Barmouth Beach
Blown Sand Management Options

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Kenneth Pye Associates Ltd.
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This report was prepared by Professor Kenneth Pye ScD PhD MA CGeol FGS (Director) and Simon James Blott PhD MRes BSc FGS (Principal Consultant).

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Kenneth Pye Associates Ltd

Research, Consultancy and Investigations

Blythe Valley Innovation Centre
Central Boulevard
Blythe Valley Park
SOLIHULL
B90 8AJ
United Kingdom

Telephone: 0121 506 9067
E-mail: info@kpal.co.uk
website: www.kpal.co.uk

Contents

		Page
	Summary	3
1.0	Introduction: scope and purpose	4
2.0	Methods and data sources	5
3.0	Environmental background	7
4.0	Historical coastal changes	9
5.0	Potential future management intervention options	14
	5.1 *Initial options identified by Gwynedd Council*	14
	5.2 *Consideration of additional options*	15
	5.3 *Requirement to consider buried infrastructure*	19
6.0	Conclusions and recommendations	20
7.0	References	21
	Tables	23
	Figures	29
	Appendix 1: Photographs taken during a site visit on 8 August 2016	92
	Appendix 2: Photographs taken during a site visit in February 2014	108

Summary

The northern part of Barmouth Beach has experienced sediment loss and falling levels for decades, whereas the southern part of the beach has experienced sediment accretion and rising beach levels, especially since construction of a causeway across the former Bar Bach channel to Ynys y Brawd in the early 1970s. Rising beach levels have favoured colonization by vegetation and growth of dunes which has required management by Gwynedd Council to maintain the amenity beach area and access to the RNLI station. However, the level of the dry sand beach between the dunes has continued to rise and now lies above high water spring tide level, with a large area above the level of the highest astronomical tide. This area is subject to high rates of windblown sand transport during periods of strong winds, notably from the northwest and west, when sand piles up against the promenade and spreads across the promenade, road, and beach car park, sometimes reaching the Cambrian Coast railway line. Historically, Gwynedd Council has cleared the sand from the promenade, highway and car park before the beginning of the summer season. Stormier than average conditions during the winters of 2013-14, 2014-15 and 2015-16 substantially increased the requirement to clear sand, and the problem may be expected to become worse if beach levels continue to rise and stormy conditions continue or become more frequent due to climate change. A requirement has been identified to develop a more sustainable solution to the sand management problem.

A Barmouth Sand Management Project scoping document was prepared by Gwynedd Council in April 2016. This document set out the proposed project approach and identified some initial potential future management options for discussion amongst members of the Sand Management Group and other stakeholders. Kenneth Pye Associates Ltd was subsequently engaged to review of the physical processes and recent geomorphological changes in the area, to evaluate the feasibility of the initial options identified in the Gwnedd Council report, and to propose modifications and /or additional options for discussion in order to assist the further development of the Sand Management Project. This report presents the results of that assessment. It is concluded that removal of the Ynys y Brawd causeway and reopening of the Bar Bach Channel would not be desirable or feasible on technical, environmental or economic grounds. It is also concluded that a composite approach involving lowering of parts of the beach and localised excavation to enlarge and deepen an existing shallow channel to the north of the causeway, combined with limited extension of the two existing dune outer dune ridges to provide a more effective wind barrier, would provide a solution with multiple benefits at realistic cost. This recommended option would maintain access from the RNLI station to the sea, would not completely block sea views from the promenade, would maintain a large area of dry sand beach for amenity use with the addition of a shallow, enclosed bathing area following inundation by high tides, would create additional areas of high value sand dune habitat, and would provide some coastal flood risk management benefits. Sand made available by lowering the general beach level in front of the promenade and excavation of the shallow channel and associated pool could be used to build the additional areas of dune, and/or it could be transported northwards to nourish the eroding beach north of the Min y Mor Hotel.

1.0 Introduction: scope and purpose

This report was commissioned by the Water and Environmental Unit of Gwynedd Council to inform the development of the Barmouth Sand Management Project. The northern part of Barmouth Beach has experienced net sediment loss and falling levels for over a century, whereas the southern part of the beach (between the Min y Mor Hotel and Barmouth Harbour) has been experiencing sediment accretion and rising beach levels, especially following the construction of a causeway across the former Bar Bach channel in the 1970s. Since that time beach levels have risen substantially and a large area now lies above the level of the predicted Highest Astronomical Tide (HAT). This has favoured colonization by pioneer sand dune vegetation and the growth of dunes since the late 1990s. The spread of dune vegetation has been controlled by Gwynedd Council, partly to maintain a large area of amenity beach and partly to prevent obstruction to the RNLI station. Consequently a wide expanse of high (mostly above HAT level), dry sand beach is exposed to wind action. During periods of strong winds, most notably from the northwest and west, sand is blown onto the promenade and beach car park, on occasions reaching the Cambrian Coast railway line.

Historically, the blown sand has been cleared from the promenade, highway and car park by Gwynedd Council before the beginning of the summer tourist season. Accumulations of sand on the seaward side of the promenade have also been cleared and the sand deposited lower down the beach near the high water mark. Accumulations of blown sand on the railway line have been cleared by Network Rail, as required. Stormier than average conditions during the winters of 2013-14, 2014-15 and 2015-16 substantially increased the requirement to clear sand, and the problem may be expected to become worse if beach levels continue to rise and stormy conditions continue, or become more frequent due to climate change. In response to this situation, there is a desire to develop a more sustainable solution for the longer term. A "Barmouth Sand Management Project" scoping document, prepared by Gwynedd Council and the Barmouth Sand Group in April 2016, set out the proposed project approach and identified a number of potential options. Kenneth Pye Associates Ltd (KPAL) was subsequently engaged to review the physical processes and geomorphological characteristics of the area, and to assess the practicality of the options prior to further discussion with stakeholders. This report provides a summary of this assessment.

2.0 Methods and data sources

Several approaches and data sources have been used in the assessment, including:

- Review of background published and unpublished literature, and information documents/ data provided by Gwynedd Council
- Examination of historical Ordnance Survey (OS) maps, aerial photographs and Admiralty charts
- Analysis of water level data for the Class ‘ A’ tide gauge at Barmouth, available from the NTSLF website
- A site visit on 30 August 2016 (see photographs in Appendix 1), and comparison with notes / photographs taken during a previous site visit in early February 2014 (photographs in Appendix 2)
- Analysis of LIDAR data acquired during the period 2003 - 2015
- Analysis of the results of an airborne drone survey commissioned by Gwynedd Council and undertaken on 16 June 2016 (including colour imagery and a digital terrain model produced by photogrammetry)
- Sediment volume calculations to quantify changes in the beach and dunes since 2003
- Estimation of the potential quantities of sediment which would need to be moved in association with a number of different beach management options

Historical maps and charts covering the period 1833 to the present, together with historical aerial photographs, were examined for evidence of changes in coastal morphology, sea defence structures, bare sand area and vegetated dune extent. LiDAR survey data obtained in 2003, 2006, 2013, 2014 and 2015 were obtained under Open Government licence. After initial assessment of data extent and quality, a decision was made to use the 2003, 2013 and 2014 LiDAR data, together with data from an Unmanned Aerial Vehicle (UAV) survey commissioned by Gwynedd Council in June 2016, to quantify changes in beach levels, tidal contour positions, and beach and dune sediment volumes. All data were processed and manipulated using the Golden Software ‘Surfer’ programme and specially written macros in Miscrosoft Excel.

Error analyses were performed by comparing elevations for the three LIDAR surveys and the UAV survey on the areas of hard surface (car parks) along the length of the frontage. No independent RTK GPS survey data were available for comparison, but the elevations quoted relative to Ordnance Datum Newlyn (ODN) are likely to be accurate to within +/-10 cm. Only very small differences (<2 cm) were found between the 2013 and 2014 LiDAR surveys, for which good ground control appears to have been available. The 2003 LiDAR data were found to show average elevation differences of -14 cm and -15 cm compared with the 2013 and 2014 survey data, respectively (Table 1). As the later surveys were of better quality and had better ground control, the 2003 data were adjusted upwards by 15cm to allow a more meaningful comparison of relative height and sediment volume change over the periods 2003-13 and 2003-14. Comparison for reference areas between the 2016 UAV survey and the

2014 LiDAR survey indicated average elevation differences of +5cm, +7 cm and 9cm (Table 2), respectively, so the UAV data were adjusted downwards using a sloping surface interpolation model to allow a better comparison of relative change compared with the LiDAR surveys . An estimate of the potential errors in calculated sediment volume for each survey, and for the change between surveys, was made using assumed elevation errors of +/- 10 cm associated with each survey.

3.0 Environmental background

Barmouth beach, located to the north of the Mawddach estuary on the eastern side of Barmouth Bay, forms a broadly triangular accumulation of sand and some shingle which widens towards the south. The beach is exposed to both long period swell waves and shorter period wind waves from the southwest, and to wind waves from the west and northwest. Some shelter from northwesterly storm waves is provided by the Sarn Badrig boulder ridge. The dominant net sediment drift direction in the nearshore zone within Barmouth Bay is from south to north, but in the intertidal zone there is a sediment drift divide just to the north of Barmouth which gives rise to net southerly sediment drift along Barmouth beach (Figure 2a). The Mawddach estuary has a small ebb tidal delta formed by interaction between tidal flows in and out of the estuary and littoral drift. Most of the estuary is flood dominant and has acted as a sink for marine and fluvial sediments throughout the later Holocene (Larcombe & Jago, 1994, 1996). However, ebb tidal flows, reinforced by river discharge, play an important role in maintaining the low water channels within the estuary and ebb-tidal delta.

The Mawddach estuary is designated as a Site of Special Scientific Interest (SSSI) and as a Special Area of Conservation (SAC), while the adjoining marine area forms part of the Lleyn Peninsula and Sarnau SAC (Figure 2b & c). Most of the beach above mean high water and the dunes have no nature conservation designation. However, the dunes, consisting of semi-mobile foredunes and areas of embryo dunes and, are priority Biodiversity Action Plan (BAP) features which are now relatively scarce in Wales and across Europe. The beach is also an asset of high public amenity and touristic value which contributes significantly to the local economy.

Much of Barmouth (excluding Old Barmouth which is located on solid rock and rising ground behind the Harbour) is built on windblown sand and underlying beach deposits which form an elongate cuspate feature at the foot of steeply rising ground behind (Figure 3). Before the construction of the promenade in the 1930s, and subsequent construction of housing estates, a significant area of partially vegetated, semi-mobile dunes existed. Benoit (1955 p. 116) noted that much of the original dune botanical interest had been lost due to building of the promenade between the wars and the Council houses after World War II, “though many of the old plants linger”. Dunes remained in the area now occupied by the beach car park and sailing club until the 1960s, but have since been covered by asphalt and concrete. During the National Sand Dune Vegetation Survey in the late 1980s and early 1990s, no significant dunes were recorded at Barmouth (Dargie, 1995). However, in a survey of dunes of potential flood risk management significance in the period 1999-2003, dunes were identified at Barmouth and designated as Site No. 86b, which, together with Site 86a (Fairbourne / Ro Wen), comprised the Mawddach Estuary dunes (Pye *et al*., 2007).

Barmouth experiences a mean spring tidal range of approximately 4.3 m, and a wide intertidal zone is exposed at low tide, especially along the southern part of the frontage. The level of the predicted Highest Astronomical Tide (HAT) is 3.26 m ODN (Table 3). This is approximately 20-25 cm below the level of the predicted 1 in 1 year extreme water level, and on average the upper beach can be expected to be covered by surge tides on a small number of occasions each year. The 1 in 10 year high water level is estimated to be between 3.83 and 3.93 m ODN (Table 4). The two highest still water levels recorded at the Barmouth tide gauge, which has a fragmentary record extending back to 1991, both reached 3.92 m ODN, on 10 February 1997 and 3 January 2014 (Table 5). Seven tides exceeding 3.65 m ODN have been recorded (Figure 4). A number of photographs taken in early February 2014 following a series of storms and high tides are shown in Appendix 2.

Recent rates of sea level rise are not well documented in West Wales. Based on the fragmentary Barmouth tide gauge record, which should be viewed with caution, mean sea level (MSL) has been rising at 4.2 to 5.0 mm/yr since the early 1990s, while mean high water (MHW) has shown a slower average rise of 2.2 mm/yr (Figure 5). The apparent rise in mean sea level is strongly influenced by low water levels which, since the tide gauge is mounted on one of the piers of the railway viaduct inside the estuary (Figure 3), are influenced by river flows and lags associated with the flow of the ebb tide through the narrow estuary entrance. The apparent lower rate of rise of recorded high waters probably provides a more representative guide than the apparent trend in mean sea level, and is of greater significance in terms of coastal flood risk management.

The UKCP09 climate projections suggested a possible rise of 61-88 mm by 2016, 120 mm by 2030 and 196 mm by 2050 (medium emissions 50th percentile model output values, Table 6), but more recent climate modelling results suggest these may be over estimates. Little confidence can be placed in the UKCP09 model forecasts of future changes in wind/wave climate and storminess, but updated climate change and sea level rise forecasts are scheduled to be published from 2017 onwards.

4.0 Historical coastal changes

The earliest useful chart of the Barmouth area, by Lewis Morris dated 1748 (Figure 6), shows two main channels at the mouth of Mawddach estuary, running to the north and south of Ynys y Brawd. The north channel is shown to take a northerly course close to the shore, which lay landward of its present position to the north of the point where the Bath House Café is now located, before swinging northwestwards towards the open sea. A cuspate foreland feature, capped by sand dunes, is shown to the northwest of Barmouth Old Town. A quay existed at this time in approximately the same position as the present quay (Figure 7) , but extended further towards the northwest, running along a line close to the present high street. Historical accounts suggest that navigation to the harbour was often difficult due to shifting sand banks and bars, and limited shelter from storm waves (Davidson & Roberts, 2005). Small boats of up to 27 tons are recorded as trading from the town as early as 1566, and Barmouth developed as a significant ship-building location between the mid-18th and mid-19th centuries. Barmouth also started to become popular with recreational visitors in Georgian times; the first Bath House was built in 1805 and was enlarged during Victorian times. The opening of the Cambrian Coast Railway in 1867, following construction of the viaduct across the Mawddach estuary, greatly increased the number of visitors and led to the construction of several more hotels, boarding houses and public amenity buildings.

Following the Barmouth Harbour Improvement Act of 1797, improvements were made to the quay and associated buildings, and a breakwater was built on Ynys y Brawd to provide more shelter for the harbour. According to Davidson & Roberts (2005) this was completed in 1802 at a cost of £1660. However, Gwynedd Council (1998) stated that the main Trywyn y Gwaith masonry breakwater was constructed between 1826 and 1840, primarily to regulate movement of the South Channel. The First Edition One-Inch Ordnance Survey map of the area, surveyed in 1833-35, shows two narrow breakwaters forming a y-shape in plan view, with an arcuate linking structure on the landward side (Figure 8). The 1843 edition of Admiralty Chart 1487, surveyed in 1835, also shows two relatively narrow structures labelled as ‘groins’, partially buried by sand in the central portion (Figure 9). However, the First Edition OS Six Inch map, surveyed in 1887, shows a much larger structure at Trwyn y Gwaith, supporting the suggestion that this was constructed after 1835. The smaller curving structure on the landward side of Ynys y Brawd, shown on the first OS One Inch map (surveyed in the early 1830s), the 1897 Six Inch map (Figure 10) is suggested by late 19th century ground photographs (Figure 11) to be a masonry wall, now buried by dune sand.

The First Edition One Inch map also shows a cuspate sedimentary foreland lying in front of steeply rising ground along the central part of the Barmouth frontage. The beach is represented schematically but appears to be relatively wide, increasing in width towards the south. A large part of this original cuspate foreland has since been lost to coastal erosion (Figure 8).

The Admiralty survey of 1835 shows a well-developed ebb-tidal delta at the mouth of the Mawddach, with a significant low water channel (labelled the N.W Swatch) running in a NW – SE direction away from Barmouth Harbour (Figure 12). A small area of dunes is indicated on the landward side of Ynys y Brawd, partially burying the breakwater, with a 'bank of stones, covered at HW", extending seawards towards the beacon (a replacement of which still exists).

The First Edition Six Inch Ordnance Survey map, surveyed in 1887, and an Admiralty Chart based on a survey in 1892, both show that the northern channel had experienced shoaling, with no clear connection to the sea at low water (Figures 10 & 12). A bar (Bar Bach) had started to grow across the mouth of the North Channel east of Ynys y Brawd.

Significant erosion evidently occurred between 1835 and 1890 along the northern part of the Barmouth frontage, north of the "Drainpipe" and Recreation Ground. To the south of this point erosion was much less severe, possibly partly due to construction of lengths of ad hoc sea defences.

The Second Edition OS Six Inch map, partially re-surveyed in 1900, shows relatively little change since 1890 (Figure 13), although erosion continued on the northern part of the frontage. By the late 1920s the early ad-hoc sea defences were falling into disrepair, and in 1930 Barmouth Urban District Council commissioned improvements which consisted of 48 timber groynes and a sloping / stepped revetment extending 1.5 miles from the Quay, south of the Bath House, to the northern end of the present promenade. Construction of the promenade itself followed shortly afterwards (Gwynedd Council, 2016). As a result of these works the high water mark was pushed seawards and significant areas of beach were reclaimed between the railway station and the Bath House.

Aerial photographs dated 1940 (Figure 14), 1941 (Figure 15) and 1950 (Figure 16), and a Revised Six Inch OS map which included a low water survey in 1950 (Figure 17), suggest that the northern (Bar Bach) channel was at that time not continuous to the sea at the level of mean low water (MLW), although a shallower channel above this level apparently extended almost parallel to the shore as far as the drainage pipe opposite the Recreation Ground. The shoaling of the Bar Bach Channel in the later 19th and early 20th centuries may have been triggered by the construction of the Mawddach railway viaduct in 1866-7. This fixed the main low water channel of the estuary close to the Quay and made it more difficult for ebb tidal flows to turn sharply to the northwest into the North Channel and encouraged more flow through the South Channel on the south side of Ynys y Brawd (Shoreline Management Partnership & Posford Duvivier, 1993; Gwynedd Council, 1998). However, other contributing factors may have included concentration of flood and ebb flow through the South Channel following the 'hardening' of the estuary entrance on both the Trwyn y Gwaith side and the Fairbourne side, and increased rates of southerly littoral sand drift along the Barmouth frontage associated with an increased frequency / magnitude of northwesterly winds and waves in the late 19th / early 20th century, and the effects of seawall construction and land claim along the Barmouth frontage from 1930 onwards.

In 1950 there was relatively little development behind the promenade south of Barmouth railway station, although areas to the north had been built on (Figures 18-22). Shortly after this date concerns were expressed about falling beach levels in front of a section of vertical sea wall at the northern end, and in 1956 the wall between groynes 25 and 34 was provided with strengthened toe protection using sheet piling encased in concrete (Gwynedd Council, 2016). However, the beach south of Min y Mor Hotel maintained a healthy width and height (Figure 22). An aerial photograph dated June 1962 shows a relatively wide dry sand beach to the northwest of the Bath House, and around the breakwaters on Ynys y Brawd, although no vegetated dunes are evident (Figure 23).

An Admiralty chart published in 1967, based on a survey in 1964, shows exposed groynes all along the frontage and a narrow but identifiable low water channel (Bar Bach) extending from the Harbour to the sea (Figure 24). An aerial photograph dated 10 April 1971 indicates that the channel was relatively wide but shallow towards its seaward end (Figure 25). A small area of partially vegetated dunes is shown adjacent to the breakwater on Ynys y Brawd.

In the period 1970-72 rock was used to build a causeway, topped by a concrete walkway, across the Bar Bach channel between a point north of the old Bath House and Ynys y Brawd. A wave return parapet wall was constructed between the causeway and the north end of the promenade, many of the groynes were rebuilt and 3000 tons of quarried granite was placed to nourish the beach at the northern end (Gwynedd Council, 2016).

In June 1973 a relatively wide, shallow channel still existed on the northern side of the causeway, linked to the sea by another shallow channel having a NE-SW orientation (Figure 26), but this progressively filled with sediment during the later 1970s and 1980s. In 1981 further work was undertaken to strengthen the Trwyn y Gwaith breakwater at the southern end of Ynys y Brawd. A stepped concrete revetment and three groynes were built on the seaward side, the level of the connecting causeway was raised and a wave return parapet wall built to match the one constructed along the promenade in 1972-74. In 1983 further improvements were made to the seawall at the northern end of the promenade by extending the wave return parapet to provide greater protection to the railway level crossing. Repairs were also made in 1984 to the wall between groynes 25A-29A and 29B-33A, but owing to faults in design and construction further repairs were required in 1990 (Gwynedd Council, 2016).

The construction of the causeway greatly reduced the tidal scour in the former Bar Bach channel, and by 1986 the northern part had become completely filled with sediment (Figure 27), and problems of blown sand incursion onto the promenade had become a matter of concern (Robinson Jones Partnership Ltd., 1987). The levels of the southern part of the beach continued to rise during the 1990s and early 2000s (Figures 28 & 29). The first pioneer dune vegetation began to appear around the year 2000 and by 2006 significant areas of low dunes had developed to the south of the Min y Mor Hotel and on the western side of the Ynys y Brawd causeway (Figure 30). The extent of vegetation cover continued to increase over time, despite heavy visitor pressure and control measures undertaken by Gwynedd Council (Figures 31, 32, 33 & 34).

Digital elevation models (DEMs) constructed from the February 2003 and March 2014 LiDAR surveys (Figures 35, 36 & 37) and the June 2016 UAV survey (Figure 38), have been compared to quantify changes in the positions of tidal contours and sediment volumes between the survey dates. Also shown on Figures 35, 37 and 38 are profile lines which have been used to quantify changes in tidal contour position. Figures 36 and 39 provide contrast enhanced versions of the 2003 and LIDAR and 2016 UAV DEMs which show more clearly the subtle topographic variations which exist on the southern part of the beach between the two dune areas. Curving low amplitude bars can be seen extending in both directions towards a shallow channel located in the central part of the open beach area, separated by a shallow channel which allows tidal waters to reach slightly lower-lying areas of the beach behind during extreme high tides. Owing to the absence of a seaward gradient these low areas sometime retain water for several weeks following a surge tide, and / or during periods when the beach water table is high following periods of sustained rainfall.

The overall net change in surface elevation between February 2003 and June 2016 is shown in Figure 40. Changes in beach level at the profile lines P1 to P11 are shown in Figure 41, and movements of tidal contours are shown in Figures 42, 43 & 44.The main changes can be summarised as follows:

- landward rollover of the shingle beach towards the railway line north of the North Car Park (accomplished in large part during the stormy winter of 2013-14)
- sediment accretion on the upper beach above the MHWS line in front of the promenade north of the Min y Mor Hotel
- sediment accretion across most of the beach above MHWS south of the Min y Mor Hotel
- sediment erosion from most of the beach below MHWS along the entire frontage, except where sand ridges have changed position on the foreshore
- significant sediment accretion within the dune areas (above the level of HAT)
- Sediment accretion within the intertidal area on the southeast side of the causeway (much of it due to deposition of sand blown over the causeway)
- sediment erosion with the Harbour
- localised surface lowering between the northern belt of dunes and the promenade (probably due largely to beach management works).

The position of the HAT contour was either stable or showed a slight seaward movement along the northern and central parts of the frontage (profiles P1 to P8) and a large seaward movement at profiles P9 and P10 north Ynys y Brawd (Table 7). The MHWS contour showed a broadly similar pattern although the seaward movement was considerably less than that of HAT (12 m and 6.2 m at profiles P9 and P10). By contrast, the MHWN contour showed a net landward movement at most of the profiles, including those in the south; i.e. the active beach showed a tendency for steepening as previously reported in the 1980s and 90s (Shoreline Management Partnership & Posford Duvivier, 1993; Gwynedd Council (1998). The OD and MLWN tidal contours show a more complex pattern of variation, partly due to the effect of migrating ridges and runnels.

Changes in the sediment volume above each tidal contour are summarized or the North Beach and South Beach areas in Tables 8 and 9. The North Beach above the levels of HAT, MHWS and MHWN experienced small increases in sediment volume (1-2 x 10^3 m^3) between 2003 and 2016, whereas the beach below MHWN experienced a net loss of approximately 20 x 10^3 m^3. The South Beach showed a net overall sediment gain of 90 x 10^3 m^3 above HAT level (much of it in the dunes), a net gain of 19 x 10^3 m^3 on the beach between MHWS and HAT, and a net loss of approximately 24 x 10^3 m^3 below the level of MHWS. The defined area of the Harbour on the southeast side of the causeway showed a small net gain in sediment volume at all tidal levels (total of 12 x 10^3 m^3, Table 10).

The increase in dry sand beach area above MHWS level after building of the causeway increased the potential source area for windblown sand transport, and also increased the requirement to clear sand from the promenade, car park, sailing club and railway line (Gwynedd Council, 2016). While sand can be mobilised by winds from any direction, incursion onto the southern part of the promenade is most frequently associated with strong winds from the northwest and west which blow across a long fetch unobstructed by dunes (Figure 45). The most severe aeolian transport conditions occur when strong winds occur without rain, and when the tides are relatively low. Extreme high tides cover the upper beach with water and large parts of the beach may remain wet for several weeks during the winter and spring, when temperatures and evaporation rates are relatively low, rainfall more frequent and the beach water table relatively high. As the beach sand is relatively fine and well sorted (typical modal size of 200 - 250 um), it is easily entrained by the wind when dry and not salt crusted (Pye *et al*., 2007: Pye & Tsoar, 2009).

5.0 Potential future management intervention options

5.1 Initial options identified by Gwynedd Council

The Barmouth Sand Management Project document prepared by Gwynedd Council and the Barmouth Sand Group (2016) identified four initial options for consideration:

Option 1 – "Continue as we are" - continue to try to find funds to remove sufficient sand annually to mitigate the problems as far as possible

Option 2 – "Allow the foredunes to link up across the beach, and potentially reclaim the area behind as amenity space"

Option 3 - "Re-establish the North Channel"

Option 4 – "A mix of Options 2 and 3 to allow a more 'natural' development of the future of the beachscape, so encouraging dune growth while allowing the North Channel to try to re-establish itself".

Under Option 1, Gwynedd Council (potentially with partners) would continue to clear sand from the promenade, highway, car park and areas immediately in front of the wave return parapet wall and beach access ramps, prior to the beginning of each tourist season, and/or as-required.

Historically the sand has been moved and deposited close to the mean high water mark, from where much of it has been transported back onto the upper beach within a short period of time. Some sand has also been blown into the harbour. Sand which has crossed the car park and onto the railway line has been removed by Network Rail when considered necessary; some of the sand has been placed adjacent to the line and some removed. Gwynedd Council have also actively managed the lateral spread of sand dune vegetation in order to maintain a large amenity beach area with clear views to the sea, and an unobstructed passage to the sea for vessels based at the RNLI station. Marker posts have been placed on the beach to mark limits where dune development has been considered acceptable.

While continuation of the present management practices is technically feasible, it is likely to involve increasing cost and may become unsustainable in the future. There will also be a continuing safety risk associated with the presence of sand on the promenade and highway, problems of blockage to drainage and continuing sediment deposition within the harbour. As a decision has already been made to seek a more sustainable alternative, this option it is not considered further in this report, although it is recognised that continuation of the present management regime may be required during the development stage of any new measures.

