Appendix A8.1 Model Development and Calibration

MARCON COMPUTATIONS INTERNATIONAL

Advanced Engineering and Environmental Solutions

Greater Dublin Drainage

Model Development and Calibration

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1. INTRODUCTION

1.1. Project Background

MarCon were commissioned in 2011 by Jacobs Engineering Ireland Ltd., to undertake a mathematical modelling study of the coastal waters of north County Dublin to determine the possible impacts on the receiving waters of discharging treated effluent through a proposed marine outfall, pursuant to the Greater Dublin Drainage project.

A preliminary modelling study was undertaken by MarCon in 2011[1] to identify a range of potential marine outfall locations along the north Dublin coastline. That study showed that two discrete areas existed within the project area where locating a marine outfall would have the least detrimental impact on the receiving marine environment.

A subsequent modelling study was undertaken by MarCon in 2013[2] to determine the relative merits of locating a marine outfall within either of the two discrete areas identified in 2011. That study showed that the southern outfall study area exhibited more favourable coastal hydrodynamic characteristics, (larger current speeds and greater water depths), than the northern outfall study area.

Following publication of the ASA and Route Selection Report (Phase 4): Final Preferred Site and Routes a detailed highly resolved hydrodynamic and water quality model was required to assess both the Construction Phase and Operational Phase impacts of the proposed outfall pipeline route (marine section) on the marine environment.

This report details the development and calibration of the highly resolved hydrodynamic and water quality model.

[1] Alternate Site Assessment Numerical Modelling Report, GP201103_doc001_04. MarCon Computations International. 2011.

[2] Alternate Site Assessment Numerical Modelling Report: Near Field Dilution and Mixing, GP201103_doc003_02. MarCon Computations International. 2013.

2. MODEL OVERVIEW

2.1. Introduction

A Mike-by-DHI 3D Flexible Mesh (Mike3-FM) hydrodynamic, solute and sediment transport model was developed to predict tidal circulation patterns in the region, along with the advection, dispersion and setting of sediment arising from dredge operations associated with construction of the GDD outfall.

The Mike3-FM model used in this study is a state-of-the-art hydrodynamic, sediment and solute transport model which can accurately compute water circulation, temperature, salinity, and mixing and transport of conservative parameters, deposition and re-suspension of cohesive and non-cohesive sediments.

The Mike-by DHI range of products, including Mike3-FM, are a market leading software suite, utilised by consultants and regulators worldwide, and represent the state-of-the-art in terms of commercial modelling software.

The model is a three-dimensional coastal model, incorporating a turbulence closure model to provide a realistic parameterization of the vertical mixing processes. The prognostic variables are the three components of velocity (u, v, w), temperature, salinity, turbulence kinetic energy, and macro-scale turbulence.

The momentum equations are nonlinear and incorporate a variable Coriolis parameter. Prognostic equations governing the thermodynamic quantities, temperature, and salinity account for water mass variations brought about by highly time-dependent coastal up-welling / down-welling processes as well as horizontal advective processes.

2.2. Model Development

The mathematical modelling study was carried out by developing a numerical model to simulate both the water circulation throughout the model domain and the transport of material from the proposed outfall location.

2.2.1. Extent

The original model developed for the preliminary modelling study in 2011[3] encompassed the coastal waters of north County Dublin, from Howth Head to Balbriggan and provided sufficient coverage for that study. For the present study it was required to investigate the possibility of any in-combination effects which might arise due to the planned Ringsend Wastewater Treatment Works Expansion project. Therefore, the original model domain had to be extended south to Shankill in south County Dublin.

The model resolution is variable, as enabled by the Flexible Meshing approach, thus allowing for higher resolution in and around areas of interest while allowing resolution to reduce as appropriate towards the model open sea and land boundaries, in order to maintain computational efficiency. Resolution increases from 500m at the boundaries to 50m in the area of interest, resulting in 16,707 computational elements.

The study area of the model extends in a south to north direction from 53.25°N to 53.625°N, (Shankill to Balbriggan), and in a west to east direction from 6.200°W to 5.875°W.

2.2.2. Bathymetry

The seabed bathymetry for the model was digitised from United Kingdom Hydrographic Office, (UKHO), Admiralty Charts and was augmented with the most recent bathymetry available from the Irish seabed survey INFOMAR project. The extent of the model domain, and the underlying bathymetry, is presented in Figure 1.

2.2.3. Temporal resolution

The model operates at an automatic timestep for all calculations, allowing the Courant criterion to be met at all times. All water elevation, current speeds, directions and dissolved parameters are calculated throughout the model domain at each time step providing a very highly resolved temporal prediction capability.

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[3] Alternate Site Assessment Numerical Modelling Report, GP201103_doc001_04. MarCon Computations International. 2011.

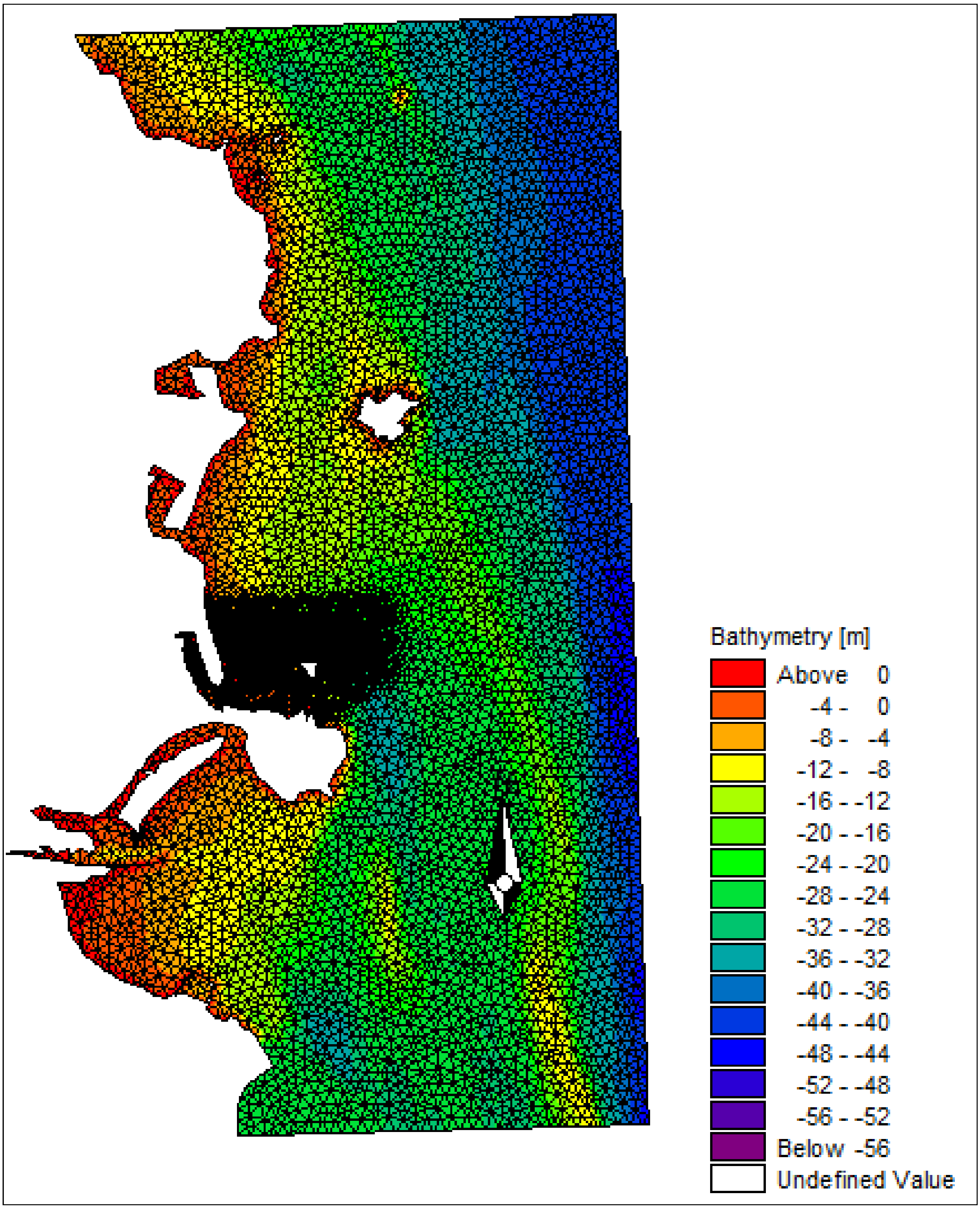

Figure 1: Extent of numerical model domain.

2.2.4. Boundary conditions

The model features two open sea boundaries at the north and south of the study area where tidal constituents acquired from the FES2004 global tidal model were used to generate time varying water surface elevations to induce tidal circulation within the model domain.

The FES2004 is a global tide model which assimilates both tide gauges and altimeter data to provide amplitudes and phases of 15 tidal constituents at a $1/8^{o}$ latitude and longitude grid resolution.

