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Assessment and Report on Dispersion Modelling at the Arklow Offshore Disposal Site

WICKLOW
ENDLESS OPPORTUNITIES

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DISCLAIMER

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EXECUTIVE SUMMARY

Gavin and Doherty Geosolutions Ltd has been commissioned by Wicklow County Council to conduct an assessment of sediment dispersion at the Arklow offshore disposal site, in connection with the proposed Eight-Year Maintenance Dredging Programme for the years 2024 to 2032. This study serves as support for Wicklow County Council's application to the Environmental Protection Agency, seeking a permit under Section 5 of the Dumping at Sea Acts 1996 to 2010, as well as Stage 1 of the Appropriate Assessment process mandated by the Habitats Directive (92/43/EEC).

Under the proposed maintenance dredging program, a total of 415,800 dry tonnes of sediment will be dredged from various areas within Wicklow Harbour, including the navigation channel, basin, and berthing pockets. The primary operations in the first year are expected to yield 113,575 dry tonnes. This value draws upon three dredging methods: Trailing Suction Hopper Dredging (TSHD) and mechanical dredging, Water Injection Dredging (WID), and Ploughing Dredging. With the TSHD method, the dredged material is designated for offshore disposal. It's projected that the first year of the campaign will witness the maximum volume dredged using TSHD in a single phase, estimated at 80,850 dry tonnes. The intended disposal site for the dredged material is the Arklow offshore disposal site, situated approximately 22.5 km south of Wicklow Harbour.

A modelling scenario was established to assess the impact of sediment dispersion on the receiving environment, both within the Arklow offshore disposal area and in the vicinity of the nearest Special Areas of Conservation (SACs). This scenario involved simulating the dumping operations for the primary year's sediment volume generated via TSHD. An 18-day simulation period, comprising 90 cycles, was considered sufficient to evaluate sediment dispersion at the disposal site.

The rate of disposal of mechanical dredging is significantly below TSHD. On this basis, TSHD disposal has been modelled and assessed as it constitutes the worst-case scenario of both disposal at sea methodologies.

The results of the simulation indicate that gravel and sand fractions settled out of suspension within the disposal site and remained close to the disposal site boundary throughout the simulation period. In contrast, the silt fraction dispersed outside the disposal site. The maximum total Suspended Solid Concentration (SSC) within the Arklow offshore disposal area reached 0.12 Kg/m^3, while in the SAC areas, the highest total SSC values were observed at Buckroney-Brittas Dunes and Fen SAC and Kilpatrick Sandhills SAC, with all other SAC areas displaying maximum total SSC values below 0.0018 Kg/m^3. Bed thickness changes within the Arklow offshore disposal area were less than 5.5 cm, while at Buckroney-Brittas Dunes and Fen SAC, they were under 4.0 cm. For Kilpatrick Sandhills SAC, bed thickness change was under 1.0 cm, and for other nearby SAC areas mentioned in the report, it was below 0.001 cm.

1 INTRODUCTION

1.1 BACKGROUND

Wicklow County Council has set out an eight-year maintenance dredging program (from 2024 to 2032) for Wicklow Harbour. This program aims to maintain the advertised charted depths of the navigation channel, turning basin, and berthing pockets within the harbour, ensuring safe navigation for vessels traveling to and from the Port. The material resulting from the dredging will be appropriately disposed of at a designated offshore disposal site known as Arklow, located approximately 22.6 km south of Wicklow Harbour.

Wicklow County Council has enlisted the services of Gavin and Doherty Geosolutions Ltd to evaluate the dispersion of spilled material during the dredging operations within Wicklow Harbour's loading areas, as well as the dispersion of material dumped at the proposed disposal site. This report focuses specifically on the assessment of material dispersion at the proposed disposal site. The assessment of material dispersion during dredging operations in Wicklow Harbour is detailed in the [1].

1.2 ARKLOW DISPOSAL SITE

The Arklow Offshore disposal site, situated approximately 0.75 kilometres offshore from Arklow, played a pivotal role in the responsible disposal of dredging material from Arklow Harbour. This endeavour was made possible through the issuance of Dumping at Sea Permit S0002-01 by the Environmental Protection Agency (EPA) in April 2011. The actual dredging works and subsequent disposal at the site occurred in 2014.

Notably, the dredged material from Arklow Harbour contained heavy metal contaminants. To safeguard the marine environment, a meticulous approach was adopted. The dredged material was carefully deposited into an excavated pit at the disposal site. A protective layer of clean sediments was then placed over it, effectively containing, and preventing the release of heavy metals into the surrounding marine ecosystem.

In accordance with international best practice guidelines for managing contaminated marine sediments, a comprehensive monitoring strategy was devised. This strategy entailed periodic assessments of the dumping site's environmental impact. Initial monitoring occurred six months after the conclusion of loading and dumping activities, followed by annual assessments. These evaluations included the collection and analysis of sediment chemistry, particle size distribution (PSD), and the assessment of macroinvertebrate communities, as outlined in the Ocean Ecology Laboratory's 2023 report [2].

This rigorous monitoring regimen reflects a commitment to environmental stewardship and ensures the ongoing protection of the marine environment surrounding the Arklow Offshore disposal site.

1.3 DREDGING OPERATIONS

As part of the Eight-Year Maintenance Dredging Programme spanning from 2025 to 2032, the loading of dredged material will be limited to specific sections of Wicklow Harbour's navigation channel, basin, and berthing pockets that contain sediments suitable for disposal at sea. The proposed disposal site for these dredged sediments is the Arklow offshore disposal site, situated approximately 22.6 kilometres south of Wicklow Harbour. The estimated total volume of sediment to be deposited at the Arklow Offshore disposal site over the eight-year duration of the program is approximately 288,750 dry tonnes. The highest volume of material to be dredged during a single dredging phase is expected to occur in the first year of the campaign, totalling 113,575 dry tonnes. This represents the worst-case scenario for the disposal and dispersion of the dredged material. The figures provided are based on the use of three dredging techniques: Trailing Suction Hopper Dredging (TSHD) and mechanical dredging, Water Injection Dredging (WID), and Ploughing Dredging. The TSHD method implies that the dredged material is disposed at the offshore site. The highest dredging volume using the TSHD technique in a single phase is anticipated in the first year of the campaign, amounting to 80,850 dry tonnes. The rate of disposal for mechanical dredging is notably lower than that of TSHD method. Consequently, we have conducted a modelling and assessment of TSHD disposal, considering it as the worst-case scenario among the two sea disposal methods.

The location of the historical offshore disposal site is shown in Figure 1-1 alongside other areas of interest representing nearby Special Areas of Conservation (SACs). These SACs include the Murrough Wetlands SAC, Wicklow Reef SAC, Buckroney-Brittas Dunes and Fen SAC, Kilpatrick Sandhills SAC, and Magherabeg Dunes SAC.

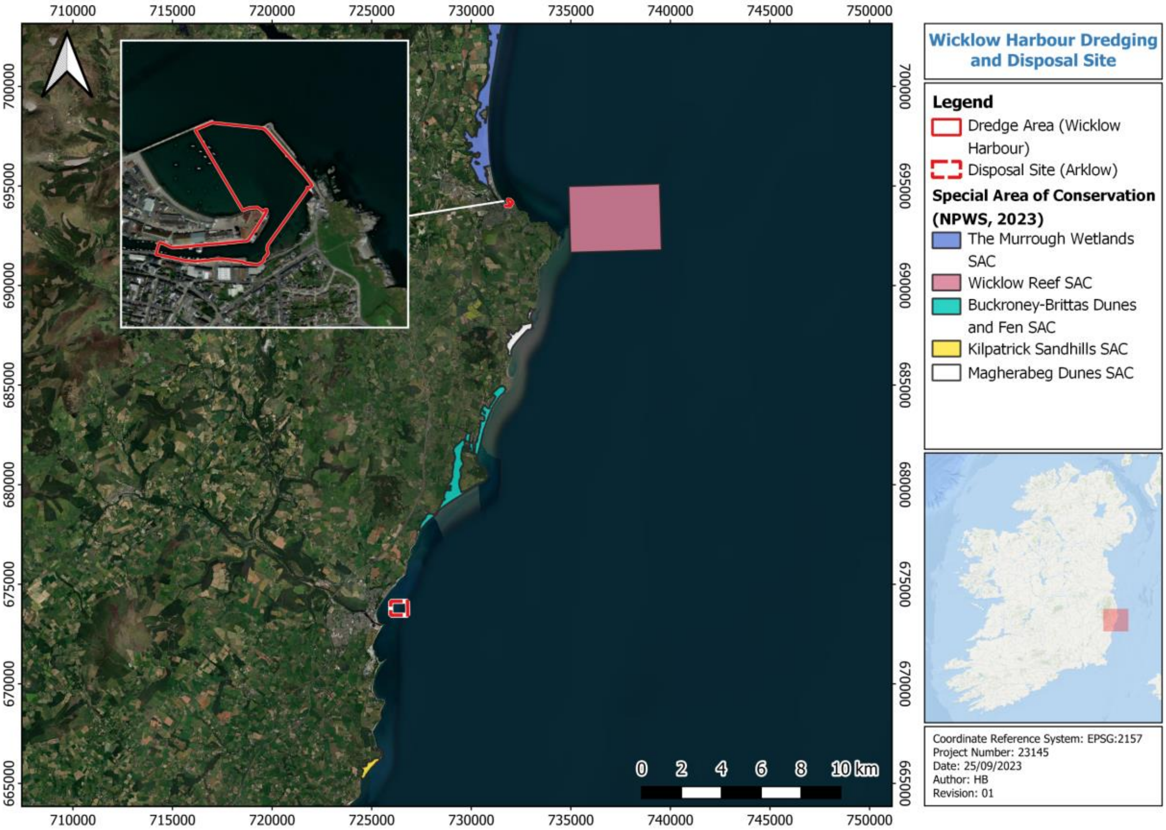

Figure 1-1 Map indicating the locations of the proposed dredge areas, offshore disposal site, and the nearest Special Areas of Conservation (including Murrough Wetlands SAC, Wicklow Reef SAC, Buckroney-Brittas Dunes and Fen SAC, Kilpatrick Sandhills SAC, and Magherabeg Dunes SAC).

1.4 SEDIMENT PROPERTIES

In 2021, two sets of sediment samples were collected within Wicklow Harbour. The initial set of samples (samples 1-7) aimed to provide the Marine Institute with insights into the physical and chemical properties of the materials in the designated dredging zones. Subsequently, the second set of samples (samples 8-11) was specifically requested by Wicklow County Council to gather information pertaining to potential future areas of interest. Figure 1-2 illustrates the precise locations of each sample, while Table 1-1 presents the results of the particle size analysis.

Table 1-1 Sediment samples in Wicklow Harbour

Reference	Gravel (> 2 mm)	Sand (63 - 2000 um)	Silt (< 63 um)	Classification
S1	8.7	42.4	48.9	gM: Gravelly Mud
S2	0	56.6	43.4	mS: Muddy Sand
S3	0	36.8	63.2	sM: Sandy Mud
S4	32.5	36.2	31.2	msG: Muddy Sandy Gravel
S5	4.6	21	74.4	(g)sM: Slightly Gravelly Sandy Mud
S6	0	29.3	70.7	sM: Sandy Mud
S7	39.8	57.3	2.9	sG: Sandy Gravel
S8	1.9	91.7	6.4	(g)S: Sandy Gravel
S9	0	94.8	5.2	S: Sand
S10	0	72.9	27.1	mS: Muddy Sand
S11	0	49.7	50.3	sM: Sandy Mud

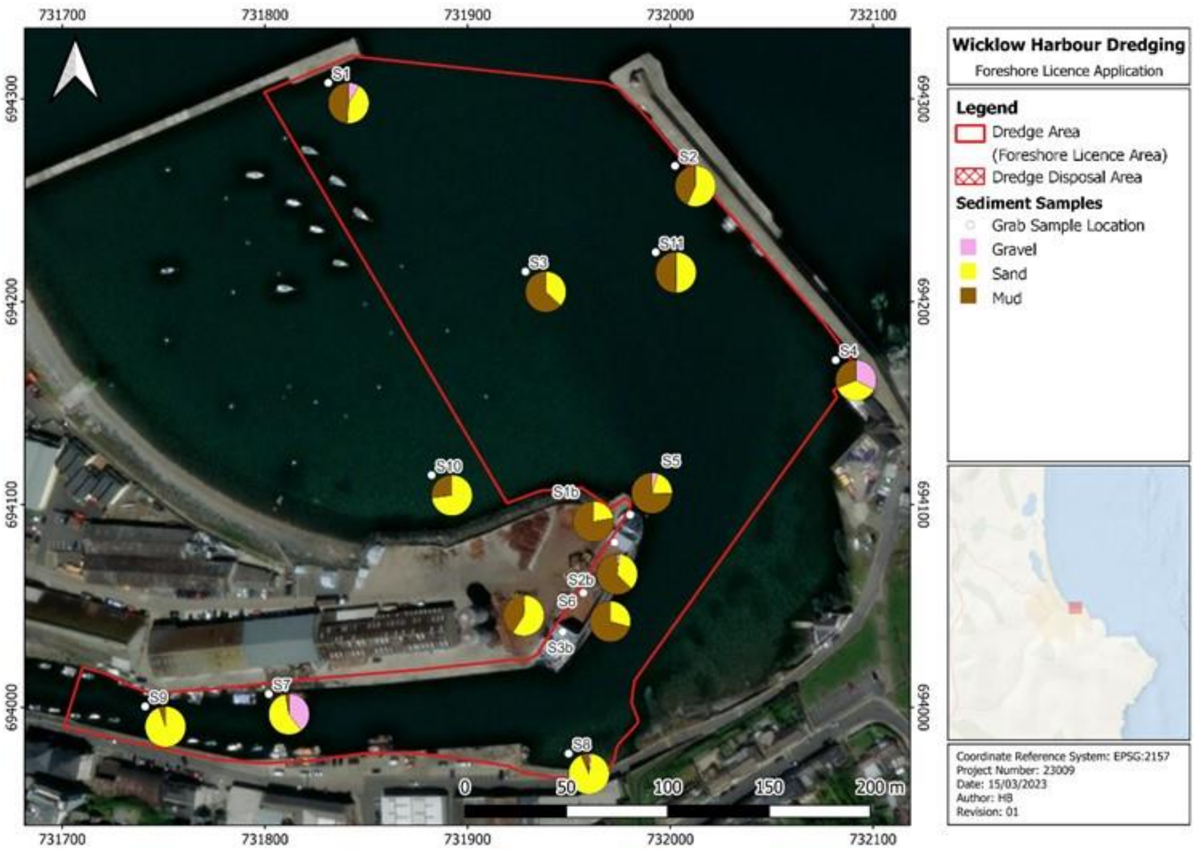

Figure 1-2 Wicklow Harbour Sediment Particle Size Analysis (PSA) from the Dredge Area (Showing Gravel: pink, Sand: yellow and Mud: brown)

1.5 MODELLING SOFTWARE

The tidal flow simulations which form the basis of the study were undertaken using MIKE 21 Flow Model Flexible Mesh (FM) modelling system developed by DHI. The MIKE system is a state of the art, industry standard, modelling system, based on a flexible mesh approach. Using these flexible mesh modelling systems, it is possible to simulate the mutual interaction between currents and sediment transport by dynamically coupling the relevant modules in both two and three dimensions. The Flow Model FM modules include the Hydrodynamic Module (HD) and the Mud Transport (MT) Module.

The MIKE 21 Flow Model FM Hydrodynamic (HD) Module is a 2-dimensional depth-averaged hydrodynamic programme that resolves the shallow water equations, or Navier Stokes Momentum, and continuity equations [3] [4]. These are resolved using a finite volume scheme. The Riemann solver [5] is used to determine the fluxes within the domain mesh, with various approximation schemes applied to resolve second order variance. The flow velocity is derived from the depth integrated resolution of the shallow water equations. Tide-induced bottom stresses are determined by a quadratic friction law which utilises drag coefficient and flow velocity. The simulated drag coefficient is calculated by resolving the Manning number (M) for bed friction [6].

The main features and effects included in the Hydrodynamic Module are:

- Flooding and drying
- Momentum dispersion
- Bottom shear stress
- Coriolis force
- Wind shear stress
- Barometric pressure gradients
- Ice coverage
- Tidal potential
- Precipitation/evaporation
- Wave radiation stresses
- Sources and sinks

The Mud Transport (MT) module [7] describes erosion, transport and deposition of mud or sand/mud mixtures under the action of currents and (if appropriate) waves. The module notably takes into account non-cohesive material which is ideal for simulating sediment dispersion from dredging activities [8]. The hydrodynamic basis for the MT Module is calculated using the Hydrodynamic Module of the MIKE 21 Flow Model FM modelling system and the MT is implemented as a coupled model with the two running concurrently. The following processes may be included in the simulation:

- Multiple sediment fractions
- Inclusion of non-cohesive sediments
- Multiple bed layers
- Flocculation
- Hindered settling
- Bed shear stress from combined currents and waves

- Forcing by waves
- Consolidation
- Tracking sediment spills
- Morphological update of the bed.

In the MT-module, the settling velocity varies, according to the salinity, if included, and the concentration taking into account flocculation in the water column. Bed erosion can either be non-uniform, i.e. the erosion of soft and partly consolidated bed, or uniform, i.e. the erosion of a dense and consolidated bed. The bed is described as layered and is characterised by the density and shear strength [7].

2 HYDRODYNAMIC MODELLING

2.1 HD MODEL SET-UP

The hydrodynamic model domain, as depicted in Figure 2-1 Numerical computational domain: a) Outline of the model domain with b) to d) spatial resolution of the unstructured triangular mesh refined for the area of interest., covers the entire Irish Sea. Within this model, there are two open boundaries: one across the Celtic Sea and another in the North Channel. These boundaries are driven by water level data obtained from the Global Tide Model [9]. Bathymetric data is referenced to OD Malin for coastal waters and Mean Sea Level for offshore areas. The extensive development and validation of this regional model are thoroughly documented in the works of Coughlan et al [10] and Creane et al [11].