Under Option 2, attempts to control the spread of dunes would cease and a more extensive foredune ridge would be allowed to develop (either naturally or by artificial encouragement) at the seaward end of the open beach area in front of the lifeboat station. It is assumed that a break in the dune ridge would need to be maintained to allow lifeboats to reach the sea, and the elevation of the dunes might need to be managed in order to allow visual monitoring. The objective would be to trap windblown sand closer to the normal high water line, to reduce the wind speeds across the area of flat beach behind the dunes, which would continue to be available for amenity use, and to significantly reduce the quantity of sand reaching the promenade and causeway. Under this option, multiple benefits could potentially arise (e.g. habitat gain and increased storm protection, in addition to decreased requirement for annual sand shift and highway cleaning. A number of variants of this option are considered in more detail below.

Under Option 3, the areal extent and elevation of the dry beach could be reduced by excavating sand to restore the former Bar Bach Channel. This would potentially create a wide area of moist sand with a much lower potential for wind entrainment. Initial estimates by Gwynedd Council, based on consideration of historical chart information and a profile survey in 2003, suggested that removal and disposal of in excess of 380 x 10^3 m^3 of sediment would be required to reinstate the channel to its historical condition. The concrete causeway and underlying rubble breakwater would also have to be broken up and disposed of. This option is considered in more detail below, together with the combined Option 4 which includes elements of Options 2 and 3.

5.2 Consideration of additional options

As part of this further assessment, a total of nine intervention options have been considered, referred to below as options A to I. These options are not mutually exclusive and could be modified or combined in the light of further discussions with stakeholder.

5.2.1 Option A: Possible reinstatement of the Bar Bach Channel

In order to further assess the volume of sediment which would need to be excavated to reinstated the Bar Bach Channel to its condition in the 1960s, before the causeway was built, the DEM based on the 2016 UAV survey was modified to include depths taken from the 1964 Admiralty survey and the position of the low water mark indicated on aerial photographs (Figure 46). The volume required to restore this topographic configuration is calculated to be 307 +/- 7 x 10^3 m^3, a figure broadly similar to the previous Gwynedd Council estimate. Most of the material removed would be sand, although there would be some rubble and concrete arising from removal of the causeway (which could be removed in its entirety or in part). Potentially, the excavated sand could be transported northwards to recharge the beach beyond the Min y Mor hotel, thereby improving the coast protection value of the beaches in that area. However, movement of this quantity of material this would require 12000-17,000 lorry or large dumper truck loads and would be a substantial project in itself. Any sediment deposition below MHWS level would require a Marine Licence, and deposition at any level on the beach would be likely to require a Habitats Regulations Assessment (HRA) to consider potential impact on the adjacent SACs. A separate repository would need to be found for rock and concrete arising from the causeway and underlying rubble barrage.

If the Channel was fully reinstated, some draw-down of the adjoining beaches would be expected, and sediment might also be imported from the adjoining coast, such that maintenance dredging would be required to maintain the depth initially created by a capital scheme. Without dredging or modifications to other channels in the Mawddach there is a strong possibility that a reinstated Bar Bach channel would again gradually fill with sediment. However, in the short to medium term reinstatement of the Bar Bach channel would recreate an area of deep water (>6m) and potentially strong currents which could pose a significant risk to bathers, and strandings on Ynys Brawdd would be likely. Improvement to public safety was a significant factor behind the decision to construct the causeway in the late 1960s.

As a modification to this option, the former channel could be partially reinstated with a shallower depth, in which case the volume of sediment required to be removed could be of the order of 100 – 200 x 10^3 m^3. While the risk of drownings might thereby be reduced, strandings on Ynys y Brawd would still be likely. Small craft moorings and beachings near the Bath House Café would still be lost, and there would be greater wave activity in the harbour under northwesterly conditions, and there could be increased risk of coastal flooding.

5.2.2 Option B: Possible lowering of the open beach area

An alternative to reinstating the Bar Bach channel would be to lower a wider area of the open beach and to leave the causeway intact. Figure 47 shows an example where the main part of the open beach between the dunes has been lowered back to 2003 levels. This option, as illustrated, would involve removal of 21 +/- 6 x 10^3 m^3 of sand which could either be used to create an artificial dune ridge nearby or to nourish the beaches along the northern part of the frontage. This option would achieve a reduction in the height of the dry sand beach of 0.3 to 0.8 m. However, although this would reduce the wind sand transport potential it would not stop it and sand would continue to accumulate against and on top of the promenade during periods of strong northwesterly and westerly winds.

5.2.3 Option C: Creation of additional areas of outer dune ridge

The purpose of creating additional dune areas of outer dune ridge would be twofold: (1) to trap and stabilize excess sand, (2) to provide a barrier to wind and reduce the potential for deflation of sand from the dry sand beach. Additional benefits could also result, including additional areas of priority dune habitat and improvements to flood defence. Potentially negative aspects of this option would be (a) a reduction amenity beach area and (b) reduced sea view from the promenade and RNLI lifeboat station.

Figure 48 shows an option where alongshore extensions to the existing outer due ridges are permitted or artificially encourage d using sand chestnut pal fencing (which could be temporary until such time as dune vegetation becomes well established). The effectiveness of sand trapping could be enhanced by planting of marram and additional 'internal' lengths of sand fencing (detailed designs would be developed prior to works being undertaken). The example in Figure 48 shows retention of a beach access gap 70-80 m wide; this would permit good visibility of the lifeboat launching and recovery area from the RNLI station but would also permit winds from the southwest to blow sand onto the promenade. Periodic clearance would therefore still be required, although on a smaller scale than at present. Although there would be some loss of amenity beach area, the most heavily used areas close to the promenade would not be affected.

5.2.4 *Option D: Extension of a narrow belt of outer dunes with narrow access gap*

With this option (Figure 49), sand fencing (and possibly marram planting) would be used to build a relatively narrow (up to c. 50 m) wide belt of dunes extending north and south of existing outer dunes, leaving only a relatively narrow (c. 20 m) access gap with offset between the two. This would provide a more effective wind barrier than option C but would reduce visibility from the promenade and access to the waterline to a greater degree. A relatively large amenity area behind the dunes would be retained.

5.2.5 *Option E: Extension of a narrow belt of outer dunes with removal of the causeway*

This option (Figure 50) combines construction of relatively narrow outer dune extension with removal of the causeway and dunes which have recently developed adjacent to it. This would result in a significant increase in amenity beach area and would allow the eastern end of the former Bar Bach channel (the intertidal part of the harbour opposite the Bath House Café) to evolve in response to natural processes). During surge tides tidal flooding of the entire beach in front of the promenade would be possible from the south, and it is possible that a shallow drainage channel (runnel) would develop in this area after an initial period when sand is likely to be transported towards the harbour by northwesterly winds. Lowering of the beach and development of a runnel linked to the harbour could be encouraged by limited sand excavation.

5.2.6 Option F: Creation of a more continuous line of inner dunes

This option (Figure 51) would involve the use of pale fencing to form a more continuous line of inner dunes close to the promenade, curving at the southern end to join up with the existing dunes which have developed recently adjacent to the causeway. Gaps in the fencing / new dunes would be left at beach access points (slipways / steps) and in front of the RNLI station. The objective would be to trap sand blow from a large area of amenity beach which would be allowed to remain on the seaward side of the new dunes. Owing to the large potential source area and wide angle over which winds could impact on the beach, high rates of aeolian sand transport are likely, with result that a wide, high dune ridge could build within a few years, leading to obstruction of views from the promenade. However, the growth in height of the dunes could be managed by pacing successive fences to encourage seaward rather than vertical growth. In the absence of any sand trapping structures in front of the access gap, blown sand would continue to blow towards the RNLI station and would require periodic clearance.

5.2.7 Option G: Creation of outer and inner dune barriers using single lines of fencing

With this option (Figure 52), some extension would be made to the outer dune ridges on either side of the open beach area, and in addition a more continuous line of inner dunes would be created close to the promenade, as described in Option F. Only a single line of pale fencing would be built in each case, and could be removed once dune vegetation is well established. A relatively wide gap would be left in the outer dune ridge, and the purpose of the inner dune ridge would be trap sand blow through this gap before it reaches the promenade. However, a direct pathway for wind transport of sand towards the RNLI station during periods of southwesterly winds would remain. Since public access to the new dune areas would still be possible, trampling and surface disturbance would still occur and establishment of dune vegetation would be delayed.

5.2.8 Option H: Creation of outer and inner dune barriers using fenced compartments

This option is similar to Option G but involves construction of closed fenced compartments to exclude the public and allow quicker growth of vegetation. More rapid growth of dunes could be encouraged by planting of marram and use of internal send fences. Some or all of the exposed fencing could be removed one vegetation is well established; it may be necessary to retain some fencing in high pressure areas near the promenade, with resultant ongoing maintenance requirement. This option would be highly effective in trapping sand but has potential disadvantages in term of loss of a significant area of amenity beach and reduced sea views from the promenade. Some windblown transport onto the RNLI slipway would also continue. Owing to the greater length of fencing required compared with Option G, construction costs would be higher.

5.2.9 *Option I: Reduction in upper beach levels and excavation of a shallow channel / lagoon, combined with extensions to the outer dune ridges*

This option (Figure 54) combines elements of several of the previously describe options, including general removal of sand to reduce the level of the upper beach close to the promenade, and use of sand fencing to create extensions to the outer dune ridges. In addition, it is proposed to enhance existing natural topographic features of the beach by excavating sand to create a deeper channel linking the sea with one of depressions which exists behind the outer dune ridges. This depression would be enlarged and depended to create a shallow pool or lagoon which would fill with water on high neap and spring tides. The pool would partially drain on the ebb tide but would retain c. 60 cm depth of water which could be used for recreational purposes in a similar way to the shallow seaward end of the former Bar Bach channel. The sand surrounding the pool would be kept damp for long periods by tidal flooding and capillary rise from the groundwater table, thereby limiting the potential for wind mobilization. Wind action on the higher remaining areas of open beach would be reduced by the construction of the outer dune ridge extensions. The causeway and existing dunes adjacent to it would be left in place to limit sand transport towards the harbour and provide continued pedestrian access to the Ynys y Brawd breakwater. Sand made available by the general lowering of the beach in front of the promenade, and by excavation of the shallow channel and associated pool, could be used to build the additional areas of outer dunes, or it could be transported northwards to nourish the eroding beach north of the Min y Mor Hotel. It is likely that the depth of the lagoon would be reduced by input of wind-blown sand over time, and periodic maintenance (sand removal) would be required to maintain the depth / volume in the medium to longer term.

5.3 Requirement to consider buried infrastructure

Consideration of the options needs to take account of the distribution and nature of infrastructure on, under and adjacent to the beach and dunes, including, drainage pipes, cables and the remains of buried groynes (Figures 55-57). The presence of these features is especially relevant to options which could involve beach lowering and channel excavation. Further investigations are required to ascertain the extent of possible buried groynes, and any costs which might be involved in their removal.

6.0 Conclusions and recommendations

Based on the results of this assessment, it is concluded that removal of the Ynys y Brawd causeway and re-establishment of the Bar Bach Channel to its previous form would not be feasible or desirable on technical or environmental grounds. The cost of such large capital works would be very considerable, and could only be considered as part of a much wider coastal defence scheme involving large scale nourishment of the north Barmouth coastal frontage.

Significant benefits could be achieved at much lower cost from a number of smaller scale options intended to reduce wind speeds and trap sand before it reaches the promenade. However, a composite approach involving lowering of parts of the beach, localised excavation to enlarge and deepen existing natural topographic features of the beach, combined with limited extensions to the existing dune outer dune ridges to provide a more effective wind barrier, could provide the greatest benefits at reasonable cost. It is recommended that further detailed consideration should be given to this option (Option I) in consultation with relevant stakeholders.

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Tables

Table 1. Results of error analysis for three LiDAR surveys covering Barmouth Main Car Park. A total of 6501 pixels were compared, with elevations (in m ODN) for the frequency distribution shown. Note that the survey on 14/02/2003 was conducted at 2 m resolution, but has been re-interpolated at 1 m resolution for the purposes of comparison with the surveys on 20/02/2013 and 03/03/2014 which were surveyed at 1 m resolution.

	14/02/2003 Elevation (m ODN)	20/02/2013 Elevation (m ODN)	03/03/2014 Elevation (m ODN)	Differences (m) 2003 to 2013	2003 to 2014	2013 to 2014
1%%-tile:	6.08	5.92	5.91	-0.16	-0.17	-0.01
5%%-tile:	6.27	6.12	6.10	-0.15	-0.17	-0.02
10%%-tile:	6.37	6.22	6.20	-0.15	-0.17	-0.02
25%%-tile:	6.60	6.45	6.44	-0.15	-0.16	-0.01
50%%-tile:	6.90	6.78	6.76	-0.12	-0.14	-0.02
75%%-tile:	7.22	7.09	7.08	-0.13	-0.14	-0.01
90%%-tile:	7.37	7.25	7.24	-0.12	-0.13	-0.01
95%%-tile:	7.46	7.32	7.31	-0.14	-0.15	-0.01
99%%-tile:	7.60	7.47	7.45	-0.13	-0.15	-0.02
			Mean difference:	-0.14	-0.15	-0.01

Table 2. Comparison of elevations (m ODN) obtained from the 3 March 2014 LiDAR survey and the 16 June 2016 UAV survey form three areas of the main car park (south-east of the Lifeboat Station), a 100 m length of Marine Parade near Min-y-Mor, and the north car park at the northern end of the sea wall. The average height difference (m) between the LiDAR survey on 03/03/2014 and the UAV survey on 16/06/2016 is shown, both calculated on a 1 m grid. Median difference at the three locations (6 cm, 7 cm and 9 cm) were used to correct the 2016 UAV survey (so that it equates to the 2014 LiDAR datum) using a sloping surface prescribed by these values.

	Main Car Park			Marine Parade / Min-y-Mor			North Car Park		
	LiDAR	UAV	Difference	LiDAR	UAV	Difference	LiDAR	UAV	Difference
1%%-tile:	5.78	5.81	0.03	5.56	5.65	0.09	5.92	5.98	0.06
5%%-tile:	5.82	5.85	0.03	5.59	5.67	0.08	5.95	6.03	0.08
10%%-tile:	5.84	5.88	0.04	5.61	5.69	0.08	5.96	6.04	0.08
25%%-tile:	5.91	5.97	0.06	5.64	5.72	0.08	5.99	6.08	0.09
50%%-tile:	6.05	6.11	0.06	5.70	5.77	0.07	6.02	6.11	0.09
75%%-tile:	6.25	6.31	0.06	5.75	5.82	0.07	6.06	6.14	0.08
90%%-tile:	6.37	6.43	0.06	5.78	5.85	0.07	6.09	6.18	0.09
95%%-tile:	6.41	6.48	0.07	5.80	5.86	0.06	6.10	6.20	0.10
99%%-tile:	6.48	6.55	0.07	5.82	5.89	0.07	6.13	6.23	0.10
Mean Difference:			0.05			0.07			0.09

Table 3. Tidal levels at Barmouth relative to Ordnance Datum Newlyn (Admiralty Tide Tables, 2016).

	m ODN
Highest Astronomical Tide (HAT)	3.26
Mean High Water Springs (MHWS)	2.56
Mean High Water Neaps (MHWN)	1.26
Mean Sea Level (MSL)	0.28
Mean Low Water Neaps (MLWN)	-0.54
Mean Low Water Springs (MLWS)	-1.74
Lowest Astronomical Tide (LAT)	nd
Chart Datum (CD)	-2.44
Mean Spring Tidal Range (MSTR)	4.30
Mean Neap Tidal Range (MNTR)	1.80

Table 4. Estimated extreme high water levels at Barmouth, after Royal Haskoning (2011b) and McMillan *et al.* (2011).

Return Period (years)	Royal Haskoning (2011)	McMillan et al. (2011)
1		3.48 ± 0.10
2		3.59 ± 0.10
5		3.73 ± 0.10
10	3.93	3.83 ± 0.10
20		3.92 ± 0.10
25		3.95 ± 0.10
50	4.17	4.04 ± 0.10
75		4.10 ± 0.10
100	4.31	4.13 ± 0.20
150		4.18 ± 0.20
200	4.44	4.22 ± 0.20
250		4.24 ± 0.20
300		4.27 ± 0.20
500		4.33 ± 0.20
1000		4.41 ± 0.30
10000		4.66 ± 0.40

Table 5. The highest 50 tides recorded at the Class A tide gauge at Barmouth during the period 1991-2015. Note that, in addition to smaller data gaps, no data exist for the periods 16/05/2003 to 11/03/2005, 12/01/2013 to 13/02/2013, 26/03/2013 to 10/04/013, and after 30/12/2015. Data source: NTSLF.

Date and Time	Observed level (m OD)	Residual at observed high water (m)	Skew surge residual (m)
03/01/2014 09:15	3.92	0.81	0.81
10/02/1997 10:00	3.92	0.73	0.73
30/03/2006 08:45	3.75	0.68	0.68
25/11/2000 20:15	3.71	1.21	1.16
01/02/2002 10:45	3.71	0.76	0.76
03/02/2014 10:30	3.69	0.61	0.61
10/03/2008 09:45	3.68	0.74	0.74
01/02/2014 09:15	3.62	0.47	0.46
23/12/1999 20:45	3.62	0.71	0.71
03/01/2014 21:45	3.61	0.79	0.79
12/01/1993 10:45	3.61	0.66	0.66
08/10/2006 20:45	3.57	0.42	0.40
06/01/2014 11:30	3.55	0.80	0.80
03/01/1998 11:00	3.55	0.94	0.90
02/03/2014 08:45	3.55	0.44	0.44
08/10/2014 20:00	3.53	0.43	0.43
29/08/1992 21:00	3.52	0.38	0.38
10/03/2001 08:30	3.51	0.54	0.53
12/12/2000 21:00	3.51	0.67	0.67
27/02/1994 09:00	3.51	0.50	0.50
01/02/2014 21:30	3.50	0.64	0.64
30/08/1992 22:00	3.50	0.42	0.42
07/10/2006 20:15	3.49	0.33	0.33
09/09/1998 22:15	3.49	0.47	0.47
07/09/1998 21:00	3.49	0.44	0.44
24/10/1995 19:45	3.46	0.64	0.57
08/09/1998 21:45	3.46	0.36	0.36
30/03/1994 22:30	3.45	0.69	0.69
28/10/2015 20:45	3.45	0.28	0.28
20/02/2007 10:00	3.45	0.36	0.36
28/09/1996 21:00	3.45	0.37	0.37
09/01/1993 08:30	3.44	0.66	0.66
05/11/1998 20:45	3.44	0.29	0.28
03/12/2006 06:30	3.44	1.18	1.18
12/08/2014 21:30	3.44	0.30	0.30
31/01/1995 08:15	3.44	0.58	0.58
07/12/2006 09:15	3.44	0.86	0.86
02/03/2014 21:00	3.43	0.58	0.58
31/03/2006 09:15	3.42	0.39	0.39
05/12/2006 08:00	3.42	0.84	0.84
30/03/1998 09:45	3.42	0.30	0.30
03/03/1998 11:30	3.42	0.69	0.69
27/02/2002 20:45	3.42	0.71	0.69
27/10/2015 20:00	3.42	0.26	0.26
11/03/2001 09:15	3.42	0.35	0.35
05/12/2013 09:30	3.41	0.40	0.40
11/01/1993 10:15	3.41	0.43	0.41
19/02/2007 09:15	3.41	0.38	0.38
09/02/1997 09:15	3.40	0.22	0.22
10/09/2010 21:30	3.40	0.22	0.22

Table 6. Projections of relative sea level rise at Barmouth, calculated from the base year of 1990 under three emission scenarios, according to UKCP09 model outputs. Values are in millimetres. The value in bold is the 50th percentile model output, and the numbers in brackets are the 5th to 95th percentile range.

Year	Low emission Scenario		Medium Emission Scenario		High Emission Scenario	
2016	**61**	(29-92)	**73**	(32-114)	**88**	(36-141)
2030	**100**	(47-152)	**120**	(52-188)	**145**	(58-232)
2050	**162**	(76-249)	**196**	(83-309)	**237**	(94-381)
2100	**357**	(163-551)	**432**	(178-687)	**525**	(203-848)

Table 7. Movement of the tidal contours between the 2003 LiDAR survey and 2016 UAV survey. Positive values indicate a seaward movement (progradation), negative values indicate landward movement (recession). No values for MLWN on P9 and OD and MLWN on P10 due to incomplete coverage by the 2016 UAV survey.

	HAT (3.26 m OD)	MHWS (2.56 m OD)	MHWN (1.26 m OD)	OD (0.00 m OD)	MLWN (-0.54 m OD)
P1	+2.4	-0.5	+2.4	-7.2	-25.7
P2	+1.6	+1.0	+1.0	-13.8	-39.0
P3	+1.2	+1.3	+2.5	-36.8	-41.7
P4	+1.8	+2.7	-0.9	-14.9	-7.7
P5	+3.4	+2.6	-4.0	+1.1	-5.3
P6	+4.2	+4.7	-14.7	-13.4	-10.4
P7	+2.0	-3.0	-18.0	+6.8	+20.1
P8	+0.0	-5.5	-11.5	+8.1	+45.7
P9	+157.9	+12.0	-39.2	-7.8	
P10	+32.6	+6.2	+0.3		
P11	-4.0	-17.5	+15.2	+16.2	+20.3

Table 8. Volumes of sediment (x 10^3 m^3) above selected tidal contours on the North Beach at Barmouth (between Profile P6 and the northern end of the seawall at the north car park). Note that the sea level at the time of the 2003 LiDAR survey was at -1.3 m OD, so volume changes cannot be calculated below MLWN for this survey. Error limits for the 2003 and 2016 surveys (expressed as ±) have been calculated assuming an error in elevations of ±10 cm, and the error shown for the 2003-2016 change is the average of the errors in the two surveys.

	North Beach					
	2003		2016		2003-2016 Change	
HAT (3.26 m OD)	1	±<0.5	2	±0	1	±<0.5
MHWS (2.56 m OD)	3	±<0.5	6	±1	3	±1
MHWN (1.26 m OD)	17	±2	22	±2	5	±2
OD (0.00 m OD)	73	±8	69	±6	-4	±7
MLWN (-0.54 m OD)	127	±12	112	±10	-15	±11
MLWS (-1.74 m OD)			280	±18		

	North Beach					
	2003		2016		2003-2016 Change	
>HAT	1	±<0.5	2	±0	1	±<0.5
MHWS-HAT	2	±<0.5	4	±0	2	±<0.5
MHWN-MHWS	14	±2	16	±1	2	±1
OD-MHWN	56	±6	47	±4	-9	±5
MLWN-OD	54	±4	43	±3	-11	±4
MLWS-MLWN			168	±8		

Table 9. Volumes of sediment (x10^3 m^3) above selected tidal contours on the South Beach at Barmouth (between Profile P6 and the Mawddach estuary, excluding the harbour to the south-east of the causeway). Note that the sea level at the time of the 2003 LiDAR survey was at -1.3 m OD, so volume changes cannot be calculated below MLWN for this survey; also the 2016 UAV survey coverage did not extend far enough south to cover the MLWN or MLWS contours. Error limits for the 2003 and 2016 surveys (expressed as ±) have been calculated assuming an error in elevations of ±10 cm, and the error in the 2003-2016 change is the average of the errors in the two surveys.

	South Beach					
	2003		2016		2003-2016 Change	
HAT (3.26 m OD)	25	±6	114	±11	90	±8
MHWS (2.56 m OD)	103	±15	212	±16	109	±16
MHWN (1.26 m OD)	358	±25	457	±23	99	±24
OD (0.00 m OD)	750	±36	835	±37	85	±36
MLWN (-0.54 m OD)	956	±40				
MLWS (-1.74 m OD)						

	South Beach					
	2003		2016		2003-2016 Change	
>HAT	25	±6	114	±11	90	±8
MHWS-HAT	79	±10	98	±5	19	±7
MHWN-MHWS	254	±10	245	±7	-9	±9
OD-MHWN	392	±11	378	±13	-15	±12
MLWN-OD	206	±3				
MLWS-MLWN						

Table 10. Volumes of beach sediment (x10^3 m^3) above selected tidal contours in the Harbour at Barmouth (south-east of the causeway). Note that the sea level at the time of the 2003 LiDAR survey was at -1.3 m OD, so volume changes cannot be calculated below MLWN for this survey. Error limits for the 2003 and 2016 surveys (expressed as ±) have been calculated assuming an error in elevations of ±10 cm, and the error in the 2003-2016 change is the average of the errors in the two surveys.

	Harbour					
	2003		2016		2003-2016 Change	
HAT (3.26 m OD)	20	±1	26	±1	6	±1
MHWS (2.56 m OD)	27	±1	33	±1	6	±1
MHWN (1.26 m OD)	53	±2	61	±3	7	±3
OD (0.00 m OD)	88	±3	98	±3	10	±3
MLWN (-0.54 m OD)	105	±3	116	±3	11	±3
MLWS (-1.74 m OD)			159	±4		

	Harbour					
	2003		2016		2003-2016 Change	
>HAT	20	±1	26	±1	6	±1
MHWS-HAT	7	±1	7	±<0.5	0	±<0.5
MHWN-MHWS	26	±1	28	±1	2	±1
OD-MHWN	34	±1	37	±1	3	±1
MLWN-OD	17	±<0.5	18	±<0.5	1	±<0.5
MLWS-MLWN			43	±<0.5		

Figures

Figure 1. The location of Barmouth in the wider context of northwest Wales and northern Cardigan Bay.

