Estimating bedform migration rates from large scale models and repeat bathymetry

Report no: 990

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Mae pennu cyfraddau mudo tonnau tywod yn arbennig o bwysig wrth ddylunio a rhoi cydsyniad ar gyfer ceblau tanddwr oherwydd ei fod yn galluogi dealltwriaeth o'r dyfnderoedd angenrheidiol ar gyfer claddu ceblau, mesurau ar gyfer paratoi gwely'r môr, a'u heffaith ar yr amgylchedd. Mae'r adroddiad hwn yn crynhoi gweithgareddau rhaglen cyfnewid gwybodaeth rhwng Cyfoeth Naturiol Cymru a Phrifysgol Bangor, gyda chefnogaeth HR Wallingford. Nod y rhaglen, sy'n dwyn y teitl 'Translating sand waves', oedd archwilio a ellir pennu cyfraddau mudo tonnau tywod o fodelau cefnforegol gweithredol a dimensiynau tonnau tywod, yn absenoldeb arolygon aml-baladr lluosog. Gallai hyn helpu gyda rhoi cydsyniad yn brydlon mewn achosion lle nad oes data hanesyddol ar gael.

Aseswyd dwy ardal: yr ardal o amgylch Aberdaugleddau, yn enwedig Banc Tywod Turbot a Basddwr Sant Gofan; ac arfordir Gogledd Cymru, yn enwedig Banc Tywod Constable. Yn y ddwy ardal hon mae ceblau tanddwr yn bodoli neu fe'u cynllunnir, ac mae arolygon aml-baladr lluosog ar gael.

Cymharwyd modelau cefnforegol a oedd ag allbynnau ar gael, a dewiswyd Model Sgafell yr Alban ar sail cydraniad gofodol-amserol a fertigol. Fodd bynnag, roedd y model yn dal i fod yn gymharol fras o ran cydraniad gofodol (grid 1 km) ac felly nid oedd bathymetreg yr arfordir neu'r banciau tywod yn fanwl iawn. Nid oedd y model yn cynnwys tonnau ac felly cafodd data o fodel NEMO â chydraniad is ei ryngosod i grid Model Sgafell yr Alban. Cyfrifwyd cludiant gwaddod gan ddefnyddio model Soulsby – Van Rijn.

Cyfrifwyd cyfraddau cludiant y llwyth gwely hefyd drwy olrhain mudiad tonnau tywod yn yr ardaloedd ble roedd gorgyffwrdd yn y fathymetreg a gafodd ei mesur.

Wrth gymharu'r ddau ddull, gwelwyd rhywfaint o wahaniaethau a briodolwyd i bresenoldeb tirffurfiau gwely môr eilaidd yn y mesuriadau a diffyg cydraniad yn y model. Roedd y gwahaniaethau'n ddigon mawr i awgrymu y byddai data o fodelau gweithredol ar raddfa fawr yn ei chael yn anodd rhagweld cyfraddau mudo tonnau tywod. Fodd bynnag, gellir defnyddio'r data i nodi amserlenni synhwyrol ar gyfer mesur y fathymetreg eto er mwyn asesu mudiad tonnau tywod trwy fesuriadau. Yn achos Banc Tywod Turbot, dylid cynnal arolygon bob 1-10 o flynyddoedd er mwyn sicrhau na chaiff tirffurfiau gwely'r môr eu camgyfrif (yn sgil tonnau tywod yn teithio llai na hanner tonfedd rhwng arolygon). Ar Fanc Tywod Constable, mae angen arolygon blynyddol neu amlach am fod tirffurfiau gwely'r môr yn llai.

Executive summary

Determining sand wave migration rates is particularly important for the design and consenting of subsea cabling because it enables understanding of required cable burial depths, seabed preparation measures and their impact on the environment. This report summarises the activity of a knowledge exchange programme between Natural Resources Wales and Bangor University, supported by HR Wallingford. The programme, called 'Translating sand waves,' aimed to explore whether sand wave migration rates can be inferred from operational oceanographic models and sand wave dimensions, in the absence of repeat multibeam surveys. This could help with timely consenting in cases where historical data is unavailable.

Two areas were assessed: the area around Milford Haven, particularly Turbot Bank and St. Gowans Shoal; and, the North Wales coast, particularly Constable Bank. Both these areas are areas where subsea cabling exists or is planned and where repeat multibeam surveys are available.

Oceanographic models with available outputs were compared and the Scottish Shelf Model selected based on spatio-temporal and vertical resolution. However, the model was still relatively coarse spatial resolution (1 km grid) and so the detailed coast or sand bank bathymetry was not well resolved. The model did not include waves and so data from a lower resolution NEMO model was interpolated onto the Scottish Shelf Model grid. Sediment transport was calculated using the Soulsby – Van Rijn model.

Bedload transport rates were also calculated by tracking sand wave migration in the areas of overlapping measured bathymetry.

Comparison of the two approaches showed some differences which were attributed to the presence of secondary bedforms in the measurements and lack of resolution in the model. The differences were large enough to suggest that data from large scale operational models would struggle to predict sand wave migration rates. However, the data can be used to indicate sensible timescales for repeat bathymetry to be taken in order to assess sand wave migration through measurements. For Turbot Bank, surveys should be taken at frequencies of 1-10 years to ensure no aliasing of bedforms (sand waves travelling less than half a wavelength between surveys). At Constable Bank, annual or higher frequency surveys are required due to the smaller bedforms.

1. Introduction

The growing demand for offshore renewable energy will require a significant level of new subsea power cables installation to connect future developments to the national grid at landfall sites across the UK. The UK's seas currently host more than 1,500 km of export cables and more than 1,800 km of inter-array cables essential for transporting renewable electricity to the grid. Marine renewable energy resources harbour a large new industry and in Wales alone is expected to bring thousands of jobs over the next 10 years (Marine Energy Wales, 2022). Besides power cables, seabed cables carry >99% of all digital data traffic, keeping us connected to the fast internet we increasingly rely on, and trillions of pounds of financial transfers a day. The annual value of UK telecommunications subsea cables industry alone was estimated at £62.8 billion and electricity subsea cables at £2.8 billion in 2016 (Elliott et al., 2016), and this will increase as we move through the green energy transition. The successful deployment of these cables depends on understanding natural processes on the sea floor and the interaction between cables and the seabed, which is often poorly understood (Figure 1a). This interaction can lead to cable exposure and damage, but it can also lead to "self-burial" of the cable (Sumer et al., 2001). The often unexpected and high costs of cable repair, and the disruption to the service they provide, can render submarine cables uninsurable. This jeopardises the resilience of the UK's energy and communications supplies, and the ambitious energy transition targets.

Not only is it important to understand seabed dynamics from an engineering perspective, but it is critical for assessing the environmental impact of subsea cabling. There are multiple offshore sandbanks around the Welsh coast which are Annex 1 habitats, and many are also designated as parts of Marine Protected Areas (i.e. Special Areas of Conservation - SACs). Sand banks are accumulations of sand, often shallower than their surroundings, which tend to form where tidal currents have deposited (and may continue to deposit) sediments over time (Stride, 1982; Dyer and Huntley, 1999). Sand waves, dunes and ripples are progressively smaller bedforms which can be found superimposed on sand banks. Their movement, or migration, over sand bank (and other sedimentary) features contribute to regional sediment transport pathways. Cables from existing and planned offshore windfarms may traverse sand banks or fields of mobile sand waves (Figure 1b and Figure 2). Changes to sand wave fields, for example through clearance to facilitate cable laying, may impact the wider sediment budget. Therefore, recovery needs to be quantified if/when these features are disturbed. Better understanding of sand wave mobility around the Welsh marine area will help understand likely recovery rates, reduce uncertainty of environmental impact assessment and support the creation of appropriate guidance to facilitate consenting. Regions of interest, due to their proximity to future Project Development Areas (PDAs) and corridors for offshore wind export cables, are around Turbot Bank in the Milford Haven area, and the Constable Bank on the North Welsh Coast (Figure 2).

The ability to quantify risk to cable infrastructure and the recovery time of sand waves and banks after the placement of cables are important components of the environmental assessment and consenting process for offshore engineering projects. To prevent cable damage, cables are often buried ("trenched") into the seabed to protect them from migrating sand waves and trawling. As the cables themselves can modify the local hydrodynamics around them (Sumer *et al.,* 2001; Leckie *et al.,* 2016; 2018; Unsworth *et al.,* 2023), and modify the seabed around the cables (Figure 1a) this can lead to failure and a delayed recovery for the sand bank. When sand banks have a corridor dredged and cleared prior to cable laying and burial, industry guidance now indicates that natural infilling is not sufficient to provide protection, so either the material is returned into the trench ("backfilled"), or the cable is protected with a rock berm. Recovery times are thus affected by the background, or natural, state of sediment transport in the region, as well as the more direct impact they have due to trenching and exposure of any cable. Therefore, appropriate and consistent advice is needed for estimating the natural mobility of these environments, and how they may respond to the installation of infrastructure.

The current level of understanding of sand wave recovery timescales and processes is insufficient because the range of environmental settings (tides, waves, sediment grain size) around the UK coast means data and lessons from past projects are not always transferable. This project focused on helping regulators to better inform industry of what evidence they need to present for the consenting process to be successful, timely, appropriate, and robust.

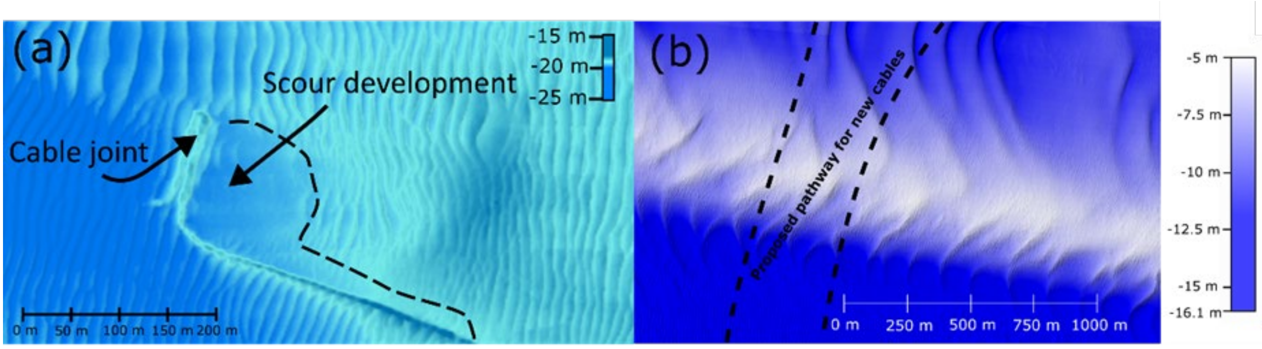

Figure 1 (a) An example of a cable joint interacting with sand waves. In the short time it was exposed for repair, scour development on the flood tide wake has occurred. (b) A likely proposed pathway for new cable routes over large sand waves on the Constable bank

2. Method

2.1. Overview of method

One of the key issues is a lack of information about the state of the seabed and the mobility of the seabed sediments. The work of Wilson *et al.,* (2018) gives an example of a shelf scale approach to the problem. However, for estimating sand wave mobility, bedform migration rates and directions need to be taken into account to assess if a sand bank sediment budget is open to the wider seas, or a closed system where sediment rotates around a central point (Hulscher *et al.,* 1993). Knowing bedform migration rates will also help with the estimation of the recovery of a sand bank or sand wave field if it were to be trenched (Nnafie *et al.,* 2020).

Much of this information can be garnered from publicly available models and repeat bathymetry surveys, but they need to be collated and used in a systematic way to assess sand wave mobility, and therefore their potential for recovery (Larsen *et al*., 2019). The approach we take in this work is outlined in Figure 3.

