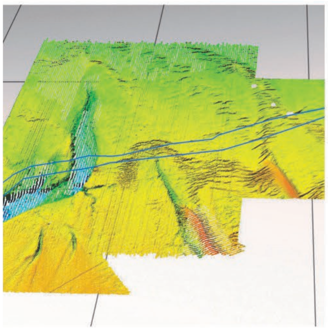
YGC

Traeth Crugan

Beach renourishment and monitoring strategy

June 2024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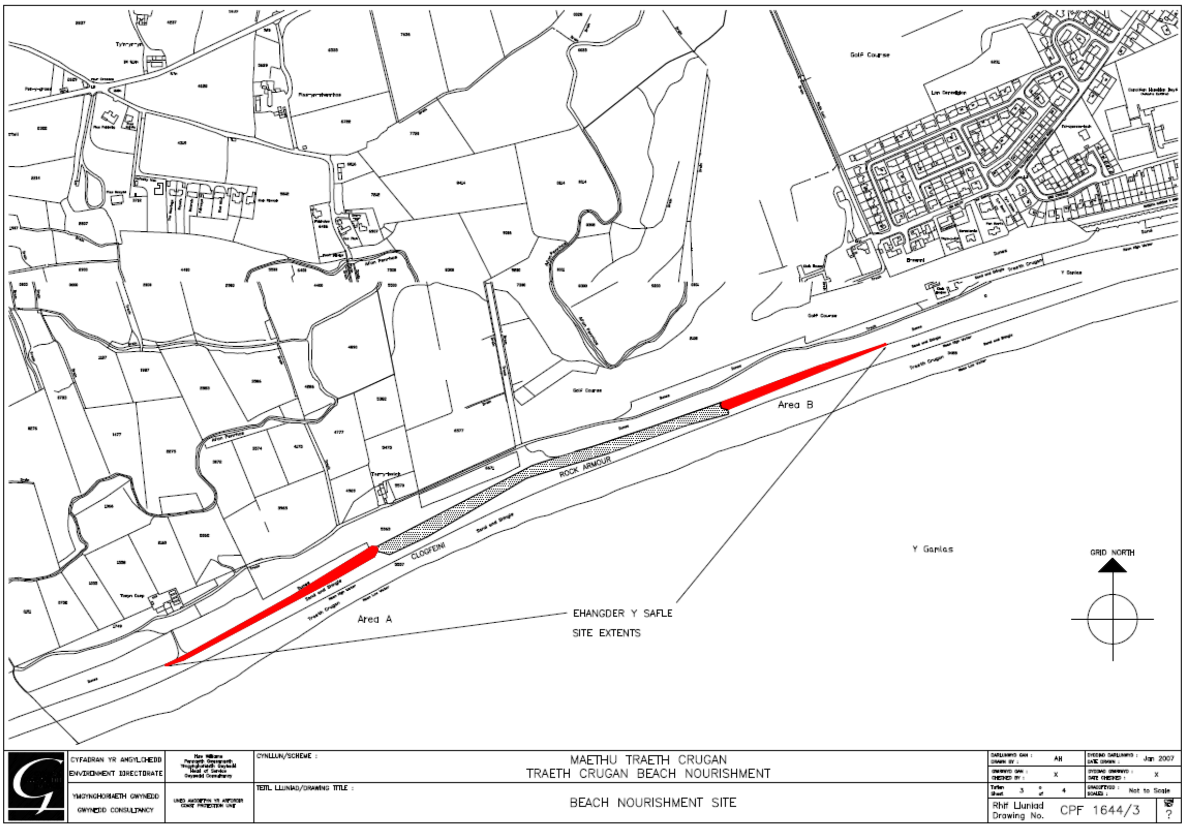
1 Introduction

1.1 Project requirements

ABPmer has been commissioned by Ymgynghoriaeth Gwynedd Consultancy (YGC), part of Cyngor Gwynedd Council (CGC), to support it in the optimisation of its cyclical beach nourishment operations at Traeth Crugan, Pwllheli. To date the beach nourishment has been completed on an *ad hoc* basis and YGC would like to move to a more pro-active management regime.

This work is required to implement the ongoing beach nourishment operations as set out in the Business Justification Case (YGC, 2022). The Business Justification Case (BJC) investigated the options to implement the conclusions of the Outline Business Case set out in 2017, namely "whilst the long-term strategy for the West catchment at Pwllheli is to implement the Managed Realignment in 2055, it also makes clear that the short-term option (Business as Usual), of nourishing the beach and dune system at Traeth Crugan, is critical".

To date, the beach nourishment has been completed every four or five years in both areas to the West and East of the revetment, as shown in Figure 1 (these West and East areas are labelled Area A and B respectively in the figure). YGC would like to move to a more pro-active management regime. This would be beneficial in terms of risk management and identify if there are opportunities to sell excess material.



Source: Faber Maunsell Aecom, (2008) : YGC Drawing n CPF1644/3

Figure 1. Beach Nourishing Sites

This project comprises of a desk-based coastal processes study and provides recommendations for the setting of trigger levels and for future monitoring of the beach at Traeth Crugan. The study utilises the significant amount of available monitoring data at the site to help examine past changes. This document, reports the key finding from the assessment, including a conceptual model of the coast, with supporting studies/analysis provided in the appendices.

1.2 Site description

The study area comprises of the renourishment area either side of the central revetment along the Traeth Crugan frontage. This frontage is located South West of Pwllheli harbour and it is characterised by a barrier beach which extends from the rock out crops at Carreg y Dafrid to the West, through to Carreg y Imbill at the Eastern end of the wider frontage (Figure 2). This barrier beach lies in front of the low-lying hinterland associated with the Afon Rhyd-hir catchment. To the West of the wider frontage, lies Llanbedorg Bay, which is backed by high ground. At the shoreline, the dune frontage has reduced to a single dune ridge that has been progressively defended by sections of rock revetment since the 1970’s.

The revetment (~650 m in length) that lies along the central section of the study frontage fronts the Pwllheli Golf Course. A second revetment (~950 m in length) lies along the Western end of the wider frontage; however, this lies outside the area of interest. Between these two areas of revetment the natural shoreline is aligned seaward of the embayment’s general curvature, which is likely to be a result of the variations and shoals in the foreshore bathymetry (the most prominent ones can be observed in the satellite imagery in Figure 2). These defences,, which protects against breach of the dunes and flooding into the Penrhos valley, also protects some isolated properties immediately at the back of the dune ridge; this includes the grade II listed Tan-y-bwlch cottage. During consultation for the SMP2 (Haskoning UK Ltd. 2011), the concern was expressed by the Penrhos community that a breach to these dunes would result in flooding to the main road where it crosses the Penrhos valley.

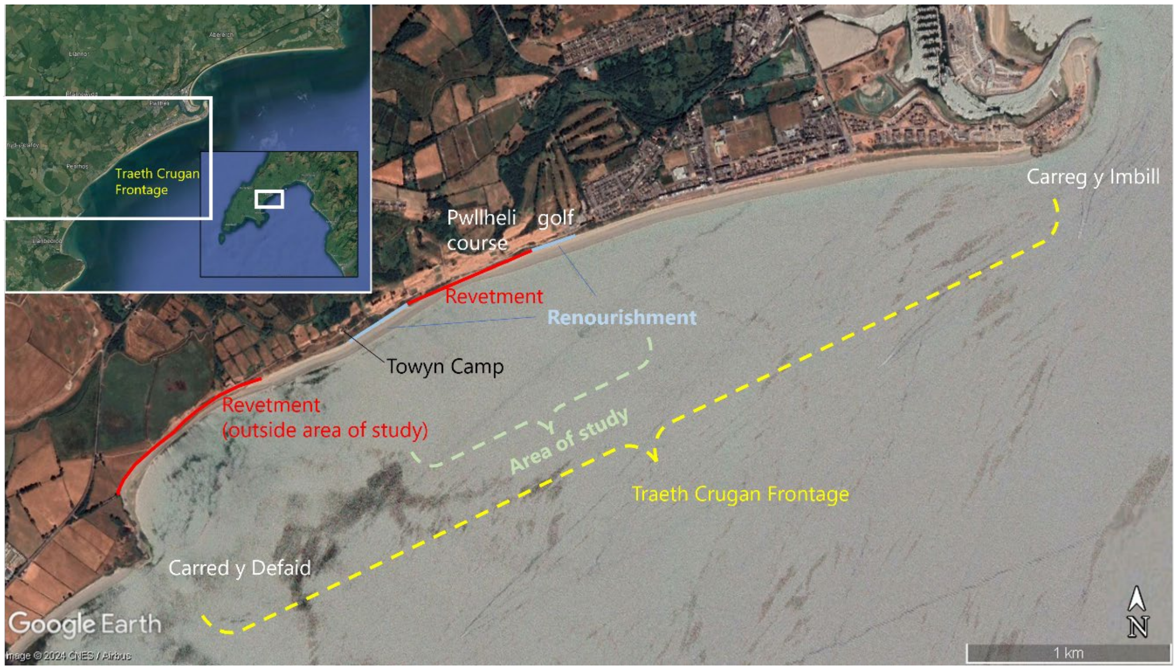


Figure 2. Location plan, showing extent of the frontage of Traeth Crugan, the revetment and the renourishment areas

The renourishment covers two areas: the main area, to the South West (SW) of the central revetment, of about 350 m in length, and the secondary area, to the North East (NE) of the central revetment, of more or less the same length. The renourishment is carried out with the sediment dredged from Pwllheli harbour, which is stored at Careg y Imbill stockpile, until required.

The topography of the study area, compiled from Welsh Government 2020-2022 LiDAR dataset (https://datamap.gov.wales), is presented in Figure 3. The figure clearly identifies the low-level hinterland associated with the Afon Rhyd-hir and Afon Erch catchments, which lies behind the barrier beaches along the Traeth Crugan.

Along the central section of Traeth Crugan, there are approximately 680 m of dune frontage, protected with rock armour. Generally, the crest level of the dunes is between 7 and 8 mODN but locally levels can be 0.5 m above and below this typical range. The dune width varies in the unprotected sections typically between 30 and 70 m with the narrowest widths occurring immediately to the West of the central revetment, and at the western end of wider frontage, where the dune finishes. Over the final 150 m of dune at the Western end the dune width is locally 10 m. Apart from the section where the dune has been protected by rock armour the dune/beach interface is located at a level of between 4.0 and 4.5 m ODN (1.5-2.0 m above MHWS level).

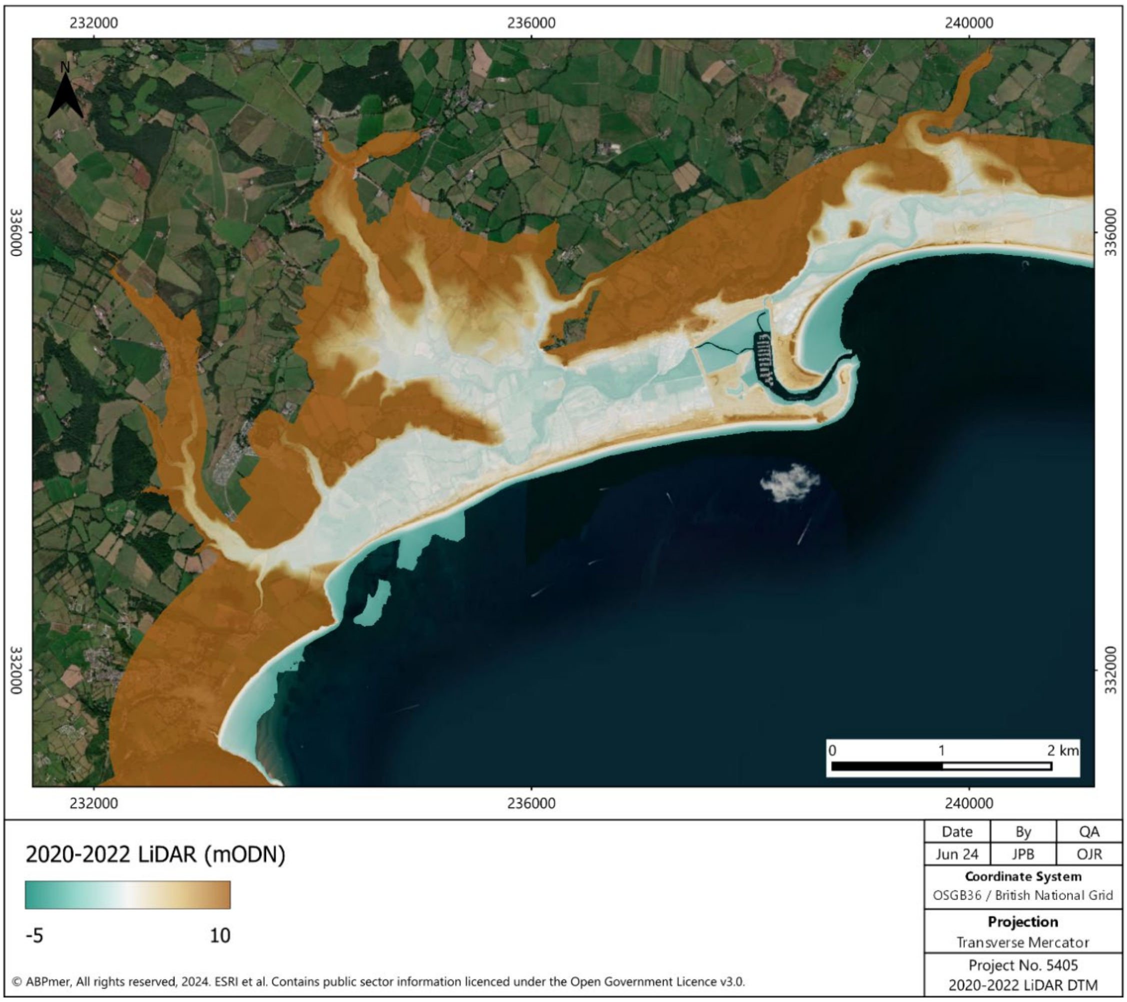


Figure 3. Topography of the study area

2 Background Information

2.1 Flood and coastal erosion risk

Faber Maunsell Aecom (2008) describes the hinterland along Traeth Crugan as reclaimed from the fluvial/coastal environment so that the majority is located below the level of the predicted highest tide. Flooding of this area is linked through pathways to low lying developed areas of Pwllheli Town, most of which is situated below the 5 m Ordnance Datum contour. The present-day flood risk map (Figure A1) show the key areas of flood risk. With sea level rise expected to increase by *circa* 1 m (see section 3.2.1), flood risk will increase in the future as shown in NRW's Flood Map for Planning[1], reproduced as Figure A2. It is not so much the overall extent of the flood risk area that changes with sea level rise but rather the depth and frequency of flood risk in the area. The SMP2 (Haskoning UK Ltd. 2011) also identifies tidal locking of the valley as a significant issue, with the slight increase in sea level making this potentially critical. Figure A3 shows the recorded flood events from NRW Coastal and Flood Erosion Risk Map.

The coastal erosion risk along the frontage has been assessed as part of the Shoreline Management Planning process and is available on the Natural Resources Wales (NRW) website[2] and shown in Figure A4 (Figure A1 to Figure A4 are provided as Appendix A).

The Shoreline Management Plan (SMP) was updated in 2011, hereon referred to as SMP2, (Haskoning UK Ltd. 2011), providing a timeline for objectives, policy and management change. The documents for the West of Wales SMP2 are available through the West of Wales Coastal Group website[3]. The SMP2 describes the whole area as very important for coastal tourism with significant holiday villages, important water sports centres and golf courses at Pwllheli and Abersoch.

For the Traeth Crugan beach the estimated No Active Intervention erosion rate is 0.3 m/yr, noting that there is a "Eroding ridge held forward by defences potential breach". The 100 yr erosion range is of the order of 60-90 m (a factor of 1.7 to 2.5 times the existing base erosion) (SMP2, Haskoning UK Ltd. 2011).

2.2 Management policy

The study frontage lies within Policy Development Zone 13 The South Llyn Bays, Management Area 31, Policy Unit 12.20 (Pen y chain to Trwyn Cilan). The Policy Units for the area are shown in Figure 4, together with their policy (DataMapWales, 2024a), Table 1.

The policy for PU 13.7 Golf Course is to Hold The Line until 2025 and the long-term policy is for Managed Realignment (Haskoning UK Ltd. 2011) states that "The Afon Penrhos flows through the town behind the shoreline frontage of Traeth Crugan. Continued defence of this frontage with a linear rock revetment is viewed as being non-sustainable and the intent would be to allow the set back of the dunes and shoreline ridge to allow the Penrhos to flow directly to the sea. This provides the opportunity to manage the whole length in front of the golf course through to South beach more sustainably. The Pwllheli Pilot is also considering ideas for diverting flow from the other main river through Pwllheli (the Afon Rhydhir) and this may reinforce the potentially beneficial impact at the coast. There would then be the need to provide a setback flood defence potentially landscaped within the area of the golf course. The flood

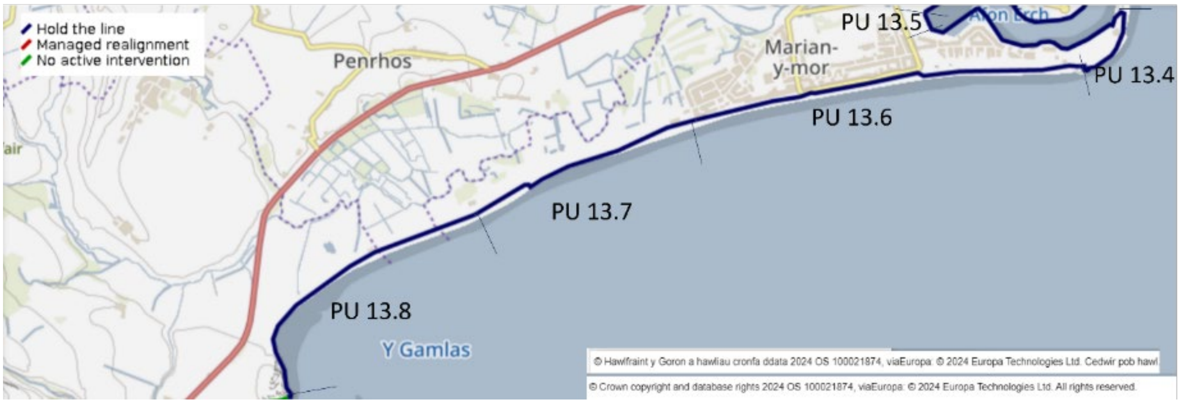
[1] The Flood Map for Planning has no official status until the Welsh Government implements its revised Technical Advice Note on Development, Flooding and Coastal Erosion (TAN15)
[2] https://flood-risk-maps.naturalresources.wales/
[3] https://www.grwparfordirolgorllewincymru.cymru/

issues to the main road would need to be addressed. The coast further to the West, along the Llanbedrog frontage would be allowed to evolve naturally." (SMP2 (Haskoning UK Ltd. 2011)[4]).

Table 1. Shoreline Management Plan Policies

Policy Unit	Location	2025	2055	2105
PU13.4	Pwllheli Harbour and entrance	Hold the line	Hold the line	Hold the line
PU13.5	Pwllheli centre	Hold the line	Hold the line	Hold the line
PU 13.6	South Beach	Hold the line	Hold the line	Hold the line
PU13.7	**Golf Course**	**Hold the line**	**Managed Realignment**	**Managed Realignment**
PU13.8	Traeth Crugan	No active intervention	Managed Realignment	Managed Realignment

Source: SMP2 (https://www.grwparfordirolgorllewincymru.cymru/page/smp2/main-document)



Source: https://datamap.gov.wales/maps/new?layer=geonode:nrw_shoreline_management_plan_policies#/

Figure 4. Shoreline Management Plan Policies

2.3 Nature conservation designations

The frontage is important for nature conservation and its habitats are protected under national and international nature conservation legislation. The nature conservation designations related to the study area are presented in Figure B1 (DataMapWales, 2024a) with associated mapped Article 17 habitats shown in Figure B2 (DataMapWales, 2024b). Figure B1 to Figure B2 are provided as Appendix B.

The designations are listed below and include the beach and intertidal area:

- Site of Special Scientific Interest (SSSI) sites:
  - Mynydd Tir y Cwmwd a'r Glannau at Garreg yr Imbill (located along Traeth Crugan frontage)
  - Morfa Abererch (located along and directly behind Abererch frontage)
  - Glanllynnau a Glannau Pen-y-chain i Gricieth: (located to East of study frontage)
- Special Protection Area (SPA) area: North Cardigan Bay (located to south-East of study area)
- Special Area of Conservation (SAC) area: Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau (located across study area)
- Local Nature Reserve (LNR) site: Lon Cob Bach (located towards back of Pwllheli harbour)

4 https://www.grwparfordirolgorllewincymru.cymru/page/smp2/main-document

3 Coastal Process Overview

3.1 Wave climate

Numerical wave modelling has been completed to provide an understanding of the nearshore wave climate. Details of the wave modelling are provided in Appendix C. Figure C4 shows offshore wave and wind roses at a point along the model boundary to St George's Channel. Offshore, outer limit of Cardigan Bay, the dominant wave direction is from the south-west (around 70% of the time), typically with significant wave heights <1.5 m (Figure C4). However, as these waves are transformed inshore they are refracted toward the coast (Figure 5). This figure shows a 1 in 1 year wave condition from SW propagating into the area of interest.

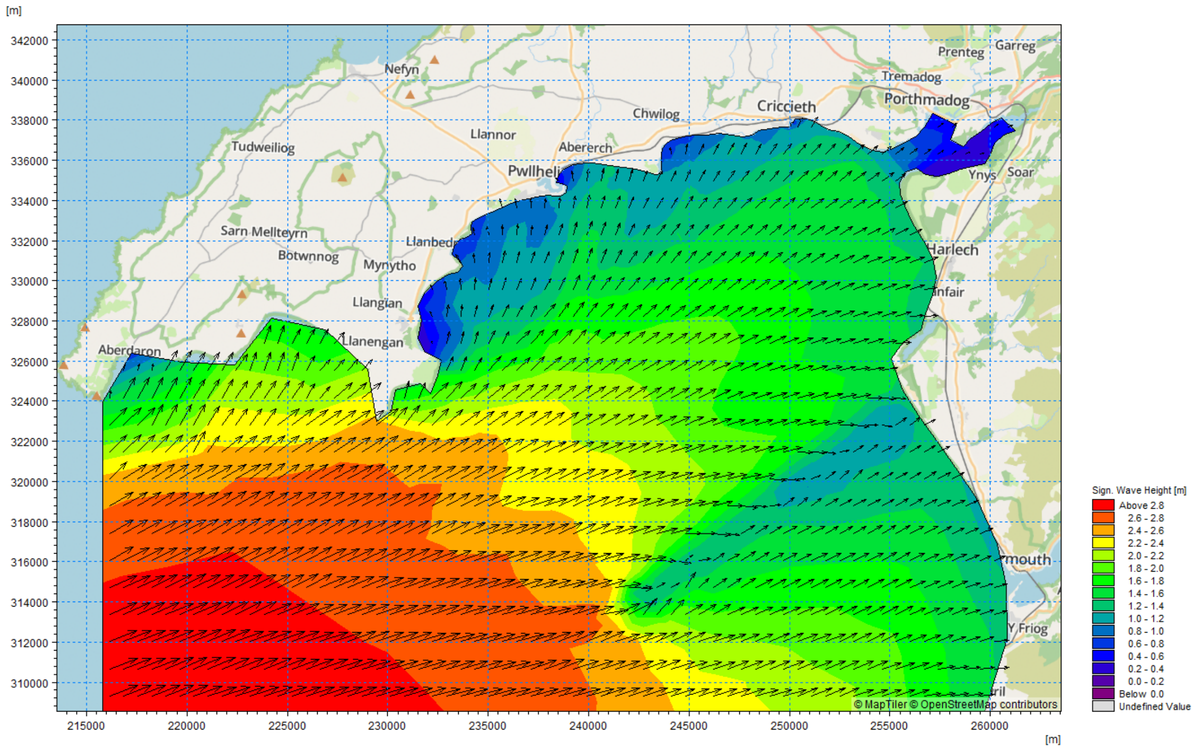


Figure 5. **Map plots of 1 in 1 year wave condition from SW**

Long-term wave condition timeseries have been extracted as wave modelling outputs at the -5 m CD (~-7.2 m ODN) contour offshore of this coast and are presented as wave roses and scatter tables in Appendix C. An example wave rose is also presented in Figure 6, for the point of the central part of the frontage. This shows wave conditions arriving from the S to SSW, with maximum annual wave heights of around 2 m. These waves are still quite oblique to the frontage; however, it is important to note, that due to the very shallow foreshore, the extraction locations are still located a considerable distance offshore and further wave refraction will occur as the wave propagate further inshore. Thus, by the time the waves reach the coast they will be significantly less oblique.

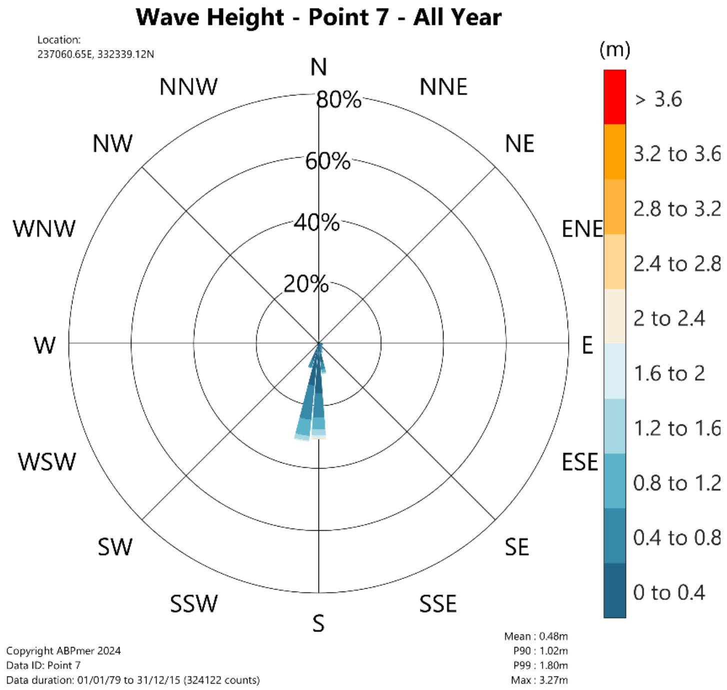


Figure 6. **Wave rose (annual) for Point 7**

3.2 Tidal regime

3.2.1 Tide and extreme water levels

Predicted tide levels for Pwllheli are presented in Table 2 (which have been taken from Admiralty Total Tide data (2024) based on local corrections from the Standard Port at Milford Haven. The conversion from mCD to mODN is -2.44. Tides are diurnal with approximately two tides a day, the neap tide range being of 1.7 m and the spring tide range of 4.5 m.

Estimated, present day extreme water levels from Coastal Flood Boundaries Dataset (CFBD) 2018 are presented in Table 2 (Environment Agency, 2019) for a point (Chainage 872) offshore the frontage.

Table 2. **Predicted present day tidal levels and extreme levels at Pwllheli**

Predicted Tidal levels Source: Admiralty Total Tide data (2024)		
Level	Tide Levels (mCD)	Tide Level (mODN)
MHWS	5.1	2.66
MHWN	3.6	1.16
MSL	2.76	0.32
MLWN	1.9	-0.54
MLWS	0.6	-1.84

Predicted Extreme Water Levels Source: CFBD (Environment Agency, 2019)	
Return Period	Level (mODN)
HAT	3.36
t1:	3.41
t50:	3.94
t100:	4.03
t200:	4.14

Source: Left: Admiralty Total Tide data, 2024; Right: CFBD, Environment Agency, 2019

3.2.2 Climate change and sea level rise

The principal consequence of climate change that will affect flooding, coastal erosion and the sediment transport regime over the study frontage is SLR. From Welsh Government Guidance (Welsh Government 2022), the 70th and 95th percentile indicative SLR allowances for Gwynedd are 0.76 m and 1.03 m, respectively for a horizon of 2100 (and 1.0 m and 1.37 m, respectively for a horizon of 2120). It is also identified that rainfall, wind and wave conditions may also increase, however, there is more uncertainly around this, and any such changes are expected to be minor compared to the changes that will result from SLR.

With a 0.76 m or 1.03 m rise in water level, the waves reaching the shoreline will be significantly greater. This together with the higher water levels will lead to greater erosional and overtopping pressures on the exiting barrier beaches and defences along the frontage. The location at which sediment transport occurs across the shore platform will also change with SLR, as wave breaking, and generation of wave induced currents will now move further up the shoreface. In addition, as the wave will be afforded less refraction by the offshore bed (which will effectively be deeper), there could also be a slight adjustment in the direction of the incident waves as they reach the coast. This could also affect longshore drift rates and transport mechanisms in the nearshore.

3.2.3 Tidal prism and hydraulic geometry

The present-day tidal prism of Pwllheli Harbour is relatively small and is restricted by the tidal lock gates on the Afon Rhyd-hir and Afon Erch. These lock gates, together with the present-day barrier beaches, prevent coastal flooding of the lower sections of the two river catchments. In the absence of the lock gates or through failure or breach of the barrier beaches, the tidal prism associated with the two catchments would be significantly greater. The tidal prism associated to these two catchments would also increase further with SLR.

3.2.4 Tidal currents

Tidal flows have been extracted from a previously developed ABPmer model of Cardigan Bay which has been calibrated against water levels at Pwllheli and Criccieth, as well as Tidal Diamond SN049D, which is located offshore of Pwllheli.

Figure D1 and Figure D2 show the flows through Tremadog Bay, at four states of the tide; Low Water (LW), Mid Flood (MF), High Water (HW), and Mid Ebb (ME) during a large spring tide in March 2007. The results are for the largest tidal range typically experienced in a year and illustrates a potential annual maximum tidal flow regime; lower tidal flow speeds will be experienced over a typical tide. These flows could also be enhanced due to meteorological and wave forcing.

The figures show that the tidal flows through Tremadog bay are generally strongest at MF and ME, with flows aligned in Southwest > Northeast and Northeast > Southwest direction respectively. Peak speeds, in the deeper water off the frontage are typically less than 0.3 m/s. During, these periods the peak flow inshore is much lower (typically less than 0.1 m/s) and direction of the flow is influenced by the headland and shallow offshore shoals. Whilst not resolved in the model, flows would also be influenced by the flow of water in and out of Pwllheli harbour.

At low water, tidal flows throughout Tremadog Bay are generally low (<0.1 m/s), although a weak flow of around 0.15 m/s is predicted just offshore of the frontage in a SW-NE direction. At this tidal state the flow will be occurring over the lower foreshore as the tidal level is low.

At high tide with the water level not covering the upper foreshore, a NE-SW flow is predicted close inshore with elevated flows, along the rocky headland, where tidal flows of over 0.3 m/s are predicted.

It is emphasised that the plots shown in Figure D1 and Figure D2 are for a very large tidal range (largest tidal range typically experienced in a year) and flows for smaller tides will be less. The flows are also relatively weak and will be strongly influenced by wind driven circulation and wave breaking. The latter will strongly influence the nearshore flow regime during period of significant wave energy.

3.3 Sedimentation regime

The SMP2 (Haskoning UK Ltd. 2011) describes the foreshore of this frontage comprises areas of exposed boulder clay and with several raised sections of harder glacial boulders. The natural shoreline across the frontage comprises a sandy beach, which has over time become more mixed in composition with coarser gravel (Faber Maunsell Aecom, 2008), backed by natural sand dunes formed from wind transported sand from the foreshore.

Along the beach there are four primary factors influencing shoreline behaviour: longshore drift, cross-shore transport, dune erosion/accretion and coastal protection works (revetment). The latter influences both longshore drift and the cross-shore transport. These mechanisms are examined below.

3.3.1 Longshore drift

The transport, or drift, of beach material along a coastline, caused principally by the action of waves and tidal currents, is the major factor in the long-term development of beaches and it is called longshore transport. Significant volumes of beach material will only be moved along the shore if there is a steady or quasi-steady current to carry it, running parallel to the beach contours. In this frontage, the main cause for these currents are the waves which break at an angle to the beach contours and in some places, to a lesser extent the variations in breaking wave heights along the beach due for example to local shoals.

Net Sediment transport rates and budgets were presented in past studies, ranging from 1,000 m^3/yr (Posford Duvivier (1996)) to 10,000 m^3/yr (Faber Maunsell Aecom (2008)) to the East, depending on location and study. Haskoning UK Ltd., 2011 indicated that the modelling of sediment drift along the frontage is very sensitive to even slight variation in the overall wave climate, so that a shift in net wave energy of as little as 5 degrees can change predictions of drift from that of no drift to rates in excess of 30,000 m^3/yr.

The predicted rates presented in these studies are vary variable, and do not identify where this transport is occurring across the shoreface. In most of the assessments undertaken to estimate these sediment transport, the complex two-dimensional (2D) nature of the shoreline (presence of headland and offshore shoals) is not included and there is limited consideration as to how tidal level and flows effect these rates. Furthermore, only net transport rates are presented without details on likely gross transport rates.

3.3.2 Cross-shore transport

As waves move onshore they are modified by a number of processes such as shoaling and refraction. There is a consequent spatial variation in the fluid motions at the bed. This is reflected in changes in the mode, magnitude and direction of sediment transport, so that different regions within the nearshore can be identified in terms of the hydrodynamics. The sediment processes in these regions result in changes in beach profiles in response to wave conditions. For example, the creation of different "summer" and "winter" profiles in response to changing wave heights and periods during a year. The beach profile will then have a feedback role in modifying the subsequent shoaling waves. Cross-shore transport occurs at smaller time scales, so that the beach profile changes, sometimes, dramatically, as a result to a single severe storm. Beach profile changes during milder conditions are slower and will allow the beach to recover many times to its original profile, the beach profile changes showing seasonal variations. These changes will normally occur within the depth of closure, calculated as about 5-7 m below MSL[5].

3.3.3 Dune erosion and accretion

Dunes are prone to erosion under two circumstances: when there are storms, so that the erosion is mainly caused by waves as the high tide mark reaches the toe of the dunes, and when there are strong onshore winds (SNH, 2000) by deflation or erosion of the dry sand surface of the dunes (dry sand). At Traeth Crugan, the erosion of the nourished material at the backshore is mainly caused by waves rather than by wind. The vegetation of the dunes increases the resistance of the sand to the aeolian forces, but uncontrolled human access to suns can destroy vegetation and make dune erosion worse. Conversely, material can be blown into the dunes from the beach, causing the replenishment of the dunes, but this is more relevant for dunes composed of finer sediment.

3.3.4 Coastal protection works (revetments)

The impact of the rock revetments is two-folded: effect on the hydrodynamic regime and effect on sediment transport processes. Rock revetments will affect the waves and wave induced current in their vicinity, which also effects sediment transport. Revetments typically follow the existing orientation of the coastline, however, erosion at the end of a revetment can lead to the revetment being aligned seaward of the adjacent coastline.