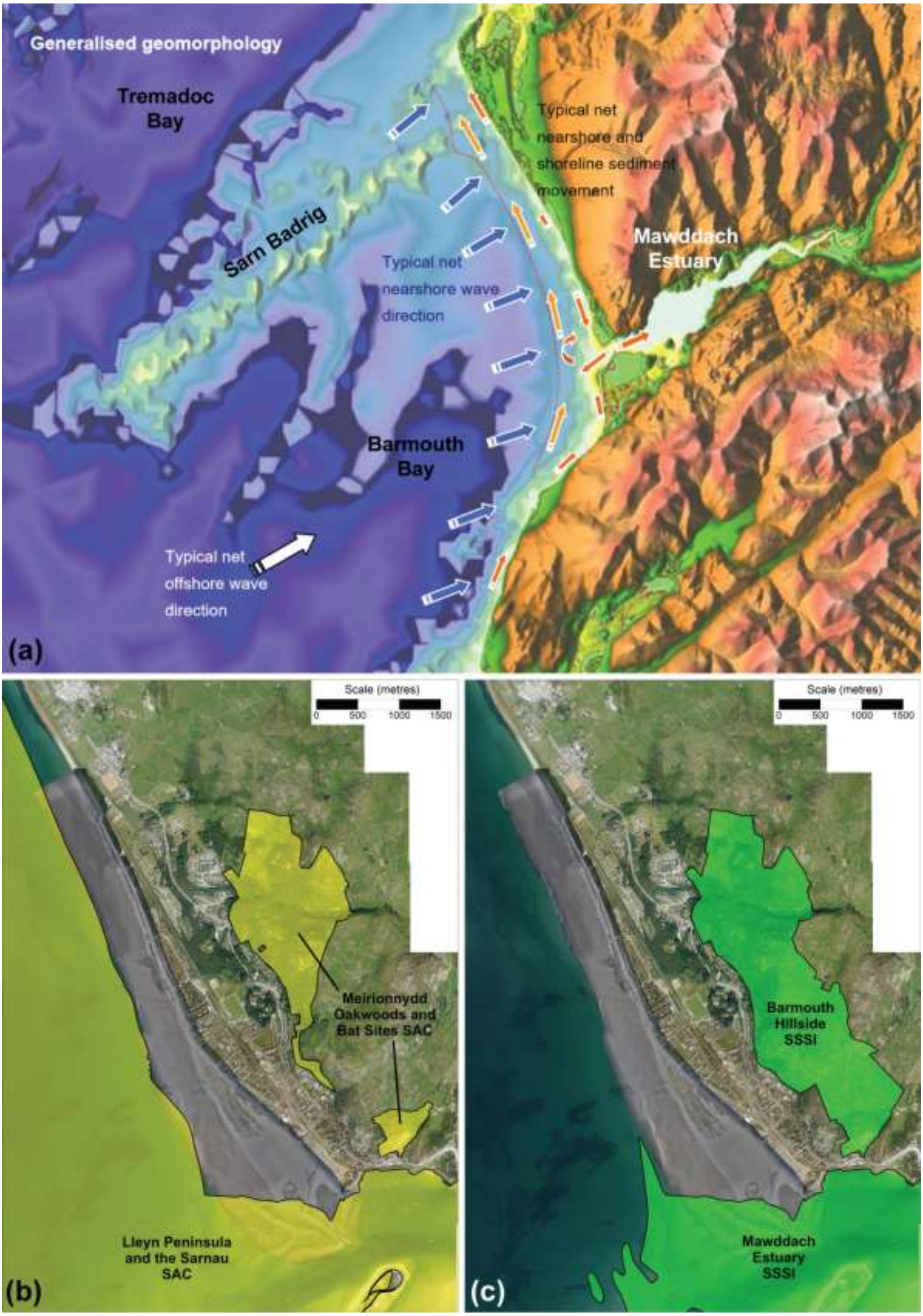


Figure 2. (a) Generalised bathymetry and topography of the Barmouth area, showing indicative offshore and nearshore wave and sediment transport directions (after Royal Haskoning, 2011a,b); (b) Site of Special Conservation designation; (c) Site of Special Scientific Interest designation.

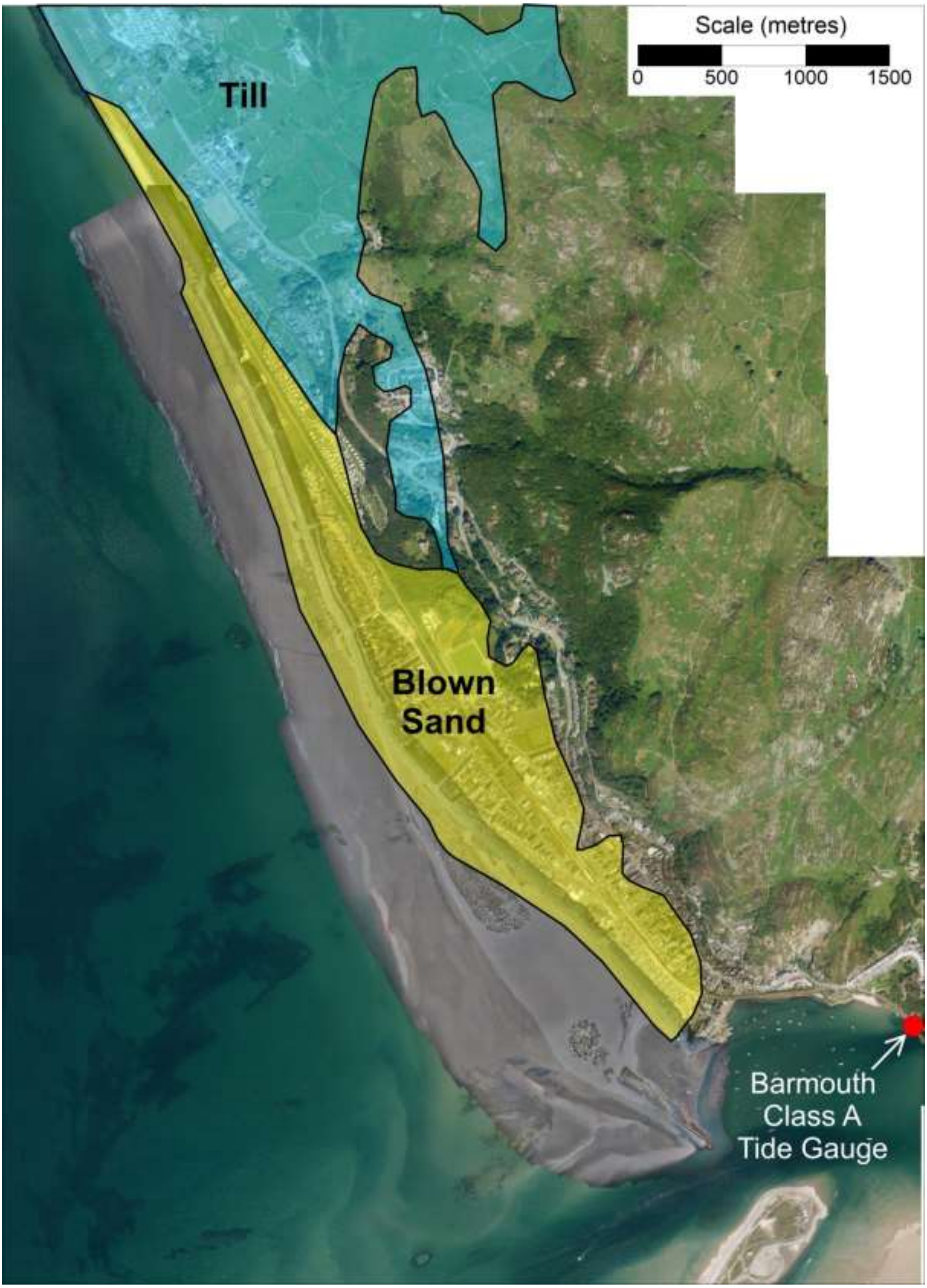


Figure 3. Superficial geology based on British Geological Survey mapping. Only blown sand and till are mapped in this area. On all other areas no superficial geology is recorded, including the land immediately behind Barmouth Harbour and beneath St David's Church.

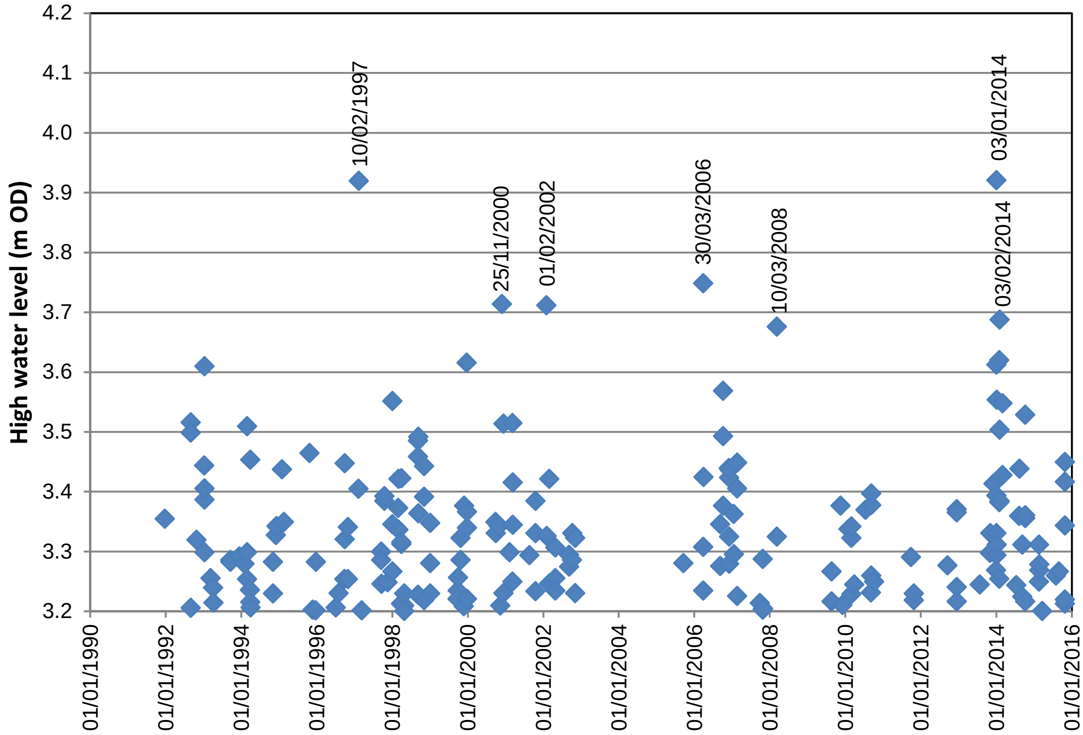


Figure 4. Tides exceeding 3.2 m ODN at Barmouth since 1991. Note the significant data gap between May 2003 and March 2005.

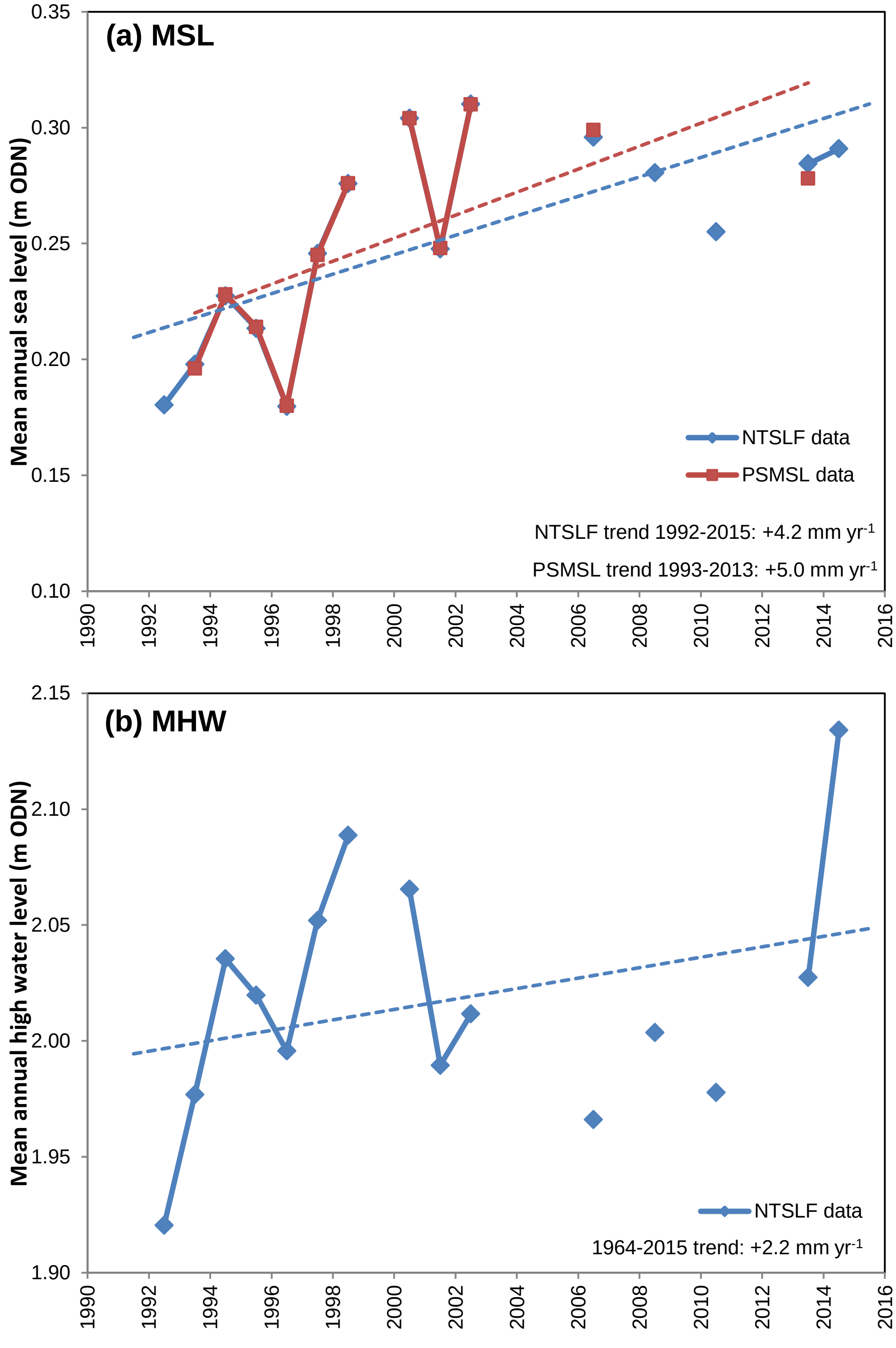


Figure 5. Records of (a) mean sea level and (b) mean high water level, recorded in each calendar year at the Class A tide gauge at Barmouth during the period 1992-2015. Data sources: PSMSL and NTSLF.

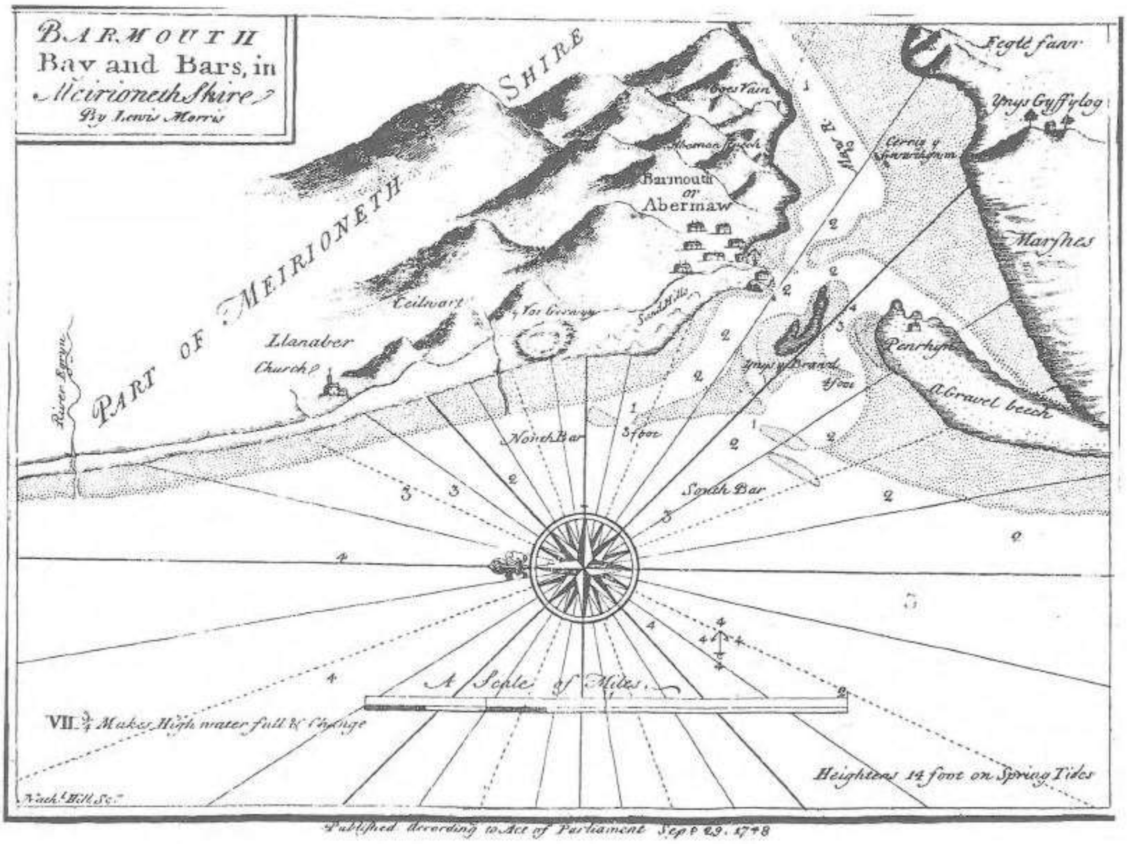


Figure 6. Lewis Morris' chart of Barmouth, 1748

Figure 7. Composite aerial image of the Barmouth area comprising the 2016 UAV photography superimposed on the 2003 aerial photography. The principal features and locations mentioned in the text are also shown.

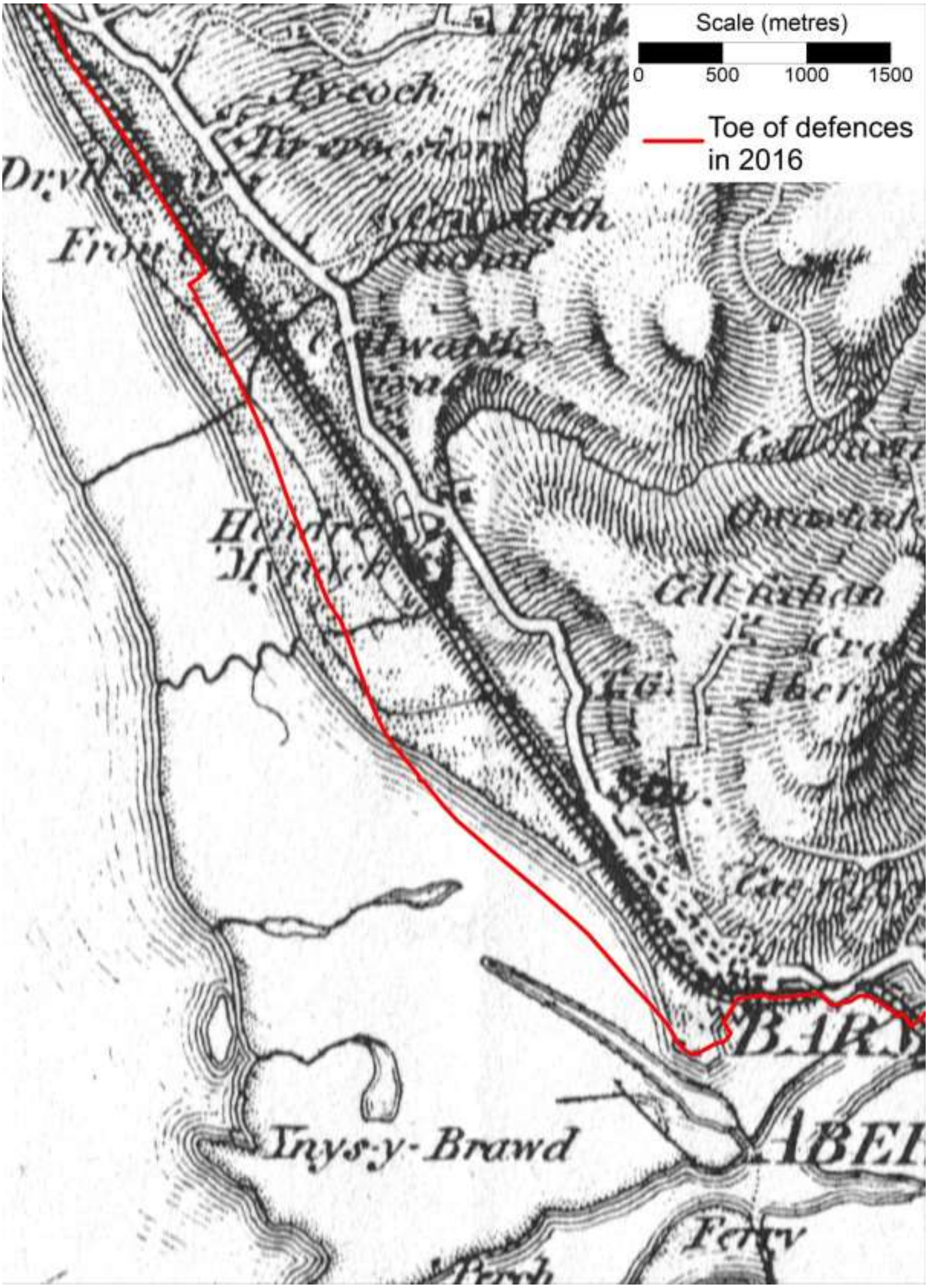


Figure 8. First edition One-Inch Ordnance Survey map, surveyed 1833-35, with the railway line (opened1867) added later.

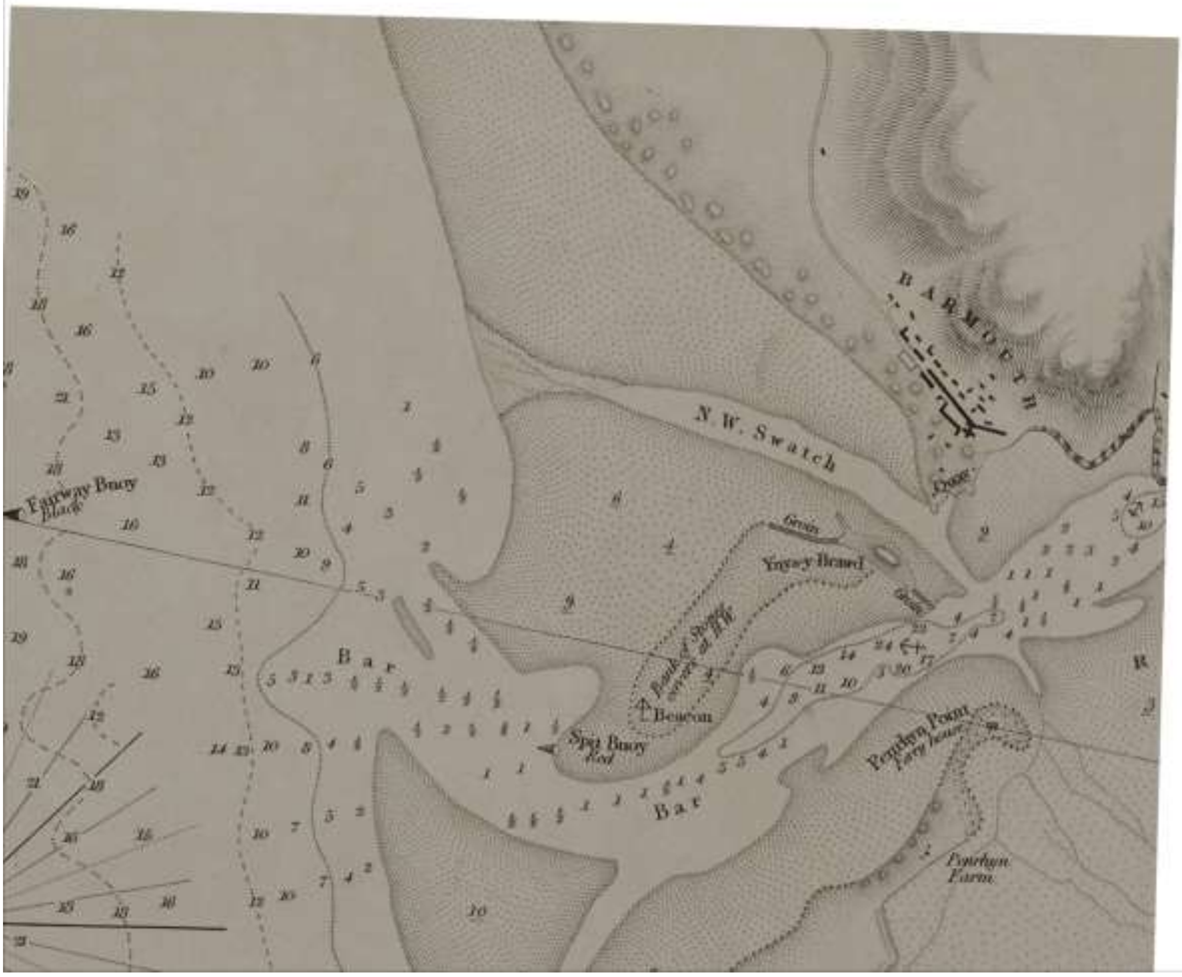


Figure 9. Admiralty Chart "Aberdovey and Barmouth" (No. 1487), published in 1843, surveyed 1835 by Commander Sheringham R.N. Soundings in feet.

Figure 10. First edition Six-Inch Ordnance Survey map, surveyed 1887.

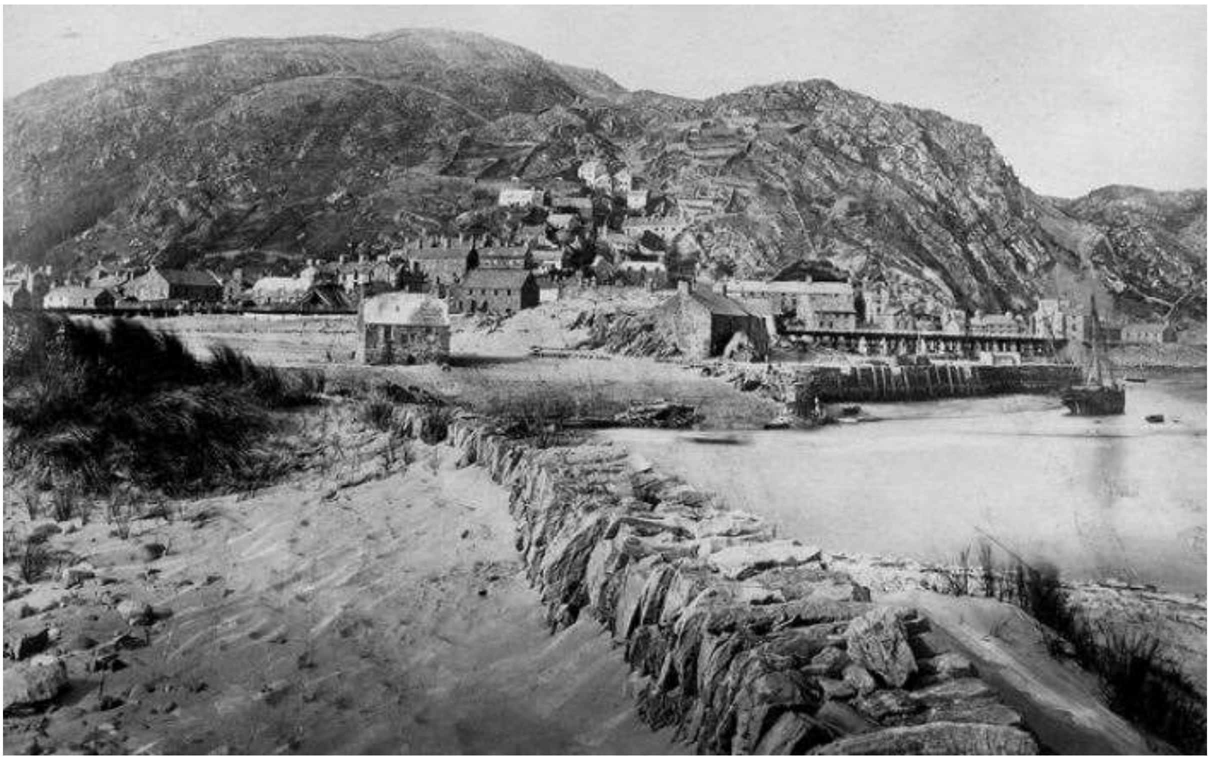


Figure 11. Late 19th century photograph showing a masonry retaining wall on the landward side of Ynys Brawd, opposite the Bath House.