To enhance the model's accuracy, updates were made to incorporate a revised coastline configuration, including Arklow Harbour's layout and the location of the river Avoca outlet. To account for river inflow into the sea, a point source with a discharge rate of 20.2 m^3/s was integrated into the model [12]. In the context of this study, an analysis was also conducted of the hydrodynamic impact of the river discharge in the designated disposal area, and the results of this analysis are presented in section 2.2.

For the primary area of interest, the model resolution was refined. The model employs an unstructured triangular mesh with four different mesh refinement areas to ensure accurate hydrodynamic computational modelling and the most precise results for the area of interest, which is the Arklow Disposal Site (as shown in Figure 1-1). The mesh element sizes exhibit variations across the model, including 2.5 km at the open boundaries, 1.5 km within a 35 km buffer zone around Arklow, an additional 15 km buffer zone refinement with 450 m element size, and 100 m within the designated disposal site region. This distribution highlights the varying levels of mesh refinement applied around Arklow and the disposal area. Additionally, specific bathymetric data (5 m x 5 m) provided by the client was incorporated into the model configuration.

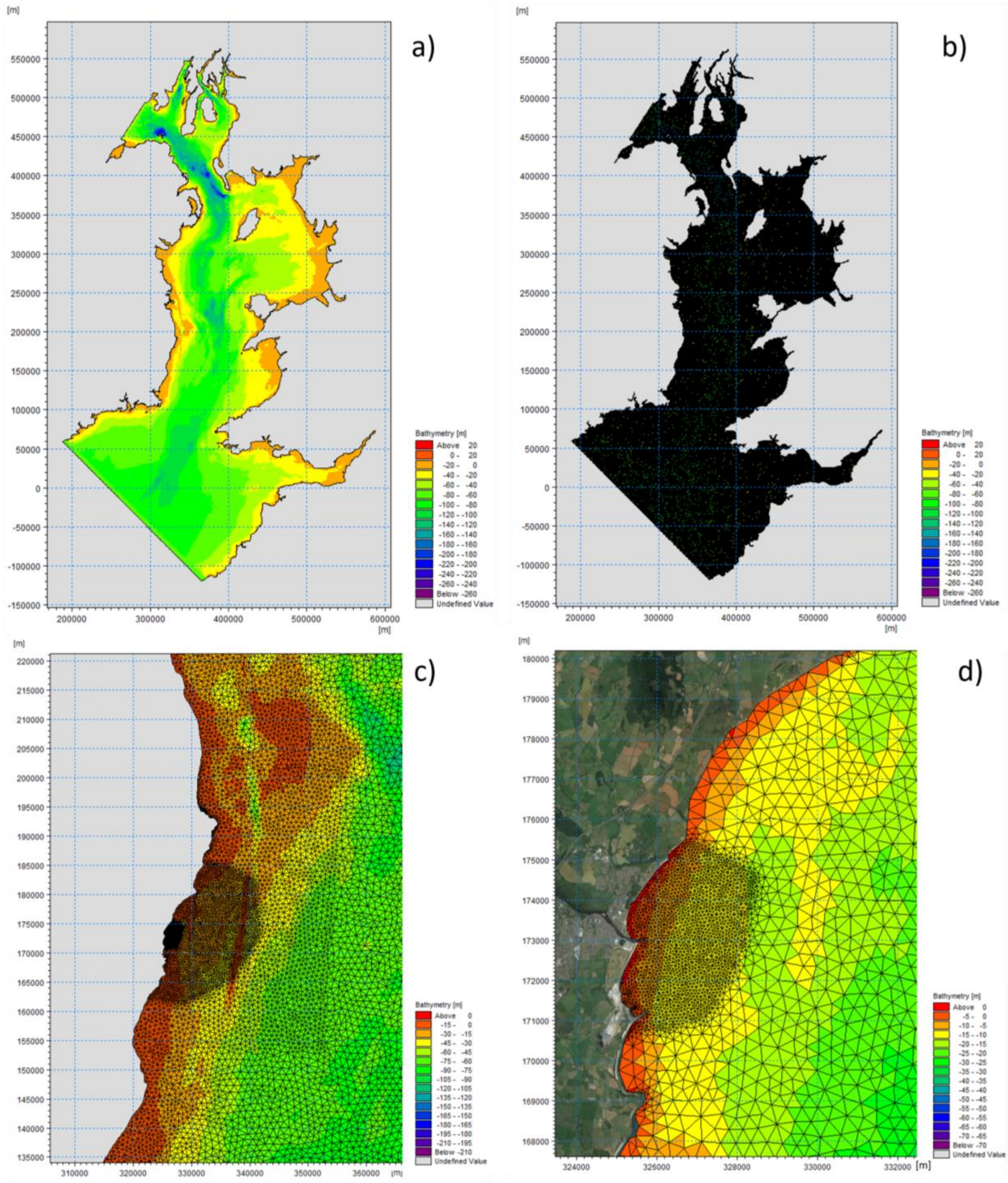

Figure 2-1 Numerical computational domain: a) Outline of the model domain with b) to d) spatial resolution of the unstructured triangular mesh refined for the area of interest.

All site-specific bathymetry datasets provided by the client underwent processing to align with the model's specific requirements. The bathymetry data for the disposal site and the harbour originated from surveys conducted in 2016. Initially referenced to Irish Transverse Mercator (ITM) and Chart Datum at Arklow (as illustrated in Figure 2-2), these datasets were subsequently transformed into the Irish National Grid (ING) and adjusted vertically to OD Malin. This transformation and adjustment procedure, outlined in Figure 2-3, was followed to prepare the data for input into the model. These modified datasets were then utilized as inputs for the model.

Furthermore, additional bathymetric data from INFOMAR and EMODnet were integrated into the numerical model to encompass the entire computational domain.

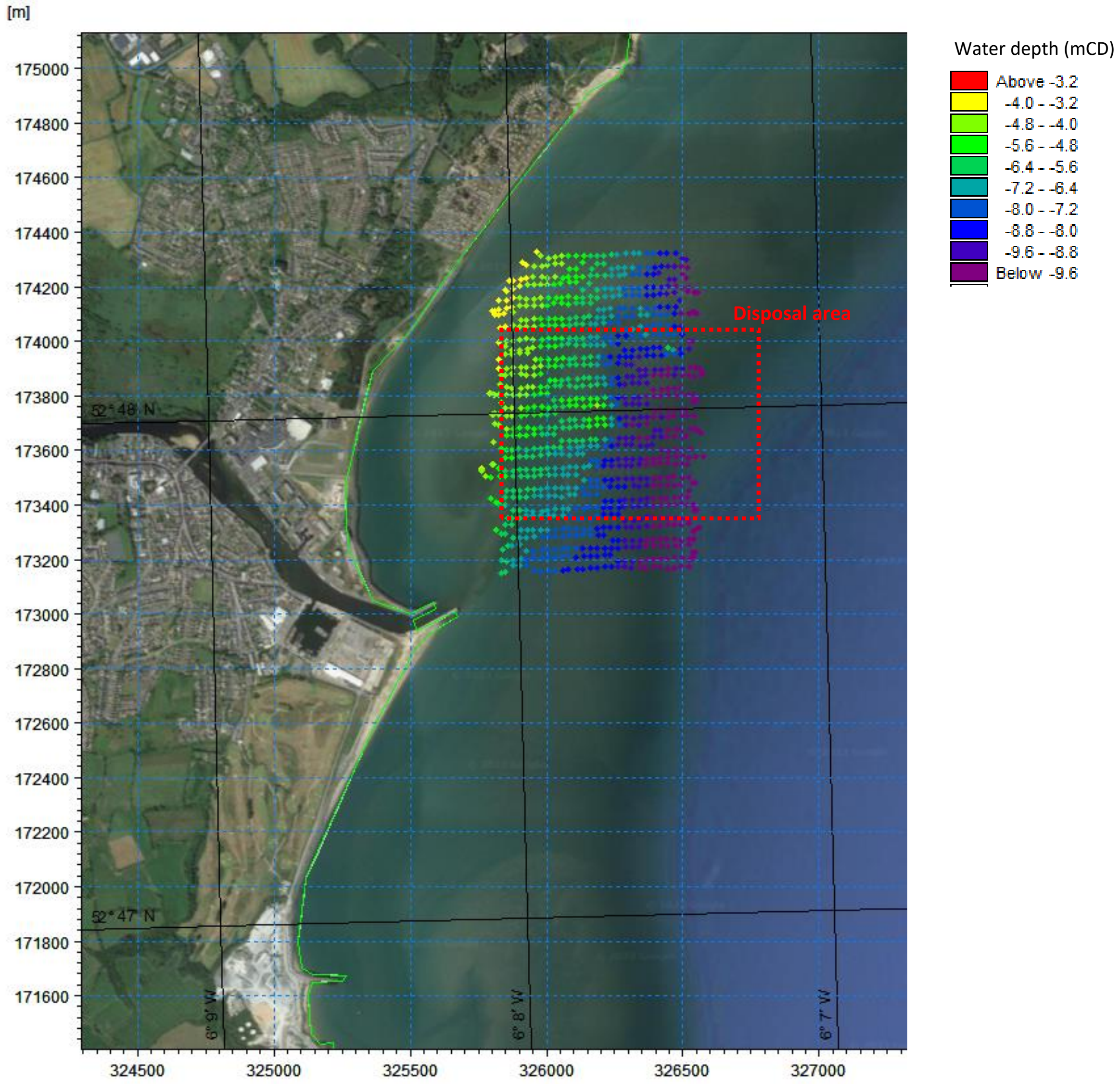

Figure 2-2 Bathymetry dataset provided by the client - 5x5 m bathymetry for Arklow offshore disposal area (2016).

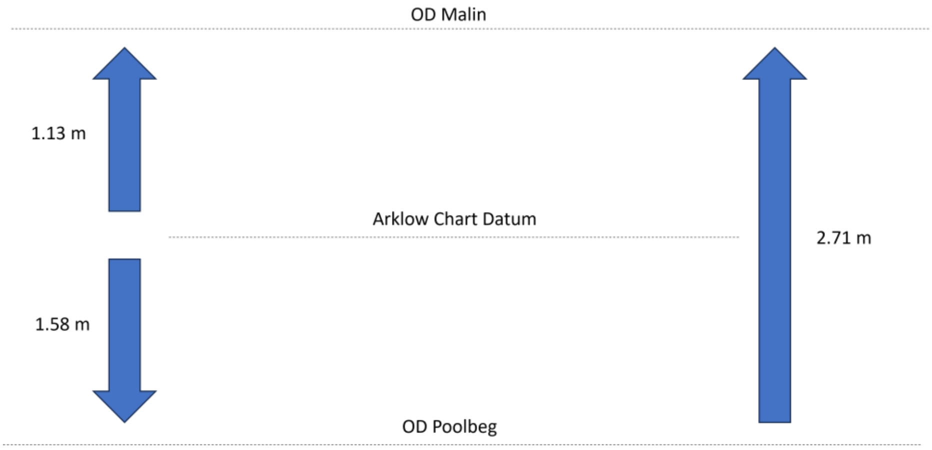

Figure 2-3 Differences between vertical reference datums

A wind file is not included in the simulation since this region is primarily influenced by tidal forces, and the transport will be primarily determined by the current flow [10].

2.2 ANALYSIS OF RIVER DISCHARGE INFLUENCE IN THE DISPOSAL AREA

GDG conducted this additional analysis because it is crucial to have a comprehensive understanding of the hydrodynamics at the Arklow disposal site, particularly concerning the impact of the Avoca River's outflow.

This analysis was prompted by the lack of available data regarding the discharge of the Avoca River at its mouth. Consequently, GDG conducted a comparison to evaluate the differences between simulations conducted with no river discharge (0.0 m^3/s) and simulations that incorporated the average river discharge as documented of 20.2 m^3/s as indicated in [12].

The hydrodynamic computations were performed within the same time frame as the calibration period (Section 2.3.1). Figure 2-4 below illustrates the velocity and direction of the current through vectors for both scenarios, one with river discharge and one without.

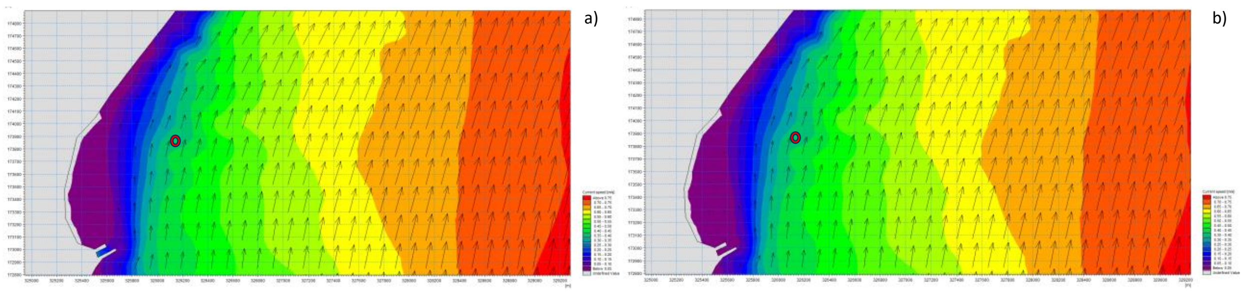

Figure 2-4 Current speed values and directions (vectors) for: a) Avoca River discharge of 20.2 m^3/s; b) Avoca River discharge of 0.0 m^3/s

Time series data for the current velocity were obtained from coordinates (326176 m, 173725 m) (Coordinate system: EPSG 2157), located within the disposal area. These time series were subsequently subjected to a comparison using the same comparison coefficients employed during the calibration process (as detailed in Table 2-2).

Figure 2-5 illustrates the time series of currents at the specified point for both scenarios of Avoca River discharge: 20.2 m^3/s and 0.0 m^3/s. Additionally, Figure 2-6 shows the disparity between the two simulated scenarios, one with river discharge and the other without. It is noteworthy that the graphs for both cases overlap, signifying a high degree of similarity in the results. This observation is further substantiated by the comparison coefficients provided in Table 2-1.

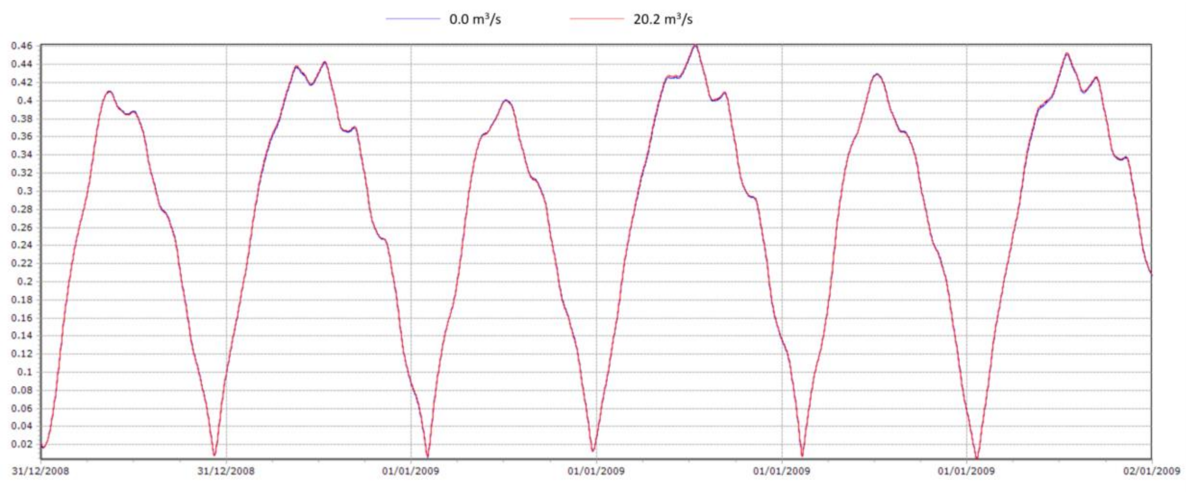

Figure 2-5 Current speed time series within the disposal site (326176 m, 173725 m) for simulations considering Avoca River discharge of 20.2 m^3/s (red) and of 0.0 m^3/s (blue).

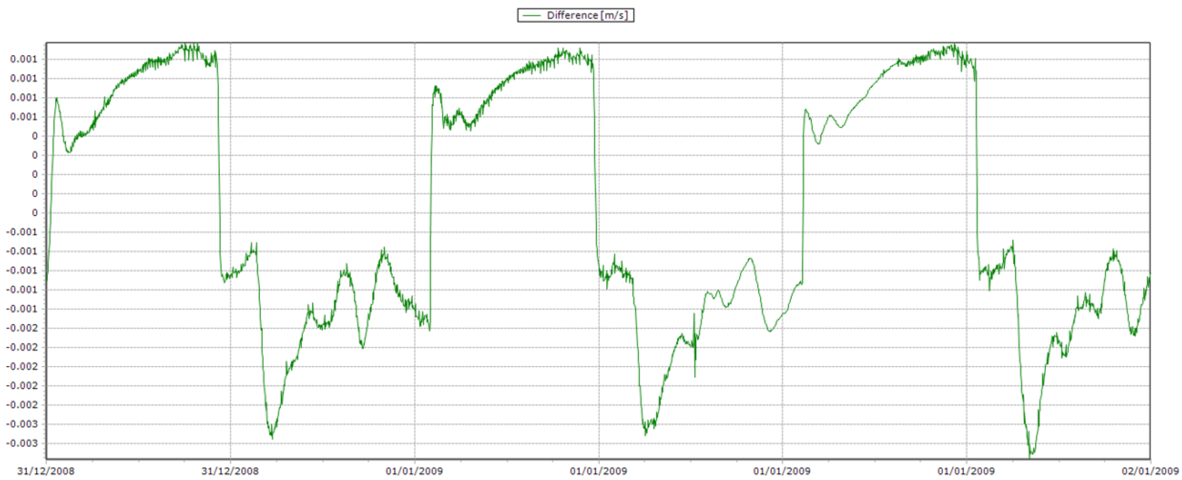

Figure 2-6 Current speed difference within the disposal site (326176 m, 173725 m) considering the comparison between the simulated scenarios considering the Avoca River discharge of 20.2 m^3/s and of 0.0 m^3/s.