The revetment results in the dissipation of wave energy whilst protecting the sediment / coastline in its lee. The rock revetment also absorbs wave energy through the voids between the rock. Wave reflection is therefore relatively minimal (compared to other coastal defences) which helps to reduce the potential for local scour and nearshore lowering. Most effects to the hydrodynamic and sediment regime are therefore be confined to the footprint of the revetment works, so they are unlikely impacting on the existing wider hydrodynamic regime with the effects predominantly confined to the immediate area of interaction with the revetment. The rock revetment, therefore, has a minimal influence on the longshore drift, providing the revetment remains aligned with the coast. If the adjacent coastline erodes significantly, then the revetment can effectively become a headland/breakwater feature and the effect on transport rates become more complex. However, this is not the case at Traeth Crugan.

3.4 Conceptual understanding

As described above, the sediment transport processes along this section of frontage are complex. The Coastal Process Conceptual Understanding (ABPmer, 2022) contains detailed understanding of the Traeth Crugan frontage, their conceptual understanding visualised in Figure 7 (reproduced from ABPmer, 2022).

This report also includes the reasons why there is conflicting information in previous conceptual understandings around the area of Traeth Crugan (Faber Maunsell Aecom, 2008, Pwllheli Geomorphology Baseline (Halcrow, 2011) and SMP2 (Haskoning UK Ltd. 2011)):

[5] From the nearshore wave results at Point 7 we have calculated the depth of closure according to Hallermeier, 1981, using Hs 12=2.3 m and T=6 s. This gives a Dc= 4.22 m relative to low water. Depending on which value of low water you use (MLWN, MLWS or LAT) this yields a value of the depth of closure of 5 m to 7 m relative to MSL.

- The previous assessments differ in their view of drift convergence and drift divergence along the Traeth Crugan frontage. The concept of drift convergence and divergence along the frontages should be treated with caution, whilst it is noted that under certain wave conditions these will occur, the shoreline is generally fixed by headlands, the bed features along the shoreline, and the prevailing wave conditions.
- Along the section with no revetment towards the western end of the Traeth Crugan frontage, where the shoreline protrudes seawards of the general bay shape, the sediment budget figure in Halcrow (2011), identifies erosion, but in the conceptual understanding plot within the same report reports accretion. Here, the shoreline protrudes seaward due to the offshore shoals, however either side of this there has been erosional pressures. From more recent imagery the central, without revetment, section also appears to have been afforded some erosion. The shoreline alignment in this location may be variable, subject to changes in offshore bathymetry.

Source: ABPmer 2022 R.4115

Figure 7. Conceptual understanding of sediment transport

4 Past Nourishment and Monitoring

The defences in the area consist of a revetment and a cyclical renourishment with sediment from the harbour. Historical information on the past nourishment campaigns and monitoring is given below. Historical dredging operations are given in Appendix E.

4.1 Past nourishment campaigns

The first beach nourishment exercise was undertaken in 2002 by Gwynedd Council, where approximately 70,000 tonnes (35,000 m^3) of dredged material was recycled and placed on the upper beach at Traeth Crugan. Subsequent nourishment operations then followed approximately every four to five years. The preferred window for carrying out the beach nourishment exercise is February to June (DHRD, 2011).

The list of renourishments since 2002 has been provided in Table 3.

Table 3. Beach nourishment volumes and dates for Traeth Crugan nourishment operations, as provided by YGC

Campaign	Year	Beach Nourishment Volumes	Date of Nourishment
Campaign 1	**2002**	Approximately 70,000 tonnes	
Campaign 2	**2007**	Approximately 70,000 tonnes	February/March 2007
Campaign 3	**2012**	Approximately 60,000 tonnes	March 2012
Campaign 4	**2016**	Approximately 65,000 tonnes	Spring 2016
Campaign 5	**2020**	Approximately 80,000 tonnes	Spring 2020

The deposition site for the nourishment since 2007, is shown in Figure 1, with nourishment occurring in two main areas:

- Western area (cited in figure as Area A): to the West of the revetment, which extends from the Western end of the revetment for about 335 m. This is the main area where the sediment is deposited.
- Eastern area (cited in figure as Area B): to the East of the revetment, which extends from the Eastern side of the revetment for about 335 m to the East. This area is secondary and does not always receive sediments or in such a large quantity as the Western renourishment area.

There are no records of the split of material between both sites for each of the renourishment campaigns.

According to client representatives, the renourishment is placed with a crest level approx. 3.5 m above beach level (in line with height of existing dunes) and approximately 5-10 m wide. The material is compacted when placed with a shoreface angle of 1:2, the toe of the nourishment being on the line where the gravel starts on the beach, see Appendix F. The shoreface of the renourishment soon becomes nearly vertical after some months of wave action, see photos in Appendix F. Storm events have a significant impact on beach morphology with YGC noting that about half of the nourishment will have been lost after the first few months.

It was noted during the site visit (Appendix F) that the renourishment material does not have any vegetation and YGC commented that the vegetation rarely grows on the renourishment material.

4.2 Past monitoring campaigns

There are two primary sources of monitoring data for Traeth Crugan: YGC and the Wales Coastal Monitoring Centre[6] (WCMC):

- Historically, YGC undertook regular beach monitoring, as outlined below:
  - Elevations along three profiles named 69, 70 and 71 (Figure 8), twice a year in the autumn and spring, from 1996 to 2019 (2002 only for Profile 71). These covered from the backshore to MLWS.
  - From 2002 to 2019, point topographic data covering a section of the dry beach at low water. The horizontal resolution of the data improved over the years from about 8 to 15 m in 2002 to about 5 m in 2019. The typical coverage of these surveys is shown in Figure 9.
  - Sediment samples at profiles 69, 70 and 71 in at four different locations across the beach (HAT, MHWS, MHWN and MSL) in June 1997 and September 2003. These have been summarised in Appendix G.
- From 2020, WCMC have undertaken and generated beach profile surveys from LiDAR, this includes (these profiles data are of secondary importance to main assessment and therefore profile location are provided in Appendix H, rather than main report):
  - Elevations along a combination of 13 profiles between 2020 and 2024 (not all profiles are surveyed at each date). These covered from the backshore to MLWS. Profile locations and dates are show in Figure H3, Figure H4 and Figure H5
  - Profiles derived from LiDAR survey shown in Figure H6 (in 2022 and 2023)

In addition, LiDAR data has also been obtained for the site for 04/2006, 02/2013 and 03/2022, from https://datamap.gov.wales.

Figure 10 summarises the datasets available and the timescales over which the data were collected.

Further details on the data obtained and used in this study are provided in Appendix H.

6 https://www.wcmc.wales/

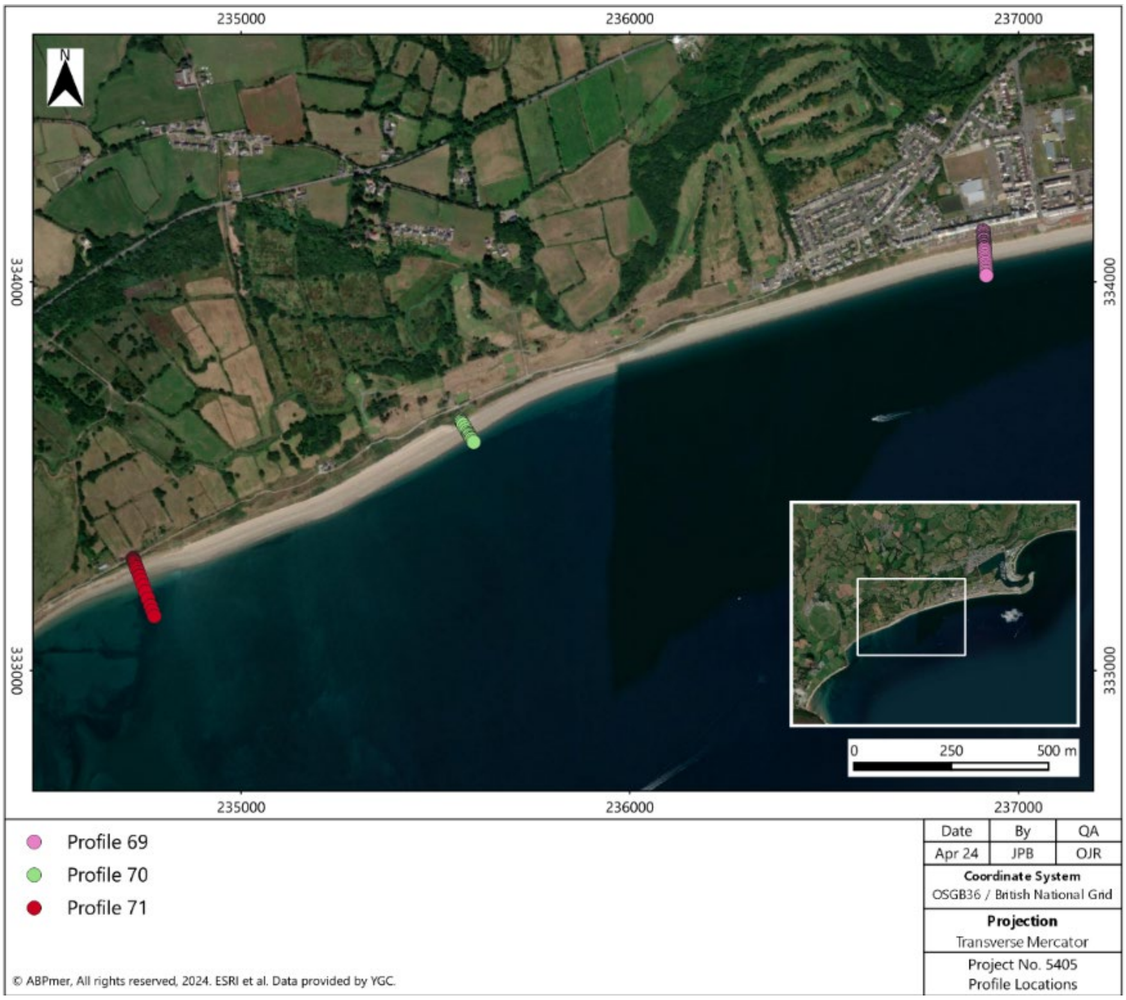


Figure 8. Location of Profiles 69, 70 and 71 provided by YGC

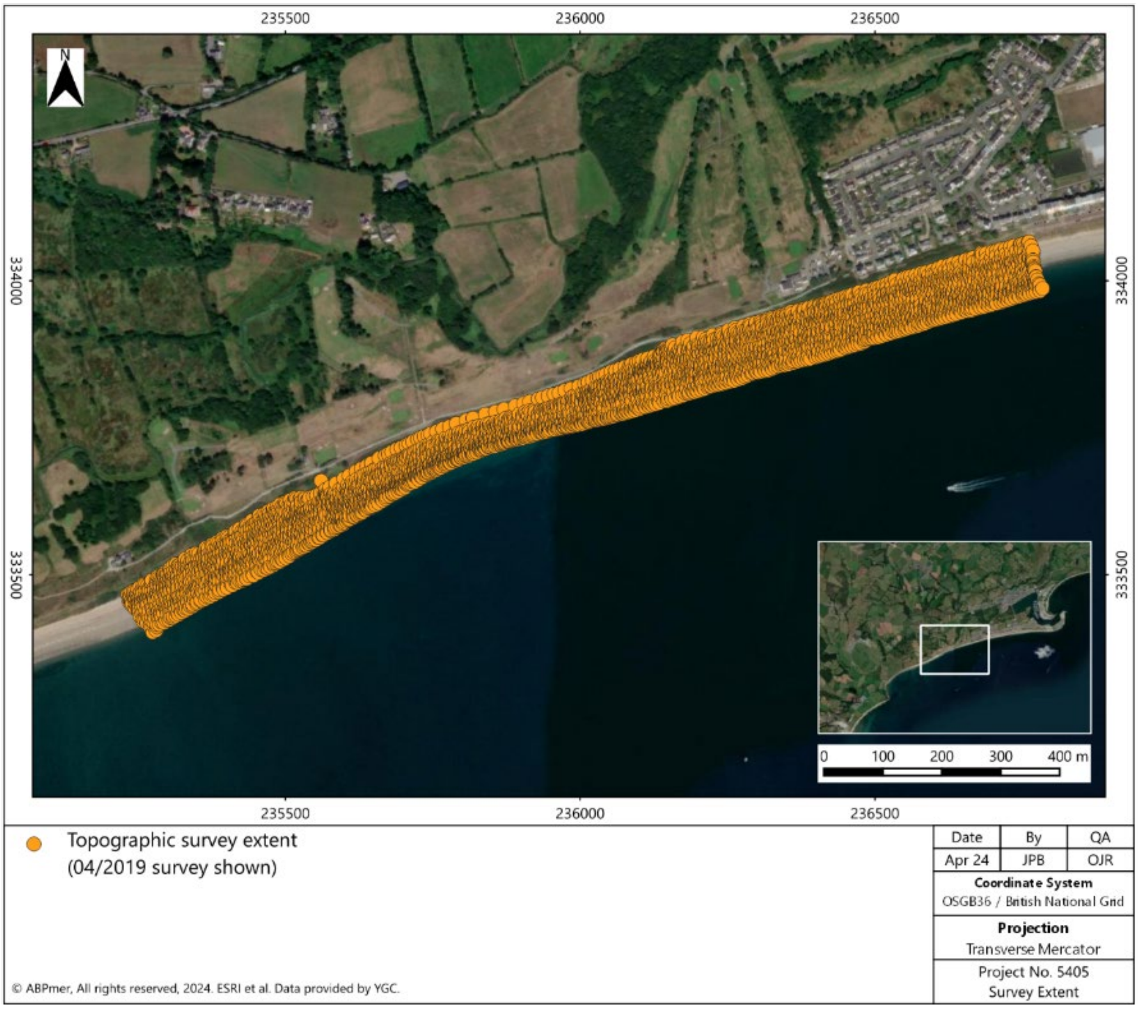


Figure 9. Topographic survey typical extent of data provided by YGC

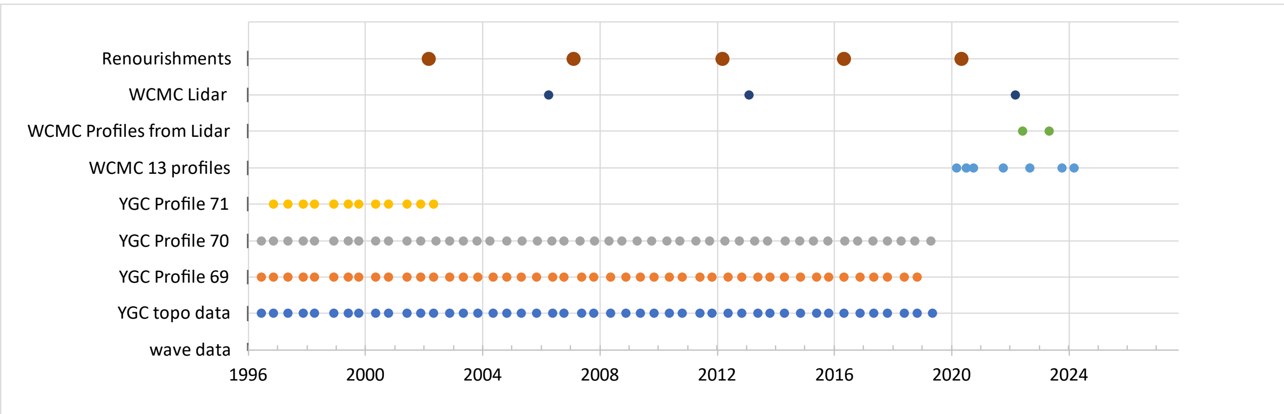


Figure 10 Timeline showing available data for the site as well as the time of the renourishments.

4.3 Review of past monitoring data

The available monitoring data has been examined and analysed to examine past changes to the frontage, including the loss and redistribution of the nourishment material. The full analysis of this data is provided in Appendix I. Key observations from this analysis are presented in the following sub sections.

4.3.1 Elevations along YGC profiles 69, 70 and 71

This dataset has an excellent temporal coverage, providing a long-term record of profile data, with some seasonal information (as there is data for both summer and winter). The downside of this dataset is that it does not extend into the shallow sloping subtidal zone. Furthermore, it is noted that (see Figure 8 for profile locations):

- Profile 69, lies to the north east of the main study area;
- Profile 70, lies in the main study area, but is located along the central revetment, and
- Profile 71, lies to the south west at the eastern end of the western revetment.

Therefore, none of the profiles cover a section of the beach where the nourishment has been placed.

The evolution of the foreshore along Profile 69 to 71, is shown in Figure 11 to Figure 13 respectively. Key observations are noted below:

- The dune at the back of Profile 69 has been growing since 2000, inter-annual and annual variations across the foreshore and no obvious erosional/accretion trends;
- Profile 70 generally appears to have accreted since about 2010 with inter-annual and annual variations across the foreshore;
- Profile 70 generally appears to show no net accretion/erosional trends, with inter-annual and annual variations across the foreshore;
- The average beach slope is 1:12 in all three profiles;
- The average vertical movement of the beach at Profile 69 and Profile 70 during the 23 years (1996-2018) is about 0.7 m and 1 m respectively:
- The average vertical movement of the beach at Profile 71 during the 6 years (1996-2001) is about 0.4 m, and
- The envelope of beach variation appears to be mostly driven by cross-shore transport. These are short-term changes as the beach at both positions do not show great variation long-term.

Figure I4 shows the position of the 0 m ODN contour and the 2 m ODN contour in time. This exercise was carried out in order to see if the renourishment on the beach backshore was having an effect on the beach levels and if so if there was a delay. The data shows intra- and inter-annual variability, especially for the 2 m ODN contour and a small accreting trend over the years for the 0 m ODN contour. Neither of the contours show, however, the influence of the renourishment, as there is not an increase of the chainage after the renourishments.

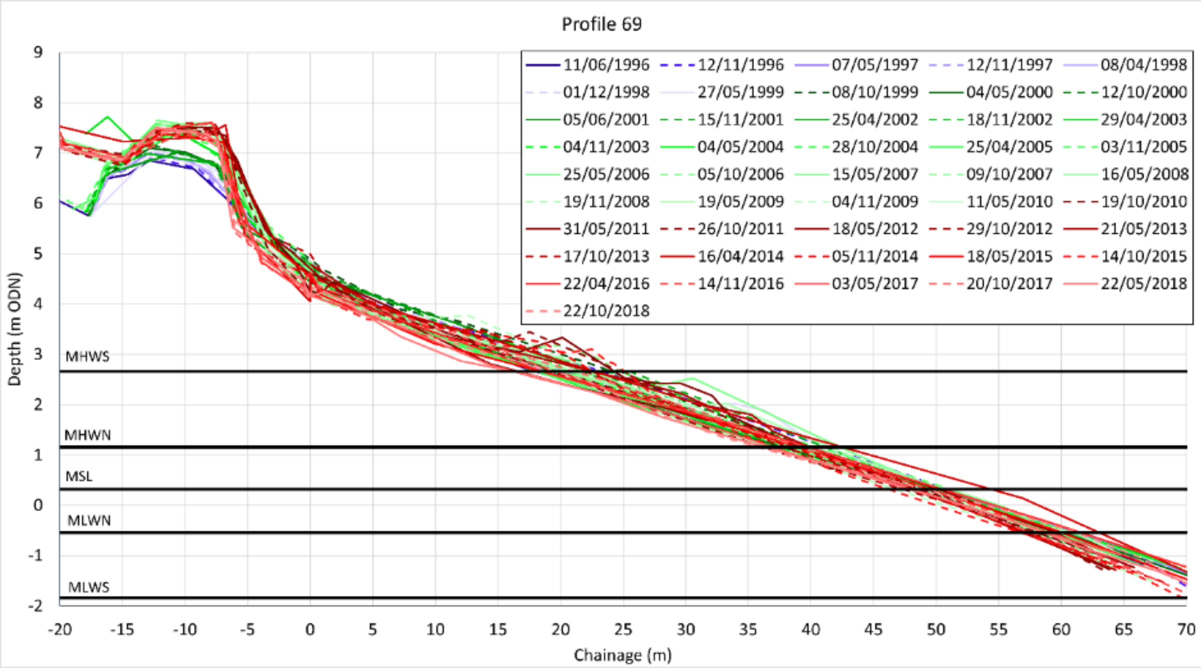


Figure 11. Profile 69 data (1996-2018)

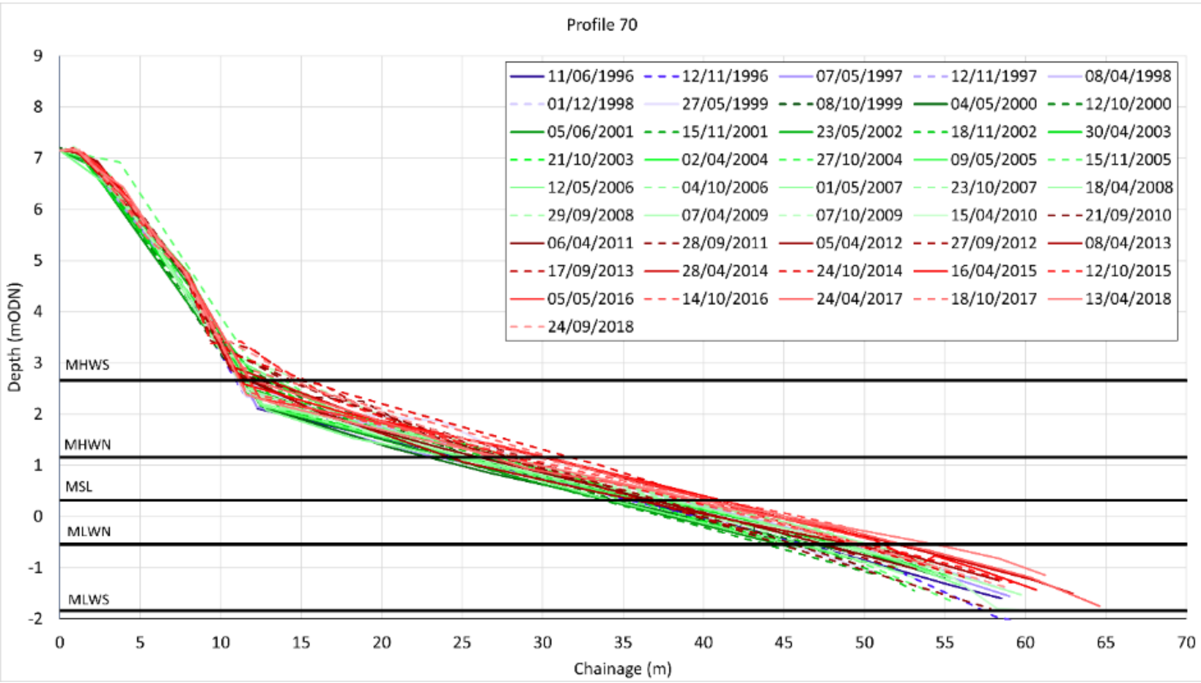


Figure 12. Profile 70 data (1996-2018)

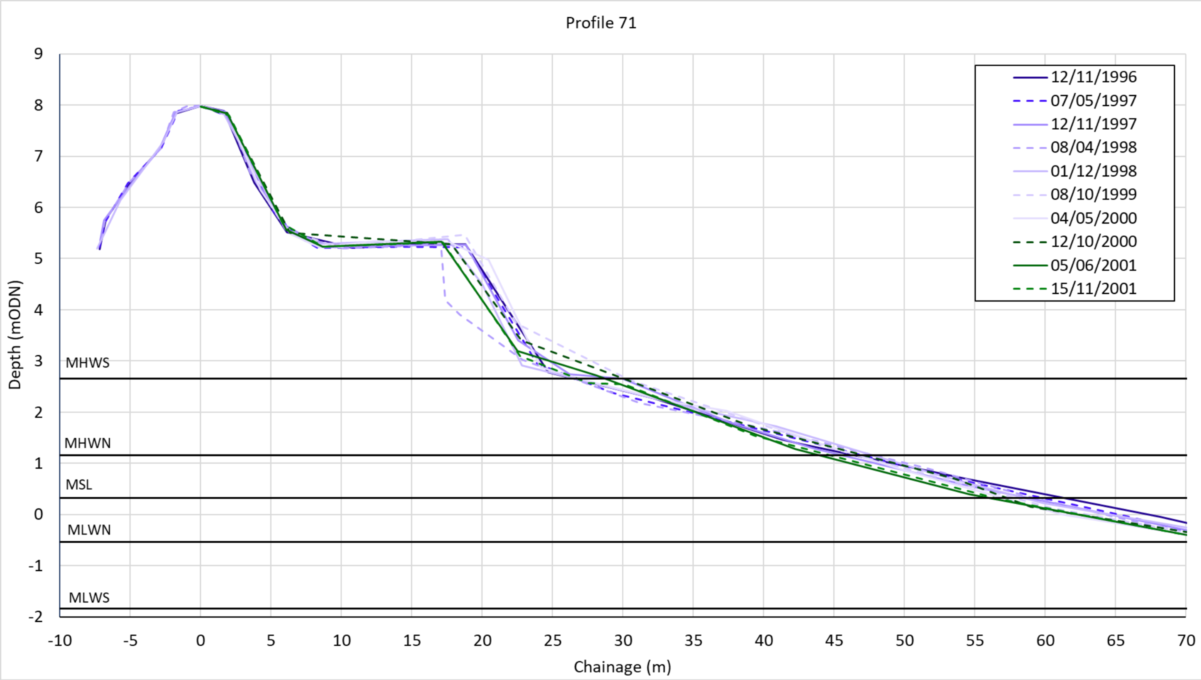


Figure 13. Profile 71 data (1996-2001)

4.3.2 Variation in MHWS position, beach volumes and beach profiles derived from topographic data sets

To examine the spatial and temporal variations of the beach, Digital Terrain Models (DTM) have been created from each of the YGC point topographic surveys and the three Welsh Government LiDAR data sets. The DTMs have then been interrogated to observe how the MHWS position and beach volumes have changed across the frontage. They have also been examined, together with extra profiles from WCMC to examine how the beach profiles have changed across the nourishment area, although the accuracy of this is caveated with the observation noted below.

For this assessment, it is noted, that whilst the YGC dataset has excellent temporal coverage, providing a long-term record with seasonal information, the resolution of the data, especially in the early years, is quite poor (around 8 m to 15 m up to 2019). Therefore, it does not resolve the steep slopes at the top of the beach, including the cliffing of the renourishment well. Nevertheless, the extensive nature and temporal coverage is of great benefit to the present assessment.

Variability of the MHWS contour

The data used for this analysis were the DTMs from YGC topographic surveys and the 3 Lidar datasets from the Welsh Government.

Beach profiles along four profiles, two in the Western renourishment area (1 and 2) and two in the Eastern renourishment area (3 and 4) (Figure 14), were extracted from each DTM, and the distance from the end of the profile to the MHWS contour identified. This distance is plotted against time in (Figure I5) to show how it has changed with time. From Figure I5, clear, inter- and intra-annual variability of the MHWS position is observed, but the effect of the renourishment is not observed on the position of the MHWS (or it is masked within the variability).

Moreover, none of the transects are showing a long-term accreting or eroding trend, as the variability is very high, again due to the swash processes on the top of the beach.

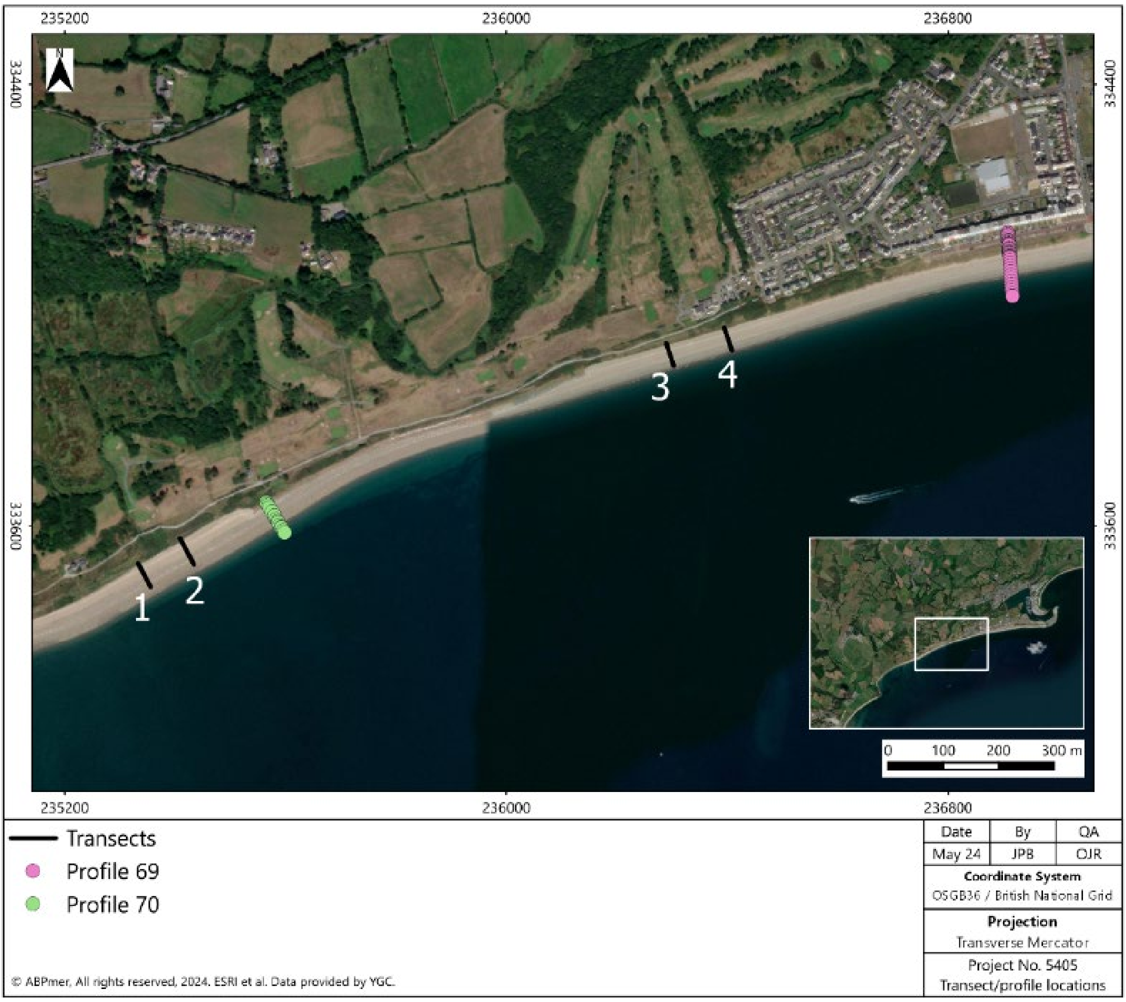


Figure 14. Location of the Transects 1-4 to show change in MHWS

Beach volume analysis

The DTMs from the YGC topographic surveys have also been analysed to examine beach volume changes in relation to different areas of the beach. The beach was thus split up into a series of zones and shown in Figure 15, and summarised below:

- Two areas in the backshore for each of the renourishment zones: WBeaN and EBeaN
- Two areas in the foreshore in front of these renourishment zones: WBeaS and EBeaS
- Two areas in the foreshore in front of the revetment: WRev and Erev
- An area to the East of the Eastern revetment, EEBea

Within this assessment, to maximise the spatial coverage of the assessment, several of the temporal datasets were excluded from the analysis. This is because the spatial coverage of these individual surveys was more limited.

Figure 15. Location of areas outlines to calculate beach volumes

The volume evolution in time for each of these areas is shown in Figure 16 (individual plots are provided in more detail in Appendix I.3 in Figure I7 to Figure I12). The volumes added in each renourishment are very noticeable in the backshore areas (WBeaN and EBeaN), especially in the Western one, as here the renourishment volumes are greater. Within 12 months to 24 months, the volume in the renourishment areas has more or less retuned back the pre-nourishment volume, and the backshore volume stabilises. The volumes within the remaining assessment areas all show a degree of variability, but they do not show any clear direct correlation with the individual renourishment campaigns. However, the foreshore to the West (WBeaS and WRev) shows a mild accreting trend over the years, whereas to the East (EBeaS and EEBea) show no general trends.

The volumes at the foreshore in front of the Eastern part of the (Erev) behaves quite differently, with a steady decline in beach volumes from 2002 to 2012, then a general increase / recovery until 2014. Since this time there has been some decline, but generally the volumes in this area have been more stable. It is interesting to note that this is the area that has been subject to the greatest overtopping, and it is questioned, whether these observed trends relate to change in the shoals just offshore. Such changes will result in the local realignment of the coastline.

