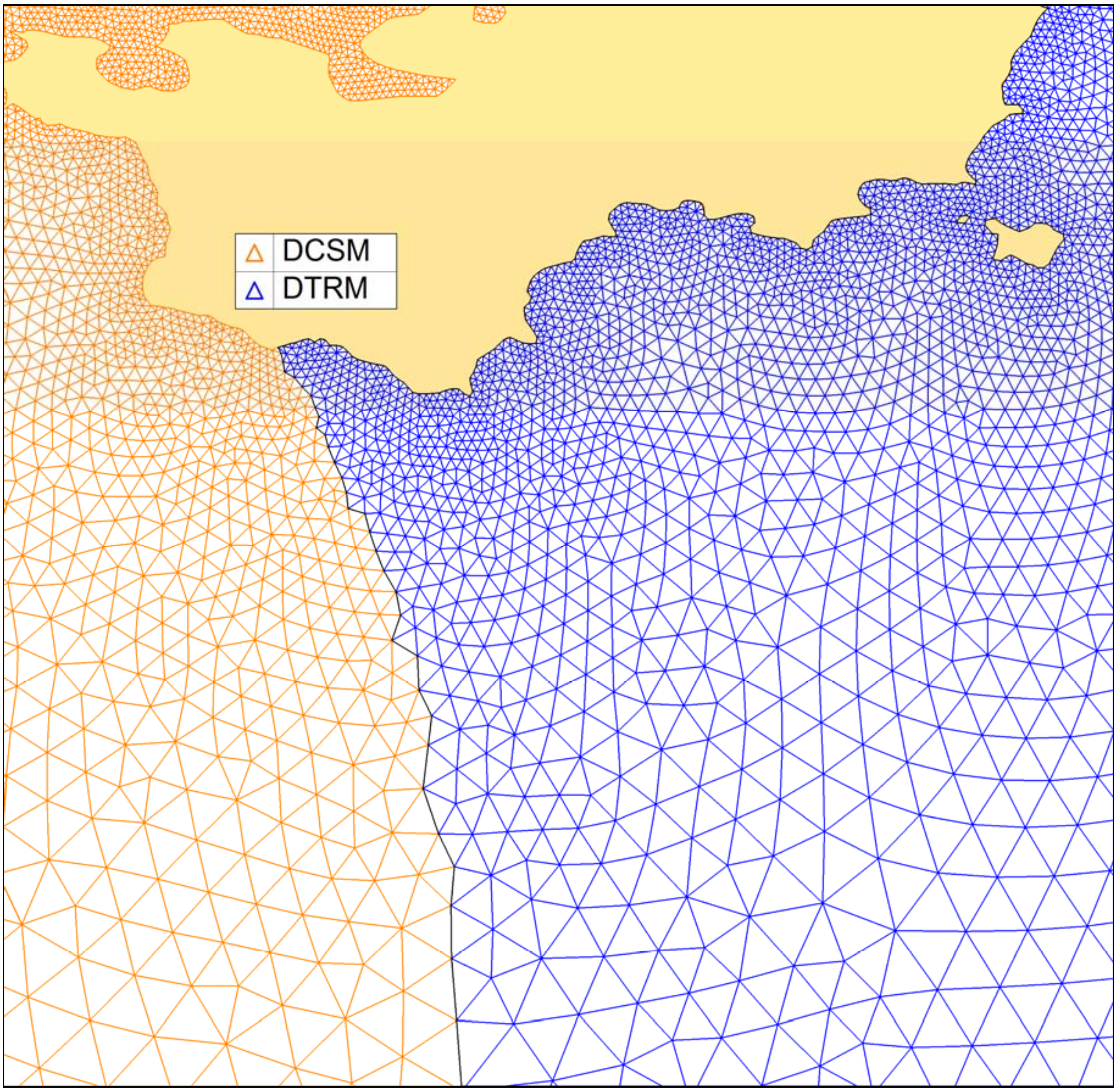


Figure 1 Tidal boundary of the Bristol Channel DTRM illustrating node-to-node boundary fitting

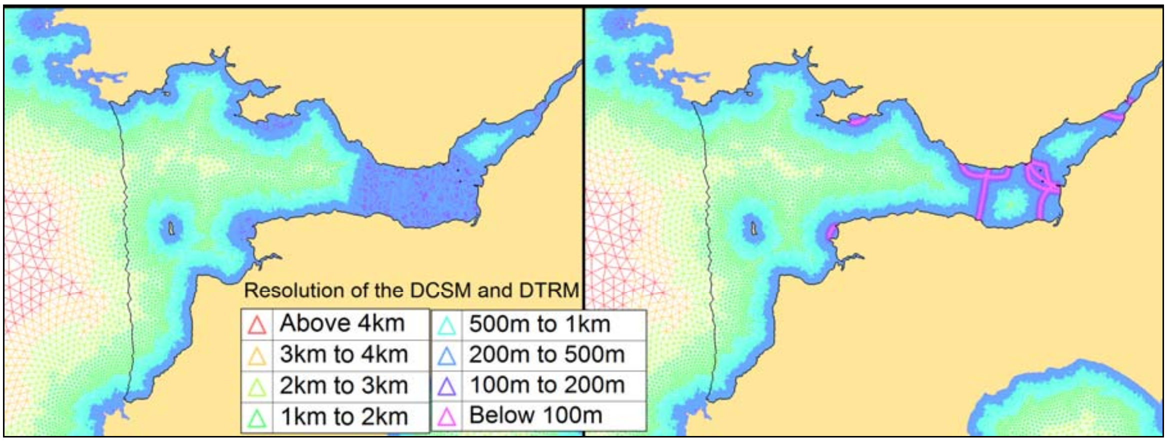


Figure 2 Extent and resolution of the DTRM in comparison to the DCSM

3.2.3 Boundary conditions of the Bristol Channel DTRM

TELEMAC-2D is driven by currents and/or water levels. In the Bristol Channel DTRM, time-varying water levels are applied along the tidal boundary. These were extracted for the prediction period from the calibrated and validated DCSM (base case scenario), at the common nodes with the Bristol Channel DTRM.

A radiative boundary condition (Thompson boundary setting, see Hervouet, 2007 and 2011) allows waves to leave the domain with little or no reflection. This ensures that the tidal boundary condition is still appropriate when the effects of the implementation of tidal range schemes reach the DTRM boundary.

3.2.4 Verification of the Bristol Channel DTRM

In keeping with the scope of works, the calibration of the DTRM was verified in relation to the full CSM. Only two of the tidal gauge stations used in the CSM calibration (refer MP02.06 – CSM (coarse and detailed versions) with supporting documentation) are located in the Bristol Channel / Severn Estuary: Hinkley Point and Avonmouth. The results of this analysis are presented in Appendix A.

