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An Optimal Calibration Procedure for a TELEMAC-2D Model of the Eastern Coast of Ireland

Garrett Keane
Technological University Dublin, garrett.keane@tudublin.ie

Andrew Stokes
Technological University Dublin

Zeinab Bedri
Technological University Dublin, zeinab.bedri@tudublin.ie

See next page for additional authors

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Authors
Garrett Keane, Andrew Stokes, Zeinab Bedri, and John O'Sullivan

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Garrett Keane, Andrew Stokes
School of Civil and Structural Engineering
Dublin Institute of Technology
Dublin, Ireland
garrett.keane@dit.ie

Zeinab Bedri, John J. O'Sullivan
School of Civil, Structural and Environmental Engineering
University College Dublin
Dublin , Ireland

Abstract—**A review of the literature shows that most model calibrations involve the adjustment of the bottom friction coefficient to minimise the error between predicted and measured tidal elevations. In this study, an alternative procedure is adopted when calibrating a Telemac2D model covering an area on the Eastern coast of Ireland. The model is forced with eight principal tidal constituents derived from the MIKE 21 global model. It is calibrated separately for the two principal constituents, M2 and S2. The field data comprises tidal elevations recorded at five locations over a full lunar cycle in October 1998 and Spring and Neap current data.**

At each node on the open boundary, the M2 amplitude supplied by Mike21 is adjusted by one of five possible amplitude multipliers (0.8,0.9,1.0,1.1,1.2) while the phase is shifted by eight possible values (-15°,-10°,-5°,0°,+5°, 10°,15°,20°). An amplitude multiplier of 1.05 and phase shift of 12.5° corresponding to the lowest error is determined by plotting the minimum error for a total of 40 simulations. The S2 tide calibration also requires 40 simulations.

Alternative strategies are investigated to reduce the total number of simulations. The application of the method of steepest descent reduces the number of required simulations to eleven.

In another approach, the amplitude modifier and the phase shift can be calibrated separately as it is shown that the amplitude modifier had minimal effect on the phases and the phase shift has negligible effect on the amplitudes. The calibration requires just five simulations to find the optimum amplitude multiplier and eight for the optimum phase shift. The friction parameter is calibrated separately using measured Spring and Neap tidal currents.

I. INTRODUCTION

The objective of a hydrodynamic modelling study is to predict the tidal elevations and currents as accurately as possible at regions of interest within the model domain such as estuaries or coastal areas. The common components of a model are the bathymetry, the bottom friction model and its selected value(s), the turbulent viscosity model and its selected value(s) and the application of tidal elevations or currents (or both together) at the open boundaries to force the model. Each one of these model inputs can have an impact on the accuracy of the model predictions.

A. Bathymetry

Bathymetric data may be derived from many sources. Digital data derived from Admiralty Charts can be sourced from a number of commercial companies such as the SeaZone division of HR Wallingford or the charts can be digitised directly. In some cases, these charts are outdated as a significant time has elapsed since the underlying hydrographic studies were undertaken. In Ireland, large sections of the seabed around the coast and in the Atlantic Ocean have been recently mapped as part of the ongoing INFOMAR programme ('**IN**tegrated Mapping **FO**r the Sustainable Development of Ireland's **MA**rine **R**esources'), jointly administered by the Geographical Survey of Ireland and the Marine Institute. This program aims to create a range of integrated mapping products of the physical, chemical and biological features of the seabed in the near-shore area. The necessity to invest time and effort into ensuring the accuracy of the bathymetry is emphasized by Bourban et al. [4] who state that "Based on experience with hydrodynamic models, the parameter with the most impact on model results is the bathymetry".

B. Friction

In the aforementioned study which describes the development and calibration of a large scale coastal shelf model of Northern European waters, the conclusion is reached that while the particular formulation of bottom friction is not important, the predicted water levels and current speeds depend significantly upon the value of the parameter applied. Also, the current speeds in some locations are dependent on the value of the turbulence viscosity. In estuaries, a common feature is the energy dissipation due to friction as waves travel landward from the lagoon mouth. In their model of the Ria de Aveiro lagoon located in the northwest of Portugal, Dias and Lopez [10] found that the magnitude of the bottom friction is a major influence on the tidal range variation due to its complex geometry, characterised by narrow channels and large areas of mud flats and salt marshes.