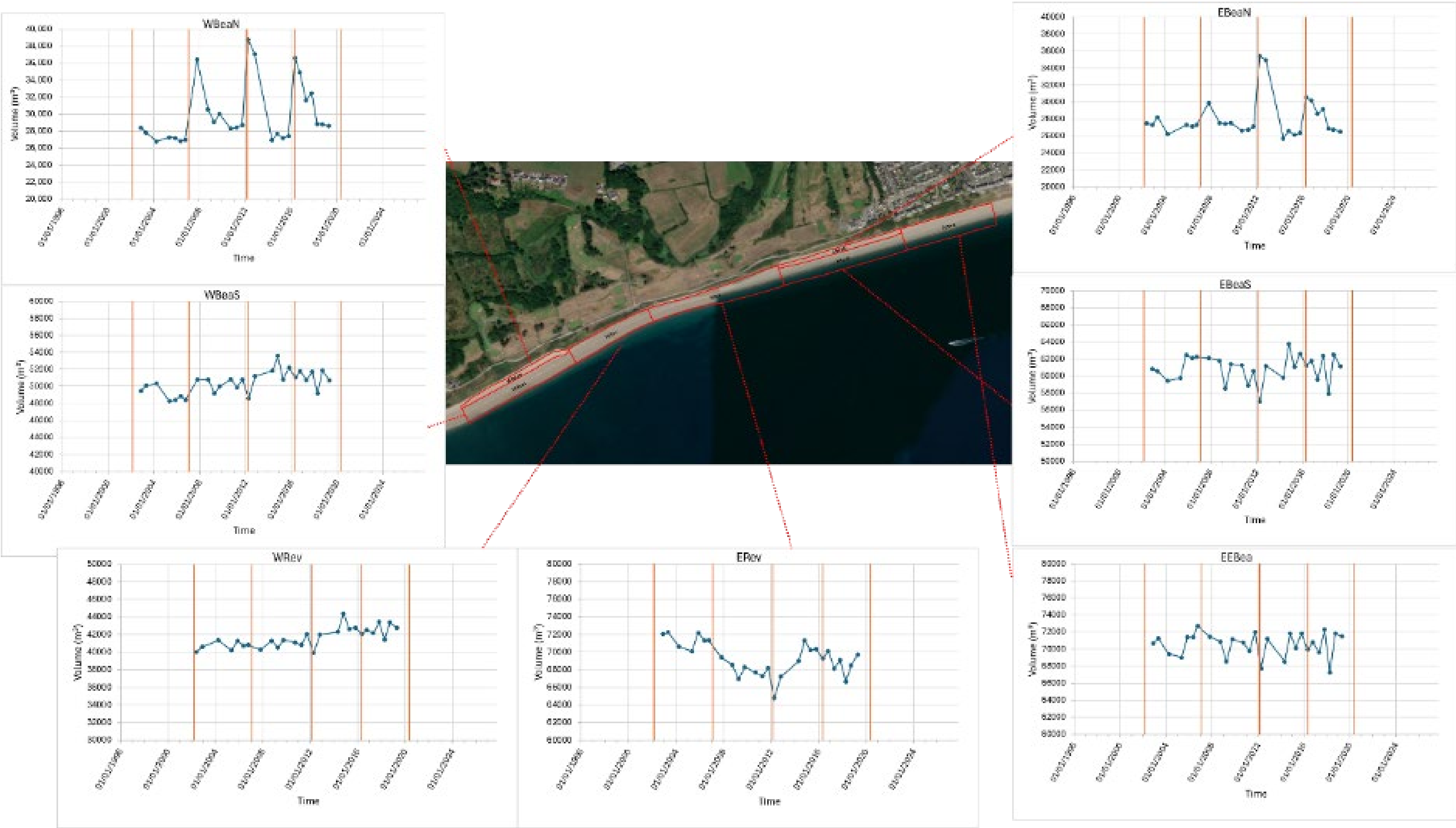


Figure 16. Evolution of the volumes at the different backshore and foreshore areas (orange lines show the renourishments)

Beach profiles response in renourishment areas

The DTMs from the YGC topographic data, ~~and~~ WCMC profile data and LiDAR data were also used to examine the profile changes along four transects (two on each side of the renourishment: Profiles A and B on the Western side and C and D on the Eastern side, location in Figure 17), following each of the five nourishment campaigns.

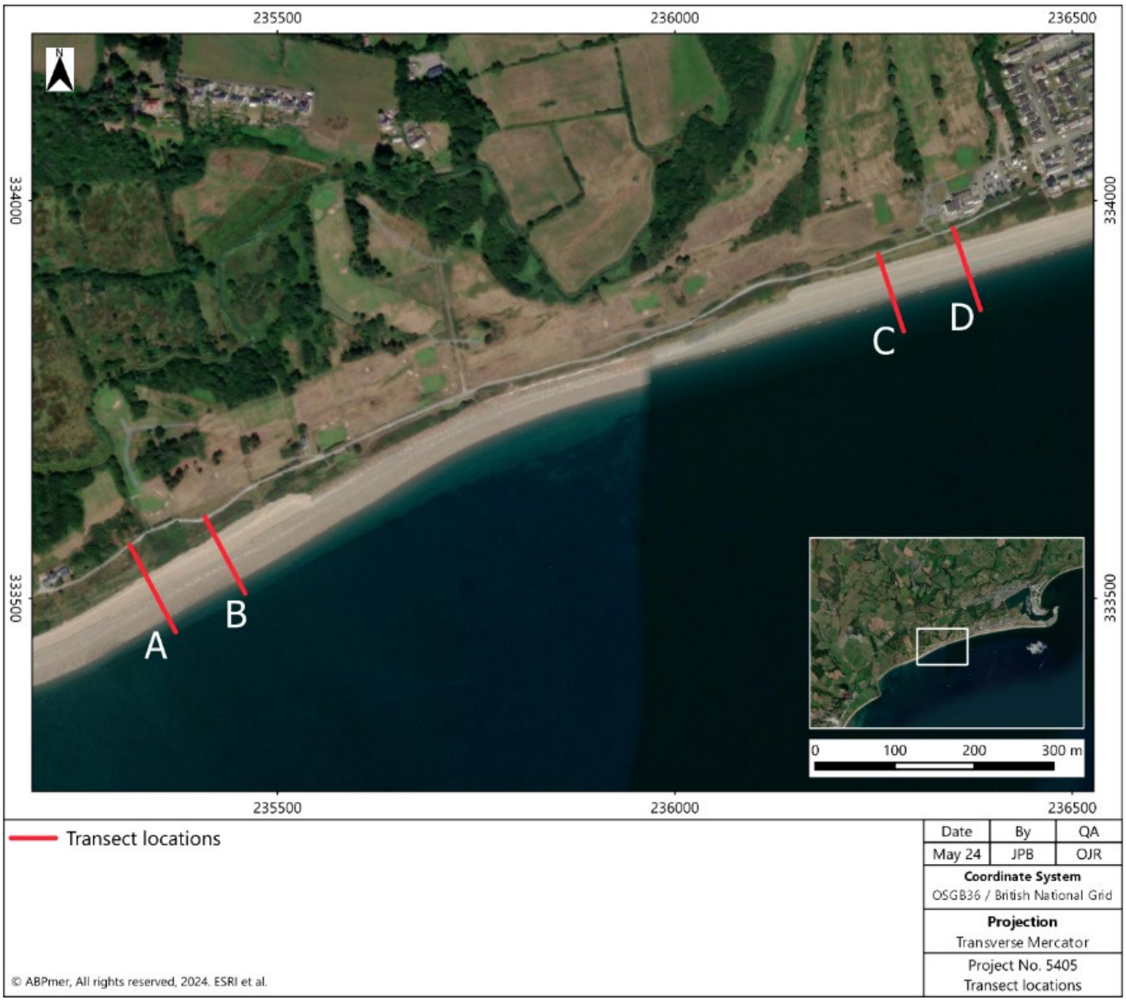


Figure 17. Location of the transects to track the nourishment

Figure 18 shows the profiles' response after renourishment campaign 4 in Spring 2016. This shows that within 6 months, a large proportion of the renourishment has already gone in the Western renourishment area (Transects A and B), with a smaller initial loss in the Eastern renourishment area (Transects C and D). After 2 years, most of the renourishment has been lost. Similar plots are provided in Appendix I.4 (Figure I14, Figure I15, and Figure I16), showing the profile response following renourishment campaigns 1 to 3. Figure 19 shows the profiles' response after renourishment campaign 5 in Spring 2020. As this data has been extracted from Lidar datasets, it is noticeable the improved spatial resolution of the profile, although the time resolution is not as good as there are only two dates available after such renourishment.

These figures show how the profiles changes, following the renourishment campaigns, however, due to the resolution of the topographic data used to develop some of the DTM used this this assessment (about 5 m in the horizontal), some caution should be adopted when examining the results of the four earlier campaigns. Nevertheless, in general some clear trends can be seen in the results as has been described anecdotally.

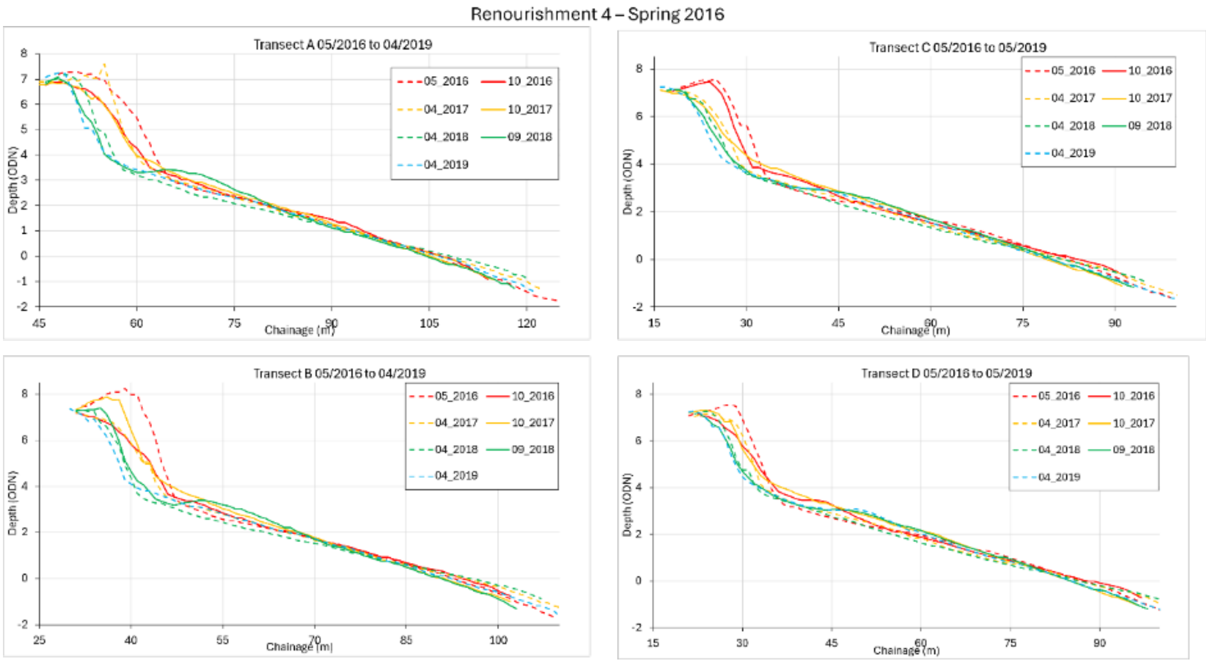


Figure 18. **Evolution of the four transects, A, B, C and D after Nourishment 4 (Spring 2016)**

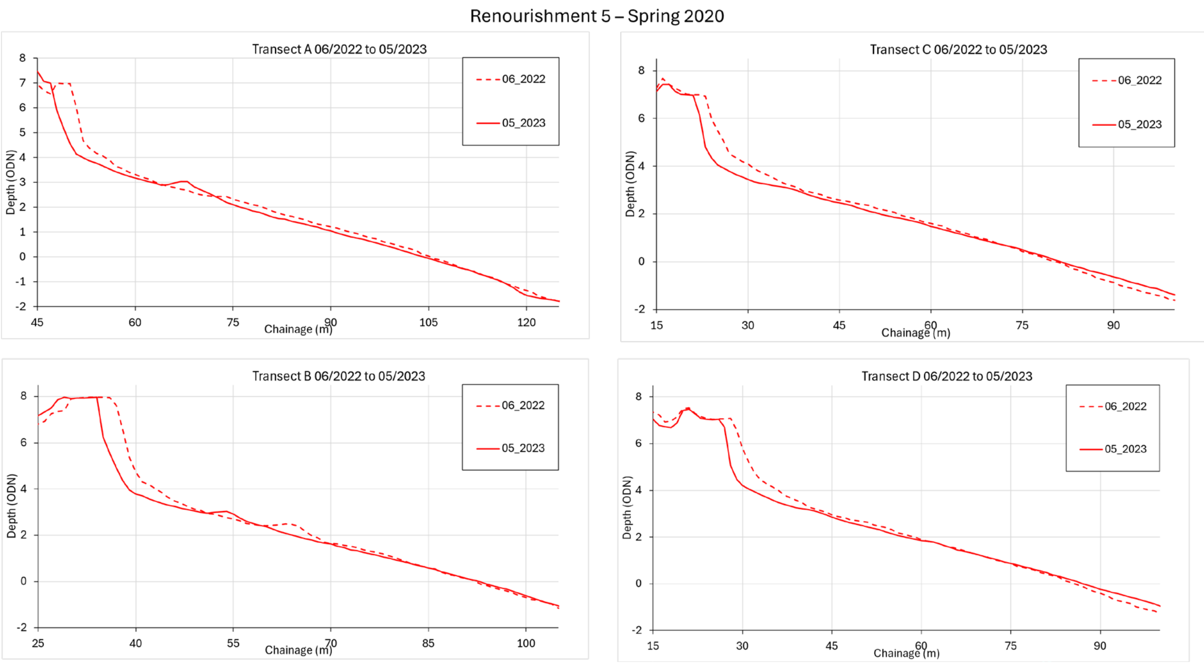


Figure 19. **Evolution of the four transects, A, ,B, C and D after Nourishment 5 (Spring 2020)**

Reviewing the results following each of the renourishment campaigns, the horizontal loss per year (mainly based in Transects A and B where the data is more consistent and clearer) are summarised below:

- Nourishing campaign 1 (Spring 2002), Figure I14: The data for the berm is not present in the data therefore it is not possible to estimate the horizontal loss following this campaign meaningfully.
- Nourishing campaign 2 (February/March 2007), Figure I15: The horizontal loss in the first year is about 7-8 m, about 1 m in the following year, and then with limited observed change after this.

- Nourishing campaign 3 (February/March 2012), Figure I16: The horizontal loss in the first year is about 5 m, and then about 8 m in the following year (note that this covers the storms of 2014, the most extreme year in terms of storms in UK). Following this there is little apparent change.
- Nourishing campaign 4 (Spring 2016), Figure 18: The horizontal loss in the first year is about 4 m, with a similar loss of about 4 m in the following year. Following this there is little apparent change.
- Nourishing campaign 5 (Spring 2020), Figure 19: The horizontal loss in the third year is about 4 m.

Similarly, rates are typically observed for Transects C and D, but following campaigns where it appears there has been less nourishment to the Eastern renourishment area, retreat rates appear less, e.g. after renourishment campaign 2. This can be expected to an extent as the beach is aligning back to its more natural, stable state.

These horizontal losses average around 6 m for the first year and 3 m for the second year, except for the nourishing campaign of 2012, where the second year saw a much bigger loss on an already depleted profile, because of the extreme storms of 2014. It is estimated that if these storms had occurred within the first year of a renourishment, the horizontal loss could have been of the order of 10 m whereas if they had occurred on the third year, they would have been of the order of 6 m. This is due to the fact that the further back a profile is, the more difficult is for the same wave to reach and remove the sediment from it.

4.3.3 Observations from LiDAR data

The LiDAR dataset has an excellent spatial coverage (hinterland, renourished area, dunes and foreshore) and spatial resolution. However, the temporal cover is poor. The three available Lidar datasets are in between renourishments: April 06 is four years after the first renourishment, February 2013 is one year after the third renourishment and March 2022 two years after the last renourishment. Taking differences of the DTMs created from these datasets does not provide much information on how the renourishment behaves as there were one or two nourishment campaigns in between LiDAR data.

The most recent LiDAR data (March 2022) is shown in Figure 20 for both the Western renourished area at the top and for the Eastern part at the bottom. The outlines in the figure are those used in the analysis of the volumes previously and are based of examination of imagery and DTM data; they are useful to bound the extent of the renourishment within the data. Two years after the renourishment, one can derive the width and the level of the crest of the material left from the renourishment in the backshore: to be of the order of 5 to 6 m crest width, with a ~2 m height (difference between the crest of the renourishment and the base of the renourishment on the beach). A similar exercise has also been carried out from the previous LiDAR datasets, the data extracted from the three datasets is summarised in Table 4.

Table 4. Approximate heights of the remaining renourishment inferred from the LiDAR data

LiDAR Date	Time After Previous Renourishment	Approx Heights of Renourished Crest (Toe of Renourishment to Crest):	Approx Width of Renourished Crest:
April 2006	4 years after renourishment campaign 1 (2002)	4.2 m (West side) 2.8 m (East side)	7.6-10 m (West side) 7.5-9 m (East side)
February 2013	1 year after renourishment campaign 3 (2012)	3.2 m (West side) 2.9 m (East side)	8.5-10 m (West side) 5.5-7 m (East side)
March 2022	2 years after renourishment campaign 5 (2022)	1.8 m (West side) 2.1 m (East side)	6.5-8.2 m (West side) 5.2-6.8 m (East side)

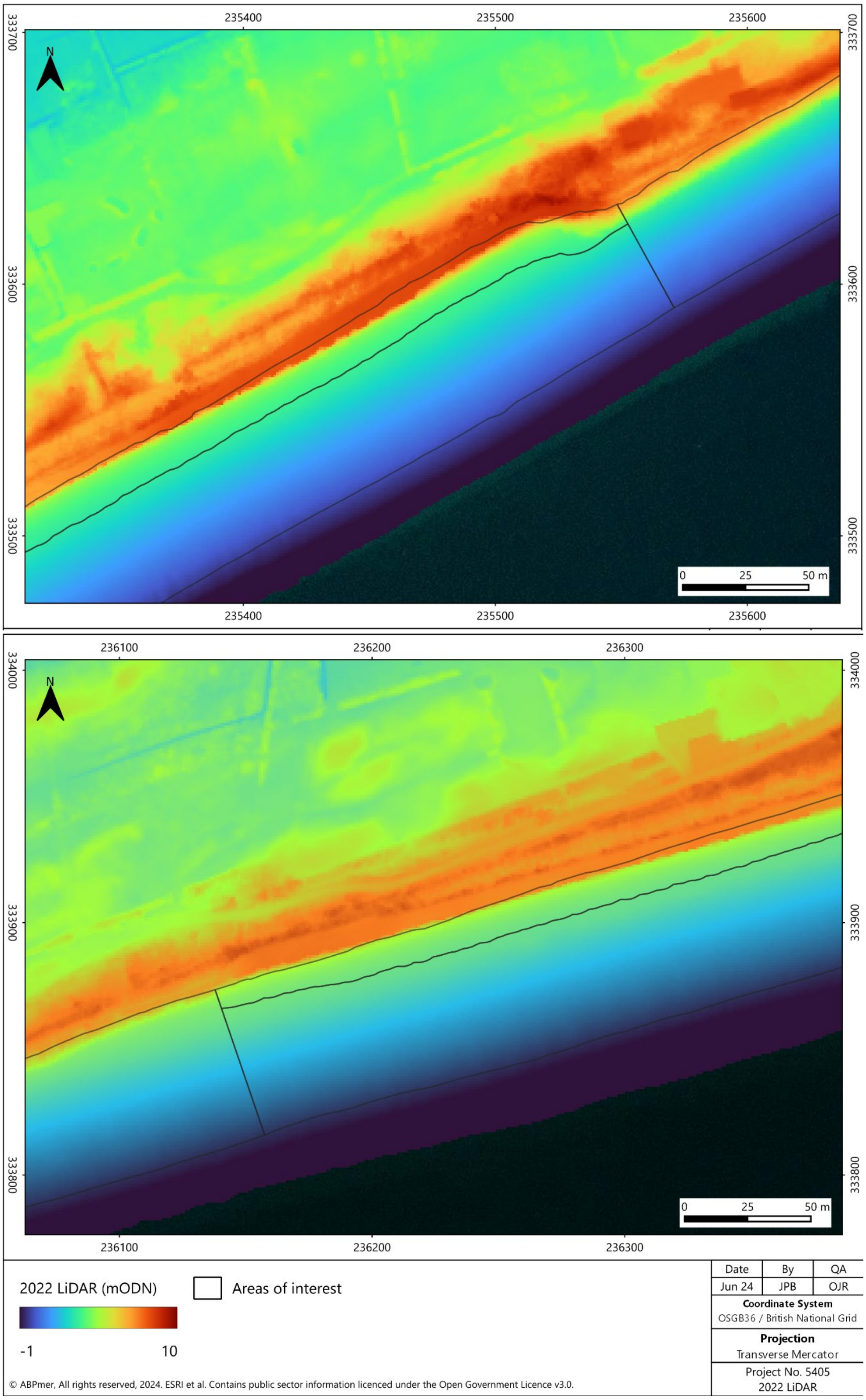


Figure 20. LiDAR March 2022 data for the Western (top) and Eastern (bottom)renourished area

4.4 Key observations and lessons learned from review of monitoring data

During the review, several observations have been made in relation to the collection of the historic monitoring data and the analysis of the available data. These observations are described in the following sections.

4.4.1 Key observations about the monitoring

The quantity of available monitoring data for this study, is significant, and much greater than that generally available, and this has been of huge benefit to the present assessment. However, several limitations with the available data sets have been observed through the study. These limitations are summarised below since they affect the accuracy and the analysis that has been undertaken. Furthermore, the identification of these limitations will also help to inform future monitoring campaigns:

- Whilst the YGC point topographic data provides invaluable spatial / temporal coverage, the spatial resolution is poor (especially with the older data). This is most critical when trying to examine the cross-shore profile where changes can be rapid.
- The three YGC profile locations unfortunately do not cover the areas that have been renourished. Together, with the resolution of the YGC topographic data, this has limited the accuracy with which the cross-shore beach response can be observed in the renourishment areas.
- Since 2020, the monitoring has been more *ad hoc* with different approaches and profiles being examined during different campaigns. This has meant there is less available data to examine how the beach adjusted after renourishment campaign 5.
- There is no reliable nearshore bathymetry or the area, nor information, as to how the nearshore bathymetry may be changing over time. The assessment has identified how beach volumes along the eastern part of the revetment (where overtopping has been greatest) has varied over the recent past, which appears to be related to offshore shoals and possible changes to these. Similarly, the coastline alignment along the frontage is also seen to be highly affected by these shoals, where the coastline natural projects seaward between the two revetments. It is important to note that the active beach extends into the sub-tidal region, with cross-shore exchange moving material to and from the subtidal region to the beach. Thus, without regular data covering this area it is not possible to determine if there is any underlying loss or gain of material across the full active beach profile.

4.4.2 Key observations from the analysis of the monitoring data

The available monitoring data has been used in earnest, with additional analyses, being undertaken to maximise the information that can be obtained from it. This includes the generation of DTM from several of the data sets and the volume analysis comparisons.

The main conclusions from the analysis are:

- The volume of material in the foreshore of the beach does not seem to show an immediate or direct link to the renourishment of material in the backshore. When the renourished material is lost from the back of the beach, it does not stay directly on the beach in front of the renourishment, but it is quicky moved along to the east by the longshore drift. Therefore, the MHWS or any other foreshore line are not good indicators of when the backshore renourishment should be triggered.

- It is, however, noted that there has been a general rise in bed levels across the western extent of the foreshore. It is not clear, however, whether this is general trend due to the additional of nourishment material to the frontage, or whether, it results from 2D effects results from shoals offshore. The continued addition of nourishment material to the frontage, however, can only be positive in helping to maintain bed levels along the wider frontage.
- The beach is subject to cross-shore transport as observed in the seasonal changes in the profile evolution. Three decades of beach profile data show an envelope of changes across the profiles with the average vertical movement of the beach during this time being about 1 m (this equates to ~8 m excursion in the horizontal), which is not significant. The lack of data offshore of the intertidal up until the depth of closure impedes drawing conclusions on whether there is a permanent loss of sediment due to cross-shore transport when large storms occur.
- Within 12-24 months of a renourishment campaign, the majority of the new renourishment material has been removed, and the beach profile responds back to that prior to the renourishment campaign. After this time, losses are much slower and to some extent the backshore stabilises until the next renourishment. This is to be expected to an extent as the beach is aligning back to is more natural stable form. It is not possible to say with certainty what would happen to the backshore if it was not nourished, whether it would remain for several years or not. It is almost certain that in the long term the backshore would go if not renourished, due to increased sea levels and storminess.
- The horizontal losses in the renourished backshore average around 6 m for the first year and 3 m for the second year, except after nourishment campaign 3 in 2012, where the second year saw a much bigger loss of about 8 m on an already depleted profile. It is expected that this is because of the extreme storms that occurred in the winter of 2013 – 2014.
- From these past observations, it is considered reasonable to assume, that if there was another severe winter, similar to that of winter of 2013-2014, that the renourishment may retreat to the order of 10 m in the horizontal if the stormy winter is within the first year of the renourishment, and about 8 m, if it is within the second year. Similarly, if the series of severe storms were to occur two or more years after the nourishment, it is estimated that the amount of retreat would be less, since limited retreat has historically been recorded two years after a renourishment campaign. However, a retreat of around 5 - 6 m, would not seem unreasonable. If the existing width of the renourished material at this time was not enough, the existing dunes behind would then be subject to erosion.
- From past LiDAR data obtained, between 2 and 4 years after the previous nourishment campaign, the remaining beach crest along the Western renourishment area is typically 6.5 – 10 m, and along the eastern renourishment area its typically 5.2 – 9 m. Thus, likely to be adequate to withstand a significant series of winter storms, although this cannot be confirmed with any certainty.
- The current cyclical renourishment operations seem very sensible and appropriate for the protection of the hinterland over the short term.
- The central revetment has two distinct zones: the Western section, which we understand requires less maintenance, is backed by higher ground levels, and has been subject to a degree of beach accretion at its toe. On the contrary, the Eastern section of the revetment needs more maintenance, suffers from overtopping and the beach levels in front of this part have been subjected to continued lowering over a number of years (although more recent there was some recovery in bed levels here). Whether the difference in behaviour is due to the difference in the orientation of the revetment, presence, and location of offshore shoals or something else, it is difficult to discern. Without the revetment in place, most likely the sea would breach and the low-lying land would have reverted back to intertidal saltmarsh, as noted by Faber Maunsell Aecom (2008).

- There is very little information about the nearshore bathymetry of the area, the only survey that in Faber Maunsell Aecom (2008) with no clear labels for the contours. To understand the nearshore bathymetry and its variability would help understand the coastal processes in the area and why the revetment behaves differently in each of its halves.

5 Recommendations for Ongoing Works

From the assessment of the coastal processes in the area and the evaluation of the available monitoring data, it is concluded that the present nourishment protocols have been providing adequate protection to the adjacent hinterland and that YGC should continue with the same protocols, namely:

Renourish both areas either side of the revetment, at a height in line with the height of existing dunes and place it at a shoreface angle of 1:2.

As for the frequency of the renourishment, it is advised that the crest of the backshore area is monitored to maintain a minimum crest.

The recommended minimum crest width in the renourished area is 6 m to allow the backshore to withstand an extreme winter period.

If stormy conditions (both in intensity and persistency) were to happen like that of the winter of 2013-2014 and this minimum crest was not available, the existing dune will be much more vulnerable to erosion. It is foreseen that the frequency of the renourishment will be similar but prescribing a minimum crest criterion as trigger level would allow to take into account the conditions that have been experienced since the last renourishment campaign.

It is important to note what would happen if more material was being used for the renourishment and therefore the initial crest of the backshore was wider. The wider the nourishment, the fastest initial losses would be expected as the renourished section is then aligned seaward and away from the natural alignment of the general beach. This would not hurt in respect to general amount of volume of material along the beach, but much greater initial losses would be expected.

We recommend reviewing this trigger level regularly when more monitoring information becomes available. The monitoring recommendations below would make this analysis more efficient and straightforward.

With regards to future monitoring, it is recommended that monitoring programmes are adapted to help track renourishment works, the renourished area crest widths, as well as general beach levels and volumes. This will provide additional information that can be used when assessing the effectiveness of the continued nourishment works. Suggestions for future monitoring works are noted below (it is recognised that these will require different level of effort, and thus associated costs):

- **Renourishing volumes**: It will be advisable to track the nourishing volumes at both sites of the renourishment, this could be as simple as counting the number of tracks that go to each area.
- **Renourished area as placed**: Once the renourishment is in place, recording of the nourished berm width is important. The best, more accurate way of doing this would be with a LiDAR survey. However, if this was not available, a topographic survey of the renourished area, making sure the crest of the nourished berm is captured, together with the base of the nourished area, the beach and the hinterland behind the nourished area. This survey will set up the baseline for that nourishing campaign against which to track its development.
- **Beach and renourished area tracking**: Biannual monitoring of the beach and the nourished backshore. The frequency and locations of beach surveying in recent years has been very variable. It would be advisable to return to biannual monitoring of the beach (and its backshore) as this would help manage the renourishment and the revetment. Ideally, topographic surveys of the beach and its backshore would be recommended, either with LiDAR or point data

covering the crest, base of the renourishment, hinterland and beach. If topographic surveys were not available, at a minimum, survey two profiles either side of the renourishment. These two profiles would be in similar positions to the derived transects in Figure 17, plus Profile 70 and a new profile in the Eastern end of the revetment, Profile 70B, as well as Profile 69. These recommended seven profiles are shown in Figure 21. These should be surveyed with at least 1 m horizontal resolution. Their seaward limit should aim to be MLWS and the landward end should reach beyond the expected point of storm wave influence, so should reach the vegetated area behind the renourishment.

- **Bathymetric data**: The above beach profile data should be combined with nearshore bathymetric surveys, ideally, at least one every 5-10 years, so that the morphological changes across the full zone of wave influence can be assessed. If this was not achievable, add bathymetric surveys to the topographic surveys, in the same line, up to a depth of about 10 m. This could be done off a small boat or a jet ski and could be done every 3-5 years.
- **Pre- and post- major storms**: A nice to have, but quick and cheap way to examine recession rate. This will entail measuring the renourished beach crest width pre and post major storms by placing stakes back of beach to aid with the measuring. It will provide a good database on how the beach crest is affected by different storms.

Figure 21. Monitoring recommendations in terms of beach profiles

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https://www.wcmc.wales/

7 Abbreviations/Acronyms

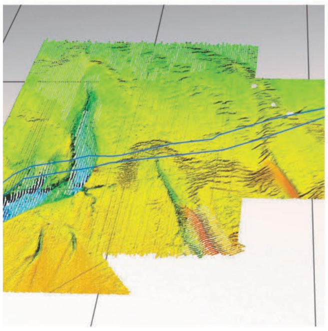
2D	Two-Dimension(al)
BJC	Business Justification Case
CD	Chart Datum
CFBD	Coastal Flood Boundaries Dataset
CGC	Cyngor Gwynedd Council
CNES	Le site du Centre national d'études spatiales- French Space Agency
Cum	Cumulative
D50	Mean or Average Particle Size
DataMapWales	Welsh Government Data and Maps Source Platform
Dc	Depth of Clousure
DHI	Danish Hydraulic Institute
DTM	Digital Terrain Model
EBeaN	East Beach North
EBeaS	East Beach South
EEBea	To the East of East Beach
EMODnet	European Marine Observation and Data Network
Erev	East Revetment
Exced	Exceedence
FRM	Flood Risk Management
HAT	Highest Astronomical Tide
Hs	Significant Wave height
HW	Hight Water
LAT	Lowest Astronomical Tide
LIDAR	Light Detection and Ranging
LNR	Local Nature Reserve
LW	Low Water
Mdir	Mean direction
ME	Mid Ebb
MF	Mid Flood
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MMO	Marine Management Organisation
MSL	Mean Sea Level
NRW	Natural Resources Wales
ODN	Ordnance Datum Newlyn
OSGB	Ordnance Survey Great Britain
OT	Overtopping
SAC	Special Area of Conservation
SLR	Sea Level Rise
SMP2	Shoreline Management Plan 2
SNH	Scottish Natural Heritage
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
SW	Spectral Wave
TAN	Technical Advice Note
Tp	Peak Period

UK	United Kingdom
WBeaN	West Beach North
WBeaS	West Beach South
WCMC	Wales Coastal Monitoring Centre
WRev	West Revetment
YGC	Ymgynghoriaeth Gwynedd Consultancy

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

Appendices


Innovative Thinking - Sustainable Solutions

ABP mer

A Flood and Coastal Erosion Risk Maps

This appendix contains the Flood and Coastal Erosion risk maps for the area.

The present-day flood risk map produced by Natural Resources Wales (NRW) is provided in Figure A1, and show the key areas of flood risk.

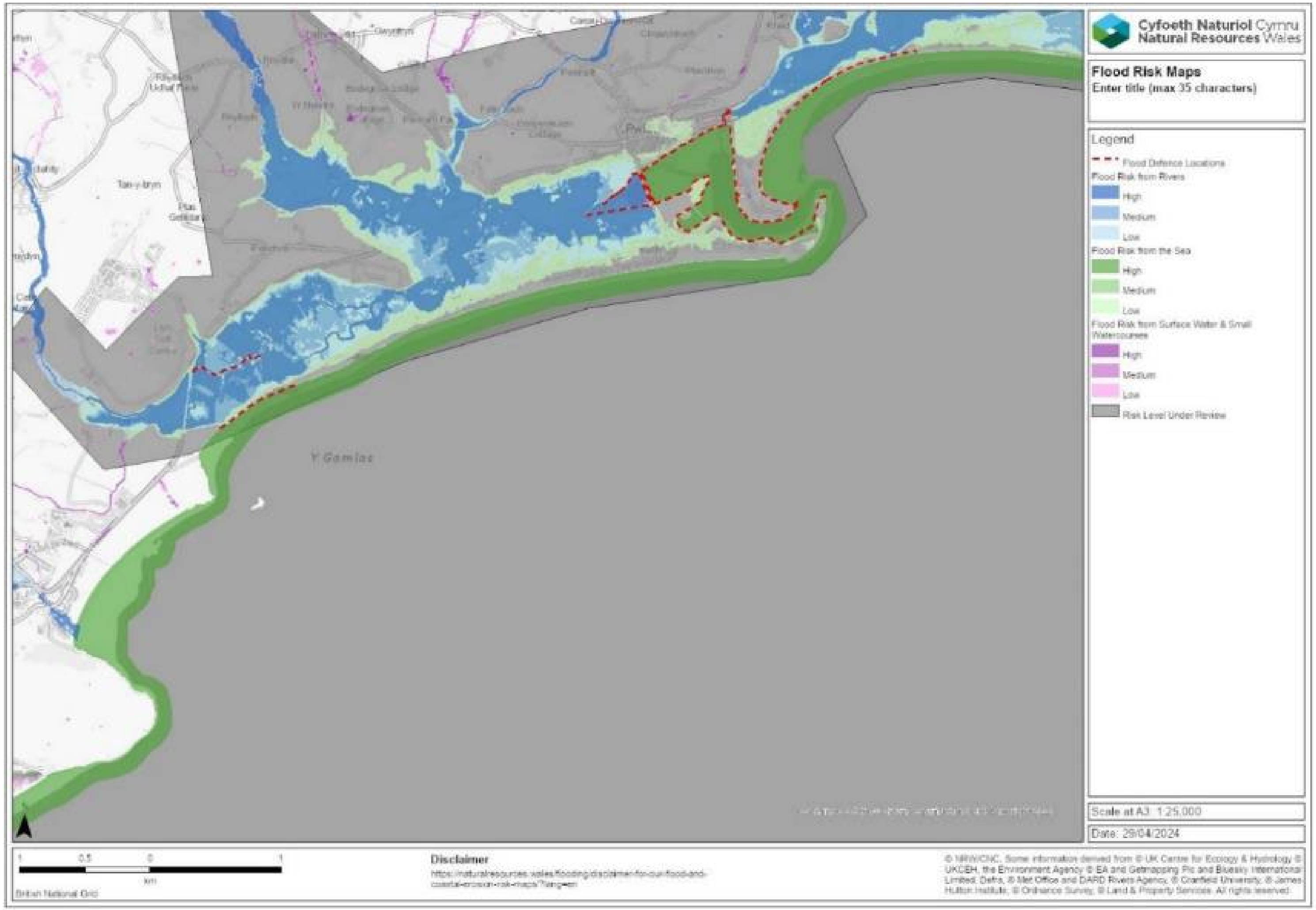
Figure A2 shows the areas of flood risk with climate change from the NRW's Flood Map for Planning[7].