Six major tidal constituents, namely, M2, N2, S2, O1, K1, and P1 were applied, with the FES2004 $1/8^{o}$ data interpolated along the north and south boundaries of the model to obtain spatially varying amplitudes and phases of the above constituents. Constituents were then modified, with reference to nearby UKHO published harmonic data.

The predominant direction of the flooding and ebbing tides at the eastern extent of the model domain run parallel to the coast, as indicated by the UKHO Tidal Stream Atlas for the Irish Sea. Therefore, the model has one streamline boundary specified along the eastern boundary of the model.

3. HYDRODYNAMIC MODEL CALIBRATION

3.1. Introduction

Calibration is achieved by fitting the model predictions to observed data, by varying the calibration coefficients. The degree of fit between model and observation determines the level of model calibration: poor fit suggests poor calibration, good fit suggests good calibration. The degree of fit will vary from location to location, depending on local conditions and how well these can be represented in the model.

To check the degree of fit between model predictions and observations, the model was compared against a suite of measured data collected as part of the present study.

During July and August 2012 a hydrographic survey was undertaken off the north County Dublin coastline to collect data with which to calibrate the hydrodynamic model. 2No. tide gauges (TG) were deployed, one each at Skerries and Howth, 3No. acoustic doppler current profilers (ADCP) were deployed on the seabed. The instruments were deployed from 12th July 2012 – 23rd August 2012. The locations of all instruments is presented in Figure 2.

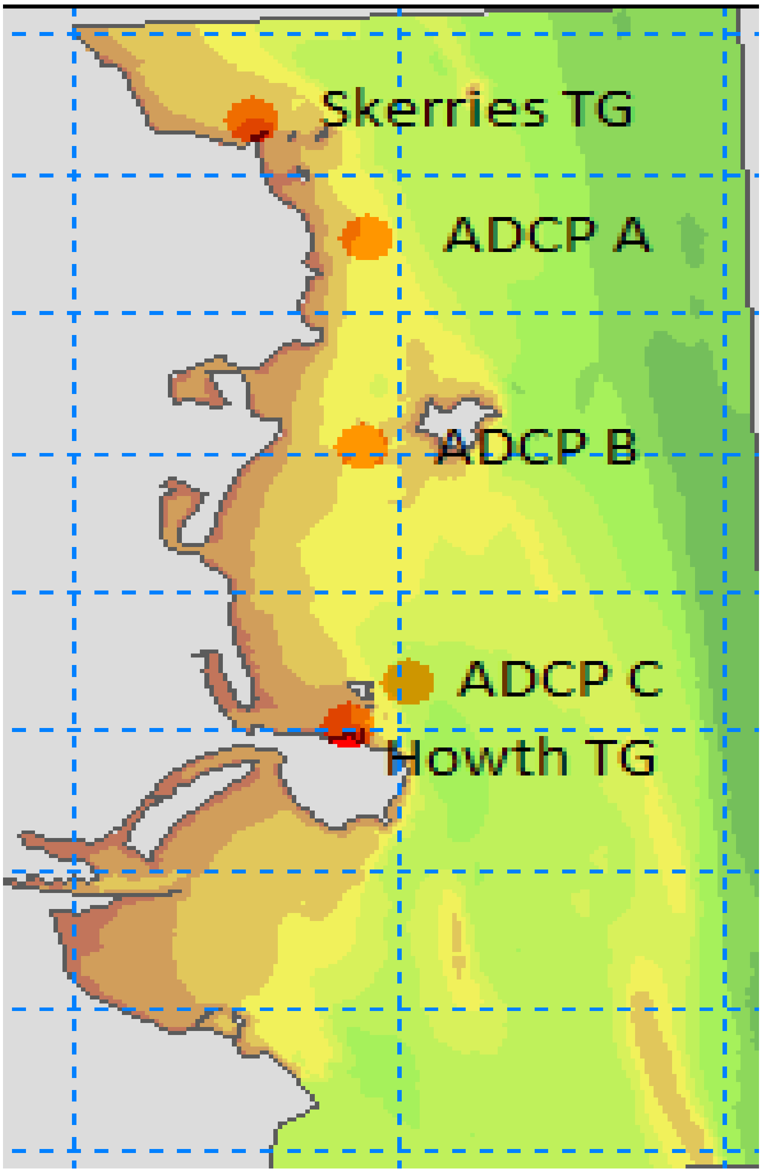

Figure 2: Location of instruments deployed from July – August 2012

The tide gauges recorded the water surface level at 10 minute intervals throughout the course of the hydrographic survey, The ADCPs recorded the speed and direction of the water currents at different depths in the water column at 15 minute intervals.

On completion of the hydrodynamic calibration, the model was validated (a cross check on the calibration process, with no further adjustment of model parameters) against further ADCP data gathered during March 2015. The locations of these ADCP deployments (1 & 2) are shown in Figure 3.

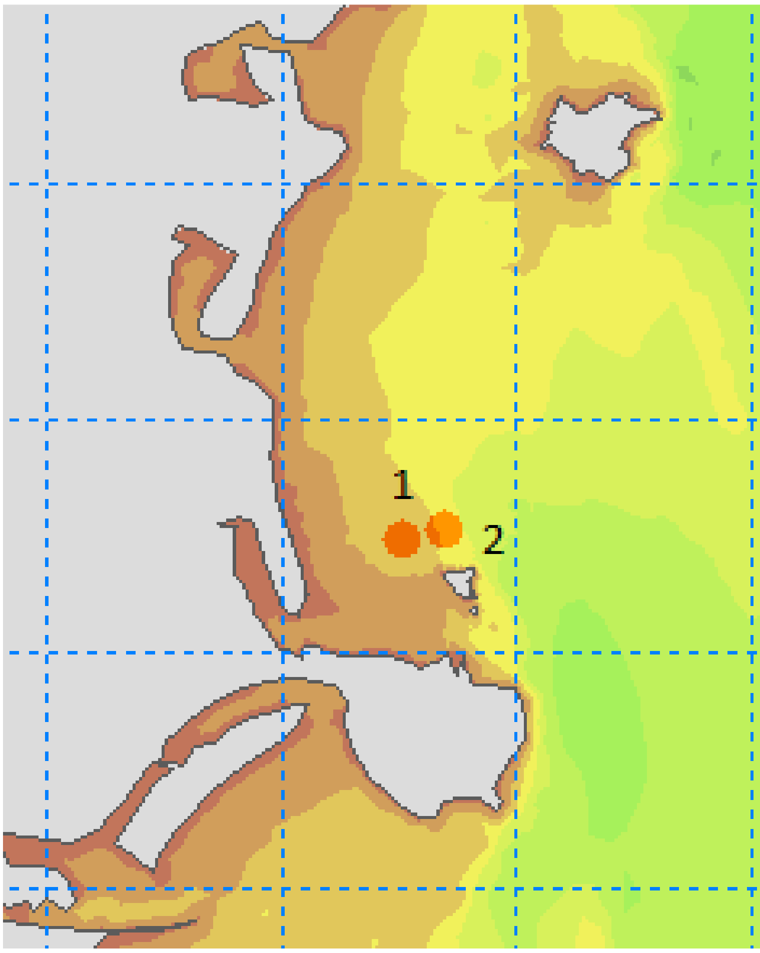

Figure 3: Location of instruments deployed from July – August 2015

The solute transport (advection) model was calibrated against 2015 dye release data from locations around the area of interest, with 4 releases taking place on a spring tide and again on a neap (20th April 2015 and 9th June 2015 respectively. The calibration was underpinned by the calibrated hydrodynamic (HD) module, and involved adjustment of the dispersion parameters within the advection-dispersion (AD) module.

3.2. Calibration Standards

Model fit to field data can be assessed in two ways:

- Visual comparison of the model output against observed data: the shape, trend, range and limits of model output and observed data; and
- Statistical comparison of the difference between observation and the model to determine the frequency with which the model fits observation within defined limits.

In practise both methods should be used, as no single method provides a full assessment of model performance.

In the case of the present calibration, current magnitudes and water levels were assessed both visually and statistically, while current directions were assessed only visually because they are derived from vector quantities making useful statistical analysis difficult, and because the visual assessment is very clear.

In the absence of a widely adopted industry standard for the definition on calibration requirements, the numerical model was considered against a set of performance metrics defined in a recent guidance note developed by ABPmer[4] based on a variety of statistical measures.

It is important to note that statistical measures only play a part of the 'fit-for-purpose' assessment of model performance with further discussion required to provide a more detailed understanding of the suitability of the model.

In addition to the performance metrics, experience has shown that visual checks are an important part of the model calibration and validation process. Visual checks can identify patterns between the measured and modelled time-series that may not be as obvious from the performance metrics.

Under certain conditions, models can meet statistical calibration standards but appear to perform poorly in a visual comparison, conversely, seemingly accurate models judged visually can fall outside of statistical standards. Generally consistent inaccuracies can be explained or justified,

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[4] Numerical Model Calibration and Validation Guidance. ABP Marine Environmental Research Ltd. File Note R/1400/112.

whilst short-term variations can, in some instances, be due to meteorological effects on collected data.