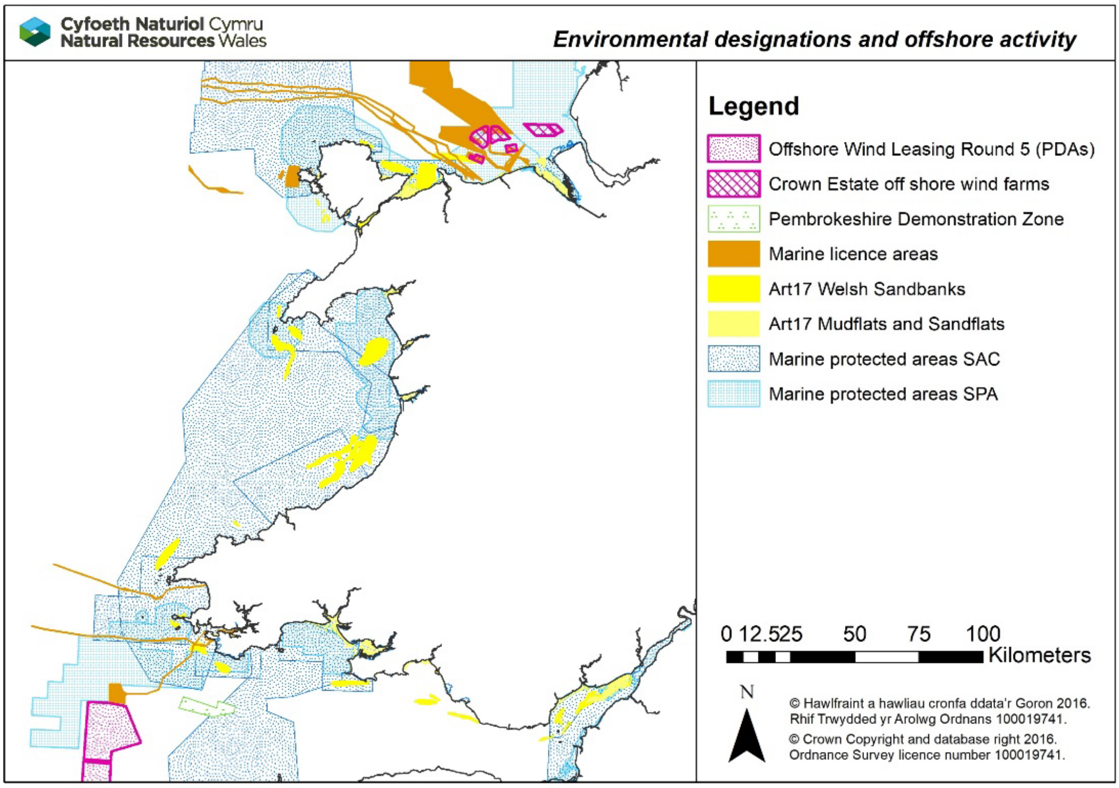

Figure 2 Annex I sand banks and offshore Marine licence areas (including cable routes)

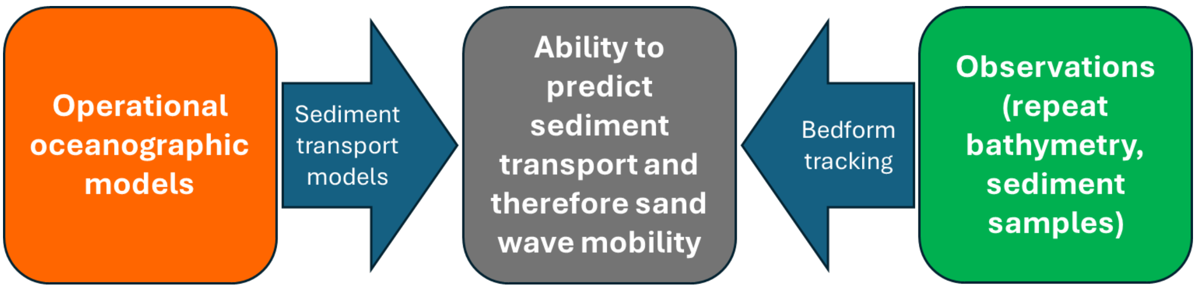

Figure 3 Conceptual outline of the report

2.2 Numerical model choice

In order to create a reasonable prediction of seabed mobility without the need for creating, running and validating a new numerical model, we decided to utilise existing models for the UK continental shelf. A number of options were found to be freely available to download, and were judged on the following criteria (Table 1):

- Spatial resolution (high resolution enough to resolve the sand banks)
- Temporal resolution (daily or tidally averaged values are inadequate, as these will miss peak bed shear stresses which may define the mobility of the sand banks)
- Vertical discretization (3D preferred over 2D, to ensure near bed current speed and magnitude are well resolved)

- Stratification and buoyancy effects (as these change the magnitude and direction of near bed currents)
- Atmospheric effects (does the model include storm surges?)
- Waves (does the model contain waves, and hence wave bed shear stress)

Additionally, models were favoured if they were already well tested and used, with existing scientific papers and DOIs (Digital Object Identifiers) to cite.

With these criteria in mind, we chose the *Scottish Shelf Waters Reanalysis Service* (SSW-RS, Barton *et al.,* 2024) as our best fit as it is one of the state-of-the-art UK shelf-sea models of high resolution, at nominally 1 km resolution near the coasts, with hourly outputs and 35 vertical layers. Freshwater inputs, stratification, and evaporation are included, and whilst the model does not contain waves, it does include atmospheric effects such as surges.

Whilst the older POLCOMS models were extensive and included waves, their lower spatial resolution and a minimum water depth of 10 m meant it was likely to not perform as well as SSW-RS near the coasts.

The mesh used in the SSW-RS with designated sand banks marked is given in Figure 4 for the south-west Pembrokeshire around Milford Haven and in Figure 5 for the North Wales coast around Constable Bank.

Table 1 The models investigated for this work and the criteria used to assess their usefulness

Model	POLCOMS	Copernicus (Nemo)	Scottish self-sea model (SSW-RS) (FVCOM)	(Horrillo-Caraballo *et al.,* 2021) *(Delft 3D)*
Years' run	1999-2005	Operational model	1994-2019	2020
Type of model	2D & 3D, Finite Volume, primitive equation	3D primitive equation	3D, Finite Volume, primitive equation	2D, Finite-Difference
Number of layers	1 to 32	50	5 to 35	1
Minimum depth	10 m	10 m	0.4 m	Unspecified
Resolution around Welsh coast	1.5 km long, 1.85 km lat. Structured grid	7 km	~ 1 km (unstructured)	<2 km (0.0167◦)
Output frequency	15 to 30 minutes, 32-layer model is daily averages	Hourly	Hourly	Possibly every 2 minutes
Fresh water input?	Yes	Yes	Yes	No
Atmospheric interaction?	Yes	Yes	Yes	No
Waves?	Yes	Yes	No	No
Bed shear stress in outputs?	No, but possible to calculate from the outputs and model setup	No	Tide yes, wave no	Tide yes, wave no

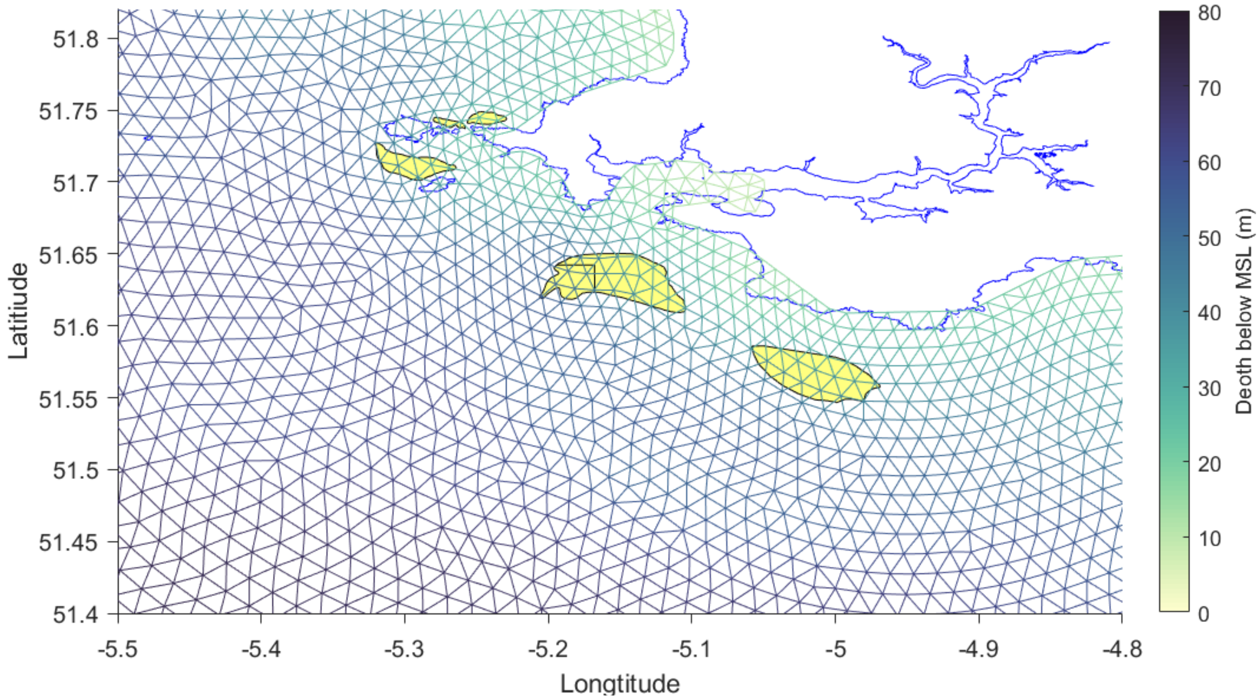

Figure 4 The model mesh, colored for depth below MSL (m), in the Milford Haven area with designated sand banks marked in yellow

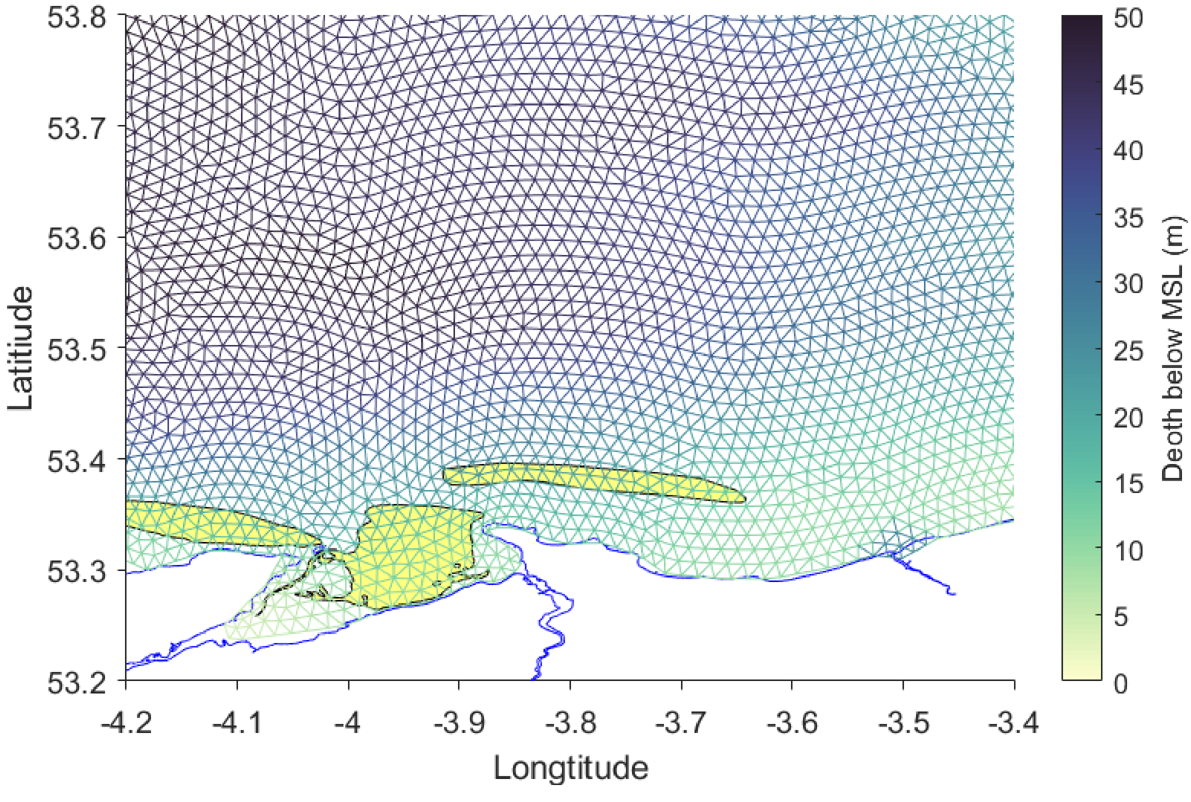

Figure 5 The model mesh around Constable Bank (marked in yellow, between -3.9 and -3.65 deg. longitude

2.3 Sediment transport rate calculation

There are a wide variety of sediment transport formulae which could be used with the model outputs. Here we have chosen to use the Soulsby - Van Rijn Model (Soulsby, 1997), as it has been widely used and can include the influence of waves. It is an empirical model which uses constants to reproduce the trends in total sediment transport:

$$q_{bed,sus} = A_s\, U_c\, [(U_c^2 + (0.018/C_d) + U_{rms}^2)^{0.5} - U_{crit}]^{2.4} \quad (1)$$

where $q_{bed,sus}$ is the unit sediment transport rates for bedload and suspended respectively (m^2s^{-1}). U_c is the depth-average velocity, C_d is the drag coefficient for the sediments, U_{rms} is the root mean square orbital wave velocity, U_{crit} is the critical threshold of motion for the sediments is set by:

$$U_{crit} \begin{cases} 0.19 d_{50}^{0.1} log_{10}\left(\frac{4h}{d_{90}}\right), if\ d_{50} < 0.0005\ m \\ 8.5 d_{50}^{0.6} log_{10}\left(\frac{4h}{d_{90}}\right)\ \ if\ d_{50} > 0.0005\ m \end{cases} \quad (2)$$

the drag due to particle roughness is defined as:

$$C_d = \left(\frac{0.4}{\ln(\frac{\max(h, z_0)}{z_0}) - 1,}\right)^2 \quad (3)$$

where flow depth is h, z_0 is the sediment roughness height (Van Rijn 2007). A_b and A_s are the calibration parameters for bedload and suspended load:

$$A_b = 0.005h \frac{\left(\frac{d_{50}}{h}\right)^{1.2}}{\left((s-1)gd_{50}\right)^{1.2}} \quad (4)$$

$$A_s = \frac{0.012 d_{50} (D^*)^{-0.6}}{\left((s-1)gd_{50}\right)^{1.2}} \quad (5)$$

where the median particle size of the sediment is d_{50}, acceleration due to gravity g (9.81 ms^{-2}), and a normalised grain size D*:

$$D^* = d_{50}\left(\frac{(S-1)g}{\nu^2}\right)^{1/3} \quad (6)$$

where specific gravity of sediment (s) is the ratio of the density of sediment particles to fluid density: ρ_s/ρ_w, and ν is the kinematic viscosity of seawater, calculated from the salinity and temperature seawater output from the model (Nayar *et al.,* 2016).

