Assessing the Health and Resilience of Dune Systems as a Coastal Defence

KPAL Report No. 200325

V2.0

03 October 2025

Kenneth Pye Associates Ltd.

Scientific Research, Consultancy and Investigations

Assessing the Health and Resilience of Dune Systems as a Coastal Defence

Kenneth Pye **ScD PhD MA FGS**

and

Simon J. Blott **BSc MRes PhD**

KPAL External Investigation Report No EX200325

This study was commissioned by Sefton Council as part of the *Our Future Coast* project which is funded by DEFRA as part of the £200 million *Flood and Coastal Innovation Programme* managed by the Environment Agency. The contents are intended for the sole use of these organizations and should not be shared with other parties without written consent from the authors.

Report history

Version 1.0	Draft	26.08.25
Version 2.0	Revised final	03.10.25

Kenneth Pye Associates Ltd

Unit 8E Millars Brook Office Park
Molly Millars Lane
Wokingham
United Kingdom
Telephone: + 44 (0)118 304 8416

E-mail: info@kpal.co.uk
Website: www.kpal.co.uk

Contents

1.0 Report scope and purpose

This project was commissioned as part of the *Our Future Coast* project with the aim of creating a new method for quantifying the current health and relative resilience of sand dunes as a coastal defence, including the identification of trigger points for management intervention. As stated in the *Project Brief*, the aims of the research undertaken are to:

- provide land managers and local authorities with a monitoring methodology to inform future decision making.
- integrate with the monitoring and analysis undertaken within the Northwest Strategic Coastal Regional Monitoring Programme and make use of data that are already collected
- develop a methodology with respect to the dune systems at Formby and Blackpool/Fylde (referred to in this report as Starr Hills / St Anne's North Beach)
- provide insights into how the quality of dune systems can be quantified from a coastal defence perspective and how coast defence monitoring can be used to facilitate a shift towards nature-based coastal protection.
- produce a methodology which is potentially transferable to other dune systems.

Specific tasks are to:

- identify and examine suitable sources of data e.g. satellite imagery, drone imagery, aerial photography (plane)
- identify the key components of the dune system to reflect health and resilience
- develop the monitoring data need and the analysis process to assess the key components
- apply the same process to historic datasets and track changes through time at Formby and St Anne's North Beach
- provide and explain examples of potential trigger points for management intervention
- produce examples of easily understood visual representations of the results for land and coastal managers.
- align methodologies with coastal defence inspections using T98 specification
- identify how the additional monitoring can be integrated with the Northwest Regional Strategic Coastal Monitoring Programme.

The deliverables include:

- monitoring methodology – including specifications, frequency, resolution etc
- analysis methodology; step by step processes.
- case studies for the Formby and Starr Hills / St Annes North Beach dunes.
- example visualisations

The locations of the two case study areas within their regional context are shown in Figure 1.

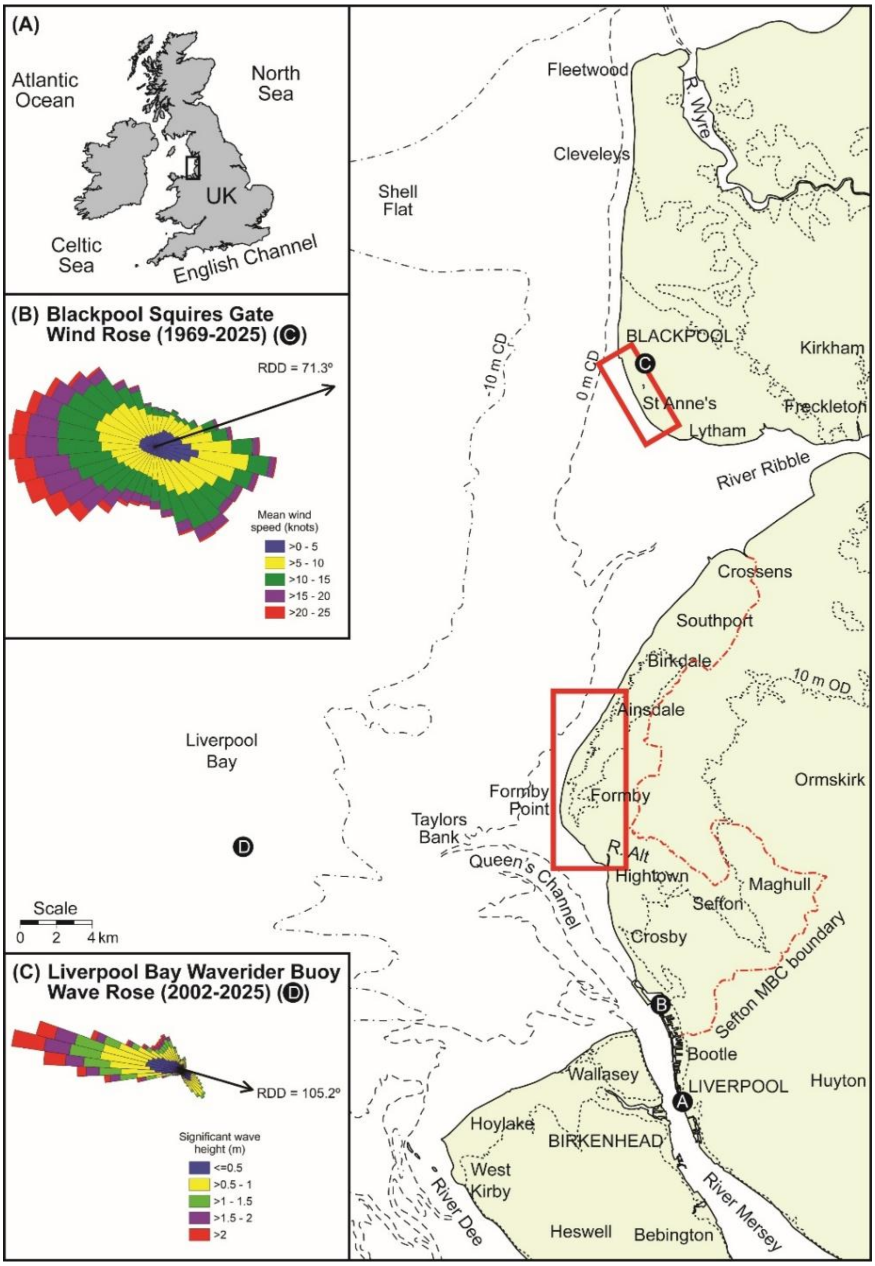

Figure 1. Location of the Formby and Starr Hills / St Anne's North Beach case study areas. Letters within black circles indicate the locations of tide gauges at Alfred Dock (A) and Gladstone Dock (B), the meteorological station at Squire's Gate Airport (C) and the WaveNet Liverpool Bay waverider buoy (D). Insets show: (A) location of the study area within the context of the UK; (B) average wind rose for winds > 11 kn at Squire's Gate, 1969-2025; (C) average wave rose for the Liverpool Bay wave buoy, with resultant travel direction for all waves scaled using wave power, 2002-2025

2.0 Background concepts and previous work

Dune systems can provide a natural coastal flood defence whilst also serving as important environments for nature conservation, tourism and recreation, military training and water storage. The 'traditional' coastal engineering approach to the management of coastal dunes, as implemented through the 18th, 19th and much of the 20th centuries in the UK and elsewhere, has been, where considered necessary, to establish and maintain dune stability through actions such as gabion wall construction, dune fencing, marram planting, afforestation and other measures to control activities which could lead to blowout development and dune de-stabilization. Management has often had the twin objectives of providing coast protection / flood defence and control of windblown sand hazard. From this traditional engineering perspective, a 'healthy', 'resilient' dune is one which is stable and able to withstand / recover from storm events so that the coastal defence value is not compromised. Since the late 1980s there has been increasing recognition that climate change and sea level rise will make it difficult to maintain dunes and other coastal defences in their present position / condition, and in the past decade the term 'adaptation' has been increasingly used to describe a more flexible approach to coastal management. However, 'coastal adaptation means different things to different people. In the UK the term is widely interpreted to mean an end to 'Hold the Line' policies and a move towards 'Managed Realignment' in which assets are relocated landwards and a secondary line of defence sometimes constructed further inland. Elsewhere, e.g. The Netherlands, adaptation strategies are interpreted in terms of a need to increase the frequency and magnitude of beach and dune nourishment in order to hold the defence line in its 1990 position, in accordance with national coastal defence policy (Keijsers *et al*., 2014).While this may be feasible when done at scale on the relatively simple, straight coast of the Netherlands, it is likely to be practical only on limited sections of the British Coast.

Since the late 1990s nature conservation bodies in the UK and elsewhere have also been increasingly concerned about the overstabilization of dunes and associated negative impacts on dune system biodiversity, in some instances leading to loss of 'favourable ecological condition' (Rees, 2021). Coastal defences have been viewed as having a negative effect on the ability of the coast to responds to natural processes, in some instances leading to loss of habitat through 'coastal squeeze'. Concerns have been expressed that 'fixed' dunes will not be able to adapt to rising sea levels and climate change, and that dune erosion will lead both to loss of habitat and a reduction in the longer-term effectiveness of dune systems as a coastal defence. In response to these concerns, measures have been taken in some locations to restore more dynamic dune environments and to adopt a 'nature-based solutions' approach to dune and wider coastal management. These measures include removal of areas of planted woodland, scrub clearance, turf stripping, re-introduction of stock grazing and, in a few places, removal of hard defences. Trials have also been initiated to encourage landward roll-back of dune systems by cutting 'notches' in the frontal dunes to enhance landward movement of sand. A more flexible approach to the control of visitor movements and other disturbance activities has also been adopted at some sites (e.g. removal of boardwalks and fencing).

Coastal Defence authorities face the challenge of achieving a balance between maintaining the traditional value of dunes as a defence and the pressures to adopt a more flexible, nature-based solutions approach which maintains, and where possible enhances, the ecological value of dunes as habitats and recreational areas. There is also a requirement to understand how dune systems are likely to respond to climate change and other factors which may cause significant coastal change in the medium to longer term. In order to plan future adaptive response strategies there is a requirement to monitor and identify 'trigger points' of coastal change which may lead to a change in coastal management practice. A first step is to understand and quantify the present health and resilience ('condition') of dune systems from a coastal defence perspective and to identify thresholds of change which may act as of 'trigger points' for management intervention or a change in management policy. This requires availability of suitable baseline information and a programme of monitoring which can be compared with the baseline and defined trigger points.

In England some coastal defence authorities, including Sefton Council and its predecessors, have monitored changes in beach levels and the position of the dune toe (seaward edge) for decades, but systematic collection of coastal monitoring data only began in the 1990s. The methods, spatial intensity and scope of data collection vary from region to region, and even within different parts of a single region according to a pre-defined risk-based strategy, and have evolved over time. The Northwest Strategic Coastal Regional Monitoring Programme (CRMP), which covers the area between the Dee Estuary and the Solway Firth, began in 2006 and includes the collection of aerial photography, and airborne LiDAR every two years, ground RTK-GNSS beach profile surveys on a biennial, biannual or quarterly basis, and single beam bathymetric and sediment surveys at approximately five year intervals). Terrestrial laser scanning surveys are also carried out in areas of particular interest, and visual inspections of coastal defence assets are conducted as considered necessary. For the Formby dune frontage beach profile and dune toes surveys have typically been carried out twice a year, supplemented by aerial photography and airborne LiDAR surveys every two years. The St. Annes to Lytham frontage has been surveyed with a similar frequency but on the St Annes to Blackpool frontage beach surveys have been scheduled quarterly.

Condition monitoring of coastal defence assets, which include beaches and dunes which are of flood risk management significance, has been undertaken as part of the Northwest CRMP in accordance with the procedures outlined in the Environment Agency (EA)'s 'T98' *Flood Risk and Coastal Erosion Asset and Inspection Accreditation Scheme*. This method is largely visual based on walkover inspections and relies heavily on surveyor knowledge of the site. The EA (2012) *Managing Flood Risk - Condition Assessment Manual* identified three tiers of inspection which can be applied. More recent good practice guidance (Environment Agency 2025) recommends that the lowest level (equivalent to Tier 1) Visual Inspections should be carried out all year round, with typical frequencies for high priority assets every 6 -12 months, medium priority assets every 12 - 24 months, and low priority assets every >24 months. Based on the *Visual Inspection* a semi-quantitative grading can be assigned to the condition of the asset, as shown in Table 1.

Where a need is highlighted by *Visual Inspection*, a more detailed *Engineering Inspection* may be carried out. In the case of dune systems, this may involve more detailed / frequent topographic surveys and/ or ground investigations. The highest level of inspection involves *Specialist Inspection*; this is generally more applicable to hard engineering structures such as seawalls, revetments and breakwaters than to sand dunes.

Table 1. Example of grading system used in the visual assessment of flood defence assets (EA, 2025)

Grade	Condition class	Description
1	Very good	Cosmetic defects that will have no effect on performance
2	Good	Minor defects that will not reduce the overall performance of the asset
3	Fair	Defects that could reduce performance of the asset
4	Poor	Defects that have potential to deteriorate and significantly reduce performance of the asset. Further investigation required
5	Very Poor	Severe defects resulting in significant or complete performance failure

A limitation of the T98 approach when applied to sand dunes is that it focuses mainly or wholly on the frontal dune area (and sometimes the fronting beach), and it is left to individual surveyor to interpret the significance of observed features such as embryo dunes, cliffed frontal dunes, or small blowouts. Little or no attention is given to the characteristics of the hind dune area which are be of particular significance in terms of the medium to long-term resilience of the dune system as a coastal defence. There is also often an assumption that the presence of embryo dunes and incipient foredunes with a gentle seaward slope (e.g. Figures 2a & 3a) are evidence of a 'healthy' defence asset, while cliffed or dissected frontal dunes (e.g. Figures 2b & 3b) represent a 'compromised' asset, regardless of the width of the dune system or the elevation of the land and any infrastructure behind.

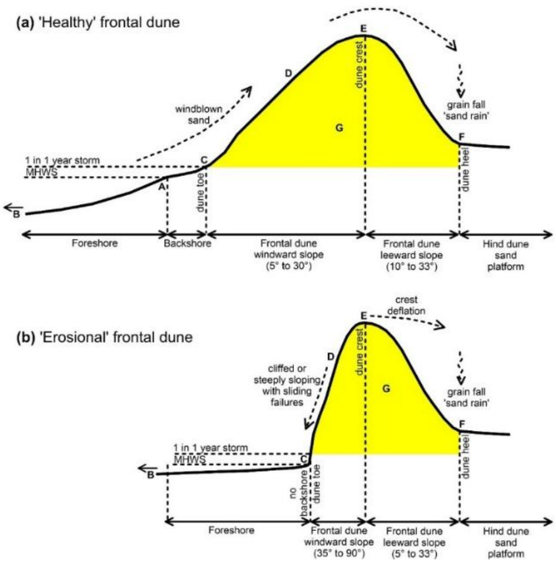

Figure 2. Concept cross-sectional diagrams for (a) a 'healthy' frontal dune; and (b) and 'erosional' frontal dune

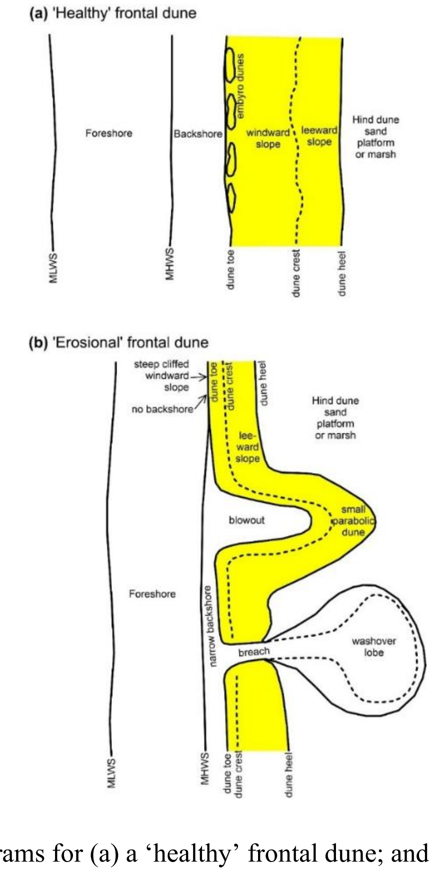

Figure 3. Concept plan diagrams for (a) a 'healthy' frontal dune; and (b) and 'erosional' frontal dune

A DEFRA-funded report published in 2007 (Pye *et al*., 2007) reviewed the role of coastal dunes as a coastal defence in England and Wales in relation to their geomorphological characteristics and other interest features. This report pointed out that, from a coastal defence point of view, the importance of coastal dune systems depends, to a large extent, on the nature of the hinterland and the value of assets which are potentially subject to marine flooding, erosion or burial by windblown sand. The highest flood risk management importance arises where extensive assets lie close to the coastal edge and below the level of storm surge inundation (Figure 4).

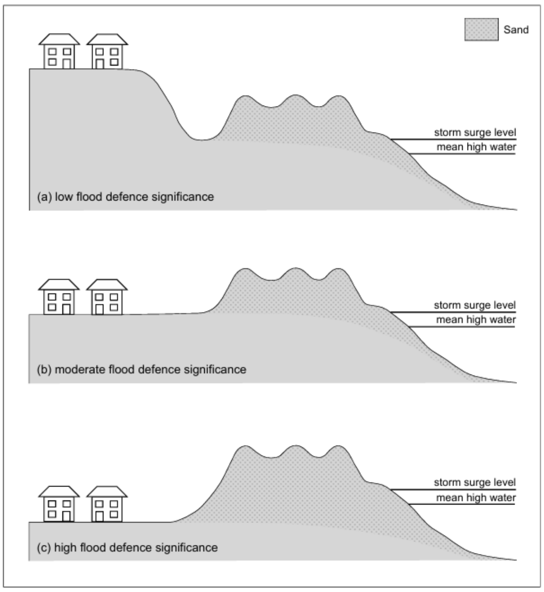

Figure 4. Schematic representation of the significance of coastal dunes for coastal flood defence (after Pye *et al*., 2007)

A subsequent report prepared for Natural Resources Wales (Pye *et al*., 2017) clarified the importance of dune system width, elevation and sand volume per unit length of coast as factors which influence the effectiveness of dune systems as coastal flood barriers. The most effective dune defences form a continuous ridge and have a large sand volume both above and below present and potential future storm surge and wave run-up levels (Figures 5 & 6).

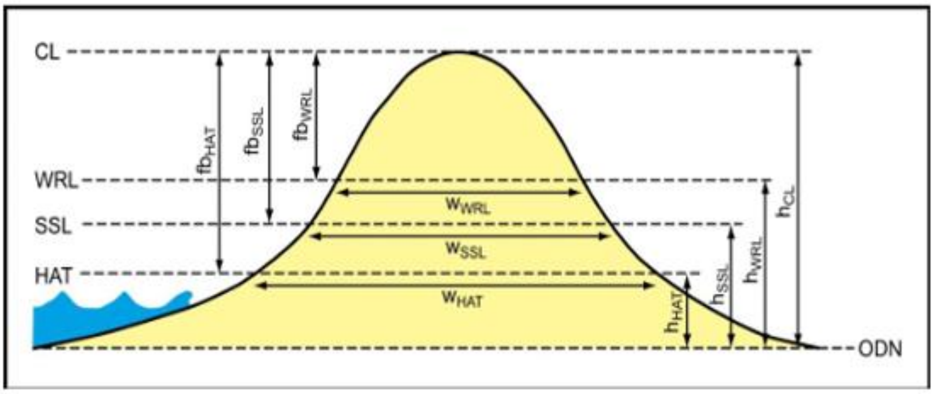

Figure 5. Concept diagram showing three defined water levels in relation to the height and width of a dune barrier. HAT = highest astronomical tide; SSL = storm surge still wate level; WRL = storm surge wave run-up level; h = height above reference datum; fb = freeboard (after Pye *et al*., 2017)

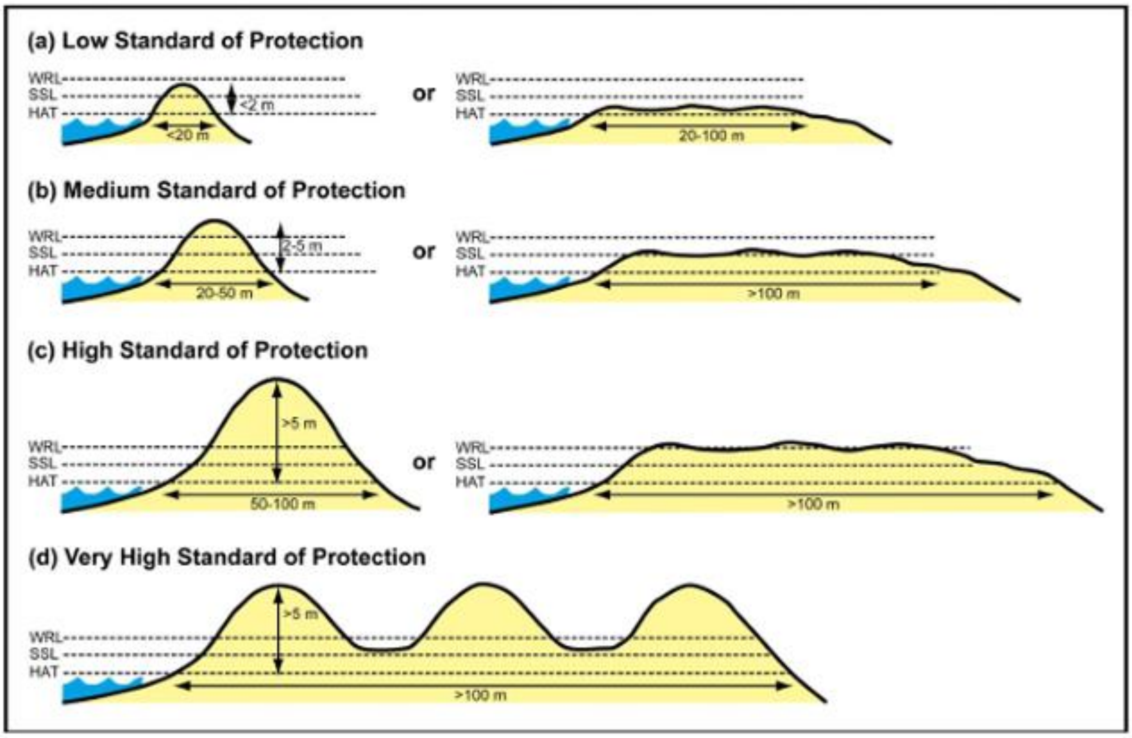

Figure 6. Conceptual diagram illustrating differences in the relative standard of protection against marine flooding provided by a sand dune barrier as a function of dune system width and crest level (after Pye *et al*., 2017)

High, wide barriers also have the greatest resilience to wave erosion during storm events. Although several metres of frontal dunes may be washed away in a series of winter storms, the dune barrier will not be breached and partial of full recovery of the frontal dunes may occur in the following years provided eroded sand is not lost from the adjacent nearshore area (i.e. the beach – dune system has intrinsic resilience).