Table 2-1 Calculated time series comparison coefficients for both River discharge of 20.2 m^3/s and 0.0 m^3/s.

Index	Value
Mean Error (m/s)	-0.0004
Mean Absolute Error (m/s)	0.0012
Root Mean Square Error (m/s)	0.0013
Standard Deviation of Residuals (m/s)	0.0012

Coefficient of Determination (-)	0.9999
Coefficient of Efficiency (-)	0.9999
Index of Agreement (-)	1.0000

These results, clearly indicate that the hydrodynamics of the disposal site are unaffected by the average river discharge.

2.3 SITE-SPECIFIC MODEL VALIDATION

The hydrodynamic model underwent a calibration and validation processes by utilizing in-situ measurements of current speed and direction. These measurements were obtained from two current meters positioned within the disposal site. The current measurements were conducted between December 23, 2008, and January 6, 2009, at two specified measurement points, as indicated in Figure 2-7. Precisely, these points are located at coordinates 326318 m, 173543 m (Coordinate system: EPSG 2157) for current meter 1 (CM1) and 326419 m, 174025 m for current meter 2 (CM2).

This measurement campaign was an integral component of the 2009 Investigations and Impact Hypothesis report, which was related to an application for the disposal of dredge spoil at sea submitted by the Arklow Harbour Commissioners [13]. The recorded current measurements consisted of time series data for current velocity. The model was executed over a period of four days to comprehensively encompass two flood and two ebb flows, covering at least three days, from December 30, 2008, to January 2, 2009.

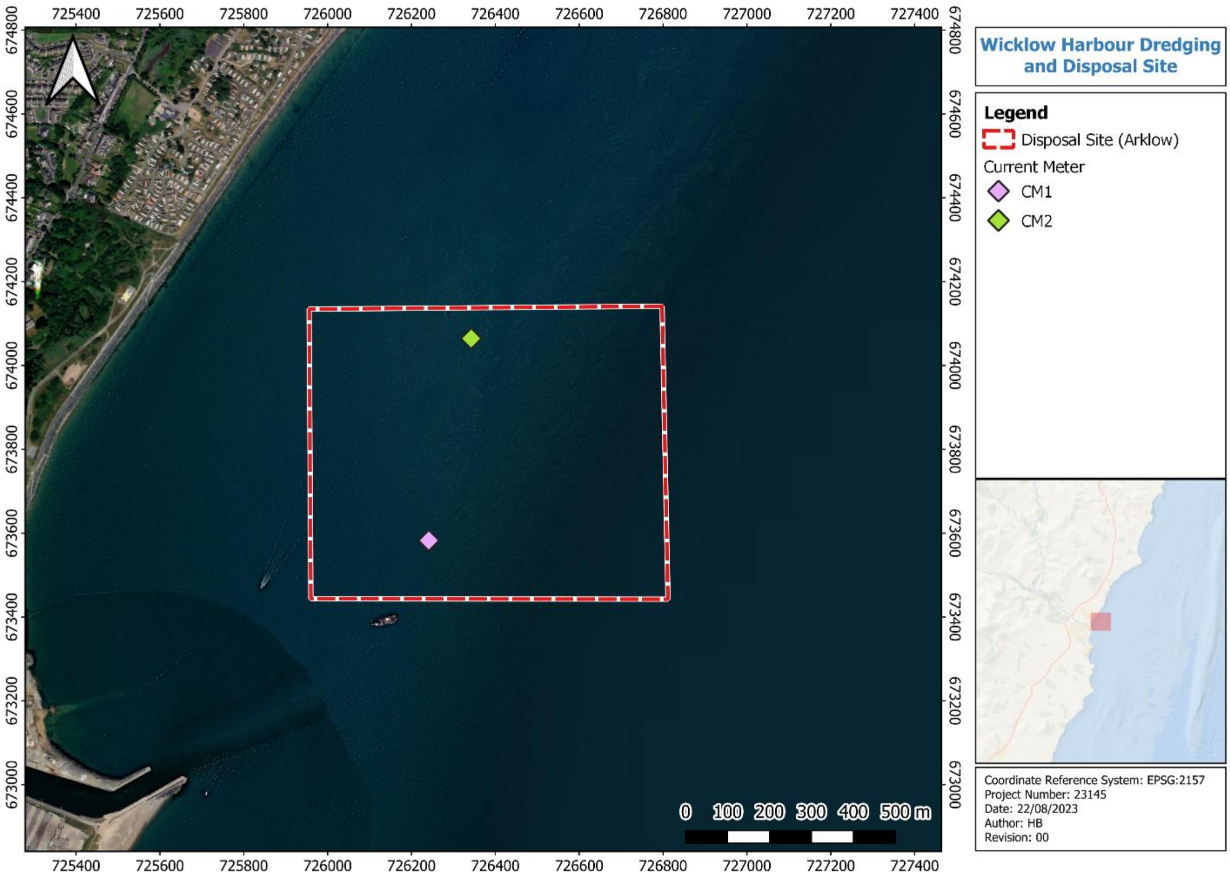

Figure 2-7 Location of the Current meter Measurements (CM1 and CM2) [13].

The complete time series of measurements from CM1 and CM2 are depicted in Figure 2-8 through Figure 2-15.

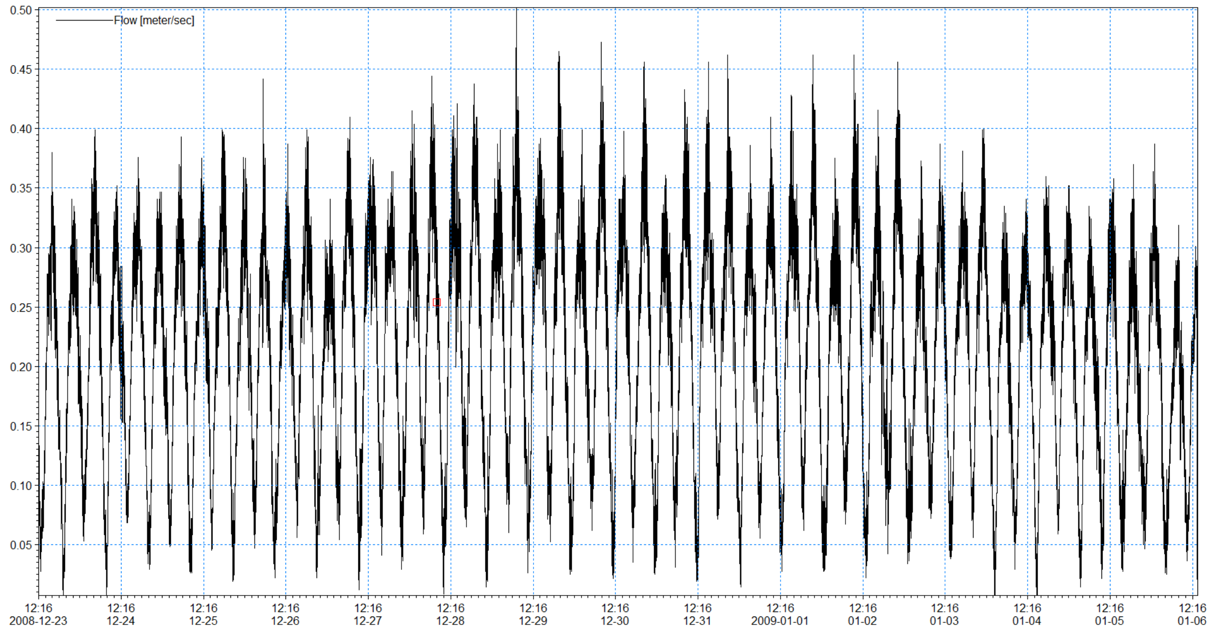

Figure 2-8 Full time series of current speed for current meter 1 (CM1)

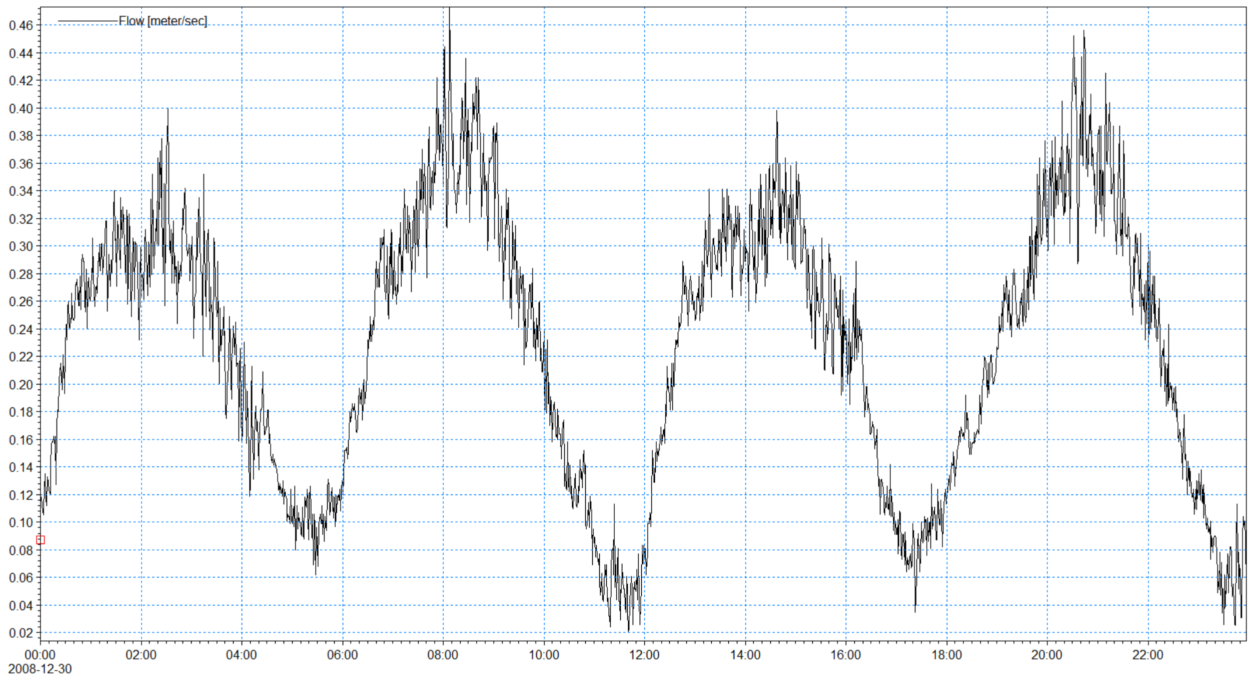

Figure 2-9 Sample of the current speed (from 30/12/2008 00:00 until 31/12/2008 00:00) for current meter 1 (CM1)

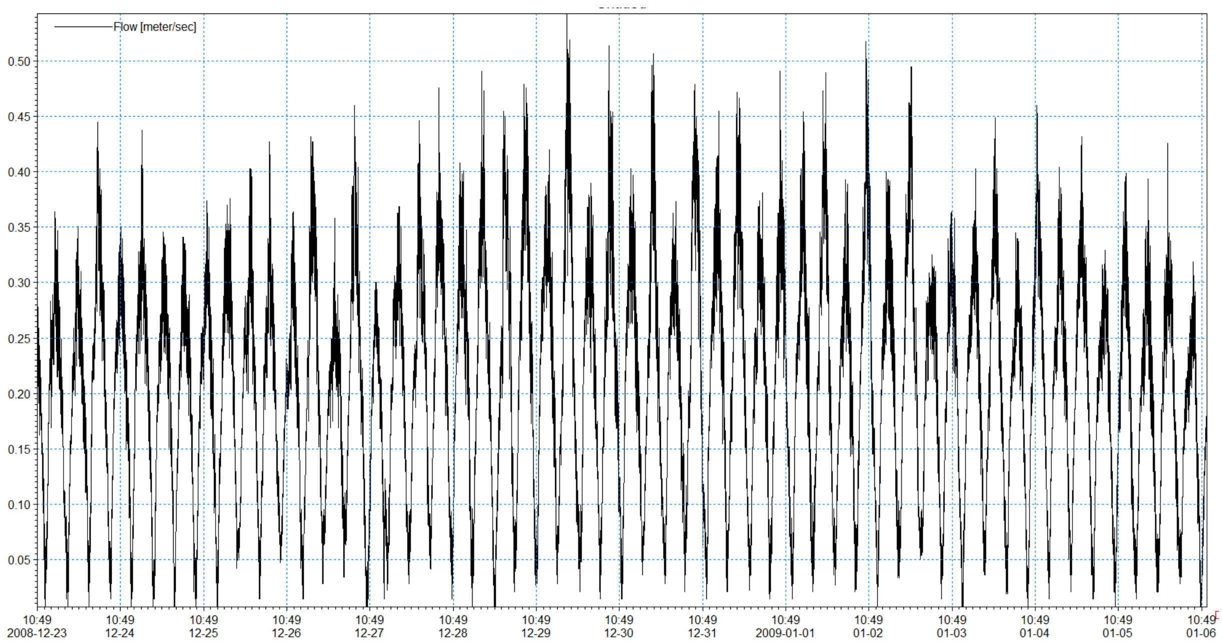

Figure 2-10 Full time series of current speed for current meter 2 (CM2)

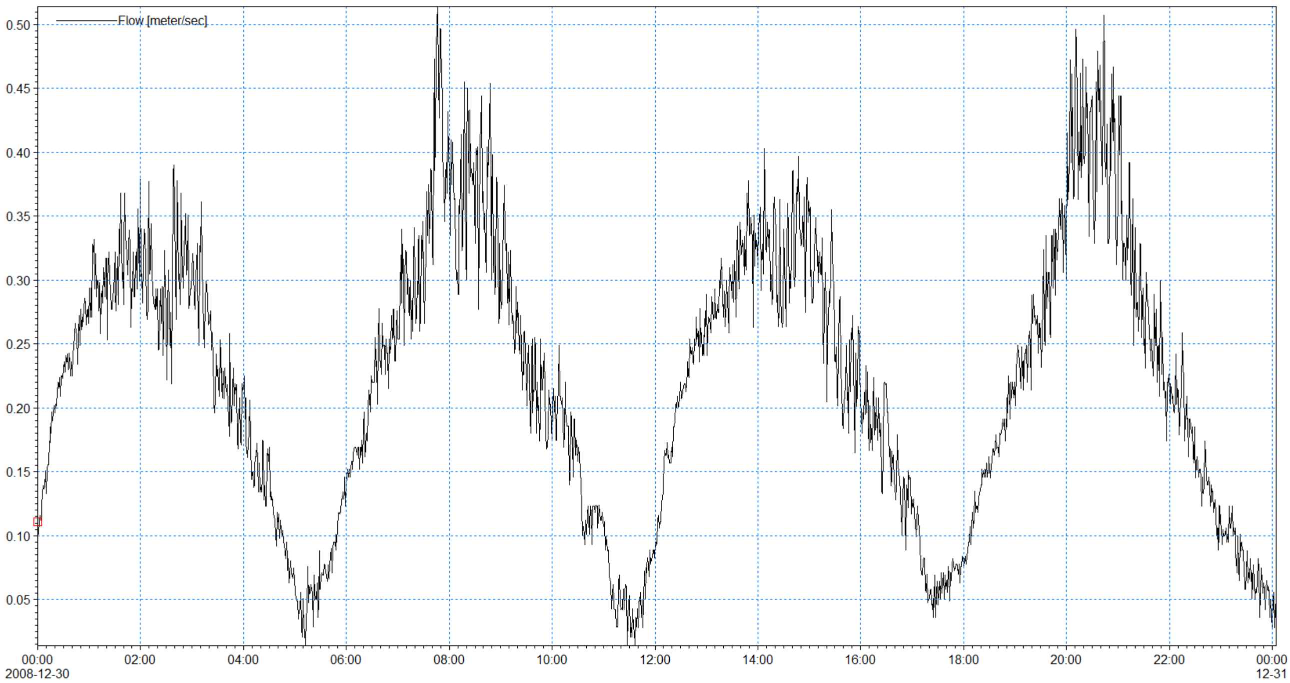

Figure 2-11 Sample of the current speed (from 30/12/2008 00:00 until 31/12/2008 00:00) for current meter 2 (CM2)

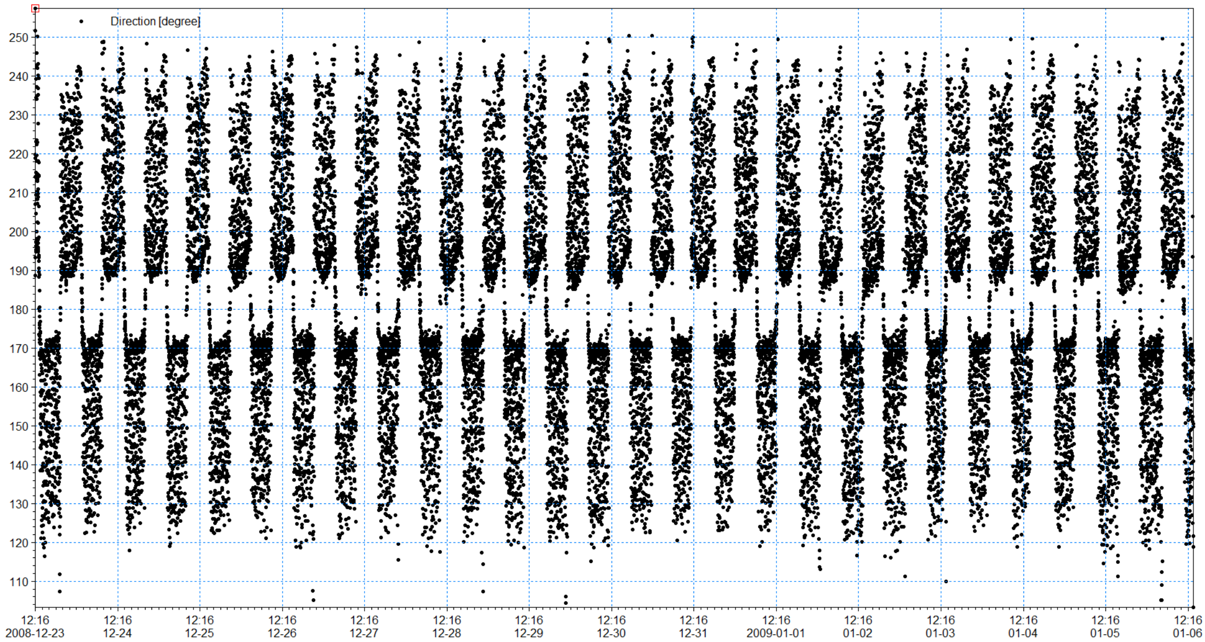

Figure 2-12 Full time series of current direction for current meter 1 (CM1)