C. Boundary Conditions

A Telemac model is driven by applying time histories of tidal elevations or currents (or a combination of these) at the seaward boundaries. While in some cases, measured data is used, most models are essentially nested models in which the open boundary data is supplied from a coarser model covering a larger area. The Extended Dublin Bay model developed by Hussey [12] was driven using six primary tidal constituents supplied by the Delft Irish Sea model. The accuracy of this data close to the Irish coast was uncertain as the model was calibrated using a large number of tidal gauges on the western coast of the United Kingdom. Tidal constituents were supplied at 24 points along the seaward boundaries of the refined model and linear interpolation was used for the intermediate points.

More recently, tidal data can be sourced from global tidal models such GOT4.7, FES2012, EOT10a, TPXO7.2, HAMTIDE and the DTU10 model developed at the Technical University of Denmark [6]. These models have a RMS (root mean square error) accuracy of less than 3 cm in the open ocean [1]. In many cases, these models are based on satellite data from the TOPEX/Poseidon (Jason 1 and Jason 2) programmes. The global models are reported to be far less accurate in coastal areas with shallower waters. In a paper outlining the development of the DTU10 model, a RMS of 1.23cm was calculated for the model output when compared to an ocean data set comprising 102 gauges in deep water. A much larger value of 12.58cm was calculated when the output was compared to a set of 195 gauges (primarily coastal) covering the northwest European shelf region [6].

D. Numerical Errors

Numerical errors associated with the modelling process itself must also be considered. Simplifying assumptions are made in the derivation of the depth-averaged Saint Venant's equations solved in Telemac2D. In general, numerical schemes tend to introduce artificial numerical diffusion while the choice of the element size is linked to discretisation errors.

II. REVIEW OF CALIBRATION METHODS

It is within the context that there are multiple sources of modelling error that the calibration process must be considered. Model calibration is a process in which any of the model inputs discussed above can be modified to reduce the variances between model predictions and field measurements of surface elevations and current velocities. The modeller should always critically evaluate the field measurements as inaccuracies are possible.

The field data are most beneficial when the measuring stations are well dispersed over the geological spread of the domain. Ideally, the calibration should be achieved while avoiding unrealistic values of parameters. The calibration methods and the number and type of measurement gauges employed in fifteen modelling studies are listed in Table 1. The review clearly indicates that the adjustment of the bottom friction parameter is the most common method.

TABLE 1 PAPER REVIEW OF CALIBRATION METHODS

Paper	**Calibration Method**	**Gauges**
Bedri [2]	Chezy Value	5 tidal 8 velocity
Blumberg [3]	Adjusting inverse shoaling coefficient, the sub-grid scale horizontal mixing coefficient and bottom frictional drag coefficient	14 tidal 6 velocity 35 salinity 35 temp.
Bourban [4]	Bed friction parameter, globally and locally Turbulent viscosity	65 tidal
Cawley [5]	Manning's n	
Cornett [7]	Strickler's roughness coefficient	2 tidal
Dias [9]	Depth dependent Manning's n	22 tidal
Giardino [11]	Bottom friction parameter	2 tidal 4 velocity
Hussey [12]	Calibrated elevations by adjusting the harmonic constants at the open boundaries and calibrated velocities by adjusting a depth dependent Manning's n value.	5 tidal 8 velocity
Huybrechts [13]	Strickler's roughness coefficient	2 tidal
McAlpin [16]	Global Manning's n value of 0.023	2 tidal
Nguyen [17]	Adjustment of the turbulent viscosity and uniform Chézy coefficient.	14 tidal
Pasquale [18]	Remote sensing imagery.	N/A
Picado [19]	Depth dependent Manning's n, 0.042 @-2m to 0.015 @ 10m	14 tidal
Sousa [20]	Adjustment of bottom friction coefficient	17 tidal
Umgiesser [21]	Strickler's roughness coefficient	12 tidal

There is a possibility that the adjustment of friction coefficient values locally in order to manipulate the model outputs can cause artificially distorted or unnatural results at other locations in the models domain [17]. It is important to preserve as much of the natural characteristics of the model domain as possible in order to reproduce a model that is as environmentally accurate as it is numerically accurate. In some cases a friction coefficient can be chosen that is either higher or lower than the natural bottom stress actually acting on the wave. It is possible that part of this change in coefficient has some physical meaning elsewhere in the model. An error elsewhere in the model could be shielded by an adjusted friction coefficient [13]. For example the use of recent sea surface elevations being used during calibration, when the source used to obtain the bathymetry of a model may be outdated.