Wide but low dune barriers can be eroded away completely or flattened during major storms because only a relatively small volume of sand is released from the dunes to the beach, and there is very limited impact on wave energy dissipation. Wave erosion of high dunes, on the other hand, provides a larger volume of sand which raises beach levels and reduces breaking wave energy; this acts to self-limit the rate of dune recession, although the rate of dune retreat is a probabilistic process influenced by a range of factors including the elevation and duration of high water levels, the direction of wave approach, rates of alongshore drift, and the resistance offered by the dunes due to sand size, degree of sand consolidation / cementation and the type /density of any vegetation present (e.g. Vellinga, 1982; van der Graf, 1986; Silva *et al.,* 2016; Itzkin *et al*., 2020).

Wide areas of relatively low dunes are often indicative of medium to high rates of coastal progradation, whereas high frontal dunes, especially if they have steep or cliffed seaward slopes, often indicate stable or eroding dune frontages (Pye, 1990). However, wide, low dune systems contain a relatively small sand volume which can be eroded away quickly if nearshore bathymetry and wave conditions change. Over longer-time scales, wide, high dune systems containing a large volume of sand have much greater resilience to coastal erosion and sea level rise than narrow, low systems, especially on exposed windy coasts where rates of aeolian transport are high and much of the eroded dune sand can be moved inland rather than lost offshore as predicted by the Bruun Rule (Pye & Bowman, 1984; Davidson-Arnott, 2005).

In terms of breach risk, the resilience of a coastal dune barrier is only as great as the weakest points; it is therefore important to identify the number, location and size of low / narrow points within the dune system. In some dune systems there may be more than one line of high dunes which contribute to the coastal defence (as along much of the Formby frontage). Identification of potential weak spots can be done by interrogation of a LiDAR DTM of the dune system, including definition and plotting of one or more elevation 'watershed' lines. Locations where the dune ridge is low and/or narrow, or crossed by tracks or artificial notches / cuts, can then be monitored in particular detail using both remote sensing data and ground inspections / surveys.

A further aspect which needs to be considered in relation to the flood defence condition of a dune system, and also as a potential source of windblown sand hazard, is the degree of stability of the sand surface. A relatively high ratio of bare sand to vegetation cover is likely to favour high rates of inland sand transport and may result in the creation of dissected ('hummocky') dune topography, blowouts or low sand sheets which in narrow dune systems may permit sea incursion under storm surge conditions. Elongated blowouts (or artificial cuts) in the frontal dunes can provide significant points of weakness in the flood barrier if they penetrate much or all of the width of the dune belt. Significant areas of bare sand can also result in sand drift on to adjacent infrastructure (roads, railways) or properties. The degree of sand surface mobility, reflected by the percentage of bare sand area relative to vegetated surface, is also a major factor which controls the potential of a dune system to move landwards under the influence of rising sea level ('rollover').

Over the past two decades there have been several attempts to develop and implement *Coastal Dune Vulnerability Indices* (CDVI) to support coastal management in different parts of the world (e.g. Martinez *et al*., 2006, McLaughlin & Cooper, 2010; Williams *et al*., 2011). The main interests have been in vulnerability to climate change, sea level rise and various forms of anthropogenic disturbance. Most of the published indices are relatively complex and involve the use of a combination of semi-quantitative and limited quantitative assessment methods. For example, the CDVI developed by Bertoni *et al*., (2019) for applications to coastal dunes at four locations in Brazil and Italy included five main groups of factors: Geomorphological Condition of the Dune System (GCD), Marine Influence (MI), Aeolian Effect (AE), Vegetation Condition (VC), and Human effect (HE), representing a total of 51 variables, 35 of which were related to biotic and abiotic factors and 16 to human factors. For each variable a value ranging from 0 (no vulnerability) to 4 (very high vulnerability) was assigned based on largely subjective assessment. The sum of the scores for the variables within each of the five groups was divided by the sum of the maximum achievable rating within each group, thereby generating a partial CDVI expressed as a percentage. The total CDVI was calculated as the unweighted average of the five partial indices as:

$$CDVI = (GCD + MI + AE + VC + HE)/5$$

Although the CDVI was unweighted, it was concluded that geomorphological (GCD) variables were of greatest importance in both regions. Seven GCD variables were specified:

1. Length of homogeneous active dune system, (ranging from <0.1 km to > 20 km)
2. Average height of secondary dunes (ranging from < 1 m to > 25 m)
3. Average height of frontal dunes (ranging from <5 m to > 25 m)

4. Foredune slope steepness (described qualitatively as moderate, gentle or steep)
5. Relative are of wet slacks determined from maps (area % expressed qualitatively as moderate, small, none)
6. Degree of dune system fragmentation (expressed qualitatively as low, medium and high)
7. Particle size of the frontal dune, ranging from < 0.1 phi (coarse) to 3 (very fine)

The lowest Class of Vulnerability (0) was assessed as being associated with very long dune systems, frontal and inland dunes > 25 m high, moderate foredune slope steepness, a moderate occurrence of wet dune slacks, low degree of dune system fragmentation, coarse sand composition, wide fronting beach, stable or prograding dune toe position, relatively low mean nearshore wave height, near-perpendicular mean wave approach angle (associated with low rates of alongshore drift), low storm frequency, high rates of sand supply to the beach and frontal dunes, a low proportion of blowouts in the dune system (<5% of the area), a high percentage of vegetation cover, low visitor pressure, absence of vehicles, and low grazing pressure. The overall mean CDVI values for the two sites in Brazil were determined to be +0.45 +/- 0.03 and 0.47 +/-0.02 while mean values from the two Italian sites were 0.33 +/- 0.01 and 0.40 +/- 0.03, all being judged to present *medium* vulnerability.

While this type of approach can be useful, particularly in the provision of baseline information, it is time consuming to undertake and for many large dune sites and it is often appropriate to use single values for each variable to characterise long lengths of dune frontage. In the context of coastal flood risk management, it is important to have high resolution, local-scale information since, as noted above, the effectiveness of a dune (or any other) defence is controlled by the weakest link.

3.0 Methods used in the present study

3.1 Approach

In the present study a distinction is made between *baseline condition assessment* and *on-going monitoring assessment.* The former requires an initial assessment of the principal physical, ecological and anthropogenic aspects relating to an entire dune system, together with the location and nature of associated assets which may be at risk, whereas on-going monitoring may focus only on the frontal dunes and / or selected inland areas of highest risk.

As noted in Section 2 above, previous work has identified the importance of dune system width, elevation and sand volume, together with degree of sand instability and degree of topographic fragmentation, as key determinants of the value of dunes in terms of coast protection and flood defence. These factors are also important influences on the magnitude of windblown sand hazard and the extent of bare / mobile sand which it may be desirable to have within a given dune system from an ecological point of view.

Many larger dune systems display significant alongshore variation in dune and fronting beach morphology, reflecting factors such as coastal orientation, exposure to wave and wind action, variations in sediment supply and sand characteristics, visitor pressure and dune usage / management practices. For this reason, a cellular approach has been adopted in this study for both the baseline assessment and subsequent 'Tier 1' flood defence condition monitoring based on periodic field inspections. To aid this process it is useful to use a checklist to record features which are present to varying degrees along prescribed sections of the dune frontage. In addition to dunes, this approach is also applicable to other types of coastal geomorphology, including beaches and shingle barriers. Example checklists, completed using data for selected cell frontages at Formby and Starr Hills, are provided in Appendix 1.

Information recorded on the checklists in the field can be entered into a central computerised database to supplement information obtained from GIS analysis or higher-level site inspections. Creation of such a database is beyond the scope of the present commission and needs to reflect the hardware, software and skill sets which are available within a given Coastal Defence Team.

The tables and figures presented for the two case study areas are intended to provide illustrations of the application of the proposed methodology rather than a comprehensive data set for each frontage.

3.2 Data used

Although several useful types of data are collected as part of the Northwest Strategic Coastal Regional Monitoring Programme, airborne LiDAR and aerial photography are particularly valuable in providing baseline information about topography and sand mobility across dune and beach systems as a whole. The value of analysing LIDAR data to quantify longshore variations in dune and beach morphology at a range of sites including Sefton has previously been demonstrated by Saye *et al*. (2005), Pye & Blott (2016a,b), and Pyet *et al,* (2017).

The most recent available LiDAR survey data (2024) have been used to for the baseline assessment of dune system morphological condition at the case study sites, and data derived from seven additional epochs (2010 - 2022) have been used to demonstrate how such data can be used to monitor changes in beach and dune parameters over time.

Rectified aerial photography from a Northwest CRMP survey in 2024 has also been used to demonstrate how such imagery can be used to quantify the relatively proportions of blown sand and vegetation in an area. Standard RGB aerial imagery can be analysed in conjunction aerial multi-spectral data (including near- and far- infrared if there is a requirement to quantify the distribution and extent of different vegetation communities and habitat types within an area.

The Northwest CRMP currently included collection of airborne LiDAR and rectified aerial photography data for ‘high risk’ parts of the Northwest every two years. Beach profiles and dune toe surveys are carried out on a more frequent basis, ranging from quarterly to annual, depending on perceived risk. Visual walkover asset inspections are also carried out at intervals based on perceived risk, in accordance with the recommendations of the Environment Agency’s ’T98 specifications. For the present purpose it was not considered necessary to use the beach profile, dune toe or visual asset inspection data, but the use of such data for other purposes is illustrated in the companion report by Pye & Blott (2025).

For the present purpose ‘filtered’ LiDAR data, from which features and large trees have been removed by computer processing of the original point cloud data, have been used, although in some circumstances there is also value in analysing ‘unfiltered’ data. The data sets used in this study were available at 1 m spatial resolution except for the 2014 survey which was at 2 m resolution.

As part of a quality control process the elevations indicated by different LIDAR surveys have been compared at selected fixed points (usually a hard surface such as a road, car park or sea wall), and comparison has also been made with ground RTK-GNSS data obtained by KPAL. The results of this exercise, and the nature of any adjustments made, are provided in Appendix 2. It should be borne in mind that for many LiDAR surveys 'fixed' ground control points are not available for beach and more seaward dune areas, giving rise to greater elevational uncertainty. The vertical accuracy of airborne LiDAR surveys is often quoted to be +/- 10 – 15 cm for bare surfaces, but errors may be significantly larger in areas of dense, tall vegetation. Cross-checking of LiDAR data against ground based RTK-GNSS survey data, which typically have a vertical error of +/- 2 - 5 mm, is recommended.

3.3 GIS analysis

For each case study area a LiDAR digital terrain model (DTM) was created using the 2024 data available on the Open Government website. All downloaded data were processed using Golden Software Surfer routines and in-house macros, mainly written in Microsoft Excel. As a first step in the analysis process one or more 'watershed' lines was interpolated from the DTM to provide an indication of variations in the position and height of the dune crest along each case study frontage. In the case of Formby more than one dune defence watershed line can be defined for parts of the frontage. The elevations along these crest 'watershed' lines were then plotted as side elevation diagrams to help identify the locations of potential weak (low) points.

A seaward 'baseline' was then established based on extraction of the 5.3 m ODN contour from the 2024 airborne LiDAR DTM. A landward baseline was also defined as the seaward limit of 'immovable' and/or 'high value' assets, taken to be features such as urban development, road and railways which conceivably might need to be protected by hard defences at some stage in the future.

The 'Grid|Slice' command in Surfer was used to extract topographic profiles from the LiDAR DTMs. In addition to profile lines along the mid point of each defined cell, additional profiles can be specified at points of identified interest (e.g. potential weak points identified from the LiDAR DTMs and elevation 'watershed' line plots (this is illustrated for the Starr Hills / St Annes North Beach study below). A variety of parameters along each profile line was measured, including distance from the landward (asset) baseline, maximum dune crest height, and sediment cross-sectional area / volume above dune toe level (5.3 m ODN). Sand volume at each profile location is expressed in terms of metre width of frontage (m^3 / m^{-1}). The total volume of sand above 5.3 m ODN within each cell was also calculated using the 'Grid|Volume' command but these data are not presented in this report.

A similar process was used to determine the position of selected beach contours along extensions of each profile in order to demonstrate how such data can be used to monitor beach changes and provide early warning of changes at the dune toe.

The 2024 aerial photographic imagery was used to determine the areas of bare sand in the case study areas. All tiles for the study area were combined in the plot window of Surfer and exported as an 8-bit Surfer grid file. This effectively creates a black and white image of the photograph, with 'lightness' represented with a value between 0 and 1. The image was inspected to determine which 'lightness' value best prescribed bare sand in the image, which depends largely on the light conditions at the time of image capture. A threshold value of 0.60 was used for the Formby area and a value of 0.58 was used for the Starr Hills / St Anne's area. Values below the threshold were blanked using the

'Grid|Math' command, and areas of bare sand displayed as red pixels. The 'Grid|Volume' command was then used, in combination with the coastal cells blanking file created above, to calculate the area of red pixels (representing bare sand) within each coastal cell. Values were exported to Microsoft Excel and Word for display and conversion to percentages of the total area in each cell.

4.0 Formby case study

4.1 Physical setting and coastal process

The eastern Irish Sea between Blackpool and Liverpool experiences a macrotidal regime with a mean spring tidal range (MSR) of approximately 8 m (Table 2). The 1 in 1 year still water level at Formby is approximately 5.33 m ODN, which corresponds approximately with the average level of the dune toe (a break of slope between the upper beach (backshore) and frontal dune). Storm surges can raise predicted still water levels by 1 - 1.5 m, and during surge tides erosion of the dune toe can occur due both to wave impact and soaking / slumping induced by standing water (Parker, 1975; Pye & Blott, 2008). The 1 in 20 year extreme still water level is approximately 5.78 m ODN (Table 3).

A wide sandy foreshore is exposed at low tide to relatively strong winds from the southwest, west and northwest (Figure 1). At present the foreshore and backshore are widest to the north and south of Formby Point at Birkdale and off Altcar. These areas have experienced substantial beach and dune progradation since the late 19th century whereas the central area around Formby Point has been eroding at least since 1900 (Pye & Neal, 1994; Pye & Blott, 2010). However, before 1900 this area experienced almost a kilometre of coastal progradation and the dune belt is still more than 1 km wide to the west of Formby township (Figure 7).

A relatively high ridge of interlinked parabolic dunes, now largely stabilised by coniferous woodland and reaching up to 35 m above ODN, extends between Birkdale and Ravenmeols and provides an effective barrier against marine flooding and windblown sand incursion. Behind the dune belt is an extensive low-lying area of former intertidal flats and peatlands which lie below the level of extreme high waters (Figure 8). Much of this area forms part of the River Alt catchment (in the south) and the Crossens Brook catchment (in the north). Groundwater levels are controlled by pumping stations at Altcar and Crossens and tidal incursion is prevented by barriers near the mouth of the River Alt and at Crossens.

Table 2. Predicted mean tidal levels at stations between Blackpool and Liverpool, taken Admiralty Tide Tables (ATT, Hydrographic Office 2024) and the Environment Agency Coastal Boundary Study (EA, 2019)

Level	Source	Blackpool	Southport	Formby	Liverpool
1:200 year	EA	6.17	6.06	6.10	6.42
1:1 year	EA	5.29	5.31	5.33	5.44
HAT	ATT	4.90	5.00	4.87	5.37
HAT	EA	4.94	5.03	4.92	5.41
MHWS	ATT	4.00	4.10	4.07	4.47
MHWS	EA	4.02	4.10	4.07	4.47
MHW	ATT	3.05	3.15	3.22	3.52
MHWN	ATT	2.10	2.20	2.37	2.57
MSL	ATT	nd	nd	0.22	0.32
MLWN	ATT	-2.10	nd	-2.03	-1.73
MLW	ATT	-3.00	nd	-2.98	-2.78
MLWS	ATT	-3.90	nd	-3.93	-3.83
LAT	ATT	-4.90	nd	-4.93	-4.93
CD	ATT	-4.90	-4.90	-4.93	-4.93
MSR	ATT	7.90	nd	8.00	8.30
MNR	ATT	4.20	nd	4.40	4.30

Table 3. Extreme water levels on the Sefton Coast (chainage number 1180), calculated by the Environment Agency Coastal Boundary Study 2018 Update (Environment Agency, 2019) and projected to the years 2050 and 2100 by UKCP18 using RCP4.5 and RCP8.5 scenarios using the additional allowance (given in the final row of the table)

Return period (years)	present	RCP4.5 scenario 50th percentile		RCP8.5 scenario 70th percentile		RCP8.5 scenario 95th percentile	
		2050	2100	2050	2100	2050	2100
1	5.33	5.47	5.72	5.53	6.03	5.61	6.30
2	5.43	5.57	5.82	5.63	6.13	5.71	6.40
5	5.57	5.71	5.96	5.77	6.27	5.85	6.54
10	5.68	5.82	6.07	5.88	6.38	5.96	6.65
20	5.78	5.92	6.17	5.98	6.48	6.06	6.75
25	5.81	5.95	6.20	6.01	6.51	6.09	6.78
50	5.91	6.05	6.30	6.11	6.61	6.19	6.88
75	5.97	6.11	6.36	6.17	6.67	6.25	6.94
100	6.00	6.14	6.39	6.20	6.70	6.28	6.97
150	6.06	6.20	6.45	6.26	6.76	6.34	7.03
200	6.10	6.24	6.49	6.30	6.80	6.38	7.07
250	6.13	6.27	6.52	6.33	6.83	6.41	7.10
300	6.16	6.30	6.55	6.36	6.86	6.44	7.13
500	6.24	6.38	6.63	6.44	6.94	6.52	7.21
1000	6.34	6.48	6.73	6.54	7.04	6.62	7.31
10000	6.71	6.85	7.10	6.91	7.41	6.99	7.68
Additional allowance		0.14	0.39	0.20	0.70	0.28	0.97

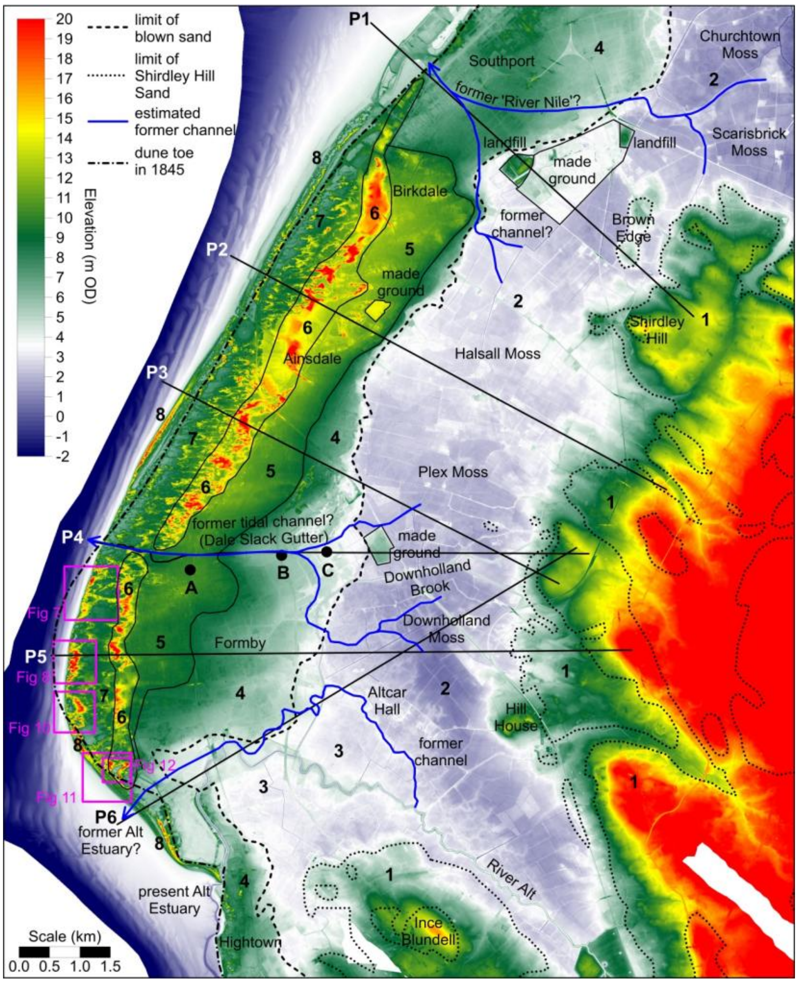

Figure 7. Composite LiDAR DTM of the Sefton coastal plain largely flown September 2018, showing extent of Quaternary deposits and possible positions of former channels

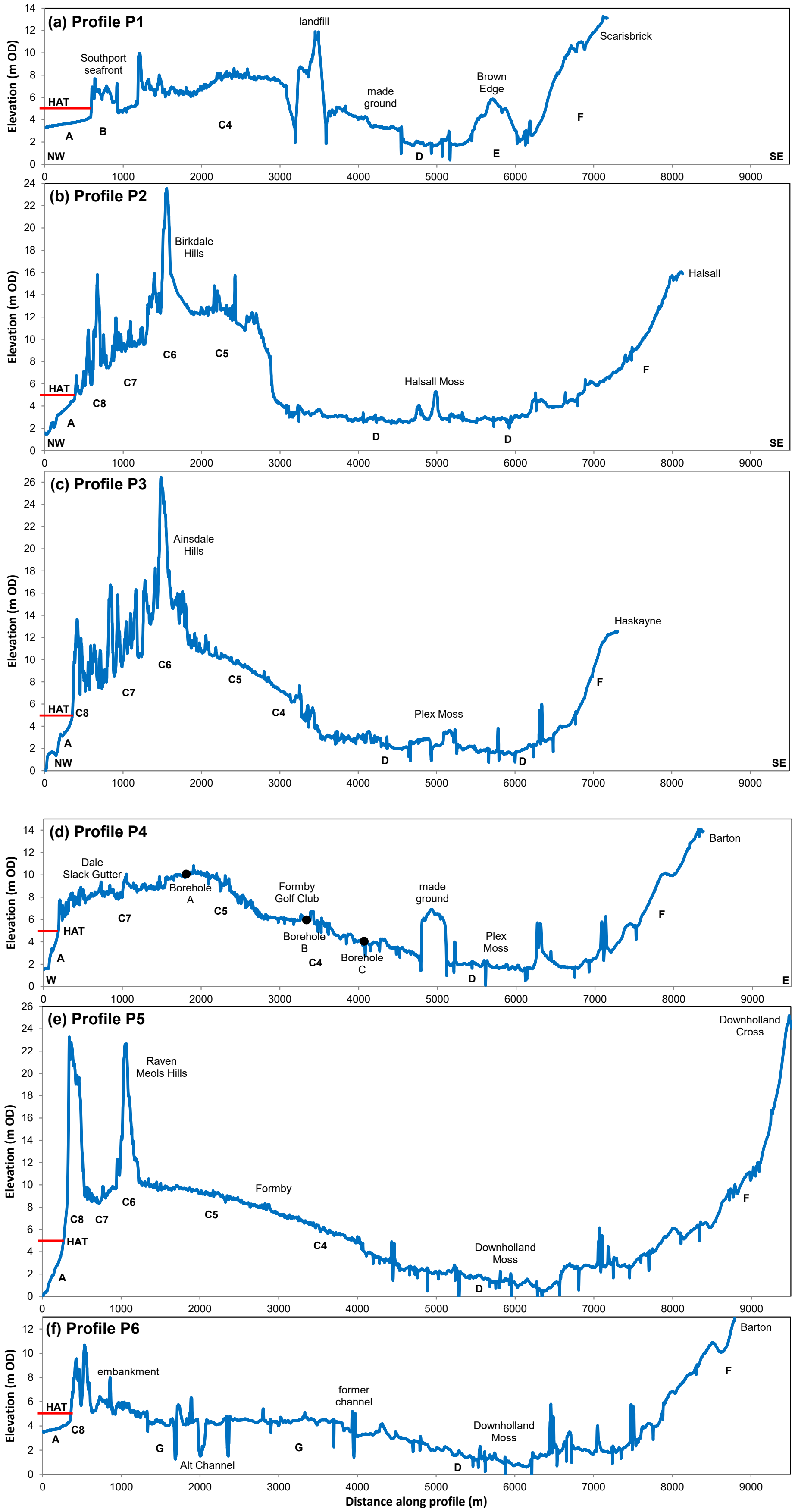

Figure 8. Topographic sections P1 to P6 taken across Figure 7

4.2 SMP Policy and Coastal Change

The Formby dune system lies with Shoreline Management Plan (SMP2) Policy Unit 9.1. The preferred management policy in all three policy epochs is Managed Realignment (Table 4). The whole of the dune area between Shore Road, Ainsdale and the River Alt has been defined as a Coastal Change Management Area (CCMA; Figure 9).