The Business Justification Case at Traeth Crugan (YGC, 2022) notes that there have been a number of flooding incidents in Pwllheli throughout history; the latest recordings included 35 residential and business properties in 2012, 6 in 2014, and 3 in 2014. The majority of these cases were caused by unmaintained gullies being hydraulically overloaded during periods of heavy rain causing increased runoff and free flowing surface water to affect properties. The Riverside area of Pwllheli also flooded in 2017 due to overflow from the main river. A JBA Consulting study conducted in 2013 recommended that, as there is risk of flooding from more than one source (fluvial and coastal), a strategic approach to any future economic appraisal is required. This ensures that there is no double counting of damages and that properties at risk from both sources are properly accounted. Figure A3 shows the recorded flood events from NRW Coastal and Flood Erosion Risk Maps.

The coastal erosion risk along the frontage has been assessed as part of the Shoreline Management Planning process and is available on the Natural Resources Wales (NRW) website[8] and is shown as Figure A4.

7 The Flood Map for Planning has no official status until the Welsh Government implements its revised Technical Advice Note on Development, Flooding and Coastal Erosion (TAN15)

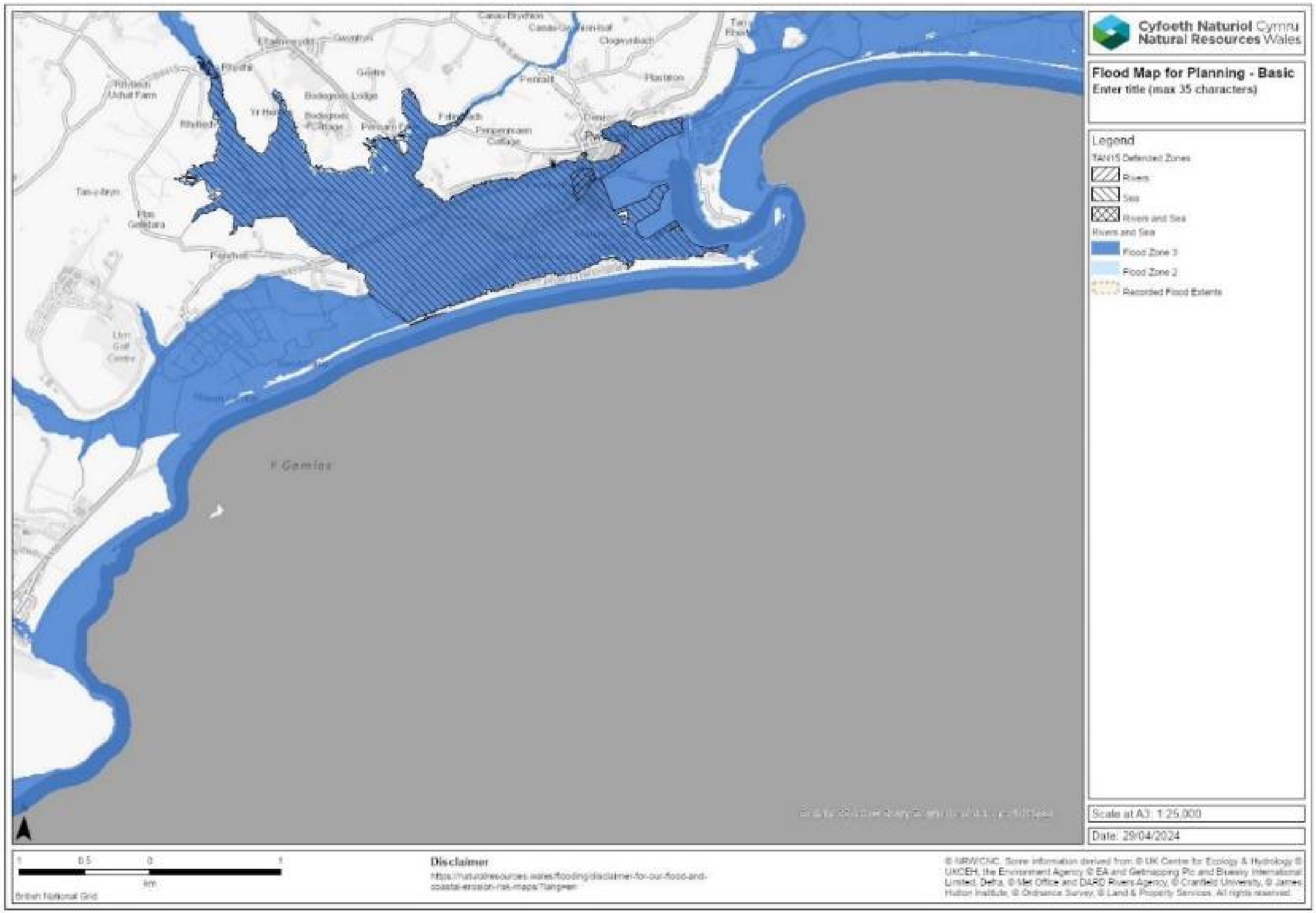
8 https://flood-risk-maps.naturalresources.wales/



Source: Natural Resources Wales Flood Risk Maps[9]

Figure A1. **Flood risk (present day with defences)**

9 https://flood-risk-maps.naturalresources.wales/



Source: Natural Resources Wales Flood Map for Planning[10]

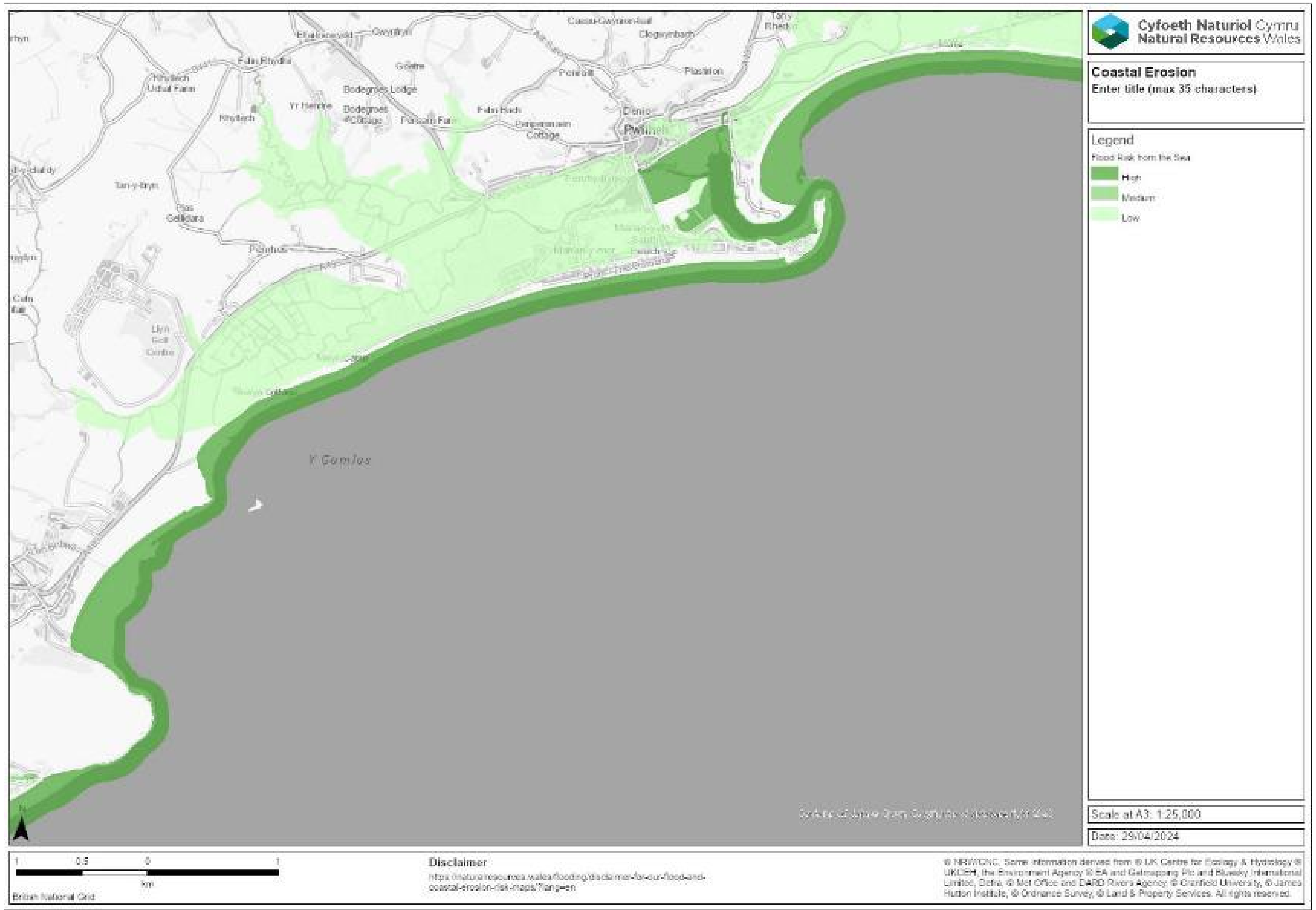
Figure A2. Flood risk with climate change (with defences)

10 https://flood-map-for-planning.naturalresources.wales/

Source: Natural Resources Wales Flood Risk Maps[11]

Figure A3. Recorded Flood Events in the area

11 https://flood-risk-maps.naturalresources.wales/



Source: Natural Resources Wales Flood Risk Maps[12]

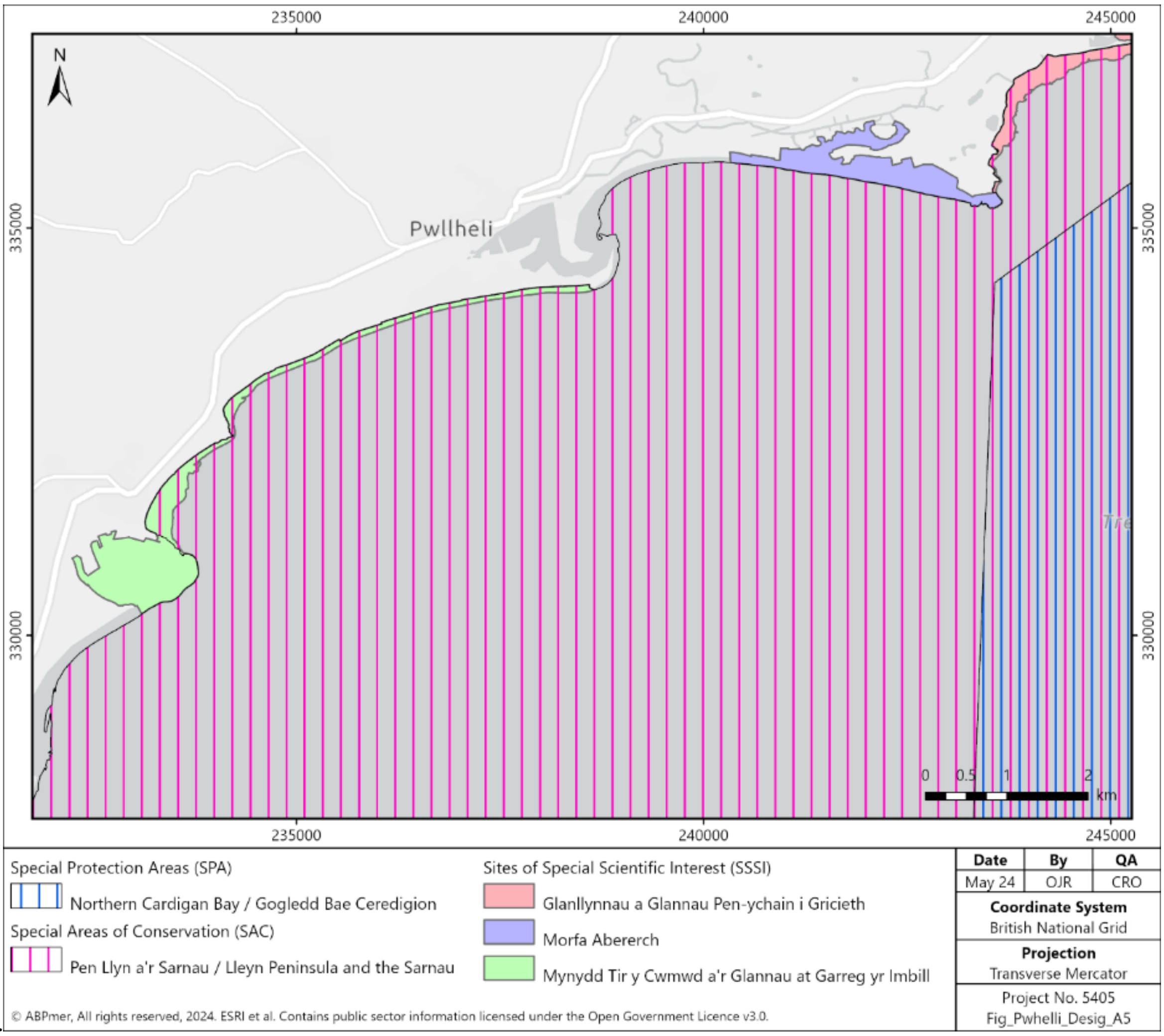
Figure A4. Coastal erosion risk (assuming no active intervention)

12 https://flood-risk-maps.naturalresources.wales/

B Nature Conservation Designation Maps

This appendix contains the Nature conservation designation maps for the area.

The nature conservation designations related to the study area are presented in Figure B1 (DataMapWales, 2024b) with associated mapped Article 17 habitats shown in Figure B2.



Source: Source: https://datamap.gov.wales/maps/new?layer=inspire-nrw:NRW_SSSI#/

Figure B1. Designated areas near Pwllheli

Source: Marine Article 17 Habitats Features | DataMapWales (gov.wales)

Figure B2. Habitat mapping for the area

C Wave Modelling

C.1 Model set up

Wave transformation modelling has been carried out to propagate offshore waves, inshore. This modelling was undertaken with the MIKE21 Spectral Wave (SW) software developed by the Danish Hydraulic Institute (DHI).

C.1.1 Regional wave model setup

A regional hindcast model was developed to simulate the wave climate in Tremadog Bay. The hindcast model extends across Cardigan Bay over an area of approximately 70 km by 40 km (see Figure C1). The grid resolution varies from 4 km at the offshore boundary and reduces to 200 m close to Traeth Crugan (Figure C1).

Model bathymetry

The regional model mesh and a zoomed in version of the model mesh showing the study area is shown in Figure C3. The model bathymetry is based on data from a range of sources including:

- LiDAR data[13]
- MMO survey data of Tremadog Bay [14]
- EMODnet data[15].

The LiDAR data was surveyed in 2018 and has a resolution of 20-50 m. The MMO survey of Tremadog Bay has an 18 m resolution and was surveyed in 2007. Bathymetry for Cardigan Bay was downloaded from EMODnet and has a resolution of 140 m.

13 https://datamap.gov.wales/maps/lidar-viewer/
14 https://seabed.admiralty.co.uk/
15 https://emodnet.ec.europa.eu/en

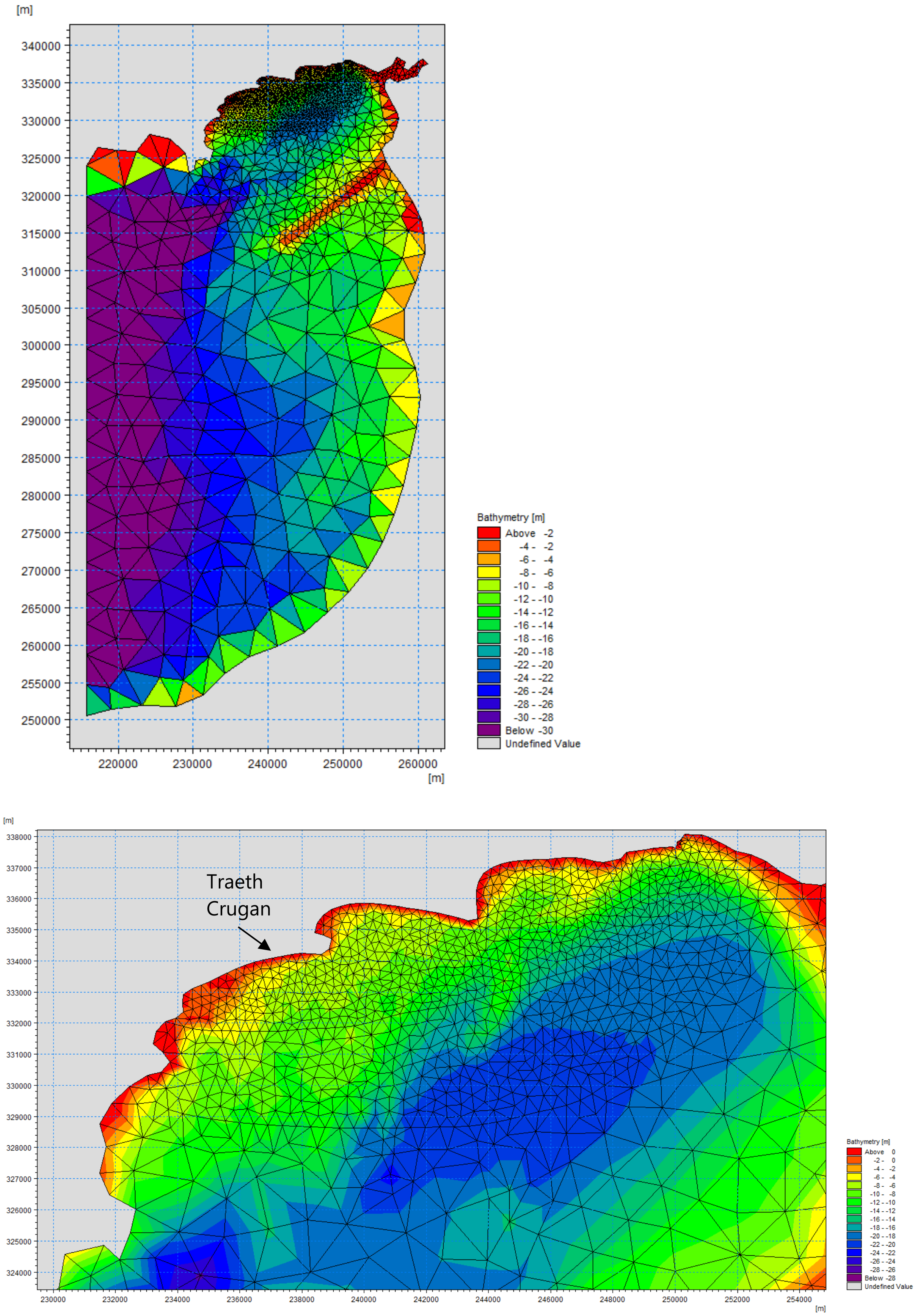


Figure C1. Hindcast Spectral Wave (SW) model mesh and bathymetry

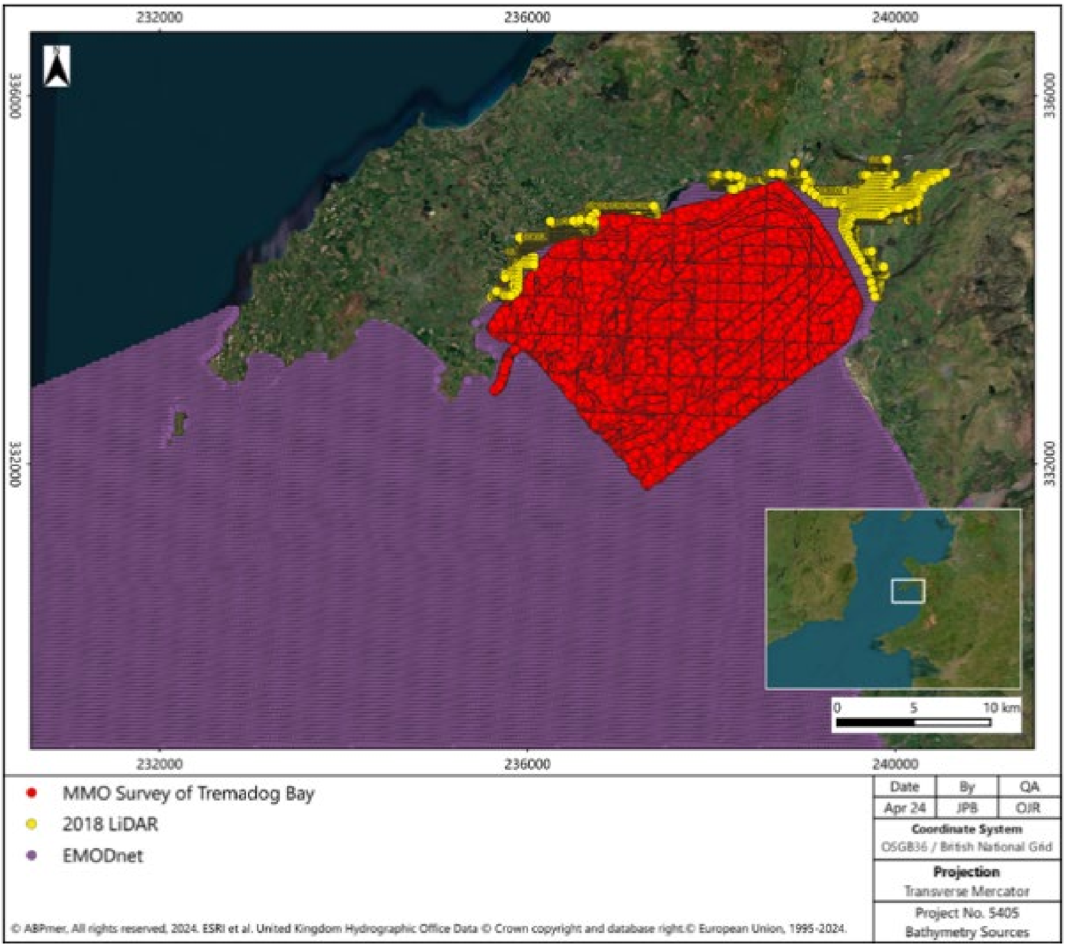


Figure C2. Model bathymetry data sources

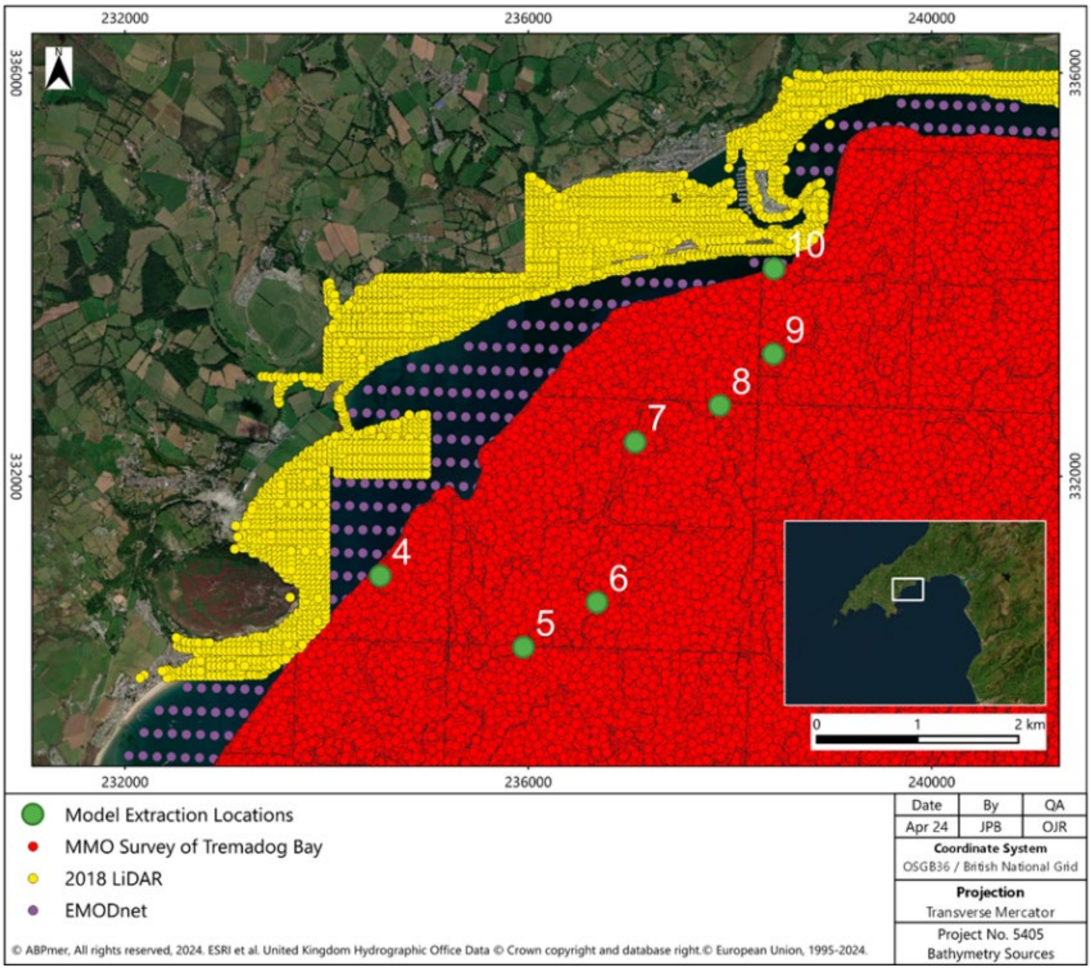


Figure C3. Model bathymetry data sources and model extraction locations, zoomed in

Offshore waves

The hindcast model was driven by a time-series of wave parameters from ABPmer's SEASTATES hindcast at the boundary across the entrance of Cardigan Bay (ABPmer, 2013). These parameters included significant wave height, peak wave period, mean wave direction and directional standard deviation (which provides an indication of wave spreading) for both wind-sea and swell parameters.

Figure C4 shows the wave and wind rose at a point along the model boundary to St George's Channel. This data is derived from the SEASTATES model which includes long-term, high-resolution wave hindcast databases for the UK shelf. The dominant wave direction is from the south-West (around 70% of the time), typically with significant wave heights <1.5 m. Wind direction is more variable but is predominantly between the West and south directions.

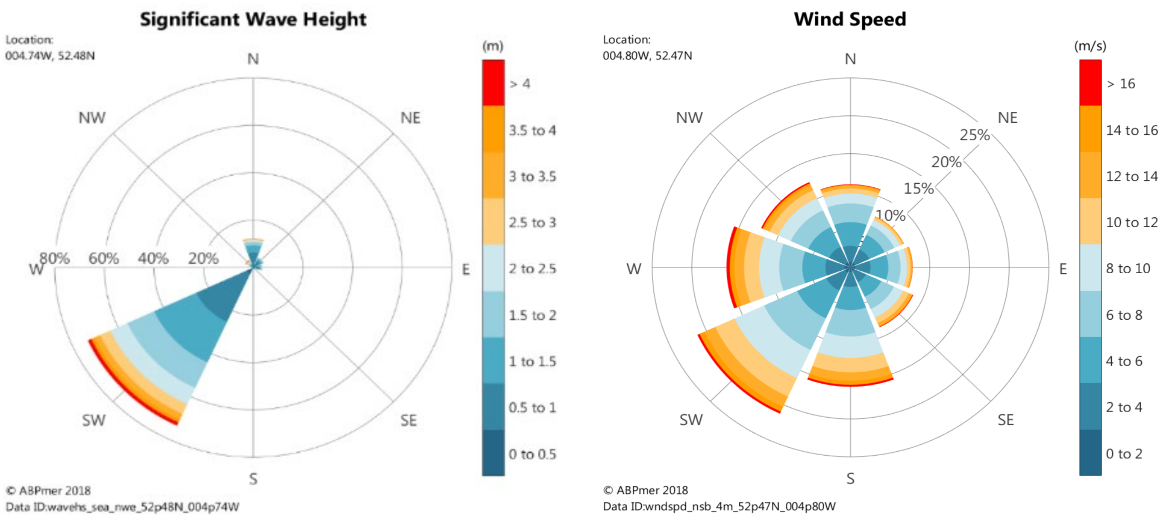


Figure C4. Wave and wind rose at model boundary

Model runs

The hindcast was run for the 37-year period between 1979 and 2015 inclusive. The model was run in fully spectral formulation with twenty-six 10 degrees directional bins between 40 and 300 degrees.

C.1.2 Nearshore waves

The wave conditions were extracted from the 37 year hindcast at seven locations along the West Beach. The locations of these nearshore points are shown in Figure C3 and tabulated in Table C1, together with the model bathymetry. This data is used to both explore the nearshore wave climate and the propagation of waves across the Traeth Crugan.

To provide an indication of spatial variations in the wave climate in Cardigan Bay, map plots of significant wave height are provided in Figure C5. The plots show conditions on 2 March 1997 when wave conditions were typical of a 1 in 1 year return period event for waves from the southwest and on 12 January 2010 when wave conditions were typical of a 1 in 1 year return period event for waves from the southeast. Waves from the East are limited by the short fetch length in this direction, and the shallow bathymetry of Sarn Badrig.

Table C1. Nearshore points location.

Nearshore Point	Easting (m OSGB)	Northing (m OSGB)	Depth (m MSL)
4	234532.179	331012.946	-7.53
5	235953.076	330306.141	-7.28
6	236681.741	330750.627	-7.84
7	237060.646	332339.116	-6.57
8	237898.611	332703.449	-7.53
9	238430.536	333213.514	-7.33
10	238437.832	334058.765	-6.97

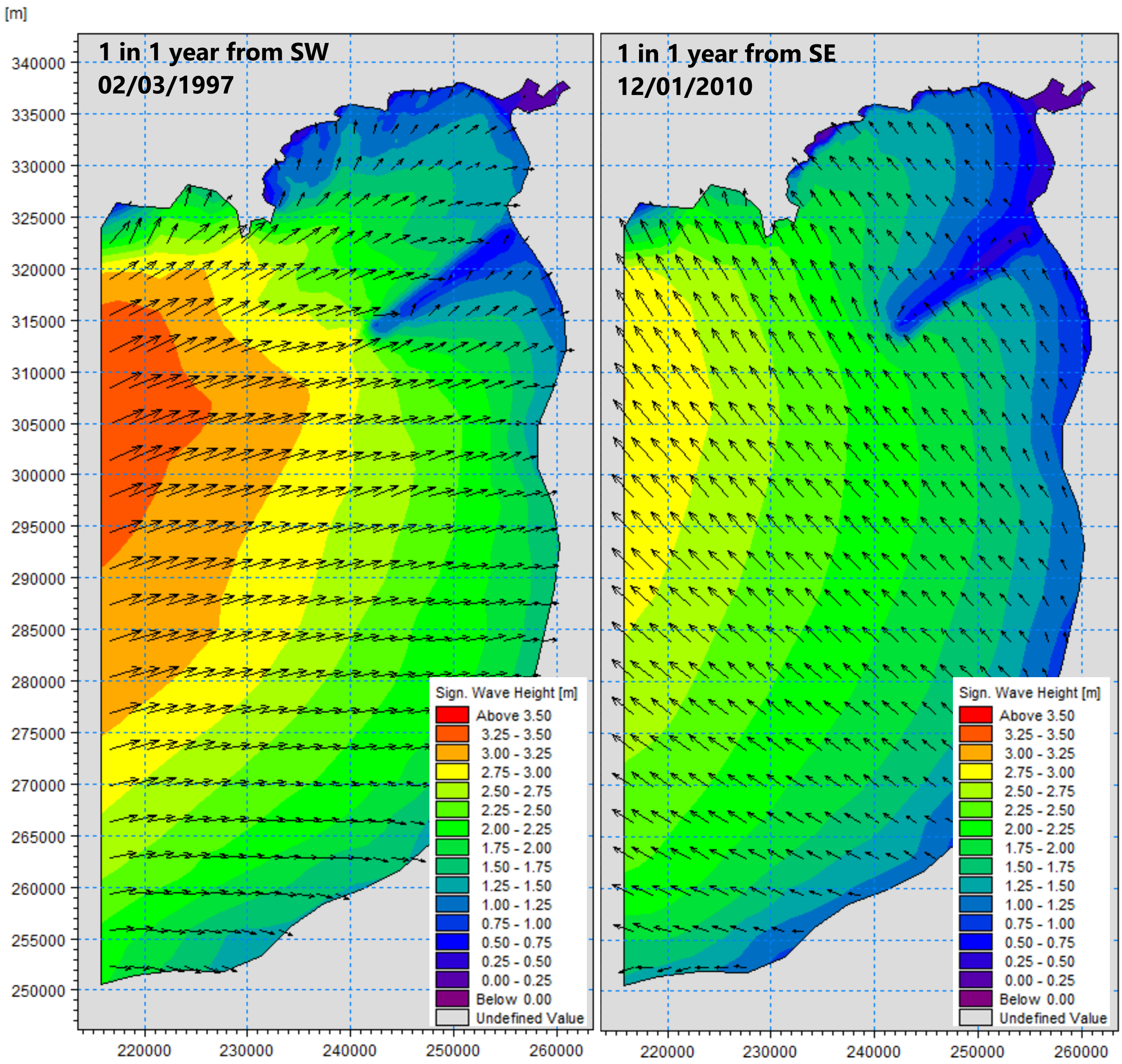


Figure C5. Map plots of wave conditions in Cardigan Bay for a 1 in 1 year wave condition

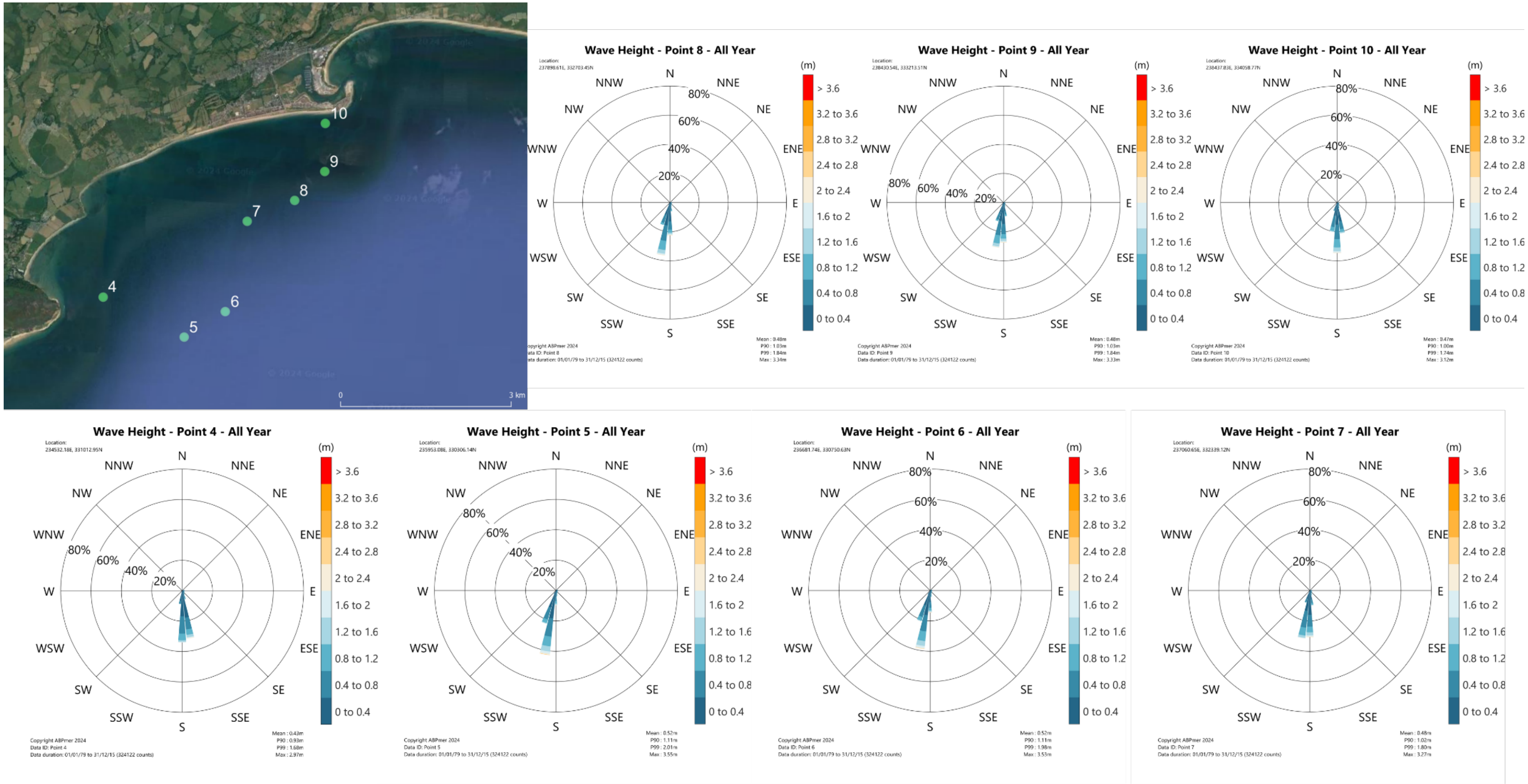
Wave roses for the nearshore Points 4 to 9 are provided in Figure C6 . These plots demonstrate the manner in which waves refract as they propagate inshore. Frequency tables for three locations have been provided in the next section as well as rose plots for all months for Point 7.