The approach taken in the Extended Dublin Bay model was to first calibrate the tidal elevations by adjusting the open boundary conditions and then to calibrate the velocities by adjusting a depth dependent Manning's n-value [12]. The calibrated tidal constituents from this study were used to force a Telemac-2D model of the same model domain which was developed to provide boundary conditions for a nested TELEMAC3D model of Dublin Bay, the boundary of which is shown in Fig. 2 [2]. The velocities in the Telemac2D model were calibrated by adjusting the Chezy value, yielding a value $50m^{½}/s$.

III. East Coast Model

A. Model Domain

As part of an INTERREG IV study (Ireland and Wales) investigating the Dargle Basin catchment area in County Wicklow, a coastal model incorporating the town of Bray in north Wicklow was required. As the existing Extended Dublin Bay model had to be extended southwards, it was decided at this stage to also expand it northwards and eastwards out to sea to incorporate other regions of interest. The model spans from Skerries in North Dublin down as far as Wicklow Head. The mesh shown with depths in Fig. 3 has 43,896 nodes.

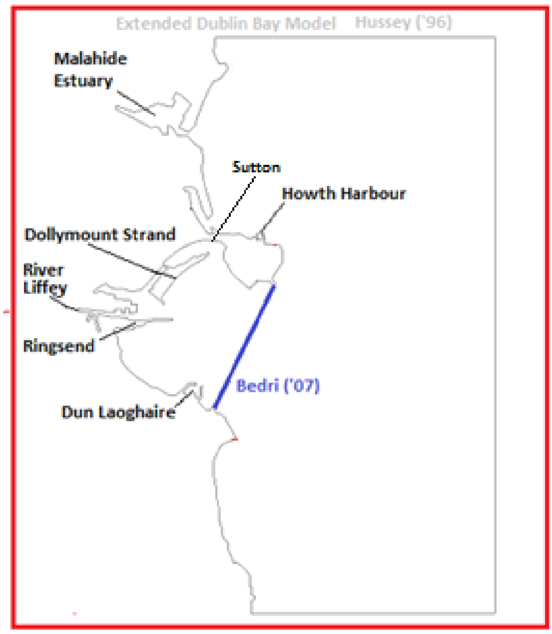

Fig 2. Extended Dublin Bay Model

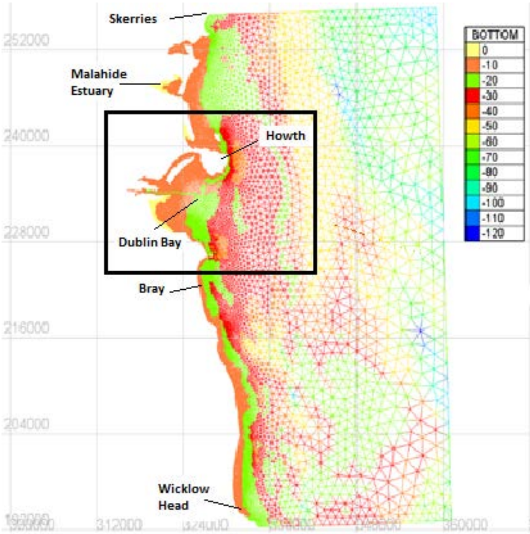

Fig 3. Mesh and Bathymetry of East Coast Model

B. Field Measurements

The field data used for comparison purposes consists of the surface elevations at five locations (A to E on Fig 4) and current measurements at eight locations (1 to 8 on Fig. 4). The black box in Fig. 3 marks the location of the gauges detailed in Fig. 4. It shows how they are concentrated around Dublin Bay and Howth. A better geographical spread of gauges is preferable.

1) Tidal Elevations

The tide at the Kish lighthouse (E) was recorded over a full lunar cycle between the 29th September and the 31st October in 1989 by Irish Hydrodata Ltd. An Aanderaa Water Level Sensor was placed on the western side of the Kish lighthouse and a harmonic analysis was performed on the recorded time series to extract the tidal constituents [15]. In addition, the tidal constituents were extracted using harmonic analysis of the data recorded during the same period at the four fixed tidal gauges at North Wall (A), North Bank Lighthouse (B), Dun Laoghaire (C) and Howth Harbour (D).