Table 4. Shoreline Management Plan policies in the short, medium and long-term for the Formby Dune System Policy Unit of the Sefton Coast

Policy Unit	0-20 yr	20-50 yr	50-100 yr	Comment
9.1 (Formby Dune System)	MR	MR	MR	Allow the dune system to evolve naturally with limited intervention to manage dunes, and manage adaptation in the erosion risk zone (such as relocating paths and car parks), subject to consents

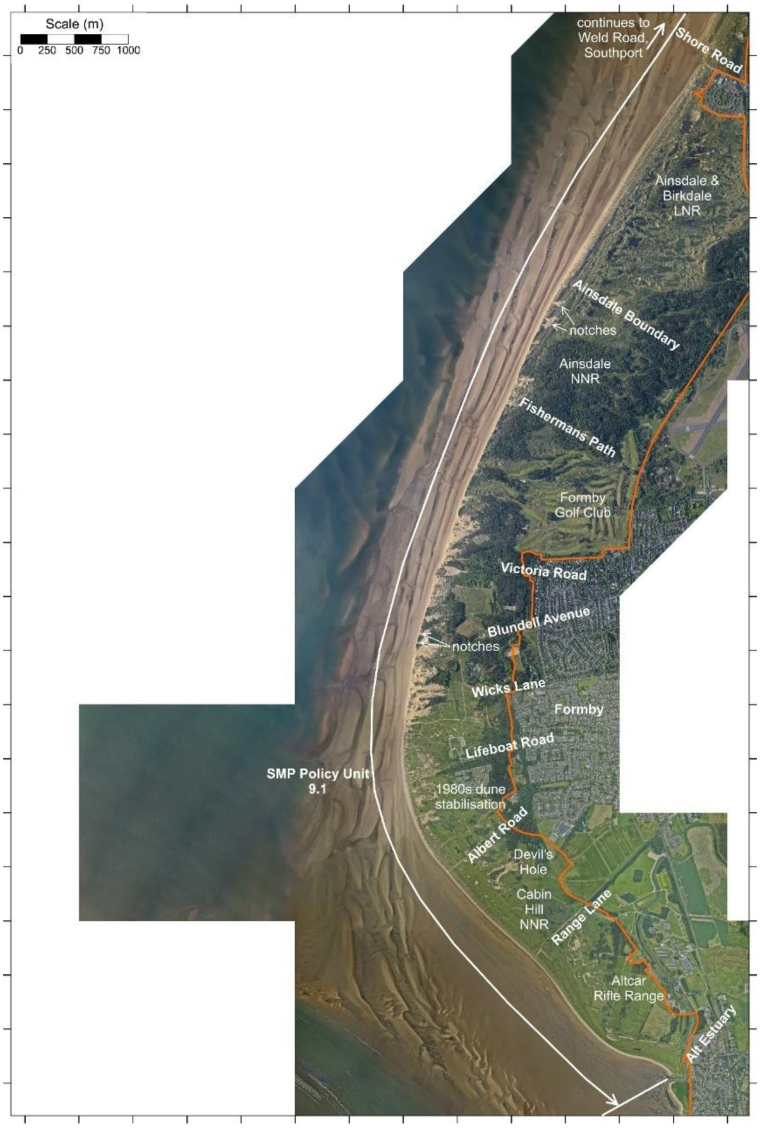

Figure 9. Aerial photograph flown 10/05/2024 showing the landward limit of the Coastal Change Management Area for Sefton Council with an orange line (the seaward extent not defined) and SMP Policy Unit 9.1 of Cell 11

4.3 Establishing a coastal dune physical condition baseline

Figure 10 is an enlargement of the 2024 LiDAR DTM for the River Alt to Shore Road section of the of the Sefton Coast which shows the general morphology of the dune belt. Along most of the coast (except south of Cabin Hill at Ravenmeols) two zones of relatively high dunes are present. The inner zone, which consists of interlinked transgressive parabolic dunes which were active until around the middle of the 19th century, forms the main flood defence for Formby and the West Lancashire Plain. The second zone occurs close to the beach. In the north, at Ainsdale, and to the south of Lifeboat Road the outer zone of high dunes takes the form of a relatively high frontal ridge which is either stable or slowly retreating. Between Fisherman's Path and Lifeboat Road the frontal dunes are heavily dissected by blowouts, active parabolic dunes and sand sheets. Some blowouts extend down to the top of the beach (see photographs in Appendix 3) and minor incursion by waves can occur during surge tides. These dunes form the first line of flood defence but are not of primary importance. To the south of Lifeboat Road the coast has been accreting for the past 40 years and a series of progradational foredune ridges lies seawards of a higher dune ridge which developed along a former erosional shoreline. The ridges extend southwards as far as a small promontory at Altcar Rifle Range. Only a single, relatively narrow, dune ridge is present in this area, backed by an artificially levelled sand plain on which the ranges have been built. This area once formed part of a wide estuary of the River Alt which was reclaimed between the late 18th and mid-19th centuries. The course of the Alt was diverted to the east and is now confined between flood banks, entering the sea near Hightown. Tidal gates prevent landward incursion of the sea towards the low ground south of Formby.

Figure 10 also shows two dune crest 'watershed' lines interpolated from the LiDAR DTM using *Surfer*. Between Shore Road and the Devil's Hole blowout at Ravenmeols two watershed lines can be defined. The Cabin Hill area to the south of the Devil's Hole was greatly impacted by sand mining in the 1960s and early 1970s. Concerns about the risk of a tidal breakthrough in this area led to the construction of a two-part flood embankment in 1975. Two watershed lines can be defined in this area, one running along the highest points of the frontal dunes and the other running along the crest of the flood embankment. Along the Rifle Range frontage only a single frontal dune watershed line is present. Elevation profiles along these 'watershed' lines are plotted in Figure 11. Along most of the length of the dune belt the inland dune ridge crest is relatively high, but it drops below 8 ODN around Wick's Lane, another area impacted by historical sand mining, and around Range Lane. Weak points are present in the Cabin Hill embankment where it is crossed by the Range Lane track and an adjacent track within the Military Training Area (see photographs in Appendix 3).

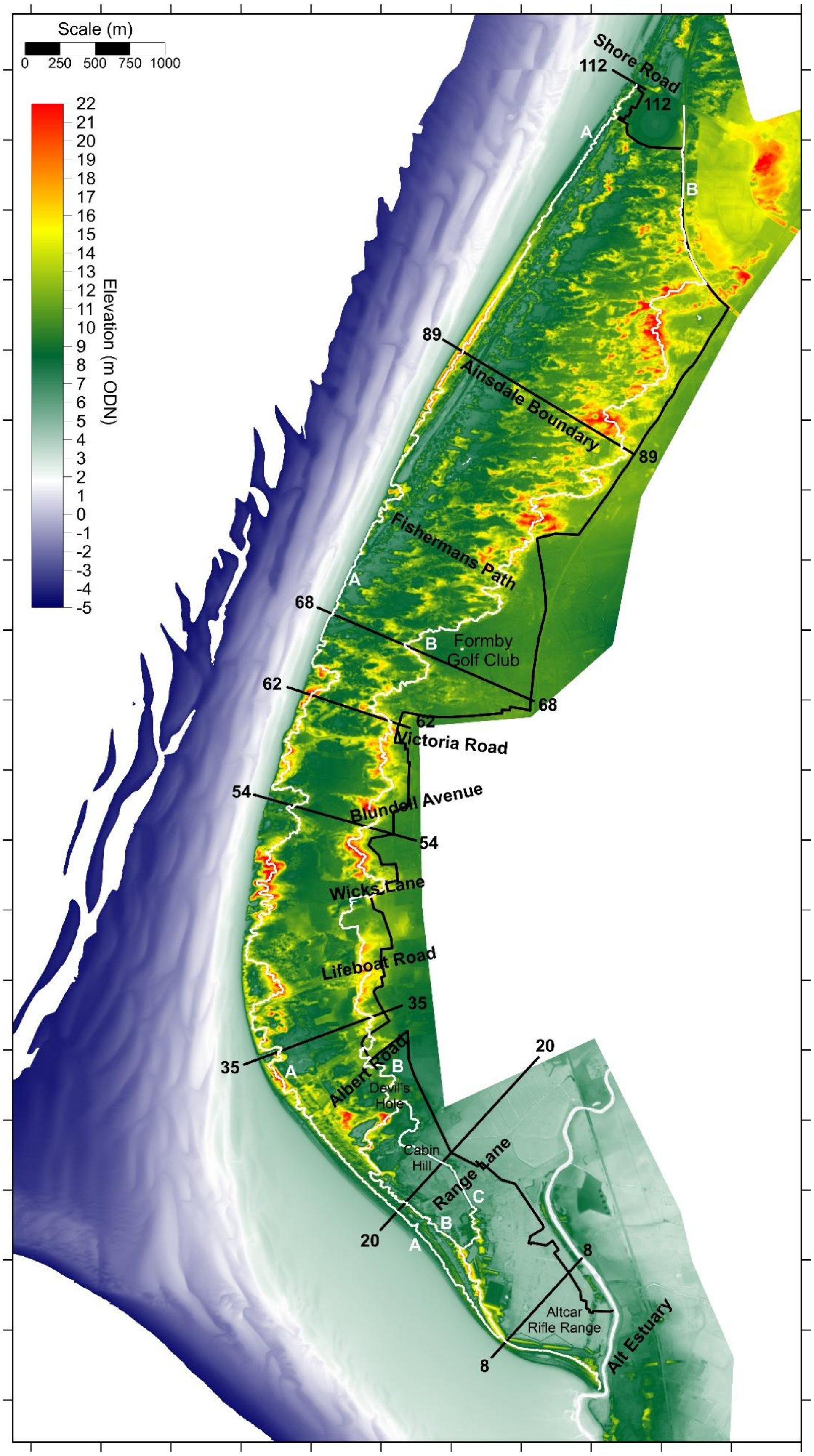

Figure 10. LiDAR DTM flown 19/09/2024. The white lines shows the watersheds along three lines: (A) the frontal dunes; (B) the inland dunes, via Devil's Hole in the south; (C) the same as (B) but via Cabin Hill embankments

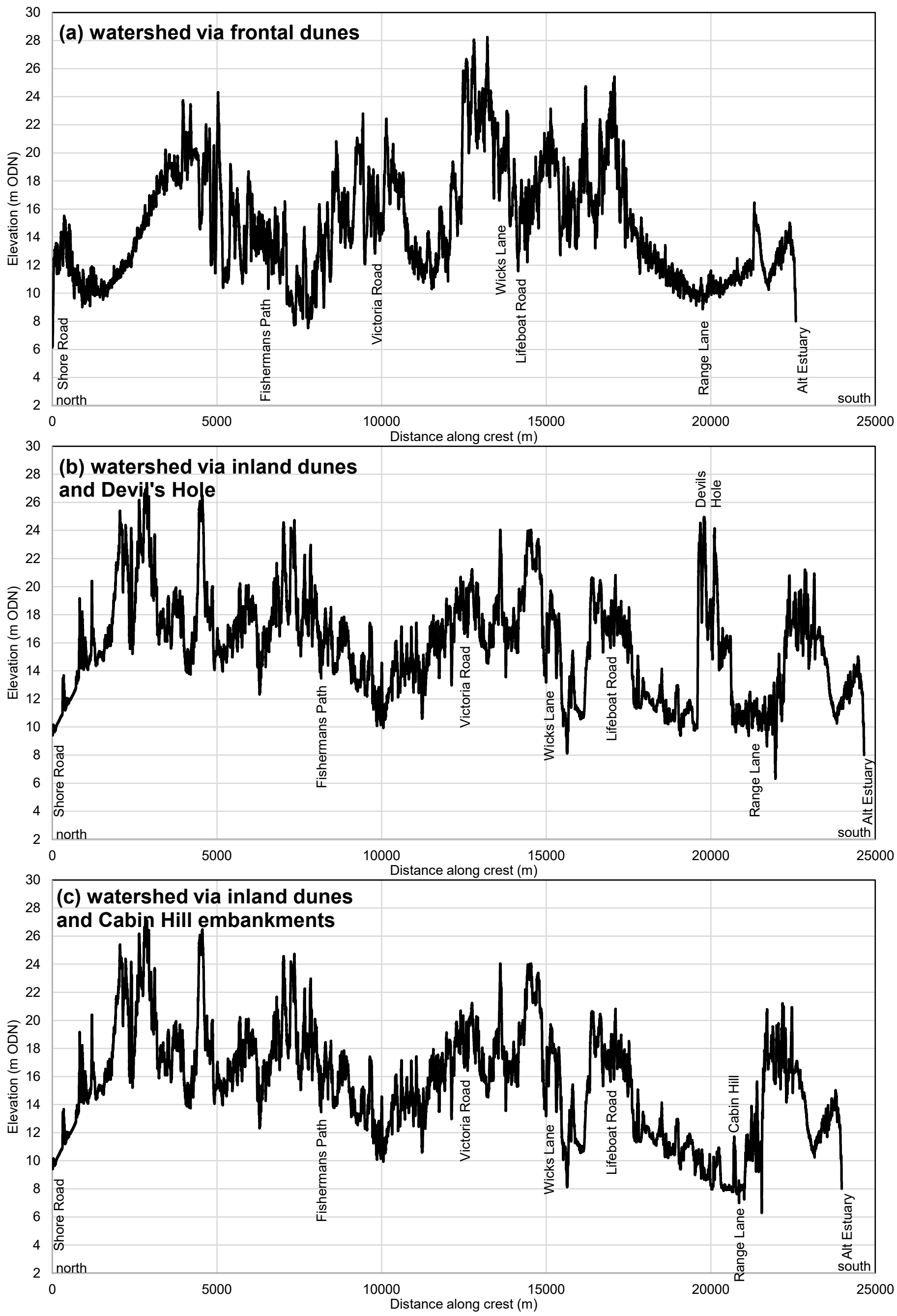

Figure 11. Topographic profiles along the three watersheds defined in Figure xx: (A) along the crest of frontal dunes B) the crest of the inland dunes, via Devil's Hole in the south; (C) the same as (B) but via Cabin Hill embankments. All are extracted from the LiDAR DTM flown 19/09/2024

In order to quantify alongshore variations in dune width, crest height and sand volume the 2024 LiDAR DTM was divided into 112 'cells', each 100 m wide at the seaward end and centred on a cross-sectional profile line (Figure 12). In this context the distance between the dune toe and the seaward limit of 'immovable' infrastructure is considered to be of central importance since it is assumed that, in the final resort, if the dunes were entirely eroded there would be a requirement to protect at least some of the infrastructure through construction of hard defences. For this reason an 'asset defence' baseline was prescribed and used to define the landward limit of each profile / cell, as shown in Figure 12. Each cell and profile line also has an intertidal extension which is not shown in Figure 12. For the purposes of method illustration, eight profiles have been selected to demonstrate variations in dune cross-sectional topography (Figures 13 & 14). The parameters determined for each profile / cell include:

- The linear distance between 5.3 m dune toe position and the seaward limit of defined 'immovable' infrastructure
- the maximum dune height along each profile
- the cross-sectional sand volume per metre width between the dune toe (at 5.3 m ODN) and the position of the most seaward 'immovable' infrastructure (road, railway, major building) e
- the rate of change in position of the 5.3 m contour in the period 2006 -2024 (positive indicates progradation and negative indicates erosional recession)
- the nature of any defences / dune management works along the toe of the dunes
- the existence or otherwise of any natural protective features (e.g. shingle berm) along the toe of the dune
- bare sand area (as % of the total area of each cell).

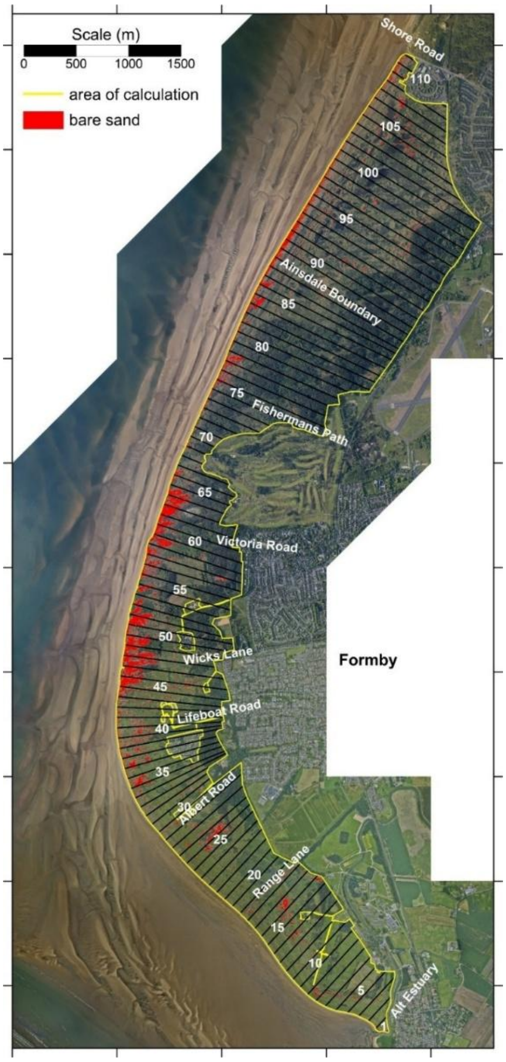

Figure 12. The 112 defined cells between the Alt Estuary and Shore Road, Ainsdale, superimposed on aerial photography flown July-September 2024. Source: National Network of Regional Coastal Monitoring Programmes (NNRCMP). Areas of bare sand quantified by GIS analysis are shown in red. The yellow lines indicate the areas within which areas of blown sand and bare, mobile sand have been calculated (note roads and features deemed to be 'immovable' infrastructure are excluded from the calculations)

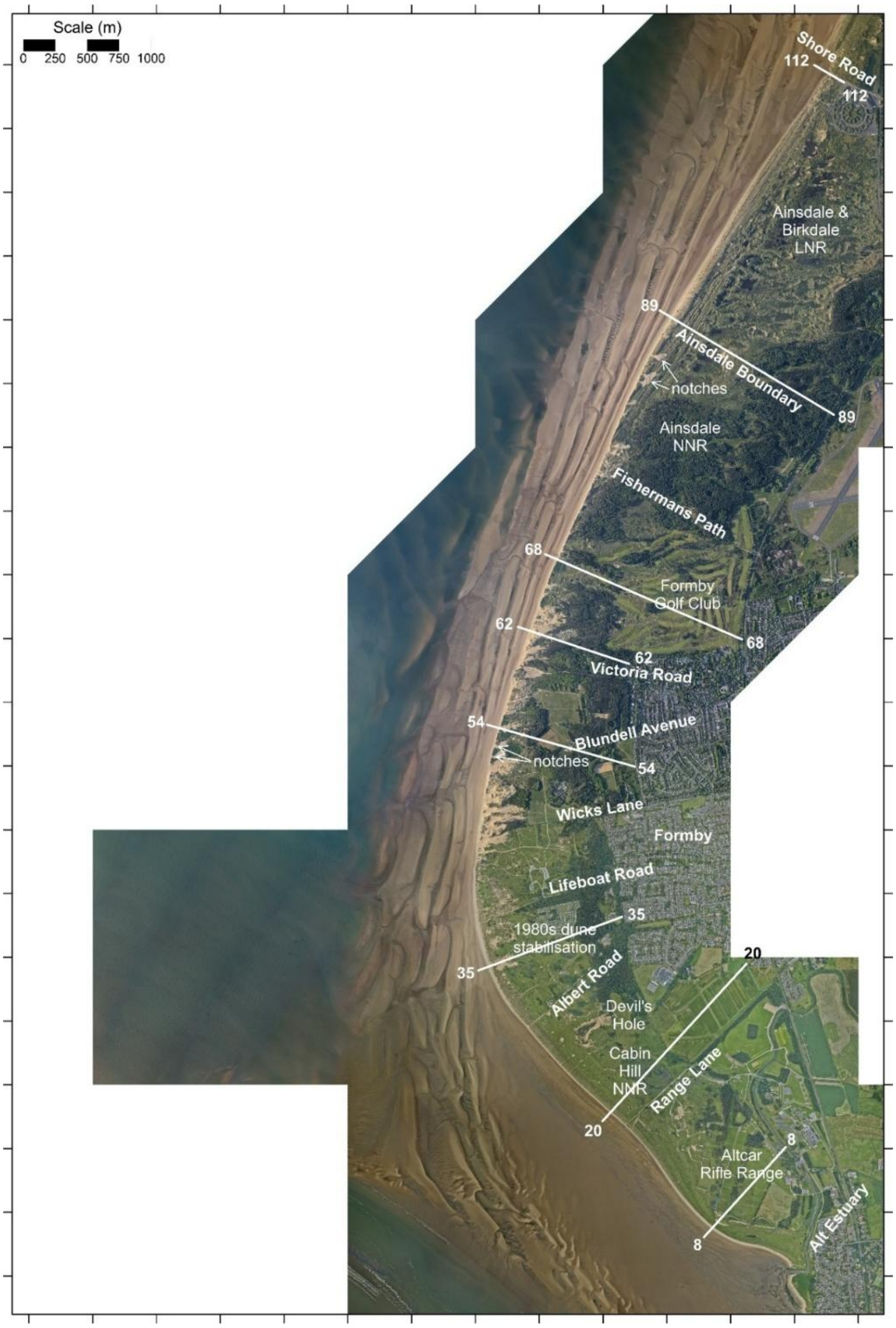

Figure 13. Location of cross-section profile lines selected for illustration in this report (base aerial photography flown 10/05/2024)