Wave data was included where available from a lower resolution NEMO model run (Bricheno *et al.,* 2015), which was interpolated using the nearest neighbour approach onto the FVCOM grid and used to calculate the wave orbital velocity $U_{rms} = U_w/\sqrt{2}$.

2.4 Multibeam data for bedform tracking

Of critical importance with any sediment transport modelling, is knowing if the predictions are realistic, as predictions can be orders of magnitudes wrong (Amoudry and Souza, 2011). Often, validation is carried out either from a Eulerian dataset, i.e. point measurements at one location over time (small spatial scale but long-time scale), or from bedform tracking to get larger scale bedform migration rates. Data for the task of bedform tracking was found from the Admiralty via its "Seabed Mapping Service"), data collected by Countryside Council for Wales (NRW's predecessor), and data collected by Bangor University (formerly available via "IMARDIS").

To calculate sediment transport rates from bathymetry data, the common 2D method uses individual profiles of bedforms to estimate a unit sediment transport rate q_s (m^2 s^{-1}):

$$q_s = 0.5\ (1 - P)u_b\eta \tag{7}$$

Where P is the porosity of the sediment (assumed here to be 0.35), u_b= bedform migration rate (m s^{-1}) which is derived from the repeated profiles, η is the bedform height (m). Here, the value of 0.5 is assuming a triangular shape to the bedforms.

However, bedform fields are rarely two dimensional in crestline, there is typically lateral variability in bedform shape and size, and this can lead the simpler 2D method to be erroneous which is why 3D methods have been sought. If available, multiple high-resolution, bathymetry transects can be used to capture the migration of 3D bedforms and derive a sediment transport rate per unit area. Following the work of Nittrouer *et al.* (2008), which built a database of sediment transport rates from repeat multibeam echosounder (MBES) surveys on the lower Mississippi river, the sediment transport rate of a mobile bedform field can be calculated from difference mapping of the repeated MBES data. Following Nittrouer *et al.* (2008), the calculation is for time difference $\Delta t = t_2 - t_1$ is:

$$\langle \Delta x \rangle = \frac{\sum_{area}[Z(t_2) < Z(t_1)]}{N_{Bedform}W_{dune}} \tag{8}$$

$$q_s = \varepsilon_{bed}\left(\frac{\langle \Delta x \rangle - \langle \Delta z \rangle}{\Delta t}\right) \tag{9}$$

Which gives a unit sediment transport rate, q_s (m^2 s^{-1}), $\langle \Delta x \rangle$ is the average migration distance, $\langle \Delta z \rangle$ is the lee face sediment deposition (+ve values), ε_{bed} is the porosity of the sediment (0.35), $N_{Bedform}$is the number of bedforms, W_{dune} is the width of the Digital Elevation Model (DEM) of difference (note: the MBES therefore needs to be cropped to the width of the dunes which are being measured). This approach has the benefit of including the complex three-dimensional nature of many sandy bedforms, as well as the spatial diversity of sediment transport rate which can occur in natural environments. Whilst the geometric measurements such as lee face deposition and migration distance are simple to calculate, error can occur due to ambiguities such as the number of bedforms (e.g. if one bedform splits into two along its crestline).

This procedure was used to calculate sediment transport rates for one section of repeated MBES data collection on St Gowans Shoal, a recent survey of Turbot Bank, and the multiple repeat MBES data available near Constable Bank on the North Coast of Wales.

3. Results

3.1. Milford Haven region

3.1.1. Numerical model outputs

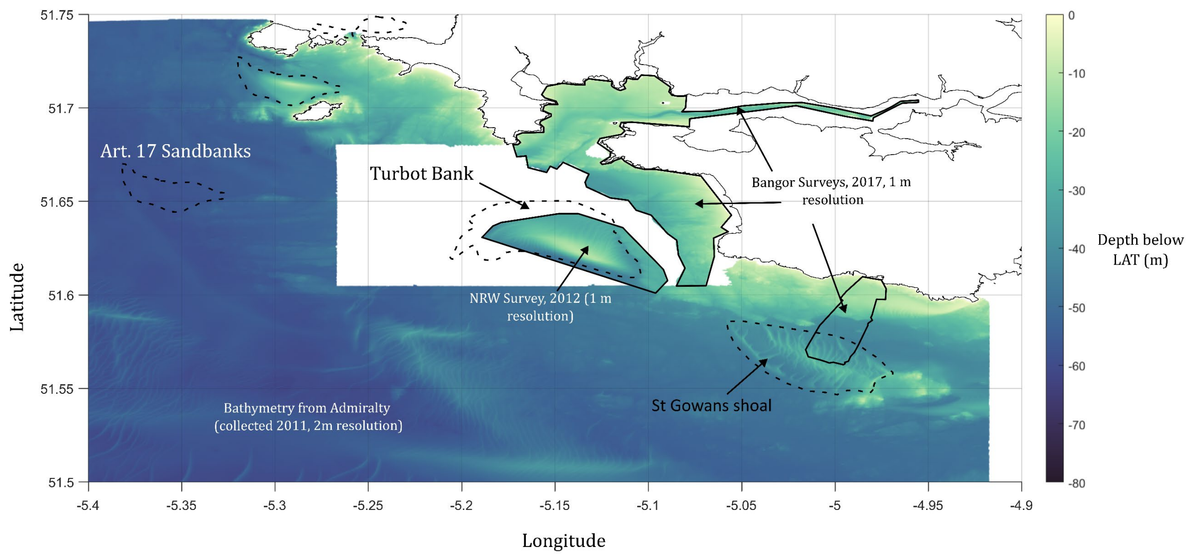

Figure 6 Overview of the Turbot Bank region and available MBES data, the more recent NRW survey is not included (because collection occurred after the official project end).

Whilst Milford Haven is reasonably well covered by high resolution MBES surveys, at the start of the project only one patch of publicly available data contained an overlap where bedforms have clearly migrated. This is the sand bank to the southeast (51.557°, -5°), known as St Gowans Shoal (Figure 6).

Tidally average flow conditions for this region were calculated for the year 2010 using hourly data from SSW-RS. 2010 was chosen as a representative year for which wave data was available. Residuals were calculated by summing over the year, where floods are positive and ebbs negative. Residual depth-averaged and near bed current flows northwards into the mouth of Milford Haven, but is deflected northwest into a large eddy overlying bedrock (Figures 7 & 8). St Gowans Shoal appears to be in a large-scale residual eddy, probably induced by the shallow bedrock around (51.55°, -4.957°). Flood tide streams are typically west to east, and ebbs streams east to west (Figure 9), with a net flux out of the Bristol Channel under tidally dominated transport conditions.

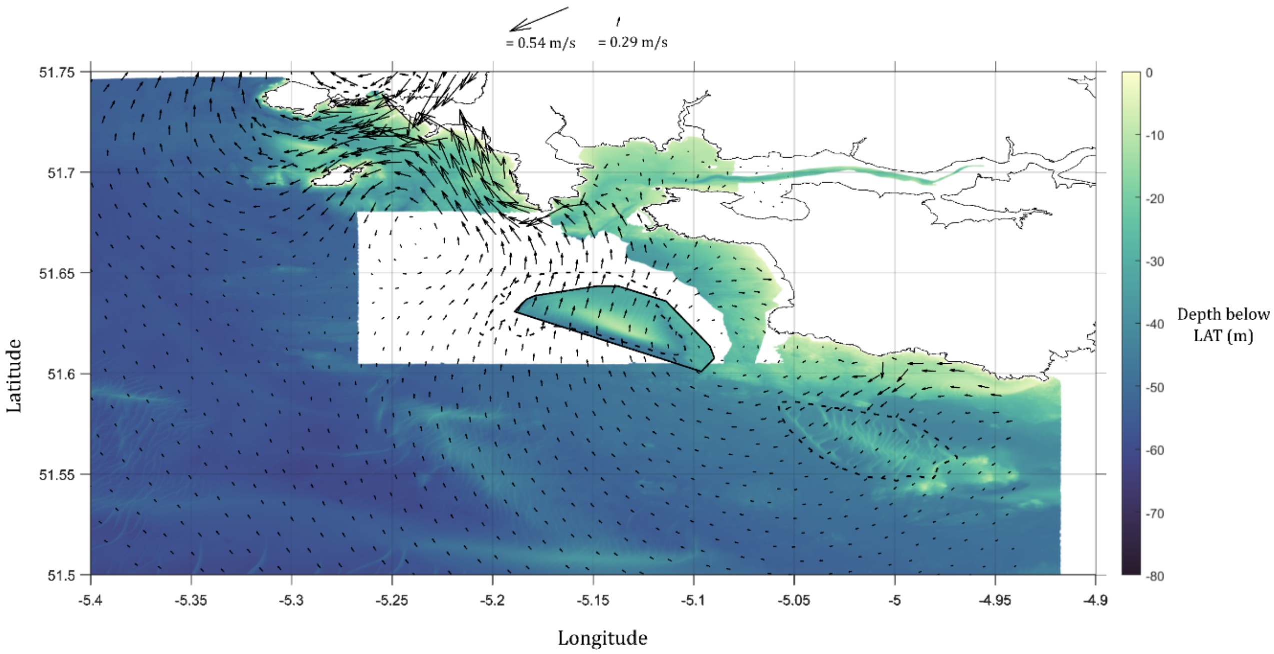

Figure 7 Residual depth-averaged flow directions for the calendar year 2010. Arrows above the figure show the maximum and minimum vector values

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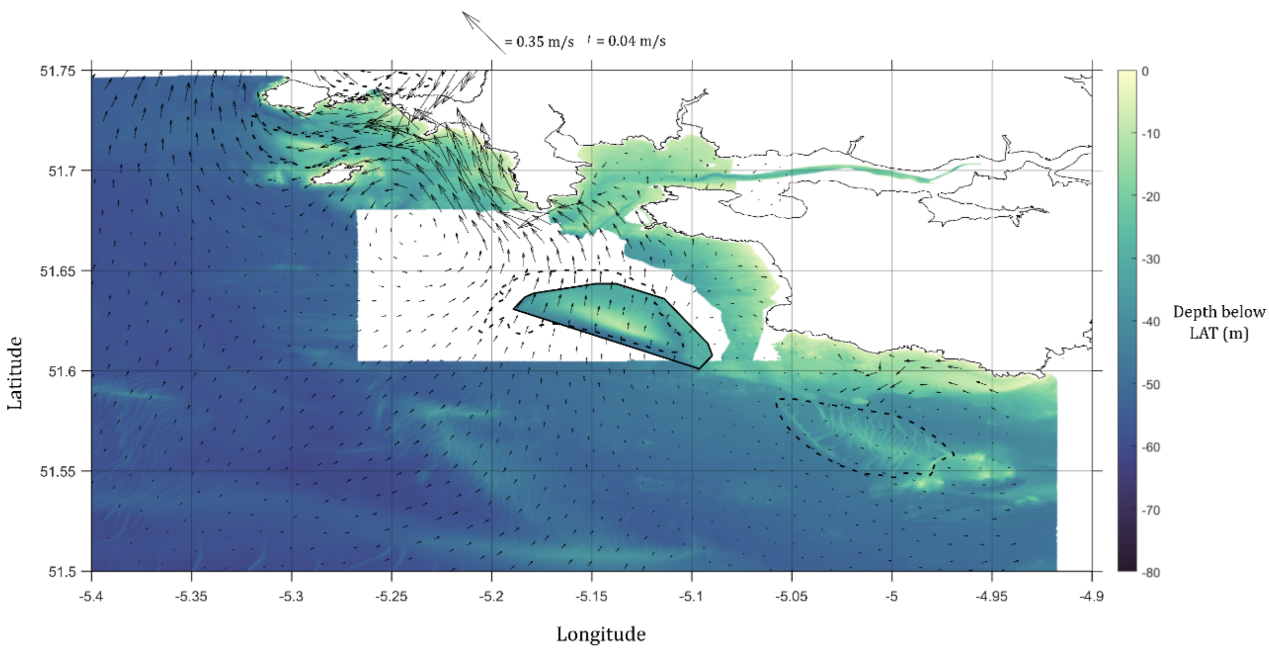

Figure 8 Residual near bed flow directions for the year 2010. Arrows above the figure show the maximum and minimum vector values.