2) Tidal Currents

Tidal currents are available at eight locations. Irish Hydrodata Ltd carried out a survey as part of the Howth Outfall Study [14]. Current speeds and directions were recorded at five depths (0.1, 0.3 0.5, 0.7 and 0.9 of the water depth) at four locations in the Howth area. The measurements were recorded for full neap and spring (or mid spring) tidal cycles. The four locations are numbered 1 to 4 in Fig. 4.

A set of current measurements were recorded at four locations in Dublin Bay in an earlier environmental study conducted by the University of Wales between 1972 and 1976 [8]. Two current measurements were recorded at each location, one 3.05m above the seabed and the other 3.05m below the surface. In most cases, the surveys spanned a full tidal cycle. These are numbered 5 to 8 in Fig. 4.

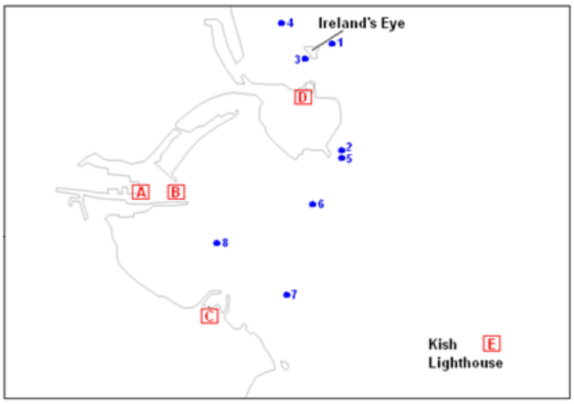

Fig 4. Location of Field Measurement Gauges

C. Boundary Conditions

The predominant tidal constituents in the Irish Sea are the M2, S2, N2, K2 semi-diurnal tides and the diurnal K1, O1, P1 and Q1 tides. These are interpolated from the Mike 21 global model along the open boundaries for the period of October 1998 corresponding to the measured elevations. The Mike 21 model is based on the DTU10 model discussed previously. A Thompson boundary is applied to the boundaries to allow outgoing waves noise to propagate freely out through the boundary.

IV. Calibration -Bulk Search Algorithm

In the section on the calibration of the Extended Dublin Bay model, it is concluded that “the tidal constituents used in the model are independent of each other”. For the model in this study, this enables the M2 and S2 tides to be calibrated separately, resulting in the need to run just two to three tidal cycles for each model run. The first model run uses the M2 tidal constituents interpolated from Mike 21 at each point on the open boundary. The accuracy of the model is quantified by calculating the root mean square error as the normalised sum of the square of the differences between time series of the predicted and measured elevations (sampled at fifteen minute intervals). The objective function is defined as the sum of the RMS values for the five tidal gauges.

$$RMS = \left\{\frac{1}{N}\sum_{i=1}^{N_0}\left[\zeta_0(t_i) - \zeta_m(t_i)\right]^2\right\}^{\frac{1}{2}} \qquad (1)$$

For each model run in the calibration process, the amplitude at all nodes on the open boundary is multiplied by a single amplitude multiplier, the phase is increased (or decreased) by a single phase shift and the resultant objective function is calculated. In the bulk search algorithm, the model is rerun for the full set of possible combinations where the amplitude multiplier ranges from 0.8 to 1.2 in intervals of 0.1 and the phase shift ranges from -15° to +15° in intervals of 5°. This requires 35 model runs in total and yields the response surface of the objective function shown in Fig. 5. The zone containing the minimum objective function is visually identified and further model runs can be performed with reduced intervals for the amplitude multiplier interval and the phase shift. For this model, a minimum for the objective function was found for an amplitude multiplier of 1.05 and a phase shift of 12.5°.

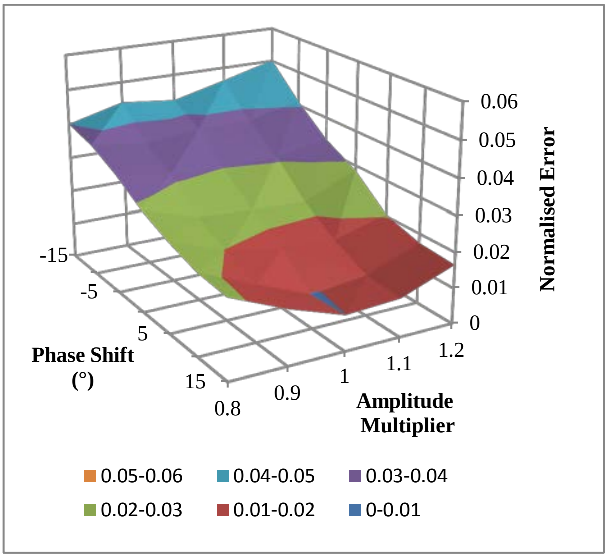

Fig 5. Variation of normalised error between the model and field measurements with amplitude multiplier and phase shift