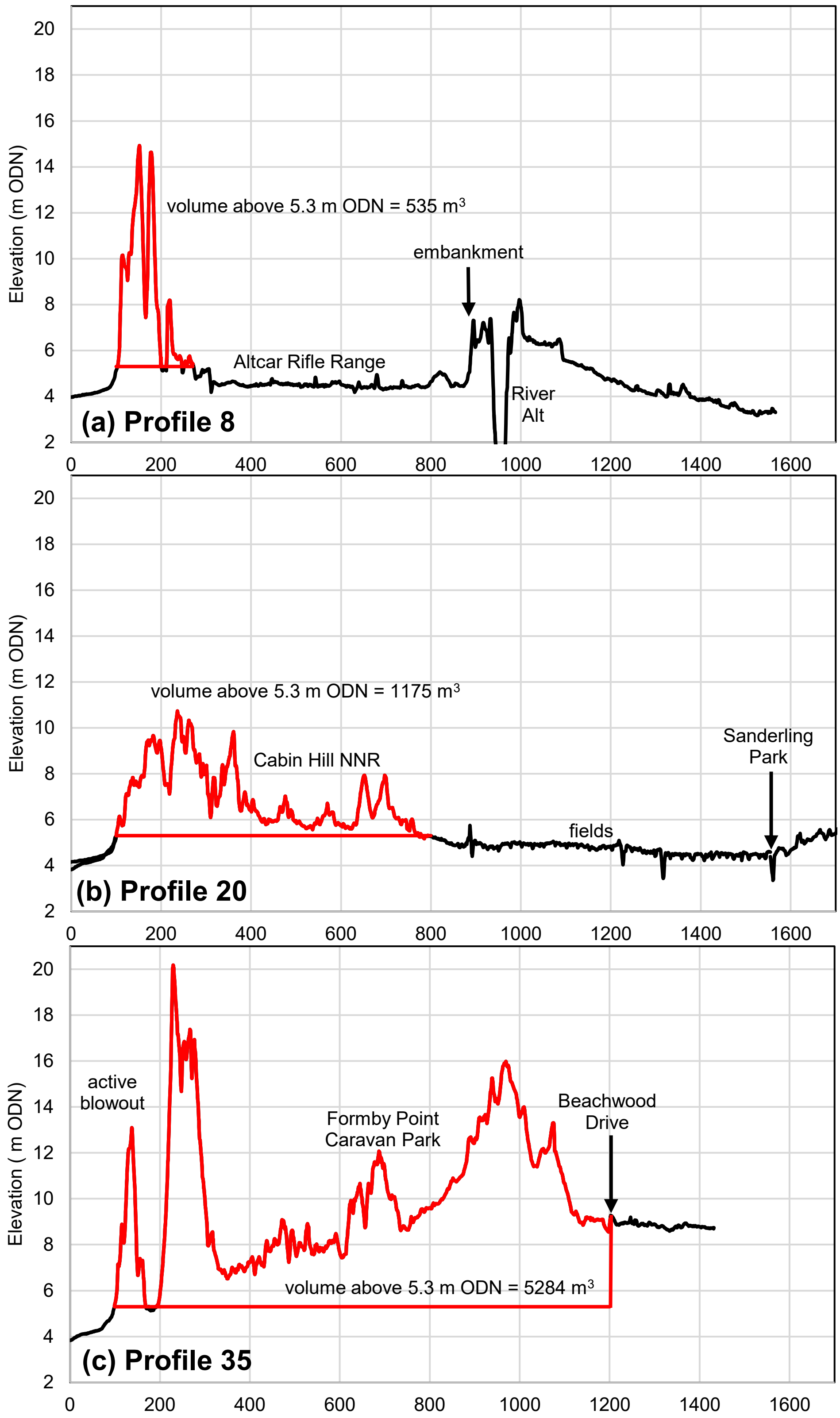

Figure 14. Selected topographic profiles across the dunes on the Sefton coast. Volumes (m^3 per m width) are given above the level of 5.30 m ODN (approximately the dune toe level, shown with a red line), taken from the LiDAR DTM flown 19/09/2024. Profile locations are shown on Figure 10

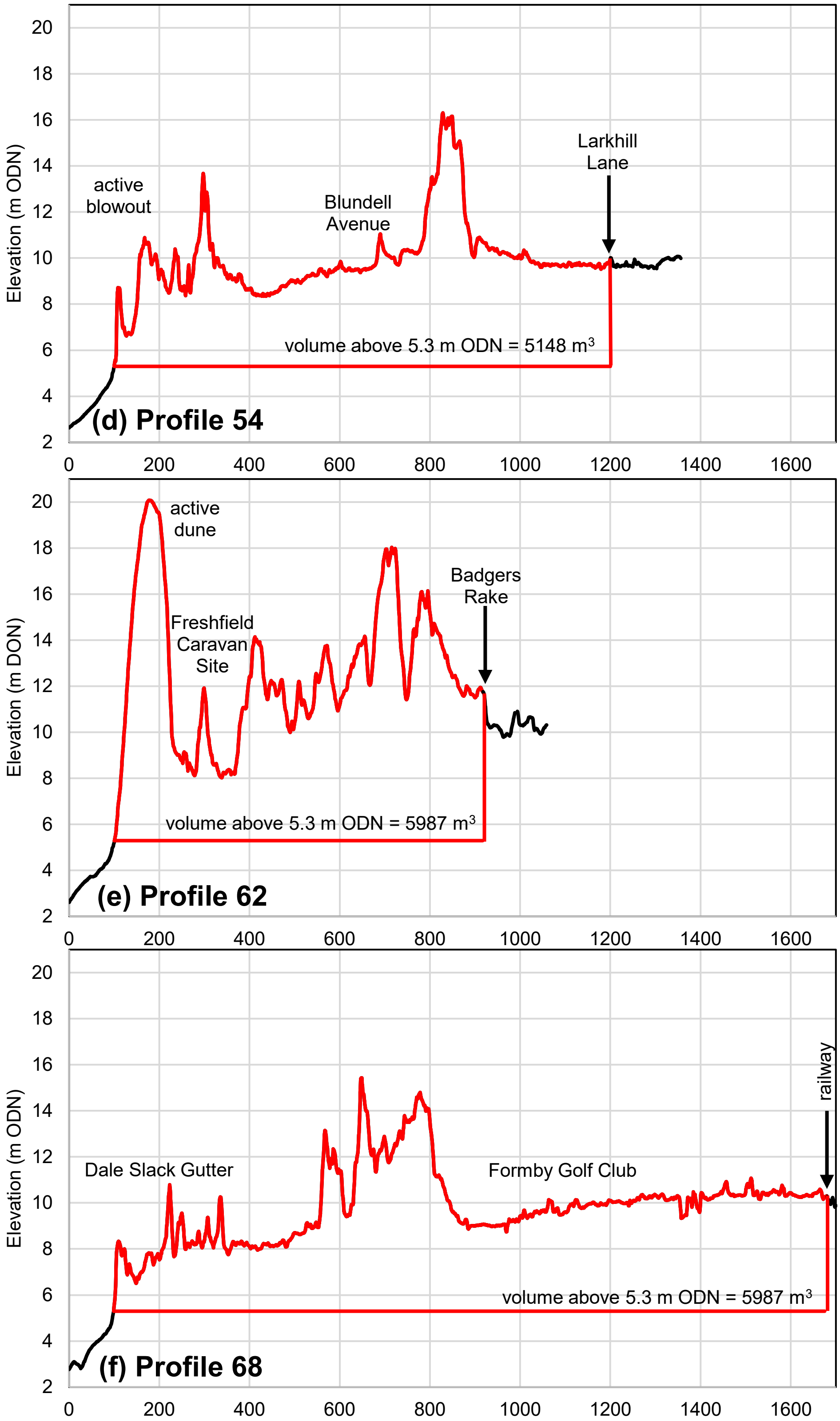

Figure 14. continued

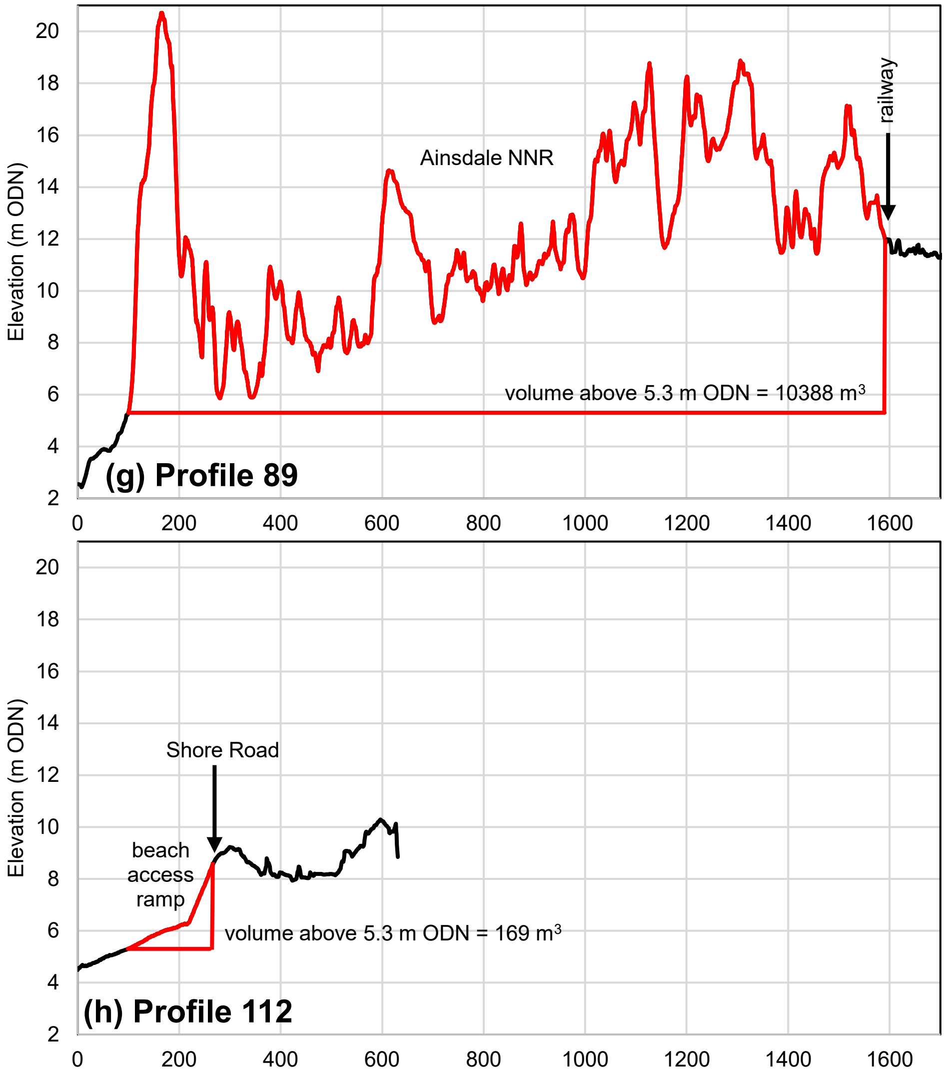

Figure 14. continued

As shown in Table 5, the width of the dune belt above 5.3 m ODN and seaward of the 'immovable' infrastructure varies considerably from 167 m at Altcar Rifle Range (profile P8) to >1581 m at Formby Golf Club (P68). However, by comparison with other sites in the UK, including St Anne's North Beach, most of the dune system is relatively wide. The maximum dune crest elevation varies from 10.5 m ODN at Range Lane (P20) to 20.6 m ODN at Ainsdale Boundary (P89). The volume of sand per metre width within the defined dune zone ranges from 169 m^3 at Shore Road, where the Coastal Road comes close to the coast near the former Pontins Holiday Village, to 10388 m^3 at Ainsdale Boundary. At profiles P68, P62 and P54 around Formby Point the dune toe receded landward between 2006 and 2024 at rates of 2.0 to 3.3 m/yr, while the position of the dune toe at the selected profiles to the north and south was either stable or showed seaward progradation. No natural or man-made defences are present along the dune toe at any of the example profile locations.

Table 5. Dune defence assessment parameters for selected profiles / cells along Formby shore, determined from LiDAR and aerial photography. Original data source: DEFRA Open Survey Data and Channel Coast Observatory

Location	Profile ID	Distance between seaward and landward 5.3 m ODN contours	Distance to infrastructure (m)	Max dune height (m ODN)	Volume per metre width above 5.3 m ODN (m^3)	Rate of change of 5.3 m OD contour per year 2006-2024 (m/yr)	Defences / management works present in front of dunes	Bare sand mobility Class for Cell	Natural shingle berm
Shore Road	112	>166	166	none	169	+2.3	none	1	none
Ainsdale Boundary	89	>1491	1491	20.6	10388	+0.2	none	1	none
Formby Golf Club	68	>1581	1581	15.4	7223	-2.0	none	1	none
Freshfield	62	>816	816	19.9	5987	-2.3	none	1	none
Blundell Ave. N	54	>1100	1100	16.2	5148	-3.3	none	1	none
Lifeboat Road S	35	>1103	1103	20.2	5284	+1.1	none	1	none
Range Lane	20	690	1456	10.5	1175	+1.8	none	1	none
Rifle Range	8	167	771	14.9	535	0.0	none	1	none

Based on the dune sand volume per metre width, the resilience of the defined dune 'protection zone' can be classified as being *Very Low (VL)* to *Very High (VH)* and the / direction rate of change in position of the dune toe can be classified as ranging from *Rapidly Prograding* to *Rapidly Eroding* (Table 6). (Note that the total volume of sand within each 100 m wide cell can also be calculated from the LiDAR DTMs, although data are not presented here). Based on a combination of these two attributes *Dune Defence Condition* can be classified, ranging from Class 1 (*Very High*) to Class 5 (*Very Low*), as shown in Table 7. Dune system sand volume is the most important determinant of Coastal Defence Condition Class. A very large volume (> 5000 m^3/m^{-1}) combined with rapid progradation (> 2 m / yr, averaged over at least 10 years) provides the most favourable condition, but erosion of the dune toe at rates (< 2 m/yr) need not give rise to concern in wide, high volume dune systems unless significant infrastructure / assets are located within 200 m of the dune toe (i.e. likely to be affected by erosion or mobile dunes within 50 years). However, rapid rates of erosion, in excess of 2 m/yr, should be matters of concern in the medium term in dune systems which have volumes of < 5000 m^3 / m^{-1}, and/ or widths of < 200 m.

A full dune system condition assessment should consider data for all of the dune cells specified along a given frontage. As noted above, the condition of a dune defence, like any other form of defence, is governed by the weakest link. Gaps in a dune barrier, in the form of natural blowouts, tracks or other low points, create potential lines of weakness which need to be identified and remedial works undertaken. Depending on context, it may be most appropriate to raise low points in the frontal dunes, where they from the primary defence, and/ or low points in the inland dunes where there is a need to build a stronger secondary line of defence.

Table 6. Classes of dune volume per metre width and erosion/accretion rates used in determining the overall dune defence assessment.

Volume per metre width above 5.3 m ODN		Rate of change of 5.3 m OD contour per year	
(m^3)	Resilience class	(m/yr)	Dune toe stability class
0 to 100	5 -Very low (VL)	> +2.0	1 - Rapidly prograding (RP)
100 to 500	4 - Low (L)	+0.5 to +2.0	2 - Gradually prograding (GP)
500 to 2000	3 - Moderate (M)	+0.5 to -0.5	3 - Stable / low rates of change (S)
2000 to 5000	2 - High (H)	-0.5 to -2.0	4 - Gradually eroding (GE)
>5000	1 - Very high (VH)	> -2.0	5 -Rapidly eroding (RE)

Table 7. Dune Defence Condition Class based on the combination of dune volume and erosion/accretion rate

Dune volume		Rapid progradation (RP)	Gradual progradation (GP)	Stable / low rates (S)	Gradual erosion (GE)	Rapid erosion (RE)
		Erosion/accretion rate				
	Very high (VH)	1	1	1	1	2
	High (H)	1	1	1	2	2
	Moderate (M)	2	2	2	3	3
	Low (L)	3	3	3	4	4
	Very low (L)	4	4	5	5	5

The overall Dune Defence Condition Class for the eight example profiles are shown in Table 8. Class 1 = *Very Good*, no concerns, Class 2 = *Good*, no major concerns, Class 3 – *Fair*, requiring minor interventions only, Class 4 = *Poor*, requiring significant remedial intervention measures, Class 5 = *Very Poor,* requiring major works.

Table 8. Dune Defence Condition Grade for selected profiles along the Formby coast

Location	Profile ID	Volume per metre width above 5.3 m ODN Class	Rate of change of 5.3 m OD contour per year 2006-2024 Class	Dune Defence Condition Class
Shore Road	112	4	1	3
Ainsdale Boundary	89	1	3	1
Formby Golf Club	68	1	5	2
Freshfield	62	1	5	2
Blundell Ave. N	54	1	5	2
Lifeboat Road S	35	1	2	1
Range Lane	20	3	2	2
Altcar Rifle Range	8	3	3	2

4.4 Bare sand area and sand mobility assessment

The extent of bare sand within each of the 112 cells at Formby, determined by GIS analysis of the 2024 aerial photography, is shown in Table 9. Values are generally < 10% with the exceptions of cells 61 – 64 north of Victoria Road, Freshfield, and cells 45-52 near Wicks Lane and Blundell Avenue, Formby. Bare sand extent can be classified on a scale of 1 to 5, where Class 1 (*Minor*) corresponds with 0 - 20% bare sand, Class 2 (*Moderate*) = 20 - 40%, Class 3 (*High*) = 40 - 60%, Class 4 (*Very High*) = 60 - 80%, Class 5 (*Essentially Unvegetated*) = 80 - 100%). The distribution of bare sand within each cell (located mostly at the seaward ends), is shown in Figure 12. The cells with the greatest bare sand extent (>5000 m^2) are almost all located around Formby Point, the section of coast with the highest rates of coastal erosion and very high visitor pressure. However, the percentage of bare sand (relative to the total blown sand area seaward of the immovable infrastructure limit) does not exceed 20% in any of the defined cells. Considered as a whole, all cells therefore have a *Potential Sand Mobility Class* of 1 (Minor).

Although mobile dunes and sand sheets are advancing inland at rates of 1 - 3 m/yr to the north of Victoria Road and in the Blundell Avenue to Wicks Lane area, they are not currently close to threatening any detached elements of 'immovable' infrastructure, such as the St Joseph's Care Home (see photographs in Appendix 3). However, inland movement of dunes and sand sheets has previously, and continues, to pose a threat to elements of 'moveable' infrastructure. These include the Freshfield Caravan Park, the seaward part of Formby Golf Club and the National Trust's Victoria Road car park which is in the process of being relocated landward.

Table 9. Bare sand extent with defined cells at Formby, calculated from aerial photography flown July-September 2024. Aerial photography Source: Channel Coastal Observatory

	Cell No.	Bare sand area (m^2)	Blown sand area (m^2)	Percentage bare sand (%)	Bare sand Class
Shore Road	112	118	2071	6	1
	111	1102	16749	7	1
	110	1802	16996	11	1
	109	1341	34672	4	1
	108	1686	72004	2	1
	107	1949	79344	2	1
	106	1926	85900	2	1
	105	2322	94445	2	1
	104	3554	100037	4	1
	103	1327	100348	1	1
	102	1189	107354	1	1
	101	1161	121124	1	1
	100	1510	128722	1	1
	99	2343	133354	2	1
	98	3130	141113	2	1
	97	2911	146307	2	1
	96	4012	148686	3	1
	95	3619	148126	2	1
	94	3481	150128	2	1
	93	3115	148228	2	1
	92	4937	148428	3	1
	91	4823	149120	3	1
	90	4755	144632	3	1
	89	4218	131812	3	1
Ainsdale Boundary	88	4127	132647	3	1
	87	2880	134314	2	1
	86	4880	110422	4	1
	85	1946	125704	2	1
	84	5862	144154	4	1
	83	3171	134499	2	1
	82	2071	124458	2	1
	81	1689	130307	1	1
	80	1414	130570	1	1
	79	1156	115538	1	1
	78	5304	112727	5	1
	77	3597	108609	3	1
	76	3610	110892	3	1
Fisherman's Path	75	2174	114393	2	1
	74	1235	72997	2	1
	73	1254	61863	2	1
	72	915	49741	2	1
	71	725	35390	2	1
	70	1023	27523	4	1
	69	1067	24519	4	1
	68	722	21312	3	1
	67	662	32647	2	1
	66	2481	56419	4	1
	65	1878	57867	3	1
	64	9165	55523	17	1
	63	10729	56835	19	1
	62	10663	72432	15	1
	61	7322	76204	10	1
	60	5987	86595	7	1
Victoria Road	59	9878	92047	11	1
	58	5387	86378	6	1
	57	5686	85670	7	1
	56	3899	92792	4	1
	55	2771	88014	3	1
	54	4224	78844	5	1
	53	3252	76038	4	1
	52	7236	73870	10	1
	51	11605	67629	17	1
	50	3915	76394	5	1
	49	12506	77963	16	1
	48	13816	83732	16	1
Wicks Lane	47	13471	92450	15	1

Table 9. continued

	Cell No.	Bare sand area (m^2)	Blown sand area (m^2)	Percentage bare sand (%)	Bare sand Class
Wicks Lane	46	10939	98497	11	1
	45	12797	101776	13	1
	44	5244	83302	6	1
	43	2053	66983	3	1
	42	2130	74014	3	1
	41	2375	68681	3	1
	40	3735	66135	6	1
	39	3232	54192	6	1
Lifeboat Road	38	3481	52229	7	1
	37	4407	50625	9	1
	36	1409	56976	2	1
	35	5234	67255	8	1
	34	2476	59500	4	1
	33	747	62186	1	1
	32	960	51876	2	1
	31	718	54270	1	1
	30	455	57335	1	1
Albert Road	29	1303	84372	2	1
	28	781	90543	1	1
	27	1363	88228	2	1
	26	5405	72901	7	1
	25	2054	68176	3	1
	24	350	76329	0	1
	23	161	71608	0	1
	22	163	69003	0	1
	21	4	68405	0	1
	20	17	64633	0	1
	19	39	66242	0	1
Range Lane	18	2287	70816	3	1
	17	956	74618	1	1
	16	4098	75889	5	1
	15	2383	81022	3	1
	14	834	76178	1	1
	13	1774	79198	2	1
	12	569	78138	1	1
	11	638	67818	1	1
	10	574	75509	1	1
	9	669	72063	1	1
	8	1724	70068	2	1
	7	1323	66543	2	1
	6	929	59058	2	1
	5	1067	52093	2	1
	4	685	53947	1	1
	3	815	39168	2	1
	2	691	22774	3	1
Alt Estuary	1	445	9454	5	1
Totals for cells 1-112:	0	356178	9209245	4	1

4.5 Future coastal change

The dune condition assessments discussed in this report relates to the present climate and sea level but projections made by the UK Climate Programme (UKCP) suggest significant changes in the coming decades. Figure 15 shows projected future mean sea levels at Formby under three atmospheric emissions scenarios modelled by UKCP and Table 3 shows projected changes in extreme still water levels for the Formby area provided in the UK Coastal Boundary Update Study (EA, 2019). There may also be changes in wave climate and storminess although modelling projections currently have a very high degree of uncertainty.