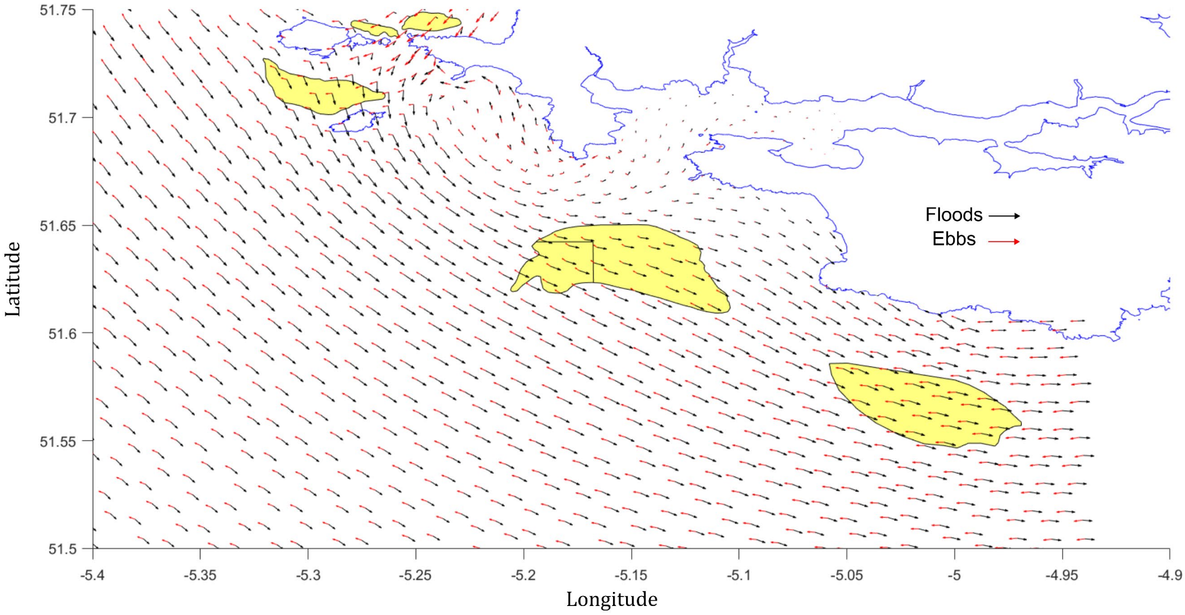

Figure 9 Mean flood and ebb current vectors for a peak spring tide. Velocity magnitudes range from near 0 to 1 m s^{-1}; median flood speed = 0.43 m s^{-1}, median ebb speed = 0.4 m s^{-1}. Yellow areas are the Article 17 sand banks.

The residual bedload sediment transport magnitude (signed based on flood and ebb direction), calculated from Eq. 1-6 using hourly data with waves, for the year 2010 is plotted in Figures 10 & 11 and highlights the two gyres either side of Turbot Bank. Peak residual sediment transport is located around these gyres, which are close to the coastline and rocky outcropping - suggesting a relatively permanent control on residual sediment transport directions and magnitude. Both Turbot bank and St Gowans Shoal have relatively low residual sediment transport rates (x10^{-7} m^2 s^{-1}) whist the coastal bedrock areas are an order of magnitude higher - perhaps unsurprising considering their lack of sediment cover.

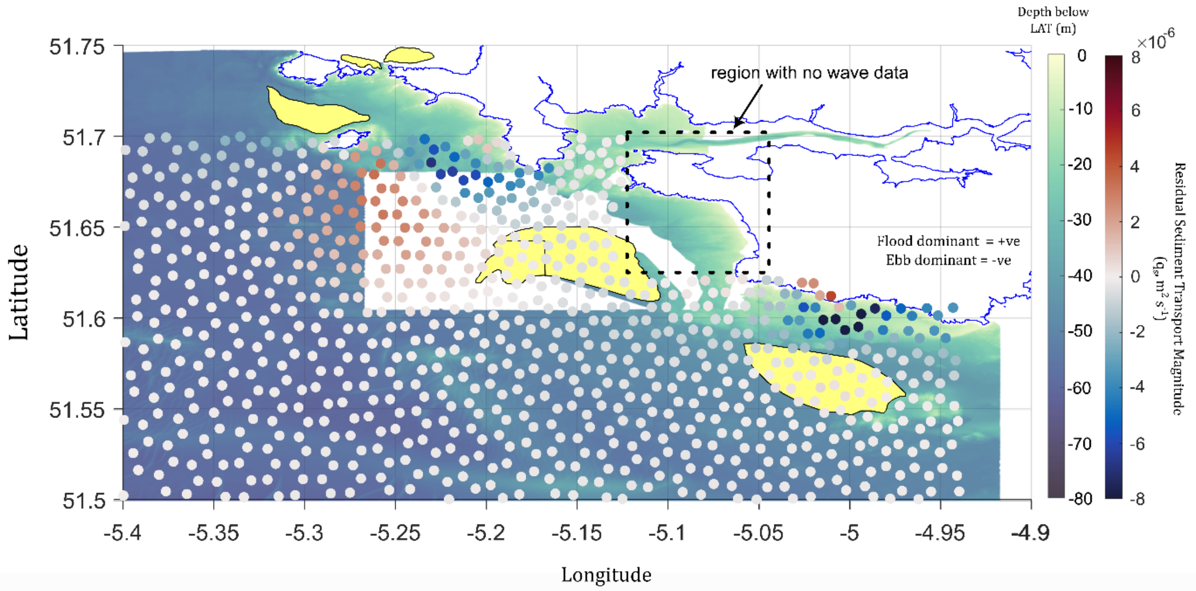

Figure 10. Residual Bedload Sediment Transport magnitude for a d_{50} of 290 µm. Positive value are flood dominant, ebb values negative.

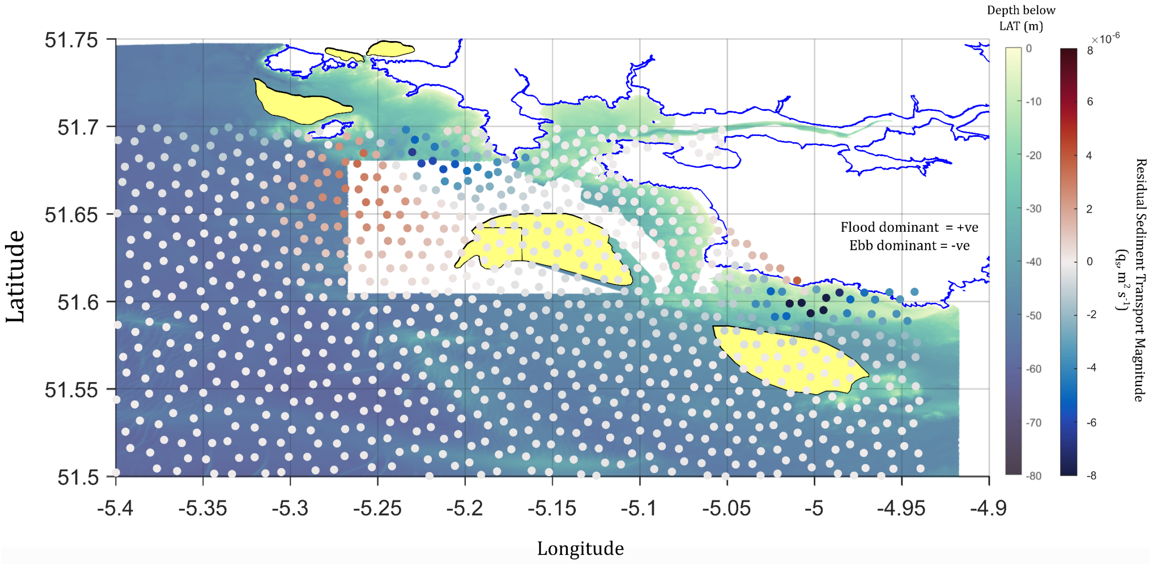

Figure 11. Residual Bedload Sediment Transport magnitude for a d_{50} of 290 μm, without waves.

3.1.2 Comparison of modelled and measured sediment transport rates around Milford Haven

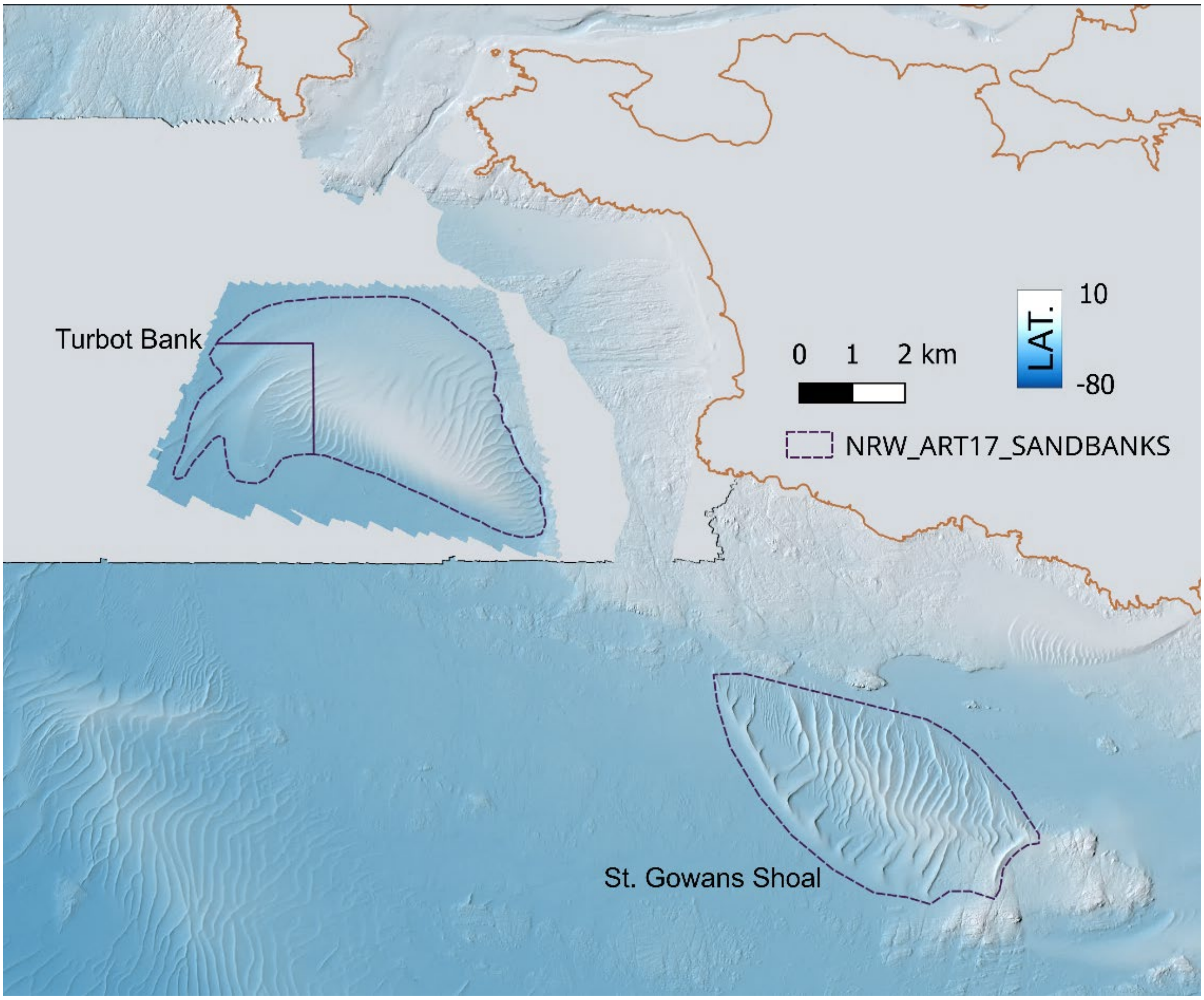

Figure 12 Close up of the bathymetry in the Milford Haven region, focusing on Turbot Bank and St Gowans Shoal. Purple dashed boundaries denote the Article 17 sand banks, and the orange line denotes the Mean High Water Springs. Depths are to Lowest Astronomical Tide (LAT)

As a first test, sediment transport for St Gowans Shoal (Figure 12) will be compared with sediment transport rate calculated via a DEM of difference approach for the available section of this sand bank (Figures 13 and 14). Then, a recent 2025 survey of Turbot Bank (shown in Figure 12) will be used with a 2012 Countryside Council for Wales (CCW), NRW's predecessor organisation, survey.

Table 2 Data Sources for Repeat MBES bedform tracking

St Gowans Shoal	Data owner	Resolution (m)
15/03/2011	Admiralty	1
10/08/2017	Bangor University	1
Turbot Bank	Data owner	Resolution (m)
28/03/2012	NRW	1
23/09/2025	NRW/ Bangor University	1