The performance metrics in the ABPmer guidance note are presented below and provide a comparative measure for both temporal and peak features of the calibration data, thus providing an initial fit-for-purpose assessment of the numerical model, which is further substantiated by visual checks. Results are presented as a range of magnitude difference, percentage difference and root mean square (RMS) values.

The following performance metrics are offered by ABPmer.

- Water levels: mean level differences should be within ±0.2m while the percentage differences should be within 15% of spring tidal ranges and 20% of neap tidal ranges. Water level phasing at high and low water should be within ±20 minutes, while RMS scores should be less than 0.2
- Flows: modelled speeds should be within ±0.2 m/s or ±10 -20% of equivalent peak observed speeds, while model directions should be within ±20^{o} of observed directions, and phasing within ±20 minutes. RMS scores should be less than 0.2, while scatter index scores should be less than 0.5.

In addition to the statistical analysis of the numerical model as described above, a further assessment of the model performance throughout the calibration period has been carried out. For this assessment, a further set of tolerances has been applied to the results from the hydrodynamic model and an analysis of the frequency (throughout calibration period) that the tolerances are met has been undertaken.

The tolerances applied to this stage of the calibration are taken from the Foundation for Water Research (FWR) guideline[5] for coastal models and are described as follows:

1. Water levels: an absolute tolerance of ±0.1m or a relative tolerance of ±10% of the measured spring tidal range

[5] A Framework for Marine and Estuarine Model Specification in the UK. Foundation for Water Research, March 1993.

2. Current speed: an absolute tolerance of ±0.1m/s or a relative tolerance of ±10% of the peak measured current speed
3. Current direction: an absolute tolerance of $\pm 30^{o}$
4. Phasing: an absolute tolerance of ±15 minutes.

In an attempt to further describe the relative levels of calibration between sites, a qualitative scale of fit has been applied, based on the FWR guidelines and described as follows:

'Excellent Fit'	-	Calibration tolerances are achieved >90% of the time
'Very Good Fit'	-	Calibration tolerances are achieved >80% of the time
'Good Fit'	-	Calibration tolerances are achieved >70% of the time
'Reasonable Fit'	-	Calibration tolerances are achieved >60% of the time
'Poor Fit'	-	Calibration tolerances are achieved <60% of the time

In addition to allowing comparison of the relative level of calibration between sites to be made, this qualitative scale also assists in making a comparison between the visual 'fit' of the data (as provided, for example, by a time-series plot of modelled versus measured data) and the statistical assessment of model performance.

3.3. Calibration Results

The model was calibrated for a 30-day period from the 18th July 2012 to the 17th August 2012, a period which included representative neap and spring tides. To achieve calibration, minor adjustments were made to the water levels along the northern and southern boundaries until the required level of accuracy was achieved.

Modelled tidal levels were compared against measured data at both the Skerries and Howth tide gauge locations in order to provide a quantitative assessment of inaccuracies in tidal characterisation.

Modelled current speeds and directions were compared against measured data at the ADCP locations A, B and C in order to provide a quantitative assessment of inaccuracies in tidal characterisation.

To quantify model calibration, a series of quantitative statistics have been calculated to compare water levels, current speeds and directions. The statistical assessment includes the derivation of the metrics listed above. The results are presented in Table 1 to **Error! Reference source not found.** with PASS and FAIL of the above metrics highlighted where applicable in Table 1 and Table 2.

Location	Water Level Bias (m)	Water Level Bias (% MSR)	Water Level RMS
Skerries	0.11	3.2	0.19
Howth	0.02	0.67	0.15
* Positive values denote model is over-predicting; negative values denote under-prediction			

Table 1: Calibration of modelled water levels against Tide Gauge data.

Location	Flow Speed Bias (m/s)	Flow Speed Bias (% Max Speed)	Flow Speed RMS	Scatter Index
ADCP A	-0.05	-4.71	0.13	0.36
ADCP B	0.04	5.19	0.10	0.28
ADCP C	0.02	1.86	0.11	0.25

Table 2: Calibration of modelled current speeds against ADCP data

Table 3 provides the results of an assessment into the frequency that tolerances are met throughout the calibration period. The results include all locations at which instruments were deployed in order that a comparison of the model performance across the domain can be made.

Location	% of Time Tolerances Are Met (%)		Qualitative Description
	Water Level	Current Speed	
Water Levels			
Skerries	92		Excellent
Howth	96		Excellent
Currents			
ADCP A		63	Reasonable
ADCP B		63	Reasonable
ADCP C		75	Good

Table 3: Qualitative summary of hydrodynamic model fit against calibration data.

3.4. Summary

In Appendix I calibration plots of water surface levels are provided in **Error! Reference source not found.** to **Error! Reference source not found.**, calibration plots of water current speeds are presented in **Error! Reference source not found.** to **Error! Reference source not found.**, and calibration plots of water current direction are presented in **Error! Reference source not found.** to **Error! Reference source not found.**.

The quantitative statistics show that, generally, the model representation of water levels at the two tide gauge locations is very good, with the water level magnitude values <0.2m whilst the percentage difference values at each location are all less than 4% which is well within the ±15% guidance value. Water level RMS values for the two tide gauge locations are shown to be within the 0.2m guidance limit.

At the ADCP A location, over the source of the calibration period, statistically the flow speed bias was well within the guidance value of 0.2. The RMS values were also calculated to be within the guidance value of 0.2 and Scatter Index well within the guidance value of 0.5. Visual inspection of the ADCP A location time-series plots presented in **Error! Reference source not found.** shows that the model is generally in good agreement with the ADCP data, although brief peaks indicated occasionally by the instrument are not reproduced by the model. Figure A1.6 shows the model to be reproducing current directions correctly on both flood and ebb tides.

At the ADCP B location, over the source of the calibration period, statistically the flow speed bias was well within the guidance value of 0.2. The RMS values were also calculated to be within the

guidance value of 0.2 and Scatter Index well within the guidance 0.5. Visual inspection of the ADCP B location time-series plot presented in Figure A1.4 that the model is generally in good agreement with the ADCP data, although the brief peaks indicated occasionally by the instrument are not reproduced by the model. Figure A1.7 shows the model to be reproducing current directions correctly on both flood and ebb tides. Note that the ADCP data can be seen to switch slightly either side of due north during the ebb tide; the model predicts a slightly more stable current direction, although the difference is small.

At the ADCP C location, over the source of the calibration period, statistically the flow speed bias was well within the guidance value of 0.2. The RMS values were also calculated to be within the guidance value of 0.2 and Scatter Index well within the guidance 0.5. Visual inspection of the ADCP A location time-series plot presented in Figure A1.5 that the model is generally in good agreement with the ADCP data, although again the brief peaks indicated occasionally by the instrument are not reproduced by the model. Figure A1.8 shows the model to be reproducing current directions correctly on both flood and ebb tides.

As a further cross-check of model performance, scatter plots have been generated for water levels at Skerries and Howth, to test correlation between TG and model data. The resulting plots are shown at Figures A 1.9 (Skerries) and A 1,10 (Howth), and show R^2 values of 97.5% and 98.1% respectively.

Model validation plots for current speed and direction are shown as Figures A1.11 to A 1.14.

At ADCP 2015-1, current speeds (Figure A1.11) are relatively weak, with some possible evidence of wind effects, also apparent in the direction plot (Figure A1.13). Wind is not included in the model validation simulation, but allowing for this the model validation at this location is robust.

At ADCP 2015-2, current speeds (Figure A 1.12) on the flood tide are well reproduced by the model. Current speeds on the ebb are under-predicted. Current directions (Figure A 1-14) are well correlated between modelled and measured.

In general, the comparison of the modelled and measured datasets, both statistically and visually, would suggest a robust calibration agreement. Overall, Table 3 shows that the model is providing an ‘excellent’ representation of water levels and, generally, between a ‘good’ and ‘satisfactory’ representation of current speeds and directions at the ADCP locations.

It is noted that the calibration of the model was ‘good’ at ADCP C location (the location of the proposed GDD marine outfall).

The summary of results presented above show that the numerical model has been successfully calibrated and validated against field measurements to provide a sufficiently accurate representation of the hydrodynamics within the study region.

4. TRANSPORT MODEL CALIBRATION

4.1. Introduction

the transport model was calibrated against 2015 dye release data from locations around the area of interest, with 4 releases taking place on a spring tide and again on a neap (20th April 2015 and 9th June 2015 respectively). The calibration was underpinned by the calibrated hydrodynamic (HD) module detailed above, and involving adjustment of the dispersion parameters within the advection-dispersion (AD) module and the Smagorinsky formulation within the HD module.

In all plots, the measured dye patches are shown in white, with all patches shown on all plots. Model patches are then overlaid to correspond to consecutive measured patches. Note that while model output represents a snapshot in the simulation timeframe, the measurement of patches at sea takes at least several minutes as the survey vessel makes numerous transects through the dye as it moves, and so strictly speaking a snapshot cannot be achieved.