V. Optimisation of Calibration Procedure

The bulk search calibration procedure resulted in a significant improvement between the model elevations and the field measurements. As the number of model runs was very time-consuming, it was decided to investigate various optimisation methods to expedite the process for future studies.

A. Principle of Superposition

The strategy of calibrating the tidal constituents separately is only valid if the tidal elevation can be treated as a linear combination of the different tidal constituents. In order to validate this assumption, the model is run for a full lunar cycle with tidal forcing using all eight tidal constituents. The output from this is compared with the sum of the output from eight separate model runs, each one forced individually by a single constituent. The comparisons at Dun Laoghaire (Fig. 6) and at an arbitrary shallow point in Dublin Bay (Fig. 7) indicate that the assumption appears to be valid for this particular model domain.

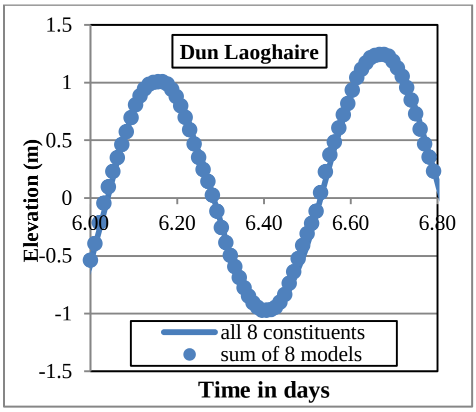

Fig 6. Principle of superposition at Dun Laoghaire

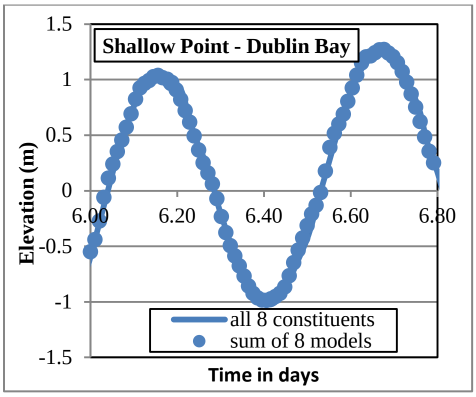

Fig 7. Principle of superposition at arbitrary shallow point in Dublin Bay

B. *Steepest Descent Algorithm*

The steepest descent method is a first order gradient based optimisation technique. In this study, this method is tested using the results from the bulk search calibration with the aim of reducing the number of model runs necessary to find the minimum root mean square error for the M2 tide. The procedure involves computing a path of steepest descent towards the point of minimum response and is carried out by following the path of maximum decrease from each point.

The response surface is a three-dimensional plot with the x and y axes corresponding to the amplitude multiplier and the phase shift respectively arranged on a regular orthogonal grid. The "starter" model driven by the Mike 21 constituents is located at the centre of this grid with the amplitude multiplier/phase shift combination of (1.0, 0°). In the first stage of the steepest descent method, this model is run along with the four models directly around it (shown as squares in Fig. 8). The model (1.0, +5°) is marked with an X in Fig. 8 indicating that it has the smallest error. The models executed in the second (triangles) and third (circles) stages are also shown in the figure. Eleven simulations are required to arrive at the same response minimum that was determined by the bulk search algorithm using 35 model runs.