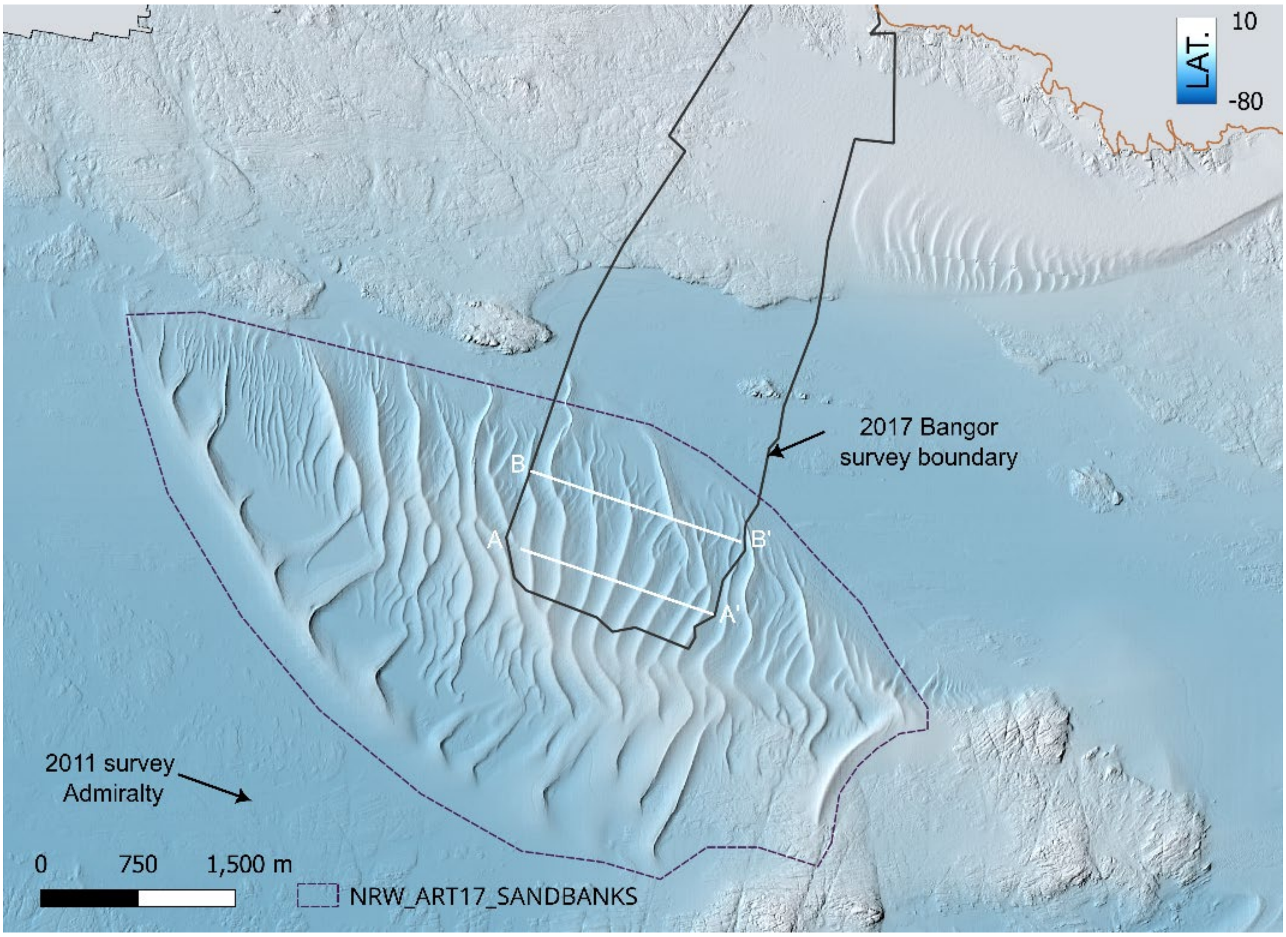

Figure 13 MBES survey data for “St Gowan’s shoal” from 2011, with the designated are marked as a dotted line and the 2017 survey extent as as solid line. overlapping MBES data. Two transects whose profiles are shown in Figure 15 are marked in white.

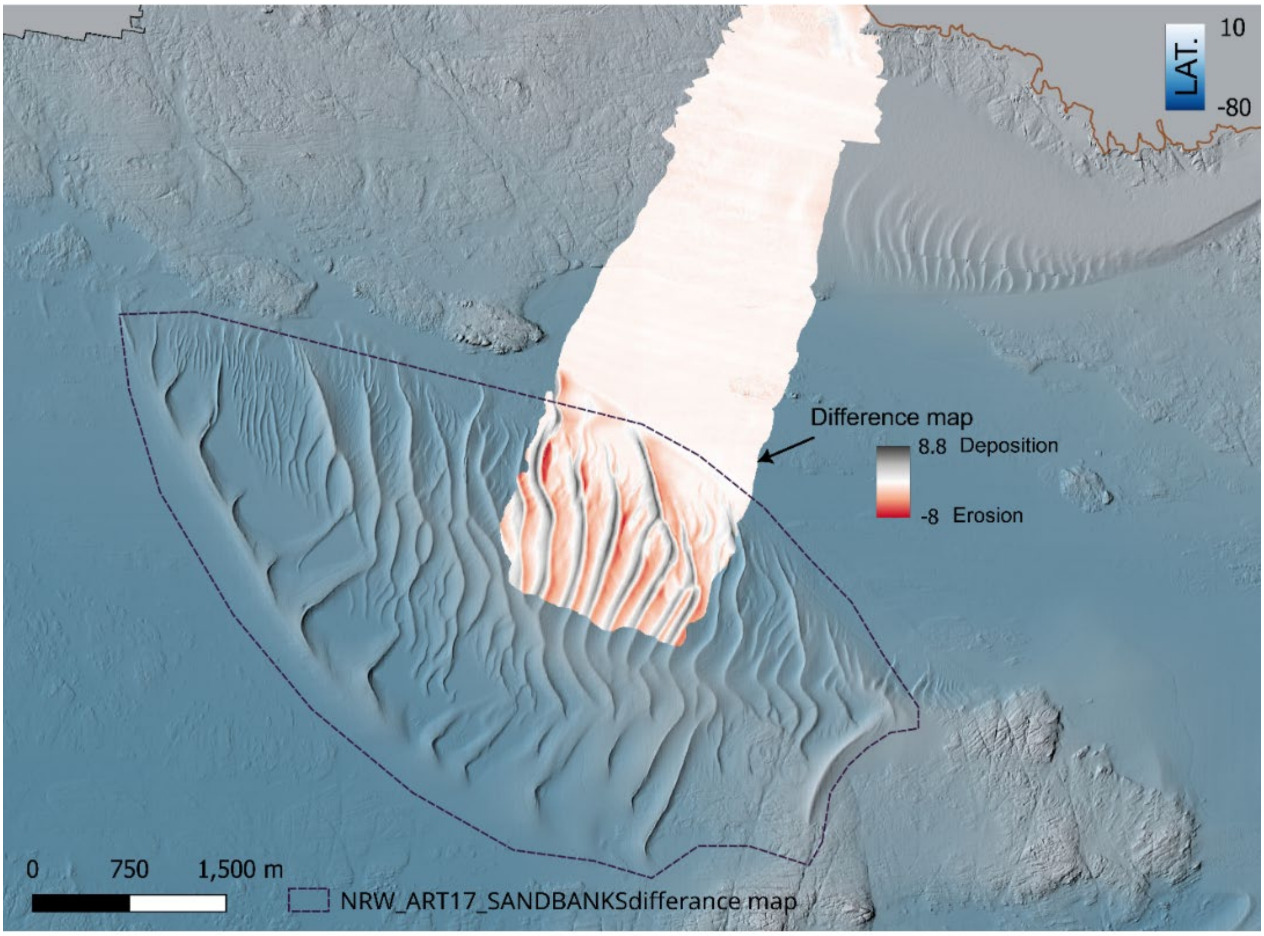

Figure 14 Difference map (black to red, m) of the MBES survey from Bangor versus the Admiralty dataset. Background DEM is the Admiralty dataset. Bedforms on the sand bank have migrated towards the North West.

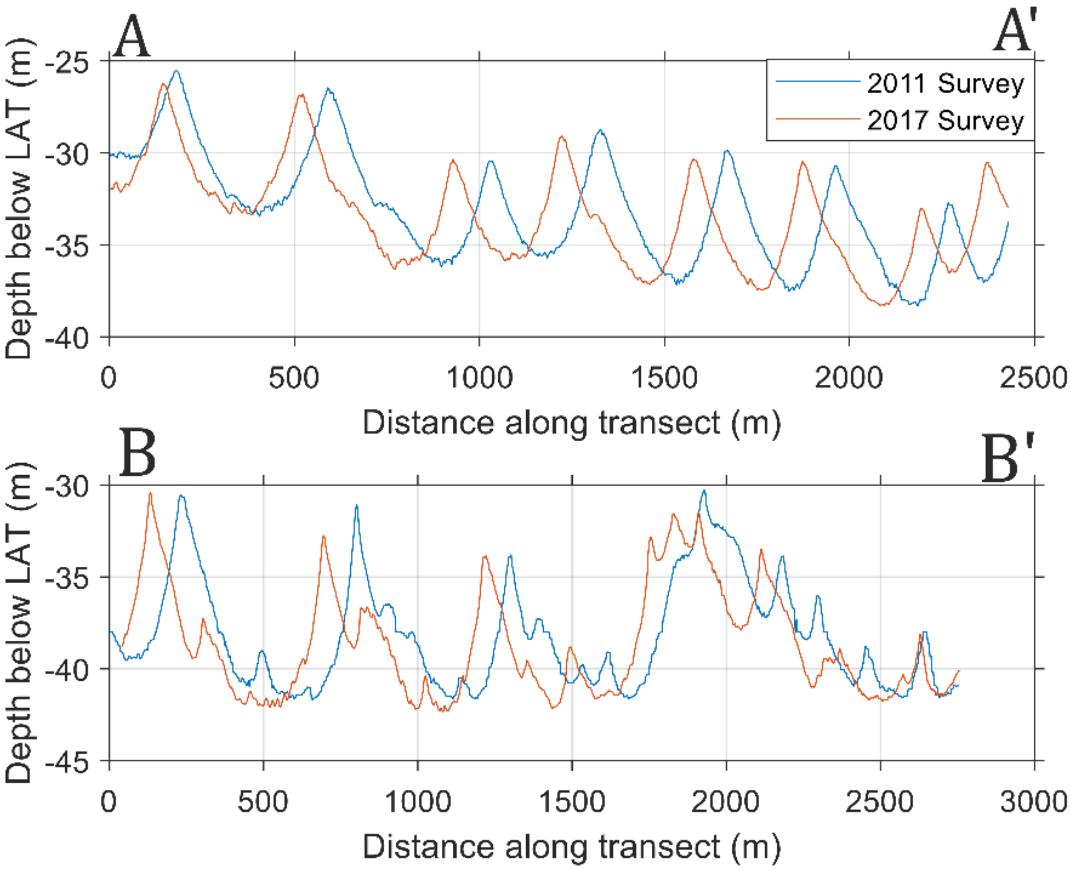

Figure 15 Seabed profiles from the 2011 and 2017 surveys of St Gowans shoal

From the transects shown in Figure 15, it is clear the sand waves on this section of St Gowans Shoal sandbank are migrating in a predominantly north west direction generally in line with the ebb tidal direction. Bedform heights range from 7-9 m high and have migrated between 80 and 120 m between the surveys (~ 16 m/year).

The difference map shown in Figure 15 was cropped to just the region covering the mobile bedforms and was used to calculate a unit sediment transport rate for St Gowans Shoal of -1.45 x 10^{-7} m^2 s^{-1}, from equations 7-8. To get a value for the residual sediment transport rate from the SSW-RS model, we used a grain size of 650 μm (the nearest d_{50} to the sand bank, via DIGIMAP and CEFAS).

Table 3. Value for measured and modelled unit sediment transport rate for St Gowans Shoal. Negative values indicate ebb tide direction, positive flood tide direction.

Measured value (q_s)	-1.45 x 10^{-7} m^2 s^{-1}
Model (with waves) (q_s)	1.31 x 10^{-7} m^2 s^{-1}
Model (without waves) (q_s)	-1.09 x 10^{-7} m^2 s^{-1}

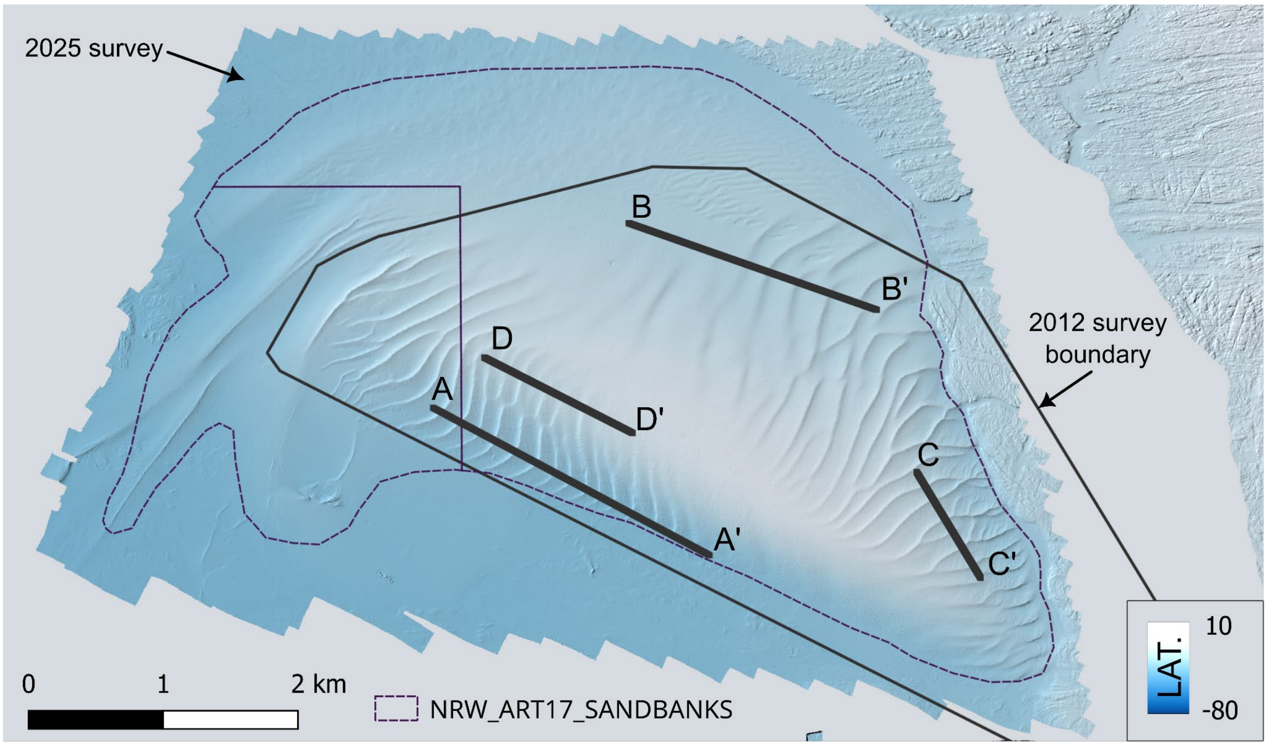

Figure 16 The 2025 Turbot Bank MBES survey, with transect locations shown.