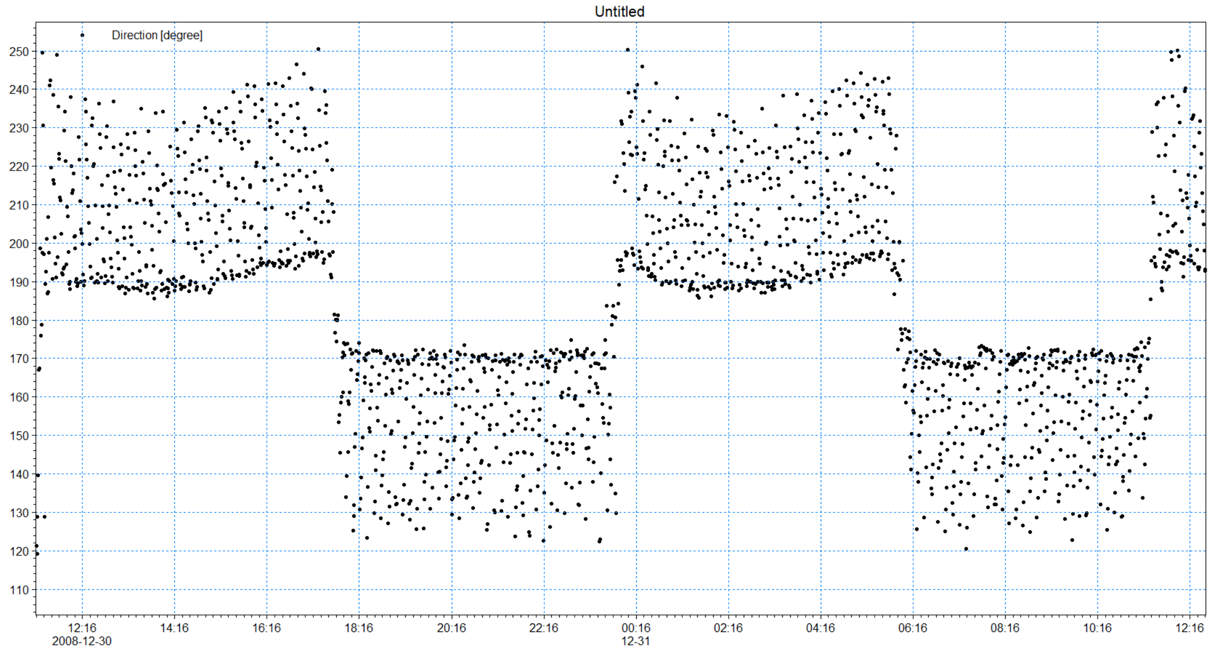

Figure 2-13 Full time series of current direction (from 30/12/2008 00:00 until 31/12/2008 00:00) for current meter 1 (CM1)

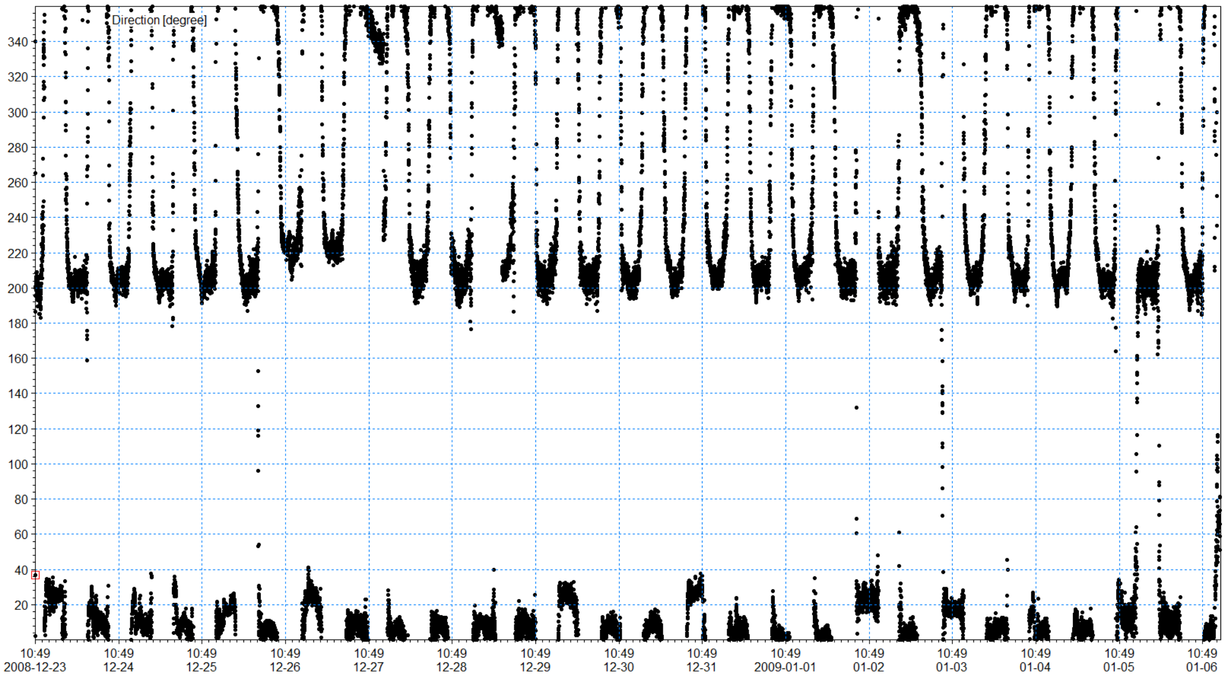

Figure 2-14 Full time series of current direction for current meter 2 (CM2)

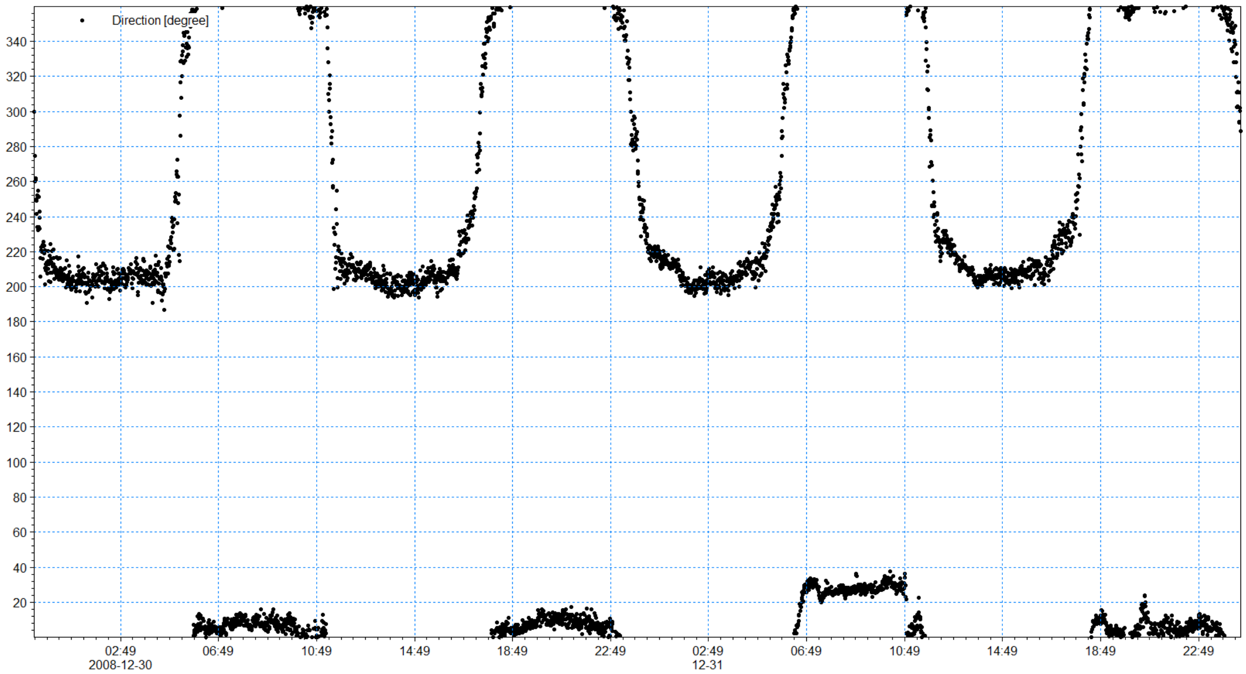

Figure 2-15 Full time series of current direction (from 30/12/2008 00:00 until 31/12/2008 00:00) for current meter 2 (CM2)

When analysing the data from the current meters, there is a specific point that requires attention to enable a proper comparison between the measurements and numerical simulations. Both CM1 and CM2 exhibit current speed values that closely align when comparing data from both sources. However, this consistency is not reflected in the flow direction values. In the case of CM1, the flow direction values significantly deviate from those of CM2 and display a limited range of directions. For the directions recorded by CM1, the differences between ebb and flood tide present only a 20 degree shift, which contradicts the typical circulation pattern observed in the local area. Normally, we would expect a wider range of direction change in accordance with the tidal circulation pattern [10] [11]. This discrepancy raises concerns regarding the accuracy of CM1's direction measurements. Consequently, we have chosen to exclude the direction values from CM1 in our analysis since they do not consistently align with the expected directions in the area. Additionally, it's important to note that we lack information regarding the measurement techniques or any operational logs. Thus, based on our data analysis, we assume that the direction values from CM1 are unreliable.

As a result, considering that the seabed in the disposal area exhibits a consistent bathymetric profile, we relied on CM2's direction measurements for both calibration and validation purposes. This provided a sufficient level of confidence in the numerical modelling values for direction.

By use of the data obtained from the current measurements, GDG successfully calibrated the Hydrodynamic model (HD). This calibration involved the adjusting the value of the Manning Number (bed resistance coefficient) to achieve optimal validation results for the site.

2.3.1 CALIBRATION PROCEDURES AND RESULTS

The hydrodynamic model underwent simulation for the specified period, spanning from December 30th, 2008, to January 2nd, 2009. This simulation involved the incorporation of tidal boundary conditions obtained from the Global Tide Model [9] and the average Avoca River discharge, as specified in [12] (20.2 m3/s). As part of the calibration process, different Manning numbers were applied for each simulation, ranging from 26 to 45.

To achieve the highest possible alignment between the simulated results and the measured data, specific comparison coefficients were utilized. These coefficients, designed to establish an optimal agreement, are detailed in Table 2-2.

Table 2-2 Comparison coefficients applied between observation data (OBS) and results from simulation (SIM).

Index	Equation
Mean Error (***ME***)	$ME = \frac{1}{N}\sum_{j=1}^{N}(\overline{OBS_j} - \overline{SIM_j}) = \overline{OBS} - \overline{SIM}$
Mean Absolute Error (***MAE***)	$MAE = \frac{1}{N}\sum_{j=1}^{N}\lvert OBS_j - SIM_j\rvert$
Root Mean Square Error (***RMSE***)	$RMSE = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(OBS_j - SIM_j)^2}$
Standard Deviation of Residuals (***STD***)	$STD = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(OBS_j - SIM_j - (\overline{OBS_j} - \overline{SIM_j})\right)^2}$
Coefficient of Determination (***R²***)	$R^2 = \frac{[\sum_{j=1}^{N}(OBS_j - \overline{OBS}) - (SIM_j - \overline{SIM})]^2}{\sum_{j=1}^{N}(OBS_j - \overline{OBS})^2 \sum_{j=1}^{N}(SIM_j - \overline{SIM})^2}$

Coefficient of Efficiency (***E***)	$E = 1 - \frac{\sum_{j=1}^{N}\left(OBS_j - SIM_j\right)^2}{\sum_{j=1}^{N}\left(OBS_j - \overline{OBS}\right)^2}$
Index of Agreement (***d***)	$d = 1 - \frac{\sum_{j=1}^{N}\left(OBS_j - SIM_j\right)^2}{\sum_{j=1}^{N}\left(\left\|SIM_j - \overline{OBS}\right\| + \left\|OBS_j - \overline{OBS}\right\|\right)^2}$

Before comparing numerical results with the observed data from CM1 and CM2, a preprocessing technique was applied to the observed data. This technique aimed to mitigate irregular spikes and outlier points in the data. It involves using a rolling average with a 5-minute window size and a standard deviation threshold of 2 [14].

To provide a bit more detail, the "de-spiking" technique is essential when working with observational data to ensure that extreme values or noise do not unduly influence the analysis. The rolling average with a 5-minute window size smooths the data by calculating the average over a 5-minute interval, which helps reduce the impact of sudden, short-lived spikes. The standard deviation threshold of 2 is used to identify data points that deviate significantly from the average, and these points are considered potential outliers or spikes.

By applying this technique, the observed data from CM1 and CM2 were made more suitable for meaningful comparison with the numerical results, as it helped remove or mitigate the effects of irregularities in the data that could otherwise distort the analysis.

In evaluating simulations for current speed, we selected the Coefficient of Determination(R^2) as the parameter, as it showed a stronger alignment with measurements from both current meters. . Additionally, a meticulous visual examination of the time series results, and measurement data played a vital role in selecting the appropriate Manning number coefficient for the final configuration of the bed resistance coefficient. In this context, a successful calibration indicates that the model's predictions closely match observed data, particularly when assessing various Manning number coefficients. A robust calibration is characterized by a combination of visual agreement between simulated and measured values and rigorous statistical assessments. Notably, the coefficient of determination, denoted as R^2, emerges as a pivotal indicator in this calibration process. A high R^2 value indicates a strong linear relationship between the model's predictions and the actual measurements, suggesting that the model effectively captures the underlying processes and dynamics of the hydrodynamics.

Consequently, after taking into account the significant variations in the Coefficient of Determination (R^2) and considering the visual analysis of current speed time series, along with the more consistent nature of the measured current speed values, it becomes apparent that the simulated values corresponding to a Manning number of 36 exhibit a higher level of agreement with the measurements. Hence, it can be concluded that the optimal coefficient for defining seabed resistance is determined to be 36. The comparison of simulated results (with a Manning number of 36) to observed values yields a coefficient of determination, R^2, greater than 0.84, indicating a correlation. Furthermore, the index of agreement (d) demonstrates a value exceeding 0.92.

As depicted from Figure 2-16 to Figure 2-23, we can observe the comparisons drawn between the measurements and numerical simulations. These comparisons involve evaluating the agreement between measured data and numerical modelling simulation employing a bed resistance coefficient (Manning number) of 36. This assessment encompasses the entire 14-day period spanning from December 24, 2008, to January 6, 2009, thus encompassing the complete neap and spring tidal cycle.

As observed in Figure 2-22 and Figure 2-23, it is evident that the simulation anticipates the shift in direction by approximately 20 minutes both before and after the recorded alteration in direction. This pattern remains uniform throughout the entire dataset as well as the numerical simulations. This is most possibly due to low current speeds resulting in the directions becoming more erratic and influenced by winds. It is important to highlight that the accuracy of direction measurements is notably influenced by sudden spikes in the data. Despite these occasional data spikes and the presence of noise, it is noteworthy that we can still distinctly observe a consistent alignment between the measurements and simulation results for both the speed and direction of the currents.

Table 2-3 provides the comparison coefficients for current speed concerning both current meters (CM1 and CM2) and for the current direction of CM2 across the 14-day period, involving simulations utilizing a Manning number of 36.

Table 2-3 Comparison coefficients for current speed (CM1 and CM2) and for current direction CM2 using a Manning number of 36 after applying a rolling average de-spiking.

Simulation Vs Measurements	Mean Error (m/s) (rad)	Mean Absolute Error (m/s) (rad	Root Mean Square Error (m/s) (rad)	Std. dev of Residuals (m/s) (rad)	Coefficient of Determination (-)	Coefficient of Efficiency (-)	Index of Agreement (-)
Current Speed - CM1	-0.0255	0.0441	0.0524	0.0458	0.8485	0.7883	0.935
Current Speed - CM2	-0.0437	0.0531	0.0652	0.0484	0.8453	0.7161	0.9208
Current Direction - CM2	-0.001	0.2528	0.7862	0.7862	0.8443	0.8157	0.957

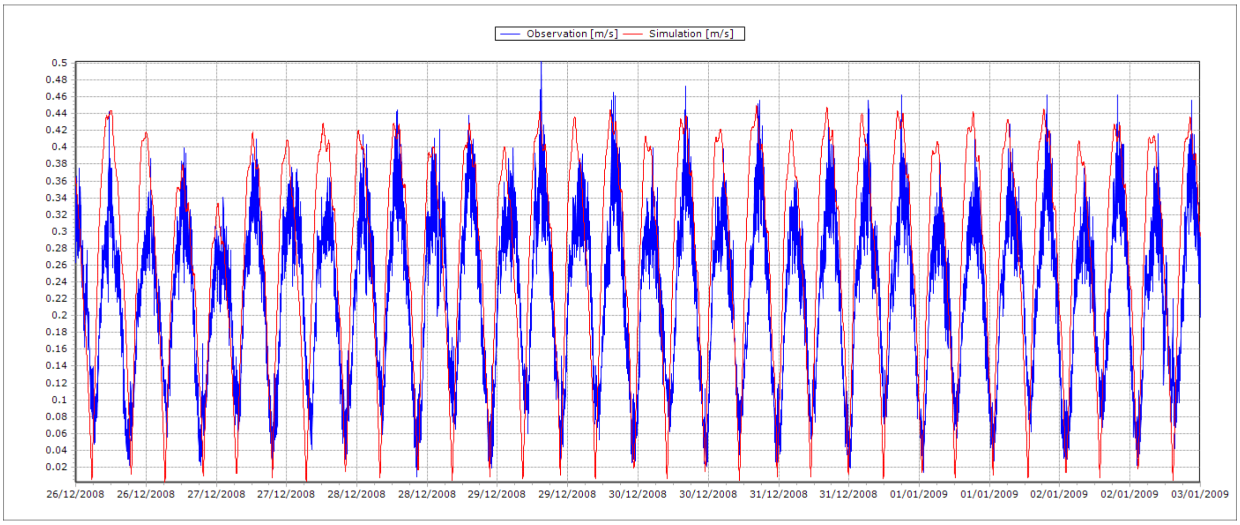

Figure 2-16 Time series of current speed measured data (blue) and numerical simulation with Manning coefficient of 36 (red) for current meter 1 (CM1).