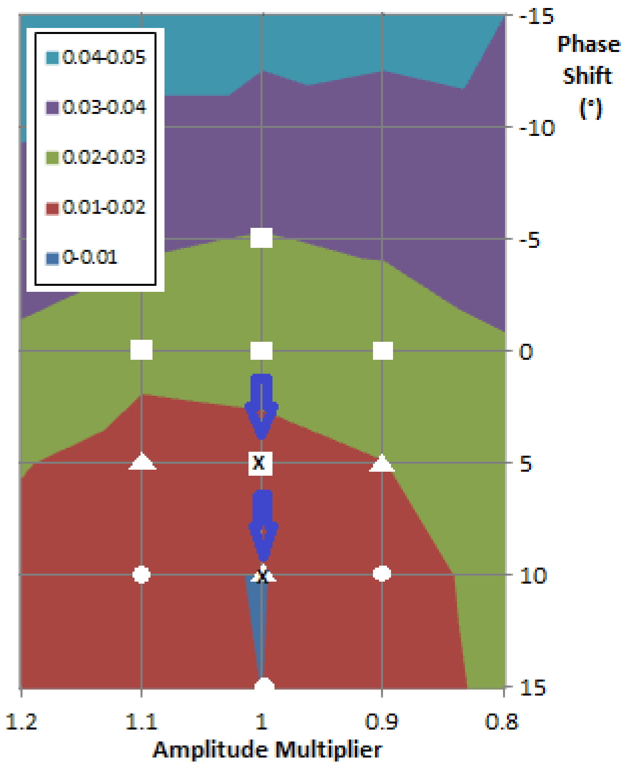

Fig 8. Calibration using the Steepest Descent Method

The response minimum can be located more precisely by continuing the process from the point (1.0, +10°) with smaller intervals for the amplitude multiplier and the phase shift.

C. *Independent Calibration of Amplitudes and Phases*

In the Extended Dublin Bay Model study, the author also states that "The most important conclusion to be drawn from this study is that, to a large degree, the amplitude and lag of a particular tide are propagated independently in open water by the numerical scheme" [12]. In effect, the predicted M2 amplitudes within the model should only depend on the open boundary M2 amplitudes and the predicted phases are only dependent on the applied phases. In order to test this proposition, the facility in Telemac2D to calculate and output the tidal constituents at specified locations is used.

The results of the bulk search calibration are analysed to test this proposition. For each model run, the percentage difference between the predicted and measured M2 amplitudes is calculated at each of the five locations. The sum of these is plotted against the amplitude multiplier for the seven different phase shifts in Fig. 9. It is clear from the figure that the amplitude is independent of the phase of the applied constituent. The minimum percentage error is approximately 0.05 for an amplitude multiplier of 1.05. The corresponding plot for the phases, Fig. 11, clearly indicates that the phases are independent of the applied amplitudes. The minimum percentage error is 0.002 for a value of 15° for the phase shift.

Table 2 shows the comparison between field measurements and the results of the model forced by the calibrated M2 and S2 constituents and the other un-calibrated Mike 21 constituents. The largest phase difference of 12.8° corresponding to 26.4 minutes in real time is calculated at Howth. There is a possible error in this data as a different analytical method was used for the harmonic analysis of the recorded time series [11].

Fig. 10 and Fig. 12 show the results for the calibration without Howth. While there is negligible difference in the amplitude plot, the error in the phases reduces to 0.00015 for a phase shift of 10.5°. It shows the importance of checking the field data upon which the calibration is based.

TABLE 2. DIFFERENCES BETWEEN MODEL PREDICTIONS (USING CALIBRATED M2 AND S2 TIDES) AND FIELD MEASUREMENTS

	North Wall	North Bank	Kish	Dun Laoghaire	Howth
Amplitude	m	m	m	m	m
Field	1.261	1.302	1.252	1.305	1.434
Model	1.360	1.366	1.346	1.347	1.441
Difference	0.099	0.064	0.094	0.042	0.007
Phase	°	°	°	°	°
Field	326.8	324.8	322.0	327.4	343.3
Model	329.6	330.2	328.5	329.4	330.5
Difference	2.8	5.3	6.5	2.0	12.8