Whilst spatial variability in the modelled residual sediment transport rate is high, with values between 1 x 10^{-5} m^2 s^{-1} and x 10^{-7} m^2 s^{-1} within 2 km of St Gowans shoal, the values from the model which covers the repeat MBES patch with bedforms were averaged and are shown in Table 3 and is a remarkably good agreement with observation. Given the relatively low-resolution modelling (for the bathymetric complexity of the region), the residual sediment transport rate estimation *without* the influence of waves produced a unit sediment transport rate of similar order of magnitude (within 25% of the measured value) and direction. The result which includes waves reverses the direction of transport suggesting that either the annually resolved bedform migration direction is unaffected by waves (i.e. tidally dominated), or that the modelling approach utilised here is not resolving wave-tide interaction over the sand bank to the level needed for accurate sediment transport estimates.

In 2025, NRW contracted a new MBES survey of the Turbot Bank to Bangor University (Figure 16). The survey was completed on 23/09/2025, marking 13 years and nearly 7 months between the previous survey of the bank. Resolution for both surveys is 1 m. As it is conceivable that some bedforms (particularly bedforms 100 m or less and < 1 m high) may have migrated too far for difference mapping to accurately generate sediment transport rates over this timeframe, estimates of sediment transport rate via this method will focus on the larger bedforms.

Transects A-D in Figure 17 demonstrate the diversity in size and shape of the bedforms on Turbot Bank, with asymmetric dune bedforms in transects A and B - with A migrating to the North West, with B migrating to the ESE. The more symmetric bedforms in C suggest more equal sediment transport directions, yet the migration of 70-80 m in transect C shows there is still a net SE sediment transport movement. For transect D, on the top of the bank, it is difficult to interpret net change and the direction of change. The residual sediment transport directions predicted from the model suggest that transport should be south to north, yet the orientation of the bedforms on Turbot Bank suggest a more rotational system exists. Higher resolution modelling is likely to be needed to produce such a flow feature here; given the gaps in high resolution bathymetry coverage,additional MBES surveys would be required.

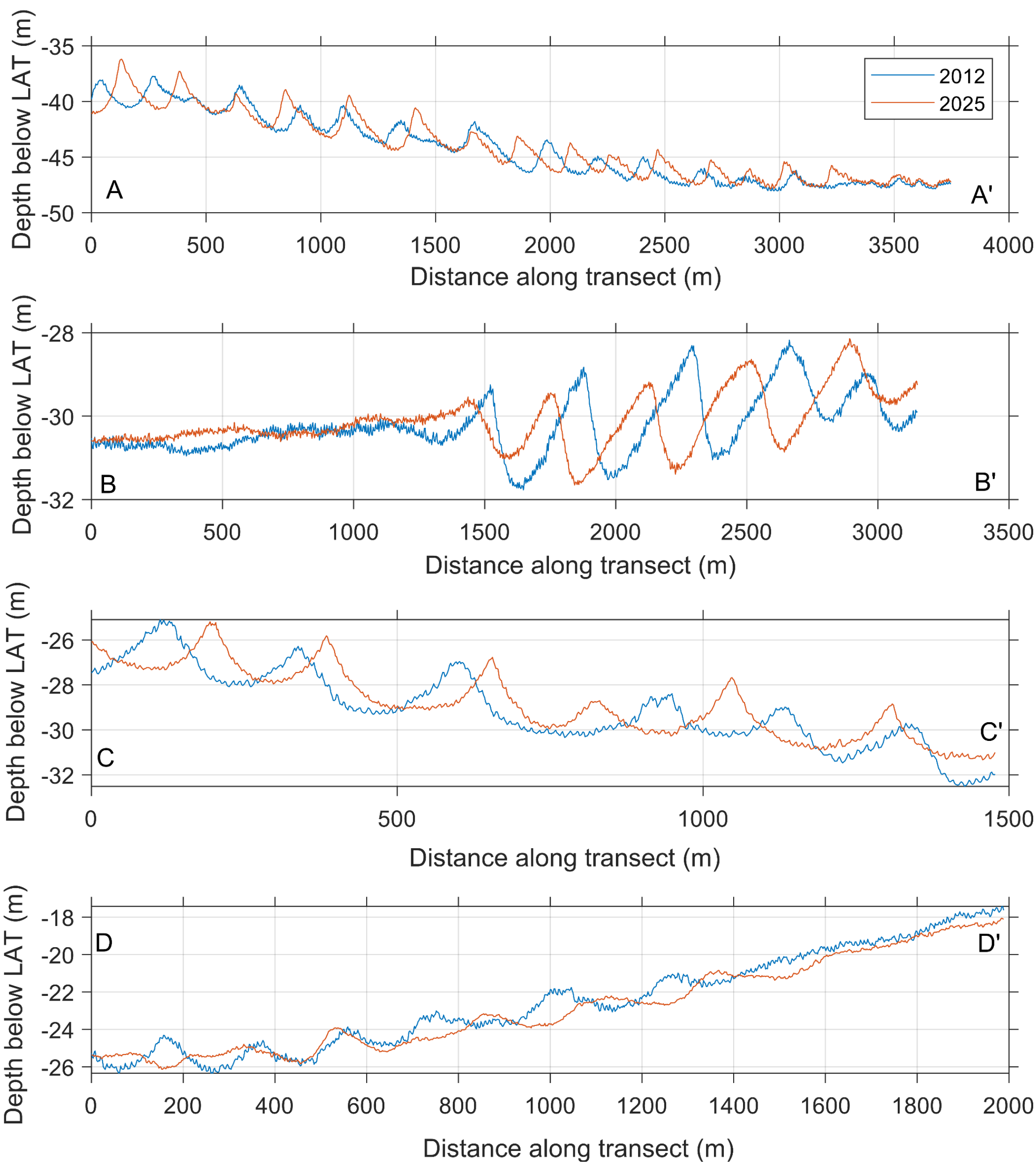

Figure 17 Bedform profiles from the transects shown in Figure 17, for both the 2012 and 2025 surveys

Seven regions were isolated for difference mapping and calculation of unit sediment transport rate as per Eq. 8-9 (Figure 18, Table 4). The comparison of measured and modelled values is poorer than the test at St Gowans Shoal. Modelled values are mostly out by an order of magnitude. Moreover, many estimates of sediment transport rate are in the wrong direction, primarily on the north and northeast of the bank where most of the bedforms are migrating to the SE - in the flood tide direction (Table 5).

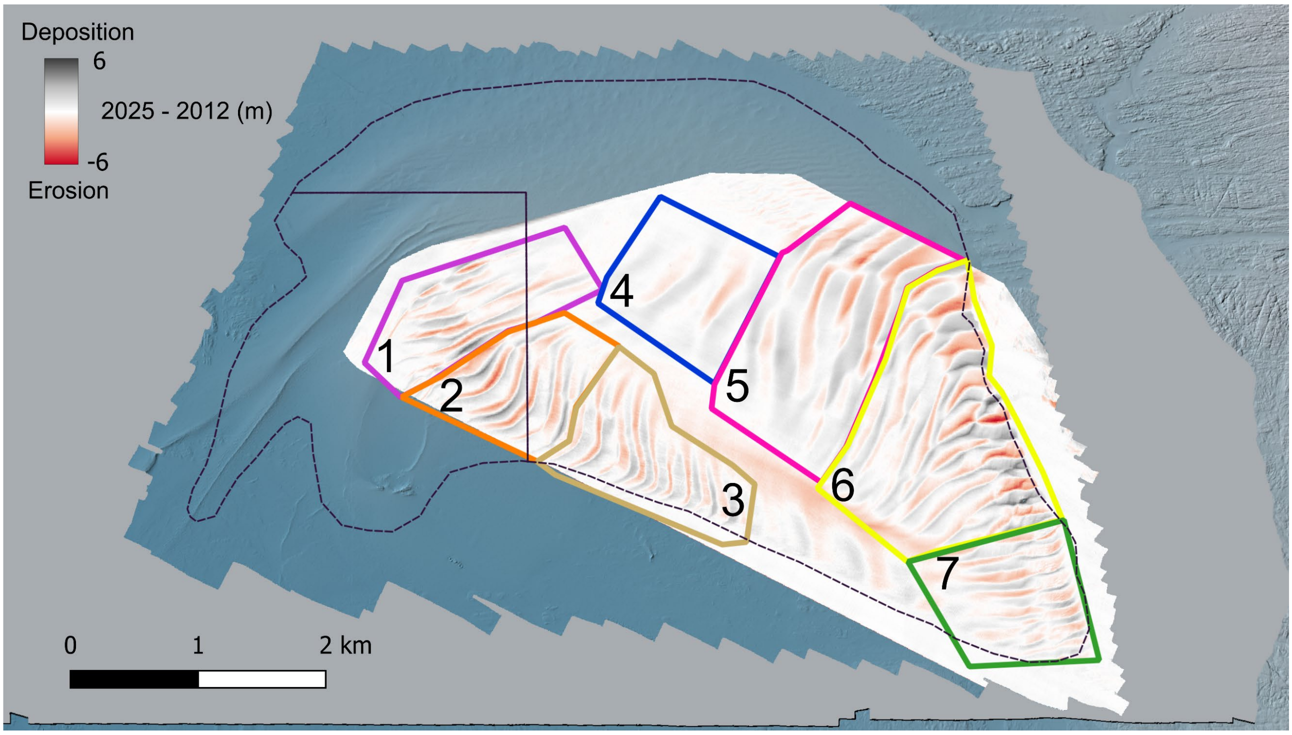

Figure 18 Polygons outlining the regions of the sand bank which were extracted for bedform tracking

Table 4 Values for unit sediment transport rate from bedform tracking, and model calculations for area marked in Figure 18.

Area	Longitude	Latitude	Number of bedforms	Width (m)	Area (m^2)	dx	Migration per year (m)
1	51.6342235	-5.1730104	5	1,880	1,244,182	70.7	5.4
2	51.6287335	-5.1681209	4	1,180	979,702	91.5	7.0
3	51.6232996	-5.1537204	10	700	1,215,945	80.6	6.2
4	51.6357215	-5.1494921	3	1,034	1,136,792	87.8	6.8
5	51.6324979	-5.1340759	5	1,905	2,099,881	73.7	5.7
6	51.625194	-5.121052	9	1,500	2,398,795	78.5	6.0
7	51.613791	-5.112564	7	1,050	1,134,478	71.3	5.5

Table 5 Measured and modelled unit sediment transport rates, positive is in the flood tide direction.

Area	Measured q_s (10^{-7} m^2 s^{-1})	Modelled q_s (10^{-7} m^2 s^{-1}) with waves	Modelled q_s (10^{-7} m^2 s^{-1}) without waves
1	-0.127	-0.96	-0.99
2	-0.210	-2.95	-2.89
3	-0.162	-7.28	-6.82
4	0.296	-5.10	-4.90
5	0.195	-3.54	-3.25
6	0.193	-4.26	-2.37
7	0.223	-4.46	-4.00

3.1.3. Implications for estimating the mobility of bedforms on Turbot Bank

Table 6. Estimates of bedform migration rates on turbot bank

Modelled residual q_s	1 m high bedforms	4 m high bedforms
q_s= 8 x10^{-8} m^2 s^{-1} (low)	7.76 m/year	1.94 m/year
q_s= 1 x10^{-7} m^2 s^{-1} (high)	9.70 m/year	2.43 m/year

Modelling and comparison with measured sediment transport rates suggest that Turbot sand bank is an active region of sediment transport. The NRW MBES survey of Turbot Bank in 2012 reveal 1-4 m high bedforms, 100-150 m long. These bedforms are somewhat smaller than St Gowans Shoal, perhaps as Turbot Bank is shallower. Modelled residual sediment transport rates for Turbot sand bank range between 8x10^{-8} m^2 s^{-1} and 1x10^{-7} m^2 s^{-1}. Using the height of the bedforms from the survey, it is possible to estimate the range of bedform migration rates on the bank using Eq. 6 (Table 6).

These rates are high enough for the migration of the bedforms to be detectable from an annual MBES survey (potentially even over 6 months, especially if large spring tides are running between the surveys), and can place an upper limit on the time difference between surveys of 10 years (assuming 100 m bedform length) to ensure bedforms aren't aliased when doing the difference mapping. Given the comparison of bedform profiles in Figure 18, it is clear that bedforms on parts of the sand bank have migrated too far for the bedform tracking method to accurately estimate the unit sediment transport rate. Given the consistency of the over prediction of the model estimates compared to observation, it is clear that either shelf scale operational models do not appropriately capture the local scale processes, and/or more observations are needed.

The tidal residual in depth average currents for the year 2010 shows a clear onshore directed mean residual current over Turbot Bank (Figure 8-9). The actual flow field over the bank will be substantially complicated by the presence of the sand bank, the bedforms, and outcropping bedrock - of which the model used herein will only have represented at the broad (1-2 km) resolution scale. This does not mean the results are not informative, as they will represent the general flow patterns at that scale - which will in turn define the more complex local scale flow patterns. Turbot Bank sits between two gyres (one to the southeast, and one to the northwest) of the bank. The significance of this large-scale rotation flow may well be to keep sediment on the bank which may have been pushed off during a flood or ebb, and it will prevent the loss of sediment to deeper waters. Longer scale, higher resolution morphological modelling is needed to confirm this hypothesis. It is recommended that if a high resolution numerical model was available, the removal (or addition) of a large section of the sediment from the bank - similar to a trenching procedure for offshore cables could be simulated (Larsen *et al.,* 2019; Nnafie *et al.,* 2020). It should be possible to also investigate how the disposal of this sediment will affect sediment transport on the bank.