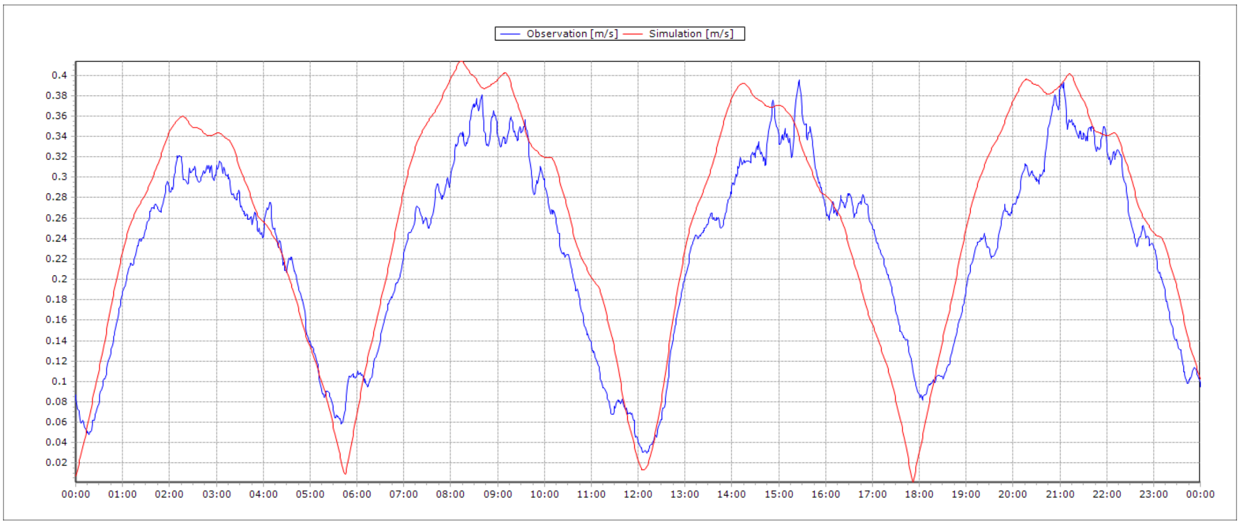

Figure 2-17 One day sample of the Time series of current speed measured data (blue) (de-spiked) and numerical simulation with Manning coefficient of 36 (red) for current meter 1 (CM1)

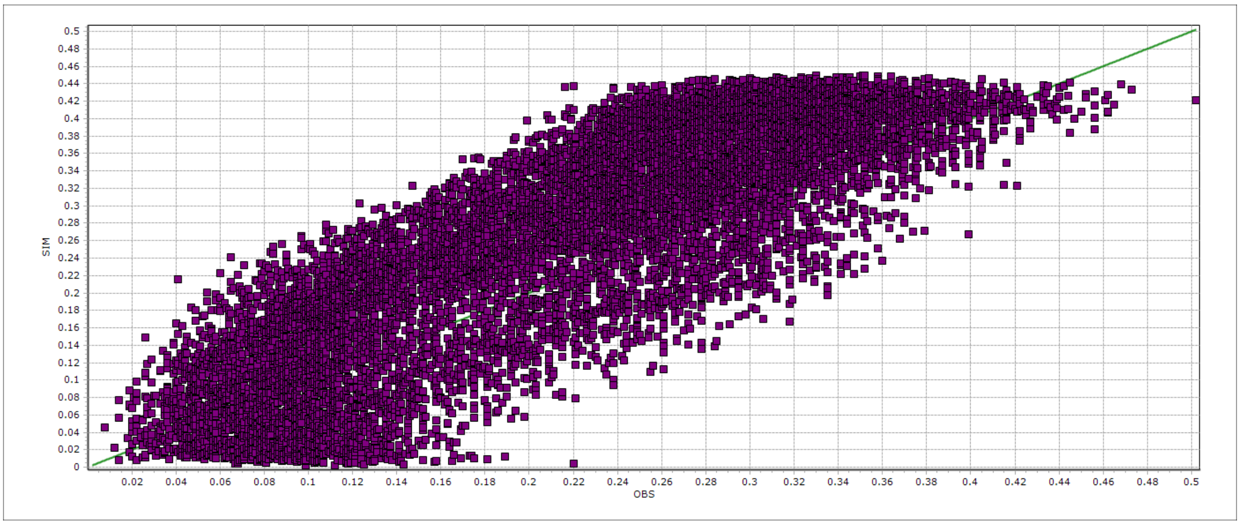

Figure 2-18 Scatter Plot of current speed measured data (OBS) and numerical simulation with Manning coefficient of 36 (OBS) for current meter 1 (CM1).

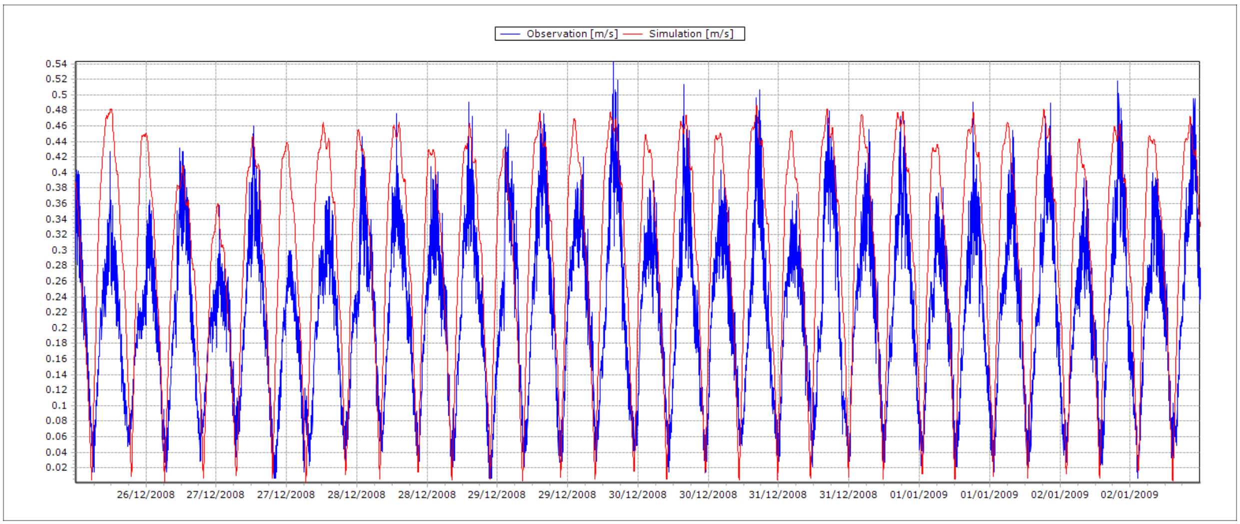

Figure 2-19 Time series of current speed measured data (blue) and numerical simulation with Manning coefficient of 36 (red) for current meter 2 (CM2) for 14 days)

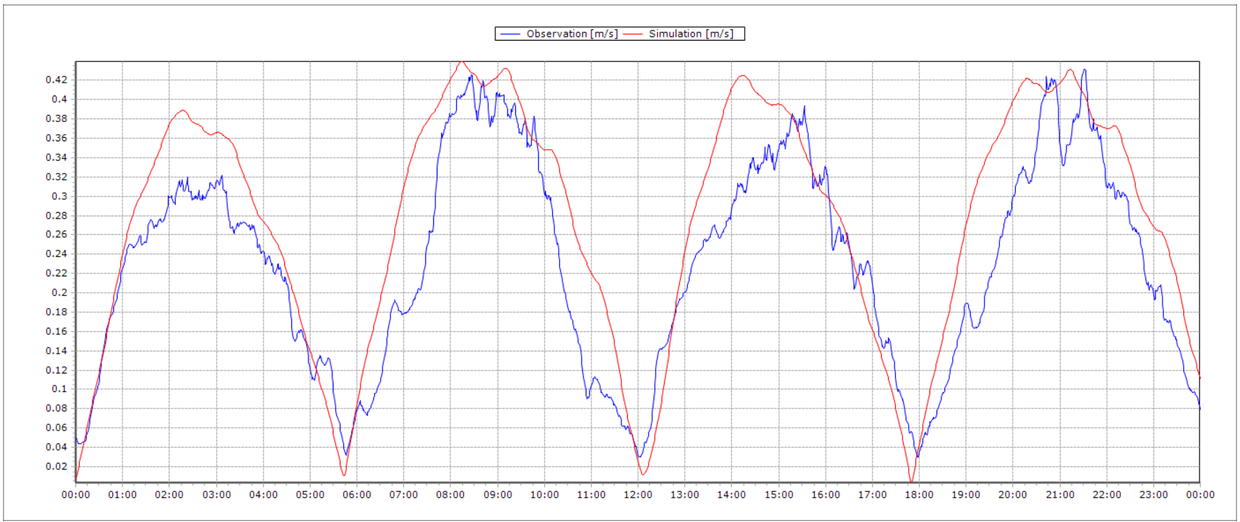

Figure 2-20 One day sample of the Time series of current speed measured data (blue) (de-spiked) and numerical simulation with Manning coefficient of 36 (red) for current meter 2 (CM2)

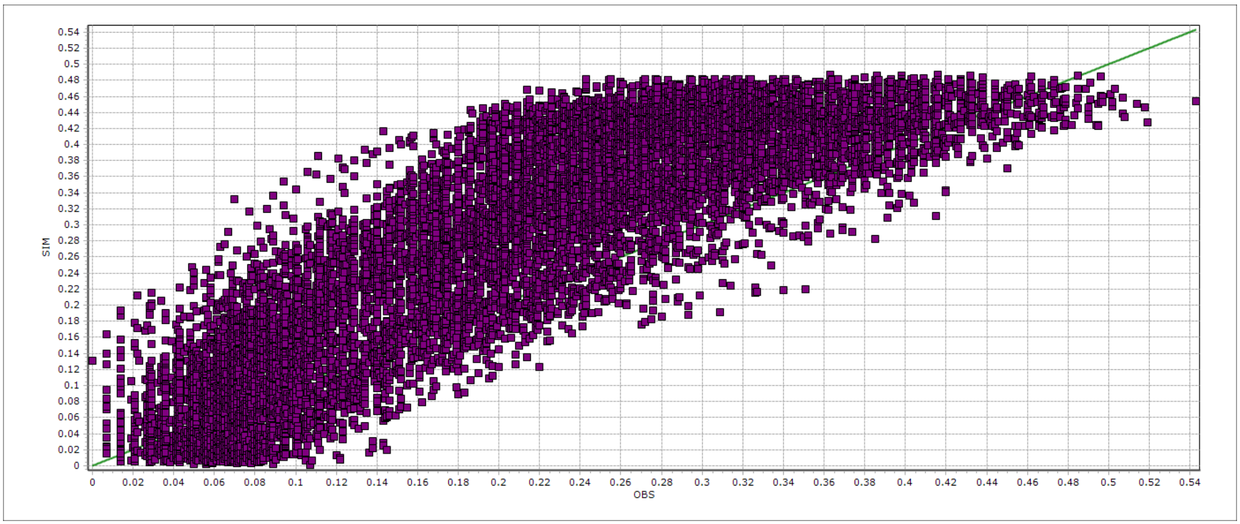

Figure 2-21 Scatter Plot of current speed measured data (blue) and numerical simulation with Manning coefficient of 36 (red) for current meter 2 (CM2) for 14 days.

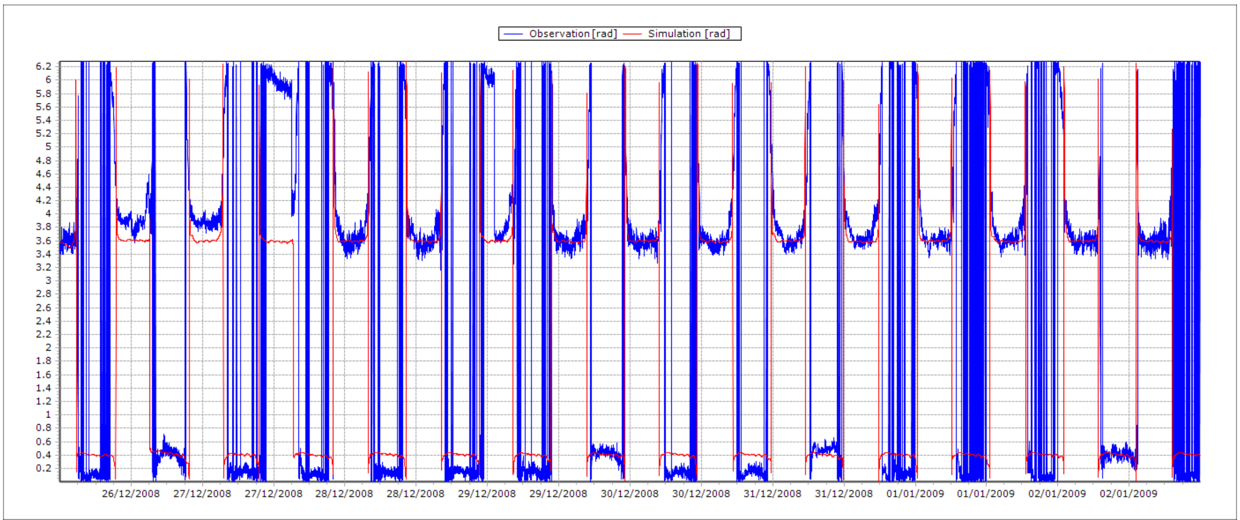

Figure 2-22 Time series of current direction measured data (blue) and numerical simulation with Manning coefficient of 36 (red) for current meter 2 (CM2) for 14 days.

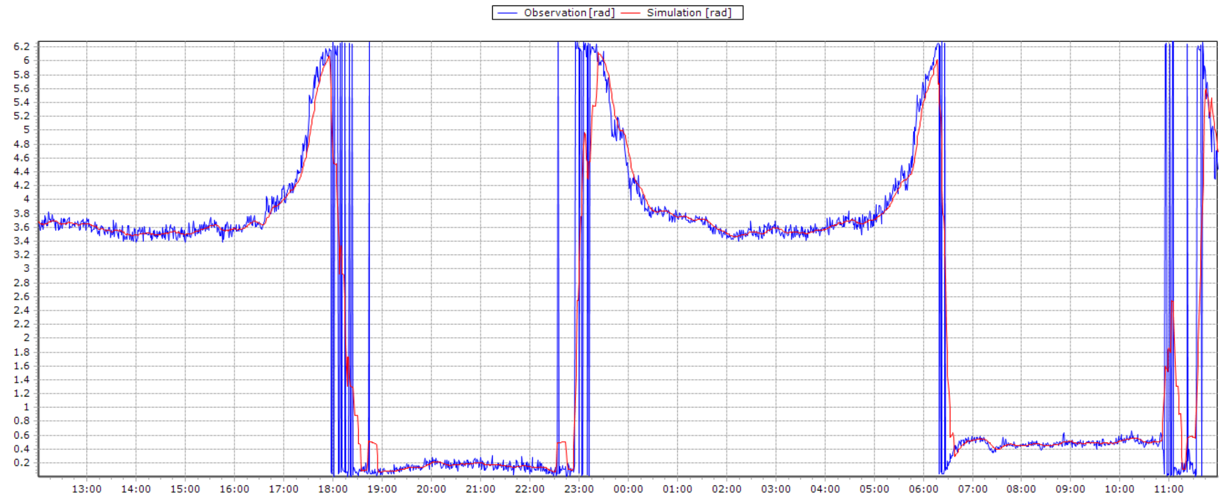

Figure 2-23 One day sample of the time series of current direction measured data (blue) (de-spiked) and numerical simulation with Manning coefficient of 36 (red) for current meter 2 (CM2)

Figure 2-24 and Figure 2-25 depict numerically simulated outcomes using a Manning number of 36 for specific timesteps chosen to represent flood and ebb tide conditions. These figures of the selected timesteps encapsulate the primary current speed values and provide indicative vectors illustrating the direction of the current.

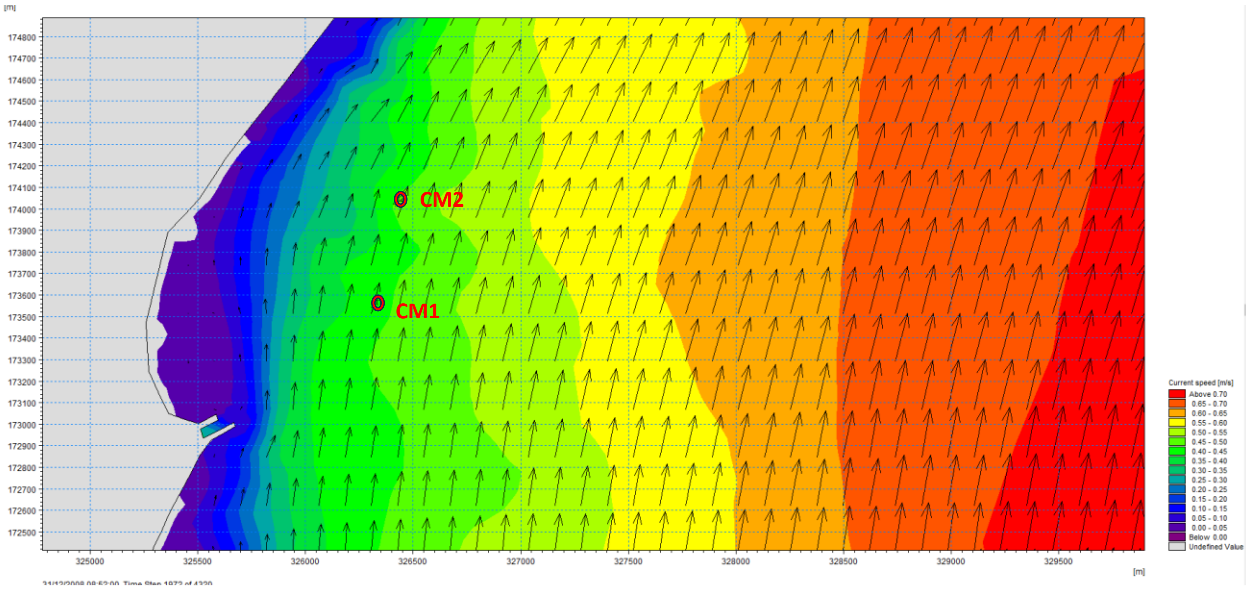

Figure 2-24 Numerically simulated results with Manning number of 36 representative of flood tide event.