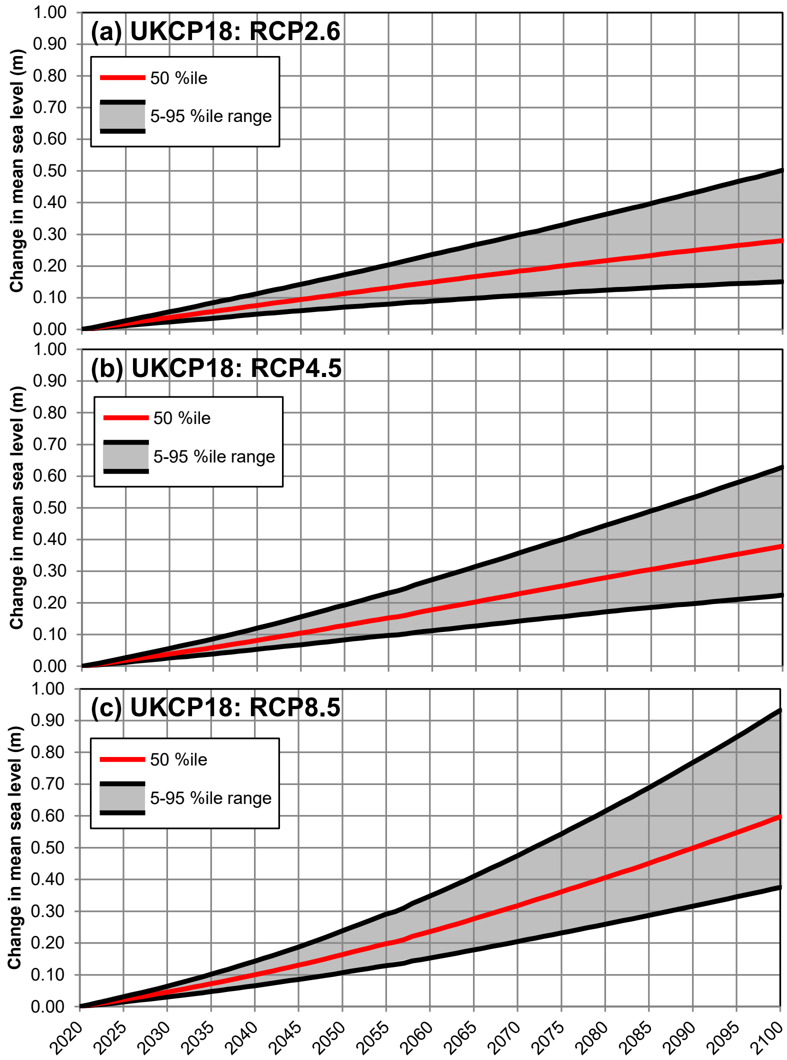

Figure 15. UKCP projections of change in mean sea level at Formby under three different greenhouse gas emission scenarios

In general, rising sea levels and deeper nearshore water may be expected to result in an increase in nearshore wave height, and the tow combined are likely to result in increased rates of beach and frontal dune areas on exposed sections of coast from which eroded sand is removed either offshore or alongshore (e.g. around Formby Point). However, on sections of coast which maintain a positive sediment budget due to onshore and/ or alongshore transport, such as at Birkdale and south of Formby Point, beach levels may keep pace with sea level rise and the dune toe position may remain stable or even continue to prograde, at least in the medium term. Figures 16 & 17 show projected future positions of the dune toe line around the northern and southern parts of Formby Point up to 2125 under a 'reasonable worst case' scenario, taking into account the coastal processes and sediment transport regime operating in the area (Pye & Blott, 2020). It is anticipated that the northern limit of erosion will move northwards over time but remain relatively unchanged in the south. It is highly likely that transgressive dunes will continue to move inland along the eroding dune frontage if large-scale stabilization works are not undertaken (Figure 18).

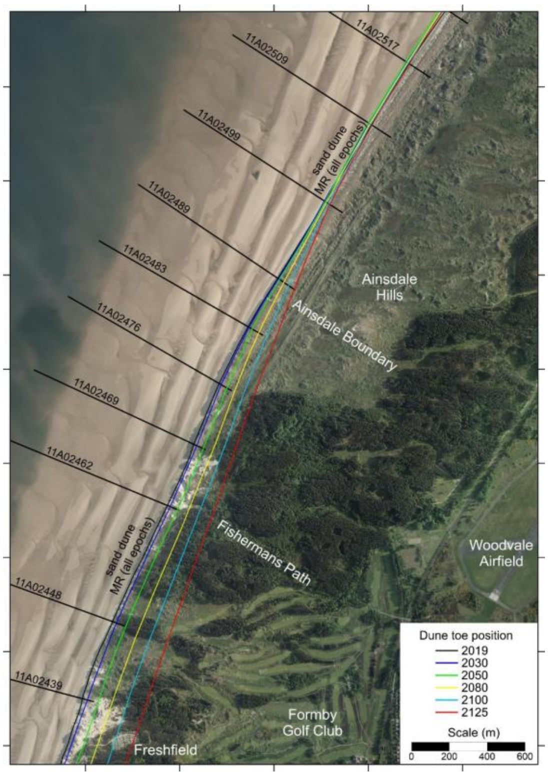

Figure 16. Projected position of the 'dune toe' level at selected dates in the future, based on Expert Geomorphological Assessment for a 'reasonable worst-case' scenario. Base aerial photography 17th May 2018 – Area 4, Formby North to Ainsdale (reproduced from Pye & Blott, 2020)

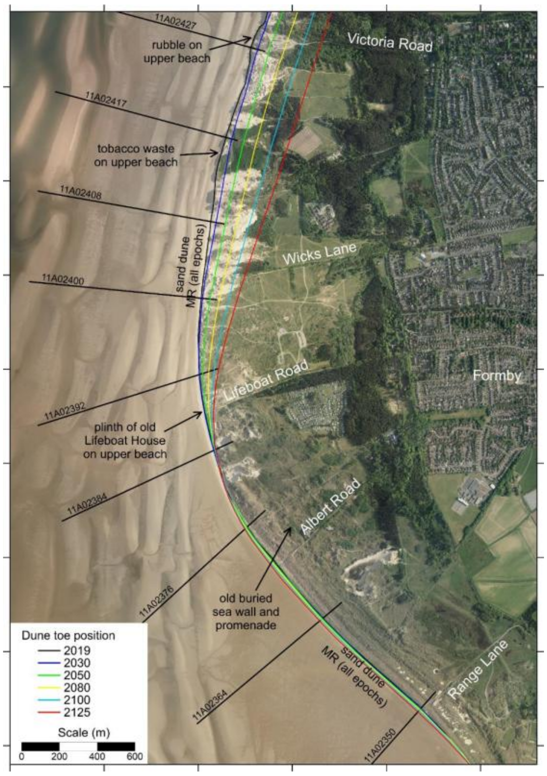

Figure 17. Projected position of the 'dune toe' level at selected dates in the future, based on Expert Geomorphological Assessment for a 'reasonable worst-case' scenario. Base aerial photography 17th May 2018 – Area 5, Formby South (reproduced from Pye & Blott, 2020)

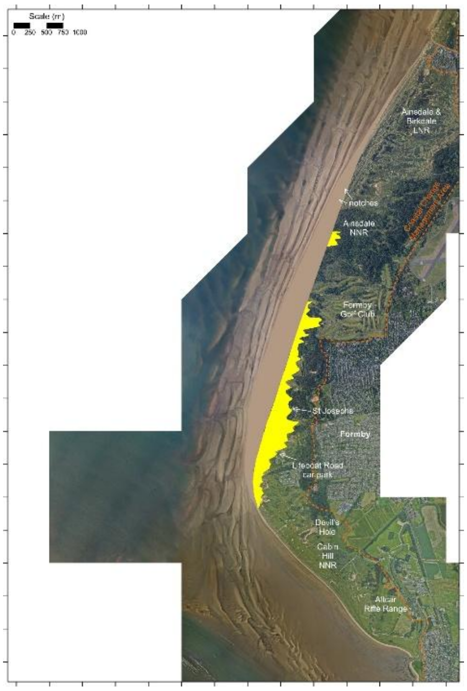

Figure 18. Projection of how the Formby coast might look in 2125 under a 'likely worst case' scenario (mobile blown sand shown in yellow)

Under a high emissions scenario, which is looking increasingly likely, mean sea level may rise by up to a metre by 2125. The elevation of the dune toe will also rise above its present level of 5.3 m ODN, potentially reaching 6.3 m ODN by 2125. There will be corresponding changes in frontal dune position and morphology. For this reason, revised frontal dune condition assessments, including determination of frontal dune height, width and sand volume, relative to changing tidal levels, should to be undertaken at intervals (suggested every 10 years).

4.6 Buffer zones and trigger points for intervention / adaptation

4.6.1 Dune ecological and coastal defence buffer zones

The sand dune habitats of the Sefton coast are some of the most significant in the country from a nature conservation point of view and it has been recognised that there is a need to maintain ecological connectivity along the coast to ensure that sub-populations of species such as Natterjack Toad (*Epidalea calami*ta) and Sand Lizard (*Lacerta agilis*) are able to migrate and interact in order to maintain reproductive viability. To achieve this, it has been proposed that an ecological buffer zone at least 200 m wide, free of obstacles such as car parks, buildings and coniferous woodland, needs to be maintained behind the seaward limit of the dunes. Within this zone there should be flexibility for natural processes to operate, including the development of blowouts and mobile dunes / sand sheets and slacks. However, there is also a requirement to ensure that mobile sand does not move inland sufficiently far or quickly to pose a threat to 'immovable' infrastructure.

4.6.2 Dune toe monitoring and intervention trigger points

As parts of the coast are rapidly changing there is a requirement for monitoring of the following:

- dune toe position (defined here as the 5.3 m ODN contour)
- the distance between the dune toe and the landward limit of the ecological buffer zone (seaward limit of semi-mobile dunes)
- the landward position of mobile sand features
- the distance between the seaward edge of 'immovable' assets and the landward limit of the ecological buffer zone and landward limit of bare sand
- bare sand area
- volume of sand within the frontal dune buffer zone

From a flood and coastal erosion risk management point of view a priority should be to monitor sections of the frontal dunes which are relatively narrow and low. This should include the condition of artificial structures which would provide flood protection in the event of erosional damage or loss of the frontal dunes. This includes the artificial flood bank, constructed in the mid-1970s, behind the area of former sand mining at Cabin Hill National Nature Reserve and northern end of Altcar Rifle Range (see photographs in Appendix 3). While there is presently a low risk of marine flooding due to a breakthrough in this area, it could be potentially vulnerable if conditions change (e.g. an unrepaired major failure of the Mersey training walls) leading to the re-establishment of the former Formby Channel).

This report is not intended to be prescriptive about which assets might be regarded as high value or worth defending. That issue would require discussion between the asset owners, the Local Planning Authority and other regulatory bodies. However, there are some assets within, and/or just beyond, 200 m of the present dune toe between Shore Road and the River Alt, the loss of which (due to erosion, frequent tidal flooding or mobile sand invasion) would result in negative economic and / or operational consequences. These include the buildings to the south of Shore Road, the seaward part of Formby Golf Club, the Joseph's Care Home, the Lifeboat Road car park, properties at the seaward end of Albert Road, and the seaward parts of the Altcar Rifle Range. Any change towards erosion, or an increase in erosion rate, in these areas would be of concern.

In most circumstances it is inappropriate to specify a single dune toe retreat distance or rate of change as a trigger point for an entire coastal frontage since erosional loss of 20 m of dunes in an area where the dune belt is >500 m wide is likely to be insignificant but where the dune belt is narrow a loss of that magnitude could present a critical threat. This is also true in terms of trigger points for interventions to control the inland movement of mobile dunes or sand sheets. A better approach is to define a critical distance seaward from a high value asset, or to define a minimum dune width or buffer zone width which may be maintained while the actual dune position changes. A staged approach can be helpful in this respect, whereby a series of trigger points / lines are defined.

Having established a line which defines the seaward position of high value 'immovable' assets, which it might well be necessary to defend, it is advisable to define a 30 m wide zone to seaward within which any hard defences could be constructed (e.g. Figure 19). For flood defence purposes it would also be desirable to maintain a zone of dunes at least 70 m wide to seaward of the defences to act as a buffer zone against wave attack. This is represented by the orange line located 100 m seaward of the asset boundary line shown on Figure 19. From an ecological perspective it is desirable to main a buffer zone of dune habitat at least 200 m wide to seaward of the new defences. This is represented by the green line shown on Figure 19, from which it is evident that the development complex at Shore Road (Discovery Centre, the unoccupied former Toad Hall Night Club, former guesthouses and the recently close Holiday Village) already presents a barrier which substantially disrupts ecological connectivity between the Ainsdale and Birkdale dune systems.

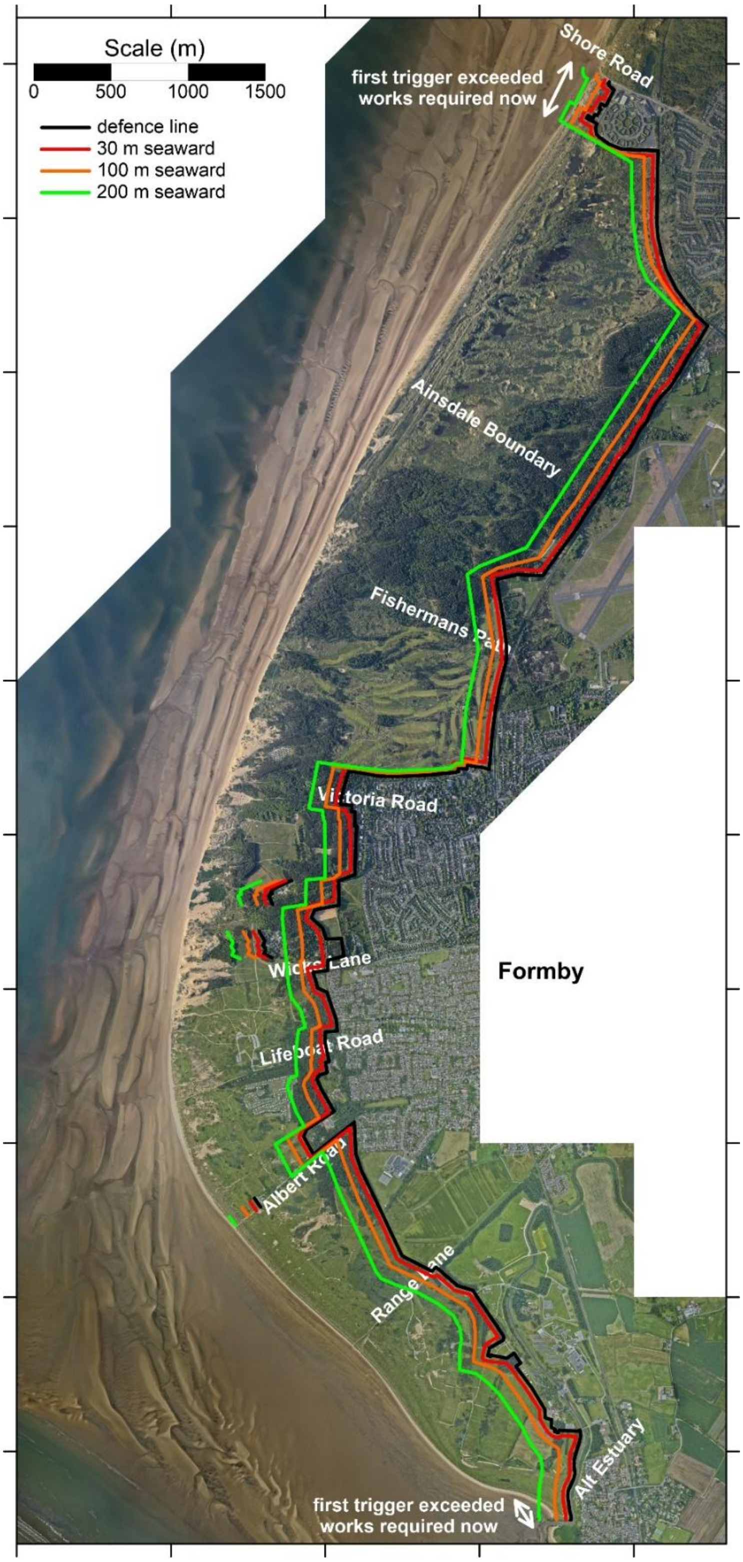

Figure 19. Proposed intervention trigger lines at Formby, with the current main defence line shown in black, and isolated defence lines at properties on Albert Road, St Joseph's Care Home and Countryside Centre. Also, trigger lines 30, 100 and 200 metres to seaward of the defence line.

4.6.3 Beach monitoring as a means of early warning

Early warning of changes in erosion / progradation conditions at the dune toe can be provided by monitoring of changes in the intertidal beach (and indeed also the sub-tidal area). This can also be cost-effectively achieved through analysis of the airborne LiDAR data, supplemented when / where necessary by annual/ biennial terrestrial RTK-GNSS surveys and five-yearly nearshore bathymetric surveys.

Table 10 provides a summary of changes in the position of selected beach contours at the eight example profiles in the period 2010 – 2024, based on LiDAR analysis. Full data for all 112 profiles are provided in Appendix 5.

Table 10. Change (m) in selected tidal contour positions between 2010 and 2024, based on LiDAR analysis. NB. Not all surveys extend down to the MLWS so data for that contour level are not presented

Profile No.	Location	HAT	MHWS	MHWN	MLWN
112	Shore Road	34	41	66	-7
89	Ainsdale boundary	3	5	-7	5
68	Formby Golf Club	-24	-17	-2	-64
62	Victoria Road	-34	-29	-24	0
54	Blundell Avenue	-48	-40	-63	-64
35	Lifeboat Road South	17	58	6	-1931
20	Range Lane	25	55	-9	29
8	Altcar Rifle Range	-1	38	-37	-31

Interpretation of the data shown in Table 10 and Appendix 6 needs to take account the dynamic nature of features such as intertidal ridges and runnels, or larger intertidal banks and channels, can produce changes of several metres to tens of metres on inter-annual to decadal timescales. For example, the relatively small retreat of the MHWN contour at Formby Golf |Club, and of the MLWN contour at Victoria Road, reflect the build-up of a low amplitude upper foreshore 'bank' in this area following the stormy winter of 2023-14. Likewise, the apparently large movement of the MLWN contour at Lifeboat Road South relates to the movement of the shallow channel behind Taylor's Bank.

4.7 Possible intervention and adaptation measures

While large-scale coastal defence works along the Formby shoreline are unlikely to be needed, or be economically and environmentally justifiable, in the foreseeable future (i.e. up to 2125), monitoring of beach contours, dune toe position and inland limit of blown sand will provide early warning of significant changes affecting the dune defence at particular locations, and allow intervention measures to be implemented and/or plans for adaptation to be drawn up, if and when the time comes.

Owing to the large width and large sand volume present within the Formby dune system erosion / further erosion of 100 m would not present a major coastal defence issue except perhaps around Shore Road and at the Altcar Military Training Area. At Shore Road the upper beach contour have been moving seaward for the past several decades, so there is low likelihood of a change to frontal dune erosion in the short to medium term. However, At Altcar Rifle Range the MHWN and MLWN contours have shown a tendency for landward movement in the past 15 years and there have been episodes od frontal dune erosion during storms. Further detailed monitoring of this area is required to assess the need for possible intervention or adaptation measures, which could range from dune fencing on the upper beach, sediment-filled geotextile bag or gabion wall construction, to landward relocation of the assets most at risk.

The inland spread of mobile dunes and sand sheets by more than 200 m could create problems if it occurs along the frontage between Fisherman's Path and Alexandra Road (which includes Formby Golf Club, the National Trust Countryside Centre, St Joseph's Care Home, Lifeboat Road Car Park, and Formby Caravan Park, some or all of which might need to be partially or wholly relocated). For this frontage it is therefore suggested that a trigger point for sand stabilization works should be defined if mobile sand advances to within 100 m of identified assets. Possible intervention measures at this stage could include:

- dune fencing, marram planting and brushwood thatching to limit the inland movement of windblown sand and to build a higher / wider frontal dune
- restrictions on visitor / vehicle access to the most vulnerable frontal dune areas
- thatching, fencing and planting on the inland dune areas to stabilize the surface or limit the rate of movement.

Adaptation measures could include:

- removal of caravans / buildings from at-risk locations (e.g. Freshfield Caravan Park, National Trust Countryside Centre)
- relocation of the most seaward holes / tees / fairways at Formby Golf Club.

5.0 Starr Hills and Anne's North Beach

5.1 Physical setting and coastal processes

The coastal frontage considered in this case study extends from the southern end of Blackpool's hard defences at Starr Gate to St. Annes Pier (Figure 20). It consists of a belt of semi-natural dunes in the north (Starr Hills) and a narrower belt of largely man-made dunes in the south between North Beach car park and St Anne's pier. These 'modern' dunes lie along the western edge of a 2 - 2.7 km wide belt of older windblown sand formed in the mid to late Holocene. This forms a barrier which protects low-lying areas on Lytham Moss from marine flooding (Cripps *et al*., 2015; Figure 21).

The southern part of the older sand belt has been levelled for housing and commercial development at Lytham and St. Anne's. The northern part has also been heavily modified since the mid-19th century. Parts were once occupied by Blackpool Golf Club and St Anne's Old Golf Club. The northern part near Squire's Gate was used as an informal landing ground around 1910-11, then for a short period as a racecourse, and subsequently as a commercial airfield which was taken over by the military in World War II. After de-requisition the aerodrome was opened again to commercial flights and the site continues to operate as Squires's Gate Airport. The land to the west of the aerodrome developed as a popular camping area in the 1930s but was taken over for construction of a military camp just prior to the outbreak of War. In 1946 the camp was transferred to private ownership and developed as a holiday camp. It was acquired by Sir Fred Pontin in 1961 and greatly expanded during the 1960s and 1970s. Following a progressive downturn in trade during the early 2000s it closed in 2009 and the site has since been redeveloped for housing.

The former St Anne's Golf course area was affected to sand mining in the 1950s and 1960s but was later taken over by Lytham St Annes Council and designated as a Local Nature Reserve (LNR). The former sand mining areas today form low-lying ground on the landward side of Clifton Drive North (Figure 21).

A number of convalescent homes were developed on the seaward side of Clifton Drive in the second half of the 19th century. These sites still exist although they have been substantially modified and partly turned into apartments. The Starr Hills dunes were subject to heavy visitor pressure between the later 1920s and the closure of Pontins in 2009. There was a high percentage of bare sand and active parabolic dunes, particularly in the area to the north of the New Thursby Nursing Home (Figure 22). Many of the dune crests in the north reach 18 m ODN while those in the southern part of Starr Hills do not exceed 16 m ODN. The more recent dunes which have been formed to the south of North Beach car park through man-made intervention are significantly lower (10 - 14 m; Figure 23).