It is apparent that the Bristol Channel DTRM agrees well overall with tidal levels observed (and re-synthesised) at Hinkley Point and Avonmouth. In all cases, the N-RMSE is 3% or less, which is comparable with the results obtained with the CCSM and with the DCSM, and well below the 10% target set in this study. The tidal range is well predicted at Hinkley Point. A slight shift toward higher levels is noted at Avonmouth. It is also shown that, at Avonmouth in particular, the Bristol Channel DTRM performs better than the CCSM and the DCSM against observed tidal levels (differences are expected because of the different resolutions of the models) as it highlights stronger effects due to seabed, which have not been picked up in the harmonic analysis for the re-synthesised water level trace. This has direct implications on the energy yield predicted by the DTRM and is, therefore, beneficial to the end-user for scheme optimisation. Overall the results presented in Appendix A confirm that calibration of the Bristol Channel DTRM is reasonable.

4 SCENARIO DEFINITION AND RESULTS FROM THE DTRM

4.1 Scenario definition

A sensitivity analysis to different tidal range technologies was carried out as part of this deliverable. Two technology options, conventional and low-head driven turbines designed by Rolls-Royce , were incorporated as part of the development of the CSM. As part of the development of the DTRM, developers of new (future) technologies were given the opportunity for their turbine characteristics to be included (and run) in the DTRM. We were not able to obtain appropriate data from any developers of new technologies. Rolls-Royce assisted by having discussions with contacts, who are apparently developing new technologies; however, they were not willing to provide data to the project. We also had contact with another developer, Snell (low-head turbine), through EDF; however, when this turbine was modelled in the 0-d model we established that the turbine data provided was not appropriate for large scale deployment. Snell is developing a larger scale turbine, but the timescales were not appropriate for inclusion in the DTRM runs.

Therefore, a sensitivity analysis was undertaken within the DTRM to test likely technology scenarios in the Bristol Channel and provide further information about the potential performance of the schemes in this model.

Each simulation is defined as a variation on an original scenario from the scenarios modelling provided in Deliverable D07 – Interactions (analysis and conclusions report), as summarised below:

- Simulation 1: Cardiff-Weston on its own with conventional turbines in ebb only mode – the aim is to provide a comparison of how the DTRM model performs in relation to the DCSM and the CCSM (vs. Additional Scenario 5 in D7a, due on 16th November 2012), as well as with other model outputs (further details in Section 4.3).

- Simulation 2: Cardiff-Weston on its own with Rolls-Royce turbines that are operating with pumping – the aim is to provide a comparison of how the DTRM model performs in relation to the DCSM and the CCSM (vs. Additional Scenario 8 in D7a due on 16th November).

- Simulation 3: Rhoose lagoon on its own with conventional turbines in dual mode – selected to review the potential of a single lagoon in the Severn Estuary.

- Simulation 4: Rhoose, Bridgwater and West Aberthaw with Rolls-Royce turbines in dual mode – selected to show the effect from a combination of lagoons.

It is noted that, prior to implementation in the full CSM, tests were performed in the TELEMAC 2-D flume model, much like was done in PM03.07 for all tidal range schemes, to ensure that pumping with Rolls-Royce turbines operated as intended. The agreement with the 0-D approach previously used in generating the parameterisation is demonstrated graphically in

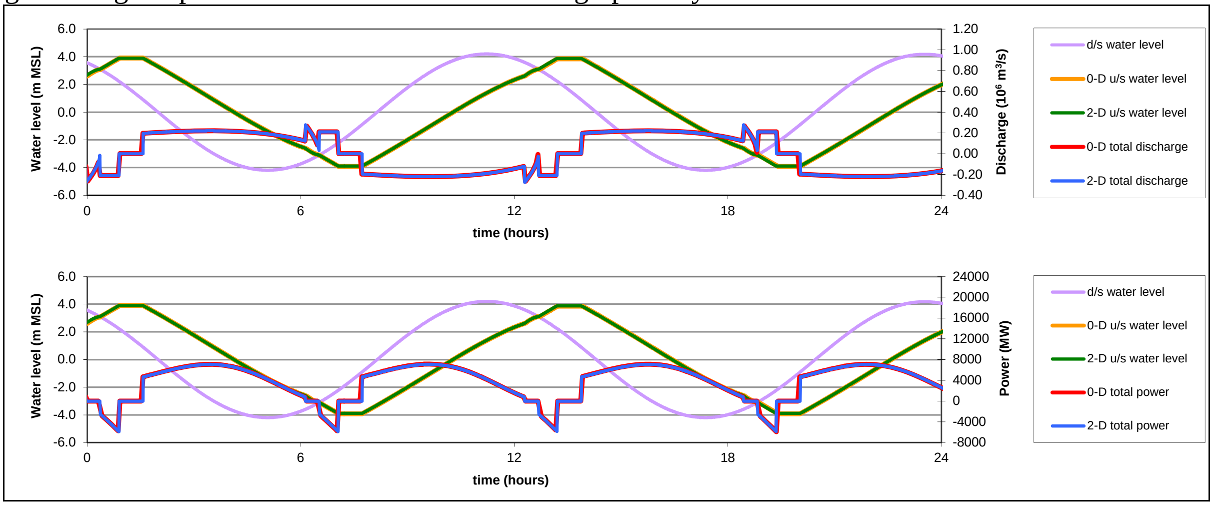
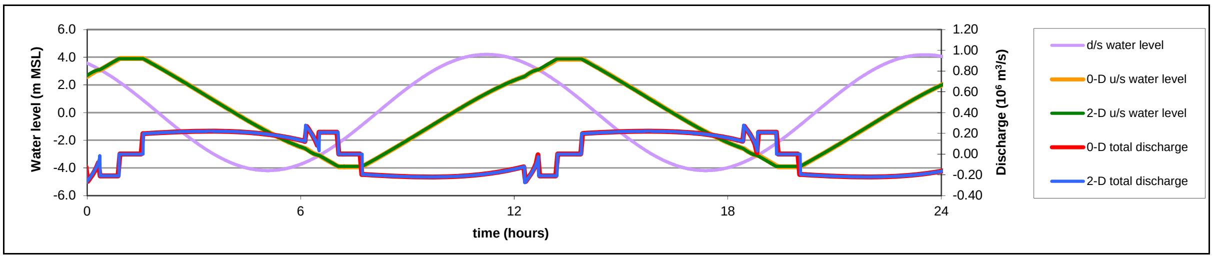


Figure 3. In this figure, the comparison between 0-D and 2-D (flume) results is shown in the form of time histories of water levels (both downstream and upstream), total discharge and total power. The excellent agreement shown in this figure demonstrates the correct implementation of the pumping algorithm and methodology in the model. This confirms functionality of the pumping algorithm in the 2-D system before it is incorporated into the DTRM for scenario runs.