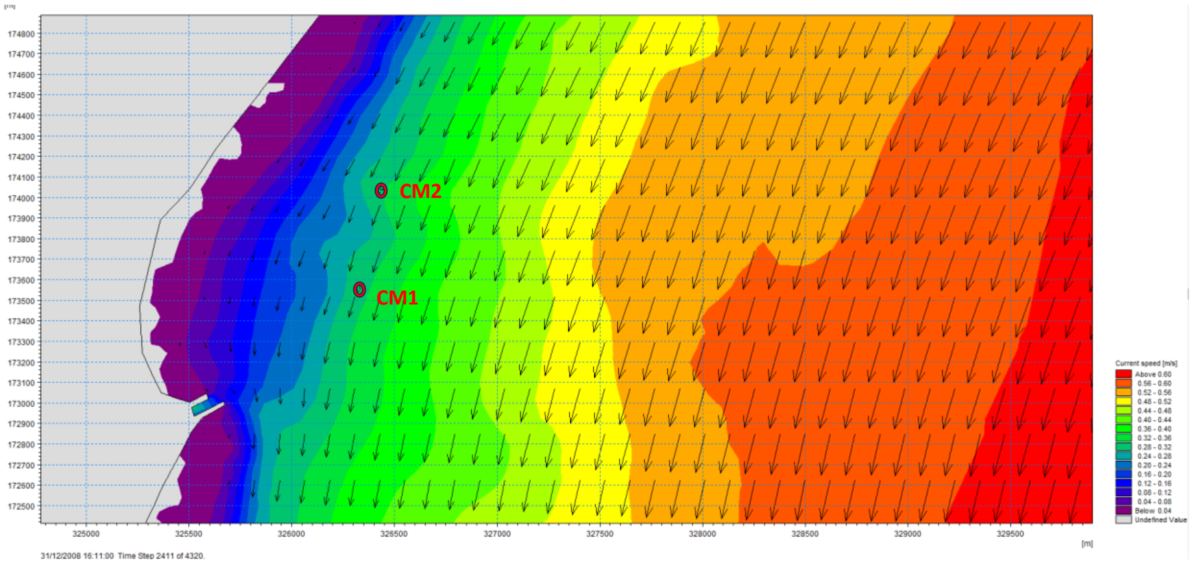

Figure 2-25 Numerically simulated results with Manning number of 36 representative of ebb tide event.

2.4 Modelling Simulations

The modelling approach incorporates the use of the MIKE 21 FM Mud Transport Module, which is driven by the Hydrodynamic Module (as discussed in 1.5).

The modelling scenario developed to address the study objectives involved simulating the dredging cycle using TSHD/Mechanical methods for the entire primary year's dredging volume. This scenario considers the worst-case situation where the highest volume to be dredged in one year is continuously deposited over 18 days in the Arklow offshore disposal area.

Further information regarding the modelling of the dredge cycle can be found in section 2.4.1.

2.4.1 Disposal dispersion modelling setup

The simulated scenario focuses on modelling the dispersion of material that is disposed of at the Arklow offshore disposal site. Each dredge cycle in this simulation has a duration of 4.49 hours, with loading taking up 0.6 hours and disposal lasting 0.18 hours (as detailed in Table 2-4).

The proposed primary year dredging volume, utilizing TSHD/Mechanical methods, amounts to 80,850 dry tonnes. This figure represents the highest volume to be dredged in any single phase throughout the entire eight-year campaign and is therefore considered a conservative estimate for this modelling scenario. The maximum daily disposal rate is set at 4,530 dry tonnes corresponding to a worst-case scenario of 5 disposal cycles.

Table 2-4 Duration of dredge cycle components

Dredge Cycle Component	Duration (hrs)
Full cycle (Loading + Sail Load + Disposal + Sail Empty)	4.49 hr
Loading	0.6 hr
Sail Load	1.84 hr

Disposal	0.18 hr
Sail empty	1.87 hr

During each cycle, the dredged material was deposited at the central point of the disposal site.

This eighteen-day simulation was designed to cover a representative spring tide cycle from December 28, 2008, to January 3, 2009, and a neap tide cycle from January 5 to January 11, 2009, up to 00:00 hours on January 15, 2009. These dates for the simulation align with the same time window used for acquiring calibration data.

As per the agreement with the client, the representative material for the disposal modelling scenario was chosen as the average of all provided sediment sample data, as outlined in Table 1-1. The selected representative sediment sample comprises three sediment classes and is detailed in Table 2-6. The critical shear stress for particle motion was determined using the following equation [15].

$$\tau_c = \theta^*(s-1)\rho_m g d_{50} \qquad \text{Eq. (1)}$$

where τ_c is the critical bed shear stress, θ^* is the dimensionless Shields parameter for the given particle size, s is the specific gravity of the particles and is calculated as the ratio of specific weight of sediment to the specific weight of water, ρ_m is the density of water, g is the constant for acceleration due to gravity, and d_{50} is the median particle size.

The drag coefficient, K, for each sample was derived using the following formula;

$$\mathrm{K} = d_{50}\left(\frac{g\rho_m(\rho_p-\rho_m)}{\mu^2}\right)^{1/3} \qquad \text{Eq. (2)}$$

where g is the acceleration due to gravity, d_{50} is median grain size, ρ_p is the density of the particle, ρ_m is the density of water and μ is the dynamic viscosity of a liquid. The settling velocity (U_t) is then calculated according to the following equation;

$$U_t = \left(\frac{4g{d_{50}}^{(1+n)}(\rho_p-\rho_m)}{3b\mu^n\rho_m^{(1-n)}}\right)^{1/(2-n)} \qquad \text{Eq. (3)}$$

whereby the b and n coefficients are tabulated to the value of K (Table 2-5) [16] [17].

Table 2-5 Determination settling velocity coefficients b and n determined based on drag coefficient K

Flow Regime	Drag coefficient (K)	b	n
Stokes	K < 3.3	24	1
Intermediate	3.3 <K < 43.6	18.5	0.6
Newton	43.6 < K <2360	0.44	0

Table 2-6 Model input sediment properties for dredging and disposal operations

Representative Material Type	Fraction	Representative grain Size (mm)	Settling Velocity (m/s)	Shield's parameter (dimensionless)	Critical Shear Stress for deposition (N/m²)	Proportion (%)
Very fine gravel	1	2	0.2996	0.039	1.25	8.0
Medium Sand	2	0.375	0.04202	0.041	0.24	53.5
Medium Silt	3	0.0156	0.0001636	0.25	0.06	38.5

3 MODEL RESULTS

Figure 3-2 displays the maximum and mean total Suspended Sediment Concentration (SSC) over the course of the 18-day simulation, which covers both spring and neap tidal cycles. The maximum total SSC plots represent the highest values observed in each cell at any given time during the 18-day simulation period. It's important to note that these values may not have occurred simultaneously nor persisted for any significant period of time. Conversely, the mean total SSC plots represent the average values in each cell at any time during the 18-day simulation period.

The results were extracted from various points, including those within the disposal area and the points closest to the disposal site, which are associated with five nearby Special Areas of Conservation (SACs): Murrough Wetlands SAC (Point 6), Wicklow Reef SAC (Point 7), Buckroney-Brittas Dunes and fen SAC (Point 8), Kilpatrick Sandhills SAC (Point 9), and Magherabeg Dunes SAC (Point 10). In the disposal area, five points were considered: (i) the central point of the disposal area (Point 1); (ii) the west-central point of the disposal area (Point 2); (iii) the north-central point of the disposal area (Point 3); (iv) the east-central point of the disposal area (Point 4); and (v) the south-central point of the disposal area (Point 5).

Table 3-1 provides a list of the results from the extracted points, while the location of these points can be seen in Figure 3-1.

Table 3-1 Point locations for the extracted numerical results.

Point Number	Name	Longitude (m)	Latitude (m)
Point 1	Arklow Disposal area Centre	326377	173751
Point 2	Arklow Disposal area West	325934	173711
Point 3	Arklow Disposal area North	326377	174073
Point 4	Arklow Disposal area East	326819	173711
Point 5	Arklow Disposal area South	326377	173349
Point 6	Murrough Wetlands SAC	331164	195920
Point 7	Wicklow Reef SAC	334906	191776
Point 8	Buckroney-Brittas Dunes and fen SAC	327543	177613
Point 9	Kilpatrick Sandhills SAC	325652	166750
Point 10	Magherabeg Dunes SAC	332210	186465

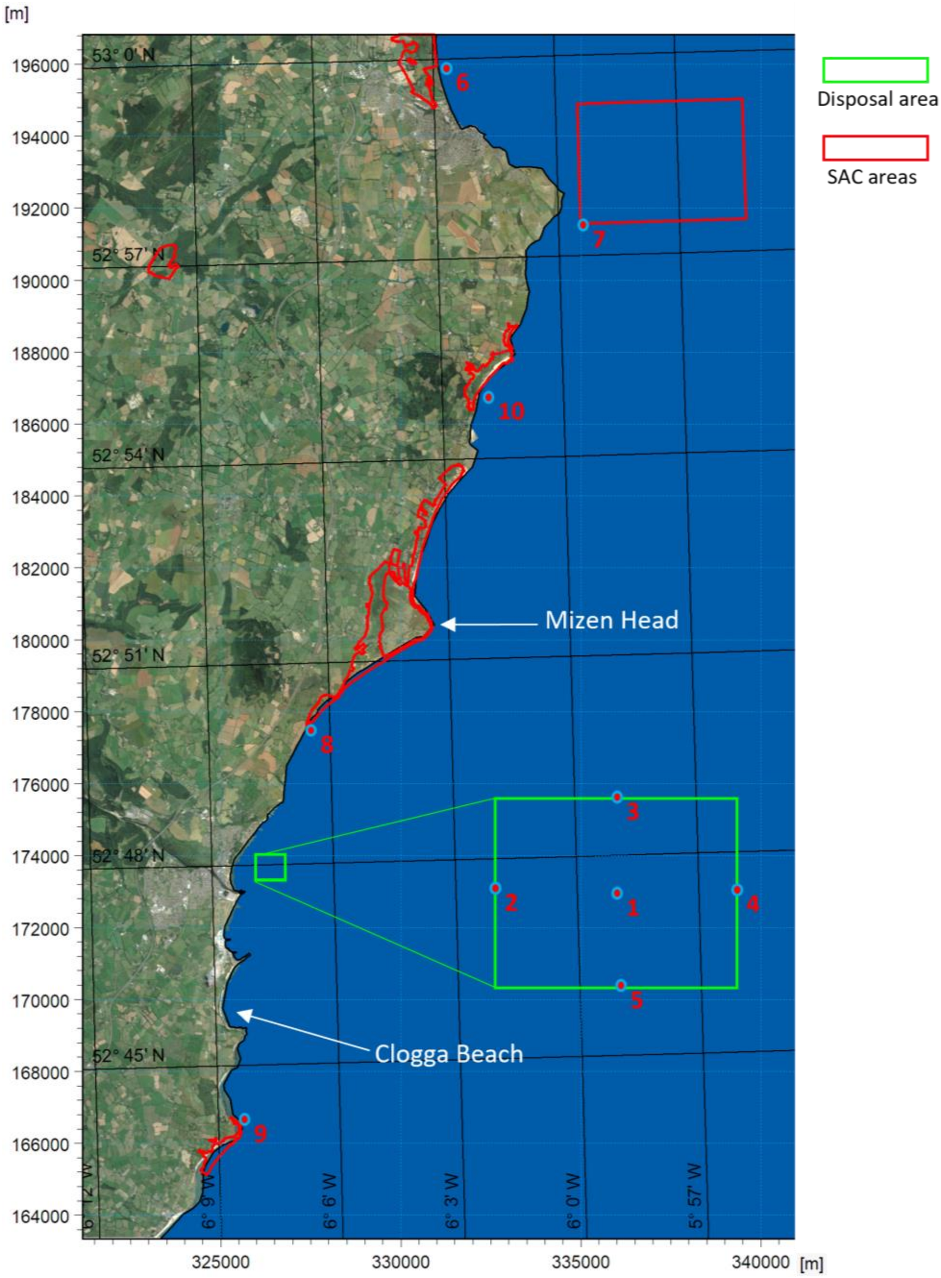

Figure 3-1 Location of the extracted results points.

The maximum total Suspended Sediment Concentration (SSC) observed at any point within the disposal site over the 18-day simulation period is approximately 0.12 Kg/m^3 (1200 mg/L) Figure 3-2 and Figure 3-3 illustrates the distribution of sediment plumes resulting from the disposal of dredged material. Both the maximum and mean SSC values are distributed to the north and south of the disposal area. Particularly, the eastern part of the disposal area exhibits significantly higher SSC values, suggesting that currents in deeper offshore areas have a significant influence on sediment transport. It's worth noting that the maximum SSC values are most prominent between Mizen Head in the north and Clogga Beach in the south. In contrast, mean SSC values are considerably lower, falling below 0.04 Kg/m^3 (400 mg/L), particularly in the southeastern part of the disposal area. The SSC values and its order of magnitude are in general accordance with the ones calculated by GDG in report [1].

Table3-2 display the Total SSC values calculated at 30-second intervals over the 18-day simulation for five points within the disposal area and five points representing the SAC areas, indicating that the highest total SSC values are located at points 2 (West) and 3 (North) within the disposal area, signifying that the net transport of the disposed material within the simulation time is primarily towards the west and north of the disposal area. Figure 3-2 and Figure 3-3 also shows that when sediments are transported north they follow the coastline and therefore deriver to northwest along the coast. Also, Table 3-2 reveals that the total SSC values in the SAC areas are significantly lower, typically below 0.005 kg/m3 (500.0 mg/L). Notably, Buckroney-Brittas Dunes and Fen SAC (Point 8) and Kilpatrick Sandhills SAC (Point 9) are the SAC areas where such low values are observed, with all other SAC areas presenting total SSC values below 0.0018 kg/m3 (180.0 mg/L).

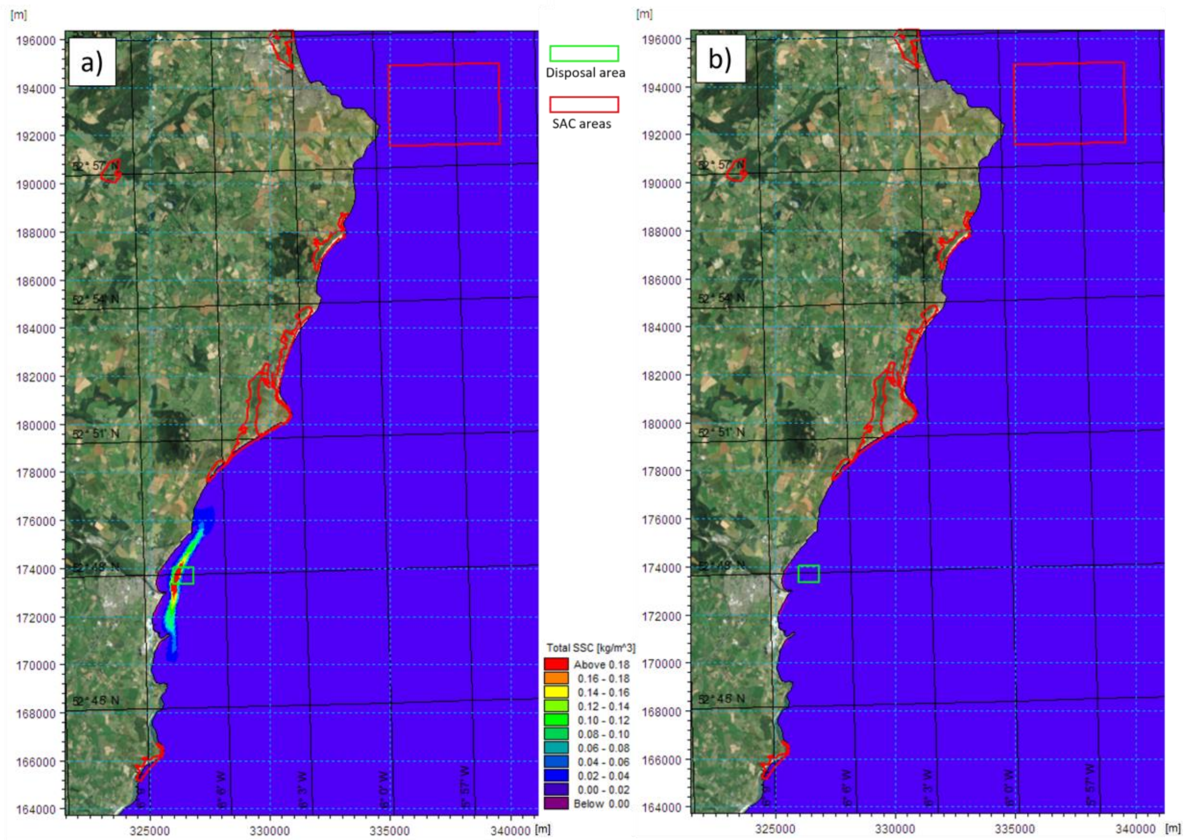

Figure 3-2 Total Suspended Sediment Concentration (SSC) considering the 18-day simulation: (a) maximum values and (b) mean values.