C.2 Frequency tables for nearshore Points 4, 7 and 9

This section contains the frequency tables at the three nearshore Points 4, 7 and 9 (see Figure C3 for locations). The exceedance tables are provided for both, significant wave height, Hs, vs. mean direction, Mdir (Figure C7, Figure C9 and Figure C11) and for Hs vs peak period, Tp (Figure C8, Figure C10 and Figure C12).

The tables are based on 37 years of data (01/01/1979 to 31/12/2015) at 1-hour intervals (324,122 data values), where:

- [Cumulative Sum (Cum. Sum)] is the cumulative total sum of counts/proportion time up to the corresponding upper bound value.
- [Exceedence (Exced.)] is the cumulative total sum of counts/proportion at or above the corresponding upper bound value.



Source: Baseline satellite image: 2024 CNES / Airbus through Google Earth

Figure C6. Wave roses (annual) for Points 4, 5, 6, 7, 8, 9 and 10

Point 4 - Hs Mdir Scatter Table - All Year - Percentage (occurences as proportion of all time in year)

Significant Wave Height, Hs (m) / Mean Wave Direction, Mdir (degN, Coming)

Lower (>=)		345	15	45	75	105	135	165	195	225	255	285	315		Cum.	
	Upper (<)	15	45	75	105	135	165	195	225	255	285	315	345	Sum	Sum	Exced.
3.5	4.0														100.00	0.00
3.0	3.5								0.00					0.00	100.00	0.00
2.5	3.0							0.00	0.03					0.03	100.00	0.00
2.0	2.5							0.07	0.28					0.35	99.97	0.03
1.5	2.0						0.00	0.29	1.48					1.77	99.61	0.39
1.0	1.5					0.00	0.03	1.20	5.73					6.96	97.84	2.16
0.5	1.0				0.00	0.05	0.25	4.63	19.95	0.03				24.90	90.88	9.12
0.0	0.5	1.93			0.53	1.78	2.81	12.81	45.90	0.22				65.97	65.97	34.03
Sum		1.93			0.54	1.83	3.09	19.00	73.37	0.25				100.00		

Figure C7. Hs Mdir scatter table - All year - Point 4

Point 4 - Hs Tp Scatter Table - All Year - Percentage (occurences as proportion of all time in year)

Significant Wave Height, Hs (m) / Peak Wave Period, Tp (s)

Lower (>=)		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		Cum.	
	Upper (<)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Sum	Sum	Exced.
3.5	4.0																												100.00	0.00
3.0	3.5							0.00		0.00		0.00																0.00	100.00	0.00
2.5	3.0							0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00													0.03	100.00	0.00
2.0	2.5						0.13	0.13	0.02	0.02	0.02	0.01	0.02	0.00	0.00	0.00												0.35	99.97	0.03
1.5	2.0					0.02	0.85	0.27	0.19	0.20	0.12	0.03	0.06	0.02	0.01	0.00	0.00	0.00		0.00	0.00							1.77	99.61	0.39
1.0	1.5				0.02	1.24	2.01	1.32	1.15	0.65	0.27	0.06	0.11	0.05	0.03	0.01	0.01	0.02	0.02	0.00	0.00							6.96	97.84	2.16
0.5	1.0			0.07	2.39	6.28	4.87	3.61	2.23	1.53	1.09	0.41	0.92	0.50	0.25	0.25	0.11	0.15	0.17	0.03	0.05	0.00	0.00	0.00				24.90	90.88	9.12
0.0	0.5	1.93	2.56	3.43	5.63	7.40	6.27	6.54	6.94	6.53	5.74	2.02	3.55	2.38	1.40	1.79	0.66	0.52	0.46	0.06	0.13	0.02	0.01	0.02	0.00	0.00		65.97	65.97	34.03
Sum		1.93	2.56	3.49	8.03	14.94	14.12	11.89	10.53	8.94	7.24	2.53	4.66	2.95	1.69	2.06	0.78	0.69	0.64	0.09	0.19	0.03	0.01	0.02	0.00	0.00		100.00		
Cumulative Sum		1.93	4.49	7.98	16.02	30.96	45.08	56.97	67.49	76.43	83.67	86.21	90.87	93.82	95.51	97.56	98.34	99.03	99.67	99.76	99.94	99.97	99.98	100.00	100.00	100.00	100.00			
Exceedence		98.07	95.51	92.02	83.98	69.04	54.92	43.03	32.51	23.57	16.33	13.79	9.13	6.18	4.49	2.44	1.66	0.97	0.33	0.24	0.06	0.03	0.02	0.00	0.00	0.00	0.00			

Figure C8. Hs Tp scatter table - All Year - Point 4

Point 7 - Hs Mdir Scatter Table - All Year - Percentage (occurences as proportion of all time in year)															
		Mean Wave Direction, Mdir (degN, Coming)													
Significant Wave Height, Hs (m) Lower (>=)		345	15	45	75	105	135	165	195	225	255	285	315		Cum.
	Upper (<)	15	45	75	105	135	165	195	225	255	285	315	345	Sum	Sum	Exced.
3.5	4.0														100.00	0.00
3.0	3.5							0.00						0.00	100.00	0.00
2.5	3.0						0.00	0.05						0.05	100.00	0.00
2.0	2.5					0.00	0.01	0.41	0.00					0.43	99.94	0.06
1.5	2.0					0.02	0.08	2.01	0.00					2.11	99.52	0.48
1.0	1.5				0.02	0.08	0.43	7.25	0.11					7.89	97.41	2.59
0.5	1.0			0.05	0.54	0.78	2.17	20.64	1.72	0.01				25.91	89.52	10.48
0.0	0.5	1.26	0.00	0.66	3.67	3.34	4.88	42.02	7.70	0.09	0.00	0.00	0.00	63.61	63.61	36.39
Sum		1.26	0.00	0.71	4.22	4.22	7.57	72.38	9.53	0.10	0.00	0.00	0.00	100.00		

Figure C9. Hs Mdir scatter table - All year - Point 7

Point 7 - Hs Tp Scatter Table - All Year - Percentage (occurences as proportion of all time in year)																													
		Peak Wave Period, Tp (s)																											
Significant Wave Height, Hs (m) Lower (>=)		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		Cum.	
	Upper (<)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Sum	Sum	Exced.
3.5	4.0																											100.00	0.00
3.0	3.5									0.00	0.00	0.00															0.00	100.00	0.00
2.5	3.0							0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00												0.05	100.00	0.00
2.0	2.5						0.02	0.09	0.05	0.08	0.09	0.03	0.04	0.02	0.00	0.00	0.00				0.00						0.43	99.94	0.06
1.5	2.0					0.03	0.38	0.29	0.34	0.45	0.33	0.09	0.13	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00						2.11	99.52	0.48
1.0	1.5				0.04	1.35	1.10	1.27	1.50	1.07	0.56	0.14	0.35	0.19	0.09	0.07	0.03	0.05	0.05	0.01	0.02	0.00	0.00	0.00			7.89	97.41	2.59
0.5	1.0			0.36	3.75	2.93	2.78	3.19	2.99	2.67	2.08	0.85	1.63	0.88	0.44	0.50	0.24	0.23	0.27	0.03	0.07	0.01	0.00	0.01	0.00		25.91	89.52	10.48
0.0	0.5	1.26	3.46	5.46	3.52	5.11	5.89	7.08	7.84	6.81	5.52	1.95	3.18	2.06	1.31	1.56	0.62	0.43	0.38	0.05	0.11	0.01	0.00	0.01	0.00		63.61	63.61	36.39
Sum		1.26	3.46	5.82	7.31	9.41	10.17	11.93	12.73	11.09	8.59	3.06	5.33	3.18	1.86	2.14	0.89	0.72	0.70	0.10	0.20	0.02	0.01	0.02	0.00		100.00		
Cumulative Sum		1.26	4.72	10.54	17.85	27.26	37.43	49.36	62.09	73.19	81.78	84.83	90.17	93.34	95.20	97.34	98.23	98.95	99.65	99.75	99.95	99.97	99.98	100.00	100.00	100.00			
Exceedence		98.74	95.28	89.46	82.15	72.74	62.57	50.64	37.91	26.81	18.22	15.17	9.83	6.66	4.80	2.66	1.77	1.05	0.35	0.25	0.05	0.03	0.02	0.00	0.00	0.00			

Figure C10. Hs Tp scatter table - All Year - Point 7

Point 9 - Hs Mdir Scatter Table - All Year - Percentage (occurences as proportion of all time in year)																
		Mean Wave Direction, Mdir (degN, Coming)														
Significant Wave Height, Hs (m) Lower (>=)		345	15	45	75	105	135	165	195	225	255	285	315		Cum.	
	Upper (<)	15	45	75	105	135	165	195	225	255	285	315	345	Sum	Sum	Exced.
3.5	4.0														100.00	0.00
3.0	3.5							0.00						0.00	100.00	0.00
2.5	3.0						0.00	0.07						0.07	100.00	0.00
2.0	2.5					0.00	0.01	0.47	0.00					0.49	99.92	0.08
1.5	2.0					0.01	0.06	2.12	0.02					2.22	99.44	0.56
1.0	1.5				0.01	0.07	0.31	7.21	0.39					7.99	97.21	2.79
0.5	1.0			0.00	0.45	0.63	1.98	19.06	3.97	0.02				26.11	89.22	10.78
0.0	0.5	1.29	0.00	0.23	3.46	3.28	4.67	39.18	10.90	0.09	0.00			63.11	63.11	36.89
Sum		1.29	0.00	0.24	3.91	4.00	7.03	68.11	15.29	0.11	0.00			100.00		

Figure C11. **Hs Mdir scatter table - All year - Point 9**

Point 9 - Hs Tp Scatter Table - All Year - Percentage (occurences as proportion of all time in year)																													
		Peak Wave Period, Tp (s)																											
Significant Wave Height, Hs (m) Lower (>=)		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		Cum.	
	Upper (<)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Sum	Sum	Exced.
3.5	4.0																											100.00	0.00
3.0	3.5									0.00	0.00	0.00		0.00													0.00	100.00	0.00
2.5	3.0							0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00											0.07	100.00	0.00
2.0	2.5						0.02	0.10	0.06	0.10	0.10	0.03	0.06	0.02	0.01	0.00	0.00				0.00						0.49	99.92	0.08
1.5	2.0					0.02	0.38	0.31	0.38	0.48	0.35	0.09	0.12	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.00						2.22	99.44	0.56
1.0	1.5				0.05	1.34	1.01	1.28	1.51	1.07	0.57	0.15	0.39	0.22	0.11	0.09	0.04	0.05	0.06	0.01	0.02	0.00	0.00	0.00			7.99	97.21	2.79
0.5	1.0			0.37	3.93	2.72	2.33	2.95	3.06	2.91	2.27	0.95	1.75	0.94	0.48	0.55	0.27	0.25	0.29	0.04	0.07	0.01	0.00	0.00	0.00		26.11	89.22	10.78
0.0	0.5	1.29	3.38	5.29	3.62	4.96	5.60	6.90	7.79	6.92	5.58	2.02	3.20	2.09	1.31	1.57	0.62	0.43	0.37	0.05	0.11	0.01	0.00	0.01			63.11	63.11	36.89
Sum		1.29	3.38	5.65	7.60	9.04	9.33	11.54	12.82	11.50	8.89	3.25	5.53	3.31	1.92	2.21	0.92	0.74	0.72	0.10	0.20	0.02	0.01	0.02	0.00		100.00		
Cumulative Sum		1.29	4.67	10.32	17.92	26.96	36.29	47.83	60.65	72.15	81.03	84.28	89.81	93.13	95.05	97.26	98.18	98.92	99.64	99.75	99.95	99.97	99.98	100.00	100.00	100.00			
Exceedence		98.71	95.33	89.68	82.08	73.04	63.71	52.17	39.35	27.85	18.97	15.72	10.19	6.87	4.95	2.74	1.82	1.08	0.36	0.25	0.05	0.03	0.02	0.00	0.00	0.00			

Figure C12. **Hs Tp scatter table - All Year - Point 9**

C.2.1 Monthly wave roses for Point 7

Monthly wave roses for Location 7, are also provided in Figure C13, in order to see the variation of the nearshore waves during different months.

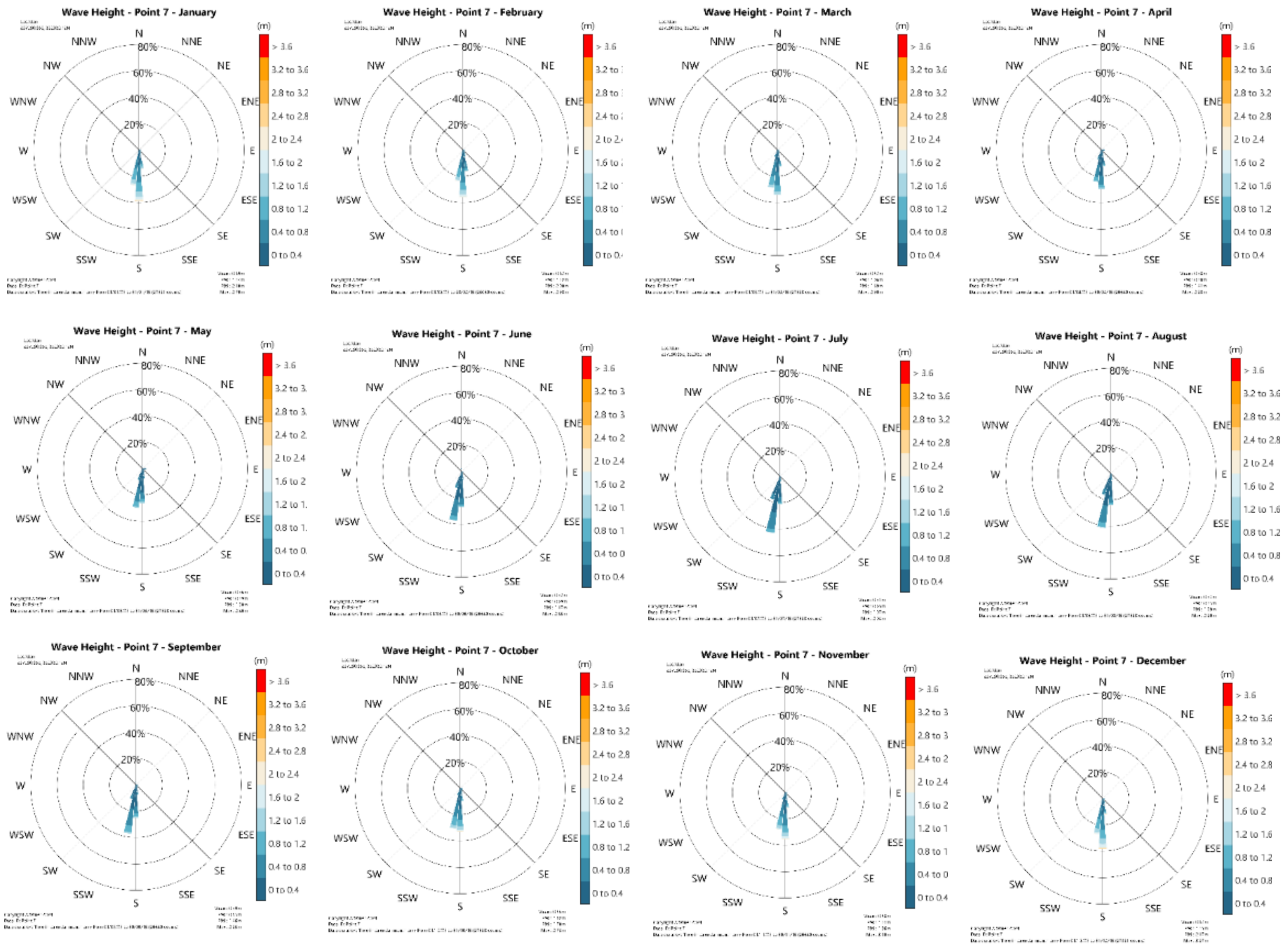
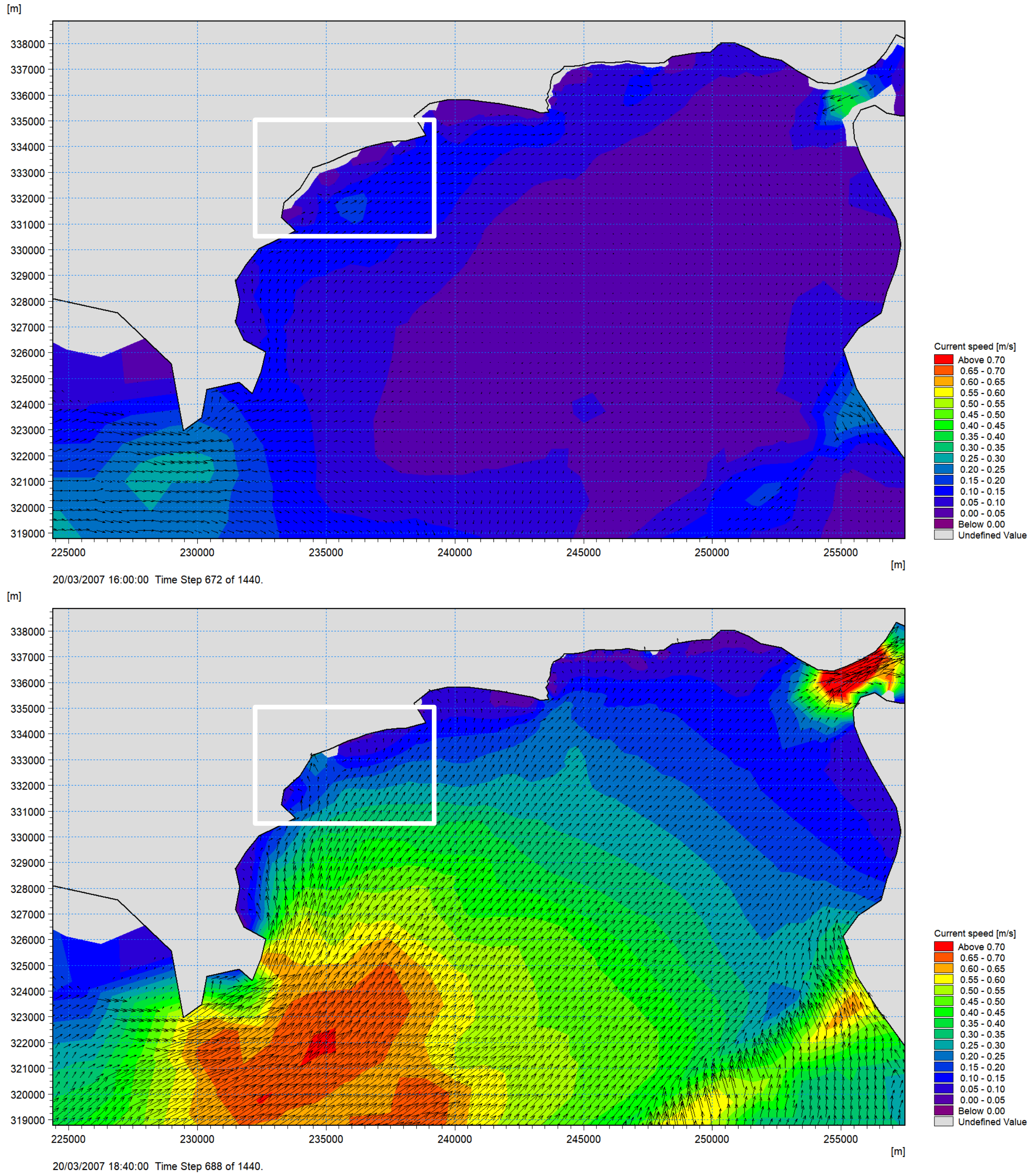


Figure C13. **Monthly wave roses for Point 7**

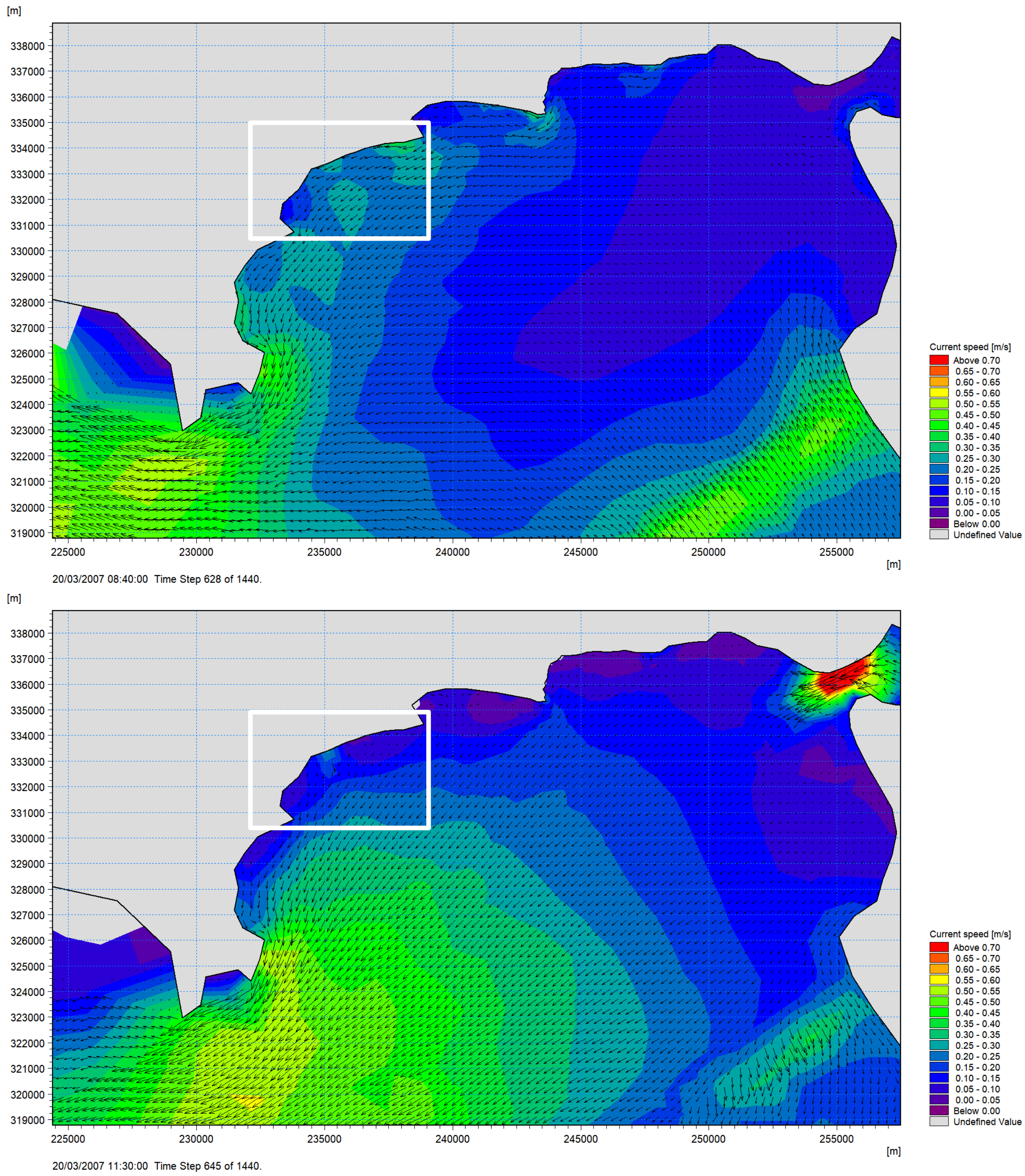
D Flow Modelling Results

Figure D1 and Figure D2 show the flows through Tremadog Bay, at four states of the tide; Low Water (LW), Mid Flood (MF), High Water (HW), and Mid Ebb (ME) during a large spring tide in March 2007. Tide timings are in relation to water level at Pwllheli. The results are for the largest tidal range typically experienced in a year and illustrates a potential annual maximum flow regime; lower flow speeds will be experienced over a typical tide.



Source: ABPmer inhouse hydrodynamic model

Figure D1. Tidal flows off the study frontage (Top: Low Water; Bottom: Mid Flood)



Source: ABPmer inhouse hydrodynamic model

Figure D2. Tidal flows off the study frontage (Top: High Water; Bottom: Mid Ebb)

E Historical Dredging Operations

It has been recognised (DHRD, 2011) that since the development of the Marina in Pwllheli Harbour in 1991 and the construction of the training arm, there has been a need to remove material from the harbour entrance to maintain navigation and that this will have to be dredged in perpetuity. It is expected that this will have to be undertaken at least once every two years, possibly more frequently depending on prevailing weather conditions. The recommendation is for local removal by land-based plant with material either stockpiled or immediately reused as beach re-charge material.

Records of dredging since 1992 are provided in Table E1, as well as records of the stockpile volume.

Table E1. Dredging volumes and dates for Pwllheli harbour, together with stockpile volumes of dredging material at Careg y Imbill pile

Data Source	Year	Dredging Volumes	Stockpile Volume	Date of Dredging
A	**1992**	8,000 m³		March 1992
A	**1994**	26,000 m³		August 1994
A	**1996**	12,000 m³		January 1996
A	**1997**	3,000 m³	6,000 m³	
A	**1998**		9,000 m³ Used 4600 m³ for construction of stilling lagoon adjacent to Morfa'r Gareg	
A	**2000**		Material used for emergency repairs in Abererch. 4,400 m³	
A	**2001**	Small dredge	5,000 m³	
A	**2001/2**	Total dredged: 47,500 m³	After dredging and nourishment 13,000 m³	
B	**2013**	13,500 m³		Spring 2013
B	**2015**	11,00 m³		Spring 2015
B	**2016**	9,500 m³		Spring 2016
B	**2017**	11,000 m³		Spring 2017
B	**2018**	13,000 m³		Spring 2018
B	**2021**	18,000 m³		Spring 2021
B	**2022**	21,000 m³		Spring 2022
B	**2023**	13,500 m³		Spring 2013

Source A: Cyngor Gwynedd Council, 2002; Source B: YGC Data (Perss Comm)

DHRD (2011) states that material which accumulates at the entrance of the harbour is the consequence of the Easterly littoral drift mechanism across the frontage as far West as Carreg y Defaid. They also state that the material which accumulates at the harbour entrance is the heavier fraction of material being moved by the littoral system and is clean sand and gravel with the lighter material being carried further into the harbour. Faber Maunsell Aecom (2008) examined samples of material dredged from the harbour entrance in 2006 and identified sand and gravel material with a D50 of between 2 and 3 mm, suggesting that material that had arrived here from the Traeth Crugan/South Beach frontage is, as would be expected from the lower parts of the beach.

F Site Visit

A site visit was conducted on 22 February 2024 at 13:00 hr. The waves conditions on the beach were calm and the tide was low (close to neaps). Representatives of YGC/CGC accompanied the team.

We walked East to West, looking at the renourishment and the revetment (a structural inspection was not carried out) to get an understanding of the area and the processes operating there. Photos are included in the appendix from East to West.

The area renourished was always denuded of vegetation, see for example Figure F1, where the steep berm of the renourishment is apparent. The renourishment material is clearly identified as the area without vegetation.

Figure F1. Left: Looking East towards the start of the renourishment at the East. Right: same location looking West

F.1 Eastern area of renourishment

The Eastern part of the renourishment is lower than the Western part, as it will be seen in the photos. The photos below show slumping of the renourishing material and the nearly vertical face of the renourishment.

The renourishment material was a mix of gravel and sand. The surficial beach material, at the base of the nourishment, was mostly sand on this part of the beach. Towards the water line, there seemed to be patches of fine gravel material on top of the sand. The front face of the renourishment area to the East of the Eastern end of the revetment was not as vertical, see Figure F3, and the height of the top of the renourishment was higher than in the Eastern end (Figure F1). In Figure F3, it is appreciated how as soon as the revetments starts the vegetation is very abundant.

Figure F2. **Left: Looking East towards the start of the renourishment at the East. Right: same location looking West**

Figure F3. **Renourishment area to the East of the Eastern end of the revetment. Left: Looking East Right: Looking West**

F.2 Revetment

The rocks at the Eastern end of the revetment have fallen, see Figure F4.

Figure F4. Left: Looking towards the East; Right: looking down onto the beach

Figure F5 shows how the toe of the revetment has lost rocks. It also shows a cyclical pattern of the shingle on the sand on the beach associated with beach cusps on the edge of the beach.

Figure F5. Looking down onto the beach

YGC/CGC representatives pointed to the repair work carried out in 2017 where about 200 bags of material from the harbour were placed on the top of the revetment (see Figure F6) and covered with sediment. The sediment is now long gone and although some bags have holes in them, most of them have remained intact. Anecdotally, the overtopping in this part of the revetment has been known to be higher than an average person's height on top of the revetment.

Figure F6. Repair work with bags full of dredged sediment

There were also signs of the geotechnical lining coming through at points, see Figure F7.

Figure F7. Geotechnical material coming through the rocks

Figure F8. **Left: Looking West. Right: looking down on to the beach towards the East**

Figure F9 shows in plan view the area where the bags were placed. It also shows the area adjacent to it, where there is very high vegetation and no access. This area is not known to suffer from overtopping (referred as OT in the figure).

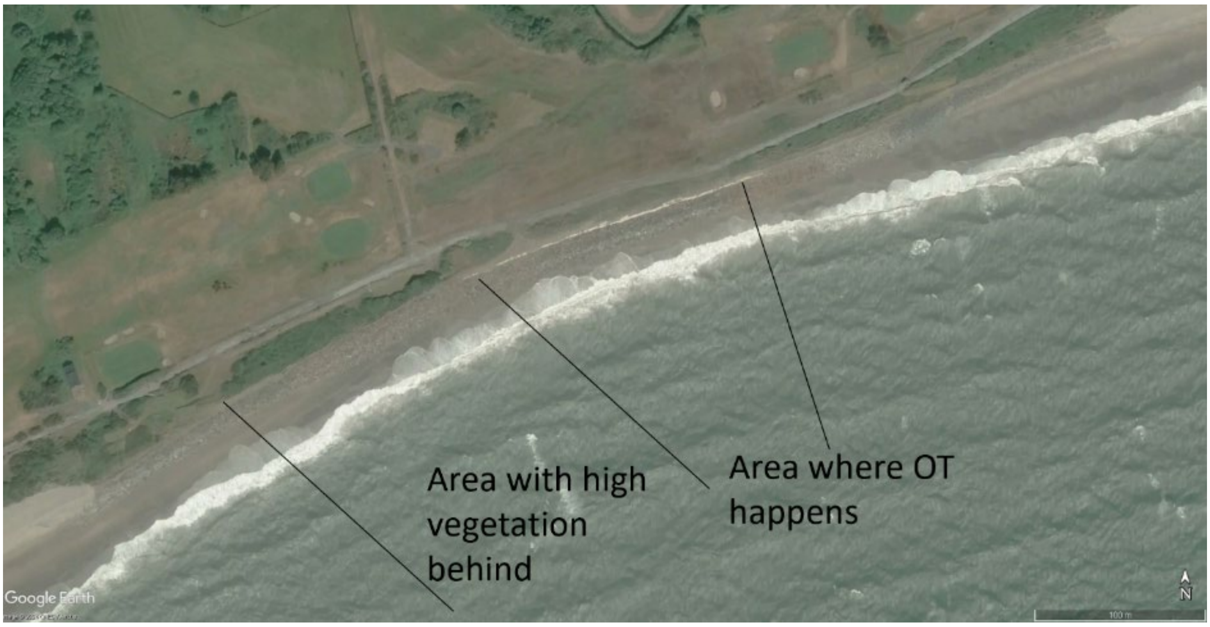


Figure F9. **Different areas of the revetment**

Figure F10. **Area with high vegetation. Left: Looking towards the West. Right: Looking towards the West.**

Figure F11 shows the Western end of the revetment, where at its base some displaced rocks can be seen. The Client representatives identified that the end of the gravel beach, as shown in this photo, is located at the base of the renourishment.