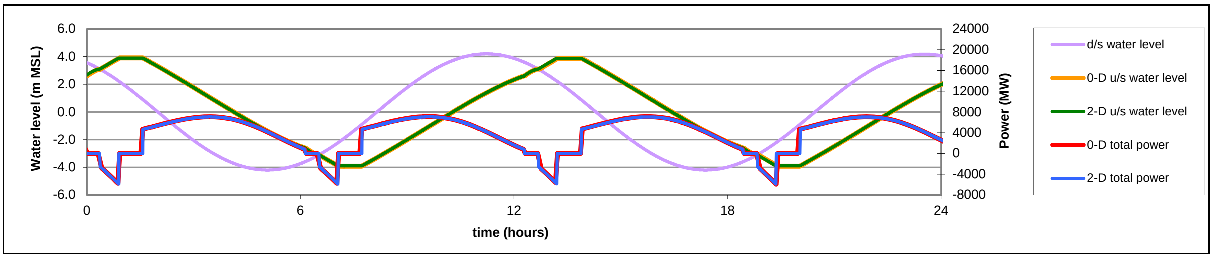


Figure 3 0-D vs. 2D flume. Implementation of pumping in the CSM

4.2 Outputs from the DTRM

The scenarios have been designed with the aim of testing the sensitivity of the DTRM and providing observations about the performance of a combination of schemes in relation to their performance in the DCSM/other models. It is noted that the DTRM would not be utilised to review far field effects and therefore these are not discussed here; however, the resulting impact on the change in tidal range within the DTRM itself can be viewed in maps within Appendix B.

Table 1 below summarises the energy yield outputs obtained from the test DTRM runs.

Table 1 Summary of DTRM scenario energy yield

	DTRM AEP results			
TWh/yr	1	2	3	4
Cardiff-Weston ebb only	15.00			
Cardiff-Weston RR pumping		14.98		
Rhoose dual			1.74	
Rhoose RR				1.06
Bridgwater Bay RR				4.28
Aberthaw RR				1.29

4.3 Discussion

Scenario 1 – Cardiff-Weston on its own with conventional turbines in ebb only mode

This is a test run to provide an indication of the performance of the DTRM in relation to previous more detailed analysis on the Severn Estuary that was completed by Black & Veatch as part of the Severn Tidal Power Strategic Environmental Assessment (SEA) Options Definition commissioned by DECC (3).

It is noted that as part of a modelling process it is required to make adjustments to the power output to account for known aspects which the modelling does not account for. For example, in the modelling completed for DECC, final adjustments were made to account for the impact of plant availability outages (5% reduction). Clearly, like-for-like comparisons are needed and discussed here.

In the DECC SEA Options Definition report, two 2D models were run and there was c.10% error in Annual Energy Production between the two modelling outputs where underlying bathymetry data and mesh resolution were the same. In that large scale study, the reason for that variance was never fully established and this highlights (to any non-modelling expert) the unknowns associated with the hydrodynamics of a tidal system. This level of variance is therefore quite likely, once all the known issues about underlying data inputs are dealt with and anaylsed.

A range of Annual Energy Production is provided in the SEA Options Definition report, which indicates for Cardiff-Weston with ebb only generation the range is 15.9-17.9TWh/yr (excluding outages). The DTRM Scenario 1 produces 15.00TWh/y, which is 5-15% lower.

The variation in the results between the DTRM and the DECC SEA Options Definition modelling is believed to be due to the difference in resolution of the bathymetry data in the intertidal zone. The DECC modelling incorporated very detailed bathymetry data collated from LIDAR, port authorities and local organisations. This data was not obtained for the ETI modelling work due to the complexity of gathering, licensing and combining large data sets. It is also beyond the resolution in the scope of works for a pre-feasibility tool. Increasing the resolution of the model and the underlying bathymetry would have the effect of increasing the storage volume of the Cardiff-Weston barrage and therefore we believe is likely to result in higher energy yields, more in line with that obtained in the SEA Options Definition report.

The 0D model results produced for this project for the Cardiff-Weston ebb only scheme indicate that there is a c. 20% reduction in the 2D modelling results. A reduction from 0D to 2D modelling is expected and are discussed in Deliverable D01.

Scenario 2 – Cardiff-Weston with Rolls-Royce low head turbines operating with pumping.

The inputs to the 0D modelling parameterisation were agreed with Rolls-Royce prior to commencement of this scenario run. 0D modelling is known to produce a potentially higher energy yield with pumping by theoretically increasing the water level upstream at high tide and decreasing the water level in the basin at low tide. The impacts of this have therefore been tested by 2D modelling.

The initial operational conditions provided from the 0D model for this run were not successfully run in the 2D DTRM on the first two attempts and an iterative process to update operating levels was undertaken to provide a reasonable operating scheme. The scheme worked; however, it is noted that further optimisation is required. To demonstrate this from the results it can be seen from the model outputs (Figure 4) that pumping is not having as much as the desired effect (as expected from 0D modelling) on increasing the levels in the basin at high tide and decreasing the levels at low tide to maximise the water movement through the turbines. In Figure 4, the red line represents the water levels downstream of the impoundment and the blue line represents the water levels upstream of the impoundment (i.e. basin level) - see D01, Chapter 4, for a full explanation. The aim with pumping is to increase the generating heads within the basin therefore increasing the blue peaks to be as high and the blue troughs to be as low as possible. This scenario, as intended, shows pumping can be incorporated into the modelling but as operating regimes including pumping are extremely sensitive this requires considerable optimisation.

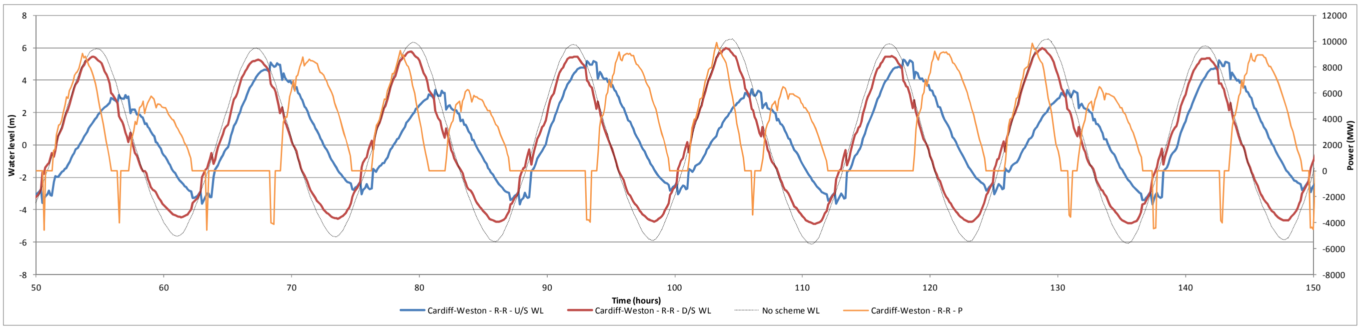


Figure 4 Cardiff-Weston with Rolls-Royce turbines operating with pumping (DCSM)

N.B See Appendix C for a larger version of Figure 4,

The energy output achieved with this in the model is 14.98TWh/y which is clearly in line with the Cardiff-Weston ebb only scheme in Scenario 1. There is likely to be some additional potential from optimisation of the scheme, and the bathymetry, per Scenario 1, will be having an impact. However, it is likely that there is a reduction of energy from the 2D model compared to 'flat' water 0D modelling (20.8TWh/y) because of the 2D effects/losses. During the transfer of water, throughout the cycle, as the turbines are pumping to fill or empty the basin, there are losses associated with the water moving around or 'sloshing' which are not reflected in the 0D model. This is discussed in the D01 report (Chapter 4) which B&V's opinion of overestimation of energy production from pumping schemes when using 0D modelling.