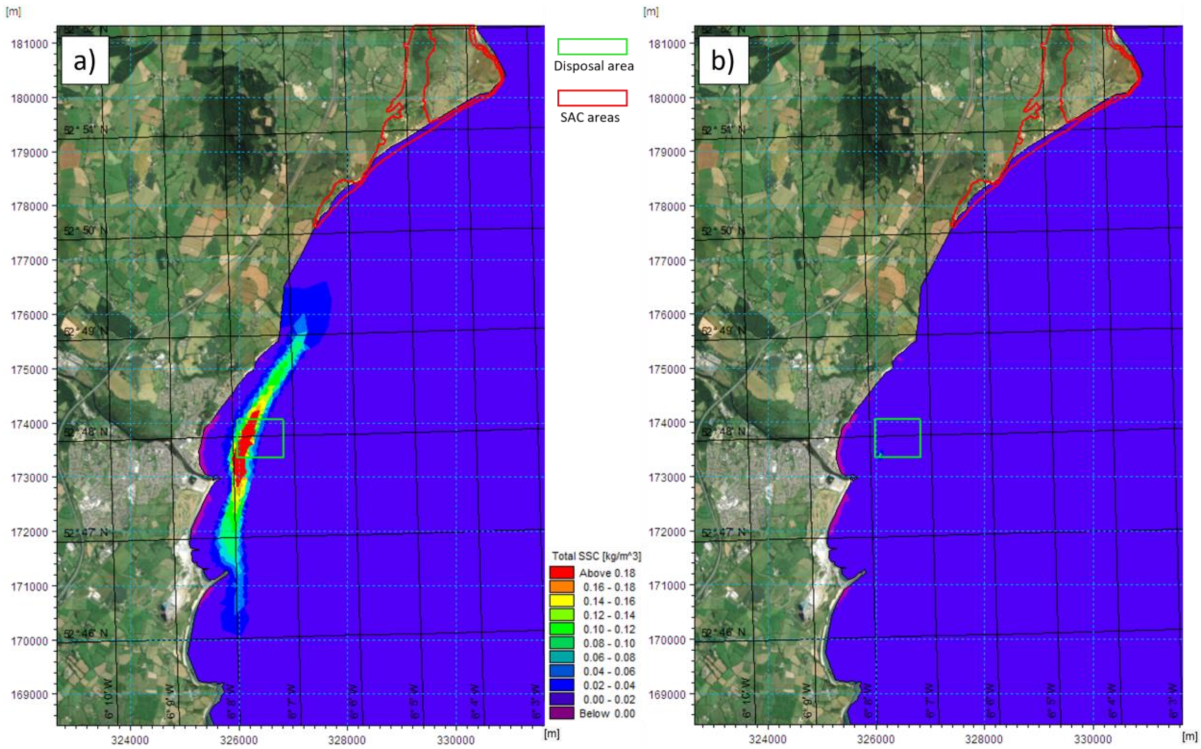

Figure 3-3 Total Suspended Sediment Concentration (SSC) – close-up view - considering the 18-day simulation: (a) maximum values and (b) mean values.

Table 3-2 Maximum total Suspended Sediment Concentration SSC for the extracted numerical results.

Point Number	Name	Max total SSC (kg/m^3)
Point 1	Arklow Disposal area Centre	0.04
Point 2	Arklow Disposal area West	0.07
Point 3	Arklow Disposal area North	0.12
Point 4	Arklow Disposal area East	0.004
Point 5	Arklow Disposal area South	0.011
Point 6	Murrough Wetlands SAC	8.2e-05
Point 7	Wicklow Reef SAC	0.0001
Point 8	Buckroney-Brittas Dunes and fen SAC	0.004
Point 9	Kilpatrick Sandhills SAC	0.005
Point 10	Magherabeg Dunes SAC	0.0018

The maximum and mean Suspended Sediment Concentration (SSC) for each of the three fractions throughout the 18-day simulation are presented from Figure 3-4 to Figure 3-9 The gravel fraction (Figure 3-4 and Figure 3-5) and the sand fraction (Figure 3-6 and Figure 3-7) remain in close proximity to the disposal site boundary throughout the dredging campaign. Maximum SSC values for these fractions are consistently below 0.001 kg/m^3 (100.0 mg/L). In the SAC areas, the SSC values for fractions 1 and 2 are negligible, registering values lower than 1 x 10^{-10} kg/m^3 (0.01 mg/L).

In contrast, the silt fraction (fraction 3) (Figure 3-8 and Figure 3-9) is transported as suspended sediment out of the disposal site and constitutes the majority of the SSC portion of the total SSC values. The distribution and concentrations of fraction 3 closely align with the overall extent of total SSC. In the SAC areas, fraction 3 exhibits values below 0.005 Kg/m^3 (500.0 mg/L) in both Buckroney-Brittas Dunes and Fen SAC (Point 8) and Kilpatrick Sandhills SAC (Point 9), while values are under 0.002 Kg/m^3 (200.0 mg/L) at Magherabeg Dunes SAC (Point 10). For the other two SACs, namely Murrough Wetlands SAC (Point 6) and Wicklow Reef SAC (Point 7), SSC values are negligible. The figures depicting the SSC for each material fraction display differing scales, primarily due to the significant variation in data magnitude among the different material fractions. Each fraction exhibits its own order of magnitude in terms of SSC. To facilitate the accurate observation of SSC patterns and the extraction of meaningful insights, we employed distinct scaling approaches to represent the results.

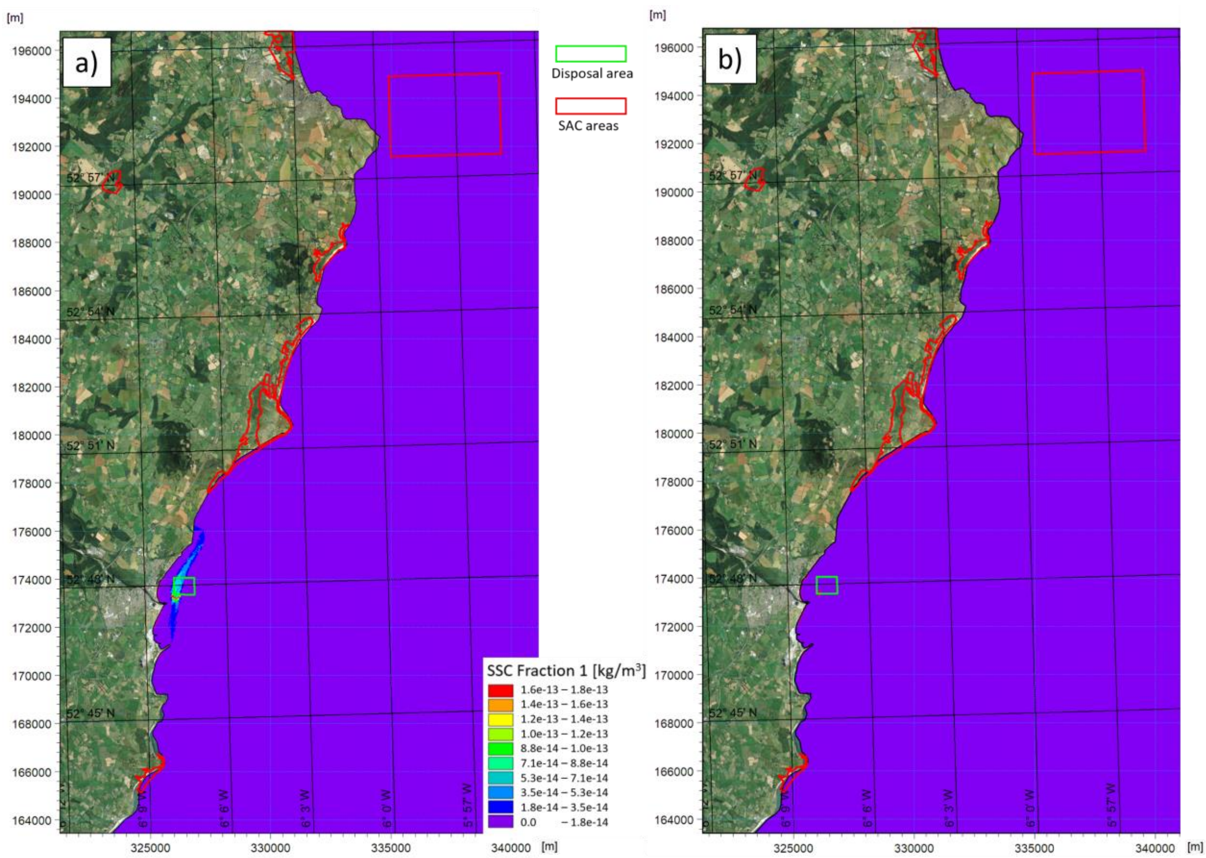

Figure 3-4 Fraction 1 - SSC considering the 18-day simulation: (a) maximum values and (b) mean values.

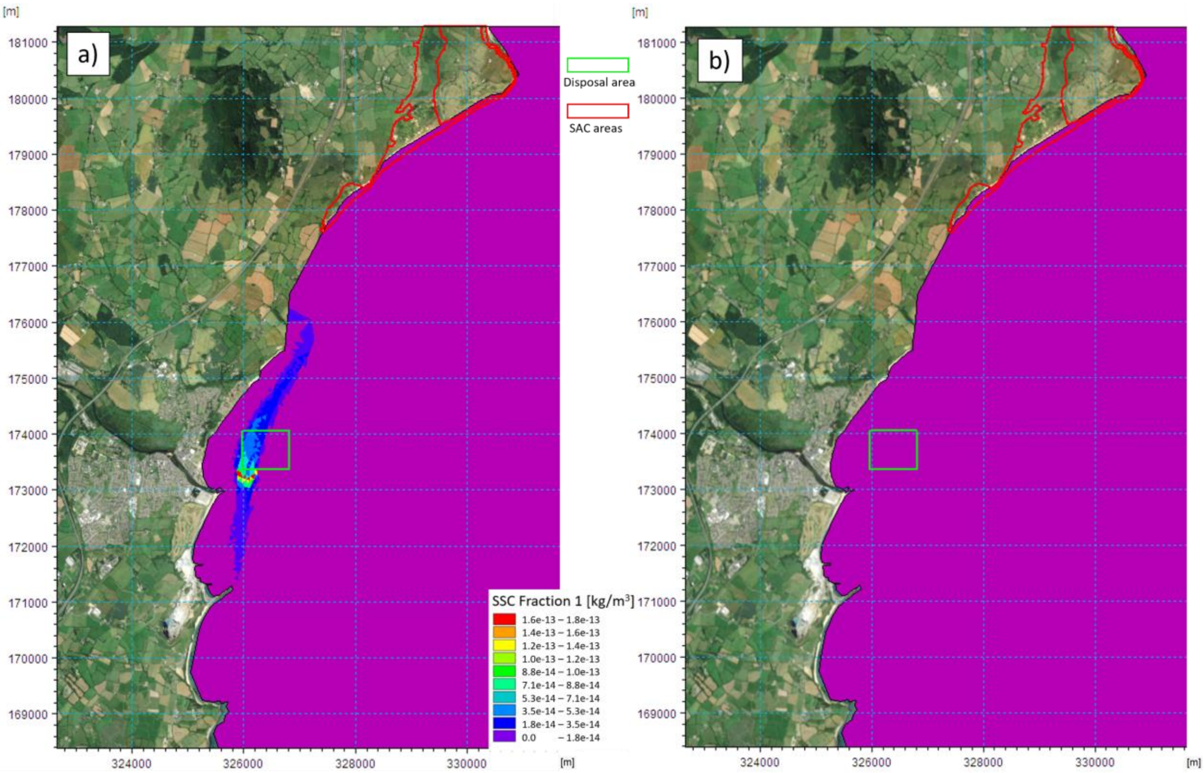

Figure 3-5 Fraction 1 - SSC – close-up view - considering the 18-day simulation: (a) maximum values and (b) mean values.

Table 3-3 Maximum Fraction 1 SSC for the extracted numerical results.

Point Number	Name	Max Fraction 1 SSC (kg/m³)
Point 1	Arklow Disposal area Centre	7.5e-17
Point 2	Arklow Disposal area West	1.0e-16
Point 3	Arklow Disposal area North	9.5e-17
Point 4	Arklow Disposal area East	2.2e-17
Point 5	Arklow Disposal area South	4.5e-17
Point 6	Murrough Wetlands SAC	1.1e-20
Point 7	Wicklow Reef SAC	5.5e-18
Point 8	Buckroney-Brittas Dunes and fen SAC	1.4e-16
Point 9	Kilpatrick Sandhills SAC	6.9e-18
Point 10	Magherabeg Dunes SAC	2.3e-17

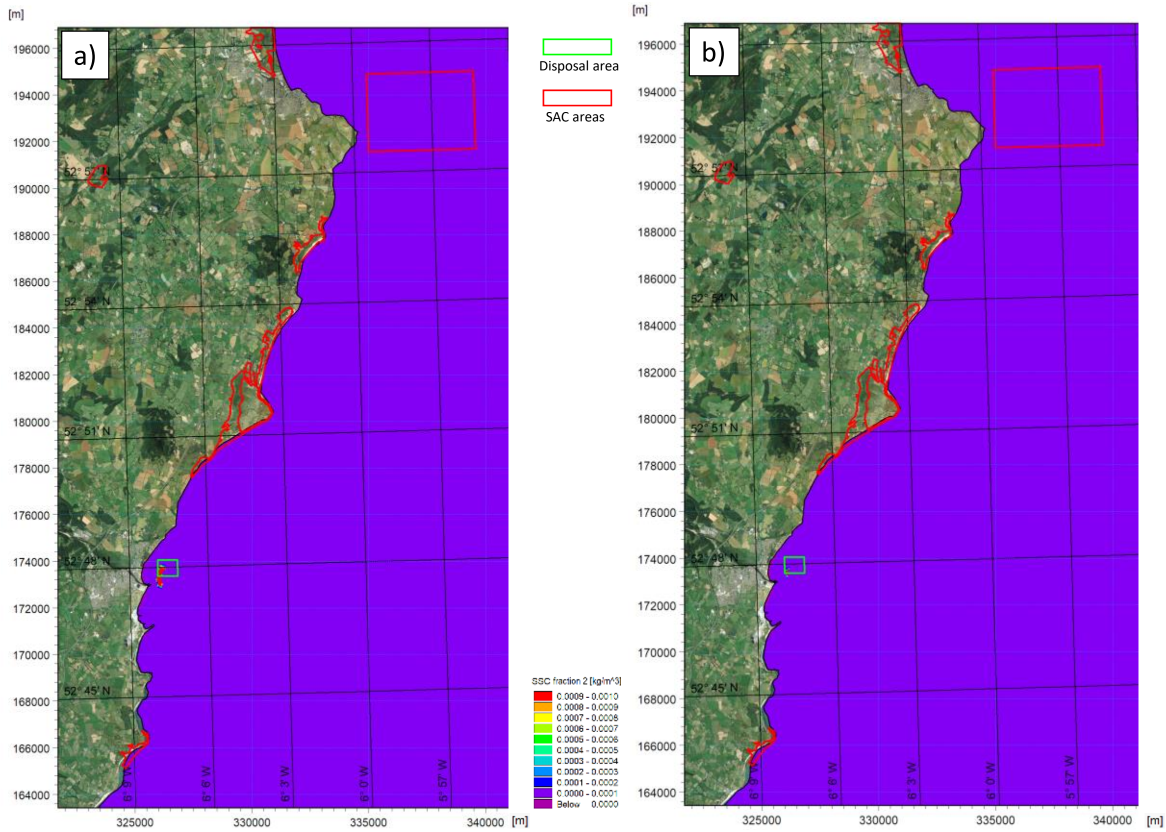

Figure 3-6 Fraction 2 SSC considering the 18-day simulation: (a) maximum values and (b) mean values.

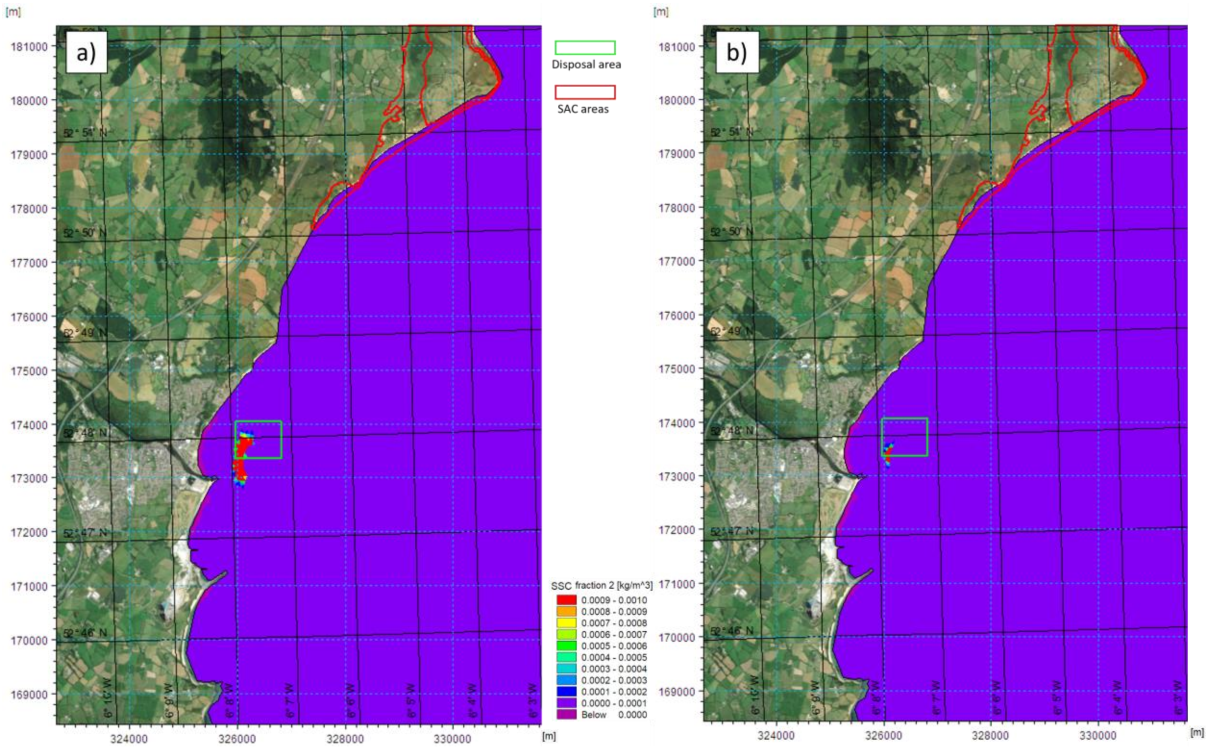

Figure 3-7 Fraction 2 SSC – close-up view - considering the 18-day simulation: (a) maximum values and (b) mean values.