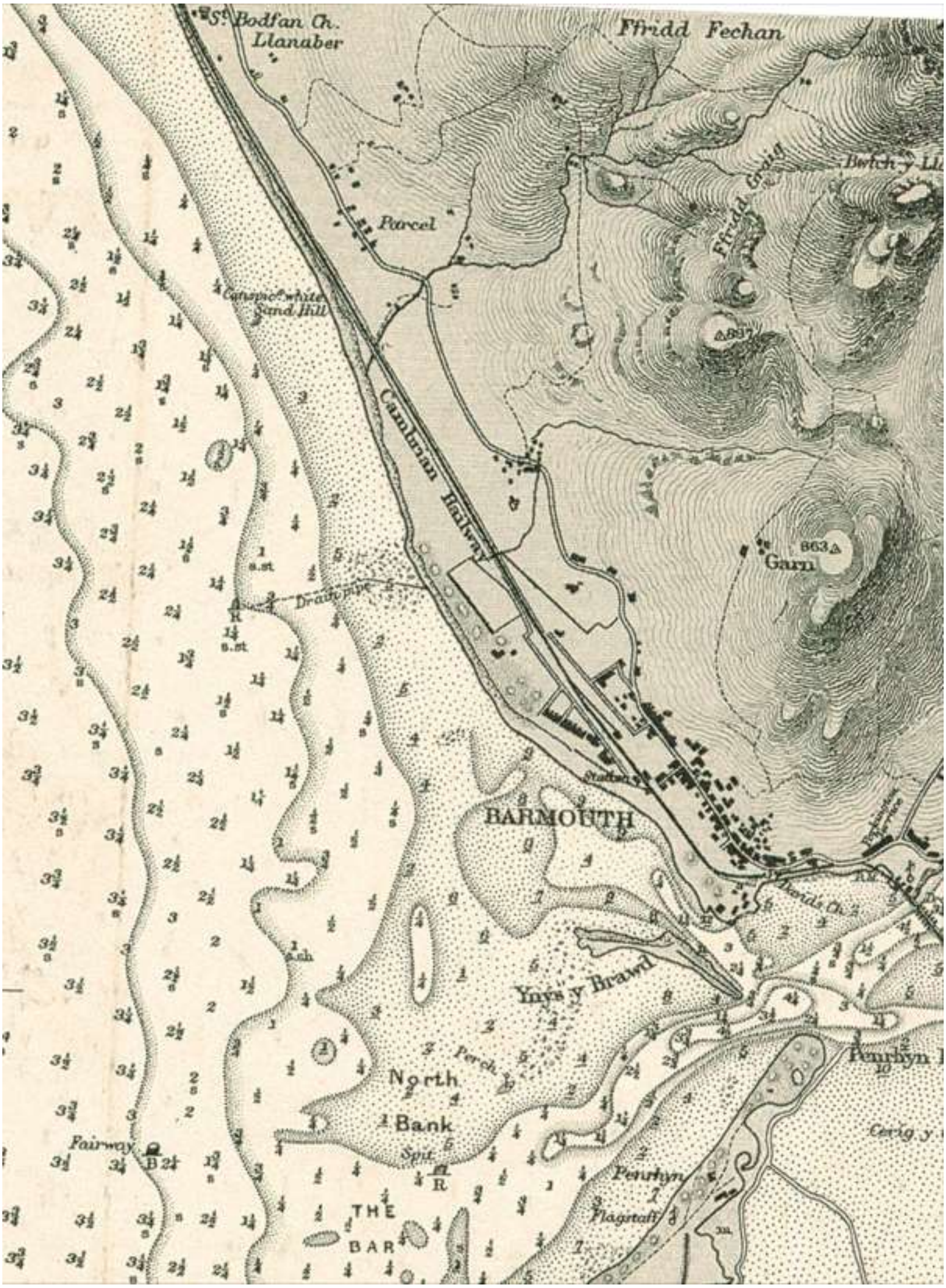


Figure 12. Admiralty Chart "Plans and Anchorages in Cardigan Bay" (No. 1484), published in 1892, surveyed 1890 by Staff Comr. W.E. Archdeacon. Soundings in fathoms.

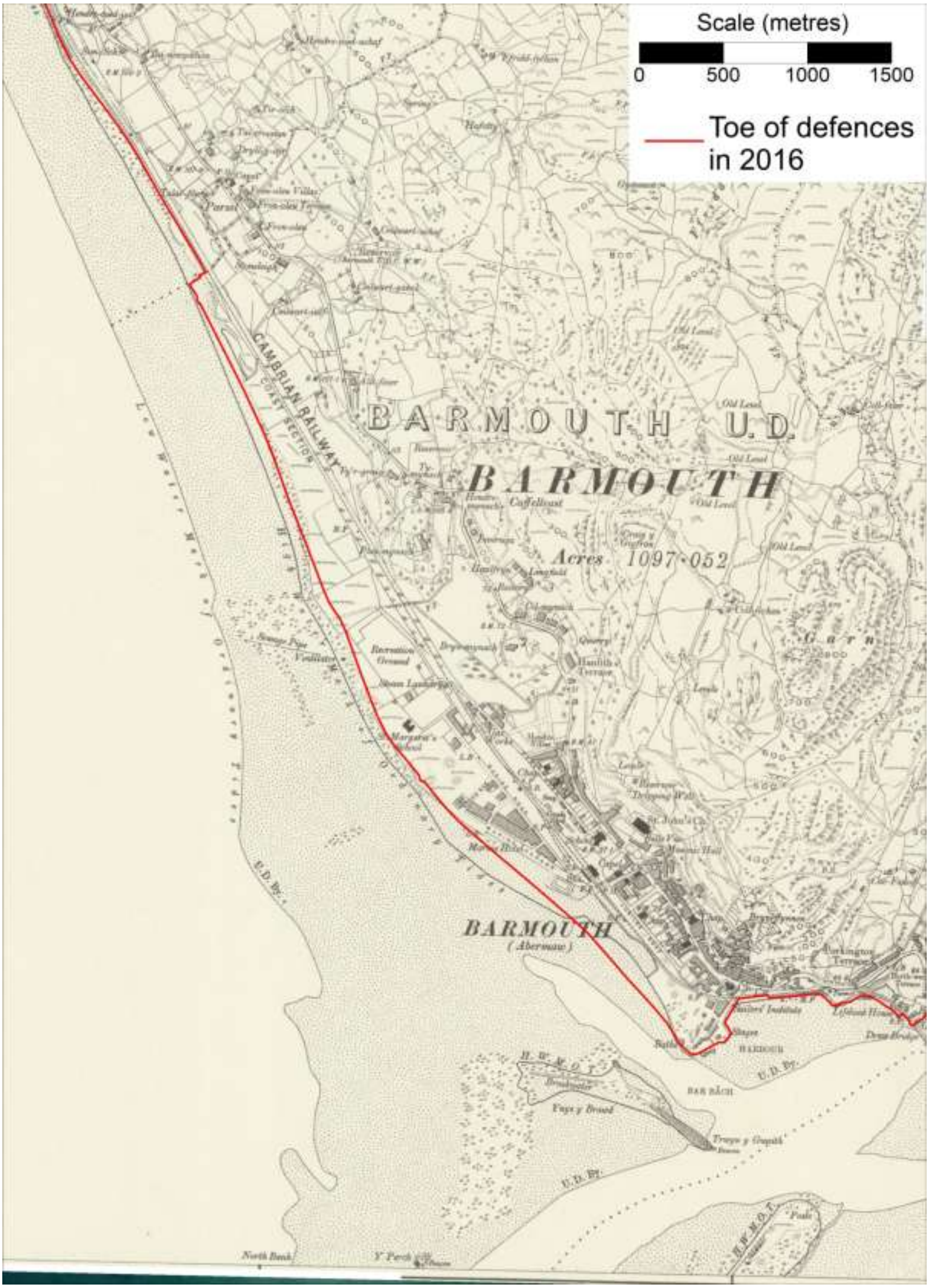


Figure 13. Second Edition Six-Inch Ordnance Survey map, surveyed 1900.

Figure 14. Oblique aerial photograph, taken 01/07/1940.

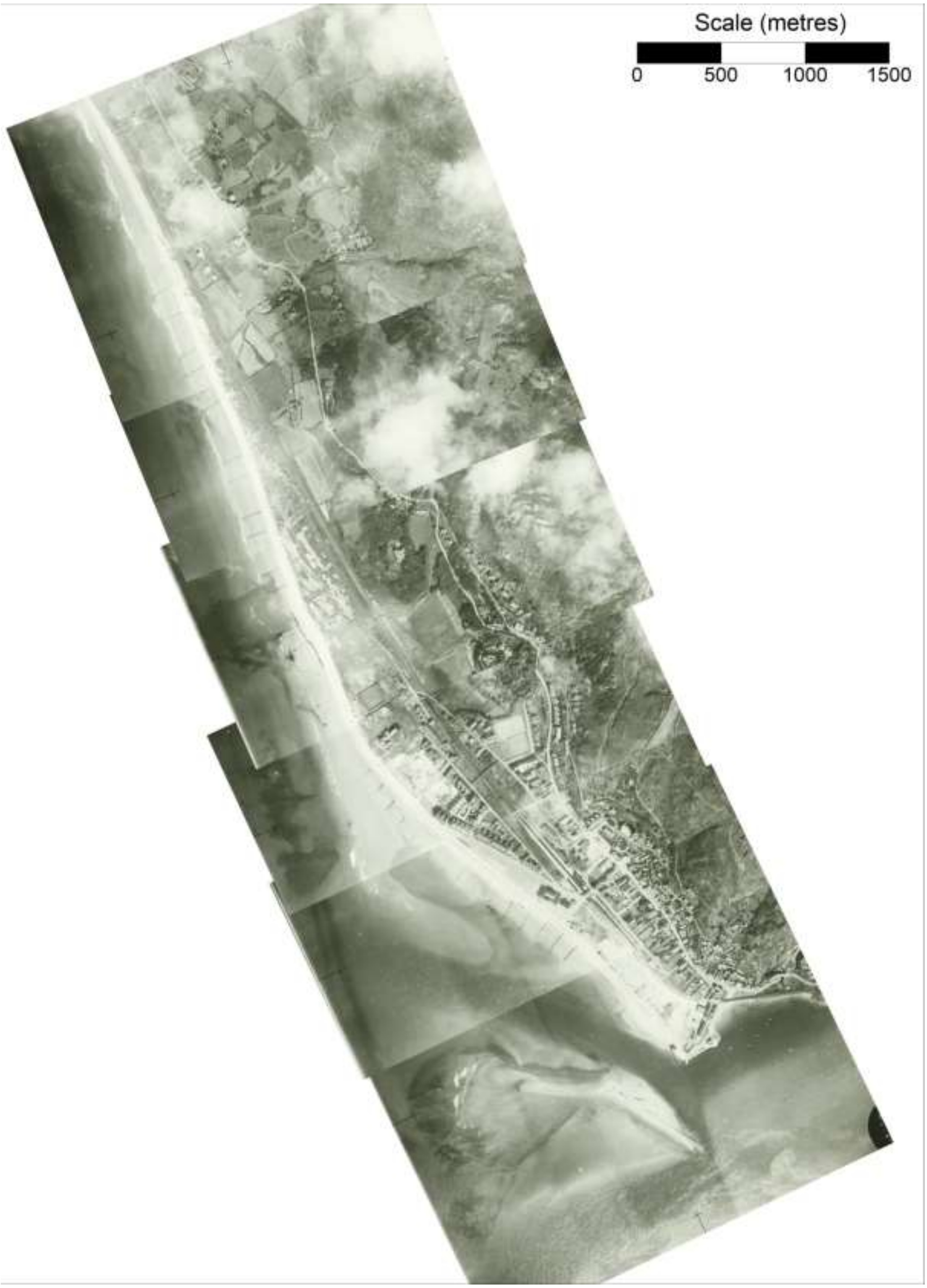


Figure 15. Vertical aerial photograph composite of the Barmouth frontage, flown 24/08/1941.

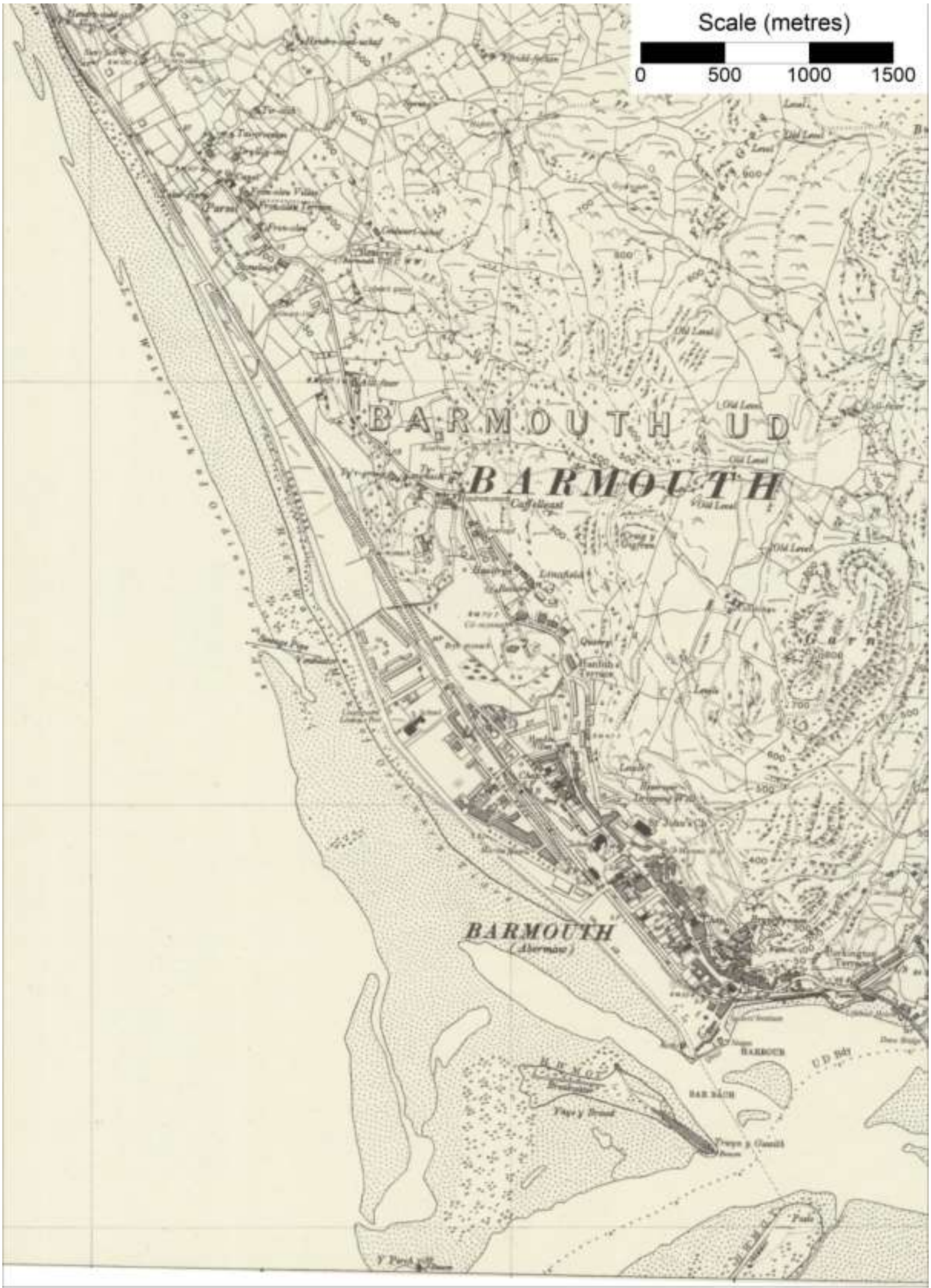


Figure 16. Revised Six-Inch Ordnance Survey map, with additions in 1949, low water marked surveyed 1950.

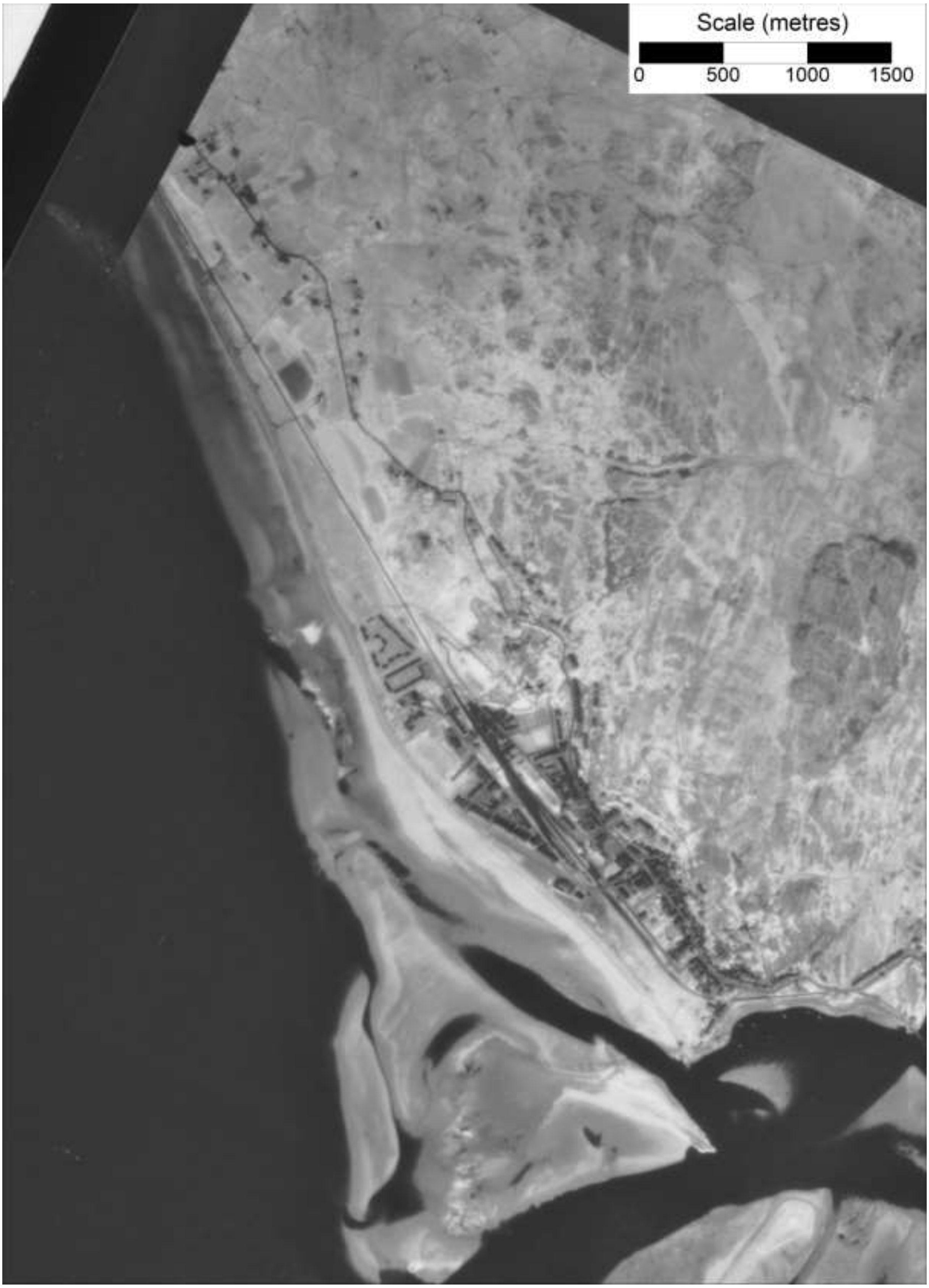


Figure 17. Vertical aerial photograph of the Barmouth frontage, flown 11/06/1950.

Figure 18. Oblique aerial photograph, taken 01/07/1950.

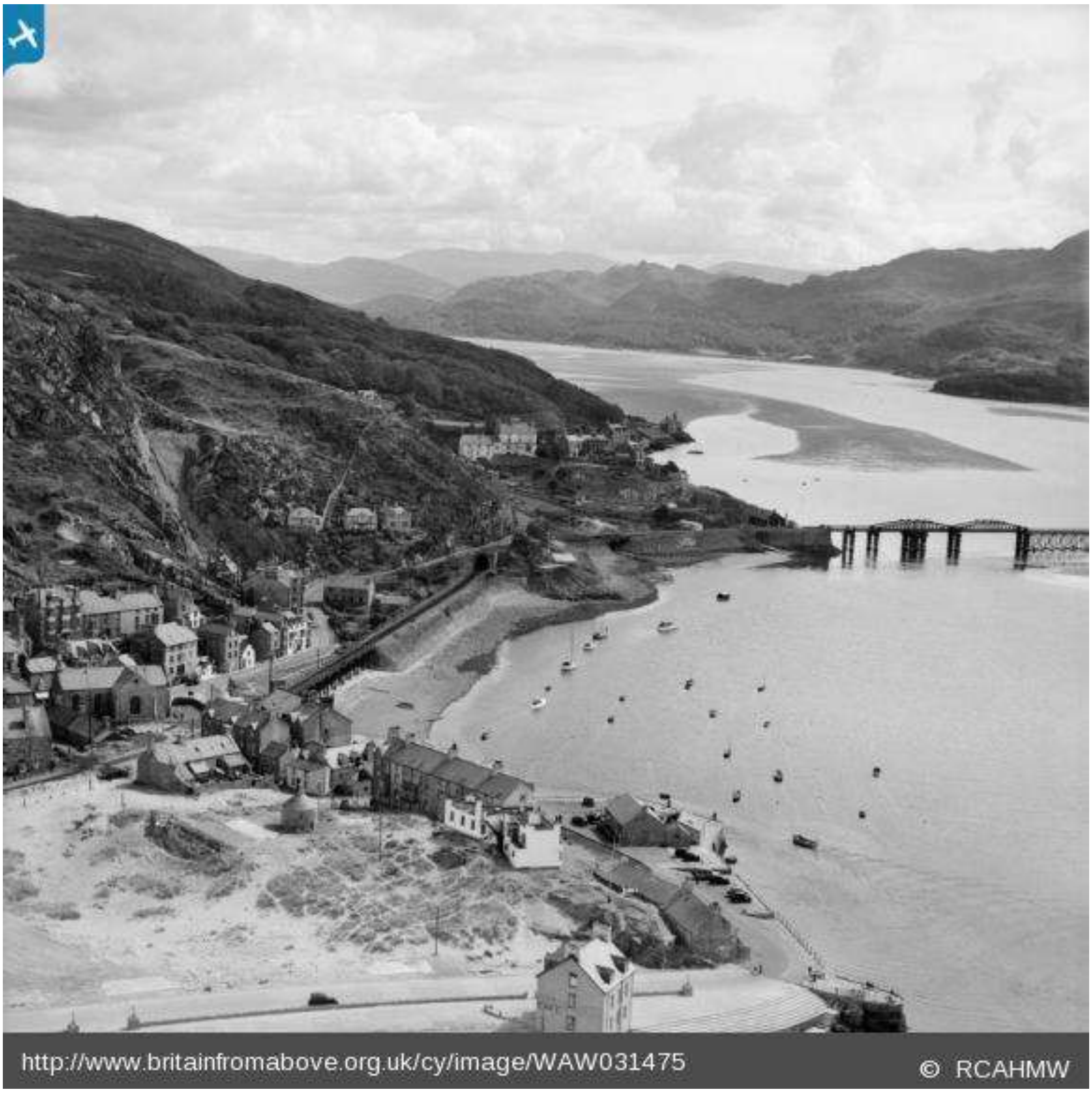


Figure 19. Oblique aerial photograph, taken 1950.

Figure 20. Oblique aerial photograph, taken 1950.

Figure 21. Oblique aerial photograph, taken 1950.

Figure 22. Oblique aerial photograph, taken 1950.

Figure 23. Vertical aerial photograph of the Barmouth frontage, flown 06/06/1962.

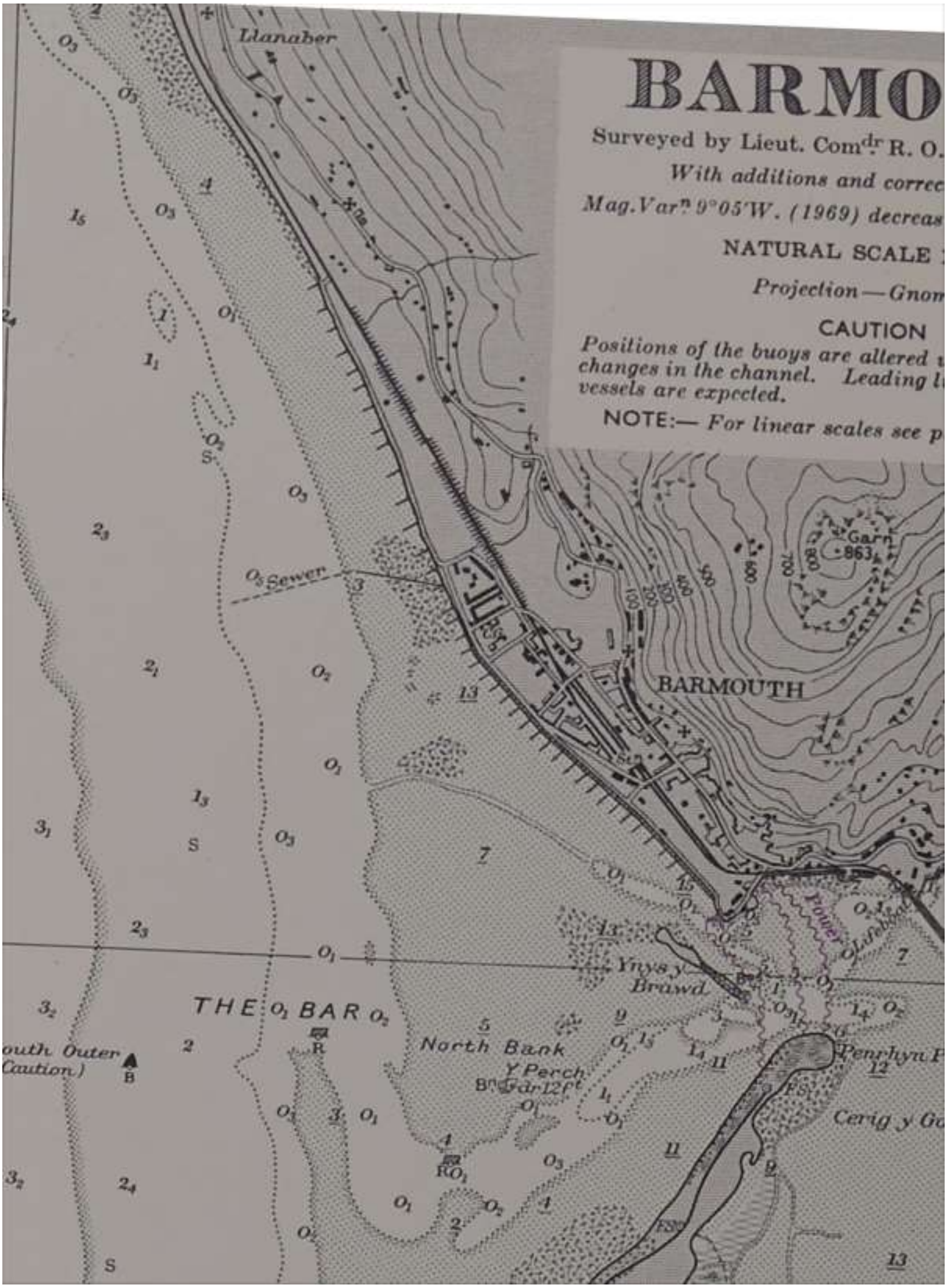


Figure 24. Admiralty Chart "Plans in Cardigan Bay" (No. 1484), published in 1967, surveyed 1964 by Lieut. Commander. R.O. Morris R.N., with additions and corrections in 1966. Soundings in fathoms and feet.