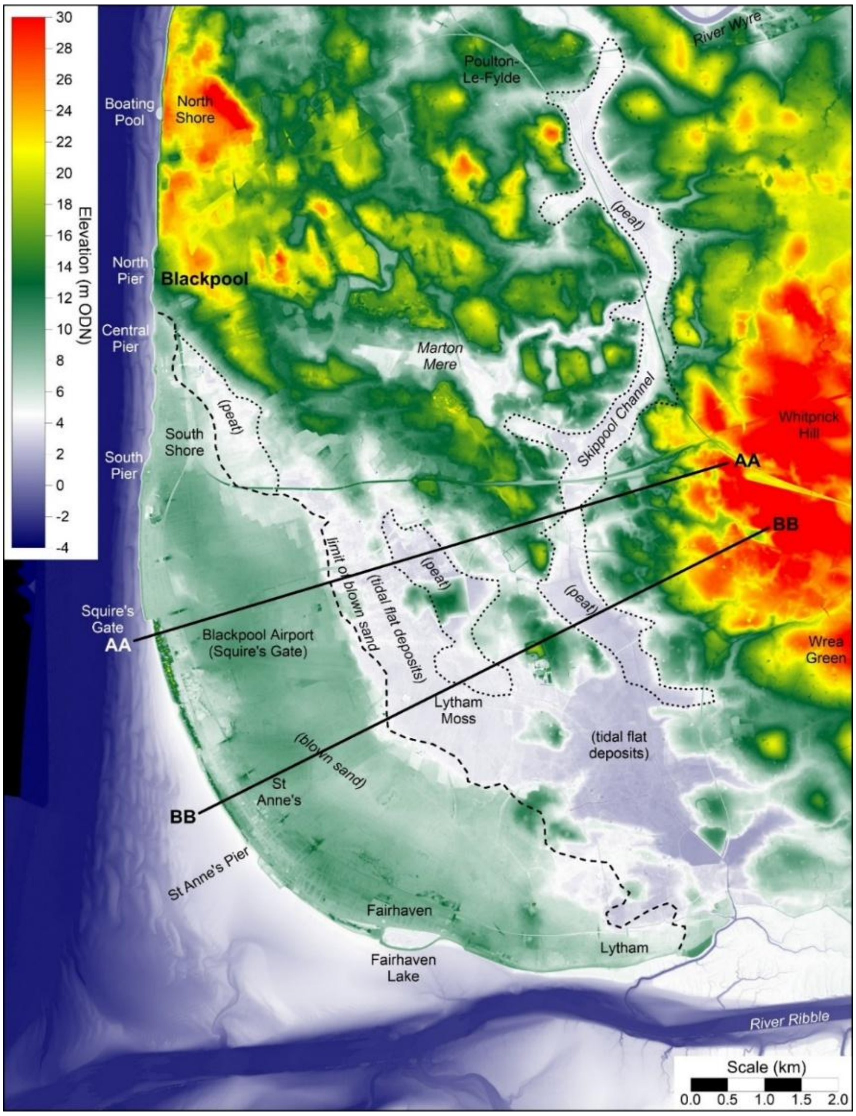

Figure 20. Composite LiDAR DTM of the Fylde coastal plain from composite LiDAR data largely flown to 2022, showing extent of Quaternary deposits

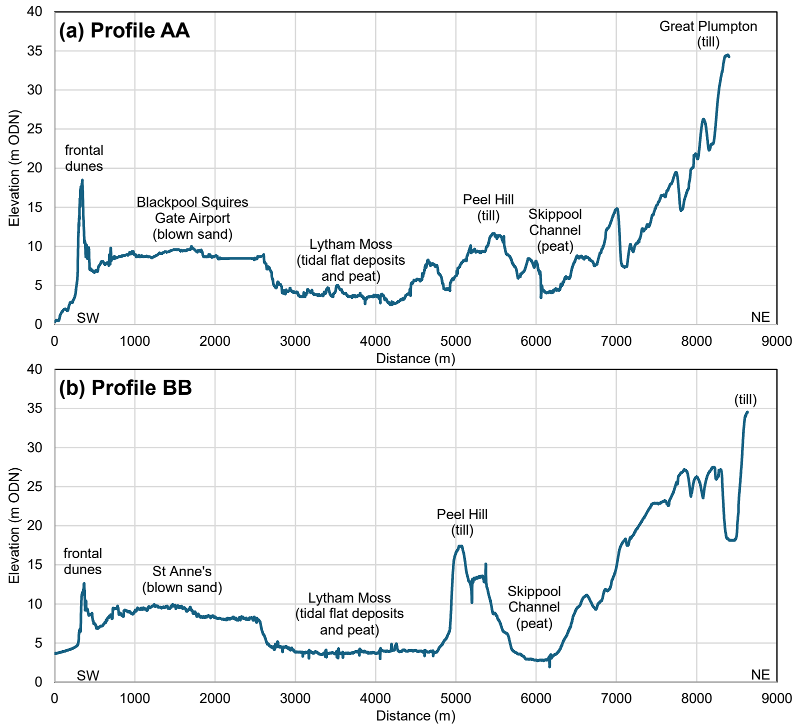

Figure 21. Topographic sections AA and BB taken across Figure 20

The area experienced a macrotidal regime with a mean spring tidal range of more than 8 m (Table 2). The present 1 in 1 still water level is approximately 5.29 m ODN (Table 11).

Table 11. Extreme water levels on the Blackpool-Lytham Coast (chainage number 1212), calculated by the Environment Agency Coastal Boundary Study 2018 Update (Environment Agency, 2019) and projected to the years 2050 and 2100 by UKCP18 using RCP4.5 and RCP8.5 scenarios using the additional allowance (given in the final row of the table)

Return period (years)	present	RCP4.5 scenario 50th percentile		RCP8.5 scenario 70th percentile		RCP8.5 scenario 95th percentile	
		2050	2100	2050	2100	2050	2100
1	5.29	5.43	5.67	5.49	5.99	5.57	6.26
2	5.41	5.55	5.79	5.61	6.11	5.69	6.38
5	5.56	5.70	5.94	5.76	6.26	5.84	6.53
10	5.69	5.83	6.07	5.89	6.39	5.97	6.66
20	5.79	5.93	6.17	5.99	6.49	6.07	6.76
25	5.84	5.98	6.22	6.04	6.54	6.12	6.81
50	5.95	6.09	6.33	6.15	6.65	6.23	6.92
75	6.02	6.16	6.40	6.22	6.72	6.30	6.99
100	6.06	6.20	6.44	6.26	6.76	6.34	7.03
150	6.13	6.27	6.51	6.33	6.83	6.41	7.10
200	6.17	6.31	6.55	6.37	6.87	6.45	7.14
250	6.21	6.35	6.59	6.41	6.91	6.49	7.18
300	6.24	6.38	6.62	6.44	6.94	6.52	7.21
500	6.32	6.46	6.70	6.52	7.02	6.60	7.29
1000	6.43	6.57	6.81	6.63	7.13	6.71	7.40
10000	6.81	6.95	7.19	7.01	7.51	7.09	7.78
Additional allowance		0.14	0.38	0.20	0.70	0.28	0.97

Analysis of historical maps and aerial photographs has shown that there has been limited change (c. 20 m) in dune toe position at the extreme northern end of the system since the mid-19th century, but there has been c. 100 m of change near North Beach car park (Figures 22 - 24). Most of the frontage was eroding in the second half of the 19th century and early 20th century when the North Channel leading into the Ribble estuary lay offshore. Following the construction of the outer parts of the Ribble training walls between 1932 and 1937 the North Channel silted up and by the 1970s a wide foreshore had developed between Lytham and Blackpool. Erosion of the dune toe continued in places until c. 1990 due to the high recreational pressure associated with leisure activities and the holiday camp. Afte that time the dune toe position stabilized and there has since been a progradational trend along much of the shore which has been encouraged since x. 2008 by the placement of posts, fencing and old Christmas trees on the backshore (Skelcher, 2008; Figure 23). The exception is at the northern end near Squire's Gate where slow erosion has continued, despite the construction of a stretch of gabion wall and chestnut paling fences (see photographs in Appendix 3). Since the closure of Pontins in 2009 the dunes in this area have continued to experience heavy visitor pressure from visitors using the adjacent Blackpool tram terminus and residents of the new housing developments on the landward side of Clifton Drive.

Figure 22. Aerial photography of the Starr Hills dunes between Blackpool and Lytham flown 11/05/2024, overlain with historical positions of the dune toe from OS maps (surveyed 1844, 1908 and 1963), aerial photography (2006, 2016 and 2024) and RTK-GNSS survey (07/03/2016 and 08/10/2024). Source: Channel Coastal Observatory

Figure 23. Aerial photography of the Lytham St Anne's area flown 11/05/2024, overlain with historical positions of the dune toe from OS maps (surveyed 1844, 1908 and 1963), aerial photography (2006, 2016 and 2024) and RTK-GNSS survey (07/03/2016 and 08/10/2024). Source: Channel Coastal Observatory

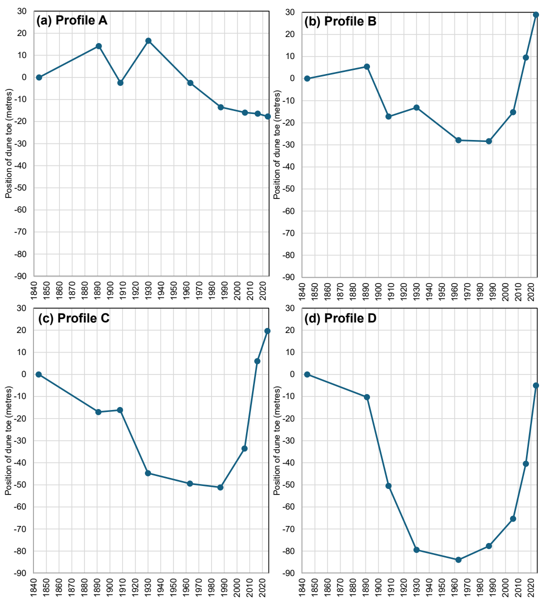

Figure 24. Seaward (positive) and landward negative) movement of the dune toe taken from OS maps (surveyed 1844, 1908 and 1963), aerial photography (2006, 2016 and 2024) and RTK-GNSS survey (07/03/2016 and 08/10/2024). The position is relative to the earliest survey in 1844

5.2 SMP Policy and Coastal Change

The frontage is covered by two SMP Policy Units. The area between Starr Gate and North Beach car park falls within Policy Unit 2.1 The preferred management policies are *Managed Realignment* in the short term and *Hold the Line* thereafter (Table 12). The Starr Hills dunes form the primary defence with no hard defences present between the dunes and Clifton Dive. Small-scale gabion defences and dune fencing are present immediately south of Starr Gate and the SMP proposes assessment of the requirement for a secondary defence line set back closer to the road in this area (see ground photographs in Appendix 4). The frontage between North Beach car park and St Anne's pier falls within Policy Unit 1.21, for which the preferred policy is *Hold the Line* in all three policy epochs (Table 12). Policies are to maintain the hard defences, where present, and dune management elsewhere. A defined Coastal Change Management Area (CCMA) includes the Starr Hills dunes and upper beach, together with the LNR on the landward side of Clifton Drive. The dunes south of North Beach car park are not included in the CCMA (Figure 25).

Table 12. Shoreline Management Plan policies for SMP Policy Units at Starr Hills and St Anne's North Beach

Policy Unit	0-20 yr	20-50 yr	50-100 yr	Comment
1.20 (Miniature Golf Course to St Anne's Pier)	HTL	HTL	HTL	Manage flood risk by maintaining the existing defences to an adequate standard where present. Undertake study to consider flood risks due to breach of dunes during storms
1.21 (St Anne's Pier to St Anne's Northern Boundary)	HTL	HTL	HTL	Manage flood risk by maintaining the existing hard defences to an adequate standard where present, or by dune management elsewhere
2.1 (St Anne's Northern Boundary to Squires Gate)	MR	HTL	HTL	Manage the dunes as the primary defence, while also determining specific requirements for a secondary defence line set back at the road south of Squires Gate to manage the risk of breaches in the dunes, and implement if viable. Flood risk mapping needs to be improved in this area

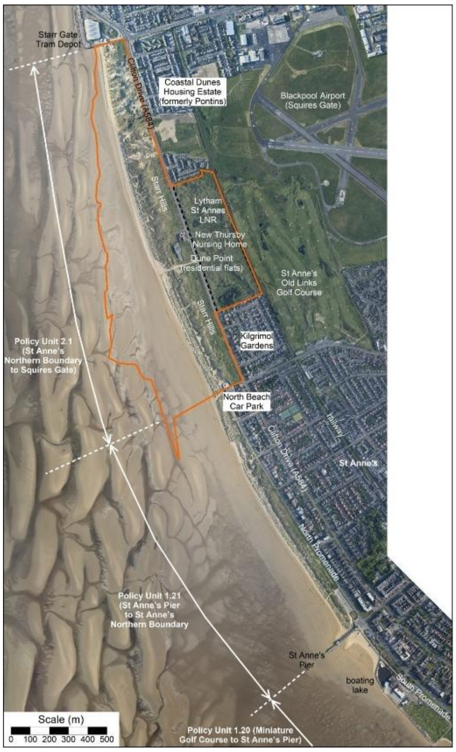

Figure 25. The Coastal Change Management Area defined by an orange line. SMP Policy Units within Cell 11b are shown in white

5.3 Establishing a coastal dune physical condition baseline

Figure 26 presents an enlarged LiDAR DTM of the coastal frontage on which the crestal maximum 'watershed' line has been superimposed. A side elevation view showing the longshore variation in maximum dune crest height is shown in Figure 27. There is general decrease in maximum dune crest elevation from north to south and two potential weak spots in the dune barrier where the maximum crest elevation is only about 6.7 m OD. One of these locations is where the dunes are cut by the track leading from Clifton Drive to the former beach sand winning storage area, the other is the approach track to the St Anne's Land Yacht Club and Beachcomber Café adjacent to North Beach car park.

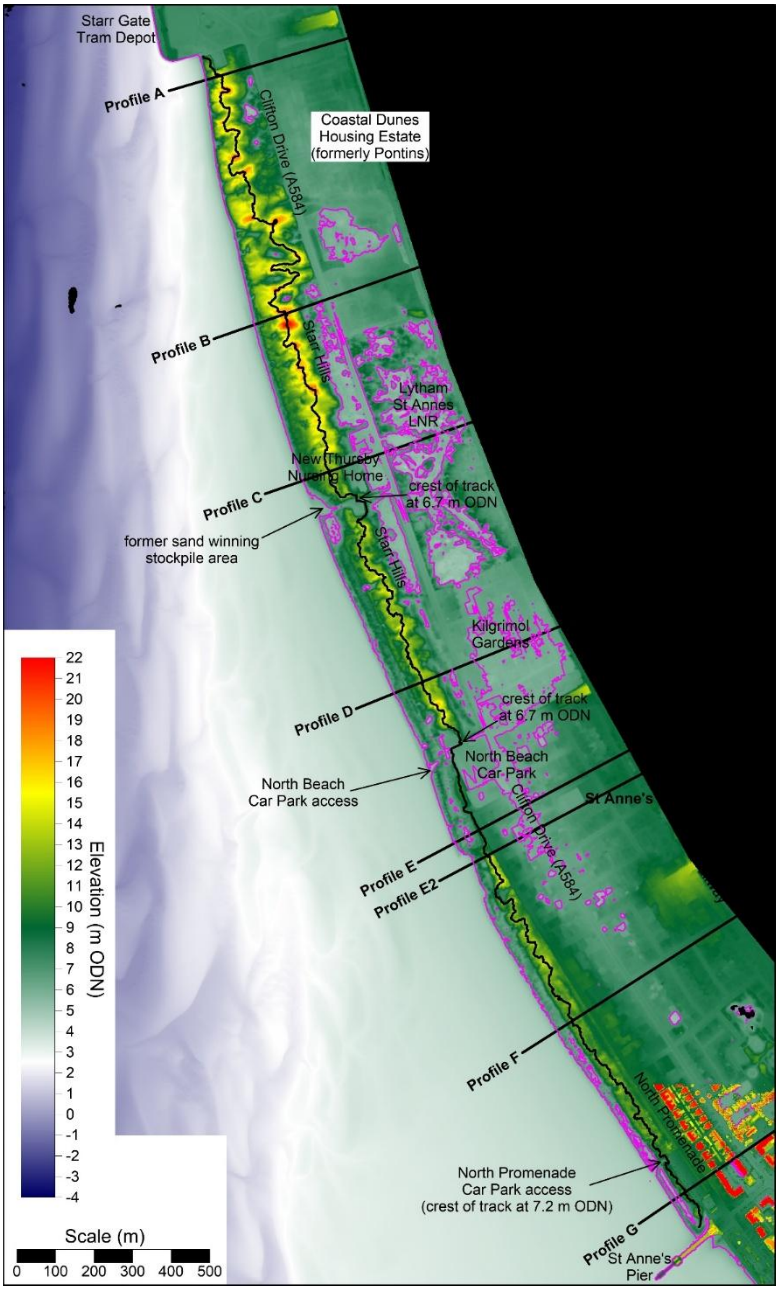

Figure 26. LiDAR DTM of the Starr Hills to St Anne's Pier frontage flown 17/09/2024. Pink lines shows extreme flood level at 6.17 m ODN; black line shows the watershed along the frontal dunes; example profile lines referred to in this report are also shown

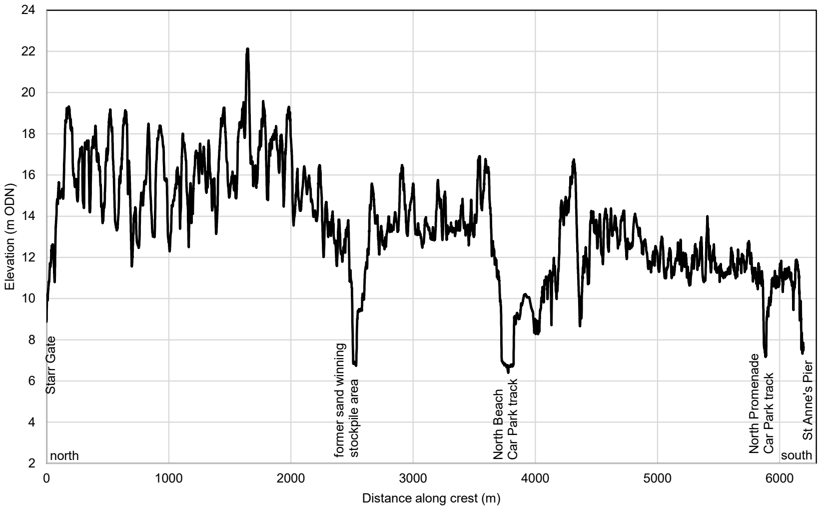

Figure 27. Topographic profile along the crest of the frontal dunes between Starr Gate and St Anne's Pier, extracted from the LiDAR DTM flown 17/09/2024, keeping strictly to the mathematical watershed: the total length along the crest is 6195 m, although the distance along the dune toe is 3310 m.

For the purposes of illustrating the alongshore variation in cross-sectional dune morphology, sand volume, and relation to other coastal defences, ten profiles have been selected at contrasting locations of interest along the coastal frontage (positions shown on Figure 28 and cross-section in Figure 29). Sand volume per metre width was calculated from the 2024 LiDAR DTM assuming a dune toe level taken as 5.3 m ODN and extending landwards as far as the defined line of 'immovable' infrastructure (taken as the seaward limit of the cycleway / path running alongside Clifton Drive in the north, and the seaward side of North Promenade and South Promenade in the south).