Table 3-4 Maximum Fraction 2 SSC for the extracted numerical results.

Point Number	Name	Max Fraction 2 SSC (kg/m^3)
Point 1	Arklow Disposal area Centre	1.2e-05
Point 2	Arklow Disposal area West	8.9e-06
Point 3	Arklow Disposal area North	1.8e-06
Point 4	Arklow Disposal area East	8.7e-13
Point 5	Arklow Disposal area South	4.1e-11
Point 6	Murrough Wetlands SAC	2.2e-18
Point 7	Wicklow Reef SAC	3.6e-15
Point 8	Buckroney-Brittas Dunes and fen SAC	2.1e-12
Point 9	Kilpatrick Sandhills SAC	1.3e-13
Point 10	Magherabeg Dunes SAC	1.2e-14

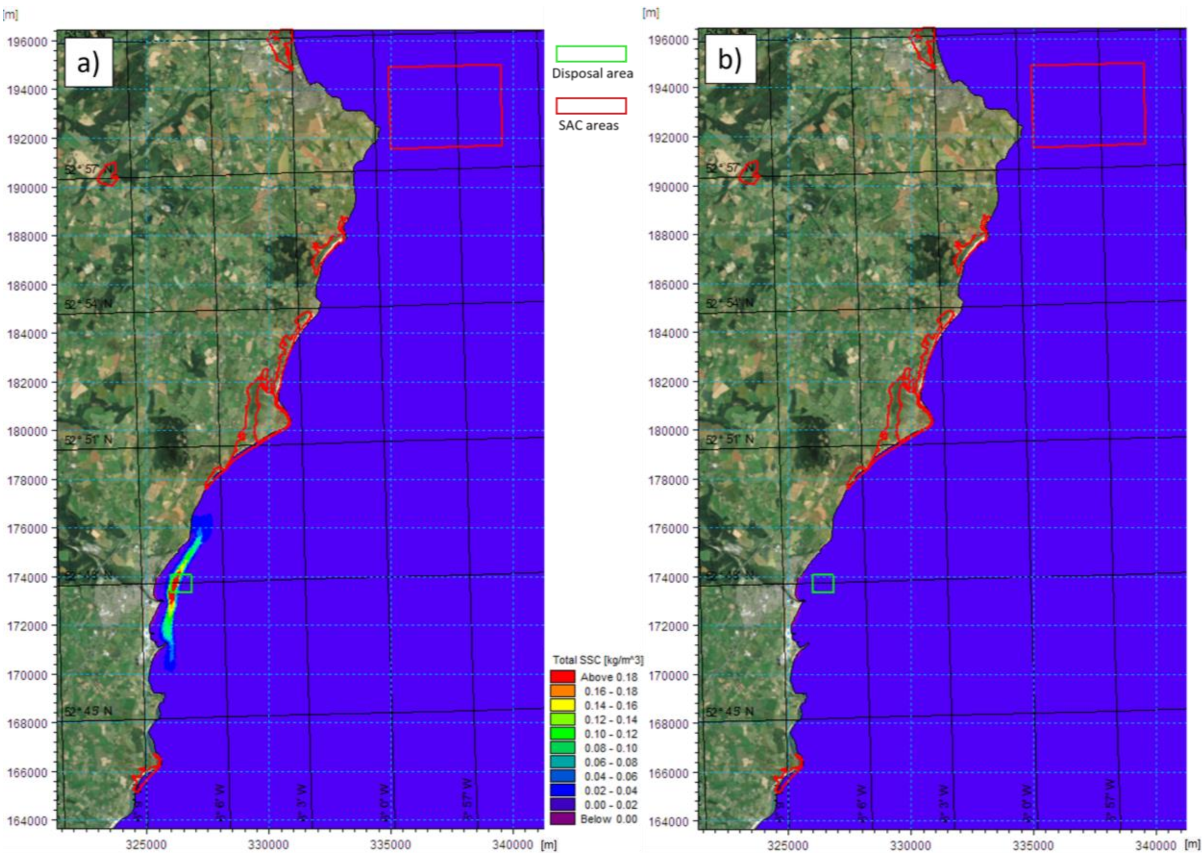

Figure 3-8 Fraction 3 SSC considering the 18-day simulation: (a) maximum values and (b) mean values.

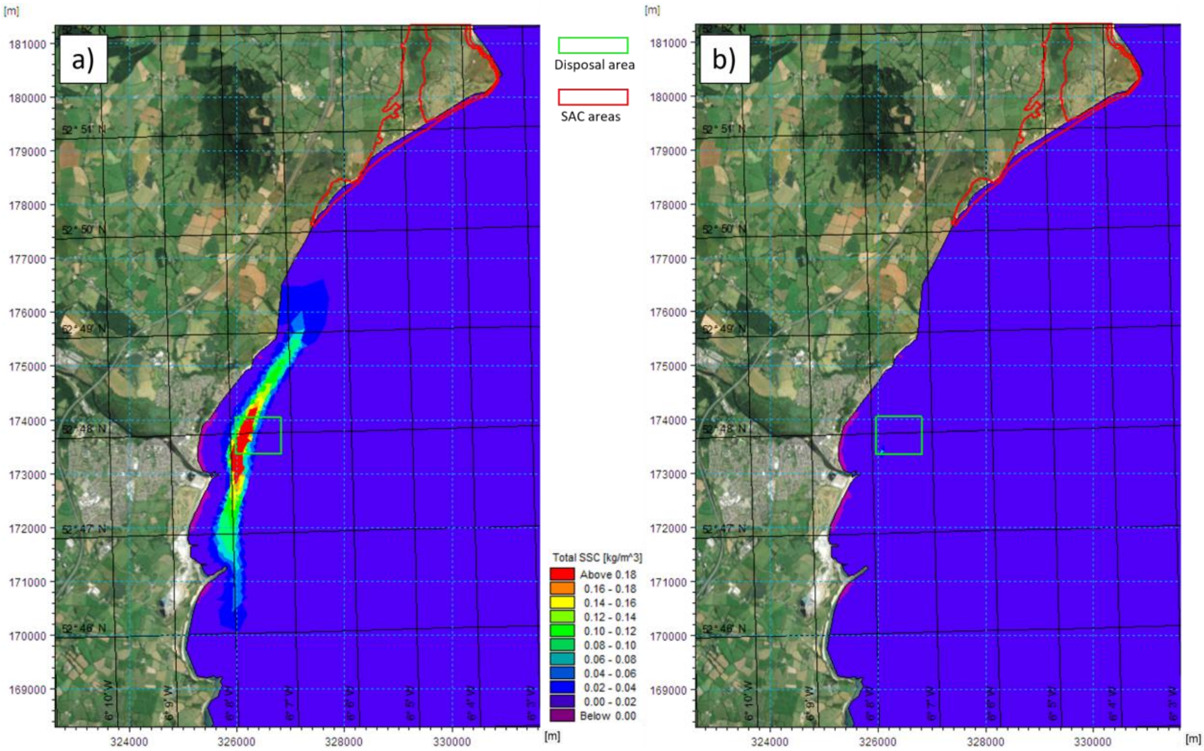

Figure 3-9 Fraction 3 SSC – close-up view - considering the 18-day simulation: (a) maximum values and (b) mean values.

Table 3-5 Maximum Fraction 3 SSC for the extracted numerical results.

Point Number	Name	Max Fraction 3 SSC (kg/m³)
Point 1	Arklow Disposal area Centre	0.05
Point 2	Arklow Disposal area West	0.09
Point 3	Arklow Disposal area North	0.09
Point 4	Arklow Disposal area East	0.004
Point 5	Arklow Disposal area South	0.01
Point 6	Murrough Wetlands SAC	0.0001
Point 7	Wicklow Reef SAC	0.0001
Point 8	Buckroney-Brittas Dunes and fen SAC	0.005
Point 9	Kilpatrick Sandhills SAC	0.004
Point 10	Magherabeg Dunes SAC	0.002

The same analysis is presented here for the evolution of bed thickness. The maximum total bed thickness over the 18-day simulation period is depicted in Figure 3-10 and Figure 3-11.

The maximum total bed thickness change observed during the simulation at the disposal site is approximately 5.5 cm, as shown in Table 3-6. This change is primarily attributed to the deposition and retention of coarser sediment fractions within the disposal site, as well as the time required within the time of each disposal cycle for the currents to transport material to the eastern and northernmost points of the disposal area. Additionally, Figure 3-10 illustrates that the hydrodynamic patterns of the site facilitate sediment transport along the shorelines (both north and south), resulting in relatively extensive minor changes in bed thickness.

The results regarding the total bed thickness over the 18-day sediment disposal simulation for each SAC area are presented in the Table 3-6. Notably, bed thickness changes are observed only for Buckroney-Brittas Dunes and Fen SAC (Point 8) and Kilpatrick Sandhills SAC (Point 9), although these changes remain below 4.0 cm. In contrast, bed change values for the other SAC areas are below 0.01 cm and can be considered negligible.

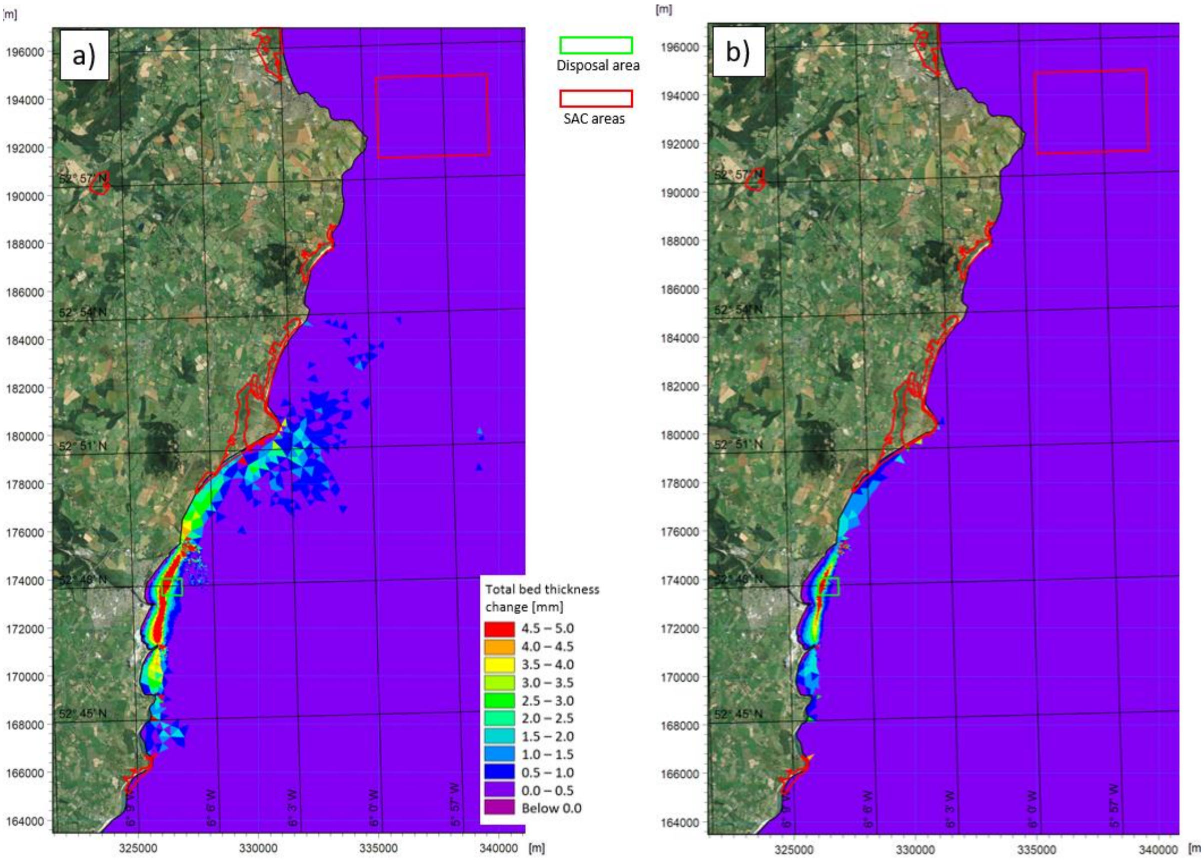

Figure 3-10 Total bed thickness change considering the 18-day simulation: (a) maximum values and (b) mean values.

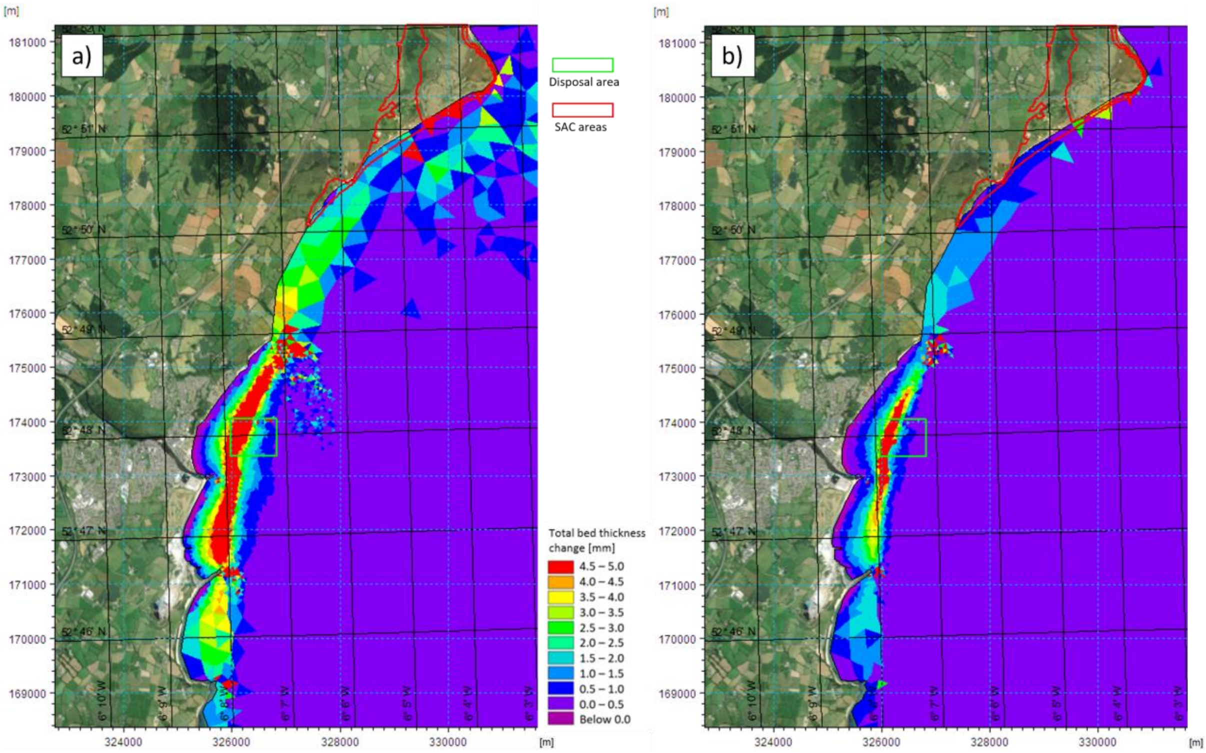

Figure 3-11 Total bed thickness change – close-up view - considering the 18-day simulation: (a) maximum values and (b) mean values.

Table 3-6 Total bed thickness change for the extracted numerical results.

Point Number	Name	Max Total bed thickness change (m)
Point 1	Arklow Disposal area Centre	0.002
Point 2	Arklow Disposal area West	0.005
Point 3	Arklow Disposal area North	0.005
Point 4	Arklow Disposal area East	0.0005
Point 5	Arklow Disposal area South	0.001
Point 6	Murrough Wetlands SAC	1.4e-06
Point 7	Wicklow Reef SAC	6.5e-06
Point 8	Buckroney-Brittas Dunes and fen SAC	0.001
Point 9	Kilpatrick Sandhills SAC	0.004
Point 10	Magherabeg Dunes SAC	4.01e-05

4 SUMMARY AND CONCLUSIONS

The modelling scenario was designed to assess the worst-case dispersion of sediment resulting from the maximum disposal of dredged material at the Arklow offshore disposal site.

The results suggest that both the gravel and sand fractions settled from suspension, predominantly staying near the boundary of the disposal site for the duration of the simulation. While there was some spread of these fractions to the north and south of the disposal site, their concentrations were minimal. Consequently, the majority of the Suspended Solid Concentration (SSC) remained proximal to the disposal area (Figure 3-4 to Figure 3-7). In contrast, the silt fraction dispersed more widely, exhibiting higher concentrations across an expansive coastal region, stretching from Mizen Head in the north to Clogga Beach in the south (Figure 3-8 and Figure 3-9).

In terms of sediment concentration, the maximum total Suspended Sediment Concentration (SSC) within the Arklow disposal area reached 1.2 kg/m^3 (1200.0 mg/L). In the Special Areas of Conservation (SACs), the maximum total SSC values are 0.005 kg/m^3 (500.0 mg/L) at Buckroney-Brittas Dunes and Fen SAC and Kilpatrick Sandhills SAC. For all other SAC areas,the maximum total SSC values are less than 0.0018 kg/m^3 (180 mg/L).

Regarding changes in bed thickness, the calculated values show below than 5.5 cm within the Arklow disposal area, below 4.0 cm for Kilpatrick Sandhills SAC, under 1.0 cm for Buckroney-Brittas Dunes and Fen SAC, and less than 0.001 cm for the other nearby SAC areas as listed in the report.

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