This run has demonstrated that the DTRM can incorporate pumping and that some optimisation can be completed within this model prior to a, recommended, run in the DCSM.

Scenario 3 – Rhoose with conventional turbines in dual mode

The energy output from the Rhoose scheme is 1.74TWh/y using conventional bulb turbines in dual operational mode. This is slightly lower than the 0D modelling results and therefore as we would expect (because, as described above for Scenario 2, there are losses associated with a 2D system which are not accounted for in 0D modelling). In the D07 report, the Rhoose (with conventional turbines in dual mode) was run in a number of schemes along with the Severn Cardiff-Weston, which resulted in a lower energy yield of c.1.2TWh/y (these results are not comparable due to the inclusion of the Cardiff-Weston barrage but are for information only).

Scenario 4 - Rhoose, West Aberthaw and Bridgwater Bay all operating with Rolls-Royce turbines

This scenario was run to provide a test case for multiple lagoons operating within the Severn Estuary. As highlighted in D07, the in-estuary effects of the Severn are larger than for some other estuaries because of the close proximity of schemes, particularly when there is a barrage installed due to the extreme effects on the surrounding resource compared to a lesser impact from lagoons as demonstrated when Cardiff-Weston is incorporated (DCSM runs in D07 and D07a)

The results for Bridgwater Bay lagoon with Rolls-Royce turbines show an energy yield of 4.28TWh/y, which is c.3% higher than the 0D modelling results when combined with Rhoose and West Aberthaw. An additional run variation was completed with only Rhoose and West Aberthaw. The energy yields from these two schemes are as expected and slightly lower than 0D modelling results. When Bridgwater Bay lagoon is incorporated with Rhoose and West Aberthaw there is a c. 1%-3% decrease in energy yield from the Rhoose and West Aberthaw schemes.

5 KEY FINDINGS

- The Bristol Channel DTRM was designed to interface with the DCSM, in compliance with specification document PM04.08. As such, its offshore boundary was fitted to elements of the DCSM mesh. Its resolution, however, is superior with areas corresponding to the three strategic regions in the Bristol Channel being well resolved, and at a resolution of c. 50 m.

- In keeping with the scope of works, the calibration of the Bristol Channel DTRM was verified at Hinkley Point and Avonmouth in relation to the full CSM. This analysis demonstrated that the DTRM agrees well with the DCSM and the CCSM with N-RMSE around 3% or less, which is well below the 10% target set in this study. At Avonmouth, it also agrees more closely with observed tidal levels than the DCSM and the CCSM. This has direct implications on the energy yield predicted by the DTRM and is, therefore, beneficial to the end-user for scheme optimisation.

- Close examination of the data showed that the tidal synthesis was not quite able to reproduce the complexity of the observed level traces, in particular at Avonmouth, where seabed effects, evident at low water, are not well represented. Comparison against observed data, as opposed to re-synthesised data (refer PM02.06B – CSM (coarse and detailed versions) with supporting documentation), is therefore deemed more true to the performance of the models in the Bristol Channel and the DTRM performs better than the DCSM, due to its higher resolution, as expected.

- Computing time for a 14 day simulation of the Bristol Channel DTRM is c. 6 hours on 3 cores. This compares very favourably to the 12 hrs guaranteed run time on a multi-core computer.

- The DTRM slightly under predicts energy yield for the Severn Cardiff-Weston in ebb only mode in comparison to the range of results presented from DECC SEA Options Definition report. The reason for this is likely to be the less detailed bathymetry in the DTRM.

- Pumping has successfully been incorporated into the model; however, as expected it requires optimisation in order to be able to draw firm conclusions about its net economic benefit.

- Lagoons are well represented in the model and the results indicate that there is a substantial improvement in performance when the Severn Cardiff-Weston barrage is removed from the scenarios. This suggests that lagoons that are physically able to be implemented in conjunction with other larger and more long-term schemes may still suffer significant degradation in energy production if such larger schemes are later implemented nearby.

6 CONCLUSIONS

It is apparent that the Bristol Channel DTRM agrees well overall with tidal levels observed (and re-synthesised) at Hinkley Point and Avonmouth. In all cases, the N-RMSE is 3% or less, which is comparable with the results obtained with the CCSM and with the DCSM, and well below the 10% target set in this study. The tidal range is quite well predicted at Hinkley Point. A slight shift toward higher levels is noted at Avonmouth. This is reflected in the lesser MAE and N-RMSE values (compared to Hinkley), and could partly be attributed to the more detailed representation of the bathymetry up the estuary.

The 4 test simulations carried out have indicated that there is a good representation of the scenarios against the 0D modelling and against existing Severn models for the Cardiff-Weston.

Key findings regarding the simulations have developed; however, we would recommend that batch runs of the DTRM are completed in order to optimise each of the scenarios if the results are to be used as the basis for more detailed work.

REFERENCES

1 - Hervouet J.M. (2007). *Hydrodynamics of Free Surface Flows: Modelling with the Finite Element Method*. Wiley Blackwell. 360p. ISBN-13: 978-0470035580.

2 - Hervouet J.M., Denis C. and David E. (2011). *Revisiting the Thompson boundary conditions*. XVIIIth TELEMAC & MASCARET User Club Conference, Proceedings. 153p. October 2011.

3 - Strategic Environmental Assessment Of Proposals For Tidal Power Development In The Severn Estuary Options Definition Report, Version 3, Volume 1.

GUIDE TO APPENDICES

Appendix A – The Bristol Channel DTRM calibration
Appendix B – The Bristol Channel DTRM scenarios
Appendix C - Cardiff-Weston with Rolls-Royce turbines operating with pumping (DCSM)

APPENDIX A – THE BRISTOL CHANNEL DTRM CALIBRATION

In keeping with the scope of works, the calibration of the DTRM was verified in relation to the full CSM (both the CCSM and the DCSM). This analysis is presented in Figures A1 and A2 in the form of time history plots comparing the predicted and observed water level traces over the full 15-day calibration period. In these plots, the horizontal axis is time; the vertical axis is free surface elevation in m. To aid visualisation of the results, the vertical axis was coloured according to range (bright blue for ±8 m, and red for ±12 m). The tidal levels predicted by the Bristol Channel DTRM are indicated as a thick blue line, those predicted by the CCSM/DCSM as thick brown or orange lines respectively. The observations are represented by a thick light green line. The levels obtained by tidal re-synthesis of observed levels are shown as black crosses for the same period.