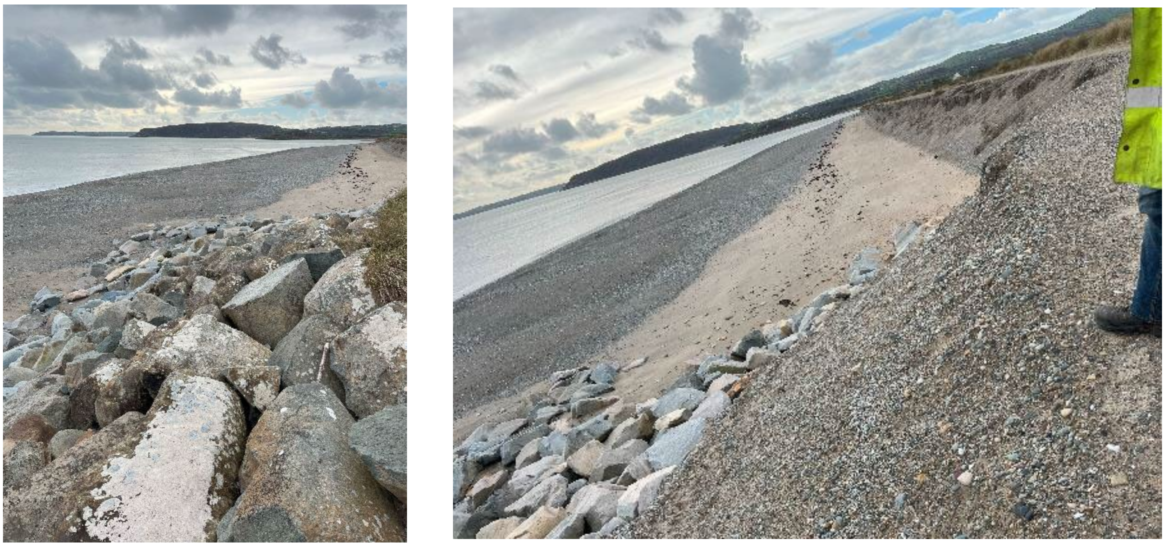


Figure F11. Western end of the revetment. Looking towards the West.

F.3 Western area of the renourishment.

Figure F12 show the start of the Western area of the renourishment. It shows the vertical face of the shoreface, the lack of vegetation on the renourished material and the beach at the toe of the renourishment.

Figure F12. Start of the renourishment at the West.

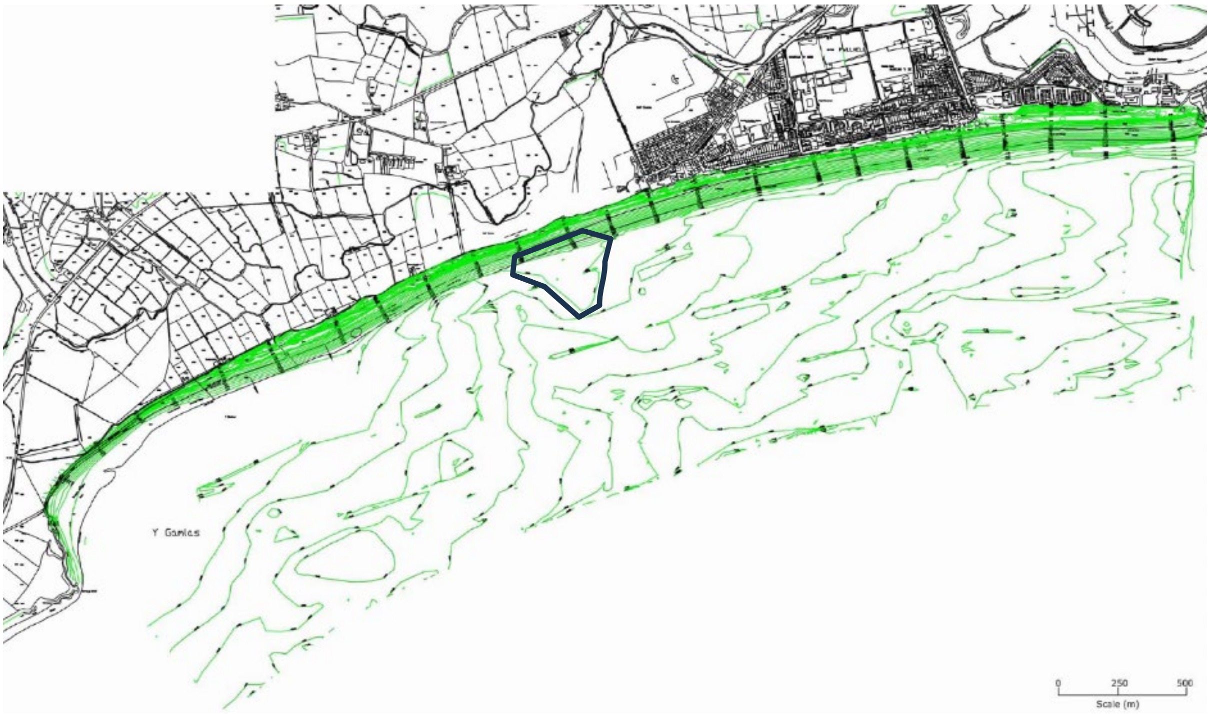
Going towards the West, similar features are also encountered, see Figure F13.

Figure F13. Renourishment in the Westen area (to the West of the revetment) Left: Looking towards the West. Right: Looking towards the East.

F.4 General observations

Halfway along the revetment, when looking towards the West, a change in the orientation of the shoreline is observed, as seen in Figure F14. It is not clear whether this is a bulge in the shoreline midway along the frontage, or a cut back in the shoreline within the foreground. In the only available nearshore survey of the beach, from Faber Maunsell Aecom 2008, reproduced here in Figure F15, one can see a shallow area by Pwllheli Golf Course, in between the clubhouse and the Eastern end of the revetment. Shoals, such as this in the nearshore will introduce localised changes in wave refraction and introduce more complex flow patterns, which may result in material being eroded from some areas with accretion in other areas. This then leads to local changes in the orientation of the coast. In this instance this could be reducing the beach level in front of the Eastern of the revetment which is subjected to the greatest overtopping revetment (see Figure F9). Such beach lowering will subject the revetment to greater wave energy and thus overtopping. Hence, it is important to understand the location and changes to the shoals in the nearshore region.

Figure F14. Looking towards the East half way from the revetment



Note: Original document does not have clear labels for the contours

Figure F15. Nearshore contours (Faber Maunsell Aecom 2008) (Blue outline shows shallow area mentioned).

G Sediment Sampling Data

As part of the monitoring efforts of YGC, sediment analysis has been undertaken on collected beach samples. At Traeth Crugan, beach, superficial sediment samples were collected at Profile 69, 70 and 71 (see location in Figure G1) in 2003 (Cartographical Surveys, 2003) and 1997 (CGC, 1997).

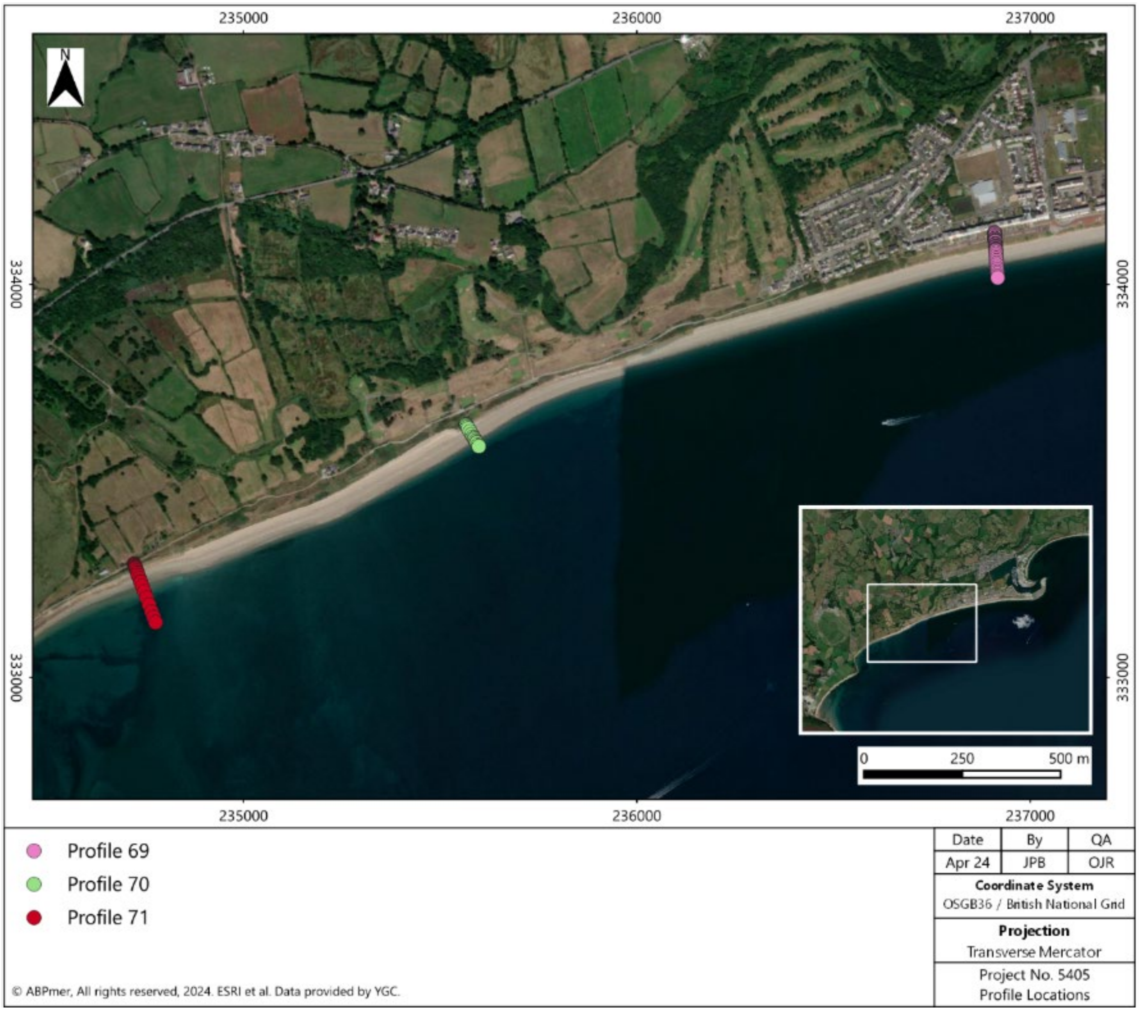


Figure G1. Location of Profiles 69, 70 and 71 provided by YGC

Samples were collected at four different locations across the beach (HAT, MHWS, MHWN and MSL). The sediment grading curves for the collected samples are shown in Figure G2, Figure G3 and Figure G4; for the 2003 sample the description given in the sampling report is also given.

Most of the samples have a bimodal shape, with one mode in the sand and the other in the gravel and one sample (at profile 70, in 2003 at MSL) is trimodal (sand, gravel and cobbles). There are also a couple of samples that are only sand (HAT and MHWS in profile 69 in 1997).

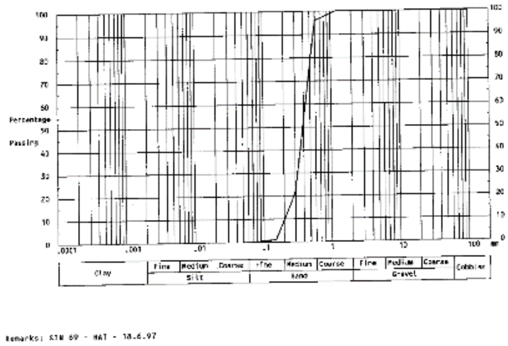
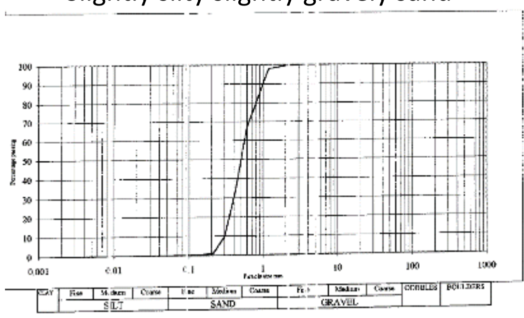
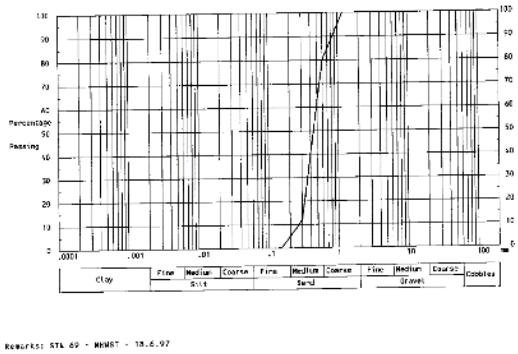
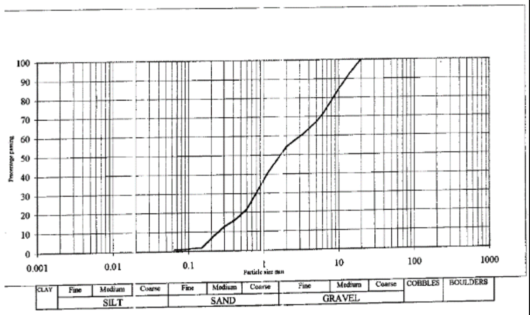
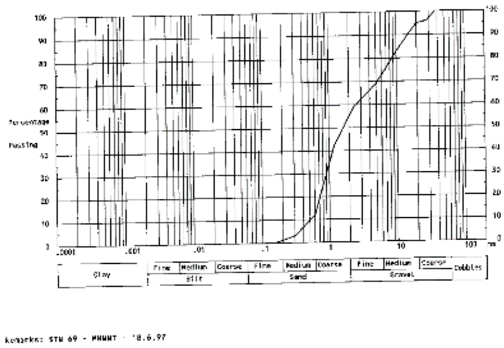
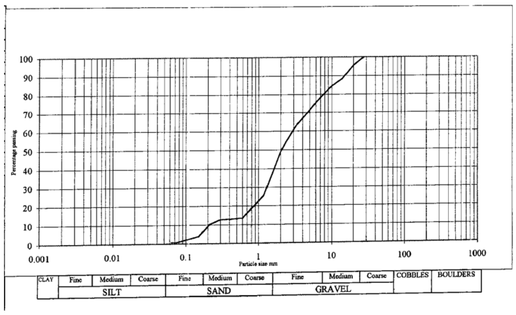
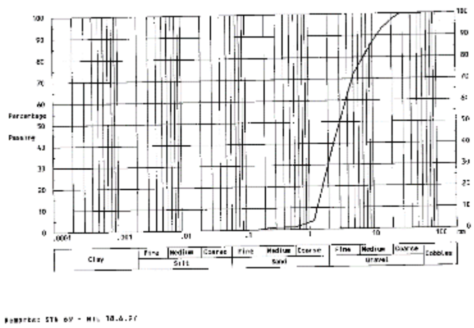
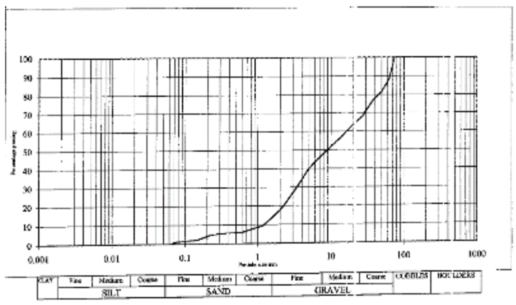
A mixed beach such as Criccieth West shore will show variation of the sediment composition between the different gradings, both spatially and temporally along the beach, dependent on how the different sediment fractions (mainly sand and gravel) have been transported by the proceeding wave conditions.

These samples therefore represent a single snapshot in time of the sediments in the surface and changes can be expected along the frontage. Some of these changes are observed when comparing the samples from the two different years.

Quoting a single median size, $D_{50,}$ in bimodal or trimodal samples is not useful, as in most cases the sediment size of the D_{50} will not be abundant on the beach. It is advisable instead to quote the D_{50} of each of the fraction present as well as a percentage of each fraction. This has been calculated for the 2017 and 2003 samples and reported in Table G1. The variability of these values is quite high and it is difficult to draw conclusions from these onto the "representative" sediment sizes and fractions on Traeth Crugan. The day of the site visit (see Appendix F) the superficial beach was mostly sand with a layer of small gravel on top.

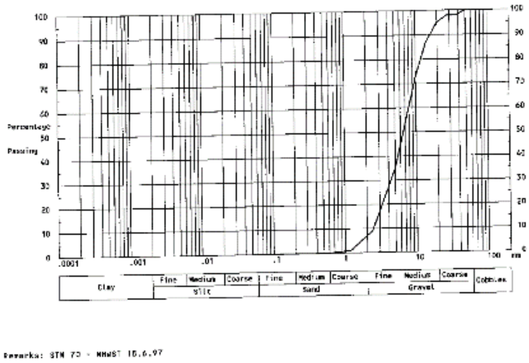
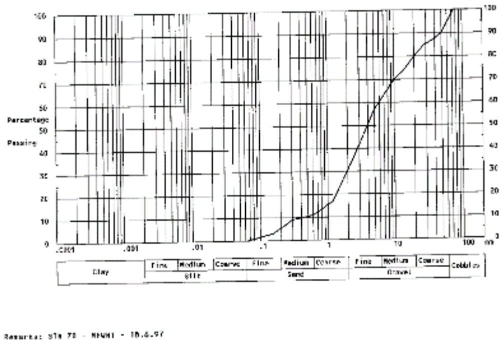
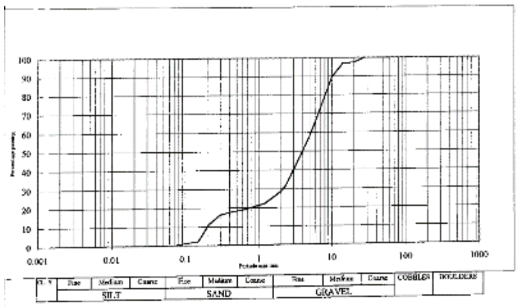
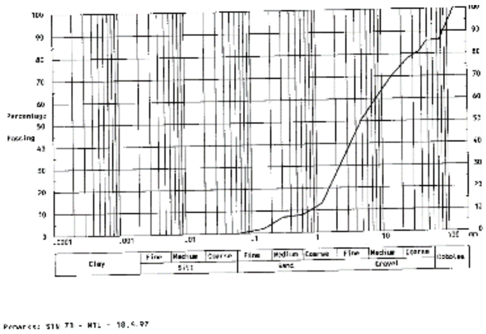
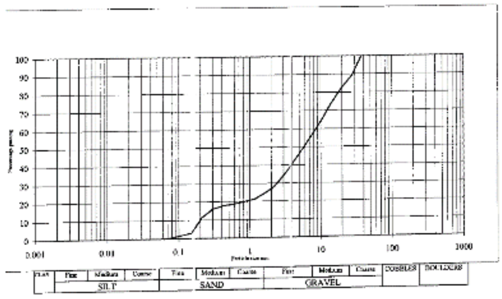
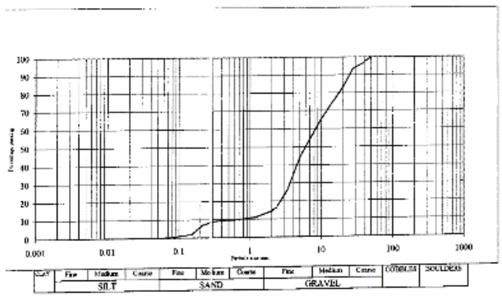
Table G1. Median grain size and percentage of gravel, sand and cobbles of the 1997 and 2003 (in square brackets) sediment samples

Sample	Location	Sand D50 (mm)	Gravel D50 (mm)	Cobbles D50 (mm)	Sand %	Gravel %	Cobbles %
69	HAT	0.4 [0.5]	N/A [N/A]	N/A [N/A]	100 [99.3]	0 [0.5]	0 [0]
	MHWS	0.45 [0.7]	N/A [7.0]	N/A [N/A]	100 [53.4]	0 [45.8]	0 [0]
	MHWN	0.9 [1.1]	9.0 [6.0]	N/A [N/A]	55 [50.9]	45 [48.4]	0 [0]
	MSL	1.5 [2.0]	10.0 [45.0]	N/A [N/A]	30 [70.5]	70 [17.6]	0 [11.9]
70	HAT	1.5	7.0	N/A	7.5	92.5	0
	MHWS	1.0 [0.25]	6.0 [9.5]	70 [N/A]	30 [28.6]	63 [71.4]	7 [0]
	MHWN	1.0 [0.2]	6.5 [25]	100 N/A	27 [26.8]	58 [73.2]	15 [0]
	MSL	0.2	27	[N/A]	[14.2]	[85.6]	[0]
71	HAT	0.8	10.0	N/A	8	92	0
	MHWS	0.8	7.0	N/A	34	66	0

	1997	2003
HAT		Slightly silty slightly gravely sand 
MHWS		Slightly silty sand and gravel 
MHWN		Slightly sand and gravel 
MSL		Very sandy gravel with cobbles 

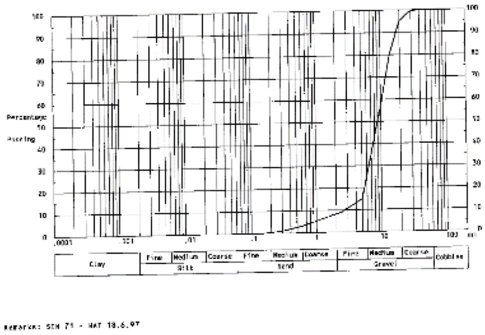
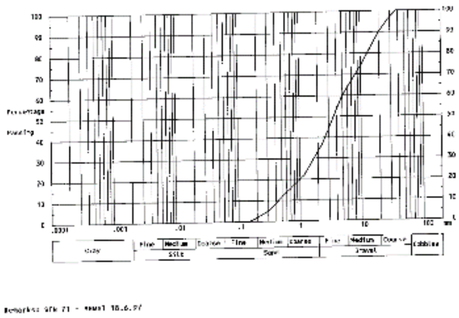
Source: Cartographical Surveys, 2003 and CGC, 1997

Figure G2. Sediment curves Sample 69

	1997	2003
HAT		Not available
MHWS		Sand and gravel 
MHWN		Sand and gravel 
MSL	Not Available	Slightly silty very sandy gravel 

Source: Cartographical Surveys, 2003 and CGC, 1997

Figure G3. Sediment curves Sample 70

	1997	2003
HAT		Not Available
MHWS		Not Available
MHWN	Not Available	Not Available
MSL	Not Available	Not Available

Source: Cartographical Surveys, 2003 and CGC, 1997

Figure G4. Sediment curves Sample 71

H Beach Monitoring Data Available

There are two primary beach monitoring data providers for the frontage along Traeth Crugan, YGC and the Wales Coastal Monitoring Centre (WCMC), as well as the Lidar data provided by the Welsh Government. The type of data, dates and frequency of the surveys are summarised in Table H1. The monitoring locations are provided in Figure H1 to Figure H6.

Table H1. Monitoring data available

Data Provider	Data	Dates
YGC	Point topographic data covering a section of the dry beach at low water. Typical extents are shown in Figure H1 *Horizontal resolution improved over the years (from 2002: about 8 m to 15 m; from 2019: about 5 m)*	2002 -2019. Twice a year, in the autumn and in the spring, specific survey dates are: 23/05/2002, 18/11/2002, 30/04/2003, 21/10/2003, 02/04/2004, 27/10/2004, 09/05/2005, 15/11/2005, 12/05/2006, 04/10/2006, 01/05/2007, 23/10/2007, 18/04/2008, 29/09/2008, 07/04/2009, 07/10/2009, 15/04/2010, 21/09/2010, 06/04/2011, 28/09/2011, 05/04/2012, 27/10/2012, 08/04/2013, 17/09/2013, 28/04/2014, 24/10/2014, 16/04/2015, 12/10/2015, 05/05/2016, 14/10/2016, 24/04/2017, 18/10/2017, 13/04/2018, 24/09/2018, 18/04/2019.
	Elevations along profiles 69, 70 and 71 (see locations in Figure H2	Twice a year, in the autumn and in the spring: **Profile 69: 1996-2019** 11/06/1996, 12/11/1996, 07/05/1997, 12/11/1997, 08/04/1998, 01/12/1998, 27/05/1999, 08/10/1999, 04/05/2000, 12/10/2000, 05/06/2001, 15/11/2001, 25/04/2002, 18/11/2002, 29/04/2003, 04/11/2003, 04/05/2004, 28/10/2004, 25/04/2005, 03/11/2005, 25/05/2006, 05/10/2006, 15/05/2007, 09/10/2007, 16/05/2008, 19/11/2008, 19/05/2009, 04/11/2009, 11/05/2010, 19/10/2010, 31/05/2011, 26/10/2011, 18/05/2012, 29/10/2012, 21/05/2013, 17/10/2013, 16/04/2014, 05/11/2014, 18/05/2015, 14/10/2015, 22/04/2016, 14/11/2016, 03/05/2017, 20/10/2017, 22/05/2018, 22/10/2018, 02/05/2019. **Profile 70: 1996-2019** 11/06/1996, 12/11/1996, 07/05/1997, 12/11/1997, 08/04/1998, 01/12/1998, 27/05/1999, 08/10/1999, 04/05/2000, 12/10/2000, 05/06/2001, 15/11/2001, 23/05/2002, 18/11/2002, 30/04/2003, 21/10/2003, 02/04/2004, 27/10/2004, 09/05/2005, 15/11/2005, 12/05/2006, 04/10/2006, 01/05/2007, 23/10/2007, 18/04/2008, 29/09/2008, 07/04/2009, 07/10/2009, 15/04/2010, 21/09/2010, 06/04/2011, 28/09/2011, 05/04/2012, 27/09/2012, 08/04/2013, 17/09/2013, 28/04/2014, 24/10/2014, 16/04/2015, 12/10/2015, 05/05/2016, 14/10/2016, 24/04/2017, 18/10/2017, 13/04/2018, 24/09/2018, 18/04/2019.

Data Provider	Data	Dates
		Profile 71: 1996-2002 12/11/1996, 07/05/1997, 12/11/1997, 08/04/1998, 01/12/1998, 27/05/1999, 08/10/1999, 04/05/2000, 12/10/2000, 05/06/2001, 15/11/2001, 25/04/2002
	Sediment samples at profiles 69, 70 and 71. Samples taken at four different levels across the beach (HAT, MHWS, MHWN and MSL)	June 1997 and September 2003
Wales Coastal Monitoring Centre[16]	Elevations along a combination of 13 profiles between 2020 and 2024. Profile locations and dates are show in Figure H3, Figure H4 and Figure H5	03/2020, 07/2020, 10/2020, 10/2021, 09/2022, 10/2023, 03/2024 Not all profiles are surveyed at each date.
	Profiles derived from LiDAR survey shown in Figure H6**.**	06/2022 and 05/2023.
DataMap Wales[17]	Topographic LiDAR data flown at low water giving full coverage of the site	04/2006, 02/2013 and 03/2022

16 https://www.wcmc.wales/
17 https://datamap.gov.wales.