Dye dispersion, particularly in an area of complex flows such as this, is a chaotic process with the likely generation of numerous smaller patches moving at different speeds and direction than the main patch. A single survey vessel can usually only run transects on one patch. The model, which is not chaotic, will generally generate a single patch, with model dispersion coefficients seeking to parameterise the average, net effect of the chaotic processes of the real world.

4.2. Calibration Results

Plots for spring dye release 1 are shown as Figure A1.15. The measured dye moves initially south west and then alters course towards the south east. It can be seen that the calibrated model reproduces the complex advection and the dispersion of the dye patch very well, with each measured patch well characterised by the model.

Plots for spring dye release 2 are shown as Figure A1.16. This release location, unlike all the others, is to the west of the area of interest, and the patch moves rapidly south-south-east. The consecutive patches are well reproduced by the model in terms of advection and longitudinal dispersion, over the extensive, relatively rapid, excursion of the patch. The observed patch appears to remain laterally very narrow, which the model does not reproduce, with the result that the final observed patch is dispersed in the model and does not therefore show up in the plot. This lateral dispersion could possibly have been tuned in the model, but to the detriment of the calibration at the area of particular interest. Nonetheless the correct representation of advection and longitudinal dispersion are indicative of a generally robust model.

Plots for spring dye release 3 are shown as Figure A1.17. The measured patch moves slowly to the south east. The calibrated model reproduces the advection and dispersion of the dye patch very well, with each measured patch well characterised by the model.

Plots for spring dye release 4 are shown as Figure A1.18. The calibrated model reproduces the advection of the dye patch very well as far as Howth Island. Dispersion is reasonably well represented, with differences considered probably due to the initial size of the patch in the model (a numerical constraint). The survey picked up remnants of undispersed dye to the south east of the island, these not being reproduced by the model.

Plots for neap dye release 1 are shown as Figure A1.19. The surveyed patch advects slowly south east towards Howth Island. This slow movement is not reproduced by the model. The reason is not clear, although circulation patterns here are relatively complex and the precise position of a dye release relative to the centre of a small gyre can have a significant effect.

Plots for neap dye release 2 are shown as Figure A1.20. The advection and dispersion of the patch as it moves south east towards Howth Island are this time well reproduced by the model, offsetting to a certain extent concerns raised by neap release 1, above.

Plots for neap dye release 3 are shown as Figure A1.21. The measured patch moves off to the north west, before slowing and turning toward the south west towards the end of the transecting. All features of this dye release are well reproduced by the model, which shows correct advection – including the change in direction – and dispersion.

Plots for neap dye release 4 are shown as Figure A1.22. The measured patch moves along a slightly curved line to the south east. Again, the model correctly reproduces this complex movement and also demonstrates a robust representation of the patch dispersion.

5. Appendix I: Model Calibration Results

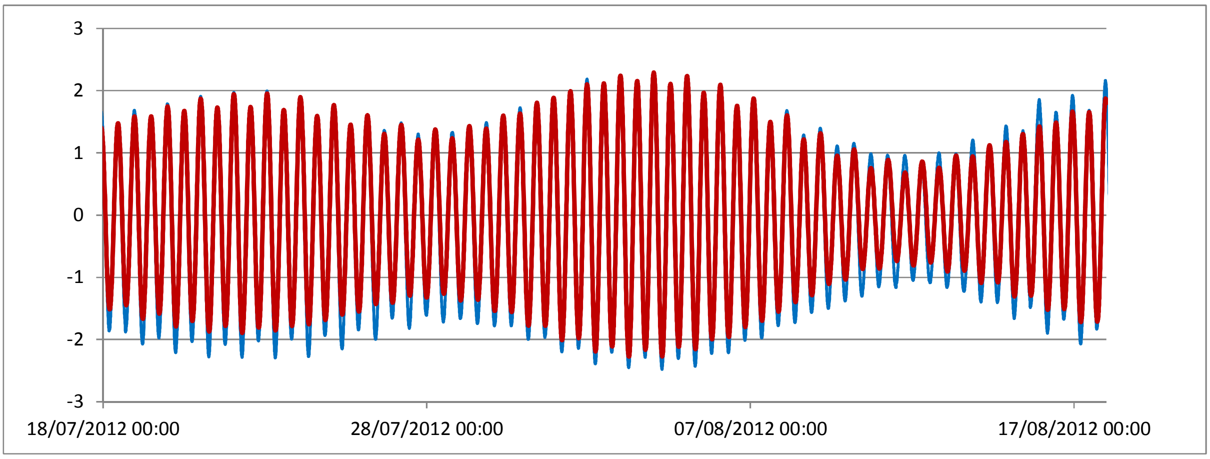

Figure A1.1 – Levels at Skerries TG (blue) v. model predictions (red)

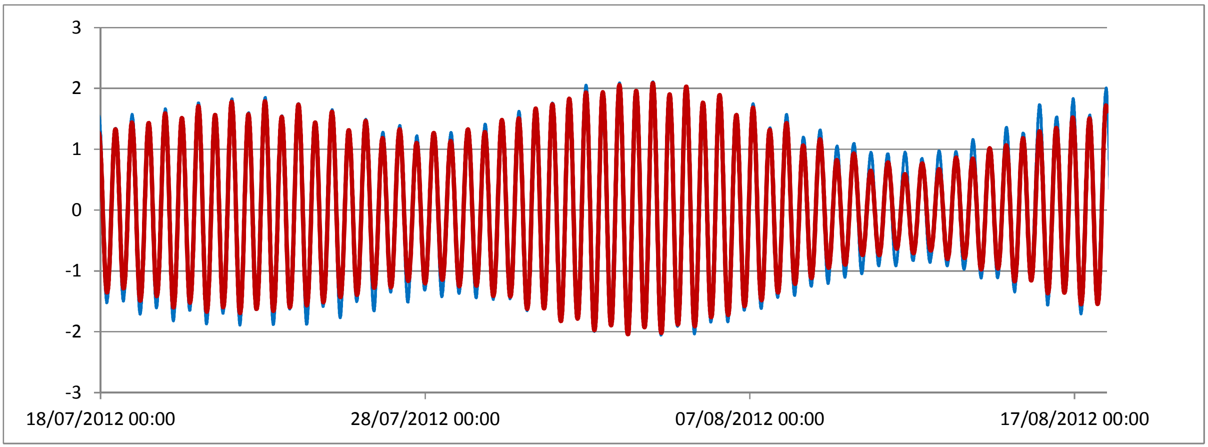

Figure A1.2 – Levels at Howth TG (blue) v. model predictions (red)

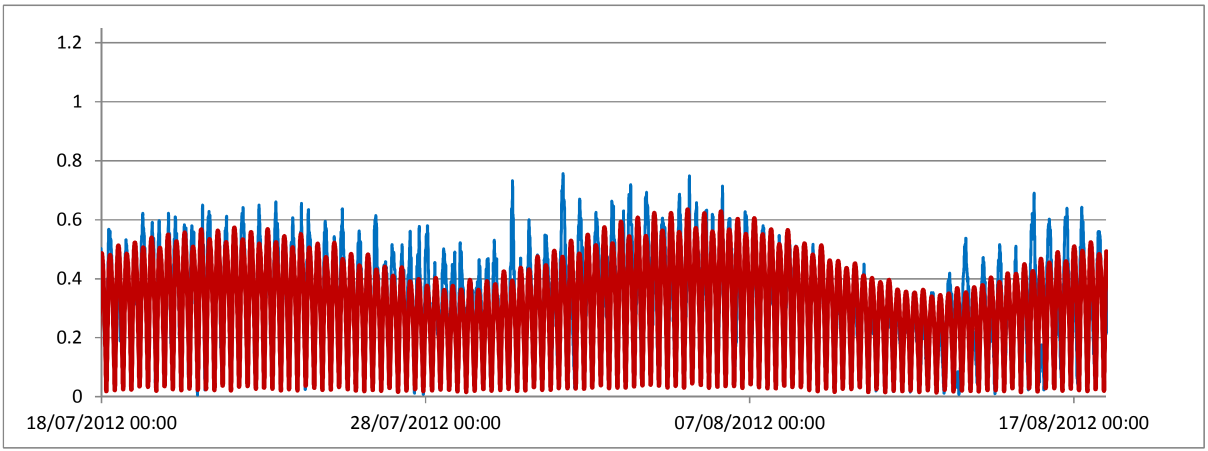

Figure A1.3 – Speeds at ADCP A (blue) v. model predictions (red)