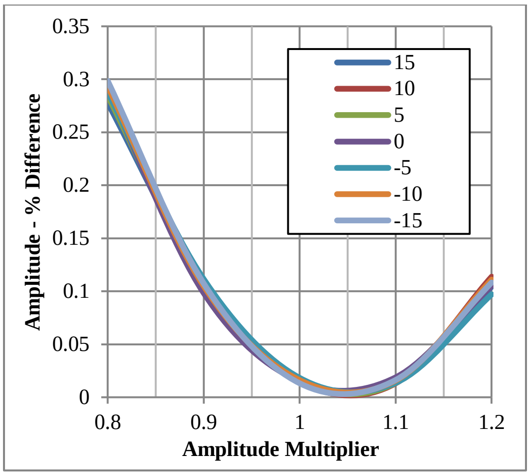

Fig 9. Variation of % difference with amplitude multiplier

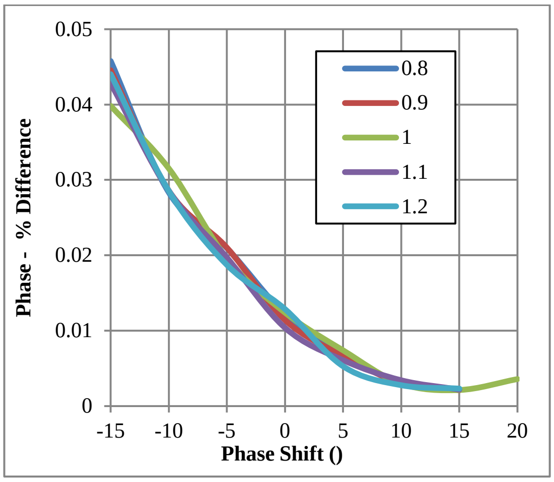

Fig 11. Variation of % difference with phase shift

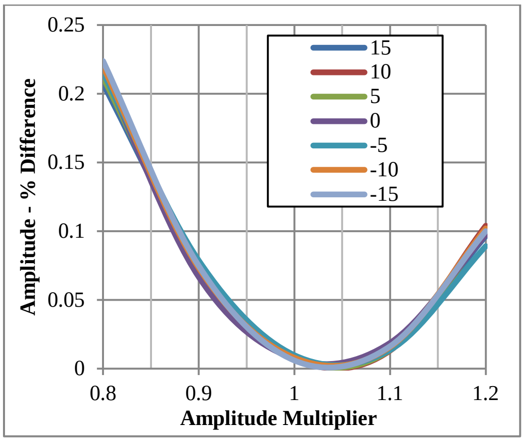

Fig 10. Variation of % difference with amplitude multiplier without Howth data

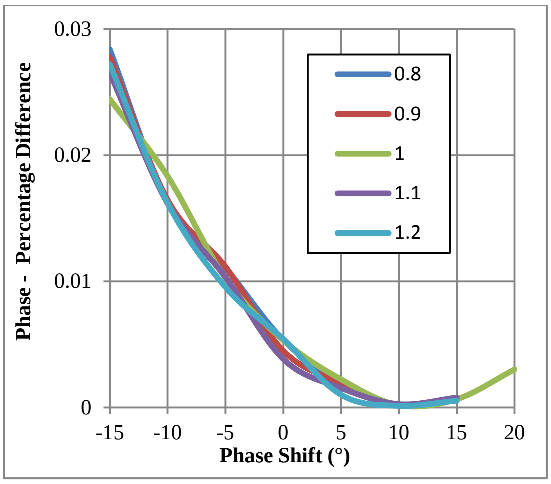

Fig 12. Variation of % difference with phase shift without Howth Data

D. Calibration of Velocities using Friction Parameter

In the extended Dublin Bay model study, the variation of the bottom friction was found to have a minimal effect on the surface elevations [14]. It must be noted that this is different to the findings of Bourban et al [4], possibly due to the smaller area covered by the East Coast model in comparison to the Coastal Shelf model. In order to assess its effect on the velocities in the current study, two more models were run using the calibrated boundary conditions with Chezy values of 30 $m^{1/2}$/s and 70 $m^{1/2}$/s. The comparison of the velocities for the three Chezy values of 30 $m^{1/2}$/s, 50 $m^{1/2}$/s and 70 $m^{1/2}$/s is shown at Stations 1 and 8. At Station 1, the amplitudes and phases of the tidal current vary significantly and the flow is faster for higher values of the friction parameter. The general direction of the flow pattern is similar for all values of the friction. This effect is similar at many of the other stations. The value giving the best fit varies with each station. Stations 5 and 7 are closest a value of 30$m^{1/2}$/s, Stations 1 and 4 fit best with a value of 50$m^{1/2}$/s and stations 3,6 and 8 fit best with the highest value of 70$m^{1/2}$/s (the results at station 2 are inconclusive).