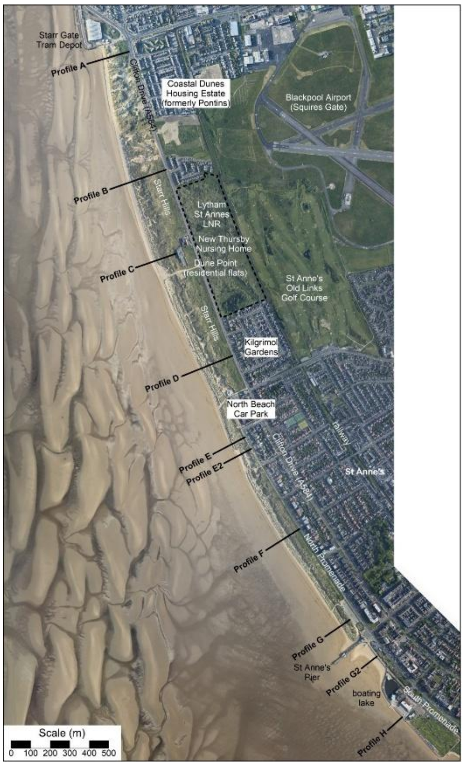

Figure 28. Aerial photograph flown 10/05/2024 showing selected profile lines for topographic cross-sections for the Blackpool-Lytham coast

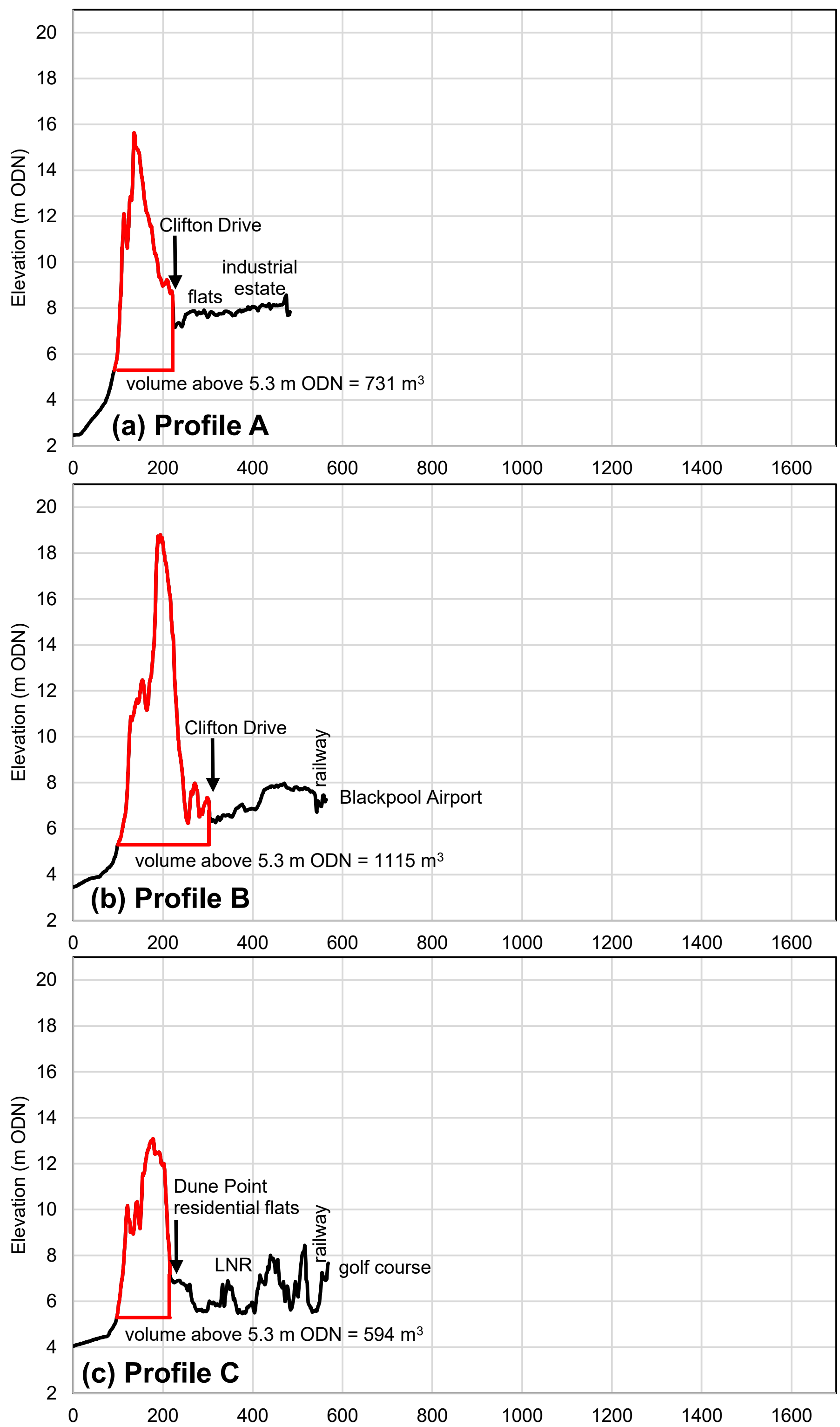

Figure 29. Selected topographic profiles across the dunes on the Blackpool-Lytham coast. Volumes (m^3 per metre width) are given above the level of 5.30 m ODN (approximately the dune toe level, shown with a red line), taken from the LiDAR DTM flown 17/09/2024

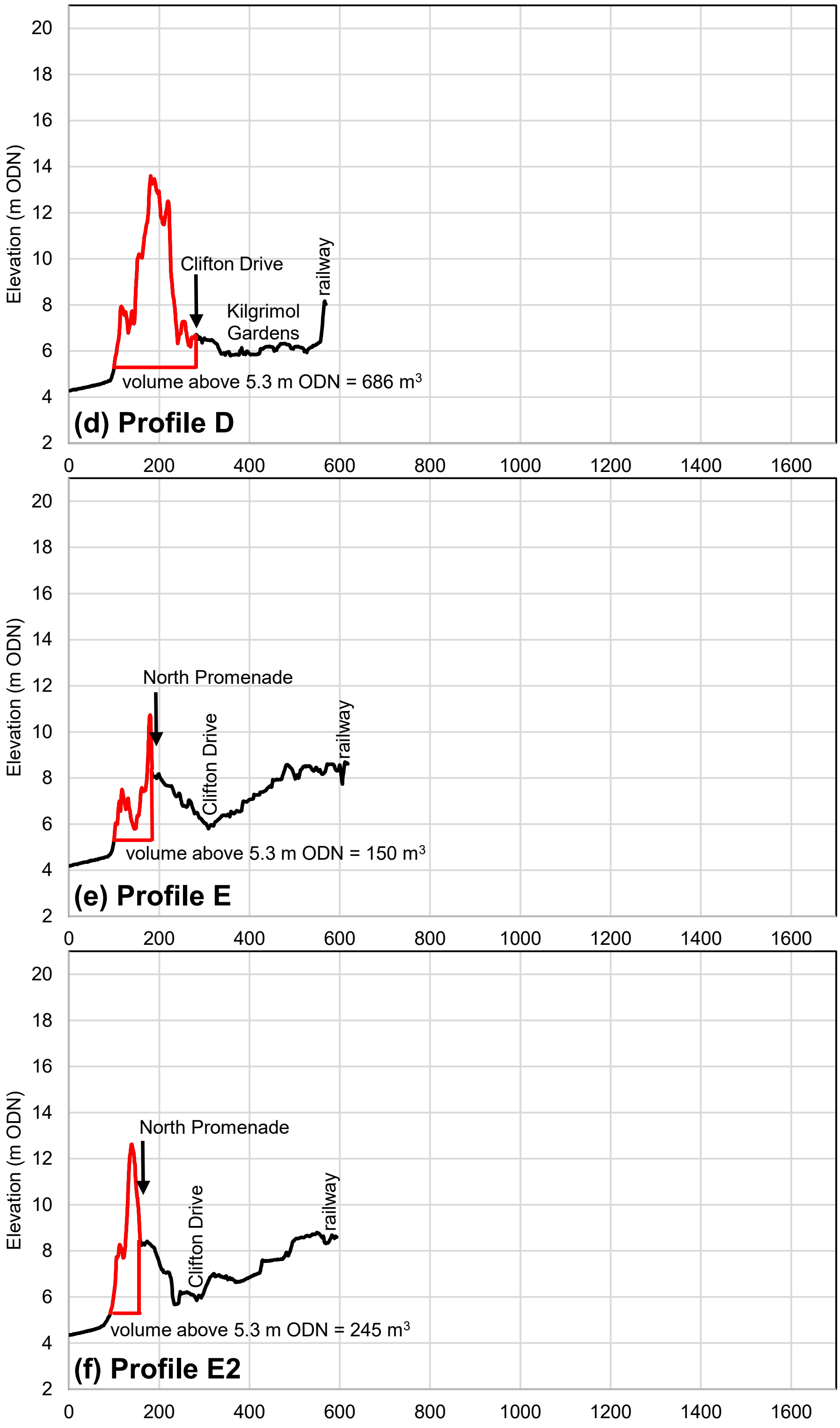

Figure 29. continued

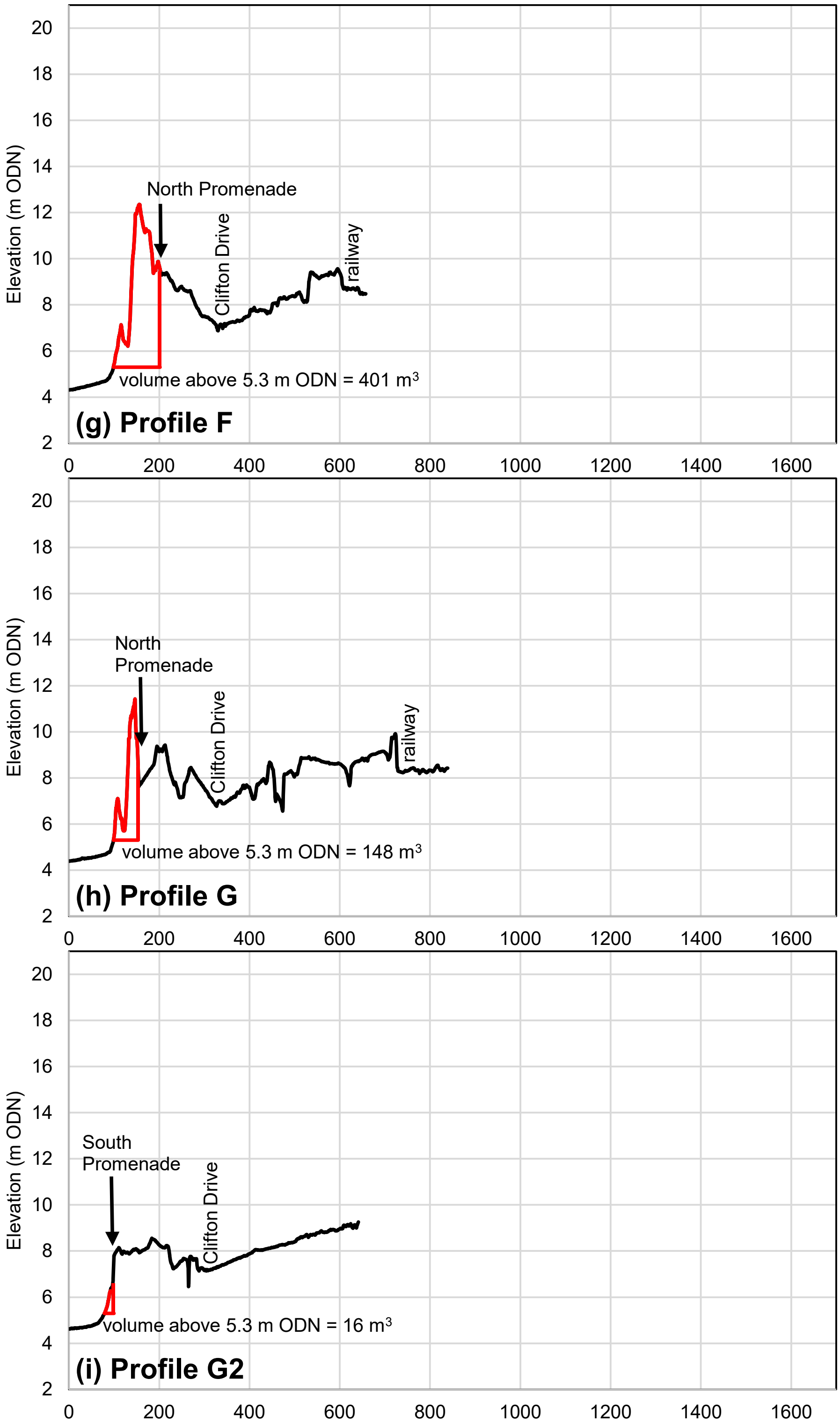

Figure 29. continued

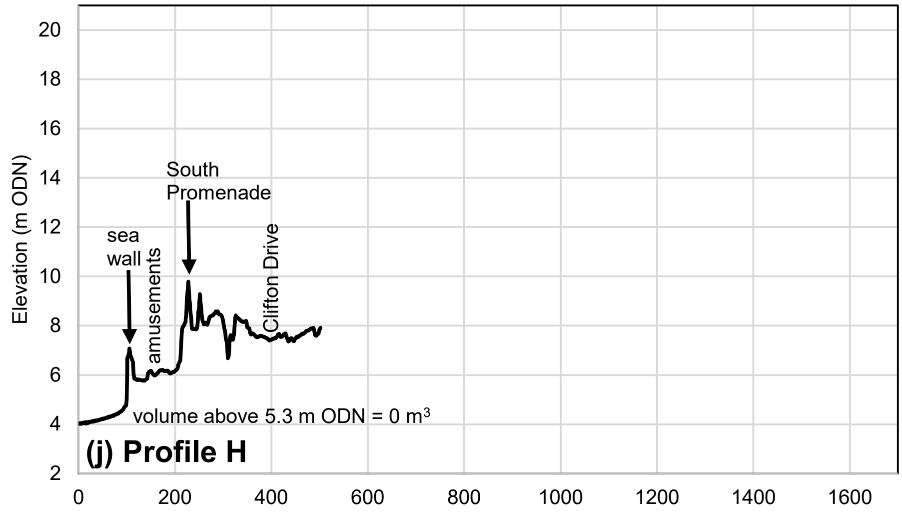

Figure 29. continued

A number of parameters relating to each of the example profiles, derived from analysis of the 2024 and earlier epochs of airborne LiDAR, are summarised in Table 13. The parameters include the linear distance between the dune toe (5.3 m ODN contour) and the edge of the defined infrastructure, the maximum dune height, the volume of sand per metre width, the rate of change in position of the 5.3 m ODN contour between 2006 and 2024, whether any man-made or natural defences are present along the dune toe, and an assessment of bare sand extent / potential sand mobility based on examination of the 2024 aerial photography (see below).

At the Starr Hills profiles A to D the width of dune between the dune toe and seaward limit of infrastructure exceeds 100 m, reaching a maximum of >203 m at profile B, whereas on the selected profiles south of North Beach car park the dune width is much smaller, reaching a maximum of c.103 m at profile F. The sand volume within the defined dune 'protection zone) varies between 595 and 1115 m^3 m^{-1} for the Starr Hills profiles but is much smaller for the profiles south of North Beach profile (16 - 401 m^3 m^{-1}). Using the terminology presented in Table 6 the dune resilience based on sand volume per metre width above dune toe level the dunes at profiles A to D can be described as *Low* (Class 4). At profiles E, E2, G and G2 to the south of North Beach car park it can be classified as *Very Low* (Class 5). Profile A just falls into the Low (Class 4) category based on sand volume.

Artificial Christmas tress, wooden posts and sections of chestnut pale fencing are present (visible) at profiles B, C, D and E. Christmas tree planting does not extend as far north as profile A, but a short section of gabions and chestnut pale fencing has been constructed to defend the eroding dune cliff in this area. Some protection for the dune toe is also provided by a low shingle berm which extends about 70 m south from the concrete wall at Starr Gate.

Analysis of LiDAR surveys flown between 2006 and 2024 has shown that the dune toe has prograded at profiles B to G at average rates ranging between 2.1 m/yr and 4.1 m/yr. Using the terminology outlined in Table 6 this rate of change can be classified as *Rapidly Prograding*. There has been no vegetated dune formation seaward of the South Promenade (profiles G2 and H) while at profile A the dune toe has receded at an average rate of 0.1 m/yr (*Stable / Low Rates of Change* using the terminology in Table 6).

Table 13. Dune defence assessment parameters for selected profiles at Starr Hills St Anne's North Beach, calculated from airborne LiDAR DTMs. Original data source: DEFRA Open Survey Data.

Profile ID	Equivalent cell number	Distance (m) between dune toe and (m)	Max dune height (m ODN)	Volume per metre width above 5.3 m ODN (m^3)	Rate of change of 5.3 m OD contour per year 2006-2024 (m/yr)	Defences / management works present in front of dunes	Bare sand / potential mobility Class	Natural shingle berm
A	36	131	15.6	731	-0.1	gabion mattress	2	Minor
B	30	203	18.8	1115	+3.4	Christmas trees	2	None
C	25	119	13.1	594	+4.1	Christmas trees	2	None
D	20	170	13.5	686	+4.6	Christmas trees	2	None
E	15	84	10.6	150	+5.8	Christmas trees	2	None
E2	14	65	12.5	245	+2.4	none	2	None
F	9	103	12.3	401	+2.8	none	1	None
G	4	54	11.4	148	+2.1	none	2	None
G2	2	20	none	16	0.0	sea wall	5	None
H	N/A	0	none	none	0.0	sea wall	N/A	None

Using the schemes outlined in Tables 6 and 7, the Dune Defence Condition for the example profiles selected for the Starr Hills – St Anne's North Beach frontage can be classified as shown in Table 14.

Table 14. Overall Dune Defence Condition for example profiles at Starr Hills – St Annes North Beach

Profile ID	Volume per metre width above 5.3 m ODN Class	Rate of change of 5.3 m OD contour per year 2006-2024 Class	Overall Dune Defence Condition Class
A	4	3	4
B	4	1	3
C	4	1	3
D	4	1	3
E	5	1	4
E2	5	1	5
F	4	1	4
G	5	1	4
G2	5	S	5
H	n/a	S	n/a

The defence condition for three of the four Star Hills profiles (B, C & D) can be classified as *Fair*, the exception being the slowly eroding and narrower / lower volume profile A close to Starr Gate which is classified as *Poor,* requiring significant remedial measures. This area also has a relatively high percentage of bare sand (34%) due to high visitor trampling pressure (see below), and there is significant problem of windblown sand deposition on the cycleway and road behind. Further interventions are required both to slow / reverse the rate of dune toe recession and to reduce the bare sand area / blowing sand hazard in the hind dune area. At profile locations E2 and G2 dune, which have been assigned an overall Dune Defence Condition Class of 5, dune creation works have either been very limited or not undertaken at all, although there is hard defence behind and floor risk is not high. In the former case the upper beach area is privately owned, and in the second, Council-owned, area there has been a desire to maintain a length of unvegetated recreational high tide beach close to the South Promenade.

5.4 Bare sand area and mobility assessment

Figure 30 shows the extent of bare sand mapped from the 2024 aerial photography. The relative percentages of bare sand within the thirty six 100 m wide cells defined for this frontage are shown in Table 15. Compared with Formby, where the 'immovable' infrastructure line lies much further back and the defined cells are much deeper, the percentages of bare sand cover are relatively large, averaging more than 27% and reaching 42 - 47% south of Starr Gate where visitor pressure is particularly high. The lowest percentages of bare sand occur in the hind dune areas to the north New Thursby Nursing Home and the Dune Point apartments, opposite Kilgrimol Gardens and in the dunes adjacent to the North Promenade. Transport of sand onto the cycleway and road is a particular problem in cells 30 – 36. In addition to creating a hazard to cyclists, motorists and residents of the new housing on the landward side of Clifton Dive, the loss of sand onto the highway serves to diminish the effectiveness of the coastal defence.

Figure 30. Extent of bare sand (red) in the dunes at St Anne's North Beach superimposed on aerial photography flown 11/05/2024. The positions of 36 defined dune cells (100 wide) are also shown. Photography source: Channel Coastal Observatory

Table 15. Percentage of bare dune sand (above 5.3 m ODN) within 36 defined cells at St Anne's north based on GIS analysis of aerial photography flown 11/05/2024

Location	Cell Number	Bare sand area (m^2)	Blown sand area (m^2)	Percentage bare sand (%)
Starr Gate	36	4199	12179	34
	35	6478	13698	47
	34	6489	15426	42
	33	7480	16129	46
	32	4687	16021	29
	31	5944	17781	33
	30	6585	19313	34
	29	4246	20387	21
	28	4025	20953	19
	27	3854	20935	18
	26	2951	18429	16
Dune Point	25	3153	11866	27
	24	6669	18132	37
	23	4032	20524	20
	22	4179	19663	21
	21	3677	18930	19
	20	4094	18415	22
	19	3341	17660	19
	18	4147	17033	24
North Beach Car Park	17	2759	8403	33
	16	2955	8579	34
	15	2586	7951	33
	14	2372	6779	35
	13	2706	8874	30
	12	2282	9659	24
	11	2348	10001	23
	10	2184	10143	22
	9	1824	10092	18
	8	1954	9784	20
	7	2161	9414	23
	6	1428	9413	15
	5	1155	7056	16
	4	1232	5780	21
St Anne's Pier	3	2150	5106	42
	2	2587	2678	97
Boating Lake	1	1771	1782	99
Totals for Cells 1-36:		126684	464968	27

5.5 Future coastal change

An independent future coastal change assessment for the Starr Hills - St Annes' North Beach frontage has not been undertaken as part of the present study but assessment made as part of the Environment Agency's Coastal erosion Risk Mapping project, last updated in December 2024, projects significant erosion of the dune system by 2055 and potential loss of the almost the entire system by 2105 under a high RCP8.5 emissions scenario. The Environment Agency Coastal Boundary Update Study (EA, 2019) projects that the 1 in 1 still level may rise up to 28 cm by 2050 and potentially up to 96 cm by 2100 under this scenario (Table 11). Unless there is a significant increase in the supply of sediment from offshore, increased water depths in general will favour larger nearshore waves and greater run-up leading to more frequent tripping / cliffing of the dune edge. Owing to the extensive area of the foreshore a large amount of lateral dune erosion will be needed to allow an equilibrium profile across the intertidal and adjoining subtidal area to be maintained. However, since this coastal frontage has relatively high exposure to onshore wind energy it is likely that erosion of the frontal dunes will be accompanied by blowout development and rollback of mobile parabolic dunes towards the road.

5.6 *Buffer zones and trigger points for intervention / adaptation*

5.6.1 Dune ecological and coastal defence buffer zones

As was suggested at Formby, from an ecological perspective it is desirable to maintain a 200 m wide belt of dunes to seaward of the fixed asset baseline in order to maintain a viable ecological dune system which can support the full range of habitats including strandline, embryo dune, semi-mobile dune to fixed dune grassland, with adequate alongshore connectivity. It is also desirable to anticipate a 30 m wide ‘laydown area’ seaward of the present ‘asset baseline’ which would likely be required to construct a new sea wall at some time in the future, fronted by a dune buffer zone to seaward which would act to protect and limit wave overtopping of any new defence. These zones are represented, respectively by red and orange line son Figure 31.

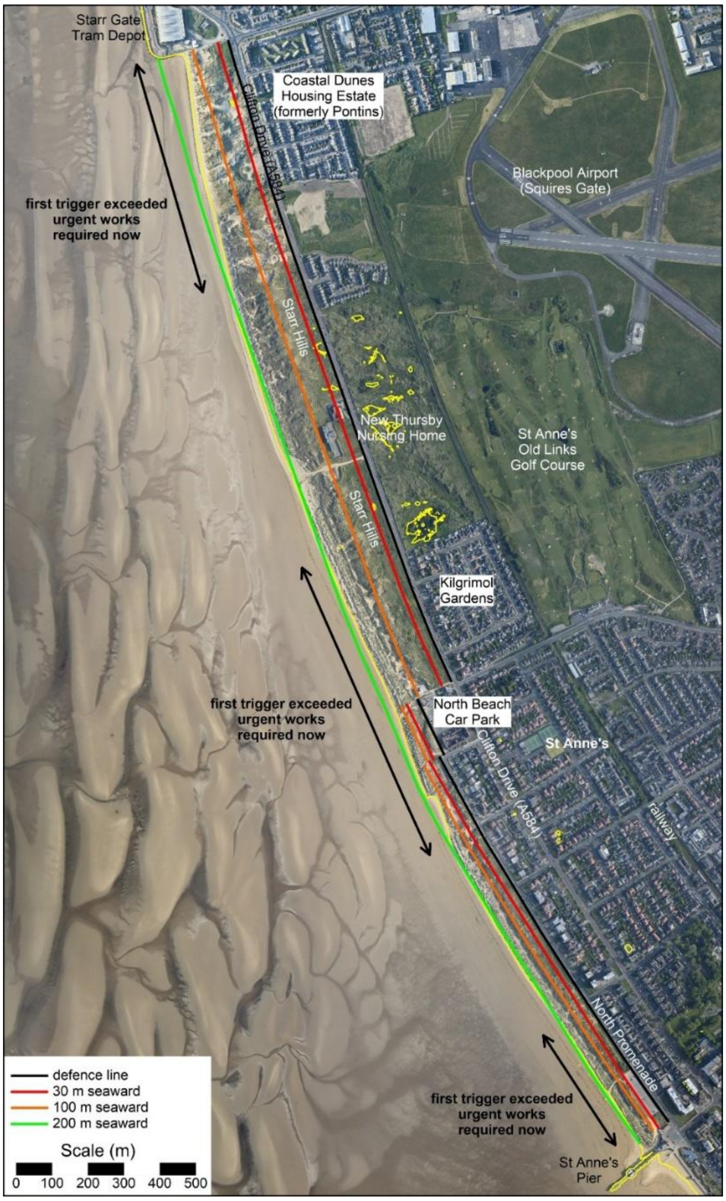

Figure 31. Suggested buffer zones and action trigger lines for St Annes North, with the current main defence line shown in black, coinciding with the North Promenade at St Annes, the North Beach Car Park wall, and Clifton Drive. Also, trigger lines 30, 100 and 200 m to seaward of a probable future asset defence line.