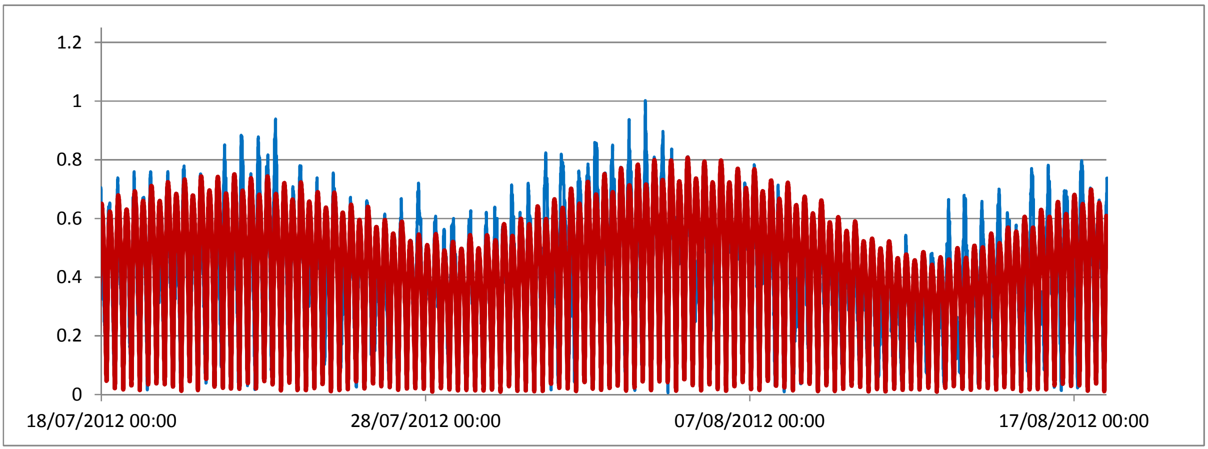

Figure A1.4 – Speeds at ADCP B (blue) v. model predictions (red)

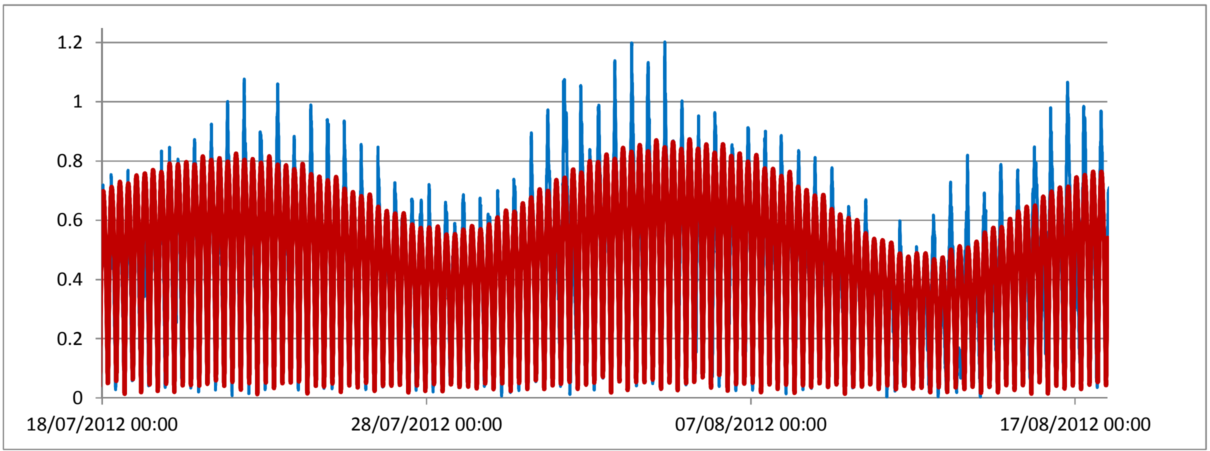

Figure A1.5 – Speeds at ADCP C (blue) v. model predictions (red)

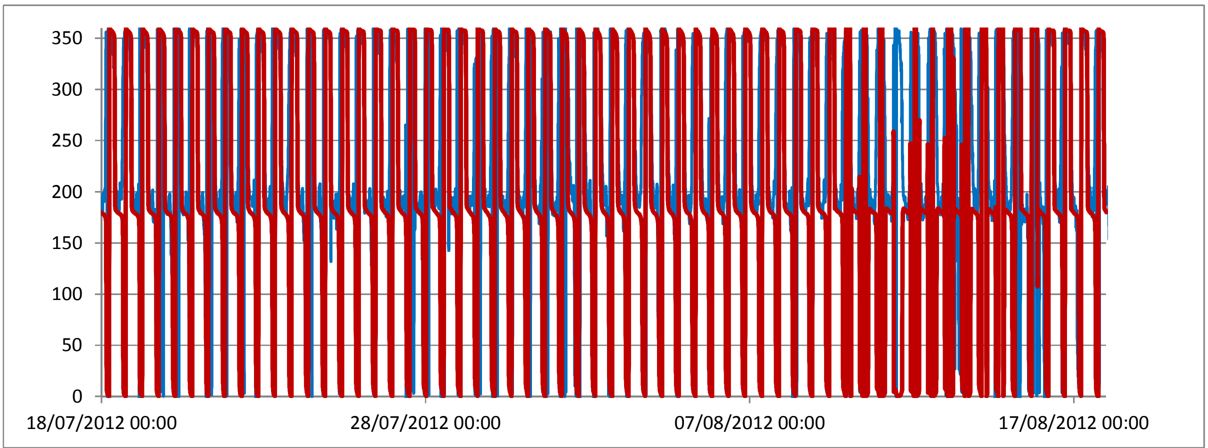

Figure A1.6 – Directions at ADCP A (blue) v. model predictions (red)

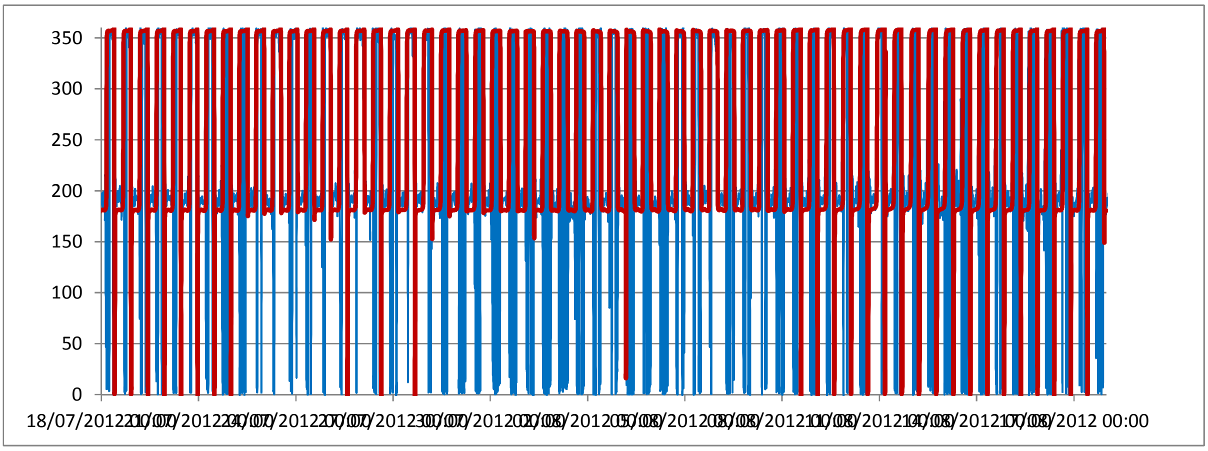

Figure A1.7 – Directions at ADCP B (blue) v. model predictions (red)

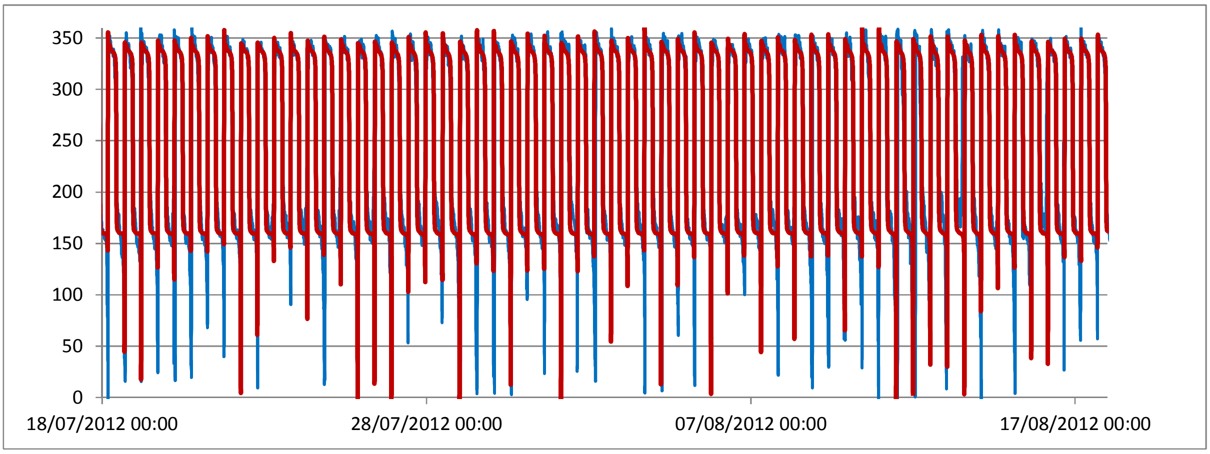

Figure A1.8 – Directions at ADCP C (blue) v. model predictions (red)