3.2 North Wales (Constable Bank)

3.2.1 Comparison of modelled and measured data

The region around Constable Bank has been surveyed numerous times over various profiles at Bangor University. This dataset, combined with the admiralty 2019/2020 dataset has created a broad set of field measurements to compare against the modelled values (Table 7, Figure 19). Measurement locations from the repeat MBES methods, and the model nodes used for comparison are shown in Figure 20. Unit sediment transport rates from the MBES method (Figure 21), show a gradually increasing sediment transport rate from west to east, as depths shallow. Sediment transport direction is uniformly west to east, along the crest of the bank (Davies *et al.,* 2023).

Table 7. Data Sources for Repeat MBES bedform tracking for Constable Bank region.

Constable Bank Region	Data owner	Resolution (m)
2010	RWE	1
15/06/2017	Bangor University	1
2019	E-W interconnector	0.5
2019-2020	Admiralty	1
01/06/2022	Bangor University	0.5
08/07/2024	Bangor University	0.5

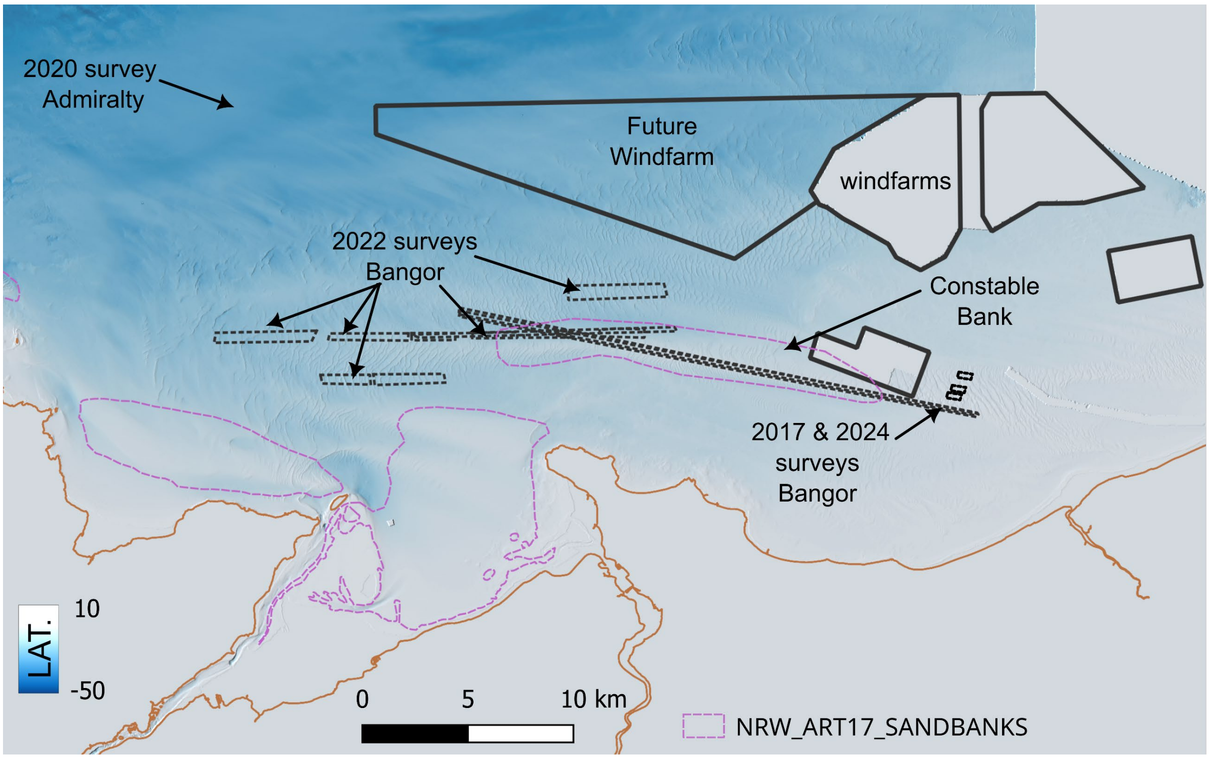

Figure 19. Overview of the Constable Bank region, bathymetry, location of Article 17 sand banks and offshore wind farms.

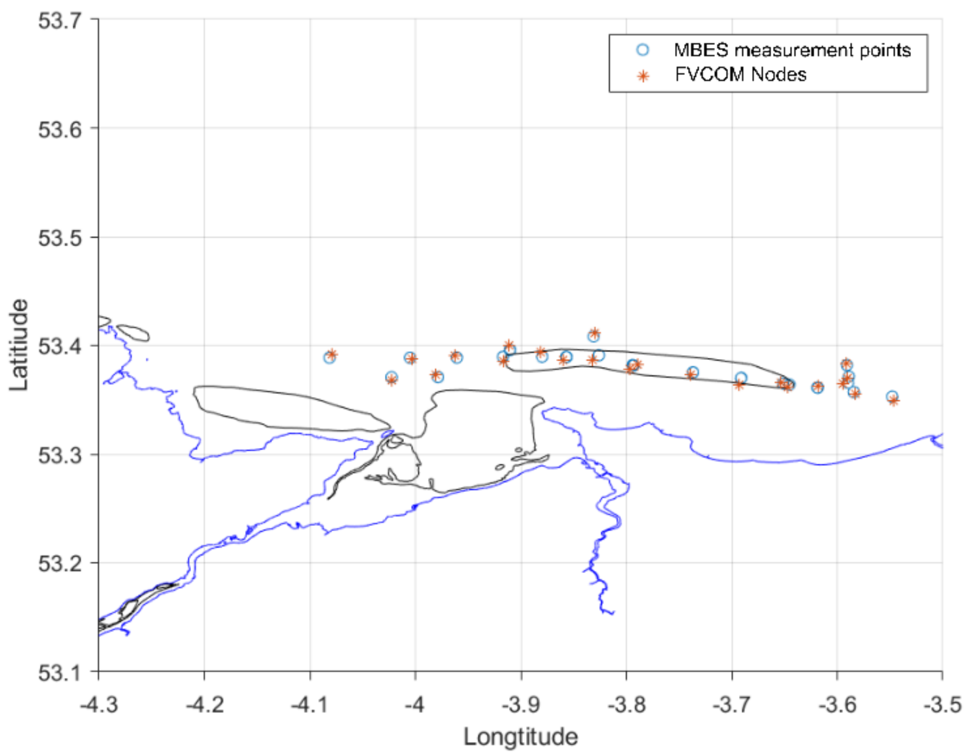

Figure 20. Location of Repeat MBES measurement points and the FVCOM (SSW-RS) nodes used for comparison. Black lines denote Annex 17 habitats- with the majority of measurements on Constable bank, Blue is the coastline.

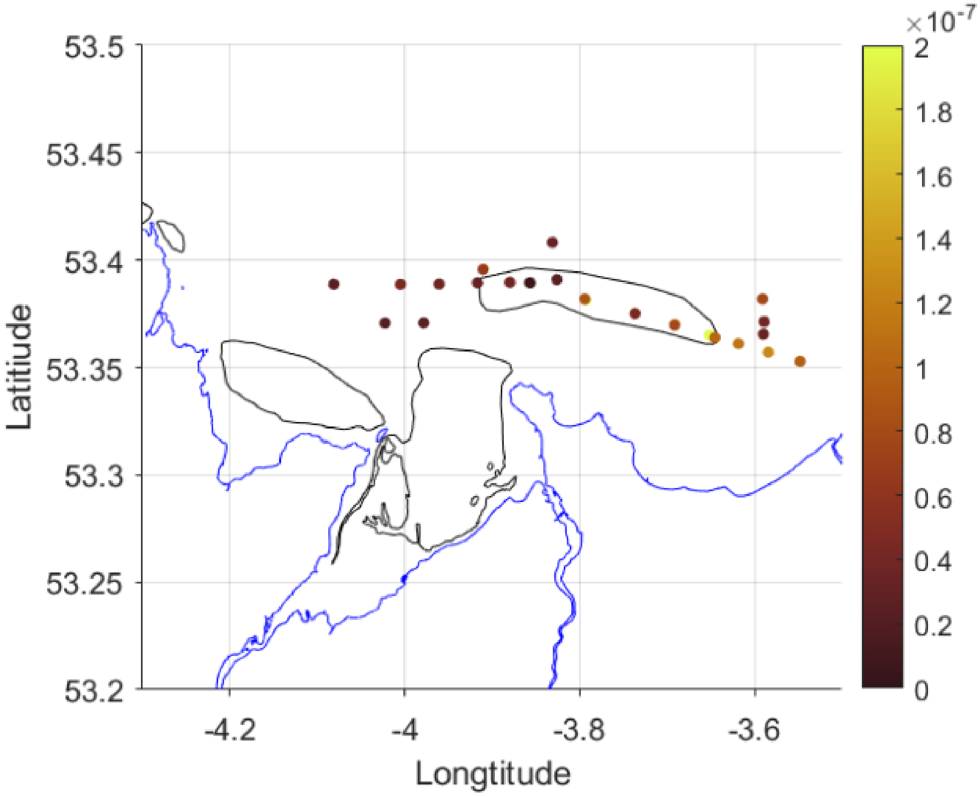

Figure 20. Unit sediment transport rates from the repeat MBES method ($m^2\ s^{-1}$). Black lines denote Annex 1 habitats; blue is the coastline.

The bedforms in the Constable Bank region are predominantly of multiple scales - with larger "host" bedforms (of low and lee sides) host to smaller superimposed bedforms. This type of bedform field presents issues for calculating sediment transport rate via bedform migration, as bedforms migrate (for a constant bed shear stress and grain size) at different rates dependent on their size (Eq. 6). In particular, for "low-angle" host-dunes, the superimposed bedforms will migrate over the stoss slope and not contribute to the migration of the host bedform (Zomer *et al.,* 2021; Cisneros *et al.,* 2020; Cisneros and Best 2024). As such, there are two separate timescales at which the bedforms will migrate, and it is possible for the DEM method to miss the contribution of the superimposed bedforms to the total sediment transport. Figure 22 shows the separation of bedform scales which has been performed here: panel (a) shows the original bedform profile consisting of 1-2 m high bedforms approximately 250 m long, with smaller <1 m high bedforms superimposed on them; panel (b) shows the host bedforms after removal of the smaller bedforms via a robust LOWESS filter; and the removed smaller bedforms are shown in (c). In this case there are nearly 200 smaller superimposed bedforms, typically < 1 m high and 10-15 m long.

With this filtering method, the calculation of sediment transport rate for the available data was split into "large only" bedforms, and "large and secondary" bedforms (Table 8). Where no large bedforms existed, bedforms were treated as "secondary" due to their small size (defined here as <1 m in height and < 100 m long.)

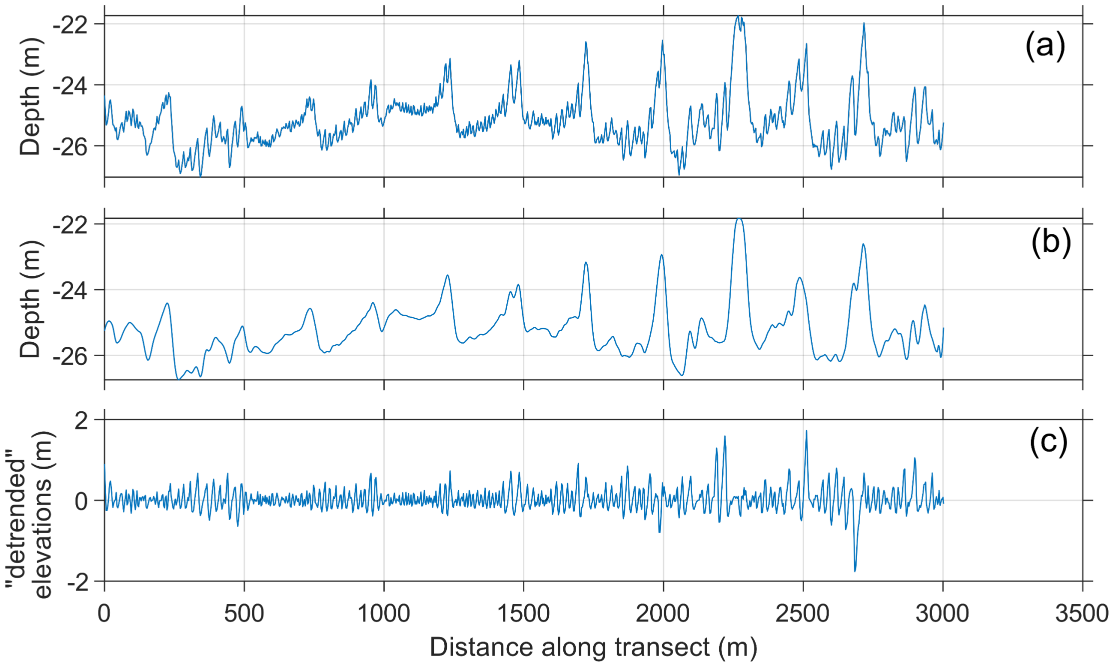

Figure 21. Profiles of bedform scales from the 2017 survey of Constable Bank. (a) The original profile, (b) the profile with smaller bed forms removed, (c) The smaller bedforms.