Figure H1. Topographic survey typical extent of data provided by YGC

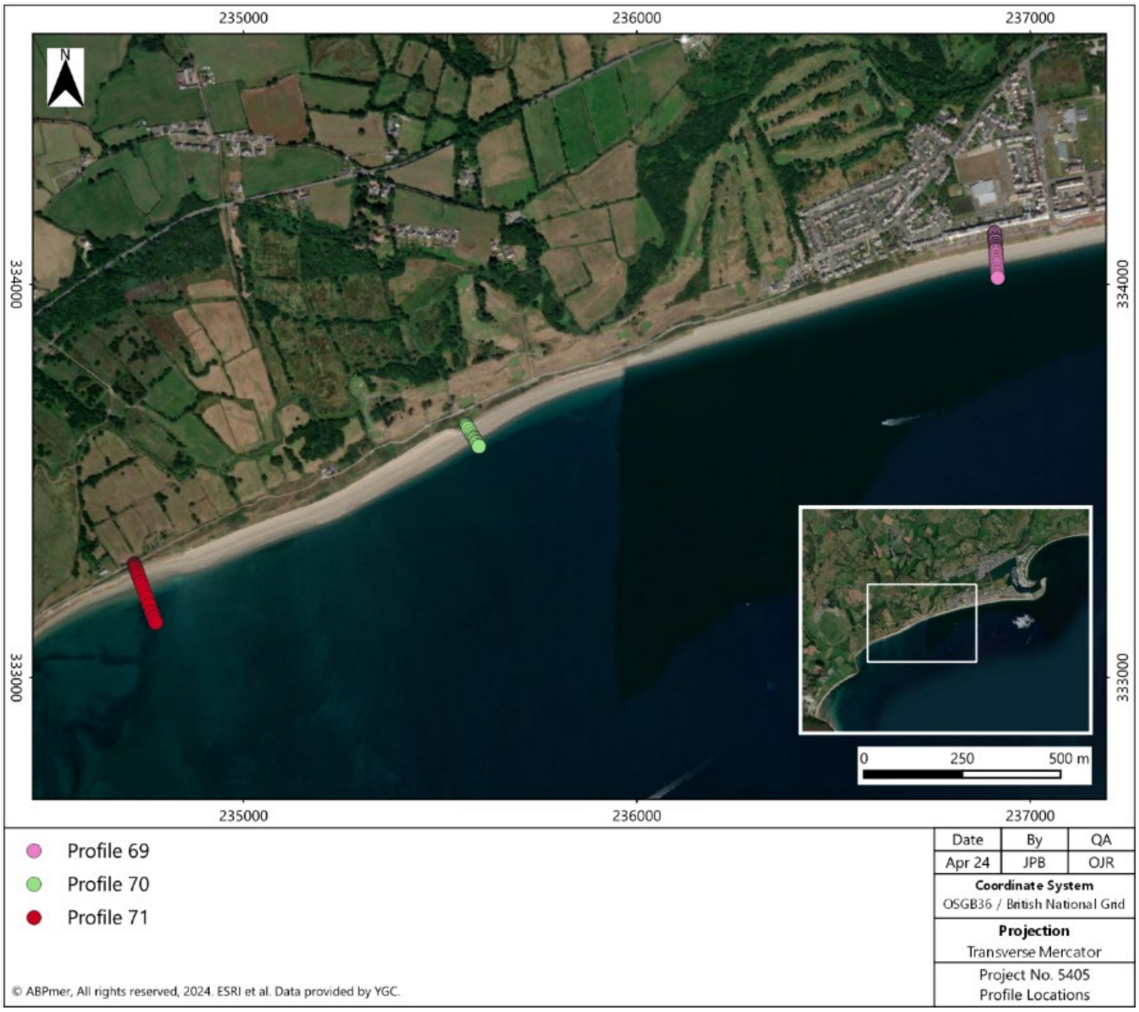


Figure H2. **Location of Profiles 69, 70 and 71 provided by YGC**

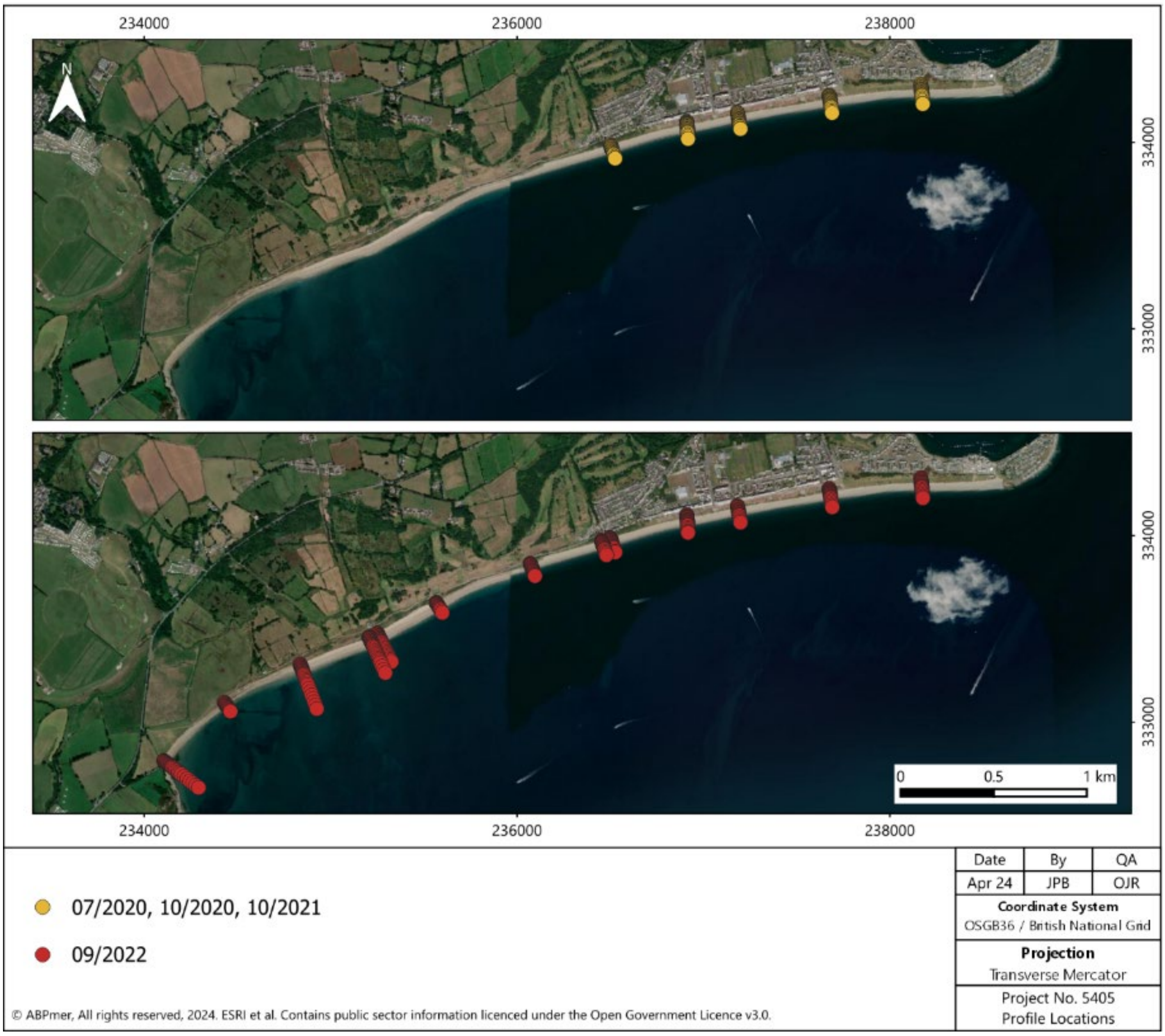


Figure H3. Location of the profiles with data 2020-22 from WCMC

Figure H4. Location of the profiles with data 2023-24 from WCMC

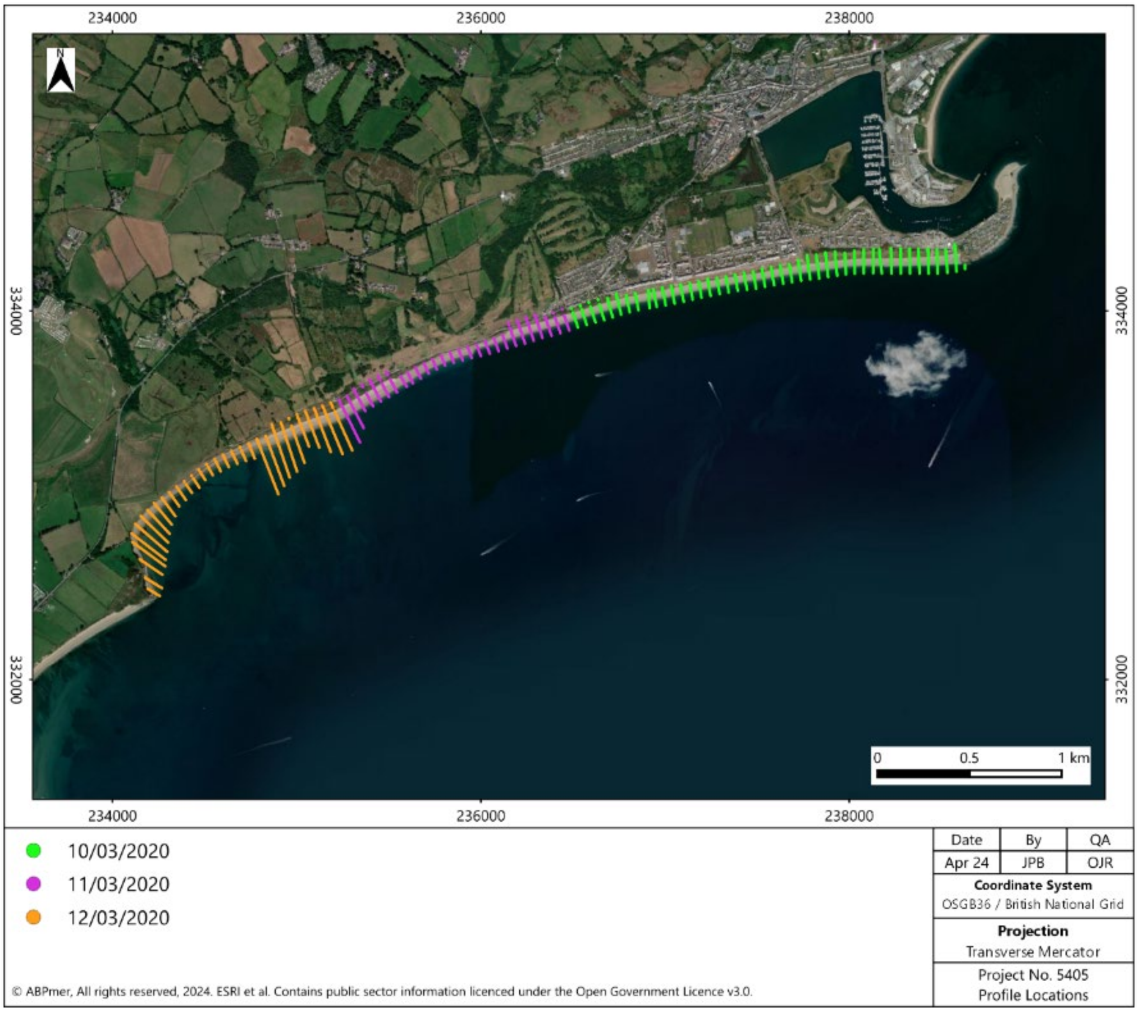


Figure H5. Location of the profiles with data March 2020 from WCMC

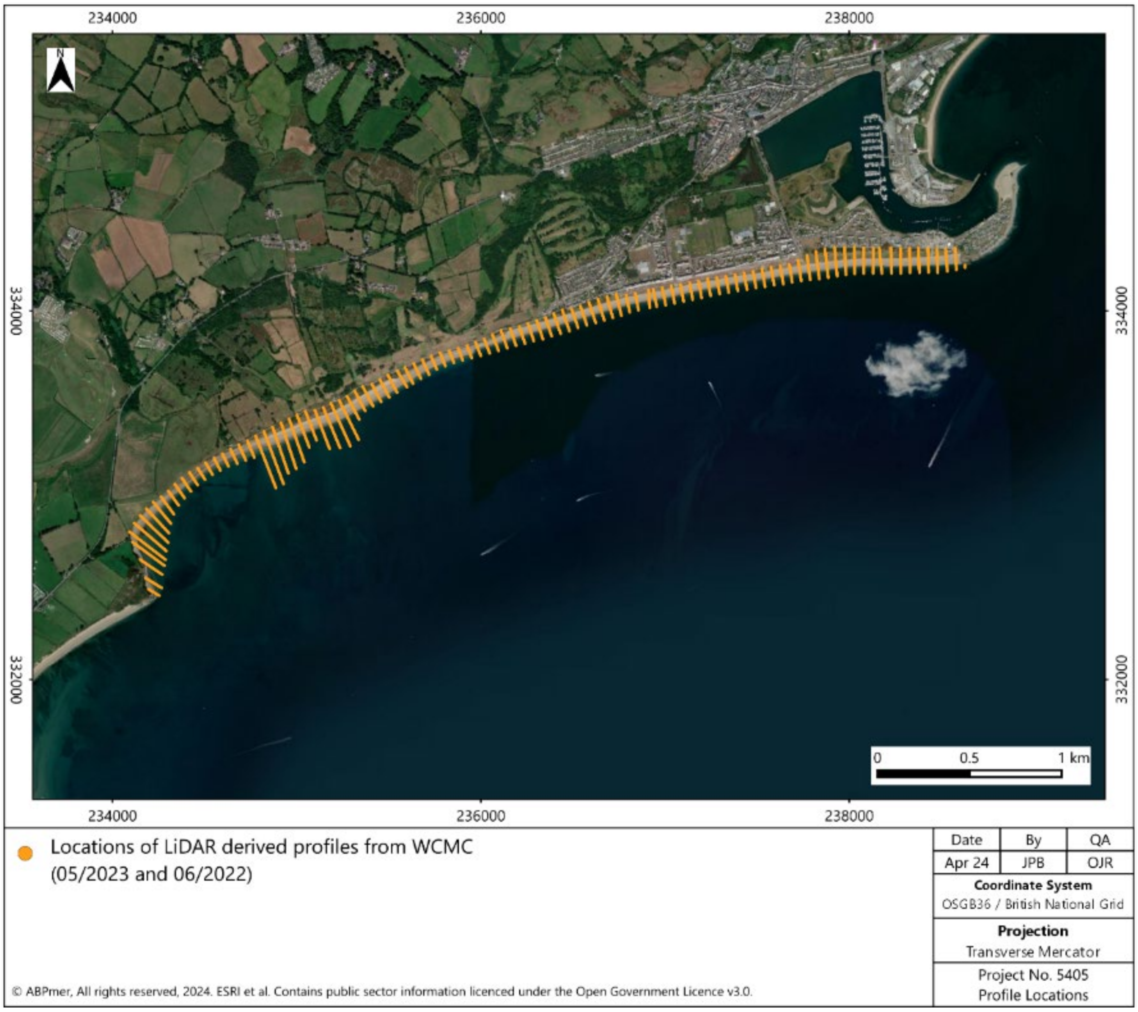


Figure H6. Location of the LIDAR derived profiles from WCMC

I Analysis of the Monitoring Data

In this appendix, figures from the analysis of the monitoring data are presented.

I.1 Profiles 69, 70 and 71

Figure I1 shows this historical evolution for Profile 69. It is observed how in this area, the dune has been growing since 2000, although there are also inter-annual and annual variations. The average vertical movement of the beach during this time is about 0.7 m, which translates to about 8 m excursion in the horizontal. The average beach slope is around 1:12. The most extreme profiles are in 22/05/2018 (one with the greatest drawdown) and 15/05/2007 (one of the heathiest).

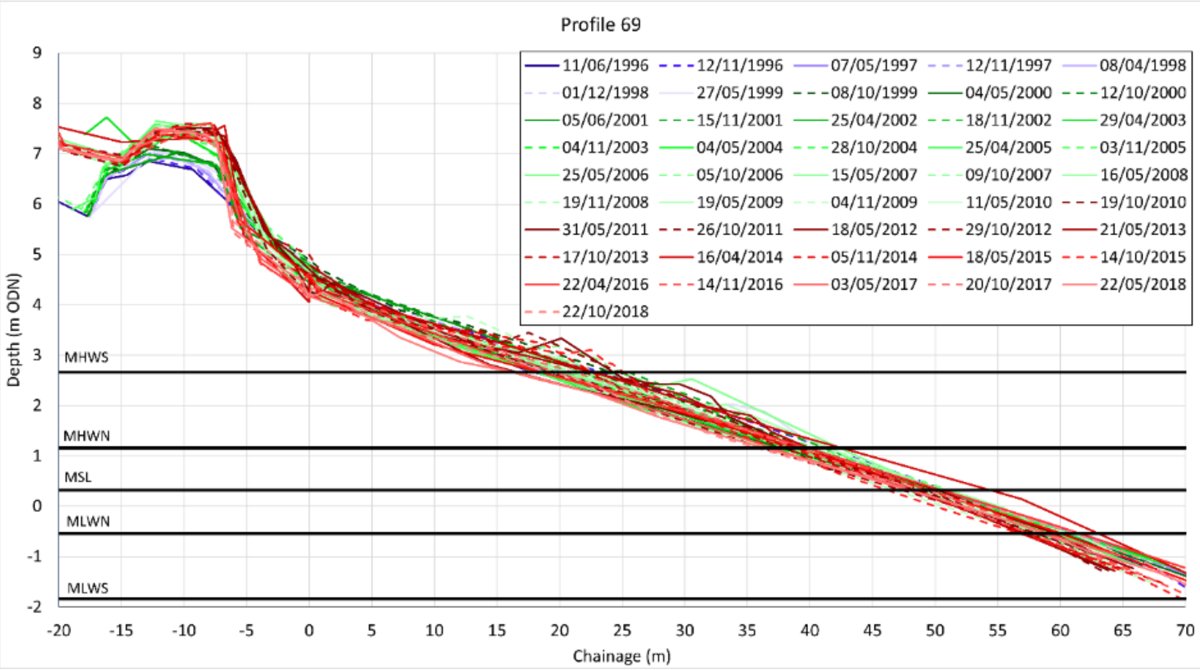


Figure I1. **Profile 69 data (1996-2018)**

Figure I2 shows the profile evolution close to the Western end of the revetment in Profile 70. The beach profile has generally been accreting since about 2010, with inter-annual and annual variations. The average vertical movement of the beach during this time is about 1 m, which translates to about 12 m excursion in the horizontal. The average beach slope is also 1:12 as in Profile 69. The most extreme profiles are in 05/06/2001 (one with the greatest drawdown) and 18/10/17 (one of the healthiest).

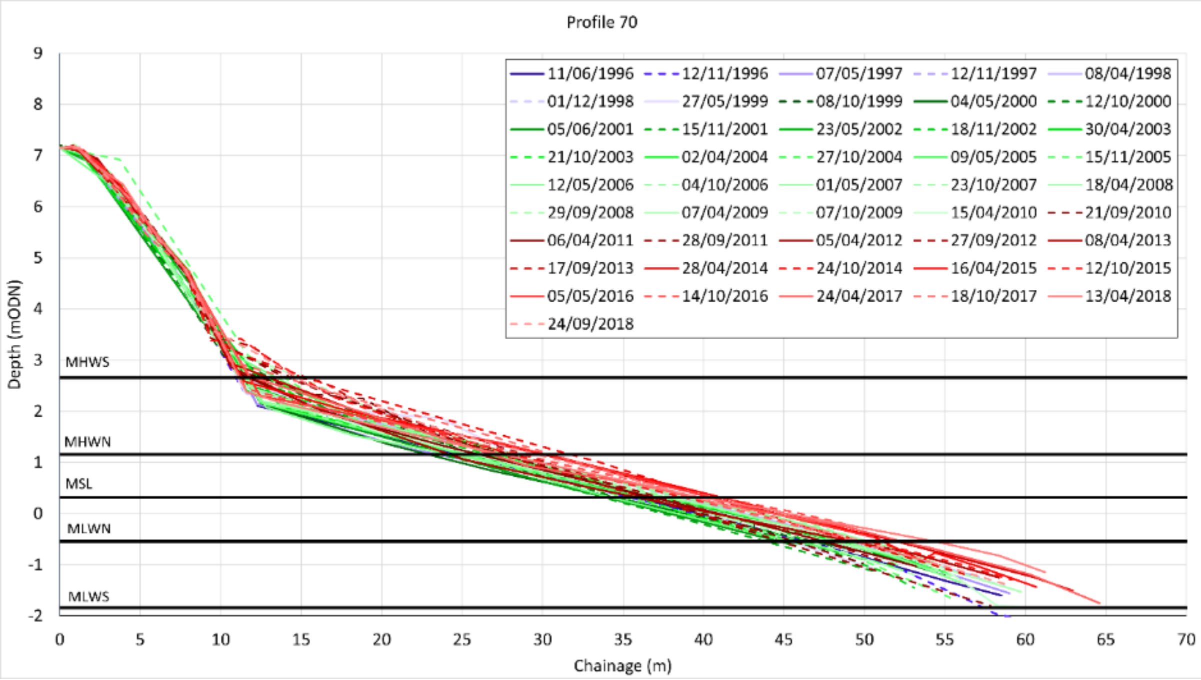


Figure I2. Profile 70 data (1996-2018)

Figure I3 shows the profile evolution from 1996 to 2001 for Profile 71, located in the Western revetment. There is no much change shown during these five years in this location.

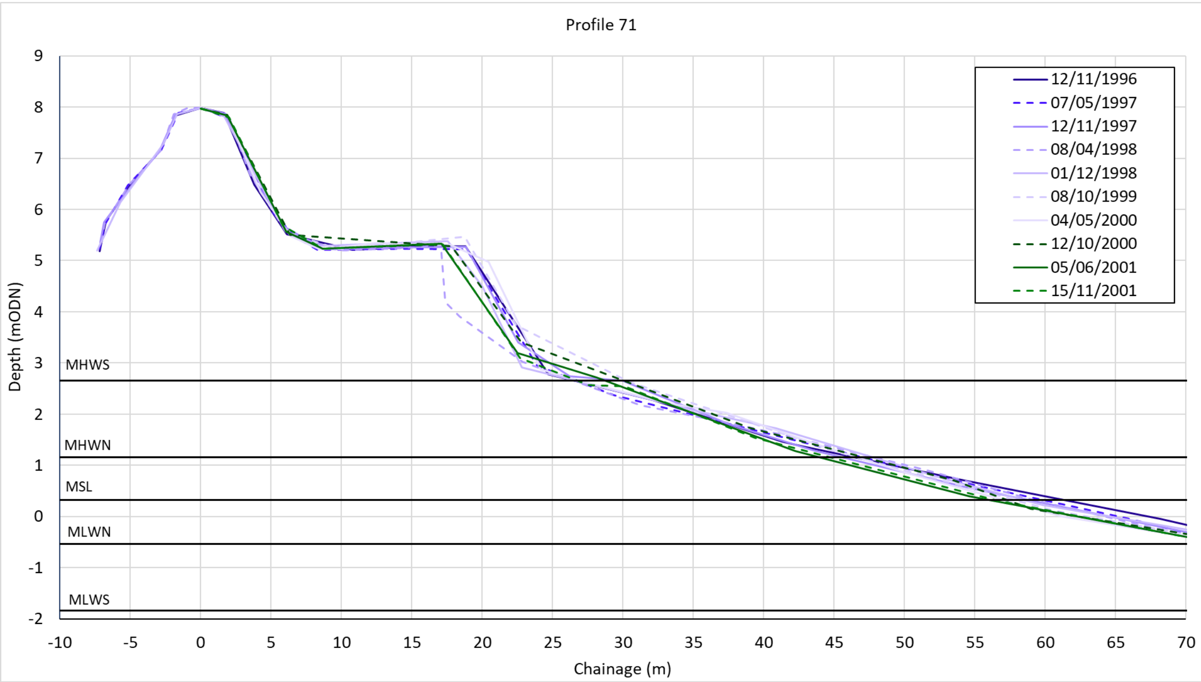


Figure I3. Profile 71 data (1996-2001)

I.1.1 Variation in contours 0 mODN and 2 m ODN position along Profile 70

The variability of a couple of contours at Profile 70, the 2 m ODN, at the base of the revetment, and 0 m ODN, has been analysed and presented in Figure I4 where the renourishment dates are also shown. This exercise was carried out in order to see if the renourishment on the beach backshore was having an effect on the beach levels and if so if there was a delay.

The intra- and inter-annual variability of the 2 m contour is greater than the 0 m contour due to the swash processes higher up on the beach; the latter one showing a small accreting trend over the years. Neither of the contours show, however, the influence of the renourishment, as there is not an increase of the chainage after the renourishments.

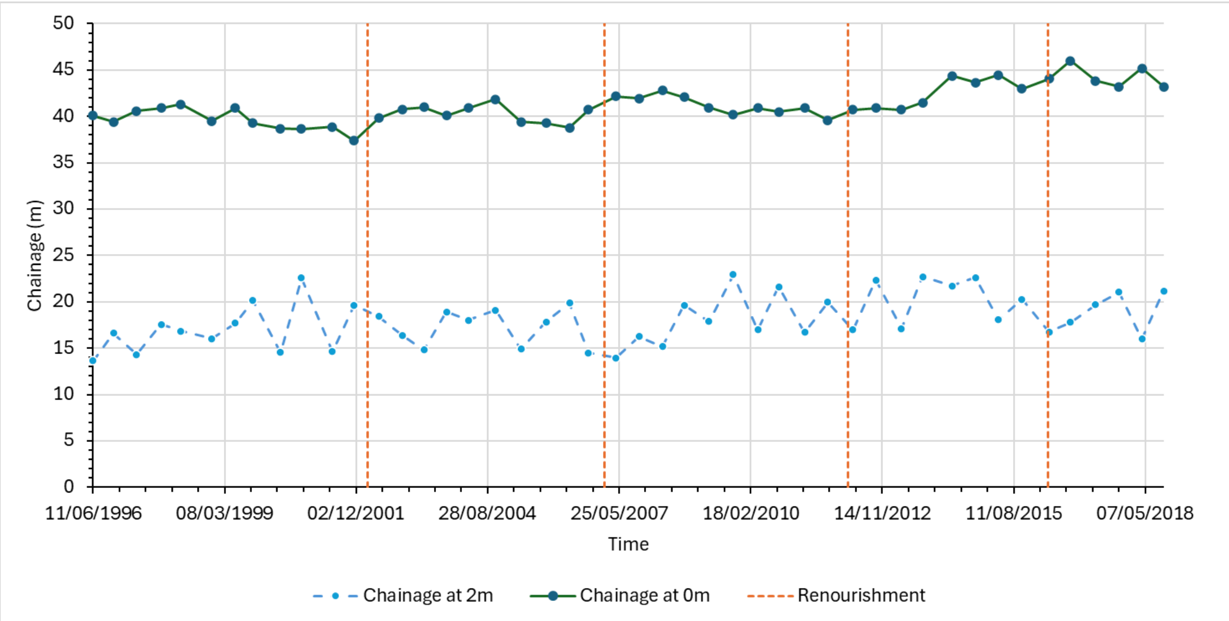


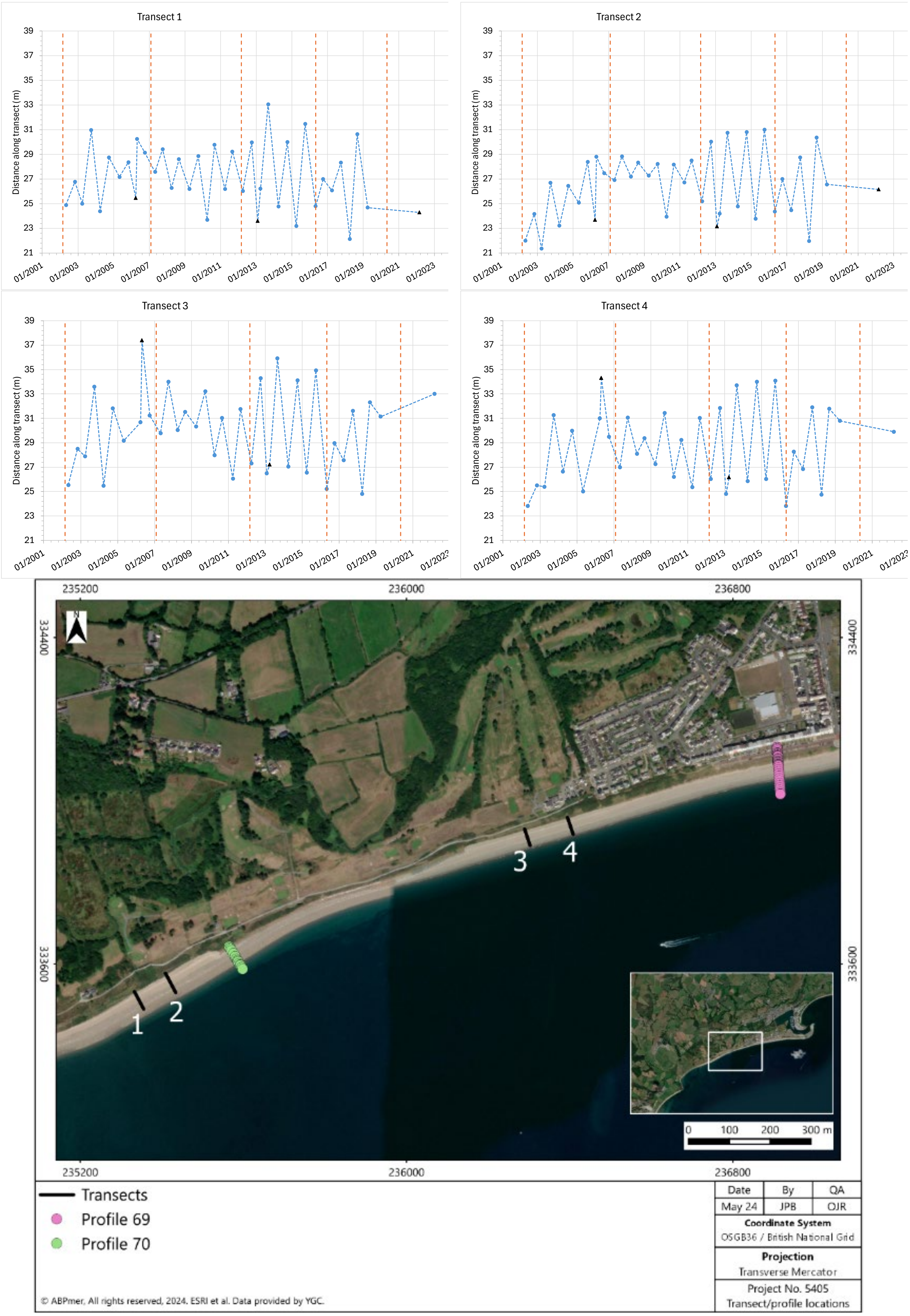
Figure I4. Variability of the contour 2 mODN and 0 mODN at Profile 70

I.2 Variability of the MHWS contour

To investigate the variability in the MHWS with time, the distance of the MHWS contour from the dunes have been examined for four transects along the frontage using the following data:

- Topographic data from YGC from 2002 up to 2019
- Wales Coastal Monitoring Centre topographic campaigns from 2020
- Welsh Government LiDAR data for 2006, 2013 and 2022

The location of the transects locations 1 to 4 and the result of the analysis is presented in Figure I5. The figures show in orange dashed lines the dates of the renourishment. In the four transects, inter- and intra-annual variability of the MHWS position is observed, but the effect of the renourishment is not observed on the position of the MHWS (or it is masked within the variability). Moreover, none of the transects are showing a long-term accreting or eroding trend, as the variability is very high, again due to the swash processes on the top of the beach.



Black triangles points show data derived from LIDAR datasets.

Figure I5. **Transect topographic data showing change in MHWS position for Transects 1-4 (2001-2022)**

I.3 Changes in the areas in the beach and the renourishment

he DTMs from the YGC topographic surveys have also been analysed to examine beach volume changes in relation to different areas of the beach.

The beach was thus split up into a series of zones and shown in Figure I6, and summarised below:

- Two areas in the backshore for each of the renourishment zones: WBeaN and EBeaN
- Two areas in the foreshore in front of these renourishment zones: WBeaS and EBeaS
- Two areas in the foreshore in front of the revetment: WRev and Erev
- An area to the East of the Eastern revetment, EEBea

Within this assessment, to maximise the spatial coverage of the assessment, several of the temporal datasets were excluded from the analysis. This is because the spatial coverage of these individual surveys was more limited.

The evolution of the volumes of sediment at each of the areas outlined in Figure I6 is shown in the figures below, Figure I7 to Figure I12.