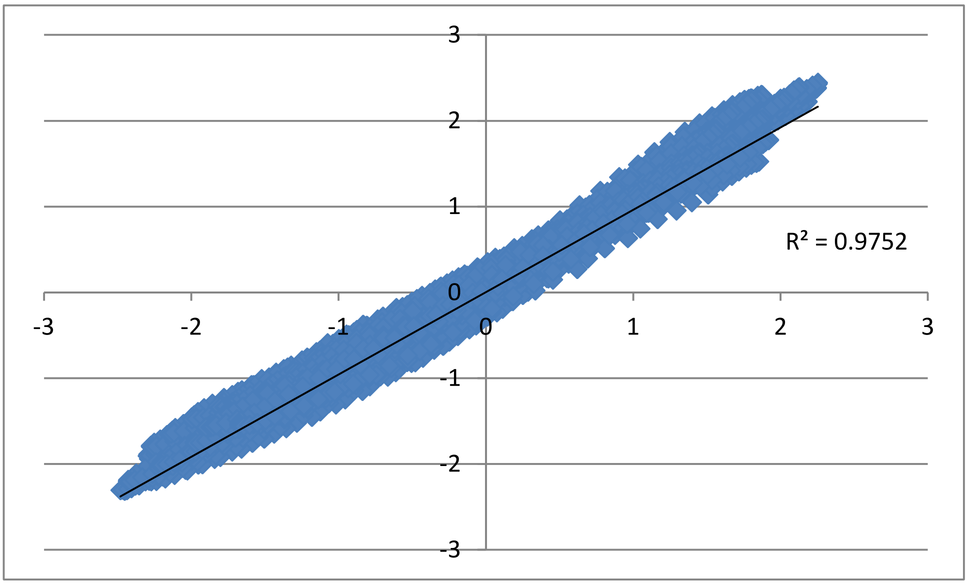

Figure A 1.9 – Water Level Scatter plot, Skerries

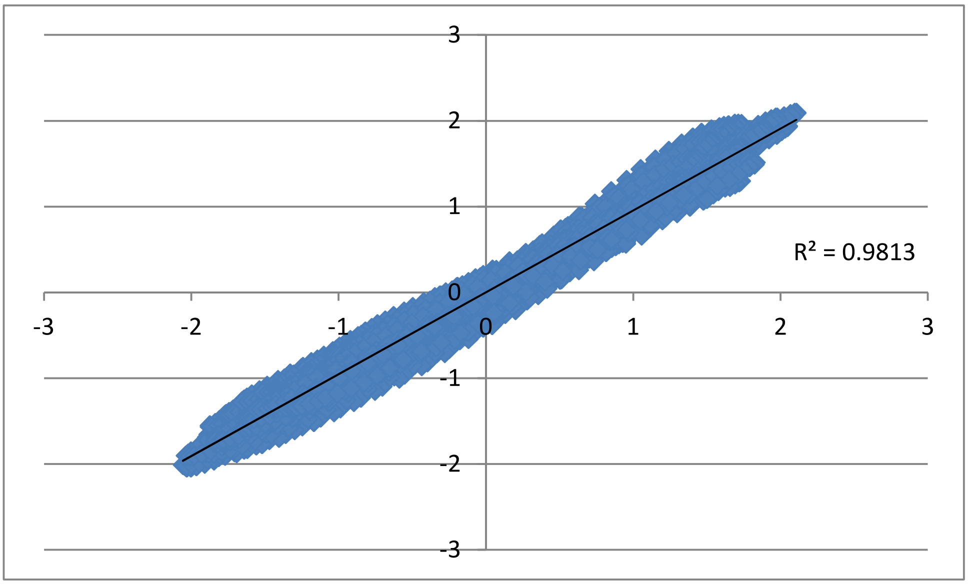

Figure A 1.10 – Water Level Scatter Plot at Howth

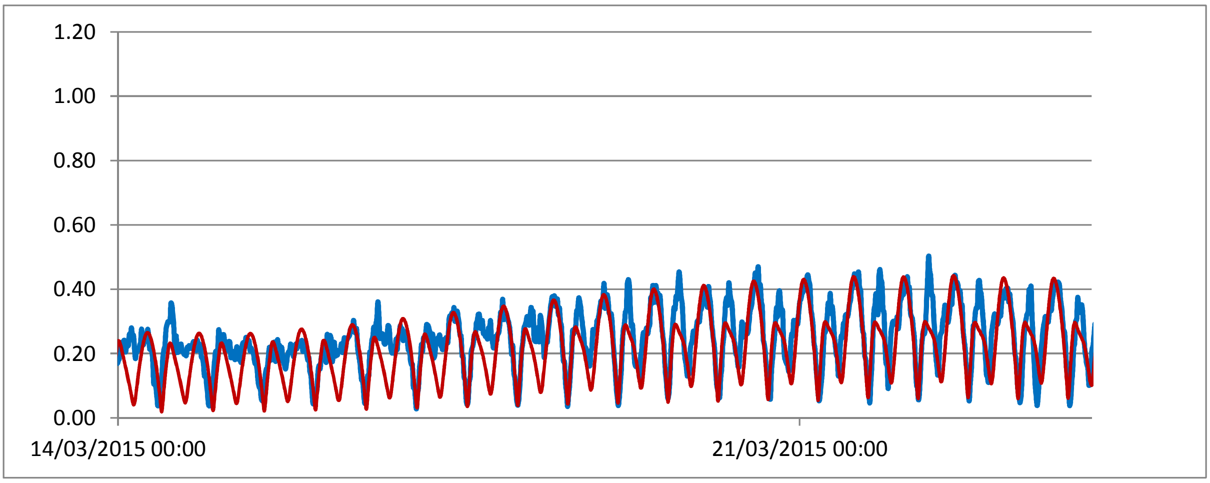

Figure A1.11 – Speeds at ADCP 2015-1 (blue) v. model predictions (red)

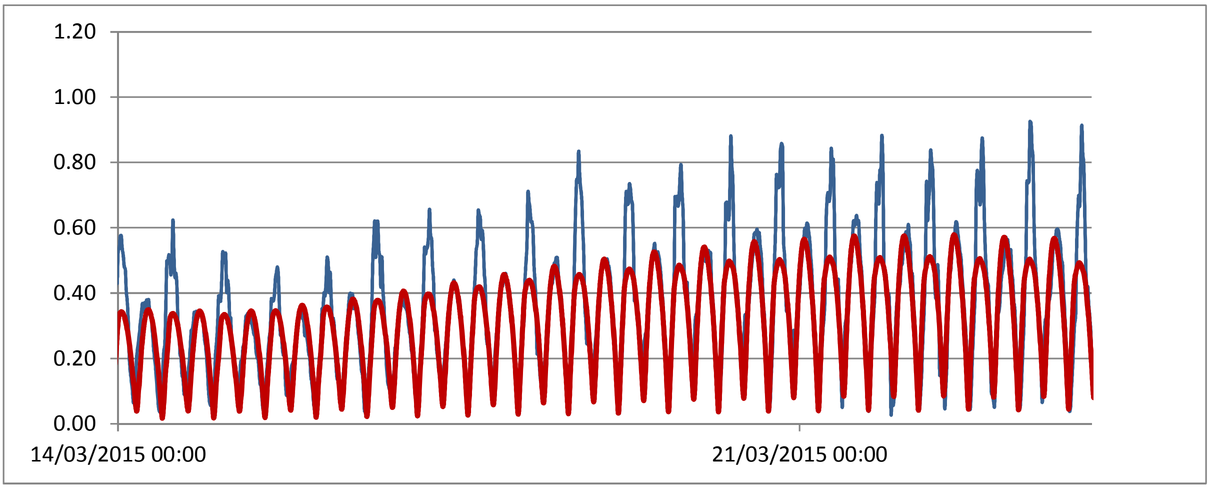

Figure A1.12 – Speeds at ADCP 2015-2 (blue) v. model predictions (red)

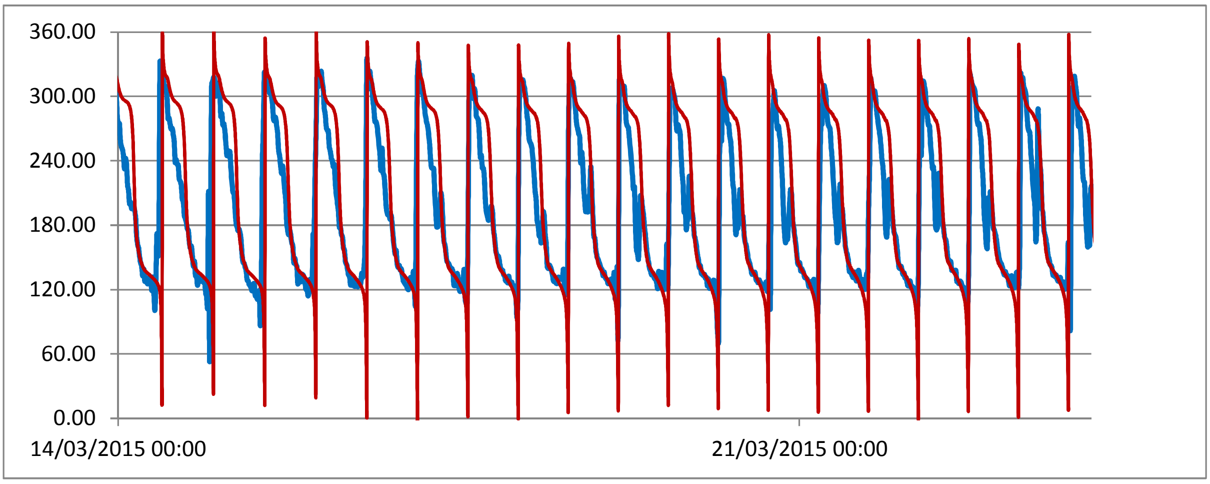

Figure A1.13 – Directions at ADCP 2015-1 (blue) v. model predictions (red)