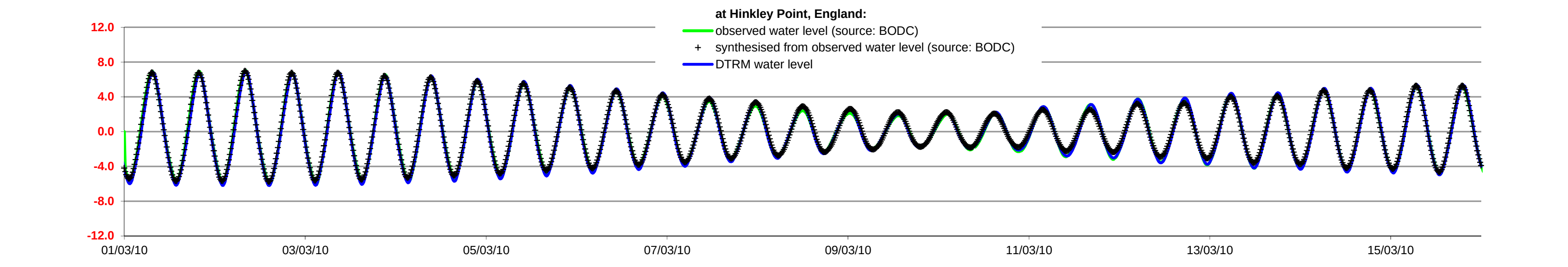
It is noted that only two of the tidal gauge stations used in the DCSM calibration (refer PM02.06B – CSM (coarse and detailed versions) with supporting documentation) are located in the Bristol Channel / Severn Estuary: Hinkley Point and Avonmouth. The results for these stations are presented in Figure A1 and Figure A2 respectively.

For reference, the *mean absolute error* (MAE) and *normalised root-mean-square error* (N-RMSE) values obtained for the DCSM and for the Bristol Channel DTRM are provided. These are relative to the re-synthesised data as was the case in PM02.06B, as well as to the observed data, because observations are available concurrently to the calibration period at Hinkley Point and Avonmouth.

It is apparent from these metrics, and from the time history plots, that the Bristol Channel DTRM agrees well overall with tidal levels observed (and re-synthesised) at Hinkley Point and Avonmouth. In all cases, the N-RMSE is 3% or less, which is well below the 10% target set in this study. The tidal range is well predicted at Hinkley Point. A slight shift toward higher levels is noted at Avonmouth. This is reflected in the lesser MAE and N-RMSE values (compared to Hinkley), and could partly be attributed to the representation of the bathymetry up the estuary.

Closer examination of the data shows that the tidal synthesis was not quite able to reproduce the complexity of the observed level traces. This is in particular relevant for Avonmouth, where seabed effects, evident at low water, are not well represented by the harmonic constituents extracted. It is, therefore, deemed that comparison of the DTRM against observed data, as opposed to re-synthesised data (refer PM02.06B), is more true to the performance of the models in the Bristol Channel. In that regard, the Bristol Channel DTRM performs better than the CCSM and the DCSM against observations at Avonmouth (differences are expected because of the different resolutions of the models). This confirms calibration of the Bristol Channel DTRM. It also has direct implications on the energy yield predicted by the DTRM and is, therefore, beneficial to the end-user for scheme optimisation.

It is noted that, in this analysis, an adjustment of 15 min was made on the predicted level trace on the basis that the boundary conditions are only known to the nearest 15 minutes, and that agreement with observations was improved (all resolution versions of the CSM/DTRM) by doing so. This could not be implemented earlier for the CSM, being a global scale model.



Against synthesised water levels

	MAE	N-RMSE[1]
DTRM	0.36 m	3%
DCSM	0.30 m	3%
CCSM	0.26 m	3%

Against observed water levels

	MAE	N-RMSE
DTRM	0.22 m	2%
DCSM	0.20 m	2%
CCSM	0.21 m	2%

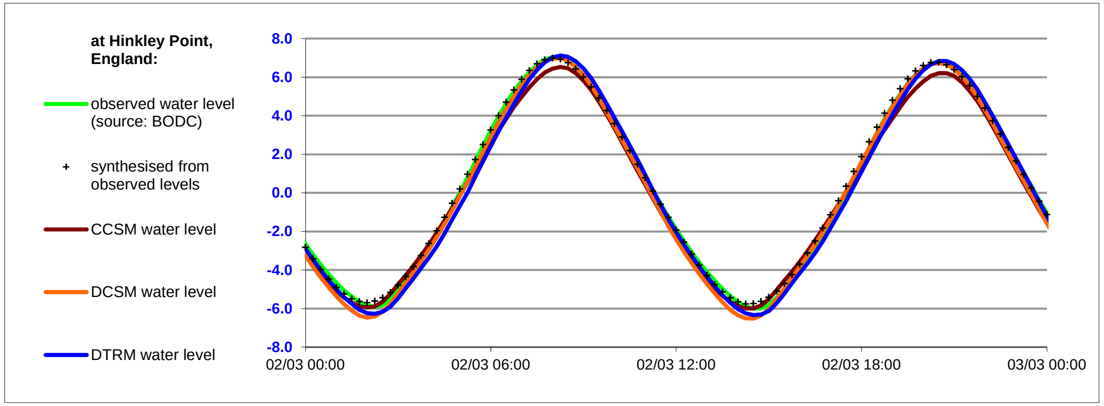
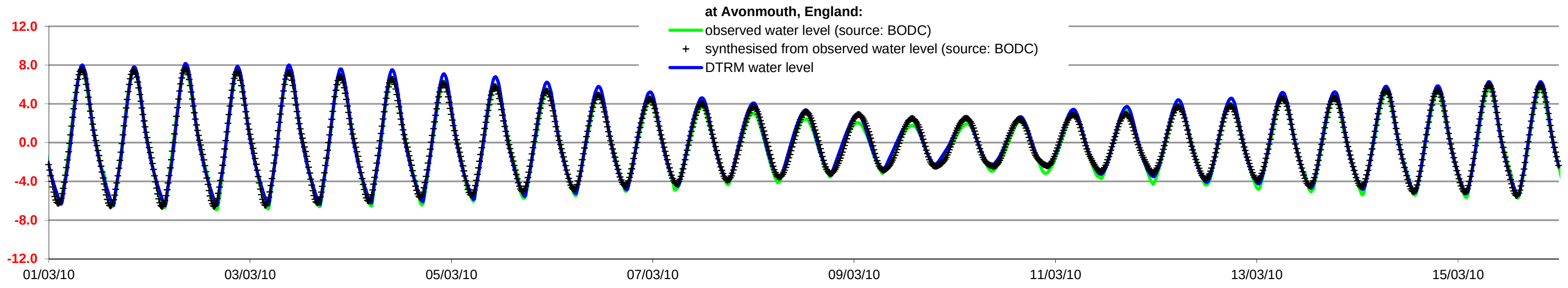


Figure A1 – Bristol Channel DTRM comparison against observed and synthesised data at Hinkley Point, England

[1] The N-RMSE is expressed relative to the maximum tidal range in the calibration period.