Figure I6. Location of areas outlines to calculate beach volumes

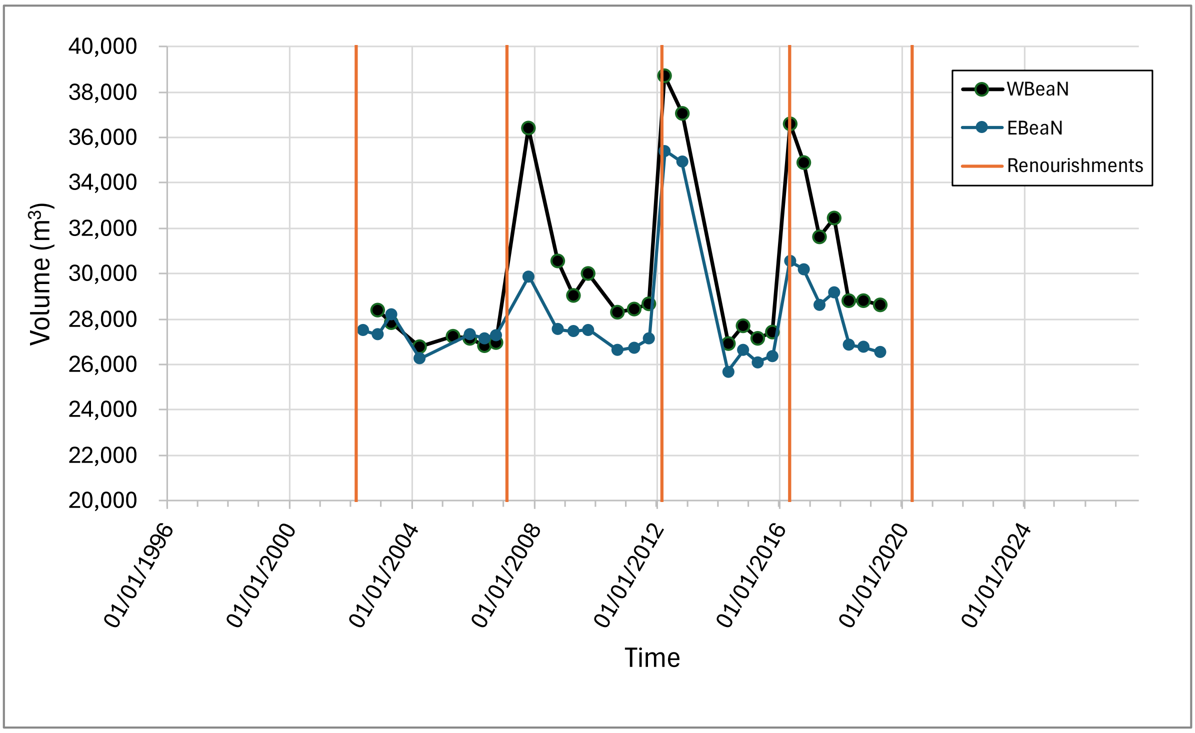


Figure I7. Evolution of the volumes in the backshore, WBeaN and EBeaN

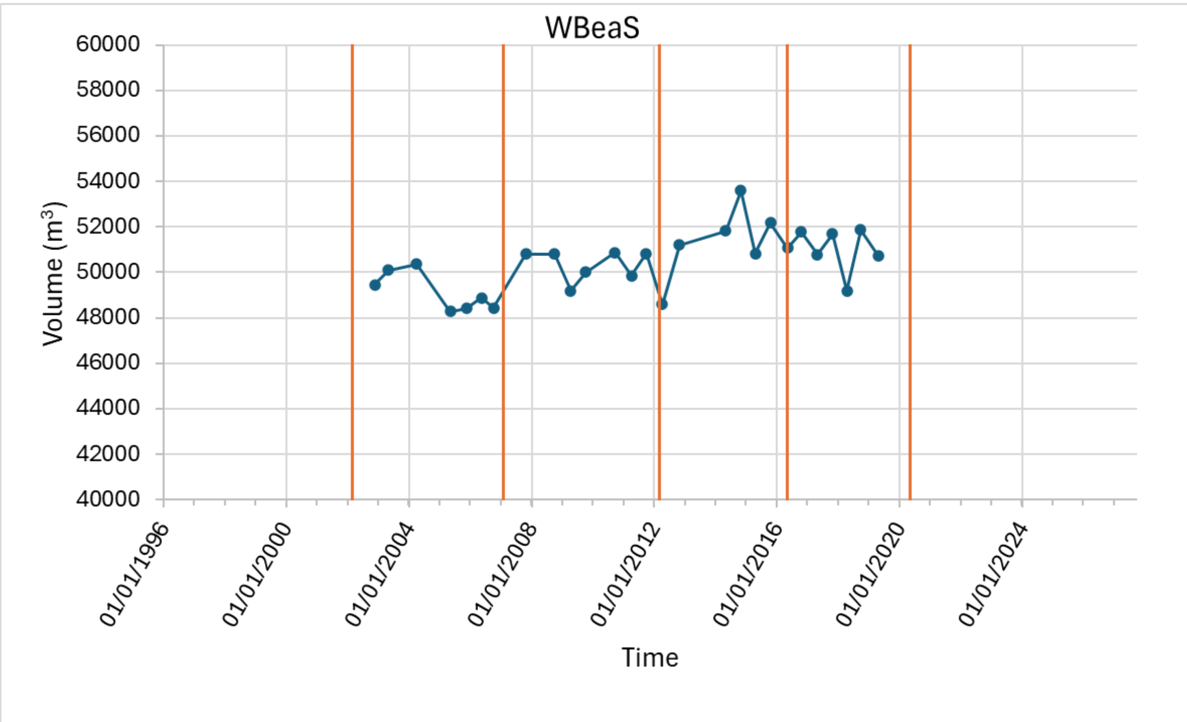


Figure I8. Evolution of the volumes in the foreshore, WBeaS

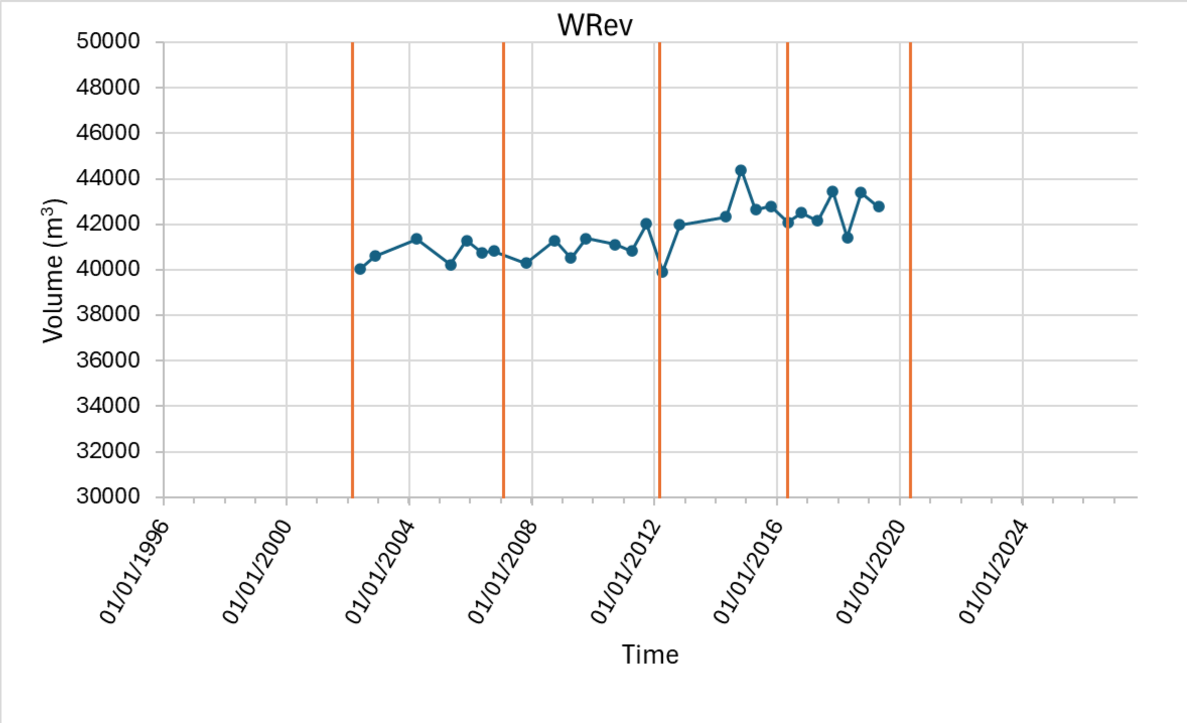


Figure I9. **Evolution of the volumes in the revetment, WRev**

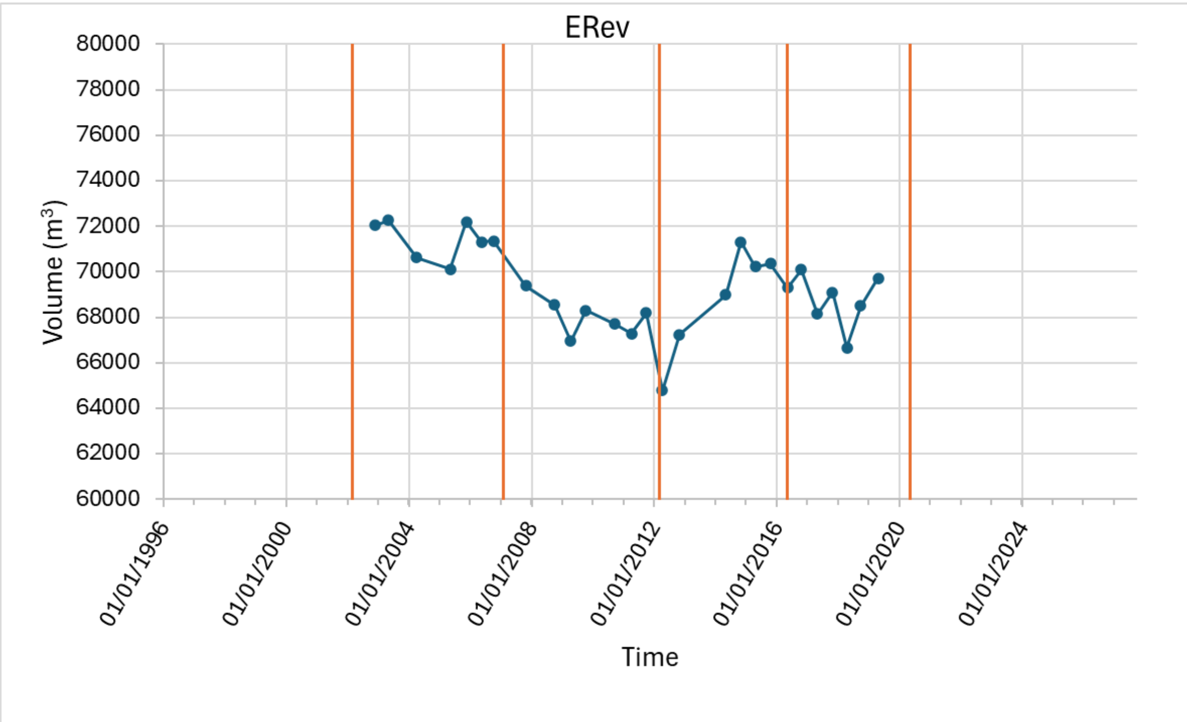


Figure I10. **Evolution of the volumes in revetment, ERev**

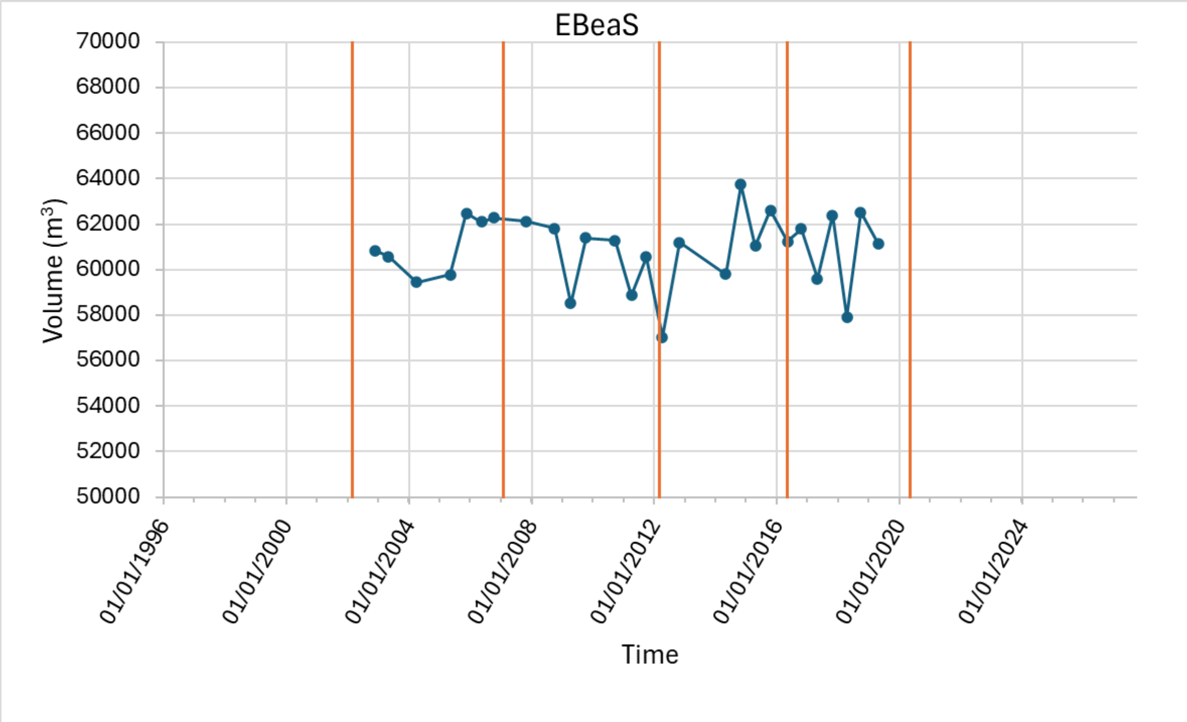


Figure I11. Evolution of the volumes in the foreshore, EBeaS

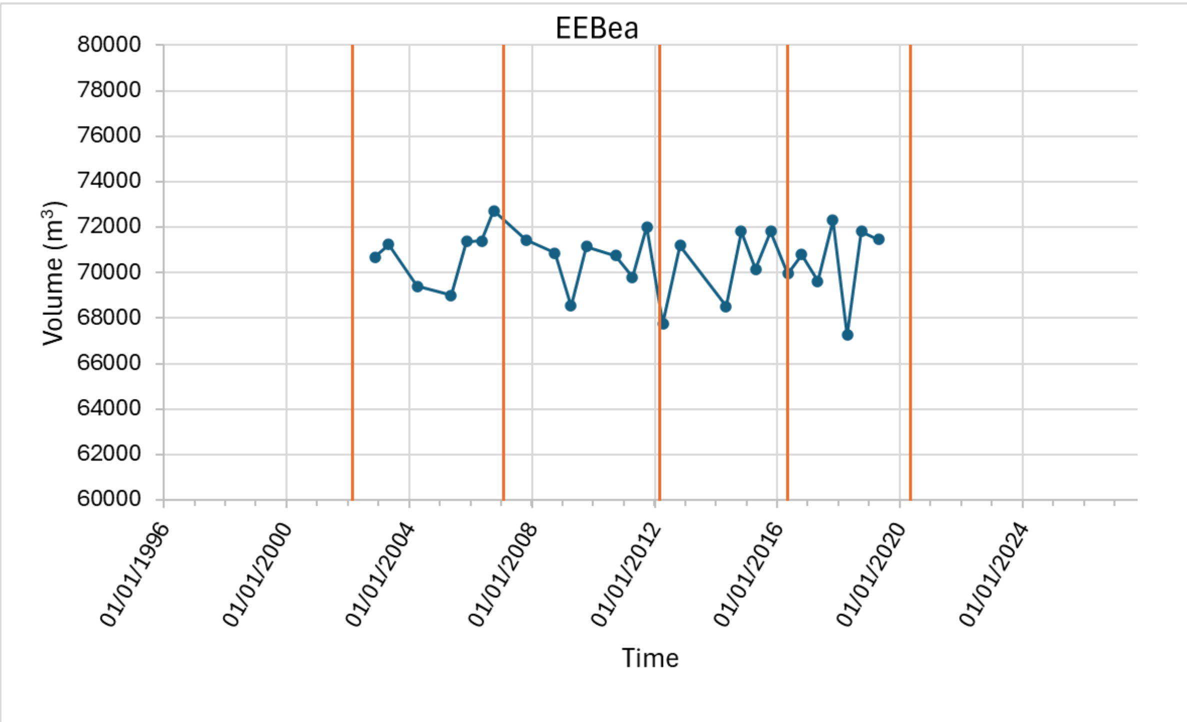


Figure I12. Evolution of the volumes in the foreshore, EEBea

I.4 Changes along four transects in the renourishment areas.

The evolution of the backshore and foreshore levels along four transects in the renourishment areas is shown this section. The data used is both the topographic data from YGC and WCMC and the LiDAR data from WCMC.

The data along the four transects (shown in Figure I13) have been sorted per nourishment campaign, so for example Figure I14 shows the data for Renourishment 4 in Spring 2016. The rest of the renourishments data is shown in Figure I15 to Figure I18. These figures show how the backshore and foreshore change over the months after each renourishment.

Figure I13. Location of the transects to track the nourishment

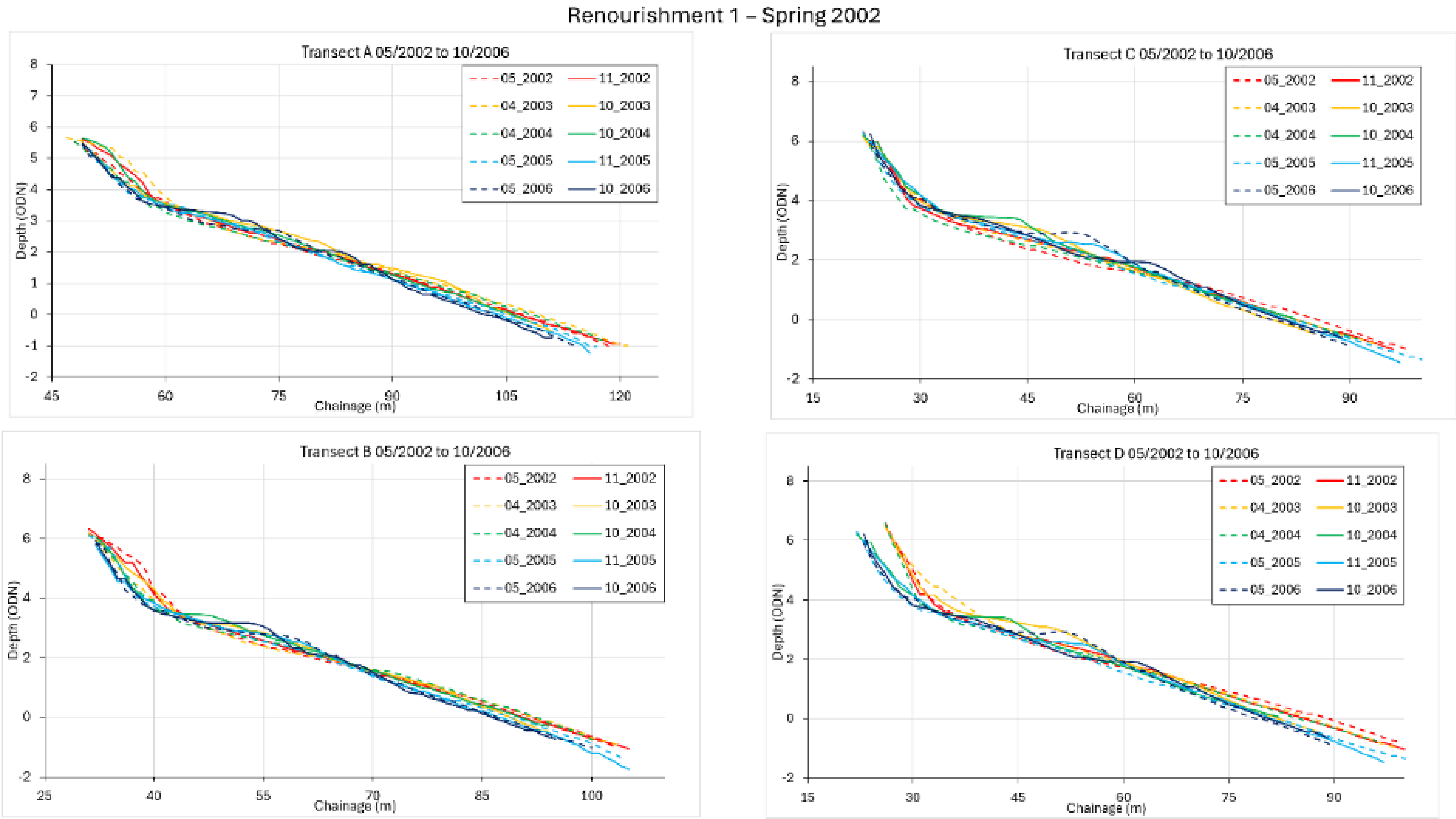


Figure I14. **Evolution of the four transects, A, B, C and D after Nourishment 1 (Spring 2002)**

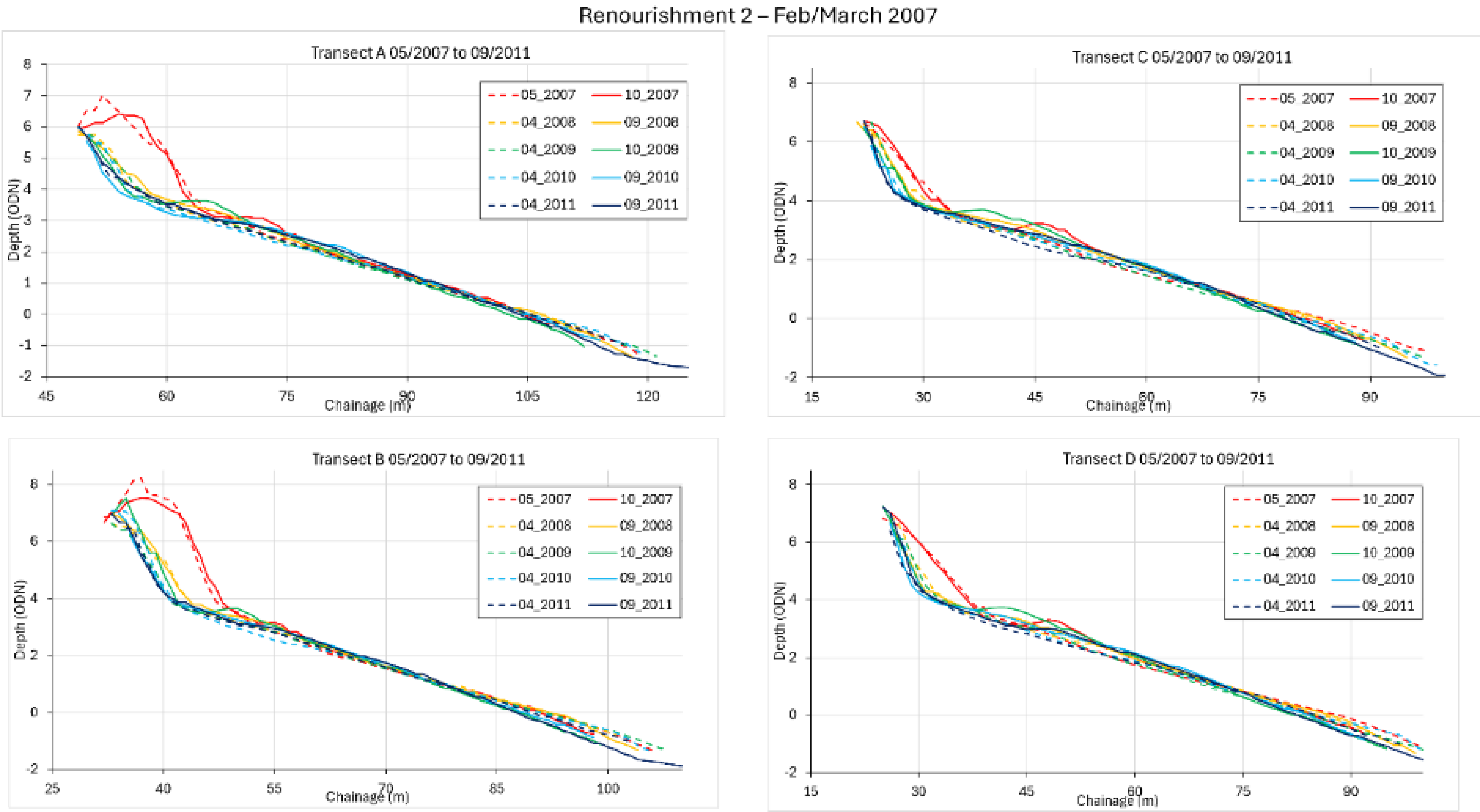


Figure I15. **Evolution of the four transects, A, B, C and D after Nourishment 2 (February/March 2007)**

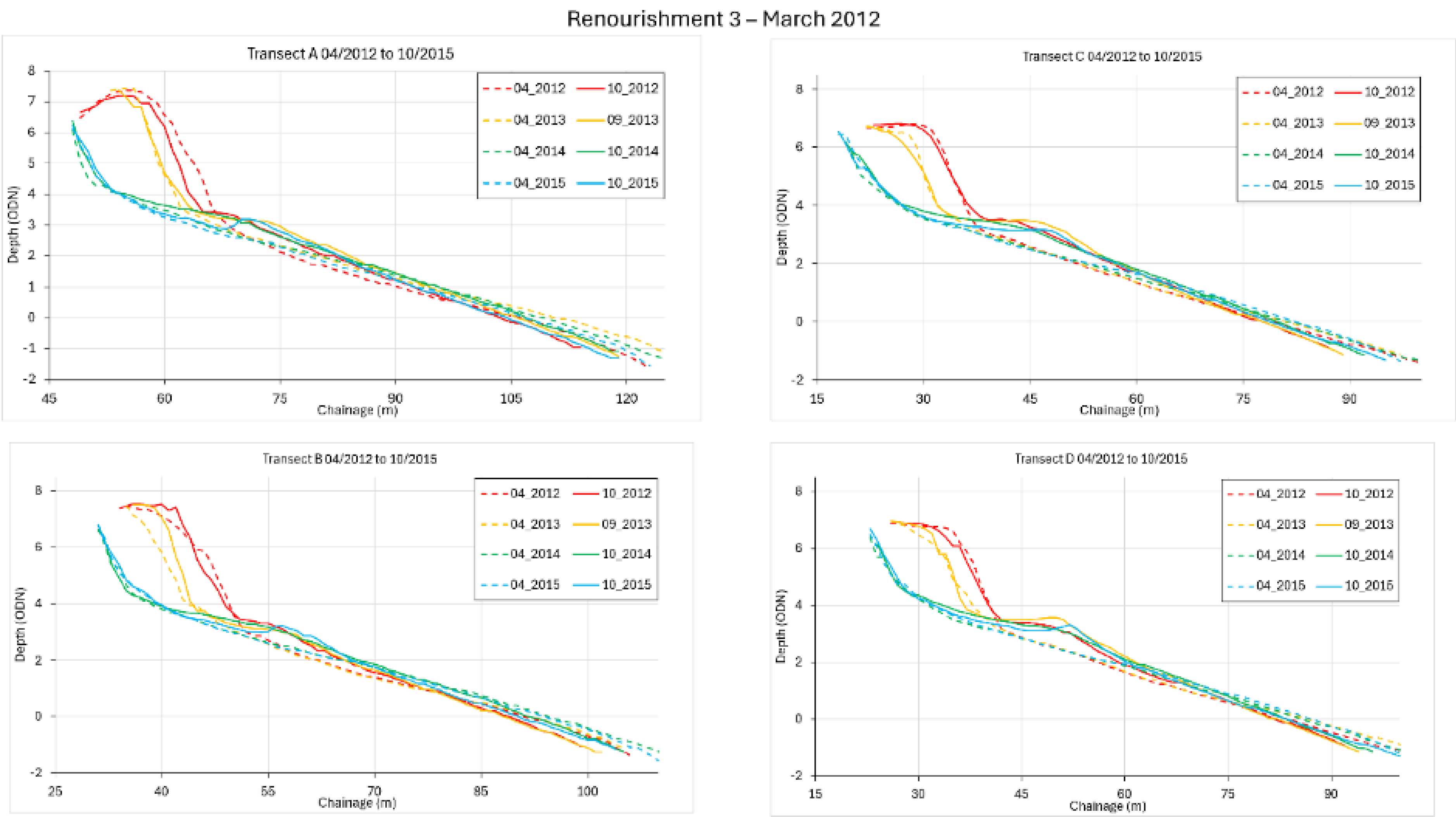


Figure I16. **Evolution of the four transects, A, B, C and D after Nourishment 3 (March 2012)**

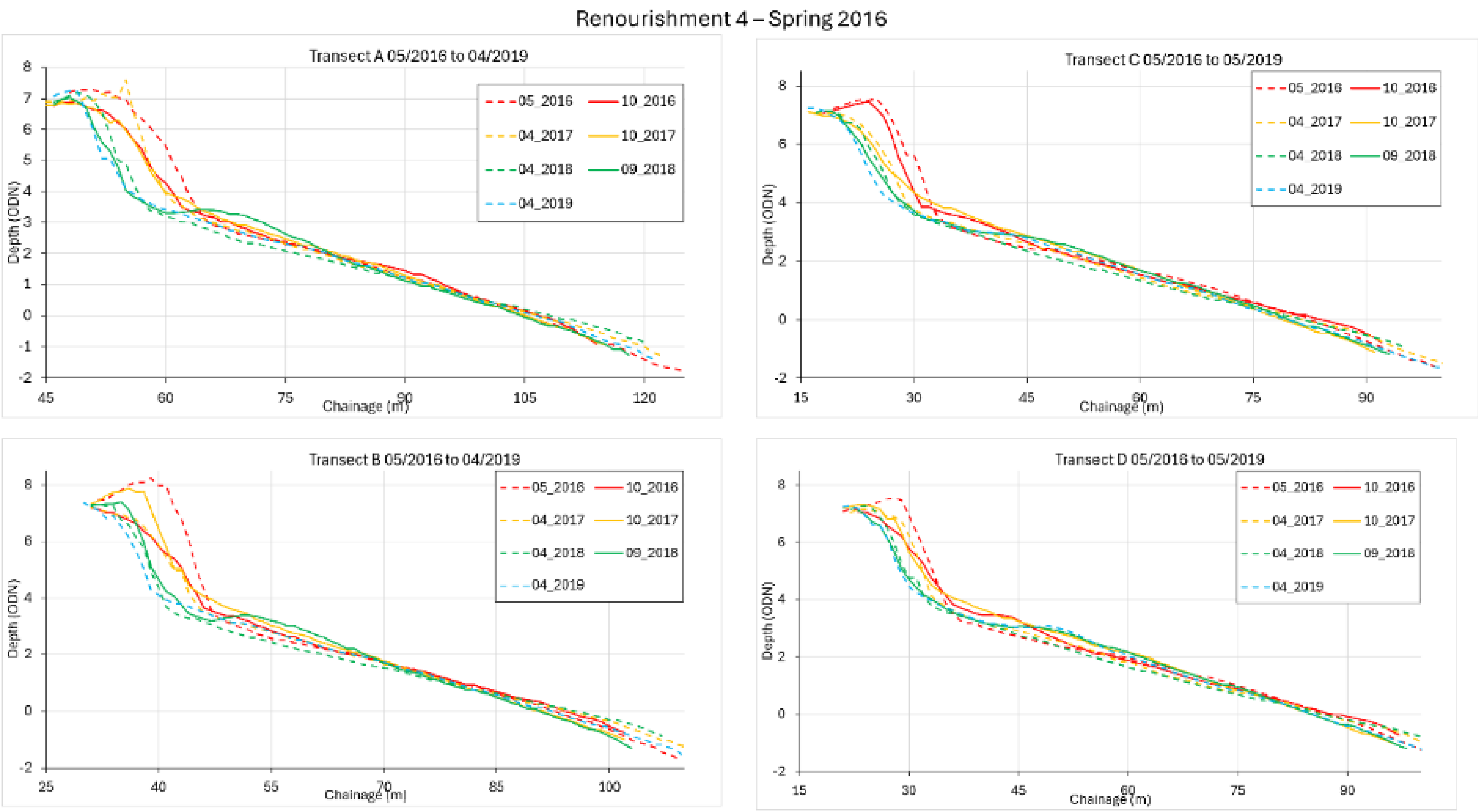


Figure I17. **Evolution of the four transects, A, B, C and D after Nourishment 4 (Spring 2016)**

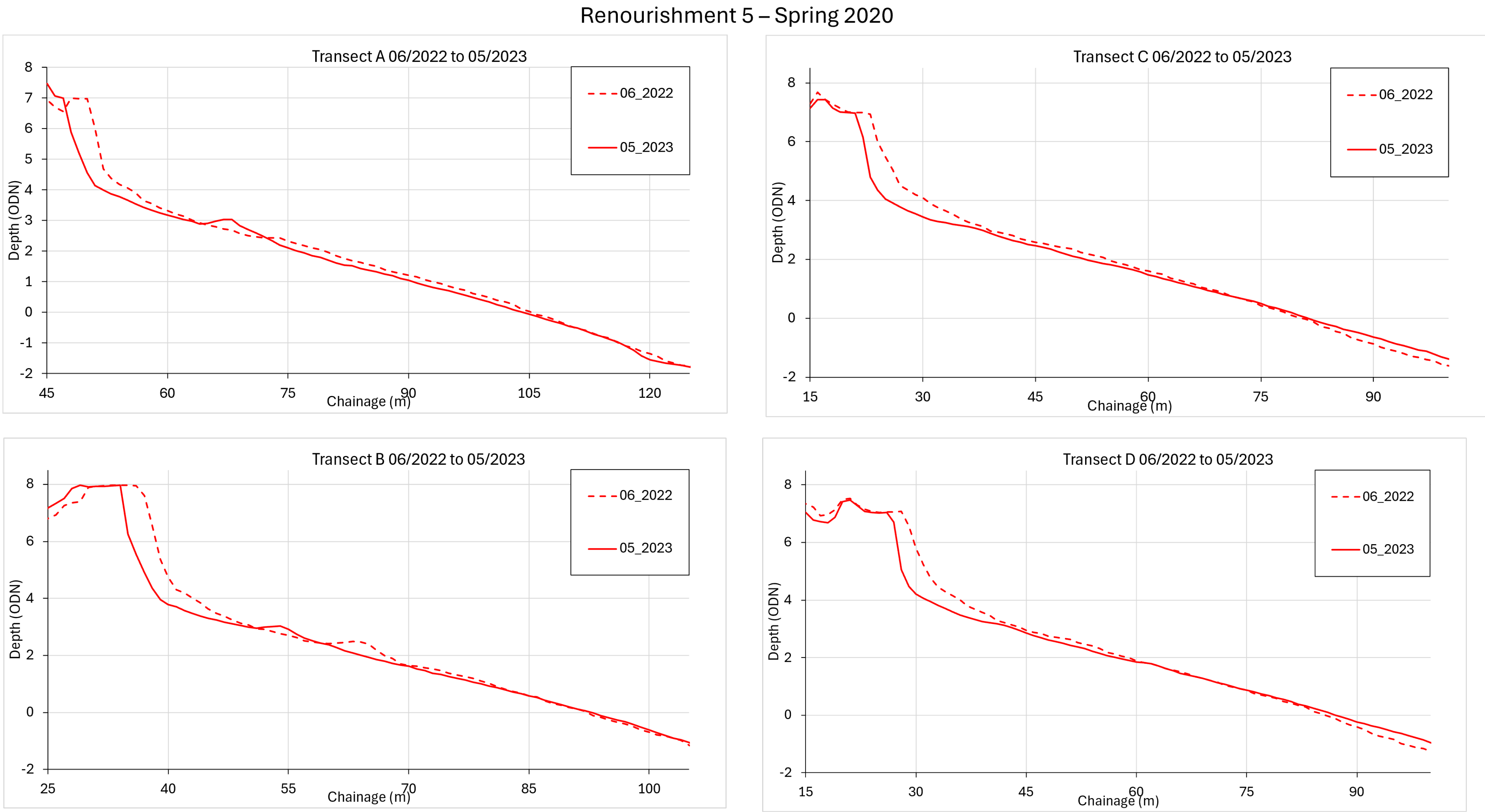


Figure I18. **Evolution of the four transects, A, B, C and D after Nourishment 5 (Spring 2020)**

I.5 LiDAR data -2022

The following figures show the most recent LiDAR data (March 2022) Western renourished area in Figure I19 and in Figure I20 for the Eastern part. The outlines in the figure are those used in the analysis of the volumes previously; they are useful to bound the extent of the renourishment within the data.

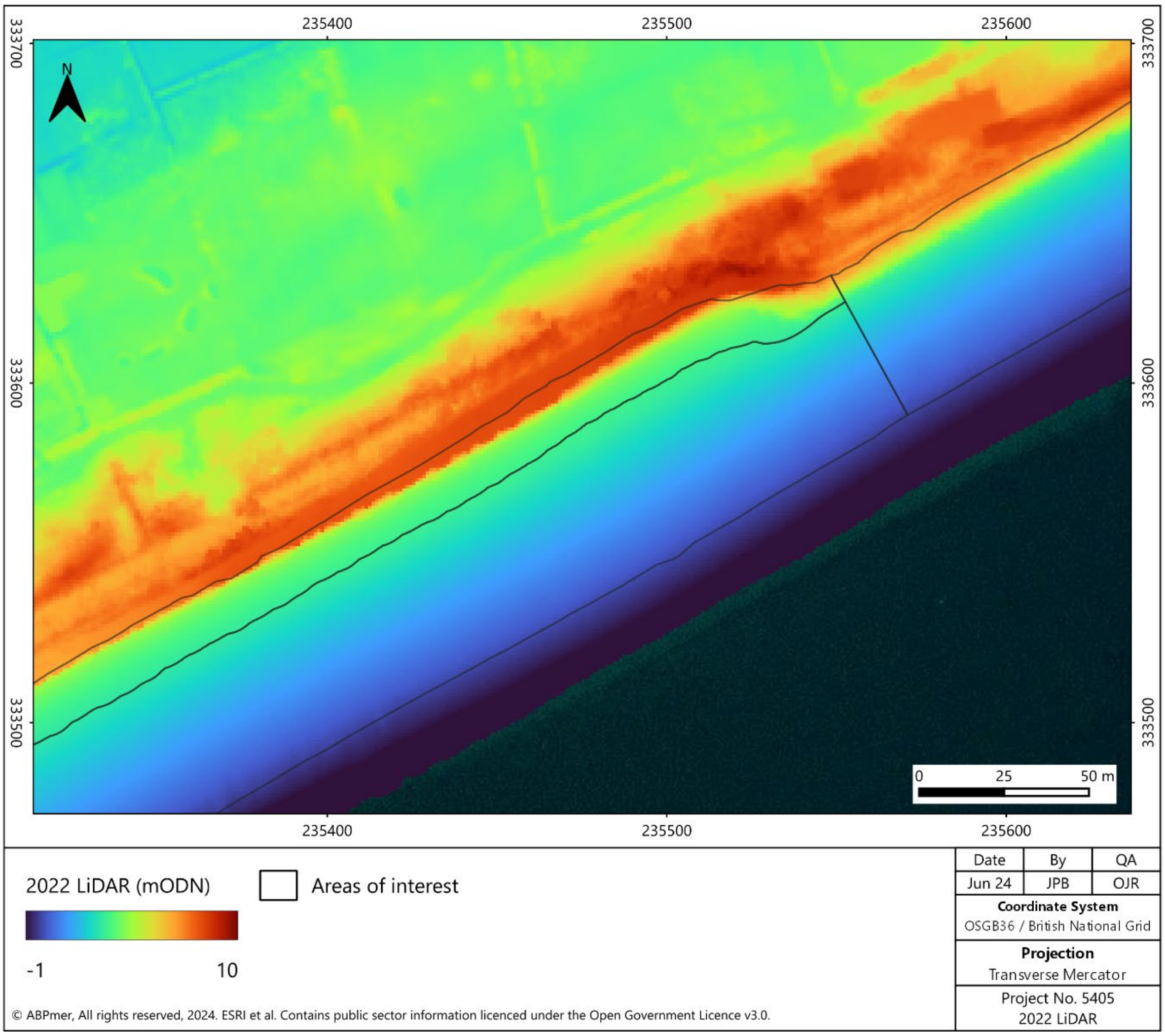


Figure I19. LiDAR March 2022 data for the Western renourished area

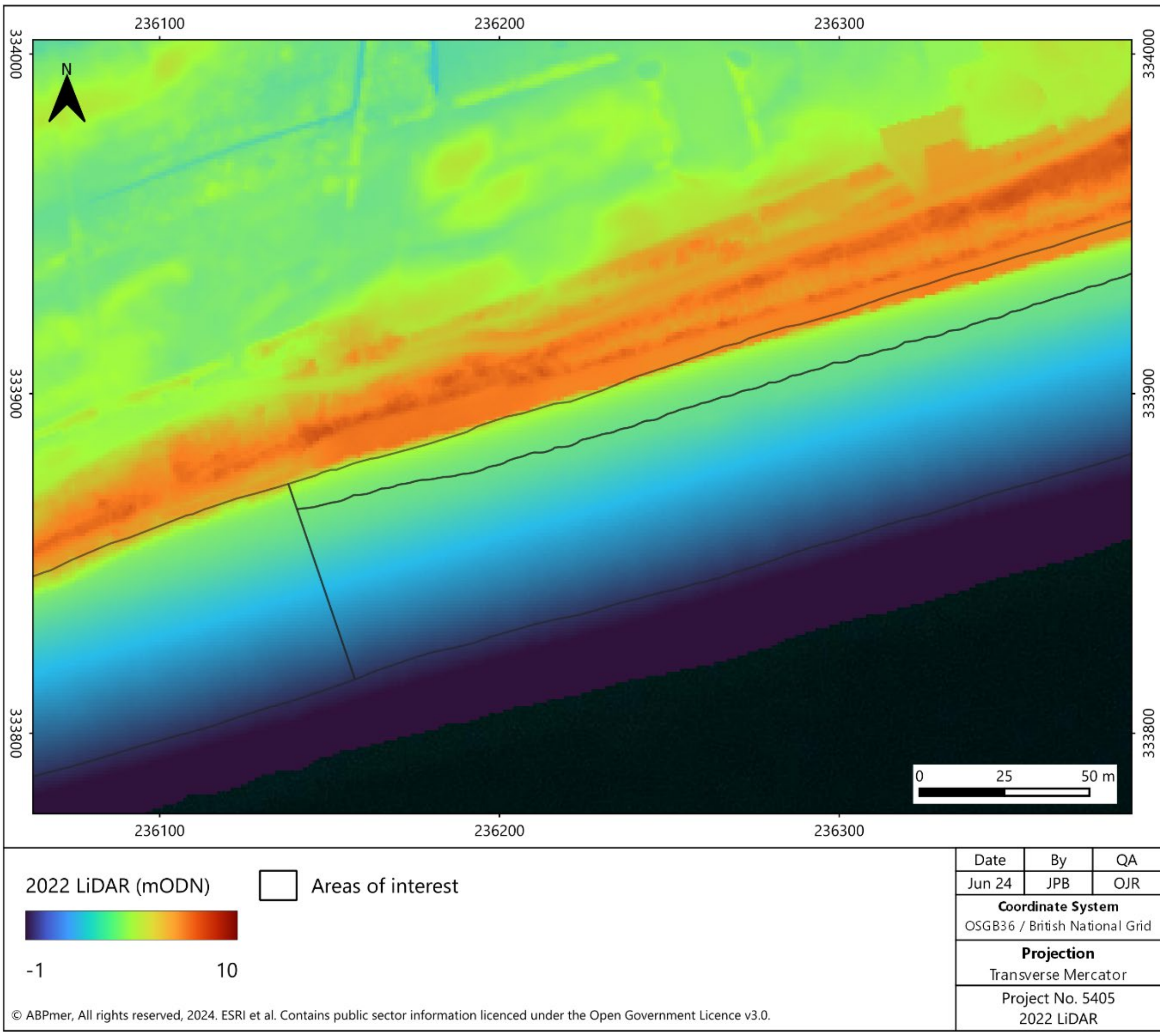


Figure I20. LiDAR March 2022 data for the Eastern renourished area

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