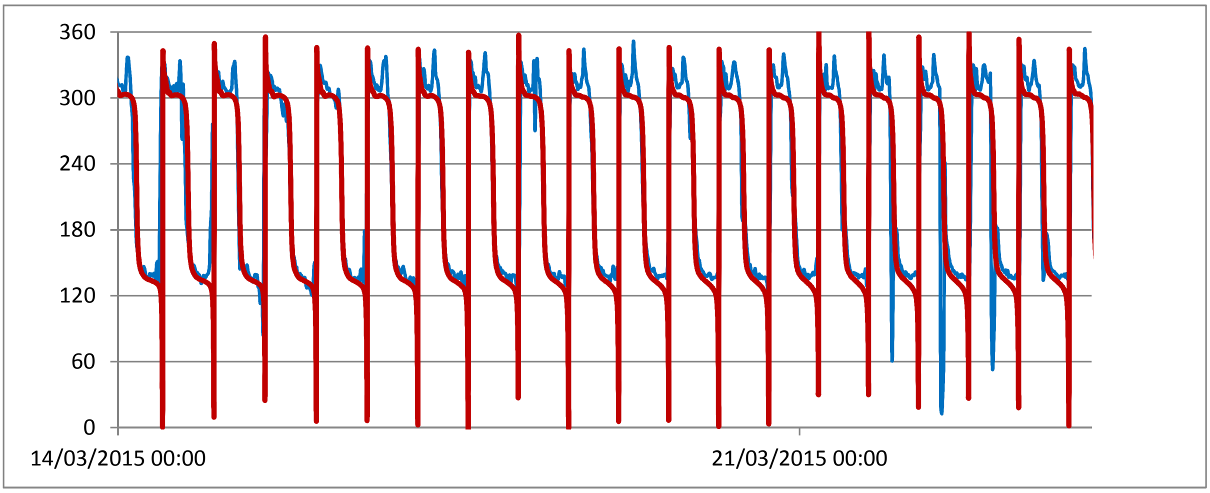

Figure A1.14 – Directions at ADCP 2015-2 (blue) v. model predictions (red)

