Supplementary

Hydrodynamic Processes Controlling Sand Bank Mobility and Long-Term Base Stability: A Case Study of Arklow Bank

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1. Supplementary Material: Numerical modelling

1.1. Hydrodynamic Model

The two-dimensional (2D) hydrodynamic model covering the entire Irish Sea developed in Coughlan et al [1] was used in this study. This 2D model was updated with additional geophysical datasets, a new refined mesh was implemented, and a new validation point was utilised. The full set-up, extent and validation details of the original pure hydrodynamic model is presented in Coughlan et al [1] whilst new updates and modifications to the model setup are outlined in Creane et al [2].

The MIKE 21 hydrodynamic model [3] determines bottom shear stress, τ_b, by quadratic friction law:

$$\tau_b = C_d \rho \bar{U}^2$$

Where C_d is a drag coefficient, ρ is the density of the fluid medium in seawater and $\bar{U}$ is the depth averaged velocity. The drag coefficient is determined as;

$$C_d = \frac{g}{(Mh^{1/6})^2}$$

Where h is the total water depth and g is the acceleration due to gravity and M is the Manning number. The original model uses a constant M for bed friction of 32 $m^{\frac{1}{3}}$ over the entire model domain. The updated model retains a constant M for bed friction of 32 $m^{\frac{1}{3}}$ over majority of the model domain, but M is decreased up to 10 $m^{\frac{1}{3}}$ along the boundaries. Due to the updates on the original model, the calibration of the model was checked at various locations and new validation statistics were generated. Full validation results are outlined in Creane et al [2] and are summarised in section 1.1.1.

1.1.1 Model Validation

Water levels were re-assessed using data from eight tide gauges along the Irish Sea coast, and from four Acoustic Doppler Current Profilers (ADCPs) located off the southeast coast of Ireland (see Figure 2 in main article to this supplementary material). A strong positive correlation was evident between all measured and simulated water levels where the average correlation coefficient across all locations was 0.99.

Similarly, simulated current speeds and directions were re-assessed against measured data at four locations, including a new ADCP dataset labelled 'Arklow' in Creane et al [2] collected at 52.72153°, -6.0278°. Generally, a strong positive correlation was evident with correlation coefficients ranging from 0.84 to 0.95. Example validation plots are provided in Figure 1 whereby full validation results are detailed in Creane et al [2].