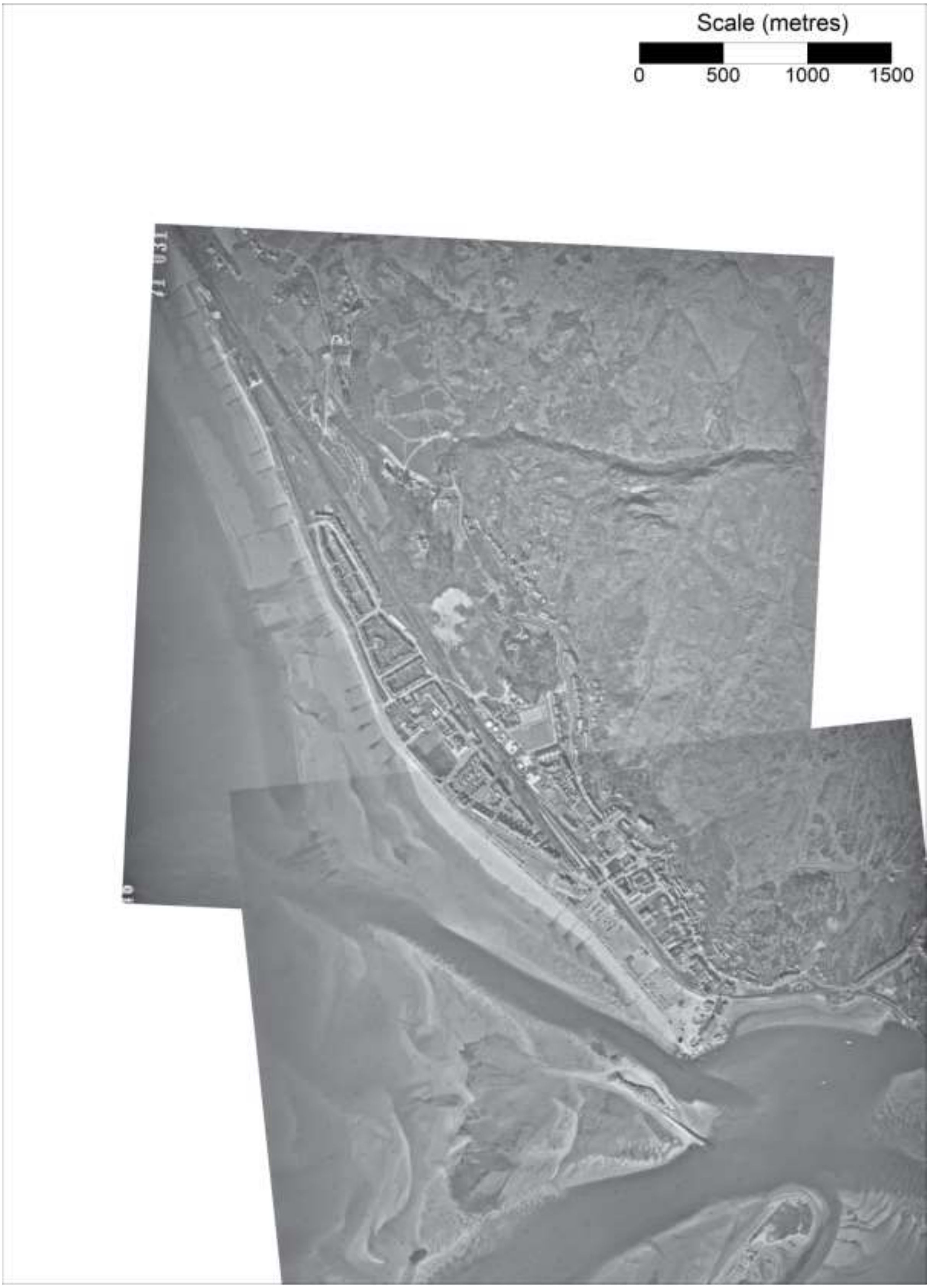


Figure 25. Vertical aerial photograph of the Barmouth frontage, flown 10/04/1971.

Figure 26. Oblique aerial photograph, taken 05/06/1973.

Figure 27. Vertical aerial photograph of the Barmouth frontage, flown 02/11/1986.

Figure 28. Vertical aerial photograph of the Barmouth frontage, flown 04/05/1993.

Figure 29. Vertical aerial photograph of the Barmouth frontage, flown 22/02/2000.

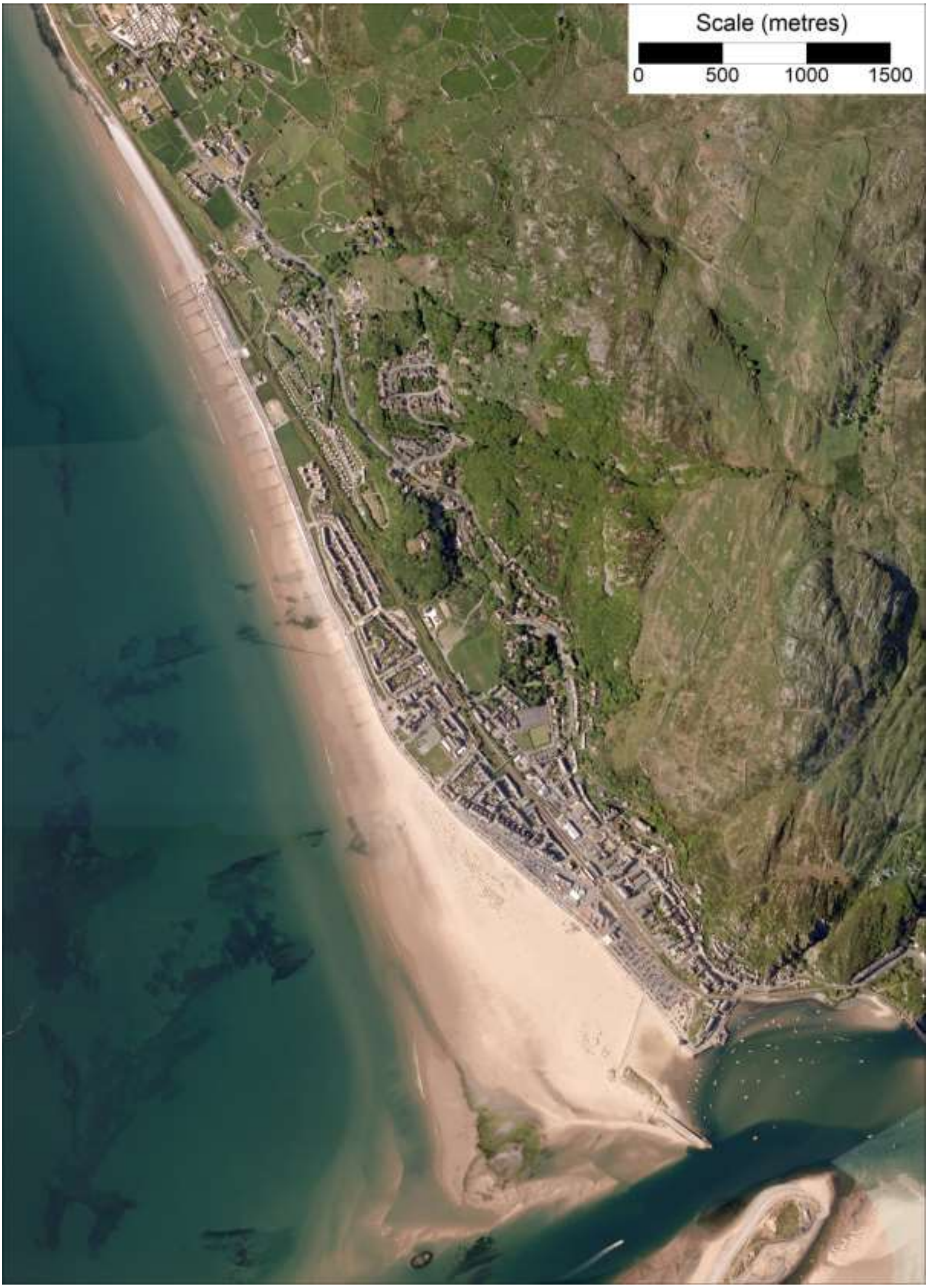


Figure 30. Vertical aerial photograph of the Barmouth frontage, flown 2006.

Figure 31. Vertical aerial photograph of the Barmouth frontage, flown 31/05/2009.

Figure 32. Vertical aerial photograph of the Barmouth frontage, flown 2013.

Figure 33. Vertical aerial photograph of the Barmouth frontage, flown by UAV on 16/06/2016.

Figure 34. Limits of dune vegetation mapped from aerial photographs 1962-2016. Base photograph taken in summer 2013.

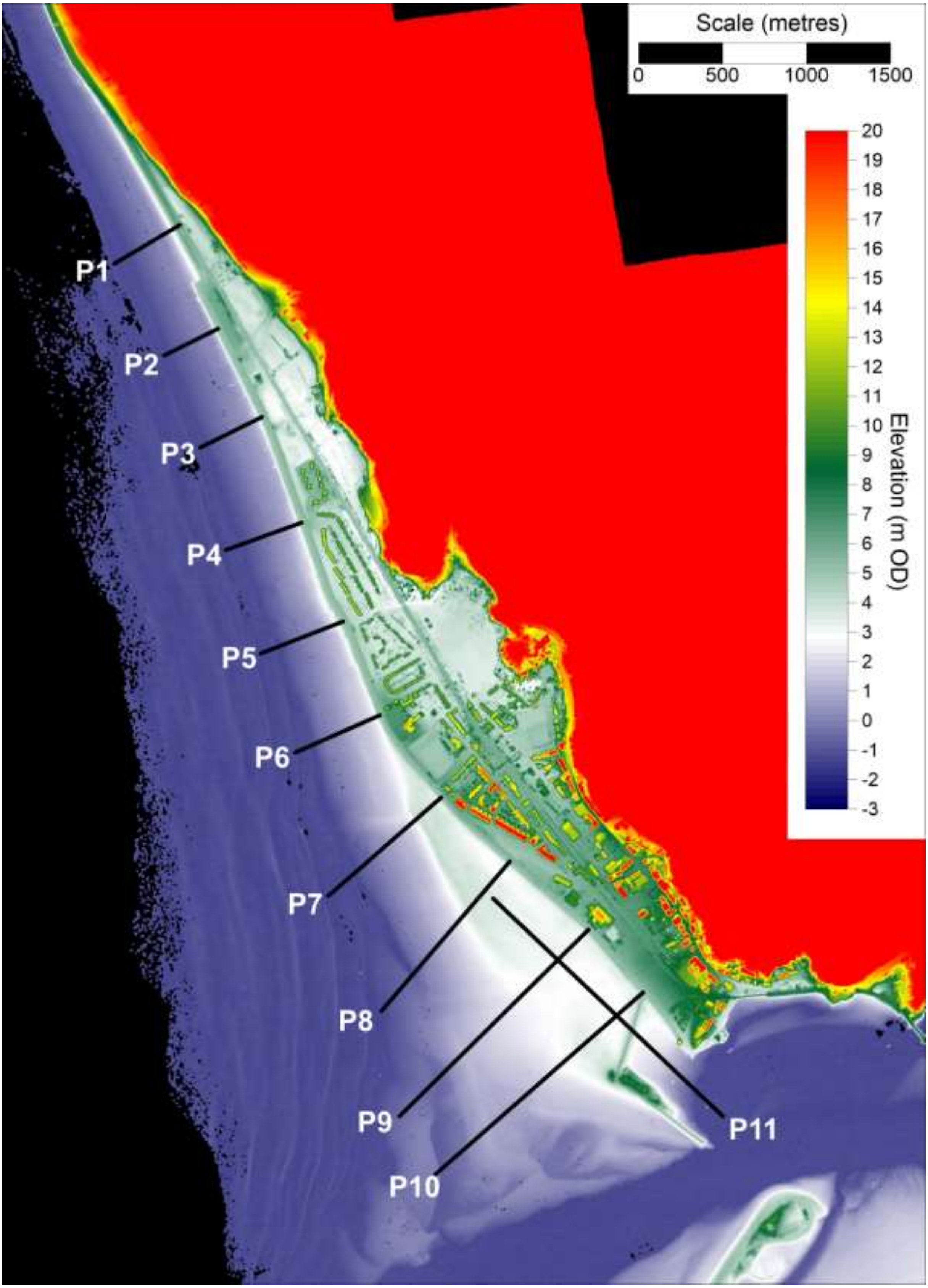


Figure 35. Digital elevation model generated from airborne LiDAR survey on 14/02/2003. Locations of cross-profiles P1 to P11 are also shown.

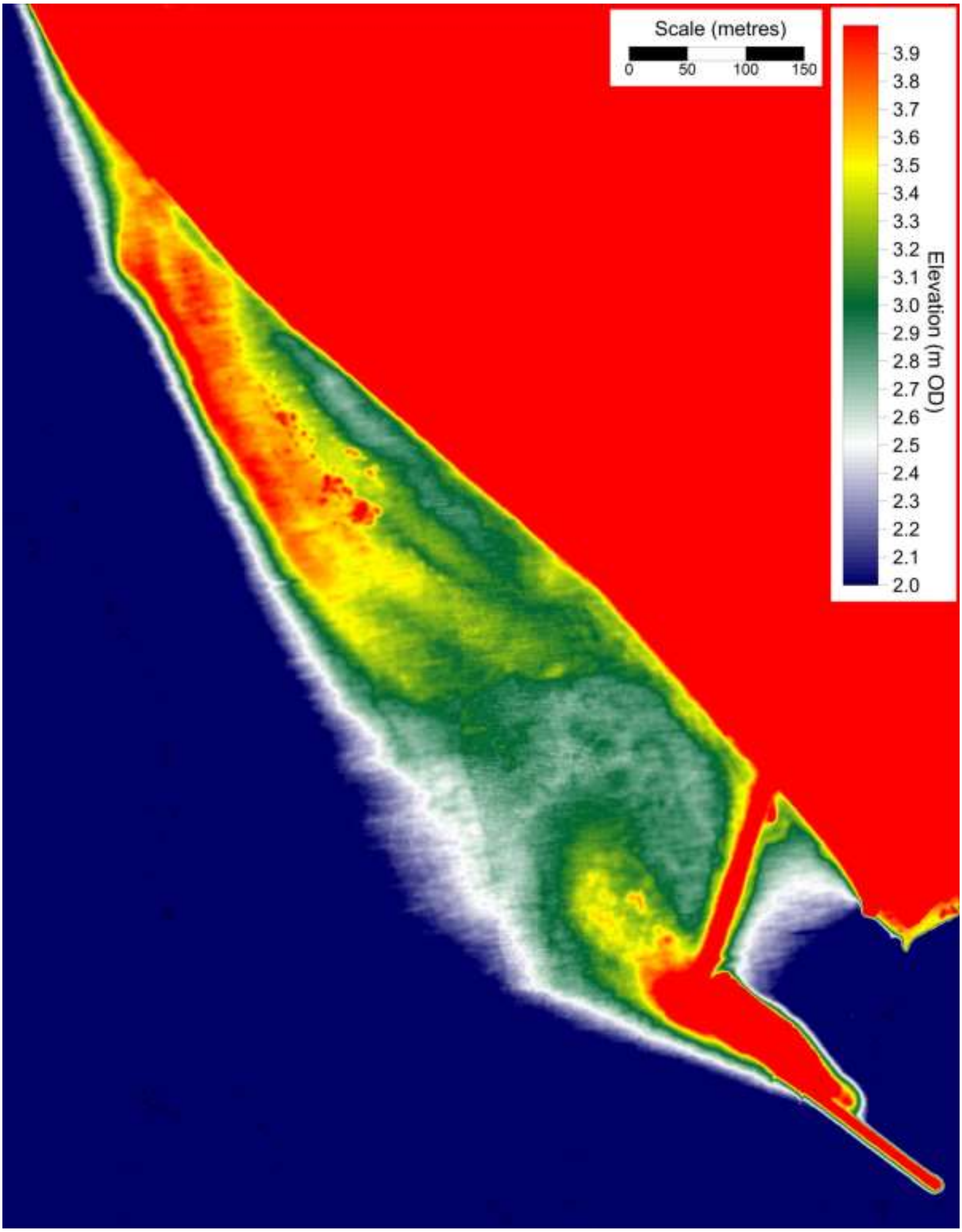


Figure 36. Contrast-enhanced and enlarged digital elevation model of the southern part of Barmouth beach based on the 2003 LiDAR survey, showing subdued spit recurve forms on which dune ridges have developed and presence of a subdued channel north of Ynys y Brawd

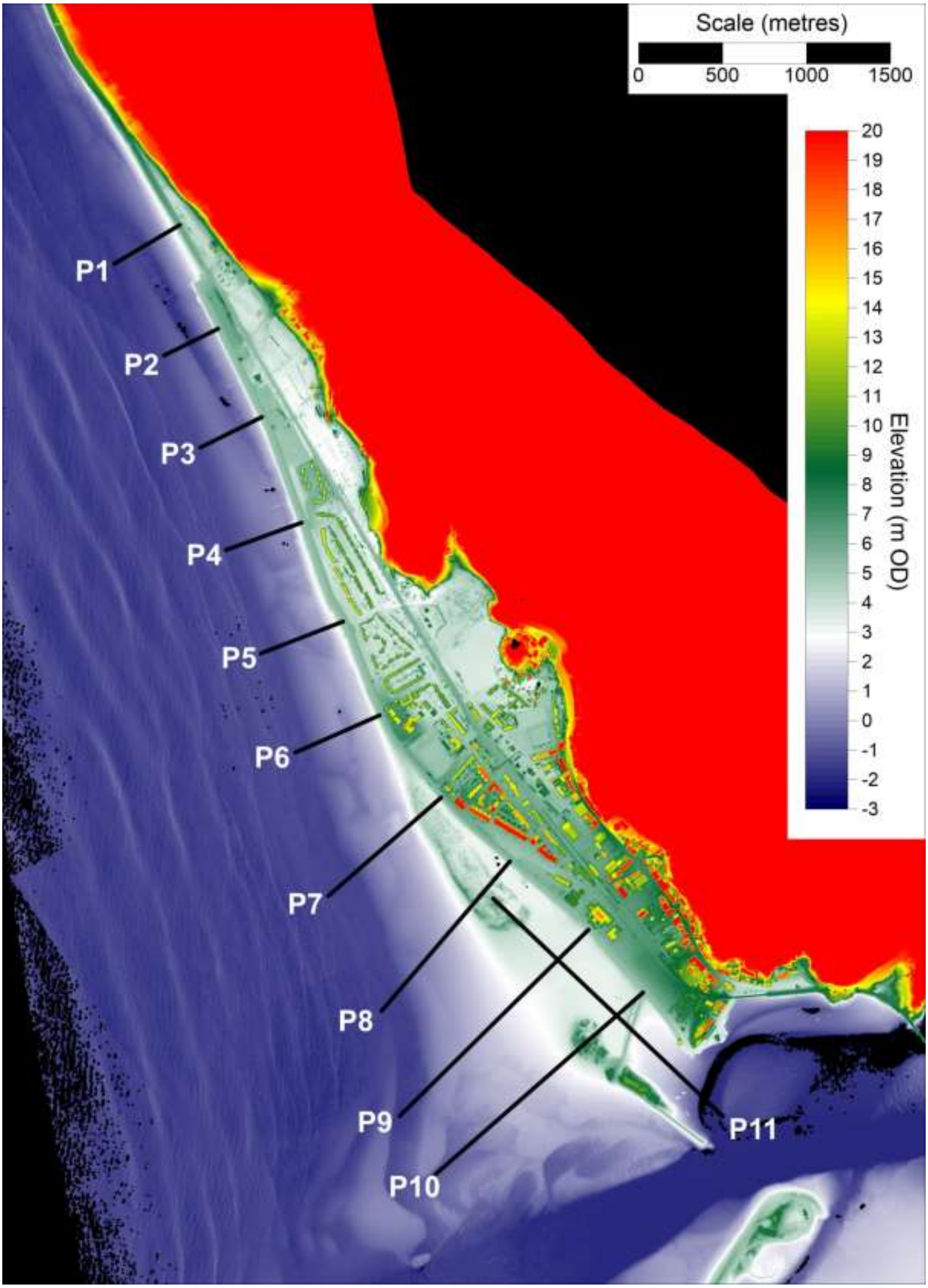


Figure 37. Digital elevation model generated from airborne LiDAR survey on 03/03/2014. Locations of cross-profiles P1 to P11 are also shown.

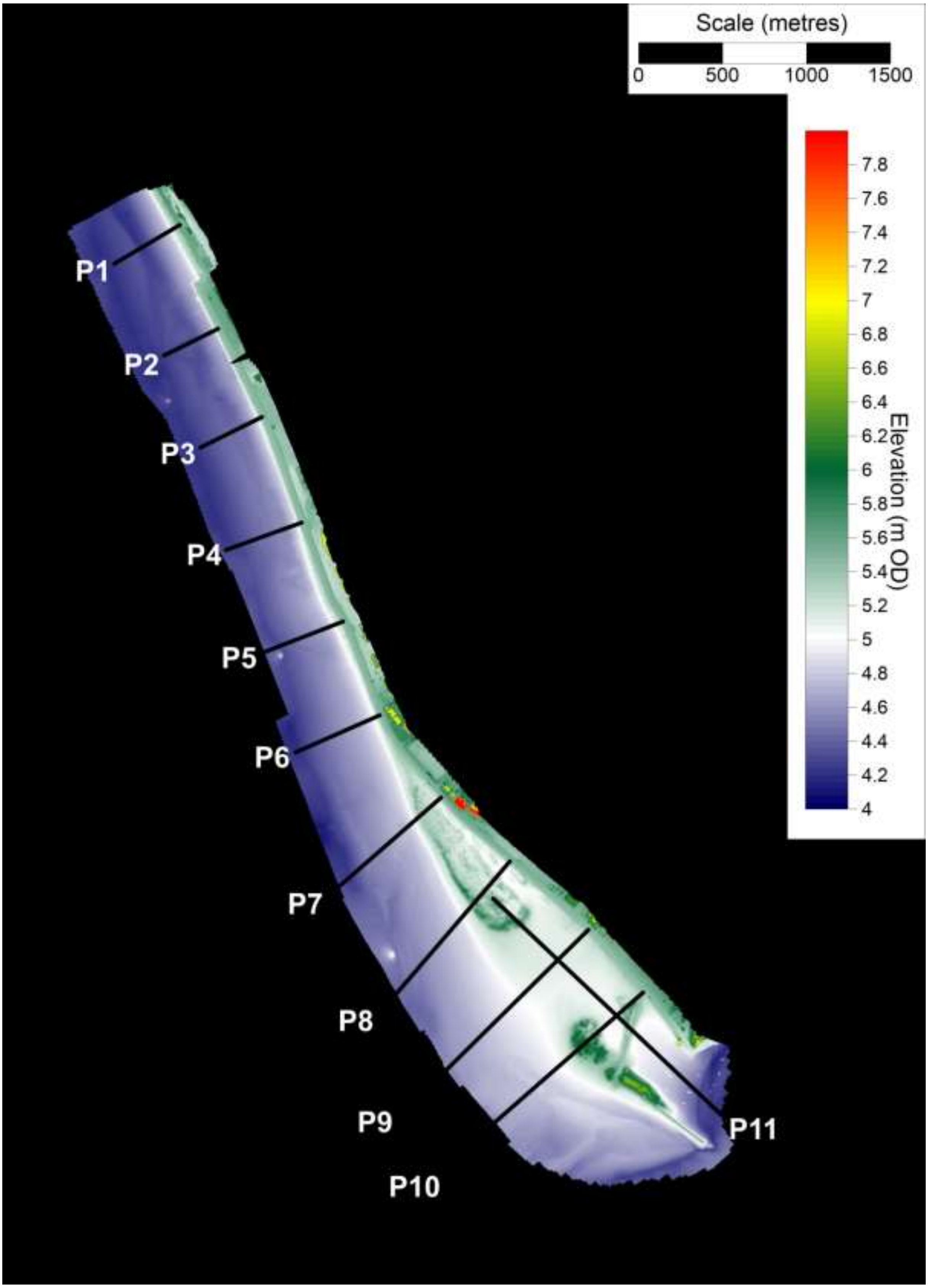


Figure 38. Digital elevation model generated from UAV survey on 16/06/2016. Locations of cross-profiles P1 to P11 are also shown.

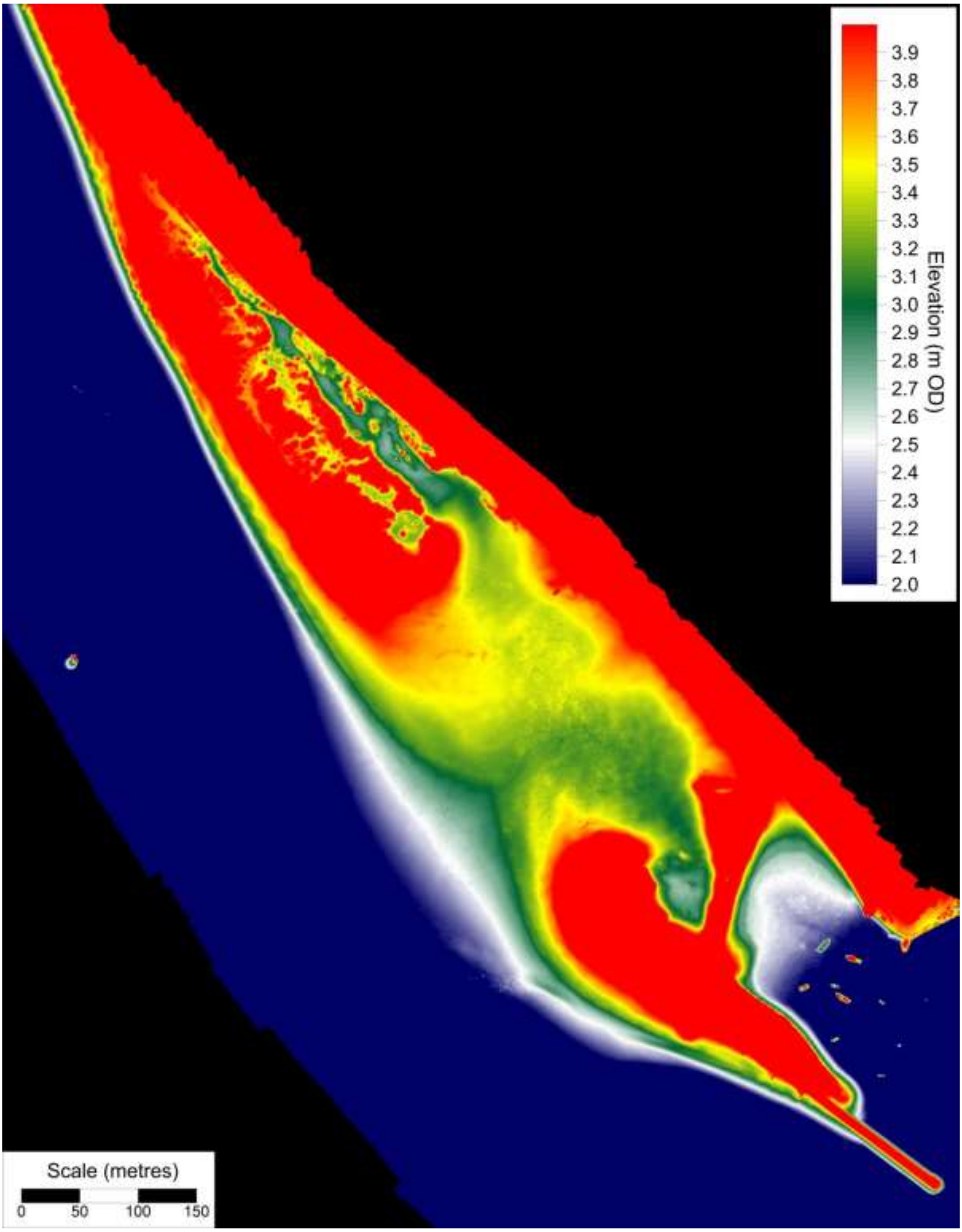


Figure 39. Digital elevation model generated from UAV survey on 16/06/2016, with exaggerated vertical scale to show the channel which has developed on the beach in front of the Lifeboat Station.