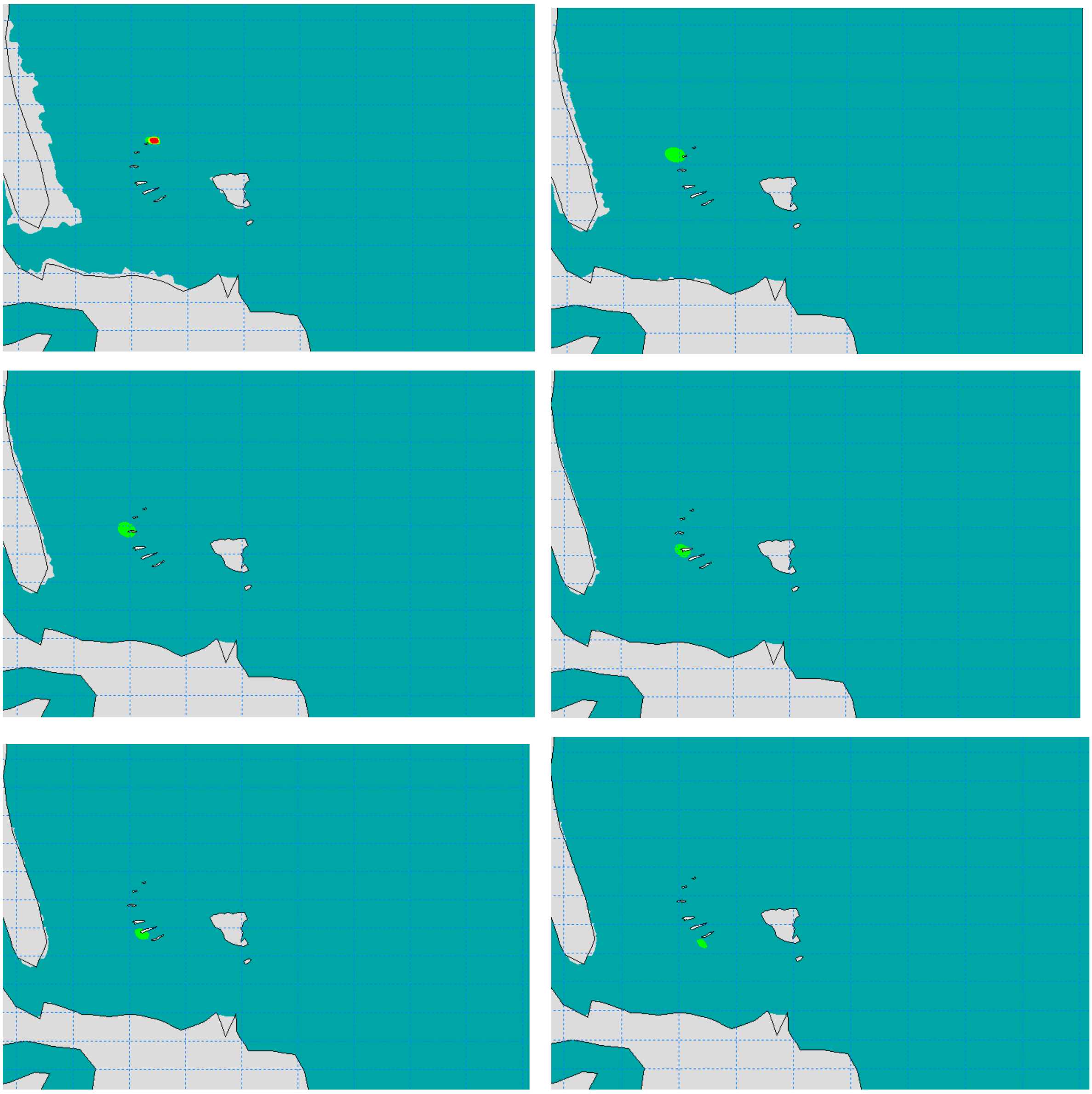

Figure A1.15 – Dye Release, Spring 1

Figure A1.16 – Dye Release, Spring 2

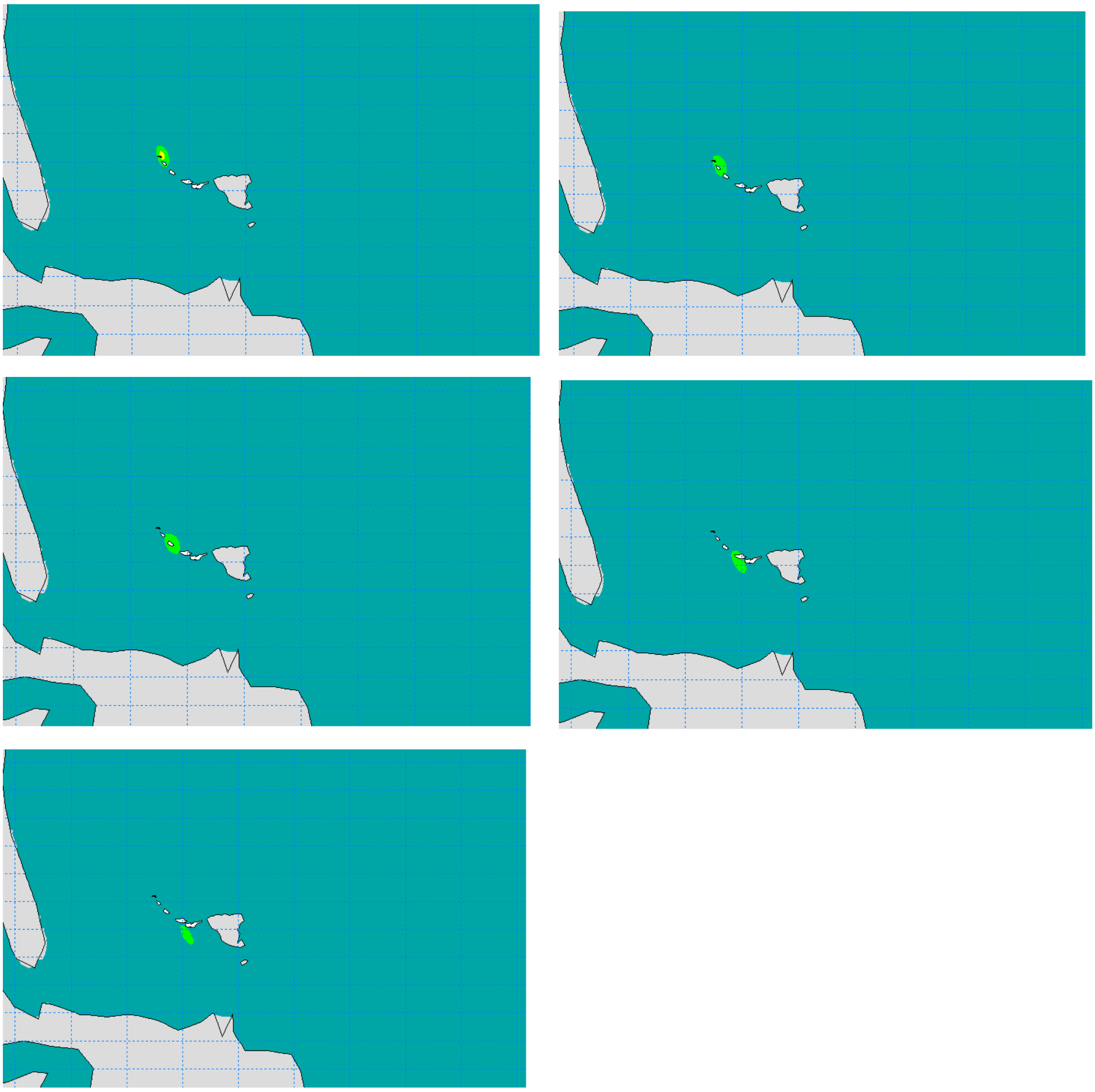

Figure A1.17 – Dye Release, Spring 3

Figure A1.18 – Dye Release, Spring 4

Figure A1.19 – Dye Release, Neap 1

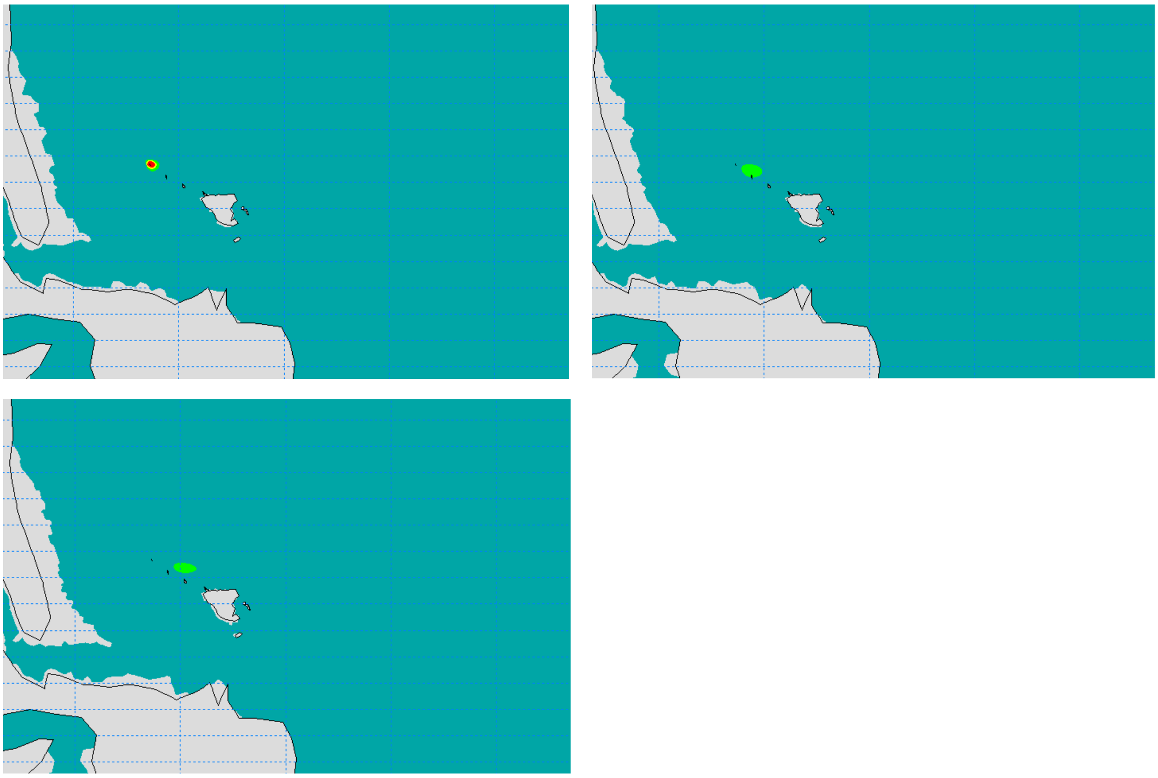

Figure A1.20 – Dye Release, Neap 2

Figure A1.21 – Dye Release, Neap 3

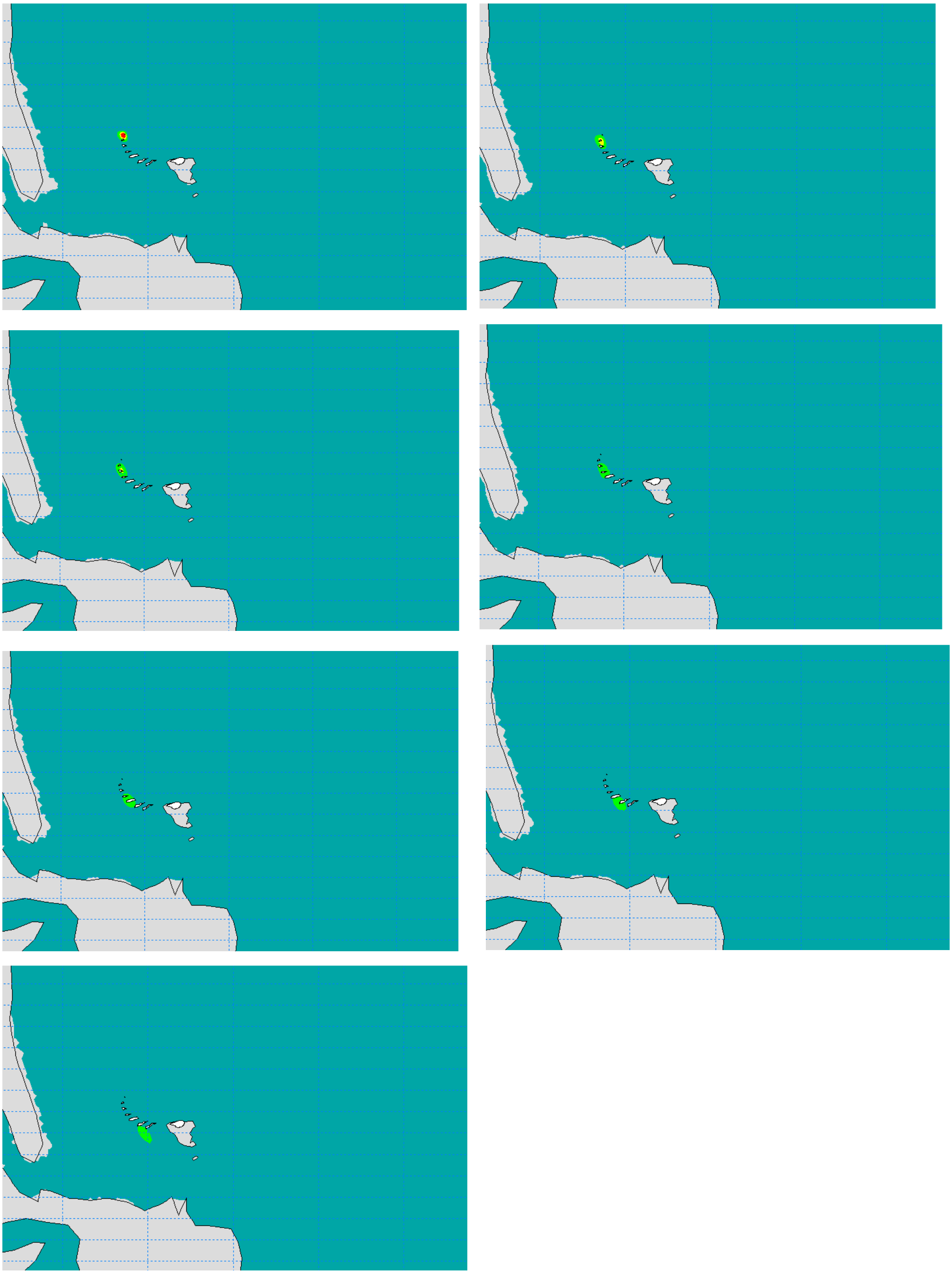

Figure A1.22 – Dye Release, Neap 4