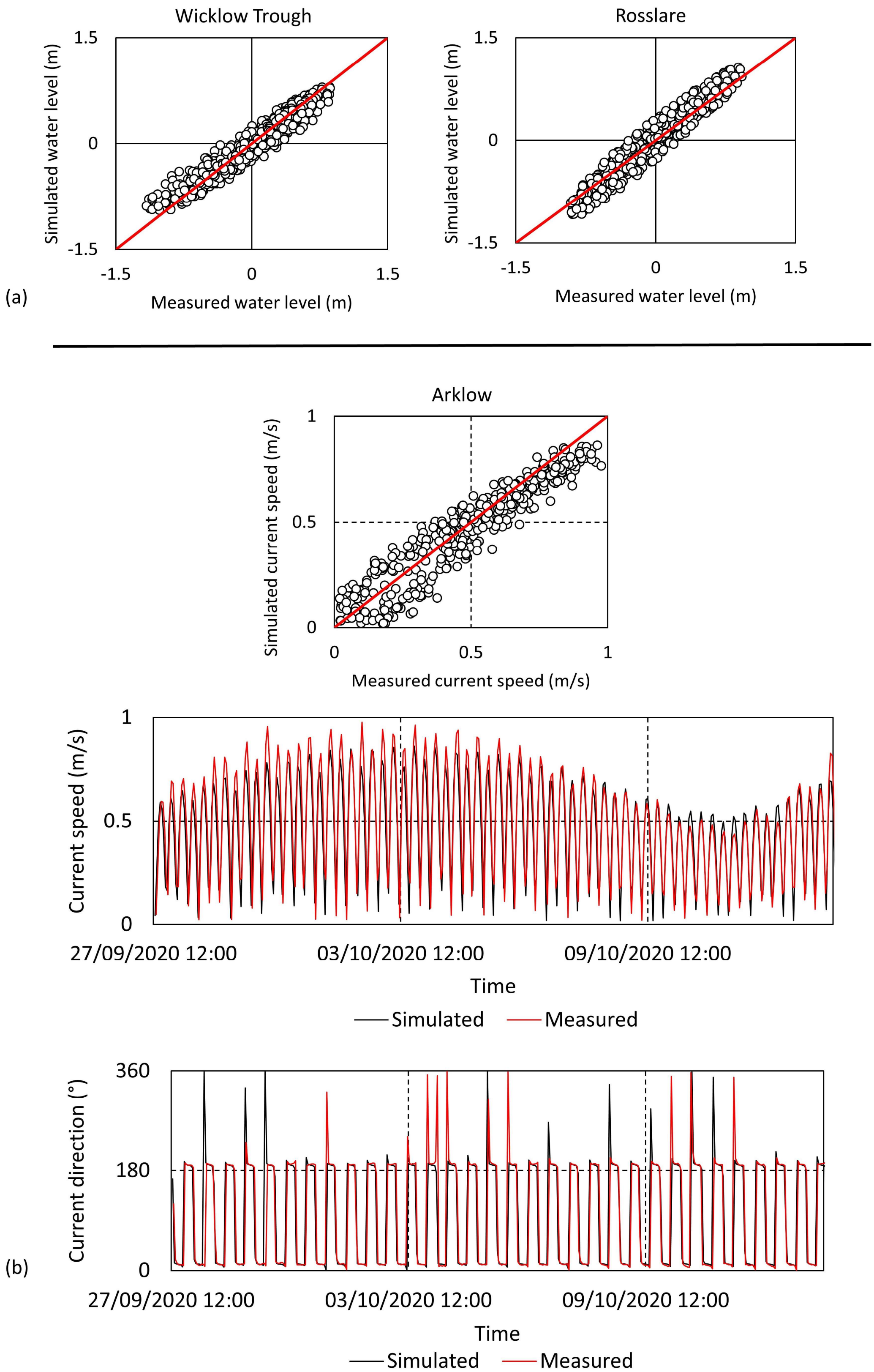

Figure 1. Comparison between measured and simulated (a) water levels from Wicklow Trough ADCP (52.95601°, −5.90135°) and Rosslare tide gauge (52.254600°, −6.334861°), and (b) current speed and directions from Arklow ADCP (52.72153°, -6.0278°). Data source: Creane et al [2].

1.2. ST modelling set-up

The MIKE 21 sand transport module [4], [5] was used to calculate the sediment transport rates of non-cohesive sediment under 'pure current' whereby the effects due to wind and wave forcing are not included. The mesh used in the simulation of the sand transport rates is the same as that is used to calculate the flow field in the hydrodynamic model (outlined in section 2 of the main article). A coupled morphological model was generated, whereby the governing equations for flow and sediment transport are merged into a set of equations, which are solved simultaneously. Coupling the hydrodynamic and sand transport modules in this way allowed morphological development to be captured by updating the bathymetry for every time step with the net sedimentation:

$$Z^{n+1} = Z^{n} + \Delta z^{n}$$

Where Z^n is the bathymetry level at present time step, Z^{n+1} is the bathymetry level at the next time step, Z^{n+1} is net sedimentation at present time step, and n is time step. Further details are presented in the MIKE 21 sand transport manual [5]. The key parameter for determination of bed level changes is the rate of bed level change, $\frac{\partial z}{\partial t}$, at the element cell centres. This parameter is based on the Exner equation, or sediment continuity equation, written as:

$$-(1-n)\frac{\partial z}{\partial t} = \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} - \Delta S$$

Where n is bed porosity, z is bed level, t is time, S_x is bed load or total load transport in the x direction, S_y is bed load or total load transport in the y direction, x and y are horizontal cartesian coordinates, and ΔS is sediment sink or source rate. For a non-equilibrium model such as this, the sediment sink/source term can be written as

$$\Delta S = \varphi_0(\eta_0) w_s (c - c_e)$$

Where η_0 is normalised no slip level above the bed, φ_0 is unit profile function for the sediment concentration, w_s is settling velocity for the suspended sediment, c is depth-averaged sediment concentration, and c_e is depth-averaged equilibrium concentration. The bed is updated continuously through a morphological simulation (at every HD-time step, in this case 30 second intervals) based on the estimated bed level change rates. The initial bed thickness of the erodible bed was designated as constant and unlimited throughout the model domain. Slope failure is not included in this morphological model.

The pure current sediment transport theory used in this model was the Engelund and Hansen [6] total-load transport theory. The model by Engelund and Hansen [6] is a total load model that needs user-specified information in order to divide the total load S_{tl} sediment transport into bed load S_{bl} and suspended load S_{sl} transport rates (m^2/s) [5]. Transport rates are obtained from the relations:

$$S_{bl} = k_b S_{tl}$$
$$S_{sl} = k_s S_{tl}$$

Whereby k_b and k_s are user defined bed load calibration factor and suspended load calibration factor respectively. In this case, both parameters are kept as the default value of 1. Total sediment transport is obtained by:

$$S_{tl} = 0.05\frac{C^2}{g}\theta^{\frac{5}{2}}\sqrt{(s-1)gD_{50}^3}$$

Where the Shields parameter θ is defined as

$$\theta = \frac{\tau}{\rho g(s-1)D_{50}}$$

Where τ is the flow shear stress, ρ is density of water, g is the acceleration due to gravity, s is ρ/ρ_s relative density of sediment and ρ_s is density of sediment. C is the Chezy number and D_{50} is the median grain size. Flow shear stress is divided into form drag τ'' and skin friction τ'. The total shear stress $\tau' + \tau''$ is estimated from the local flow velocity V and the local Chezy number C:

$$\tau = \rho g \frac{V^2}{C^2}$$

For skin friction the following approximate friction formula is applied

$$\theta' = 0.06 + 0.4\theta^2$$

Sediment density and porosity were defined as constant 2.65 and 0.40 respectively.

The equilibrium mass concentration (c_e) (g/m^3) is calculated as the suspended load divided by the water flux and converted from volumetric concentration to mass concentration [5]:

$$c_e = \frac{S_{sl}}{Vh} s10^6$$

Where V is velocity (m/s) and h is water depth.

The following correction is applied to account for the slope effect on the sediment transport rate:

$$S_s = \left(1 - \alpha \frac{\partial z_b}{\partial s}\right) S_{bl}$$

Where z_b is bed level, s is stream-wise (horizontal) coordinate, α is model calibration parameter, S_s is bed load along streamline, s, and S_{bl} is bed load as calculated from sediment transport formula [5].

A varying grain diameter (D_{50}) map was defined for the model domain comprising both surficial and synthetic sediment samples. Surficial sediment samples were collected using either a Day Grab sampler or the Shipek sampler during four MOVE offshore survey campaigns in September 2020 (CV20010), September/October 2020 (CV2036), March 2021 (CV21035) and December 2021 (CV21034). All sediment samples were processed by sieving or laser granulometry. Furthermore, sediment samples containing raw granulometric data was compiled from Geological Survey of Ireland (GSI). The MOVE and GSI datasets were combined, and statistical analysis was carried out using the R package 'geotech' [7].

Due to limited grain size availability outside our area of interest, the synthetic sand D_{50} dataset produced by Wilson et al [8] was utilised. This dataset was clipped to represent the model domain beyond the -70 m contour line extending geographically from Carnsore Point (52.17056°, -6.355278°) to Skerries (53.58389°, -6.101111°). This was to ensure mostly in situ measured grab samples would represent the south-western Irish Sea. A number of artificial D_{50} values were also placed in the target area using combined analysis of bathymetry, backscatter, surrounding D_{50} values and the EMODnet seabed substrate map. These artificial samples were placed in areas where a significant deficit of measured samples was evident in order to produce the most realistic interpolated dataset when comparing against coarse seabed substrate maps such as the EMODnet seabed substrate map [9].

1.2.1 Suspended sediment model validation at various points in the model domain

Using an ADCP dataset collected at 52.72153°, -6.0278°, Creane et al [2] produces a robust spatial timeseries of ADCP-based SSC_{solids} where the correlation coefficient between estimated SSC_{solids} and directly measured SSC_{solids} is 0.87. Combining this dataset with other ADCP outputs and water-sampled-based SSC_{solids}, Creane et al [2] successfully validates the suspended sediment transport component of the 2D model at multiple locations off the east coast of Ireland to a relatively high accuracy given underlying assumptions of the model, using three out of four tested validation techniques (Technique 1, 2 and 4). The location of these validation points includes all 'water sample' data points and the ADCP located on the western side of Arklow Bank shown in Figure 2(b) of the main article. The model validation techniques used include; i) validation of 2D modelled suspended sediment concentration ($SSC_{sediment}$) using water sample-based SSC_{solids} (Technique 1), ii) validation of the flood-ebb characteristics of 2D modelled suspended load transport and $SSC_{sediment}$ using ADCP-based datasets (Technique 2) and iii) validation of the 2D modelled peak $SSC_{sediment}$ over a spring-neap cycle using the ADCP-based SSC_{solids} (Technique 4). Full details are outlined in Creane et al [2] and a summary of the results is provided below:

Technique 1: Validation of 2D modelled $SSC_{sediment}$ using water sample-based SSC_{solids}

This involves the comparison between modelled $SSC_{sediment}$ and directly measured SSC_{solids} collected via water sampling at four stations non-associated with ADCP deployments. This technique displays very good validation results and is recommended to combine with technique 2 and 4. An example comparison at one location is provided in Figure 2.