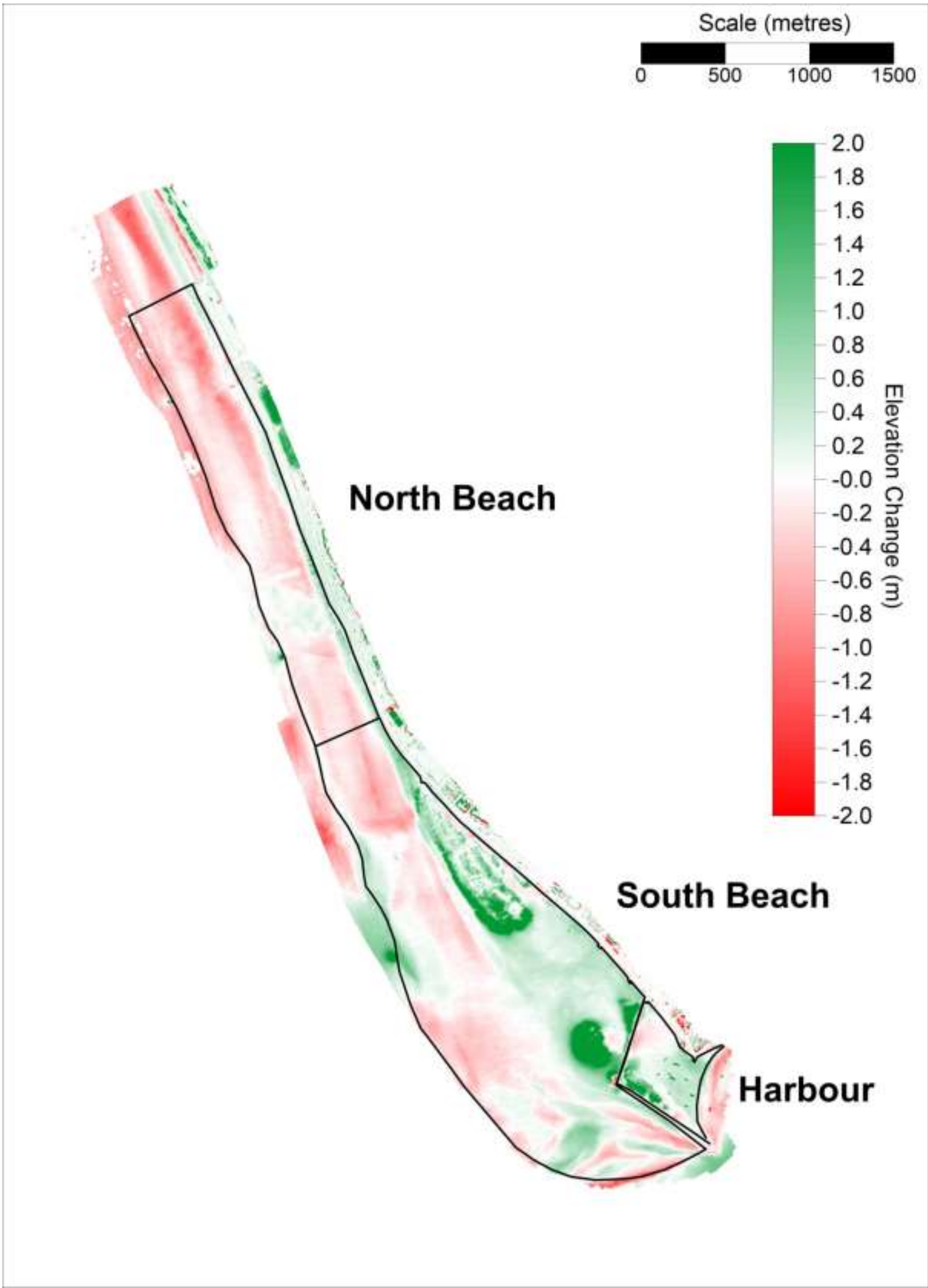


Figure 40. Change in elevation between 14/02/2003 and 16/06/2016, calculated from the difference between digital elevation models generated from the 2003 LiDAR and 2016 UAV surveys. The areas of volume calculations are highlighted by black lines.

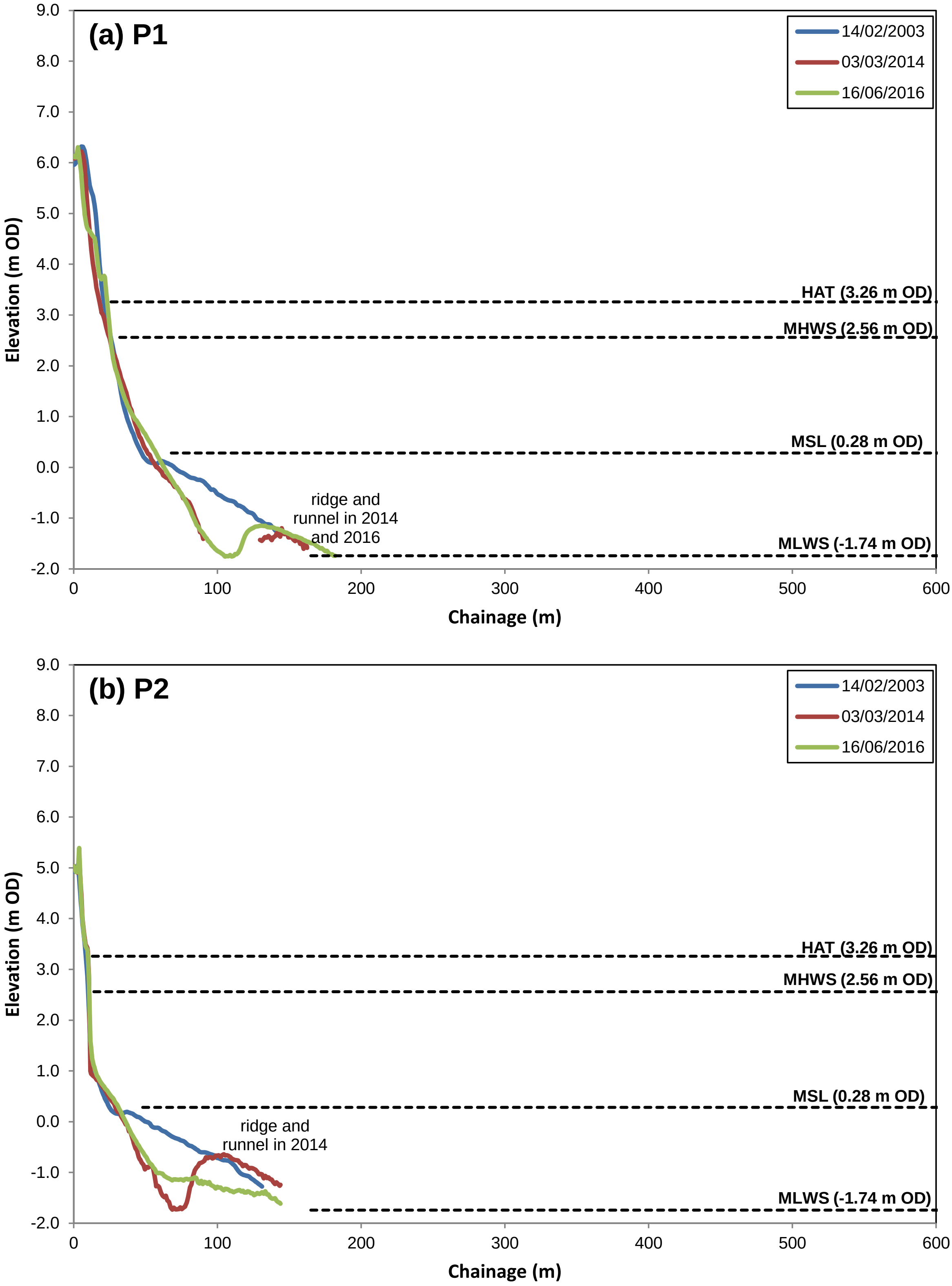


Figure 41. Cross-sections of the dune and beach at Barmouth, from airborne LiDAR surveys flown on 14/02/2003 and 03/03/2014.

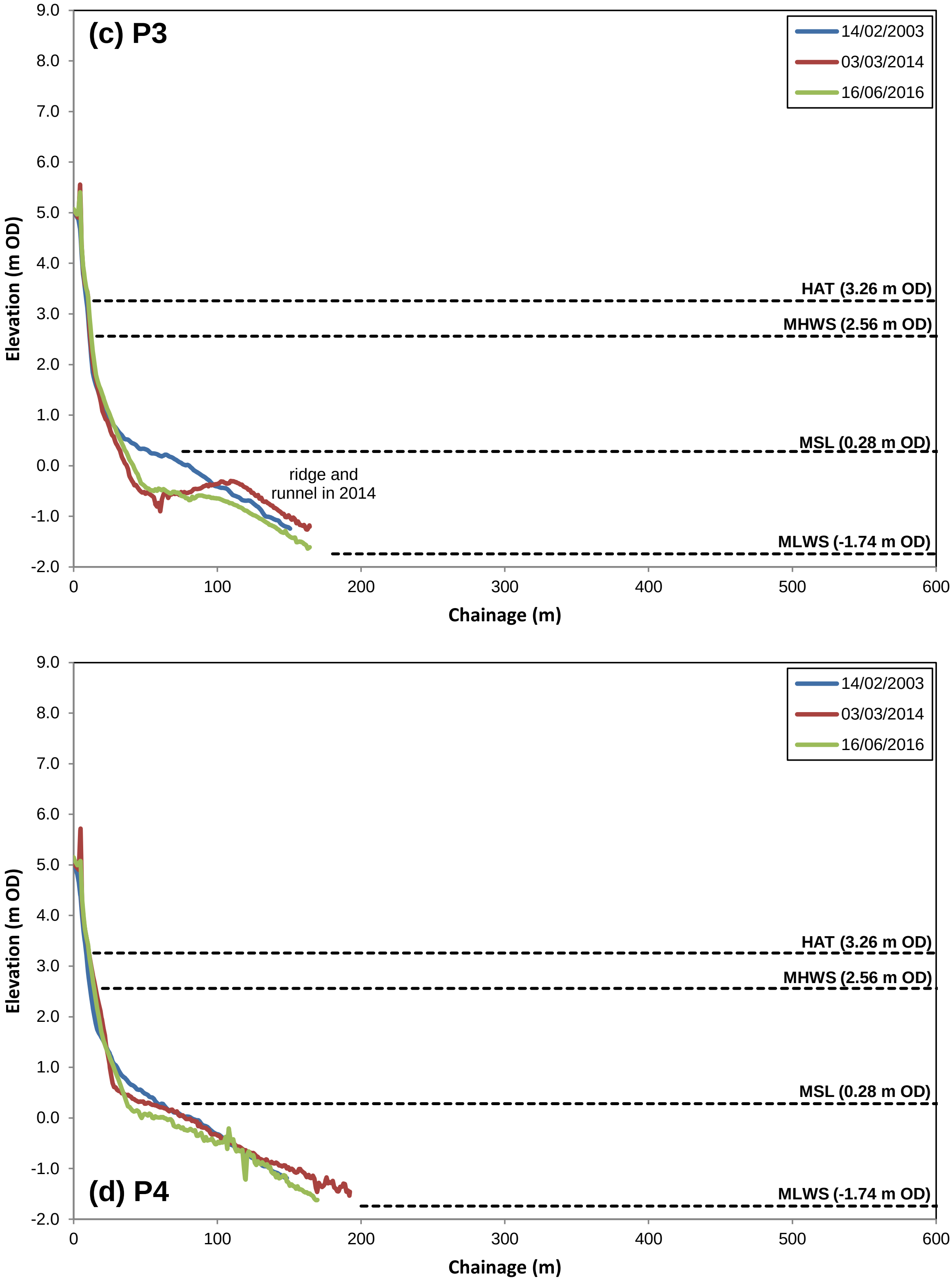
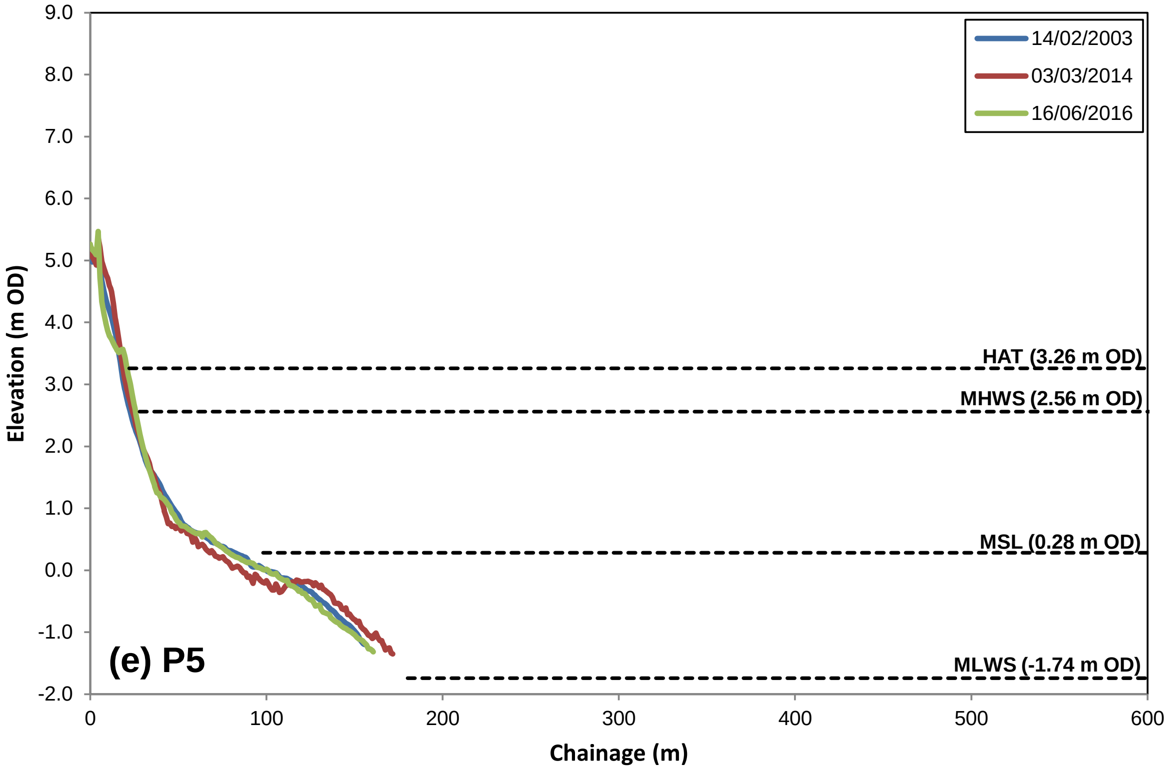


Figure 41 continued.



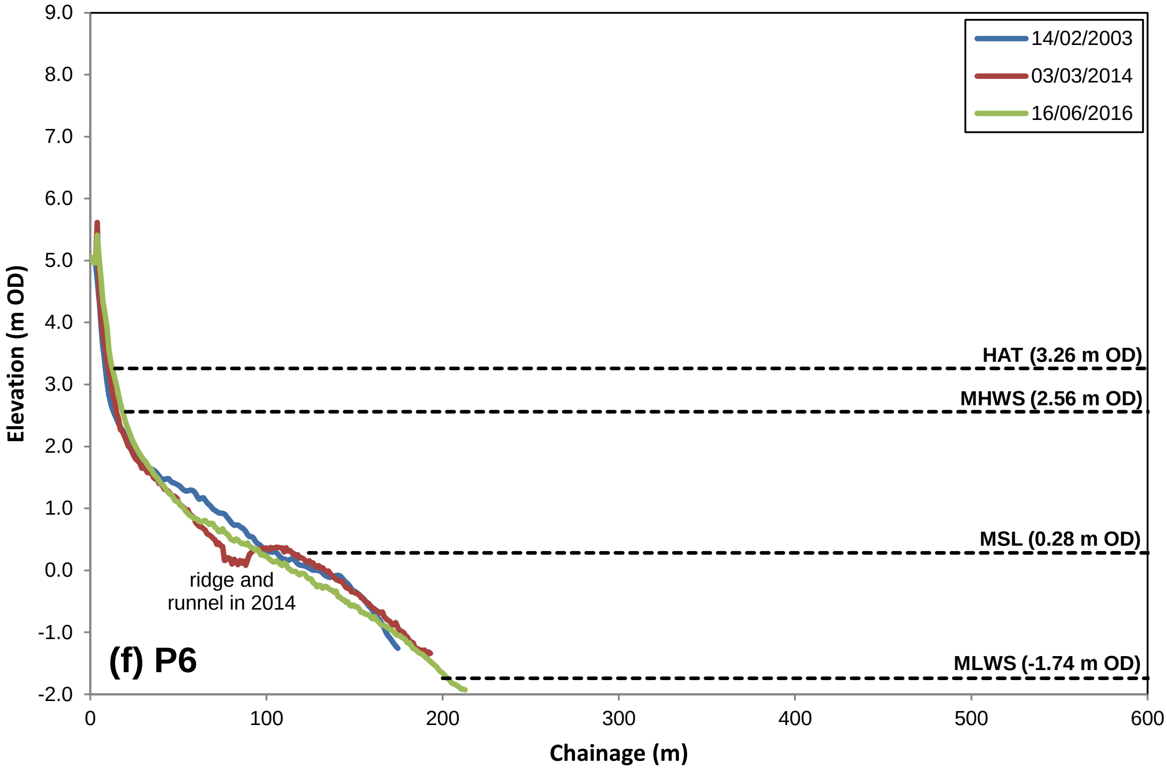
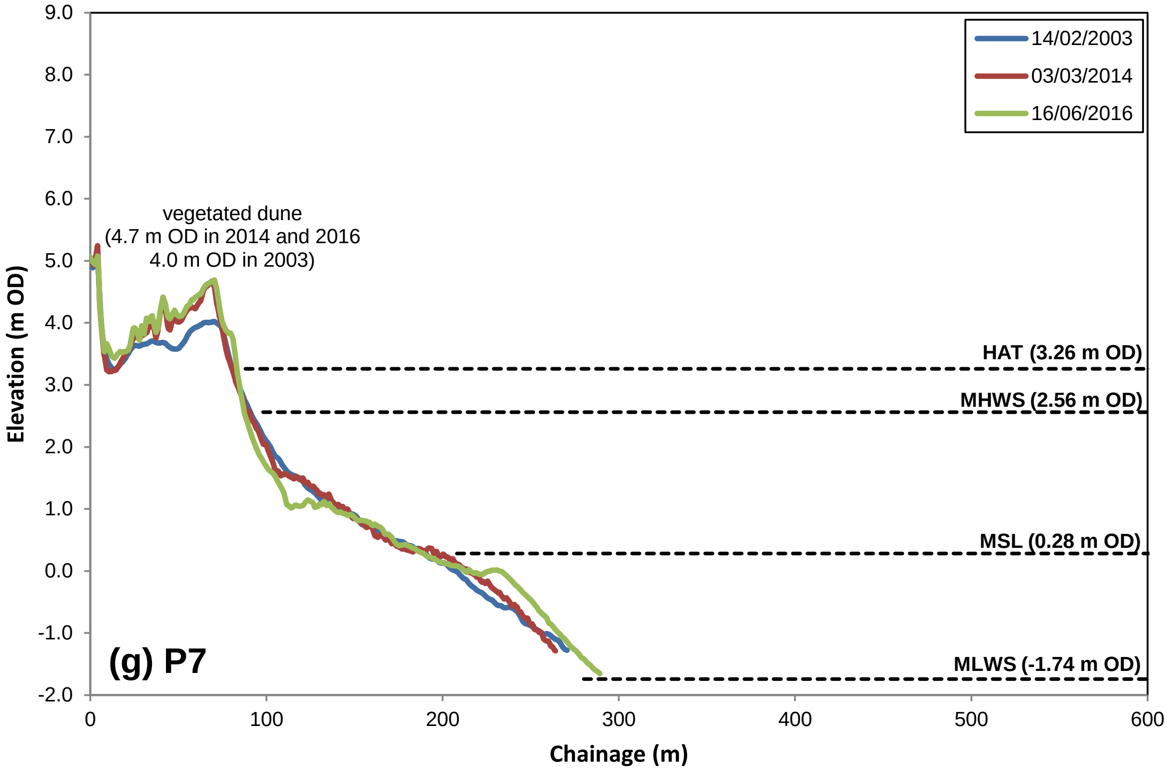


Figure 41 continued.



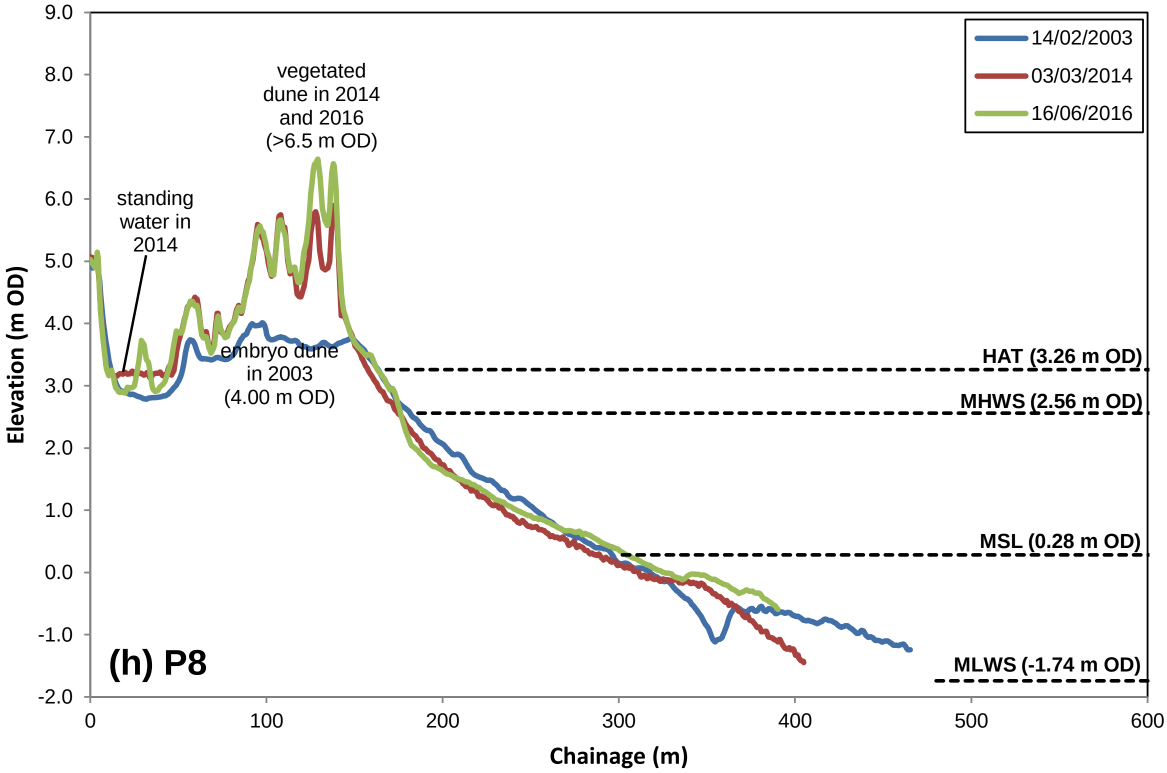
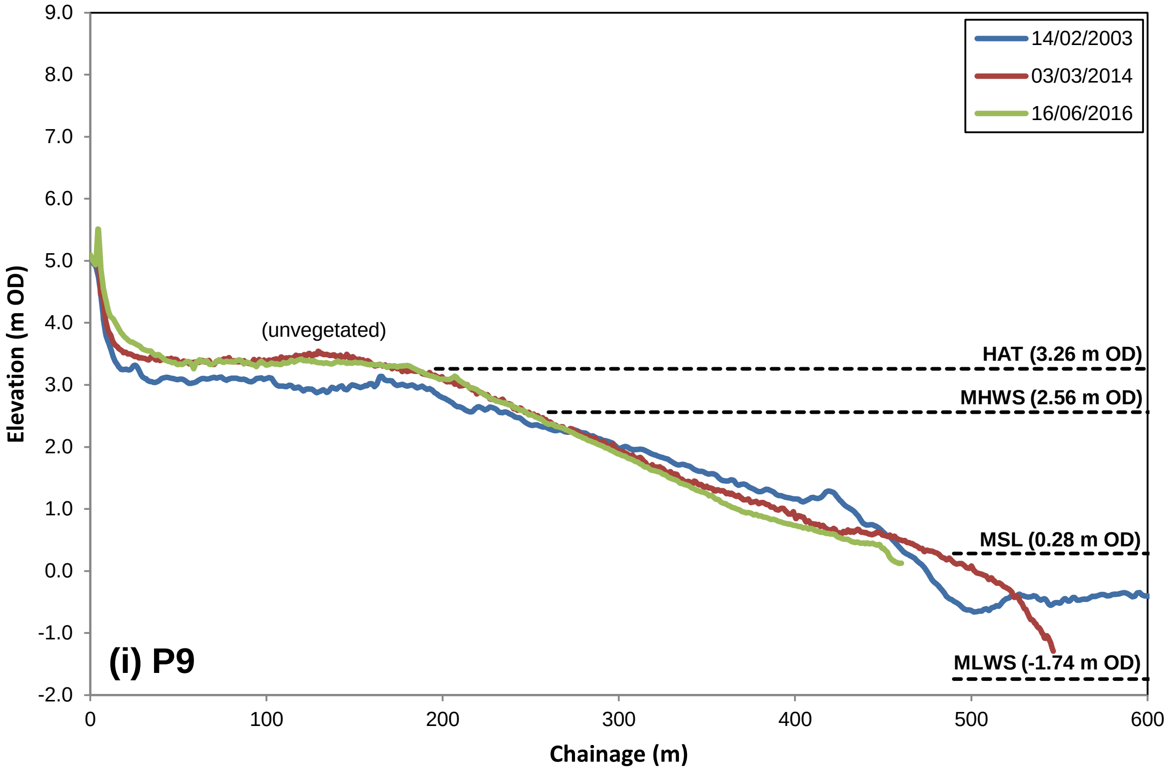


Figure 41 continued.