Table 8. Table of measurements from the Constable Bank region, using the repeat MBES method

Lon (decimal deg.)	Lat (decimal deg,)	No. large bedforms	No. secondary bedforms	width (m)	area (m^2)	dx (secondary only)	dx (large and secondary)	q_s (m^2 s^{-1}) (secondary bedforms only)	q_s (m^2 s^{-1}) (large and secondary)	q_s (m^2 s^{-1}) (model prediction)
-3.58984	53.36560	10	0	320	374,383	N/A	57.8	N/A	3.42E-08	8.89E-08
-3.58900	53.37133	8	0	820	1,063,482	N/A	96.6	N/A	3.92E-08	1.09E-07
-3.59092	53.38192	4	0	1,400	1,826,918	N/A	173.5	N/A	7.68E-08	1.96E-07
-3.91014	53.39580	15	228	150	337,915	9.9	140.8	1.78E-08	2.70E-07	3.11E-07
-3.85712	53.38948	0	182	140	356,691	7.2	N/A	1.34E-08	N/A	4.16E-07
-3.79310	53.38160	9	182	80	210,709	6.3	126.8	1.47E-08	2.98E-07	4.03E-07
-3.73678	53.37525	14	34	65	174,627	22.0	102.2	4.54E-08	2.11E-07	1.74E-07
-3.69103	53.37011	12	36	65	139,087	35.1	87.7	7.84E-08	1.96E-07	1.57E-07
-3.65128	53.36510	10	30	75	173,056	54.9	115.3	1.20E-07	2.53E-07	1.34E-07
-3.61881	53.36114	6	21	75	108,417	45.9	183.5	4.67E-08	1.87E-07	1.08E-07
-3.58432	53.35708	7	24	75	134,013	46.7	213.7	2.78E-08	1.27E-07	1.94E-08
-3.54786	53.35287	15	32	55	109,374	39.0	83.2	4.58E-08	9.76E-08	-3.21E-08
-3.83102	53.40826	0	134	130	766,372	N/A	368.4	N/A	3.15E-08	4.86E-07
-3.82610	53.39091	0	73	120	366,277	N/A	41.8	N/A	2.38E-08	4.97E-07
-3.87985	53.38965	0	72	120	569,667	N/A	48.8	N/A	3.90E-08	3.19E-07
-3.91692	53.38945	0	61	120	533,763	N/A	47.8	N/A	3.22E-08	2.15E-07
-3.96068	53.38883	0	77	120	504,847	N/A	32.5	N/A	3.86E-08	2.56E-07
-4.00509	53.38871	0	82	125	912,077	N/A	51.1	N/A	4.60E-08	2.95E-07
-4.08136	53.38876	0	203	125	1,362,200	N/A	18.1	N/A	2.50E-08	4.48E-07
-3.97859	53.37082	0	121	105	746,051	N/A	14.3	N/A	2.54E-08	1.80E-07
-4.02259	53.37075	0	86	130	530,952	N/A	12.6	N/A	2.30E-08	1.86E-07
-3.91051	53.39571	44	244	325	520,113	56.1	10.1	6.59E-08	1.19E-08	3.11E-07
-3.85669	53.38944	0	249	305	226,013	N/A	5.8	N/A	6.09E-09	4.16E-07
-3.79411	53.38190	14	225	150	97,413	65.4	4.1	8.90E-08	5.54E-09	3.93E-07
-3.73673	53.37508	16	219	102	561,018	29.1	2.1	4.38E-08	3.20E-09	1.74E-07
-3.69134	53.36983	12	175	110	414,893	83.7	5.7	7.91E-08	5.42E-09	1.57E-07
-3.64534	53.36392	9	106	106	391,740	121.0	10.3	1.02E-07	8.65E-09	1.09E-07
-3.58984	53.36560	7	64	120	308,742	118.4	13.0	1.13E-07	1.23E-08	1.08E-07

The comparison between measured and modelled unit sediment transport rates is complicated by the presence of the "secondary scale" bedforms. Whilst the data is within an order of magnitude of the modelled values, the overall trend is poor (Figure 23) when looking at all the data. Isolating measurements to when there was larger scale bedforms shows a much better, if noisy, trend; whilst with measurements of sediment transport rate using only the secondary scale bedforms no trend is present. Recent residual sediment transport rates for the same region were also predicted by Davies *et al.,* (2023), which for Constable Bank were an order of magnitude higher at 1 to 2x10^{-6} (m^2 s^{-1}), as this is a combination of bedload and suspended loads. Taking our model outputs for May (the same month as modelled by Davies et al.), we achieve values of q_s of similar magnitudes when combining bedload and suspended loads 1 - 4.5x10^6 (m^2 s^{-1}), slightly higher perhaps due to the smaller grain size used in our study (275 µm, versus 700 µm in Davies *et al.,* 2023), which was informed by grab samples from Constable Bank. Given the different numerical models used between these two studies, the similarity in q_s is encouraging when assessing model validity. It does also highlight that measuring sediment transport rate via bedform migration will not give an estimate of total (bedload and suspended load) sediment transport, and will instead predominantly represent bedload. This does not exclude the possibility of suspended load being present at bedform locations but that will only be revealed by direct measurement of suspended sediment flux or modelling.

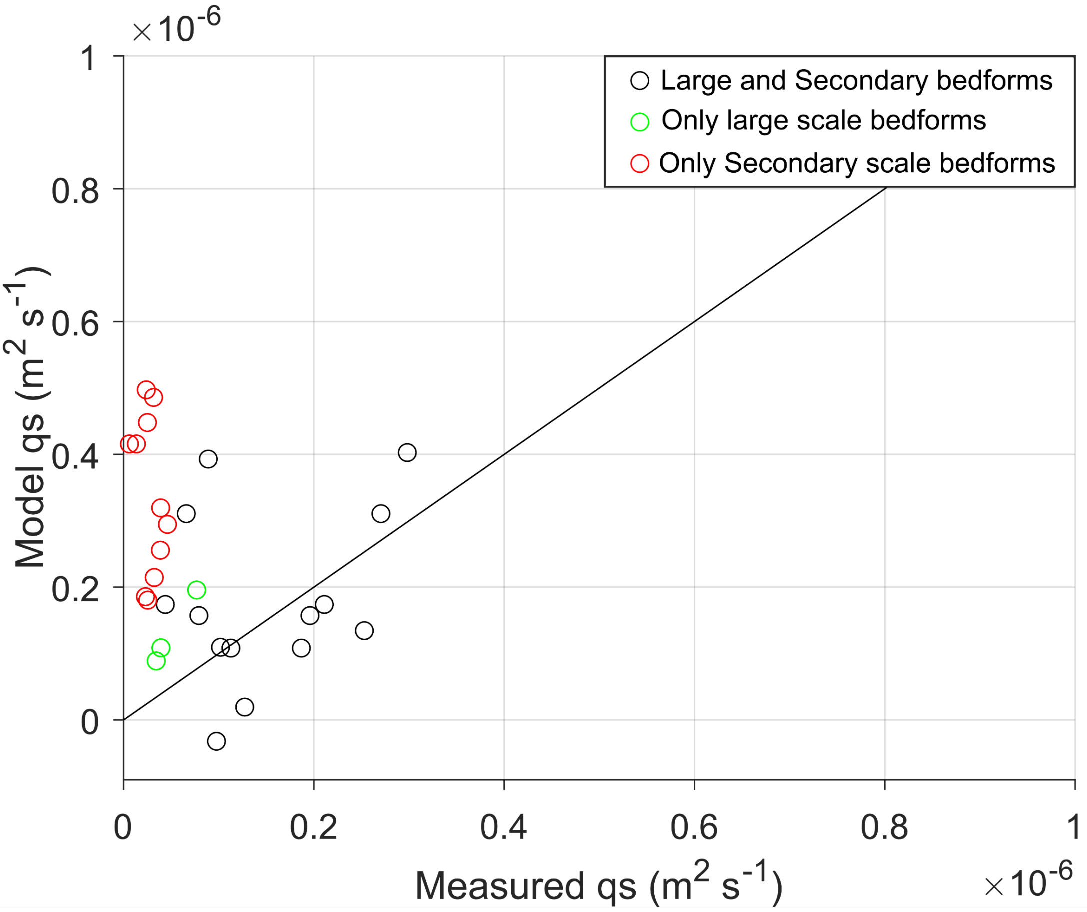

Figure 22. Comparison of measured (MBES timeseries) and modelled (using the SSW-RS results) values for unit sediment transport rate q_s.

The values of unit sediment transport from the modelling done herein is bedload - primarily as bedload is the largest contributor to (subcritical) bedform migration. Following Mohrig and Smith (1996) and Naqshband *et al.,* (2014), 10% of the suspended sediment transport typically also contribute to bedform migration via capture of sediment in the lee face flow separation bubble. Adding this contribution to the bedload sediment transport for the Constable Bank dataset (Figure 23) increases the model q_s by 1.7x to 1.9x, which would further reduce the quality of the comparison with measured values.

Our current understanding is that the presence of smaller bedforms is reducing the unit sediment transport as measured by the repeat bathymetry method (Eq. 8-9), due to the migration of these smaller bedforms being aliased by the time difference between MBES measurements. For an equal unit sediment transport rate, smaller bedforms migrate faster than larger ones (Eq. 7) particularly for low angle dunes (Zomer *et al.,* 2021). An estimate of the timescale for repeat MBES surveys to capture these bedforms, as well as the larger "host" bedforms is given below. Ideally, the time difference should not let the bedforms migrate by more than half of their wavelength for the method of Nittrouer *et al.,* (2008) to be most accurate.

To get an estimate of this timescale, the heights and wavelengths of the bedforms were used with a range of modelled unit sediment transport rates (1 - 6 x10^{-7} m^2 s^{-1}), which produces migration rates between 10 and 400 m per year. Given the wavelength of these smaller super imposed bedforms is typically 10 to 20 m long, this indicates annual (or larger) gaps between surveys will be missing this fraction of sediment transport. Given a daily range of values between 0.1 and 1.6 m of migration, a 5-10-day window (during springs) would be required to capture the sediment transport due to superimposed bedform migration.

3.2.2 Implications for estimating the mobility of bedforms around Constable Bank

The range of bedforms scales in this environment places constraints on scheduling of repeat MBES surveys needed to adequately measure the sediment transport rate, and bed response to disturbances. The relatively small scale of the super-imposed bedforms places temporal and resolution constraints on adequate measurement (Table 9). Spatial resolution of at least 0.5 m^2 is necessary to resolve these features and repeats on a timescale of twice a week over spring tides would be needed to be able to track bedforms of this scale. However, the migration of the larger scale bedforms (100 – 400 m long) should be possible with annual measurements. The larger bedforms are a type of low angle bedform (lee sides < 30 degrees), so the superimposed bedforms migrate over the lee sides – rather than become captured by the host bedform and contribute to the migration of the host bedform (Zomer *et al.,* 2021; Cisneros and Best, 2024). As such the migration of these larger bedforms will not capture the total (bedload) sediment transport rate.

Table 9 Estimated bedform migration timescales using bedform heights and estimated annual residual unit sediment transport rates

Modelled q_s (m^2 s^{-1})	Bedform height (m) 0.1	Bedform height (m) 0.5
0.0000001	97.0 m per year	19.4 m per year
0.0000006	582.2 m per year	116.4 m per year
0.0000001	0.3 m per day	0.1 m per day
0.0000006	1.6 m per day	0.3 m per day

4. Conclusions

Modelled bedload transport rates have been calculated from a freely available shelf-scale oceanographic model. When used with information concerning bedform dimensions from MBES surveys, it is possible to estimate sand wave migration rates with some confidence. However, the sandbanks are poorly resolved in the model grid and bathymetry which leads to innacuracies. Therefore, the main usefulness of this method and process (at present) is to create a guide for the frequency of bathymetric surveys which are used for directly measuring sand wave migration rates; particularly when there is little to no prior information of the mobility of the sand waves. If higher spatial resolution and well validated models were available, it is likely rates could be estimated with greater confidence.

The frequency of bathymetric surveys should be less than the time taken for a sand wave to migrate half its wavelength for most accurate results. This timescale can be estimated if sediment transport rates and bedform heights and lengths are known.

Caution should be taken when dealing with multiple scales of bedforms (0.1 m to >100 m in wavelength), as smaller bedforms migrate substantially faster than their larger bedforms. If there are smaller bedforms superimposed on larger “host” bedforms, then how these scales interact will affect how representative the estimated sediment transport rate derived from bedform tracking is. If the angle of repose of the host bedform is > 30 degrees, then any smaller superimposed bedforms should actively contribute to the migration of the host bedform via avalanching along the lee face. As such, measurement of the host should give a measurement of the total sediment transport due to bedform migration. For low angle host bedforms (typically with lee face angles < 20 degrees), it has recently been found that the smaller, superimposed, bedforms will migrate over their host and not contribute to its migration (bypass migration). It is yet unclear how the two scales of bedforms interact in this situation. In this case, higher frequency and higher spatial resolution measurements will be needed to capture the sediment transport rate due to these smaller bedforms, as they represent a separate migration flux to the larger host bedforms.

5. Acknowledgements

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Appendices

Data Archive Appendix

No data outputs were produced as part of this project. The project was a knowledge exchange project making use of existing data.

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