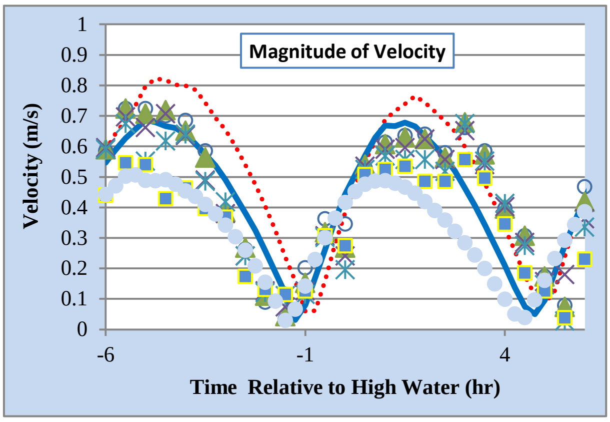

Fig 13. Amplitudes of Tidal Currents at Station 1

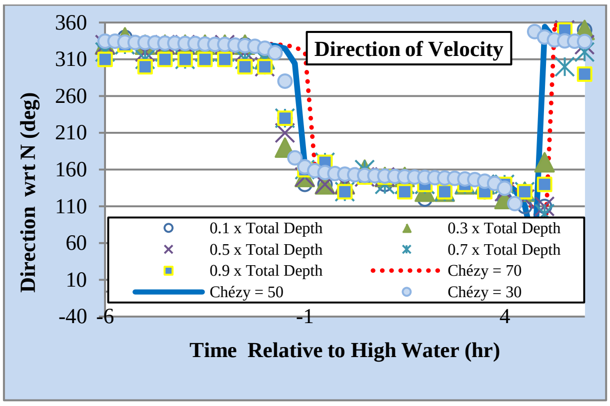

Fig 14. Directions of Tidal Currents at Station 1

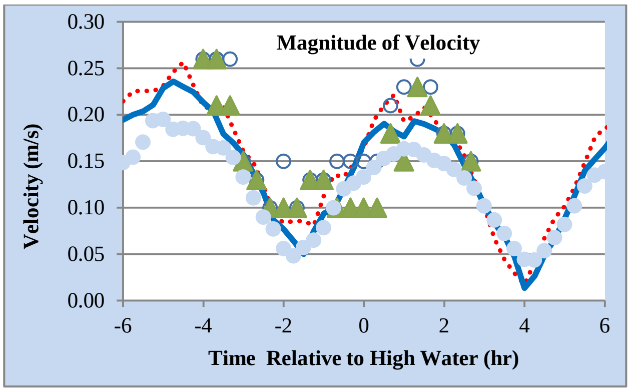

Fig 15. Amplitudes of Tidal Currents at Station 8

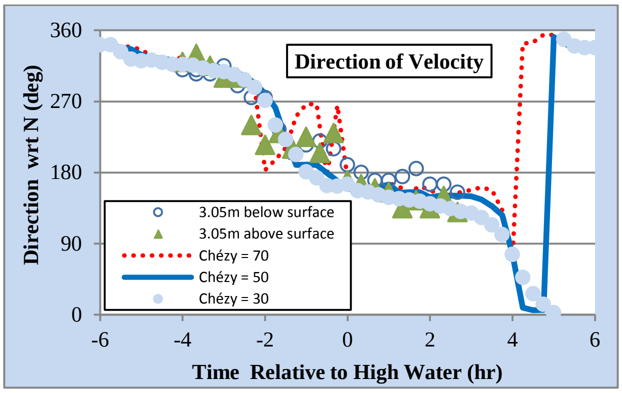

Fig 16. Directions of Tidal Currents at Station 8

VI. CONCLUSIONS

The calibration undertaken using the bulk search algorithm resulted in a significant improvement between the tidal elevations measured at five locations and the corresponding model predictions at five locations within the model domain.

The principle of superposition test indicated that it is valid to assume that for this particular model domain, the constituents could be treated separately. Many other studies would indicate that this assumption is invalid and that tidal constituents interact with each other and with the shallow bathymetry. It may that it is only valid for a model domain like this one with large areas of open sea and relatively simple gradually sloping estuaries [1]. Further investigation is needed.

The assumption that they can be treated independently facilitates a large reduction in the simulation time as only a few tidal cycles are needed for each model run.

The steepest descent method proves to be very useful as it reduces the number of model runs to eleven. However, more runs are needed to zone in on the minimum error.

The final method which calibrates the amplitude and phase independently appears to be very promising and requires less runs than the steepest descent method to accurately locate the amplitude multiplier and phase shift resulting in the minimum error.

It is proposed to apply the method again using a new set of field measurements with an improved geographical spread.

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