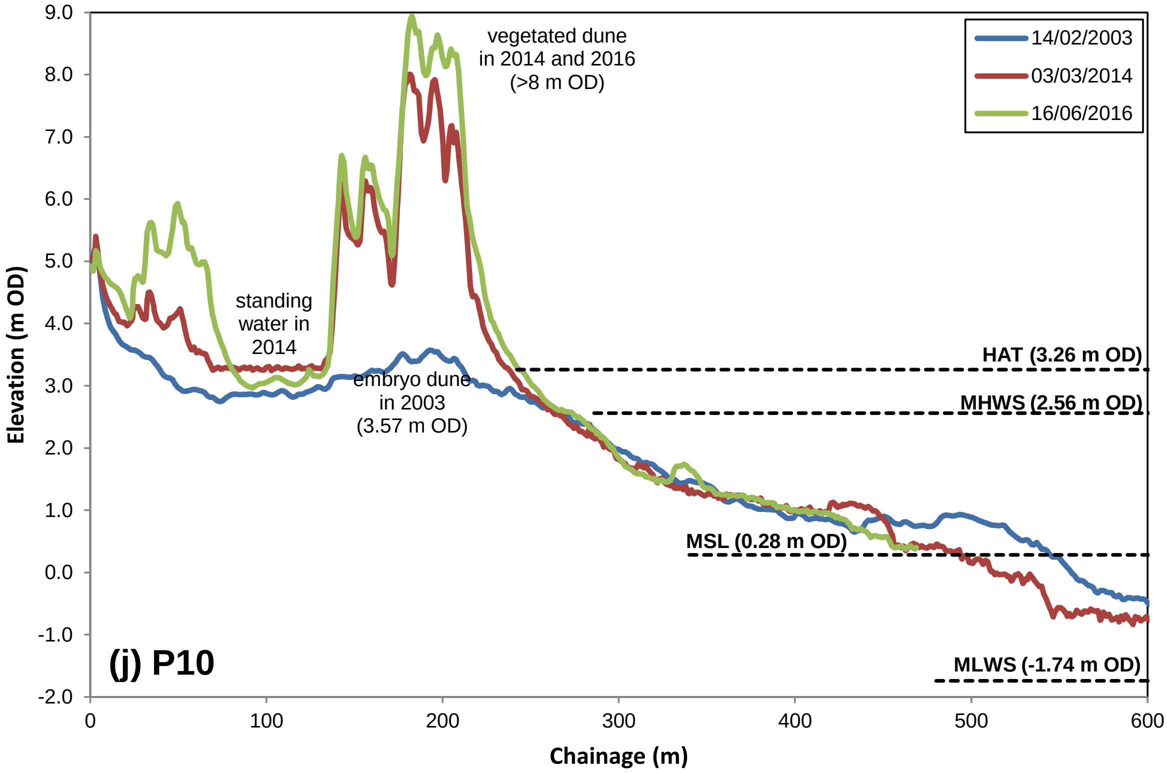


Figure 41 continued.

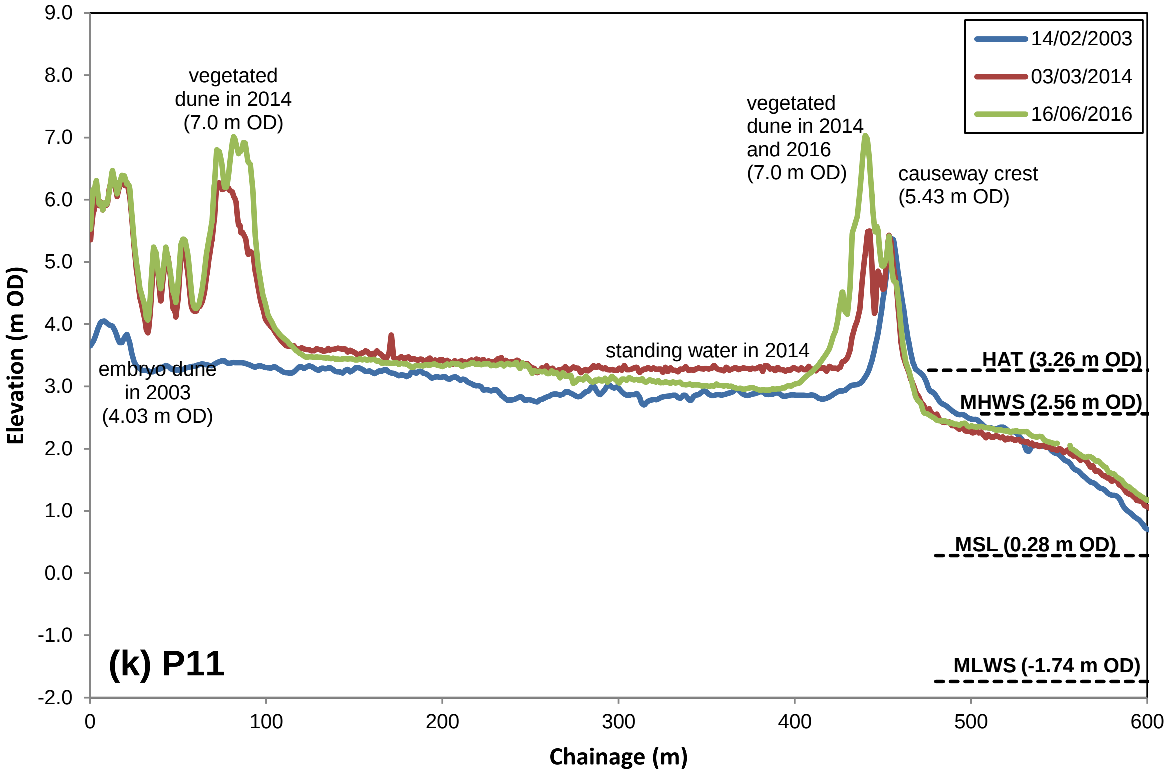


Figure 41 continued.

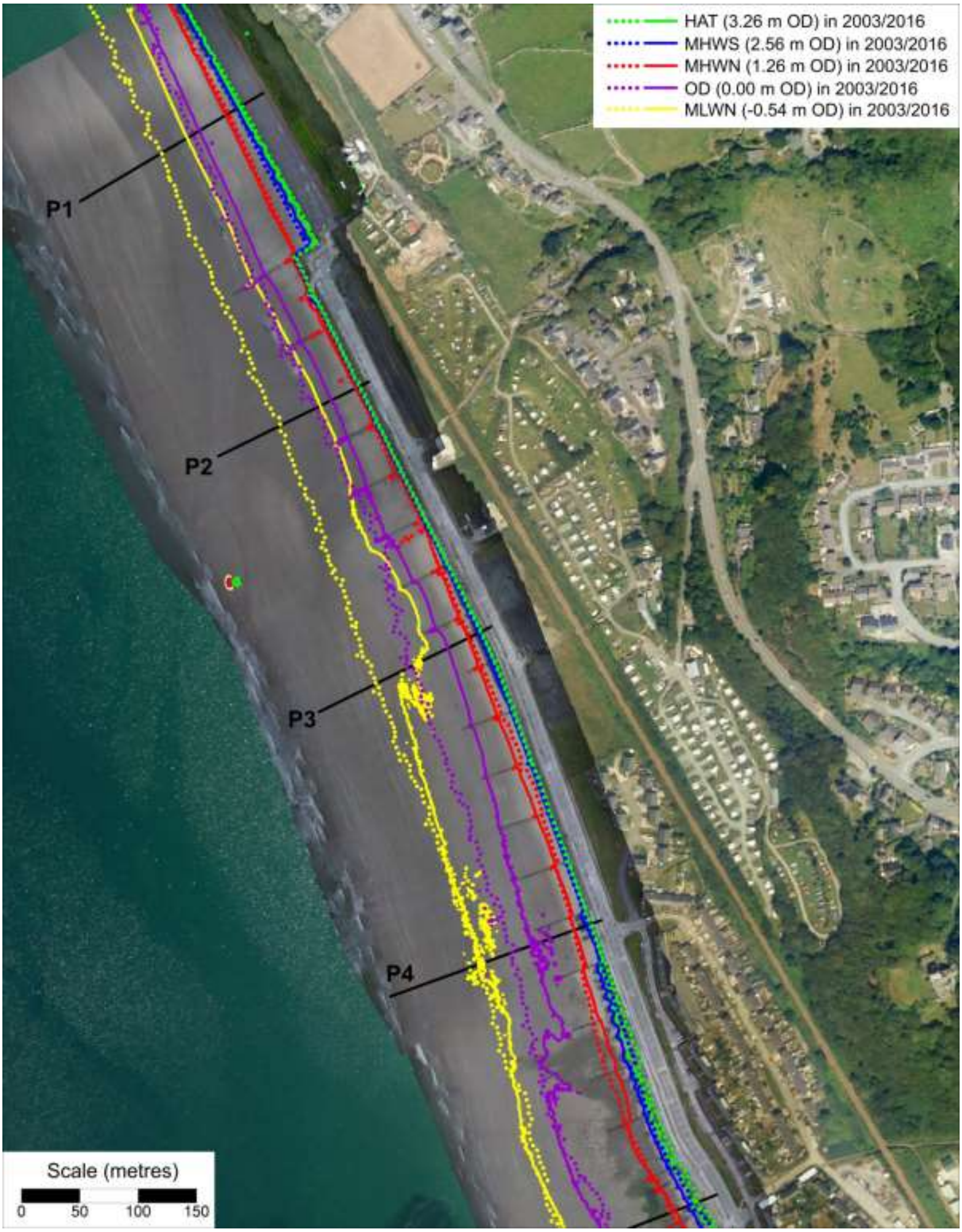


Figure 42. Changes in the position of tidal contours between profiles 1 and 4, from the 2003 LiDAR and the 2016 UAV surveys.

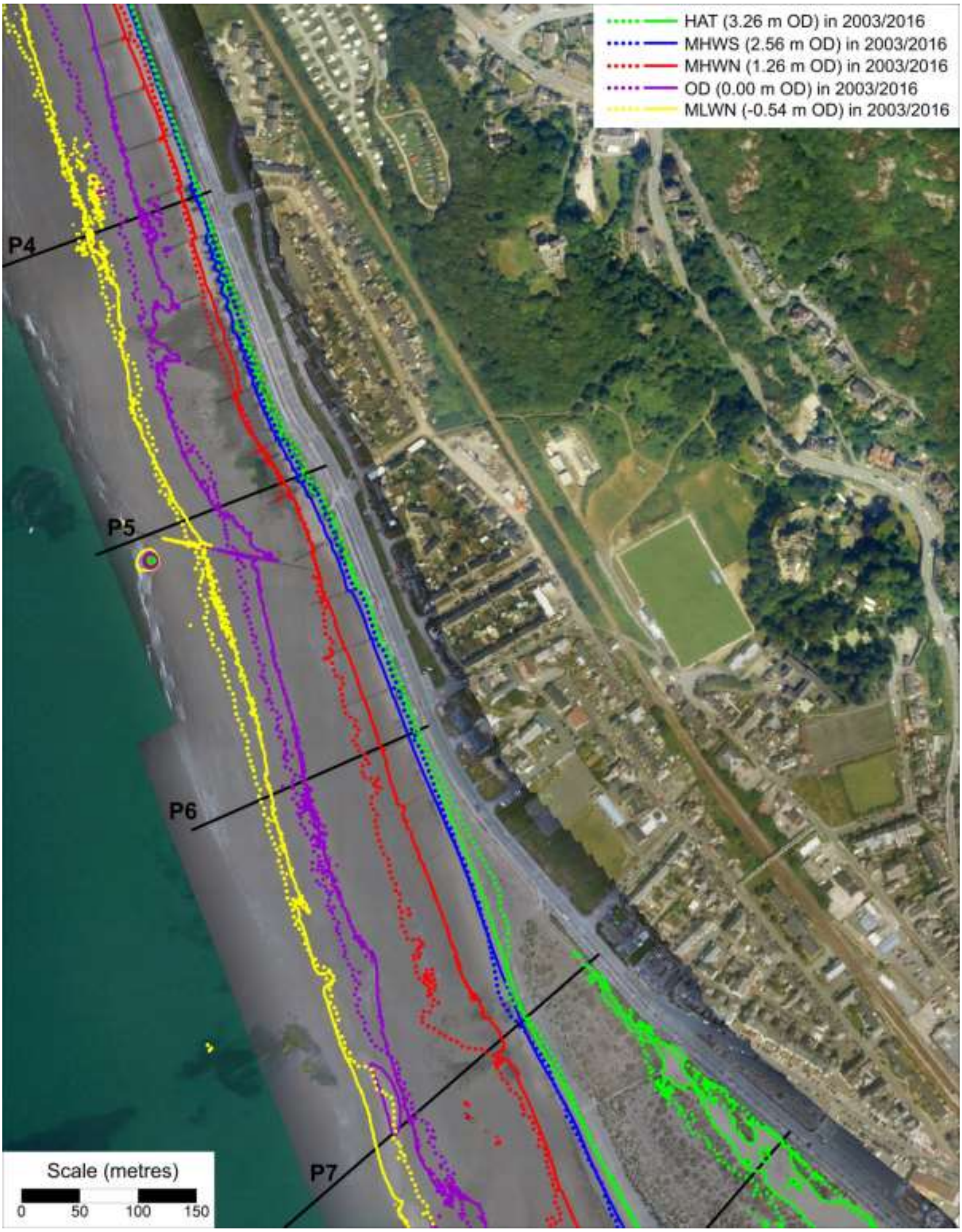


Figure 43. Changes in the position of tidal contours between profiles 4 and 7, from the 2003 LiDAR and the 2016 UAV surveys.

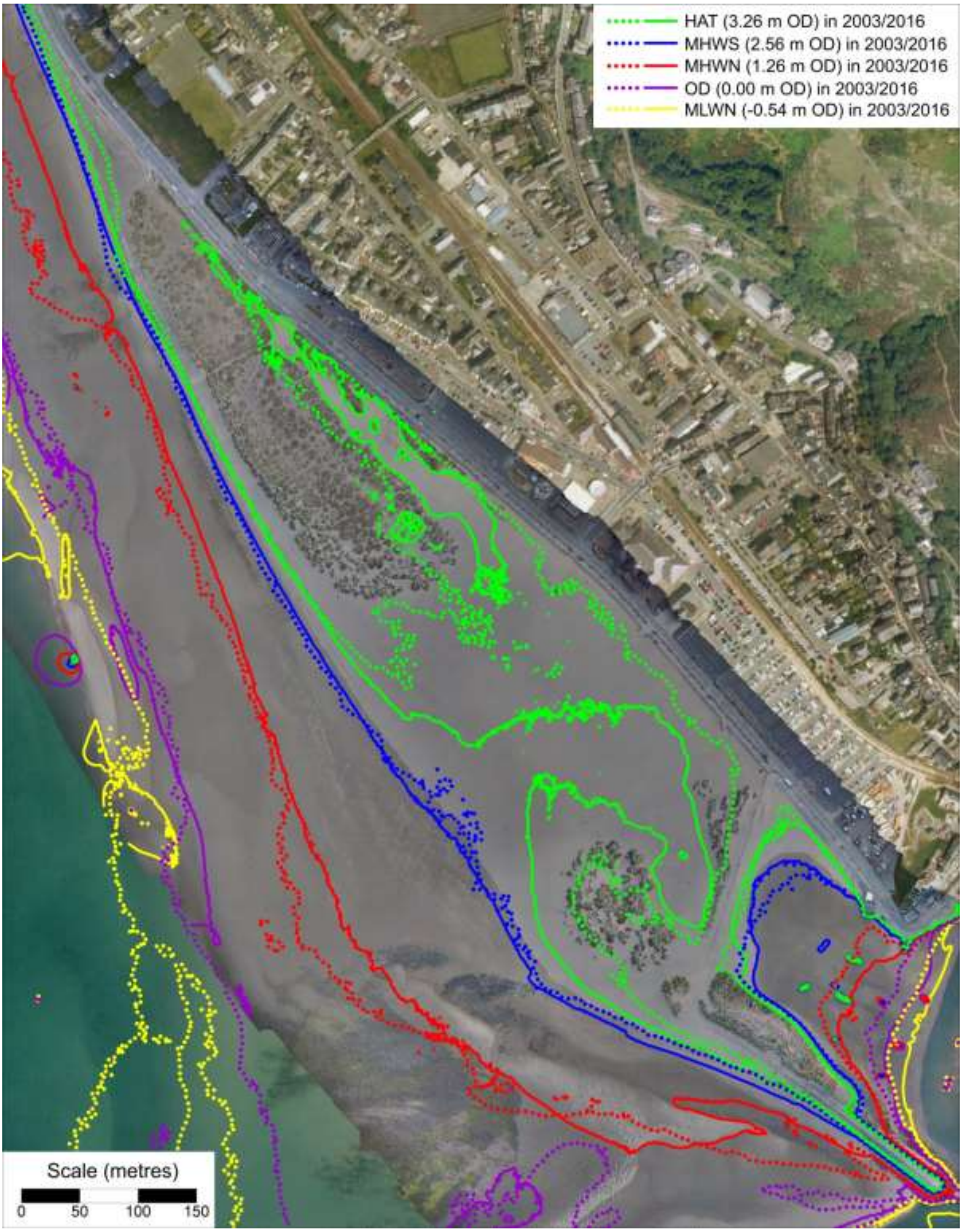


Figure 44. Changes in the position of tidal contours between profiles 7 and 11, from the 2003 LiDAR and the 2016 UAV surveys.

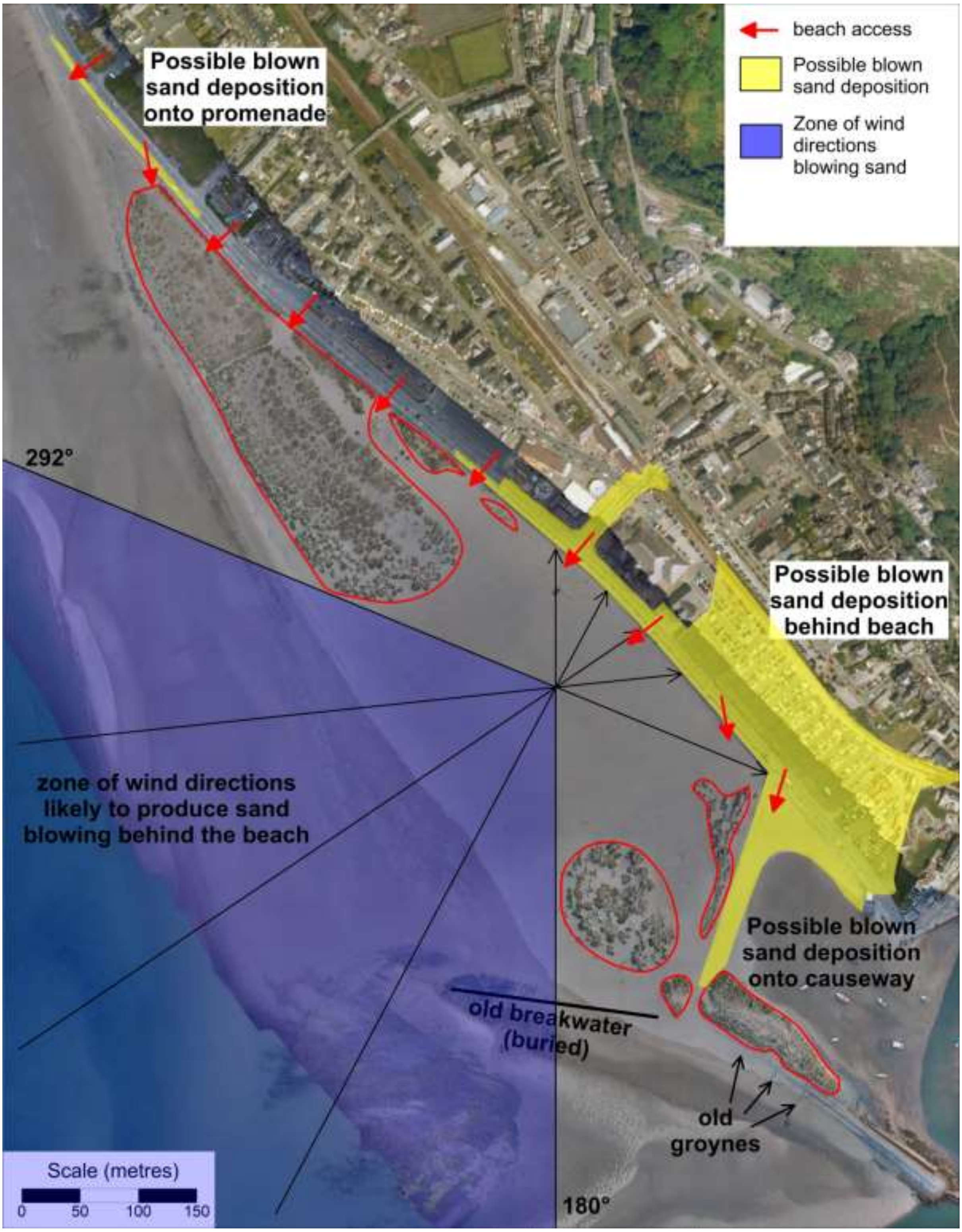


Figure 45. The zone of wind directions likely to produce sand blowing behind the beach, between 180° and 292° (south to west-north-west). The red lines indicate the limits of vegetation mapped in 2016 by the UAV survey. Base photo is from the UAV survey on 16 June 2016, with the offshore and areas behind the promenade covered by photos flown in 2013. The yellow area shows the current extent of blown sand risk behind the beach.

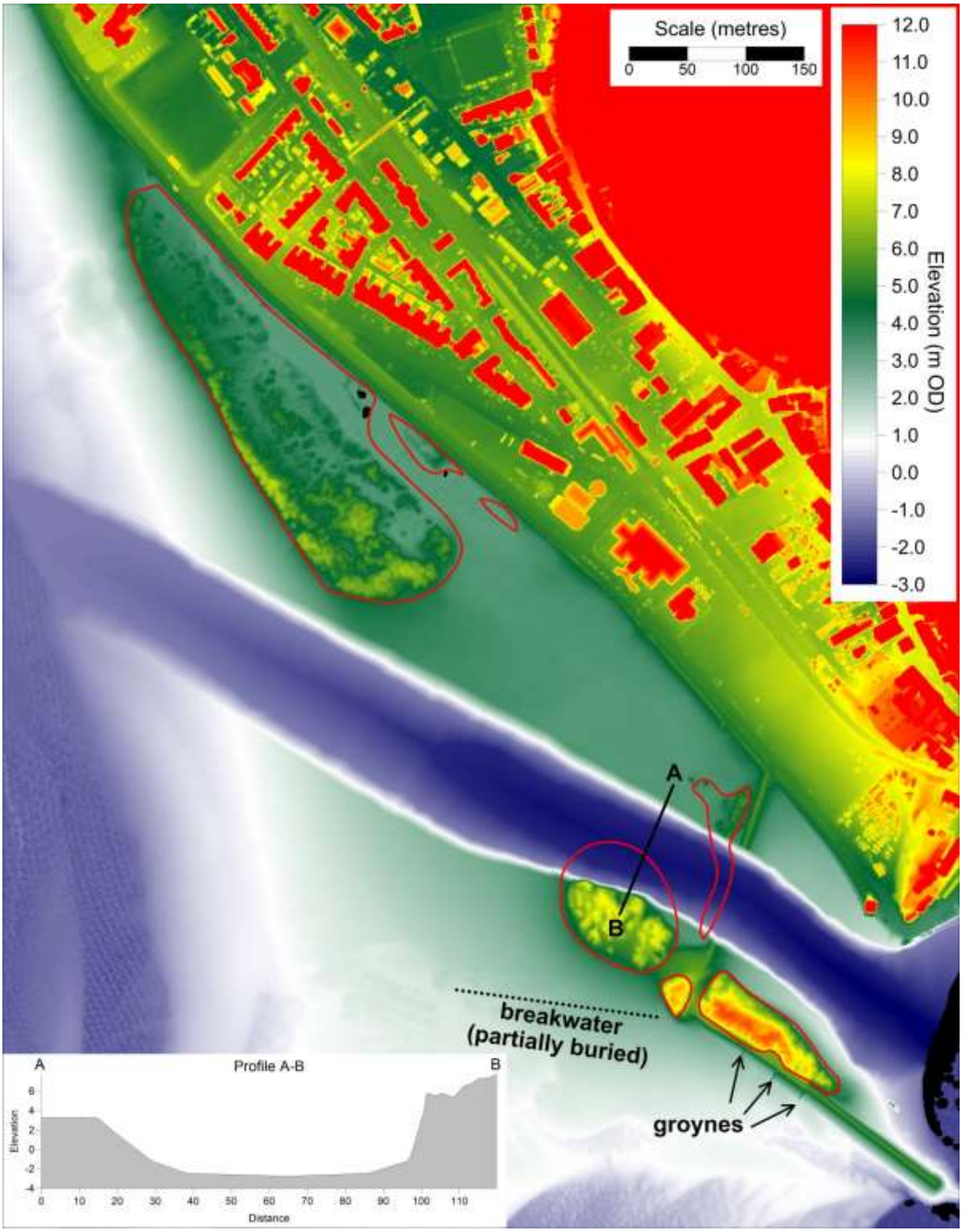


Figure 46. Option A: Reinstate the Bar Bach channel. The dimensions are taken from Admiralty survey of 1964, and low water mark from 1971 air photograph. The volume difference, compared to the 2016 UAV survey, is 307 x10^3 m^3 of sediment (± 7 x10^3 if allowing for a 10 cm error in the UAV survey).