Against synthesised water levels

	MAE	N-RMSE[2]
DTRM	0.40 m	3%
DCSM	0.40 m	3%
CCSM	0.42 m	3%

Against observed water levels

	MAE	N-RMSE
DTRM	0.36 m	3%
DCSM	0.42 m	3%
CCSM	0.50 m	4%

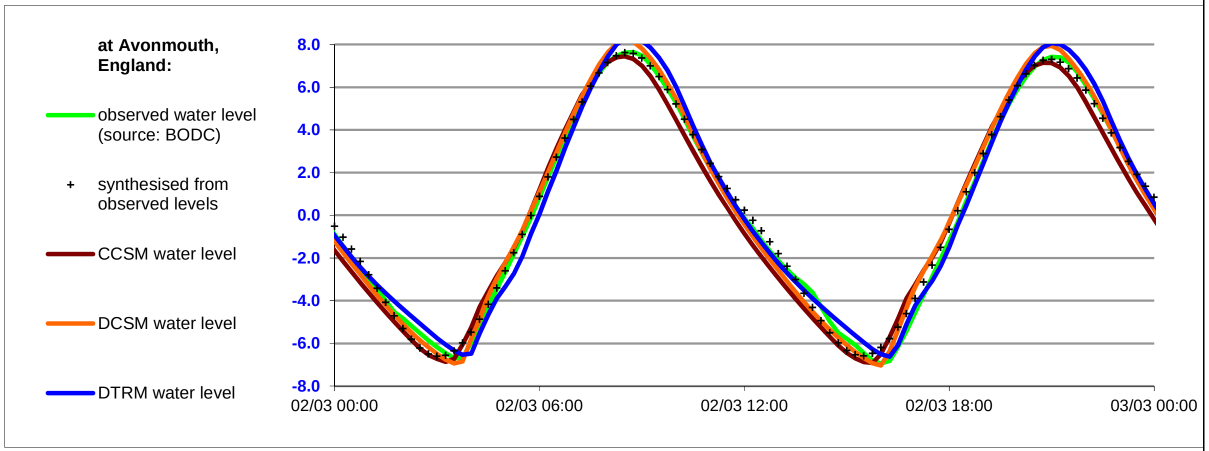


Figure A2 – Bristol Channel DTRM comparison against observed and synthesised data at Avonmouth, England

[2] The N-RMSE is expressed relative to the maximum tidal range in the calibration period.

APPENDIX B – THE BRISTOL CHANNEL DTRM SCENARIOS

Simulation 1: Cardiff-Weston on its own with conventional turbines in ebb only mode – the aim is to provide a comparison of how the DTRM model performs in relation to the DCSM and the CCSM (vs. Additional Scenario 5 in D7a, due on 16th November 2012), as well as with other model outputs (further details in Section 4.3).

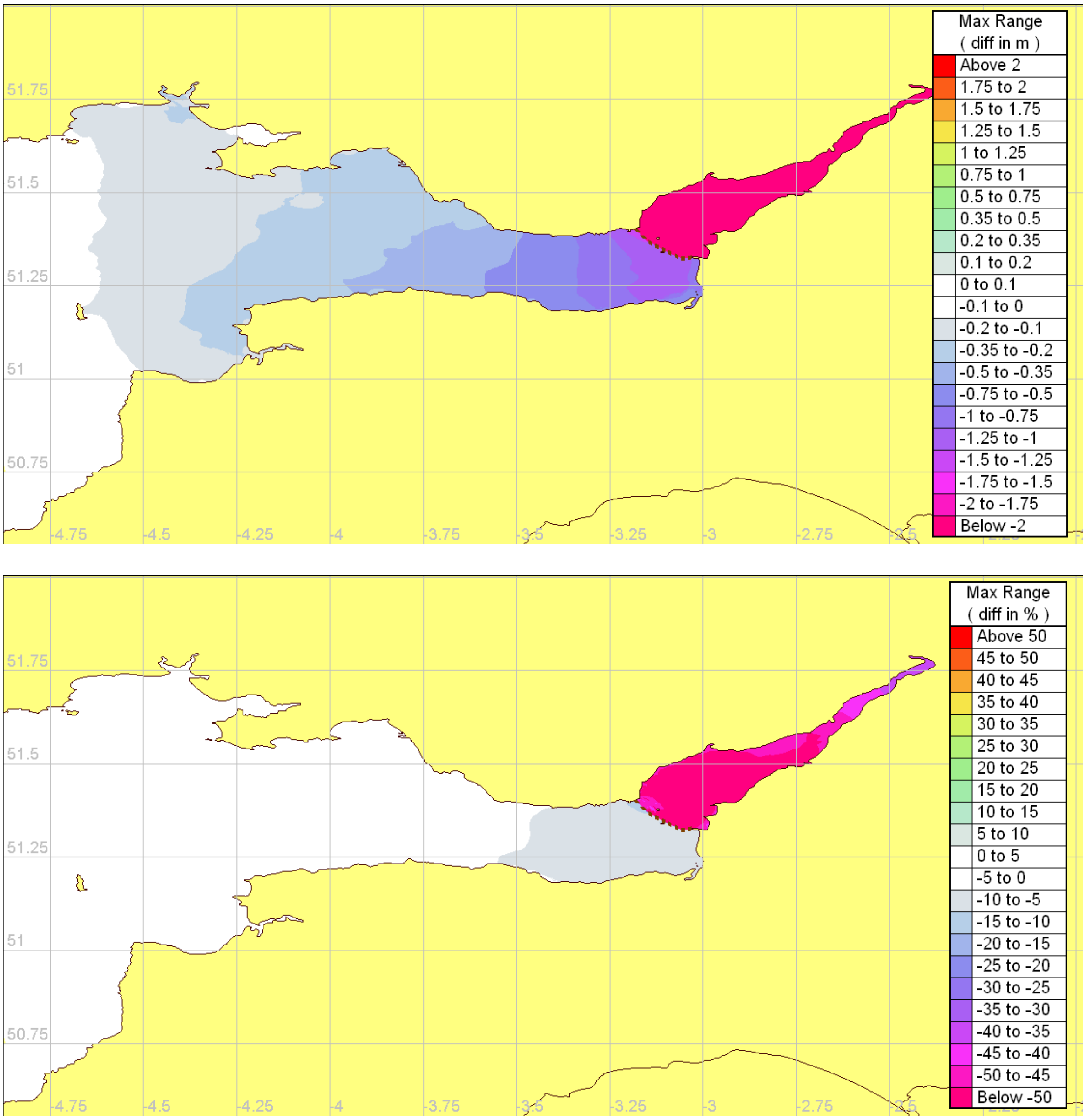
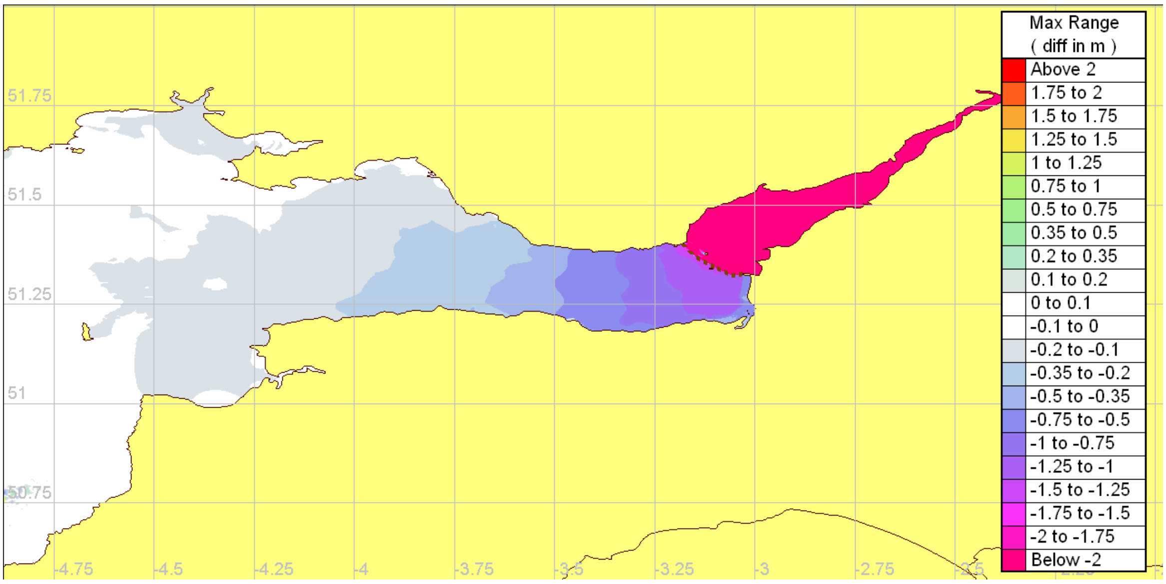