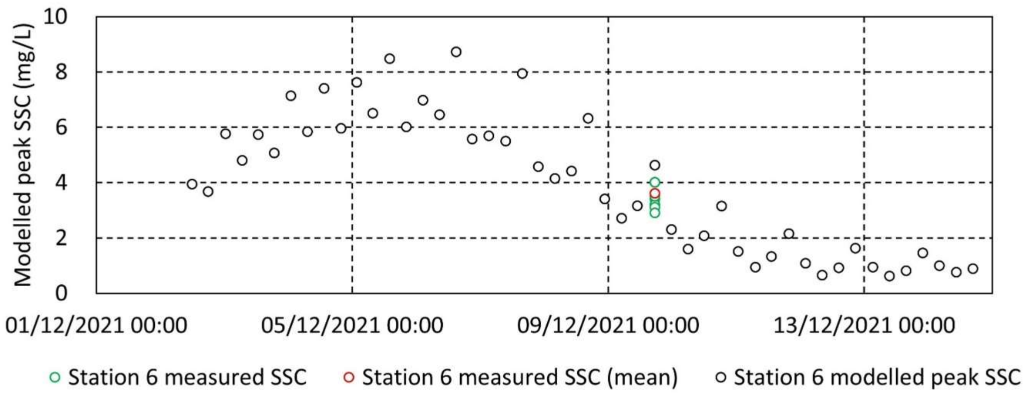

Figure 2. Comparison of 2D modelled peak $SSC_{sediment}$ against measured SSC_{solids} samples at sampling station 6 (-5.953°, 52.551°). Data source: Creane et al [2].

Technique 2: Validation of the flood-ebb characteristics (tidal asymmetry) of (i) 2D modelled suspended load transport and (ii) $SSC_{sediment}$, using ADCP-based datasets

Measured currents from the ADCP exhibit a flood-dominant tidal current direction. Both modelled residual tidal current and residual suspended load transport agree with the nature of this tidal asymmetry [2]. This provides a high degree of confidence for the directional component of modelled suspended sediment transport at this location.

In parallel, the ADCP-based SSC_{solids} spatial timeseries can be used as a calibration/validation technique for the relative magnitude of modelled $SSC_{sediment}$ in the water column over a flood-ebb tidal cycle. The bottom-water, mid-water, surface-water and depth-averaged ADCP-based SSC_{solids} datasets were analysed alongside the measured current speeds and directions. All four datasets show a higher concentration of SSC_{solids} in the water column for a higher percentage of time during the flood tide in comparison to the ebb tide. This is a direct consequence of the flood-dominance nature of the tide. When analysing modelled $SSC_{sediment}$ alongside modelled current speeds and directions, there is a very good agreement with this asymmetrical tide-SSC relationship whereby a higher concentration of $SSC_{sediment}$ is present in the water column over flood tide (N – NNE) in comparison to ebb tide (S – SSW).

Technique 4: Validation of the 2D modelled peak $SSC_{sediment}$ over a spring-neap cycle using ADCP-based SSC_{solids}

A strong positive correlation exists between the depth-averaged SSC_{solids} and modelled peak $SSC_{sediment}$, where R is 0.82 (Figure 3). The relationship between these modelled values and the mid-water ADCP based SSC_{solids} is strong positive, where R is 0.81.

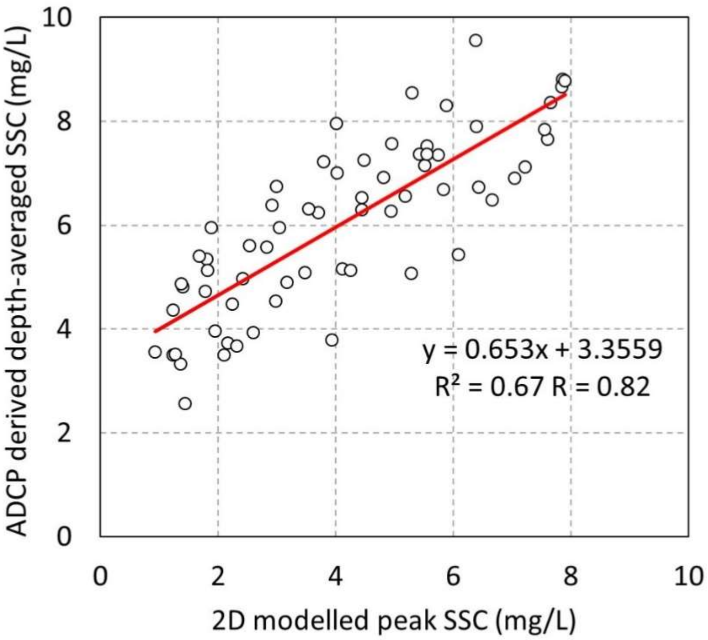

Figure 3. Correlation between 2D modelled peak $SSC_{sediment}$ and ADCP-based depth-averaged SSC_{solids} . Data source: Creane et al [2].

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