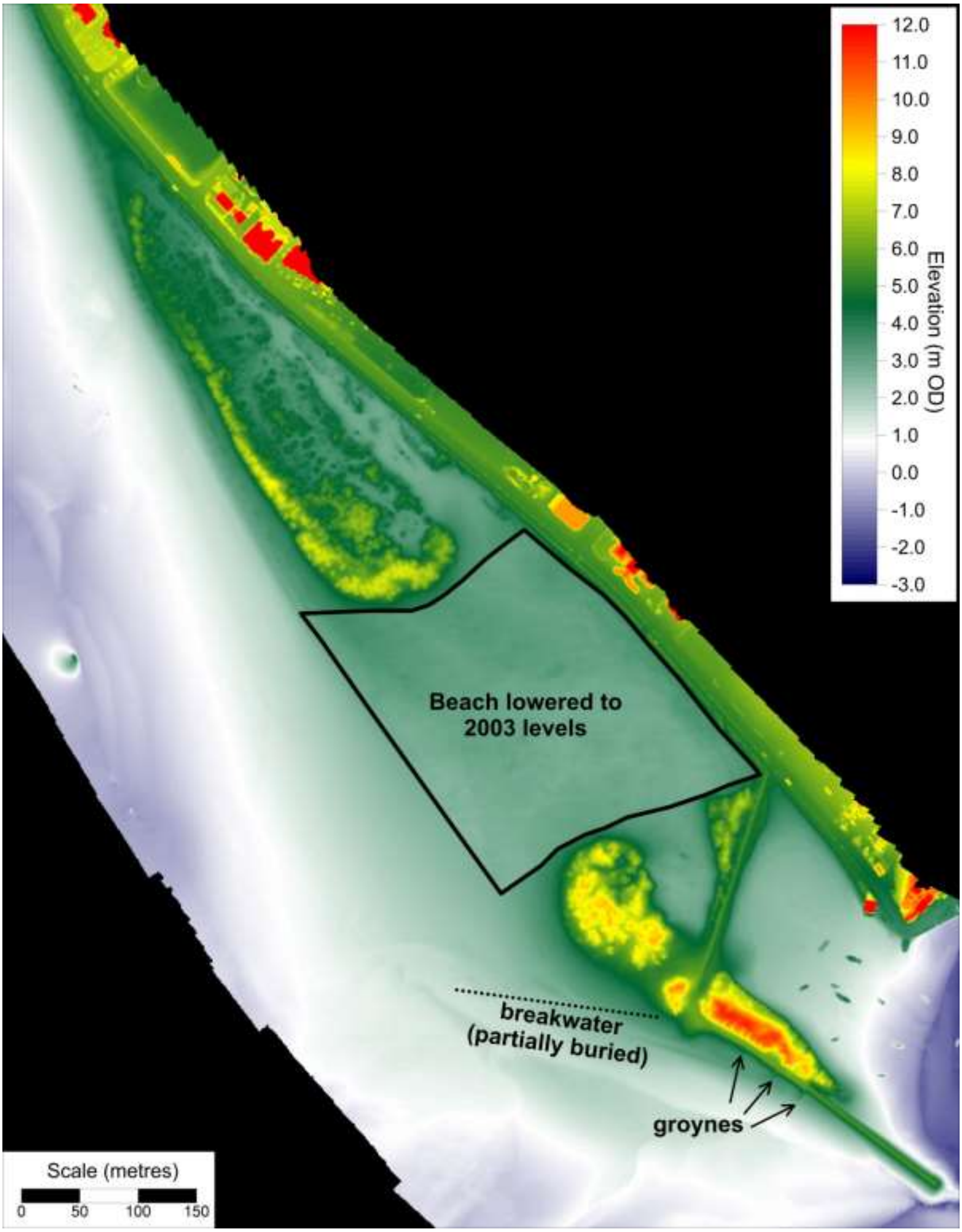


Figure 47. Option B: Lower the main part of the beach between the sand dunes to 2003 levels. The volume difference, between the 2003 LiDAR and the 2016 UAV surveys, is 21 $x10^3$ m^3 of sediment (± 6 $x10^3$ if allowing for a 10 cm error in the UAV survey). This sediment could be transported to the beach north of this image to replace the losses since 2003

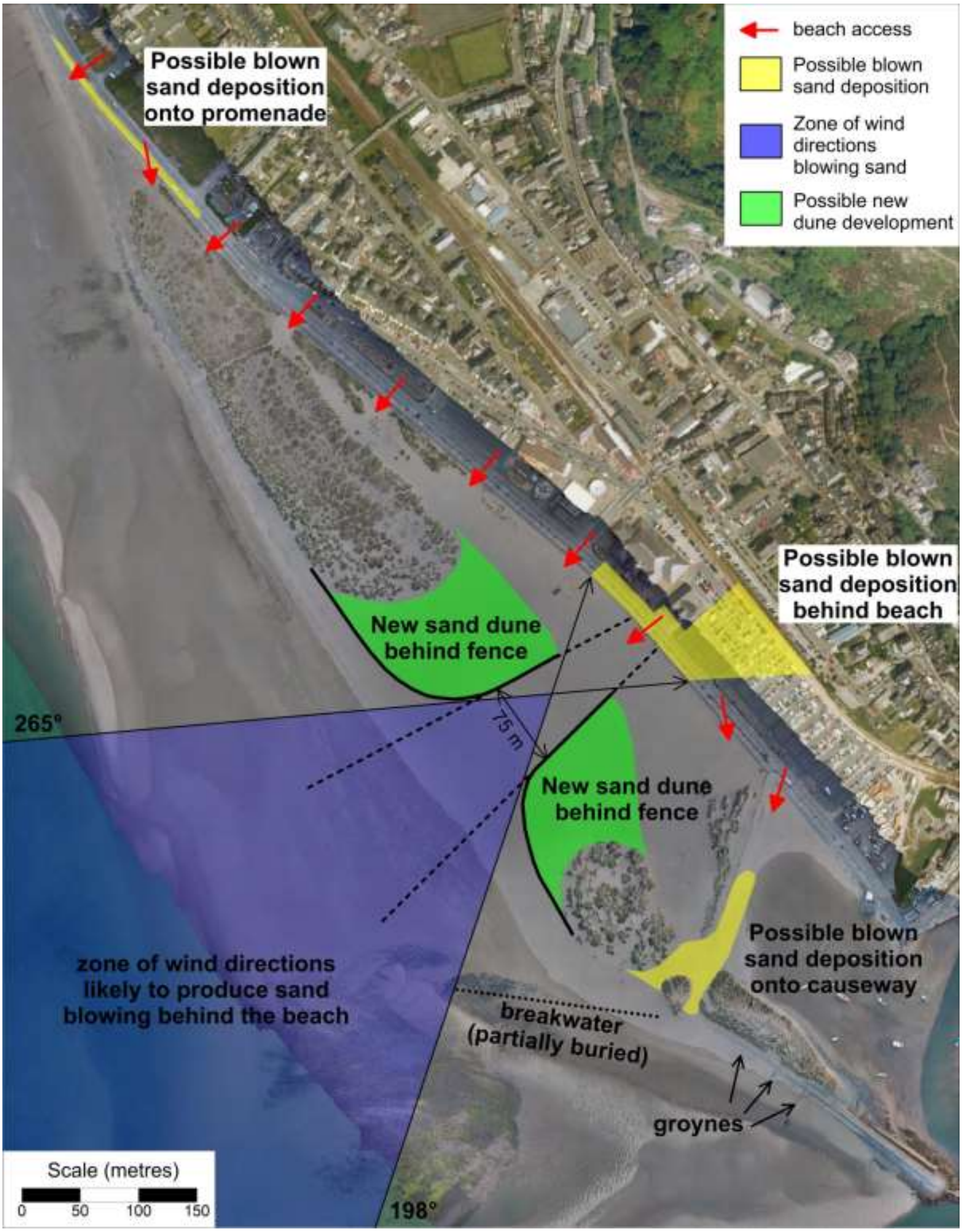


Figure 48. Option C: Expansion of the outer dunes only, extending the full width of the dune belt but leaving a wide gap (black lines indicate temporary sand fencing, 270 m long on north side, 245 m long on the south side). The blue area shows the zone of wind directions capable of producing blown sand behind the beach, and the yellow area shows the likely extent of blow sand. The red arrows indicate beach access points.

Figure 49. Option D: Extension of the outer dune ridge only, half the width of the existing dunes but leaving a narrower gap (black lines indicate sand fencing, 455 m long on north side, 390 m long on the south side). The yellow area shows the likely extent of blown sand. The red lines indicate the limits of vegetation mapped in 2016 by the UAV survey and the red arrows indicate beach access points.

Figure 50. Option E. Extension of the outer line of dunes, half the width of the existing dune belt, removal of the causeway but no reinstatement of Bar-Bach channel, creation of fenced compartments to allow establishment of vegetation (black lines indicate temporary fencing, 550 m in the north, 660 m in the south).

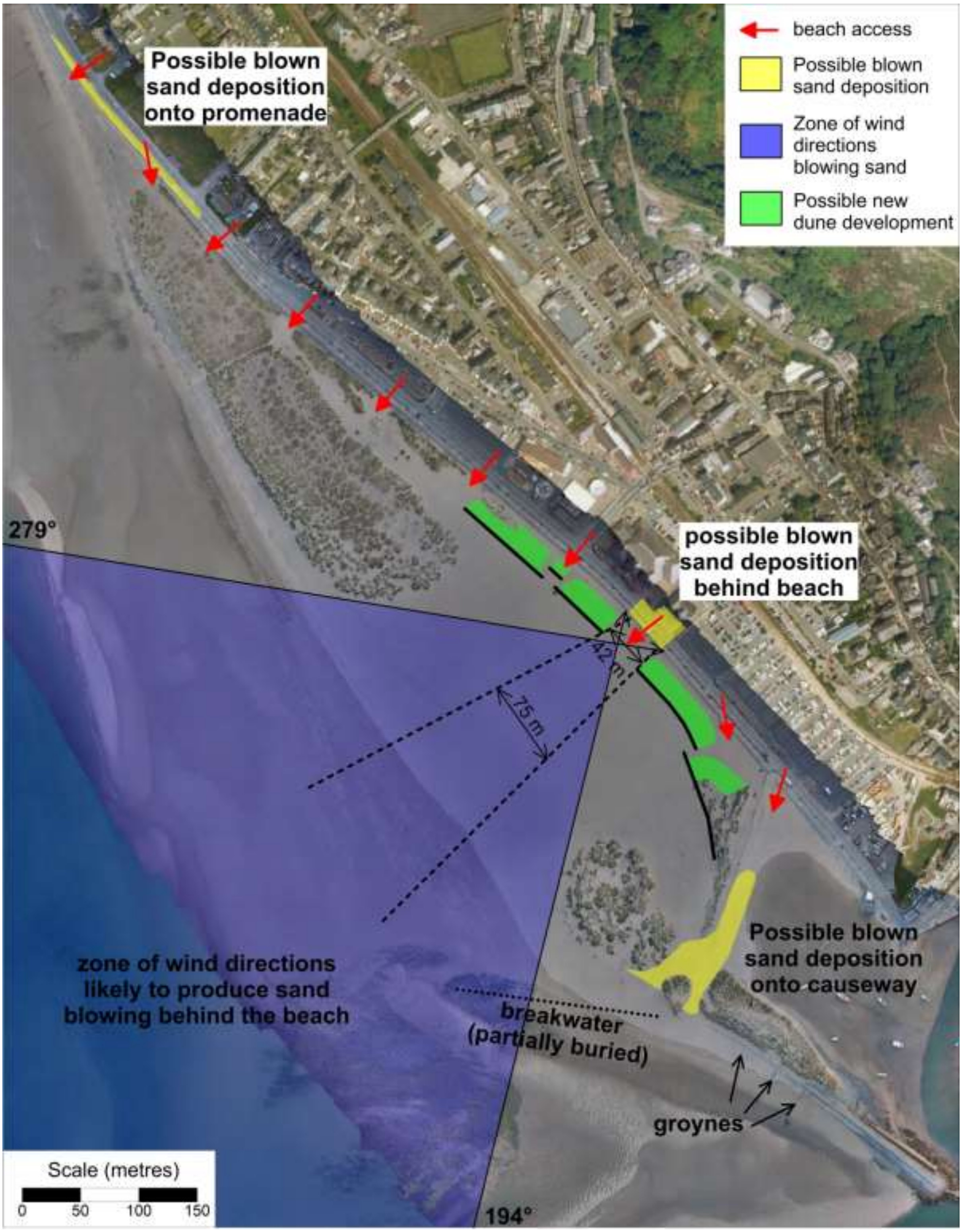


Figure 51. Option F: Enhancement of inner line of dunes only (black lines indicate temporary sand fences, total 365 m long, with breaks to allow beach access). The blue area shows the zone of wind directions capable of producing blown sand behind the beach, and the yellow area shows the likely extent of blow sand. The red arrows indicate beach access points.

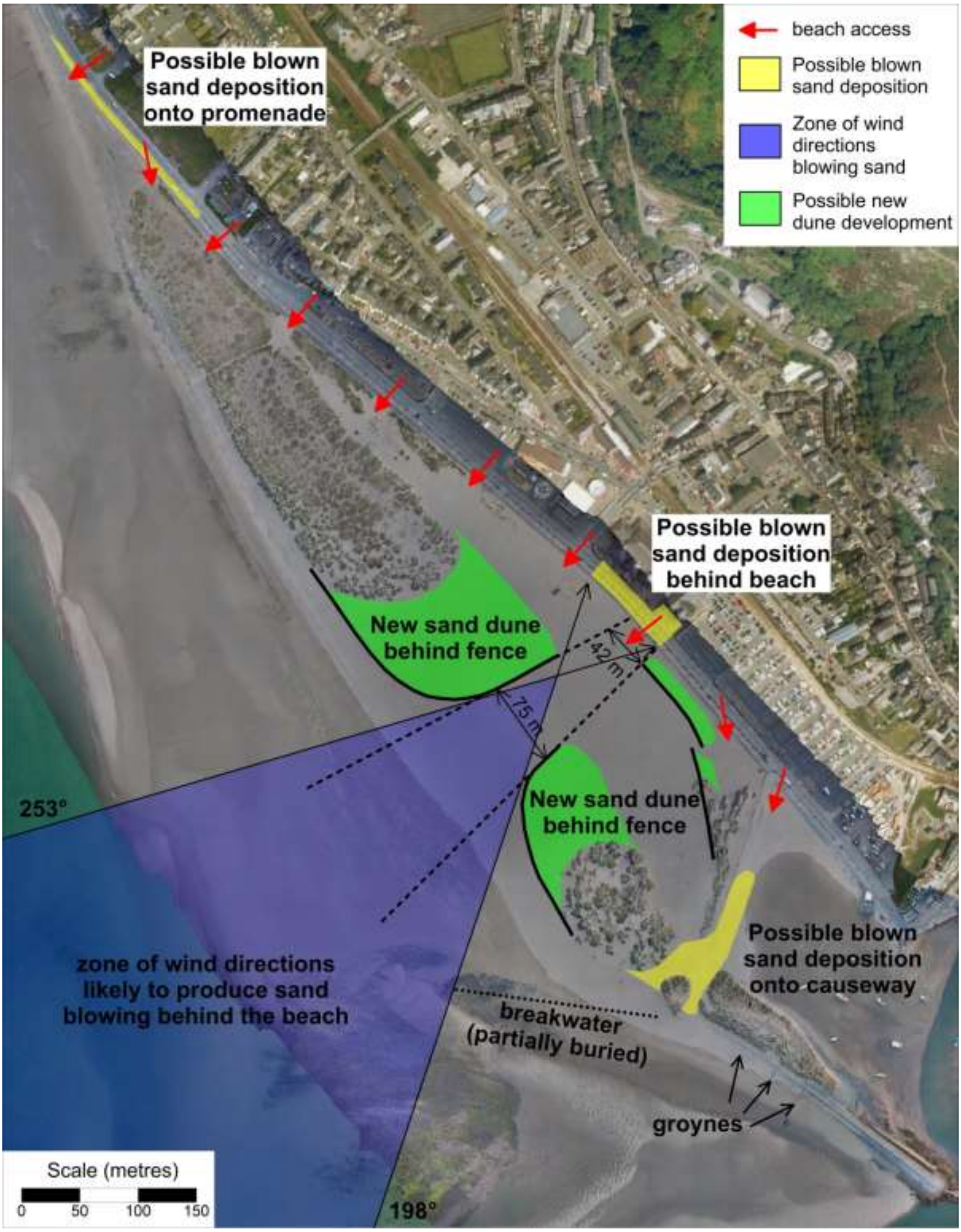


Figure 52. Option G: Enhancement of both outer and inner dunes (black lines indicate temporary sand fencing, 270 m long on north side, 185 m long on the south side, 190 m long along the back of the beach with a break to allow beach access). The blue area shows the zone of wind directions capable of producing blow sand behind the beach, and the yellow area shows the likely extent of blow sand. The red arrows indicate beach access points.

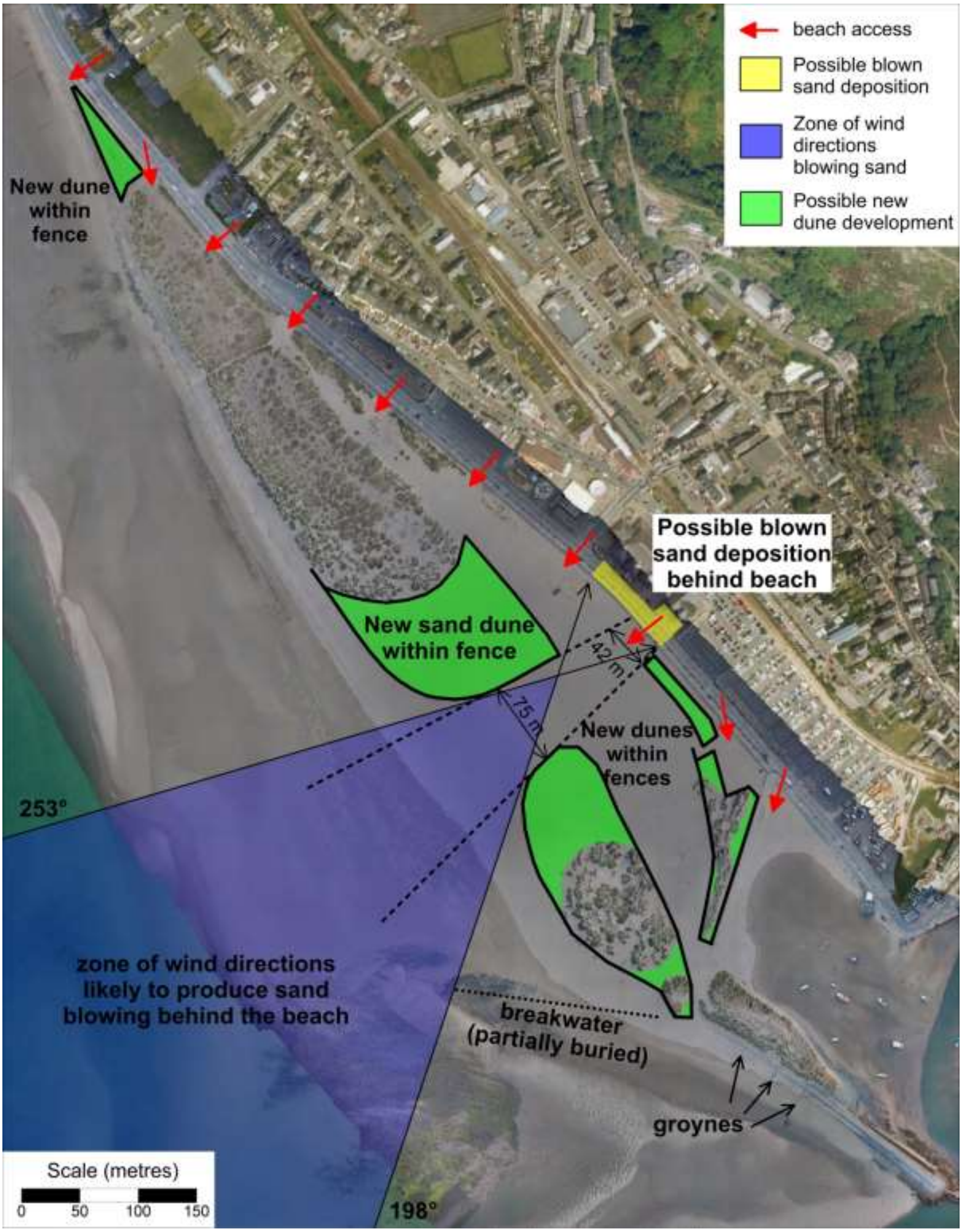


Figure 53. Option H: Enhancement of outer and inner lines of dune, with temporary rear sand fences to create closed compartments to prevent vegetation trampling by visitors (total length of fencing is 555 m on the north side, 585 m on the south side, 200 m along the back of the beach, 400 m to the west of the causeway, and 240 m at the northern end of the beach). The blue area shows the zone of wind directions capable of producing blow sand behind the beach, and the yellow area shows the likely extent of blow sand. The red arrows indicate beach access points.

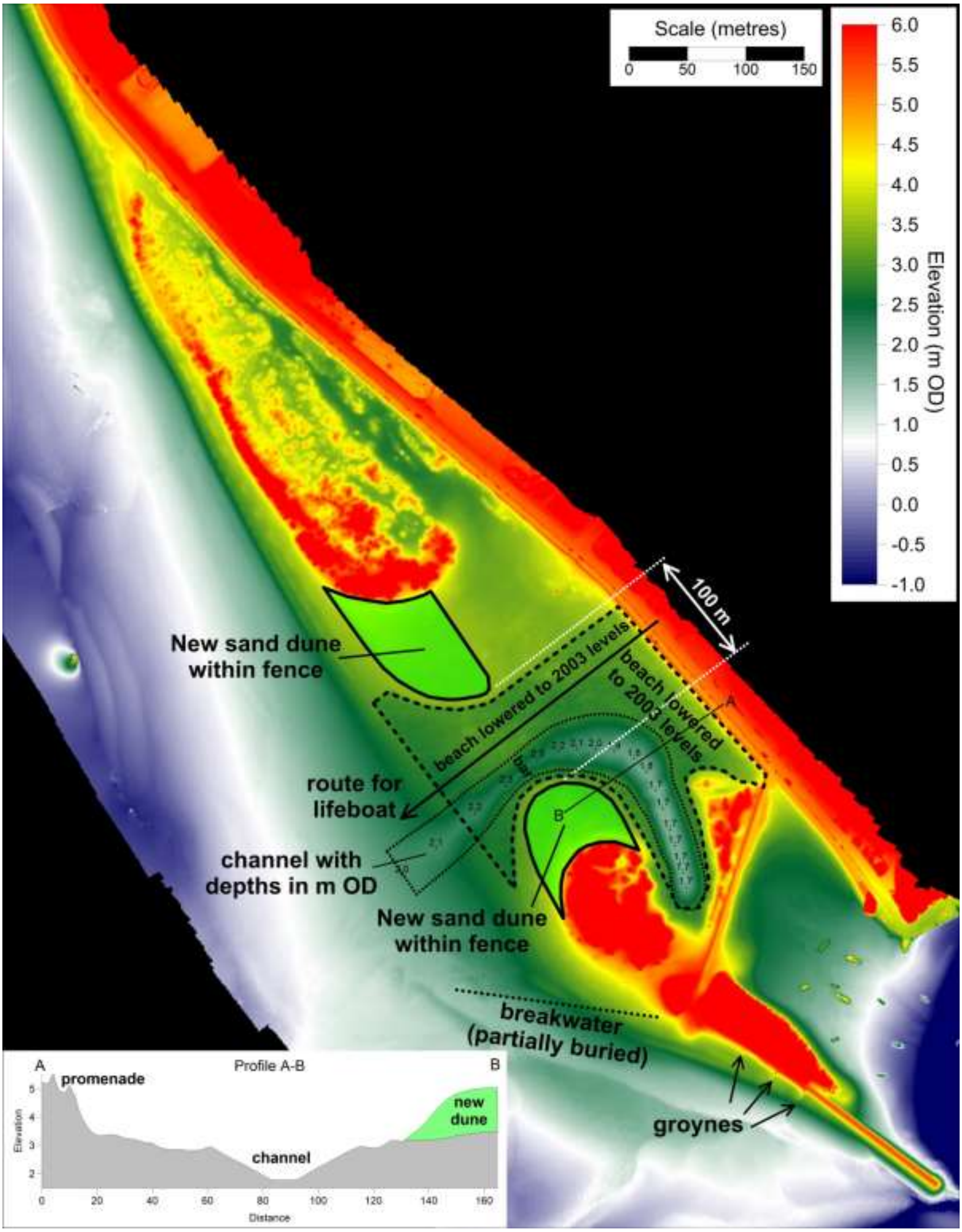


Figure 54. Option I: Lowering the main part of the beach between the sand dunes to 2003 levels, excavation of a shallow channel with a bar at c. 2.3 m OD and 'lagoon' with base at 1.7 m OD, expansion of the dune areas on either side using some of the sand from the excavated areas (black lines represent sand fencing, 380 m in the north and 360 m in the south). The total volume of sand to be excavated would be 18110 m^3. The area enclosed by fencing to create new dunes is 7130 m^2 to the north and 5090 m^2 to the south (12200 m^2 total). Excavated sand could therefore be added to the new dune areas to an average depth of 1.48 m. The excavated pool would have a maximum depth of 0.86 m on a MHWS high tide and maximum of 0.6 m on a spring low tide (in practice the level would probably drop to 0.4 m to 0.5 m due to seepage through the bar at low tide)

Figure 55. Location of infrastructure on the north beach (information sources: Dyr Cymru plans and Ordnance Survey maps)

Figure 56. Location of infrastructure on the central beach (information sources: Dyr Cymru plans and Ordnance Survey maps)

Figure 57. Location of infrastructure on the south beach (information sources: Dyr Cymru plans and Ordnance Survey maps)

Appendix 1

Photographs taken during a site visit on 8 August 2016

Photograph A1.1. View from the southern part of the promenade towards Ynys y Brawd; Bath House Café on the left

Photograph A1.2. View from the southern part of the promenade towards the Ynys y Brawd causeway

Photograph A1.3. View landwards along the Ynys y Brawd causeway. Only the parapet is visible due to burial of most of the structure by windblown sand

Photograph A1.4. View northeast from the from the Ynys y Brawd causeway across the existing relatively low-lying area of wet sand

Photograph A1.5. View seawards along the Ynys y Brawd causeway

Photograph A1.6. Northern arm of the rubble breakwater exposed on the Ynys y Brawd foreshore

Photograph A1.7. View northwards along the Trwyn y Graith stepped concrete breakwater

Photograph A1.8. View towards the southeast across the wide expanse of dry sand beach north of Ynys y Brawd

Photograph A1.9. View across the high dry sand beach towards the Barmouth RNLI station

Photograph A1.10. View northeast across the high dry sand beach towards the main dune belt

Photograph A1.11. View north along the seaward side of the main dune belt

Photograph A1.12. View north along the beach just south of the Min y Mor Hotel

Photograph A1.13. The upper beach near the Min y Mor Hotel which forms a transition zone between net erosion to the north and net accretion to the south

Photograph A1.14. Degraded groynes and low beach to the north of the Min y Mor Hotel

Photograph A1.15. View north along the upper beach and Marine Parade north of the Min y Mor Hotel

Photograph A1.16. View south along the northern part of the promenade south of the Min y Mor Hotel

Photograph A1.17. View south along the north-central part of the promenade

Photograph A1.18. View south along the promenade north of the RNLI station

Photograph A1.19. The central part of Barmouth Beach which is most heavily used for amenity purposes

Photograph A1.20. The new RNLI lifeboat station, opened in 2004

Photograph A1.21. View towards the sea from the lifeboat station

Photograph A1.21. View northwest across the amenity beach from a point south of the lifeboat station

Photograph A1.22. View south along the upper beach adjacent to the south-central part of the promenade where sand has been excavated to create a trough adjacent to the wave return wall

Photograph A1.23. Slipway partially blocked by windblown sand, southern part of the promenade

Photograph A1.24. Windblown sand on the promenade by the Bath House Café

Photograph A1.25. Accumulation of windblown sand on the railway line and against the rear wall of the main beach car park

Photograph A1.26. Accumulation of windblown sand on the railway line adjacent to the south east corner of the beach car park; view towards the southeast (Mawddach estuary)

Photograph A1.27. Accumulation of windblown sand on the railway line adjacent to the south east corner of the beach car park; view towards the northwest (Barmouth station)

Photograph A1.28. Barmouth beach hazards warning sign

Appendix 2

Photographs taken during a site visit in February 2014

Photograph A2.1. View north along the Trwyn y Graith breakwater, with ‘stripped’ beach to the left, exposing three groynes and the remains of the southern arm of the old rubble breakwater

Photograph A2.2. Rock armour at the seaward end of the Ynys y Brawd causeway, exposed by wave erosion of the beach and dunes during the winter storms of December 2013 - February 2014

Photograph A2.3. The northern end of the Ynys y Brawd dunes, trimmed by wave erosion during the winter storms of December 2013 - early February 2014, after some re-deposition of windblown sand

Photograph A2.4. Windblown sand on the promenade and road by the southern beach car park, view looking northwest

Photograph A2.5. Windblown sand on the promenade and road by the southern beach car park, view looking southeast towards the Bath House Cafe

Photograph A2.6. The re-profiled shingle beach immediately adjacent to the car park at the northern end of the promenade; this area and other areas further north were was seriously overwashed during the winter of 2013-14, leading to temporary closure of the railway

Photograph A2.7. Low beach level exposing groynes along the northern Marine Parade frontage

Photograph A2.8. Stable mixed sand and shingle upper beach near the Min y Mor Hotel