Figure B1 – Bristol Channel DTRM, Results of Simulation 1

Simulation 2: Cardiff-Weston on its own with Rolls-Royce turbines operating with pumping – the aim is to provide a comparison of how the DTRM model performs in relation to the DCSM and the CCSM (vs. Additional Scenario 8 in D7a due on 16th November).



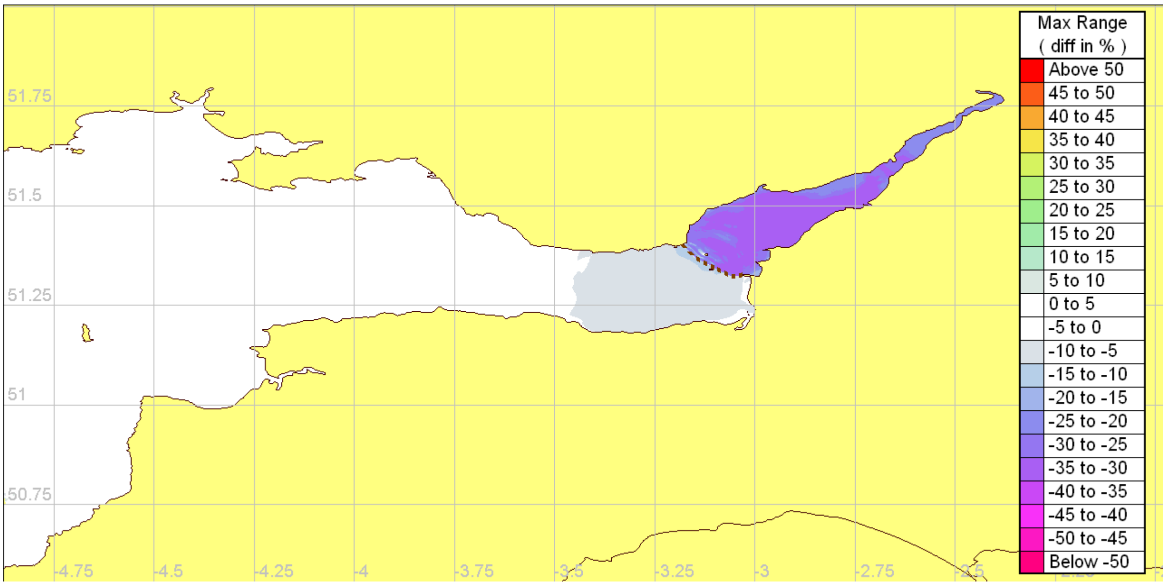


Figure B2 – Bristol Channel DTRM, Results of Simulation 2

Simulation 3: Rhoose lagoon on its own with conventional turbines in dual mode – selected to review the potential of a single lagoon in the Severn Estuary.

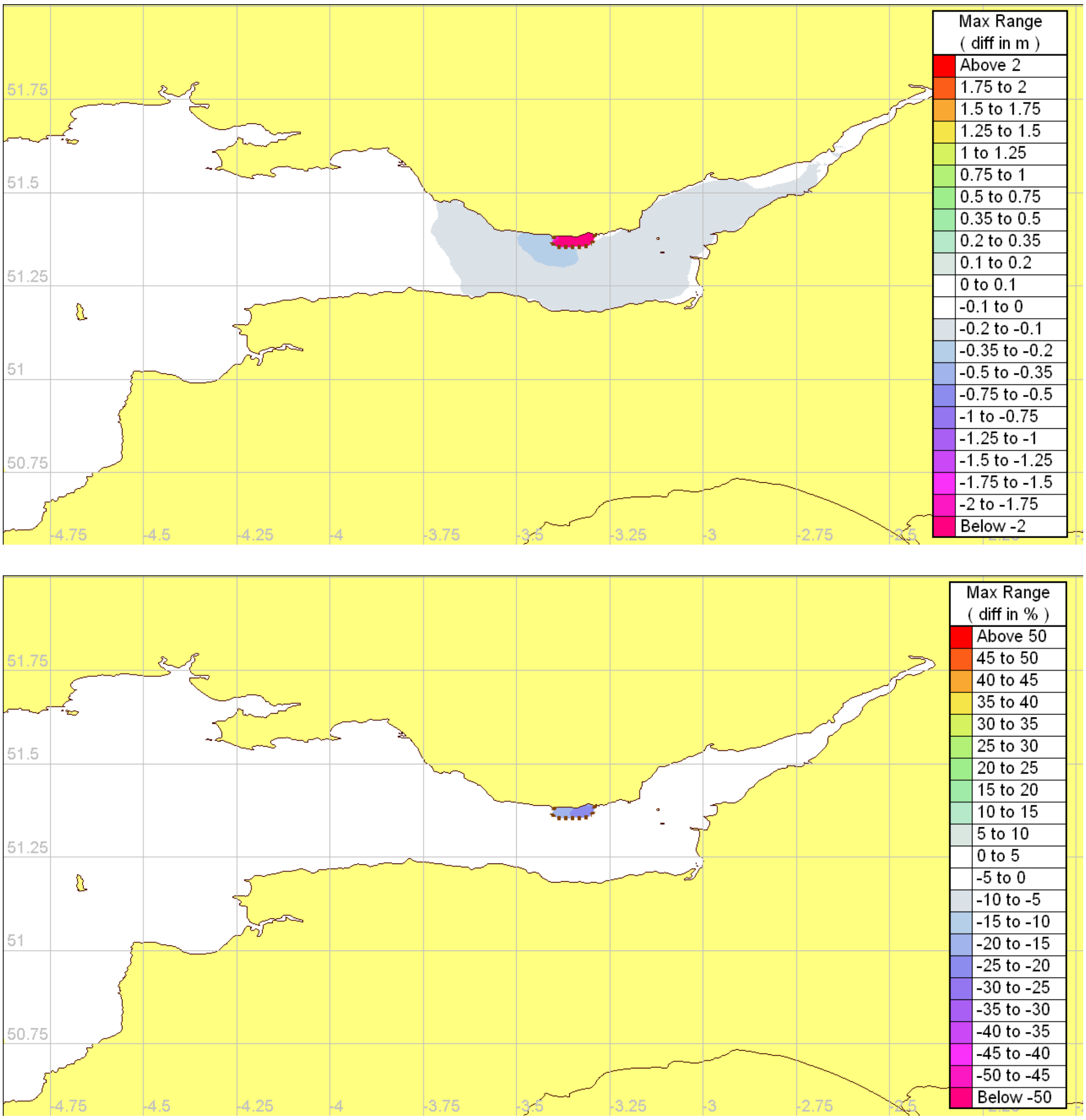
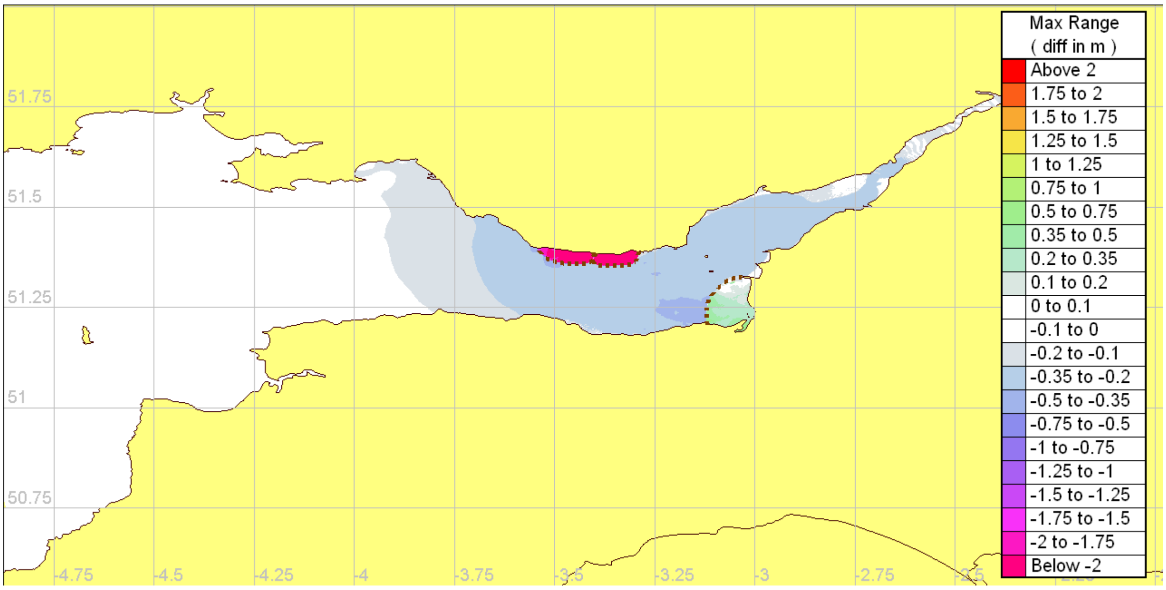


Figure B3 – Bristol Channel DTRM, Results of Simulation 3

Simulation 4: Rhoose, and West Aberthaw with Rolls-Royce turbines in dual mode – selected to show the effect from a combination of lagoons.



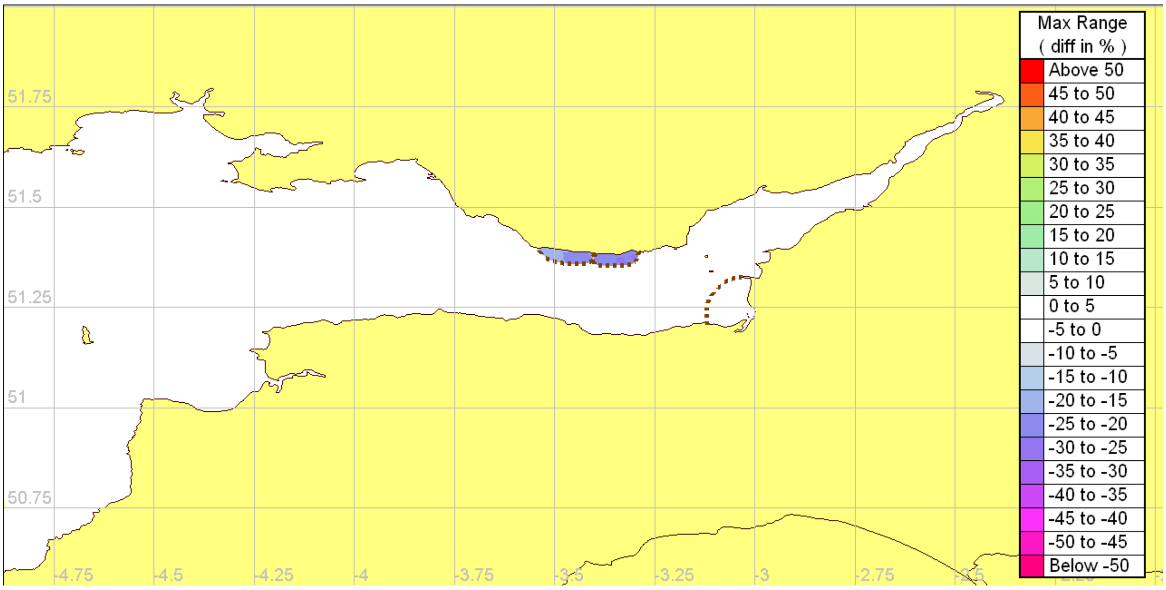


Figure B4 – Bristol Channel DTRM, Results of Simulation 4

Appendix C - Cardiff-Weston with Rolls-Royce turbines operating with pumping (DCSM) (as per Figure 4).