5.6.2 Dune toe monitoring and intervention trigger points

It is suggested that present dune management should aim to achieve and maintain a belt of dunes which has a width of at least 200 m along the Starr Hills frontage (north of North Beach car park), and at least 100 m along the North Promenade and South Promenade frontages. Intervention works should continue to be undertaken to achieve these targets where they are not currently met, although this is likely to be difficult at the eroding northern end of the system without importing shingle and sand. Under present conditions it is likely to be possible along the dune frontage north of North Beach car park if more effective measures are taken to keep pedestrians off the newly accreting embryo dunes / incipient foredunes. Further dune progradation could probably also be successful along the frontage between North Beach car park and St Annes pier since the backshore has shown a consistent widening trend in this area since 2006 (see next section).

It is suggested that if, in the coming years, and as projected, the recent historical stability / progradation trend is reverse by higher water levels and/ or greater storm wave activity associated with climate change and sea level rise, management measures should be increasingly focused on limiting sand instability and mobile dune movement in order to limit windblown sand deposition on the highway and in adjoining properties. If / when the dune toe recedes to a point where the dune system is only 100 m wide the options for a significant change in management policy should be considered (e.g. plan for the construction of a new sea wall seaward of the cycleway / road).

5.6.3 Beach level monitoring as a means of early warning

As pointed out in relation to Formby, monitoring of beach contours can provide useful early warning of changes which may affect the dune toe and/ or inland dunes. Table 17 provides a summary of changes in upper beach tidal contours at the example profile locations, based on analysis of LIDAR data for the period 2006 - 2025. Changes between individual LiDAR epochs are presented in Appendix 6. The results summary shows that the HAT line has moved seawards by 58 m near North Beach car park, with the amount of progradation decreasing both to the north and south. As a result of this the dune front has developed a slight convexity in plan. The MHWS and MHWN contours have shown a slightly different pattern of change, moving landward at the northern end of the frontage but with increasing amounts of seaward movement south of North Beach car park. By contrast, the MHW contour has shown landward movement along almost the entire frontage, resulting in steepening of the upper part of the intertidal profile. The causes of these changes need further investigation, including collection and analysis of data sets which cover the lower beach and subtidal contours.

Table 17. Summary of changes in distance between the asset defence baseline and selected tidal contours at eight example profiles 2006-2024. Note most LiDAR surveys do not extend much beyond the MHW level; nd = no data

Location	Profile	Equivalent cell	HAT	MHWS	MHWN	MHW
Starr Gate	A	36	-4	-3	-13	7
Fletcher Drive	B	29	26	-5	-16	-15
New Thursby Home	C	25	34	-7	12	-73
Kilgrimol Gardens	D	19	46	4	49	-115
North promenade	E	15	58	41	34	-116
North promenade	E2	14	25	44	47	-125
North promenade	F	9	31	56	27	-155
North promenade	G	4	22	72	128	nd
South promenade	G2	2	-2	105	111	nd
Boating lake	H	n/a	0	108	71	nd

4.7 Possible intervention and adaptation options

A progamme of dune management interventions has been carried out at St Annes North Beach and Starr Hills since 2008. This has included works to control mobile sand in the inland dunes areas and interventions to widen the dune belt by encouraging the formation of new incipient foredunes through erection of sand fencing and placement of old Christmas trees. These works are currently funded largely by the Environment Agency in order to support delivery of the SMP2 policy. The work has had notable success along much of the frontage with the exception of the section immediately south of Starr gate where the upper beach has been losing sediment and the dune toes has shown a long-term trend for slow erosion.

Options for short term interventions include:

- continuation of dune toe advancement works, notably between St Anne's Pier and North Beach car park where continued widening of the backshore creates favourable conditions
- nourishment of the beach south of Starr Gate to raise / widen the backshore and provide more favourable conditions for incipient dune development (although sediment is likely to continue to be lost southwards)
- 'hardening' of the dune front south of Starr Gate using geobags or wooden wave breaks
- sand fencing, using f geotextile matting and further marram planting south o Starr gate to reduce landward sand movement

Options for medium to longer term interventions include:

- large-scale beach nourishment and dune creation works
- raising of the sea wall at North Promenade and South Promenade
- construction of a new sea wall between Starr Gate and North Beach car park to protect the main road and properties behind
- construction of new defences around the isolated properties at New Thursby Nursing Home, Dune Point Apartments and sand yacht Club.

6.0 Conclusions

It is concluded from this study and previous work that airborne LiDAR surveys provide the most useful method of monitoring changes in a range of parameters which define the condition of dune (and adjoining beach) systems for coastal defence purposes. They allow synoptic data to be obtained for large areas cover the entire dune system and adjoining beach (surveys should ideally be undertaken on low spring tides). Both filtered and non-filtered data are useful, although for the purposes of DTM construction filtered data are of greatest value. A spatial resolution of 1 m, interpolated from the primary point cloud data, is sufficient for this purpose. Surveys are presently undertaken every two years as part of the Northwest Coastal Regional Monitoring Programme. While this is adequate, there would be additional benefit from annual surveys undertaken in the spring. All LiDAR surveys should be accompanied by adequate ground control surveys using RTK-GNSS, and a metadata report which identifies the nature of ground control and post-survey data processing methods used.

Key parameters which can be quantified and monitored using the LiDAR data include total dune system area, sand volume and changes in the position of the dune toe and mobile dune features. Analysis is best undertaken by dividing a dune system into a series of defined 'cells', each centred on a profile line perpendicular to the dune toe (acknowledging that the dune toe orientation as well as position may change over time). Distances, maximum dune crest height and volumes per metre width can be calculated for the profiles alone, or in combination with analysis of data for entire cells. Other cross-sectional profile lines can be specified at points along the shore which are of particular interest.

A summary of the recommended methodology is shown in Table 18 below. In this study the GIS operations were performed using the Golden Software suite and Microsoft Excel, but the generic steps can be replicated using any GIS software.

Table 18. Summary of steps to be used in the quantification and analysis of dune cells and profiles

Step 1	Prepare a LiDAR DTM for analysis: check the accuracy with other LiDAR epochs or RTK-GNSS ground control points surveyed on level hard surfaces such as roads or car parks. 'Blank' any areas not required in the analysis, such as areas covered by sea or standing water
Step 2	Use the most recent LiDAR survey to plot the 'dune toe' contour (5.3 m ODN for the case studies in this report), and extract the line as a polyline
Step 3	Truncate the polyline at the chosen start and end positions of the study site, and use a smoothing routine to eliminate small-scale meanders in the line: this is the **baseline** for the analysis
Step 4	Extract points at 100 m spacing along the baseline and place a perpendicular bisector at these positions: these are cell boundaries. Ensure the boundaries are long enough to cover the seaward and landward extent of the study area (usually at least 1 km in each direction), and join the seaward and landward ends to polygons: these are the **coastal cells**
Step 5	Extract a point 50 m from the start point of the baseline, and then at 100 m spacings along the baseline (i.e. at 50, 150, 250 m etc) and place a perpendicular bisector at these positions: these are the **coastal profiles**. Ensure the boundaries are long enough to cover the seaward and landward extent of the study area (usually at least 1 km in each direction)
Step 6	Define an **asset boundary** for the study site by drawing a polyline dividing important infrastructure that should be protected from the natural dunefield. The asset boundary should be joined to the baseline at each end of the study site: the resulting polygon defines the **landward calculation area**
Step 7	Define an **asset boundary** for the study site by drawing a polyline dividing important infrastructure that should be protected from the natural dunefield.
Step 8	Profile distance calculations: select a processed and corrected LiDAR DTM and use a slicing routine to extract elevations along the coastal profiles created in Step 5. Formulas or macros in a spreadsheet program can be used to extract the distance of selected tidal contours from the starting point of each coastal profile. Changes in positions of these contours between different LiDAR DTMs can be compared to monitor change over time.
Step 9	Profile volume calculations: Formulas or macros in a spreadsheet program can be used to calculate the cross-sectional area beneath each coastal profile to selected tidal contours. The area is equivalent to the volume per metre width of frontage. Changes in volume between different LiDAR DTMs can be compared to monitor change over time.
Step 10	Cell volume calculations: select a LiDAR DTM and use a 'blanking' routine to remove data not required in the analysis, such as landward of the asset boundary specified in Step 6. Use a volume routine to calculate volumes with the upper level defined by a selected LiDAR DTM, the lower level defined by a selected tidal contour, and the calculation area specified by the coastal cells defined in Step 4. Export the volumes to a spreadsheet program. Repeat for other selected tidal levels. Changes in volumes between different LiDAR DTMs can be compared to monitor change over time.
Step 11	Prepare a high resolution (ideally 25 cm) aerial photograph for bare sand analysis. Define the 'dune toe', either by manually drawing a polyline on the photograph, or from a contemporaneous RTK-GNSS walkover survey, or 5.3 m ODN contour from a contemporaneous LiDAR DTM. Blank areas of the photograph seaward of the dune toe, or landward of the asset line, or any other

	areas not required in the analysis (buildings, standing water etc). Convert the photograph to an 8-bit (greyscale) grid file. Display the grid file as a colour map with pixels above a threshold value of 0.60 (i.e. 'bright' areas). Adjust the threshold value until only 'bright' bare sand areas are identified (by comparison or overlay with the original photograph). Use a blanking or math routine to remove pixels below the threshold.
Step 12	Bare sand area: use a counting or area/volume routine to calculate the area of pixels in the grid file created in Step 11 (above the threshold) with the calculation area specified by the coastal cells defined in Step 4. Export the areas to a spreadsheet program. Changes in areas between different photography surveys can be compared to monitor change over time.

Based on a consideration of the two parameters which are considered to be most important, dune sand volume and direction / rate of change in position of the dune toe, a *Dune Defence Condition Class* can be assigned for each profile and/ or associated cell using the terminology applied to the Environment Agency's T98 inspections:

- Class 1 = *Very Good*, no concerns
- Class 2 = *Good*, no major concerns
- Class 3 – *Fair*, requiring minor interventions only
- Class 4 = *Poor*, requiring significant remedial intervention measures
- Class 5 = *Very Poor*, requiring major works or adaptation

The *Dune Condition Class* for eight example cells / profiles at Formby range from Class 1 (covering most of the coast between Ainsdale and Ravenmeols) to Class 3 (the frontages at Range Lane and Altcar Military Training Area). At the example profiles chosen for the Starr Hills / St Annes North Beach case study site the assessed *Dune Condition Class* varies between 3 (most of the Starr Hills frontage, excluding the northern end) to 5 (short section in front of the North and South promenade where artificial dune shave not been constructed or are very narrow / have a small sand volume).

Additional useful information about changes in bare sand area / vegetation extent / density, which relates to blowing sand hazard, can be obtained from aerial photography, ideally undertaken at the same time as the LiDAR surveys. The extent of bare / potentially mobile sand which may give rise to a blowing sand hazard can also be classified (for individual cells, groups of cells or the dune system as a whole) as follows:

- Class 1 = Minor (0 - 20% bare sand)
- Class 2 = Moderate (20 - 40% bare sand)
- Class 3 = High (40 - 60% bare sand)
- Class 4 = Very High (60 - 80 % bare sand)
- Class 5 = Essentially Unvegetated (80 -100% bare sand)

None of the 112 defined cells at Formby contain more than 20% sand and are therefore classified as having *Minor* potential instability in terms of risk to major assets. The highest values (10 - 20%) occur behind the eroding sections of shore around Formby Point. While there is no immediate threat to immovable assets in this area at present, monitoring of the position of mobile sand sheets and dunes is required at least annually. If mobile sand advances to within 100 m of any defined asset the options for control works or adaptation of assets should be assessed.

In the smaller Starr Hills – St Annes North Beach dune system there is relatively greater pressure from visitors and almost all of the 36 defined cells have > 20% bare sand, with values of 29 - 47% in cells at the northern end of Starr Hills where there is a significant problem with blown sand onto the cycleway and road (Clifton Drive). There is immediate need for further sand surface stabilization and sand trapping works in this area.

If airborne LiDAR and aerial photography surveys continue to be undertaken every two years it is recommended that ground inspections should also be undertaken in alternate years between LiDAR surveys, in addition to after major storms. At the simplest level the inspection may involve a visual walkover assessment, aided by the use of a feature checklist and appropriate ground photographs for each defined cell frontage. Example checklists are provided in Appendix 1 to this report. The boundaries of each cell need to be identified on the ground using RTK GNSS equipment (ideally hand-held or back-pack mounted). This equipment can also be used to undertake a full dune toe survey at the same time, and/ or to establish beach levels and the condition of artificial notches, blowouts or coastal defence structures.

7.0 References

Bertoni, D., Sarti, G., Alquini, F. & Ciccarrelli, D. (2019) Implementing a Coastal Dune Vulnerability Index (CDVI) to support coastal management in different settings (Brazil and Italy). *Ocean and Coastal Management 180: https://doi.org/10.1016/j.ocecoaman.2019.104916*

Cripps, C., Burke, H.F., Lee, J.R. & Haigh, E. (2016) *The Fylde, Lancashire: Survey of the Quaternary Geology*. British Geological Survey Open Report OR/16/013, British Geological Survey, Keyworth, 47pp.

Davidson-Arnott, R.G.D. (2005) Conceptual model of the effects of sea level rise on sandy coasts. *Journal of Coastal Research* 21 1166-1172 + 1193.

Environment Agency (2012). *Managing Flood Risk – Condition Assessment Manual*. Bristol: Environment Agency.

Environment Agency (2019) *Coastal flood boundary conditions for the UK: update 2018.* Technical summary report SC060064/TR6. Environment Agency, Bristol.

Environment Agency (2025) *Flood risk asset maintenance and inspection: good practice guidance*. Published 31 January 2025. Available at: Flood risk asset maintenance and inspection: good practice guidance - GOV.UK

Fylde Council (2015) Fylde Council Coastal Strategy 2015-2032. Fylde Council.

Itzkin, M., Moore, L.J., Ruggiero, P., Hacker, S.D. & Biel, R. (2020) The influence of dune aspect ratio, beach width and storm characteristics on dune erosion for managed and unmanaged beaches. *Earth Surface Dynamics Discussions* https://doi.org/10.5194/esurf-2020-79

Keijsers, J.G.S., Giardino, A., Poortinga, A., Mulder, J.P.M., Riksen, M.J.P. & Santinelli, G. (2014) Adaptation strategies to maintain dunes as flexible coastal defence in the Netherlands. *Mitigation and Adaptation Strategies for Global Change* DOI 10.1007/s11027-014-9579-y.

Martinez, M.L., Gallego-Fernandez, J.B., Garcia-Franco, J.G., Moctezuma, C. & Jimenez, C.D. (2006) Assessment of coastal dune vulnerability to natural and anthropogenic disturbances along the Gulf of Mexico. *Environmental Conservation* 33, 109-117.

McLaughlin, S. & Cooper, J.A.G. (2010) A multi-scale coastal vulnerability index: a tool for coastal manager? *Environmental Hazards* 9, 233-248.

Parker, W.R. (1975) Sediment mobility on a multi-barred foreshore (Southwest Lancashire, UK). In: Hails, J.R. & Carr, A.P. (eds.) *Nearshore Sediment Dynamics and Sedimentation*, John Wiley & Sons, London, 151-179.

Pye, K. (1990) Physical and human influences on coastal dune development between the Ribble and Mersey estuaries, northwest England. In: Nordstrom, K.F., Psuty, N.P. & Carter, R.W.G. (eds.) *Coastal Dunes: Form and Process*. John Wiley & Son Ltd., Chichester, pp. 339-359.

Pye, K. & Bowman, G.M. (1984) The Holocene marine transgression as a forcing function in episodic dune activity on the eastern Australian coast. In: Thom, B.G. (Ed.) *Coastal Geomorphology in Australia*. Academic Press, Sydney, pp. 179-129.

Pye, K. & Blott, S.J. (2008) Decadal-scale variation in dune erosion and accretion rates: an investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology* 102, 652-666.

Pye, K. & Blott, S.J. (2010) Geomorphology of the Sefton Coast sand dunes. In: Worsley, A.T., Lymbery, G., Holden, V.J.C. & Newton, M. (Eds.) *Sefton's Dynamic Coast*. Coastal Defence: Sefton MBC Technical Services Department, Ainsdale-on-Sea, 131-160.

Pye, K. & Blott, S.J. (2016a) The relative effect of the UK's stormy winter 2013-2014 on dune erosion: Case study of the Sefton Coast, Northwest England. *Shore and Beach* 84 (2), 31-48.

Pye, K. & Blott, S.J. (2016b) Assessment of beach and dune erosion and accretion using LiDAR: Impact of the stormy 2013-14 winter and longer-term trends on the Sefton Coast, UK. *Geomorphology* 266, 146-167.

Pye, K. & Blott, S.J. (2020) *Sefton Future Coastal Change Assessment*. KPAL External Investigation Report No. EX020720 prepared for Sefton Council, Kenneth Pye Associates Ltd., Reading.

Pye, K. & Neal, A. (1994) Coastal dune erosion at Formby Point, North Merseyside: causes and consequences. *Marine Geology* 119, 39-56.

Rees S. (2021) *Definition of Favourable Conservation Status for Coastal Sand Dunes*. Natural England, 64pp.

Saye, S.E., van der Wal, D., Pye, K. & Blott, S.J. (2005) Beach dune morphological relationships and erosion/accretion: an investigation at five sites in England and Wales using LIDAR data. *Geomorphology* 72, 128-155.

Silva, R., Martinez, M.L., Oderiz, I., Mendoza, E. & Feagin, R.A. (2016) Response of vegetated dune - beach systems to storm conditions. *Coastal Engineering* 109, 53-62.

Skelcher, G. (2008) *Fylde Sand Dunes Management Action Plan*. Prepared on behalf of the Fylde Sand Dune Project Steering Group, December 2008, 100pp.

UKHO (2024) *Admiralty Tide Tables United Kingdom and Ireland (Excluding Isles of Scilly, English Channel to River Humber, Channel Islands and European Channel Ports.* NP201B Volume 1B 2025. UK Hydrographic Office, Taunton.

Van der Graaf, J. (1986) Probabilistic design of dunes; and example from The Netherlands. *Coastal Engineering* 9, 479-500.

Vellinga, P. (1982) Beach and dune erosion under storm surges. *Coastal Engineering* 6, 361-387.

Williams, A.T., Duck, R.W. & Phillips, M.R. (2011) Coastal dune vulnerability among selected Scottish systems. *Journal of Coastal Research Special Issue* 64, 1263-1267.

Appendix 1

Frontal dune inspection template
Formby and St Anne's North Beach examples

Coastal Defence Dune Inspection Record Sheet

Coastal Dune Cell Number 49 ....

Location description Formby Wicks Lane North ....

Positional coordinates of start and end of inspected area 327075E 407260N to 327082E 407359N

Date of inspection 4 April 2025 ....

Name of Inspector K Pye ....

Condition Grade (high to low)	**1**	**2**	**3**	**4**	**5**	**Comments**
Observations on frontal dune						
Nature of seaward dune slope	Gently sloping ☐	Steeply sloping ☐	Cliffed ☒	Over-hanging ☐	Breached ☒	....
Bare sand ramp at dune toe	>95% ☐	60-95% ☐	40-60% ☐	5-40% ☐	<5% ☒	....
Strandline Vegetation	>95% ☐	60-99% ☐	40-60% ☐	5-40% ☐	<5% ☒	....
Incipient foredunes	<95% ☐	60-99% ☐	40-60% ☐	5-40% ☐	<5% ☒	....
Frontal dune slope veg. density	>95% ☐	60-95% ☐	40-60% ☐	5-40% ☐	<5% ☒	....
Shingle berm at dune toe	>95% ☐	60-99% ☐	40-60% ☐	5-40% ☐	<5% ☒	....
Blowouts	<5% ☐	5-40% ☐	40-60% ☒	60-95% ☐	>95% ☐	....
D50 Sand size (mm)	1.0-2.0 ☐	0.5-1.0 ☐	0.25-0.5 ☐	0.125-0.25 ☒	0.063-0.125 ☐	....
Management measures						
Sand fencing / posts	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Christmas trees / brushwood	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Gabions	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Wooden revetment / groynes	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Rubble revetment	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Concrete wall / revetment	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Steel piling wall	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Geotubes	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Movement of dune front trend						
Eroding	<5% ☐	5-40% ☐	40%-60% ☐	60-95% ☐	>95% ☒	....
Stable	<5% ☒	5-40% ☐	40%-60% ☐	60-95% ☐	>95% ☐	....
Prograding	<5% ☒	5-40% ☐	40%-60% ☐	60-95% ☐	>95% ☐	....
Visual Condition Grade	**A** ☐	**B** ☐	**C** ☐	**D** ☐	**E** ☒	....

Coastal Defence Dune Inspection Record Sheet

Coastal Dune Cell Number 26 ....

Location description St Anne's North Beach New Thursby North ....

Positional coordinates of start and end of inspected area 330760E 430596N to 330730E 430692N
....

Date of inspection 5 April 2025 ....

Name of Inspector K Pye ....

Condition Grade (high to low)	**1**	**2**	**3**	**4**	**5**	**Comments**
Observations on frontal dune						
Nature of seaward dune slope	Gently sloping ☒	Steeply sloping ☐	Cliffed ☐	Over-hanging ☐	Breached ☐	....
Bare sand ramp at dune toe	>95% ☐	60-95% ☐	40-60% ☒	5-40% ☐	<5% ☐	....
Strandline Vegetation	>95% ☐	60-99% ☒	40-60% ☐	5-40% ☐	<5% ☐	....
Incipient foredunes	>95% ☐	60-99% ☒	40-60% ☐	5-40% ☐	<5% ☐	....
Frontal dune slope veg. density	>95% ☐	60-95% ☐	40-60% ☒	5-40% ☐	<5% ☐	....
Shingle berm at dune toe	>95% ☐	60-99% ☐	40-60% ☐	5-40% ☐	<5% ☒	....
Blowouts	<5% ☐	5-40% ☐	40-60% ☐	60-95% ☐	>95% ☒	....
D50 Sand size (mm)	1.0-2.0 ☐	0.5-1.0 ☐	0.25-0.5 ☐	0.125-0.25 ☒	0.063-0.125 ☐	....
Management measures						
Sand fencing / posts	100% ☒	60-99% ☐	40-60% ☐	1-40% ☐	0% ☐	....
Christmas trees / brushwood	100% ☒	60-99% ☐	40-60% ☐	1-40% ☐	0% ☐	....
Gabions	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Wooden revetment / groynes	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Rubble revetment	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Concrete wall / revetment	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Steel piling wall	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Geotubes	100% ☐	60-99% ☐	40-60% ☐	1-40% ☐	0% ☒	....
Movement of dune front trend						
Eroding	<5% ☐	5-40% ☐	40%-60% ☐	60-95% ☐	>95% ☐	....
Stable	<5% ☐	5-40% ☐	40%-60% ☐	60-95% ☐	>95% ☐	....
Prograding	<5% ☐	5-40% ☐	40%-60% ☐	60-95% ☐	>95% ☒	....
Visual Condition Grade	**A** ☒	**B** ☐	**C** ☐	**D** ☐	**E** ☐	....

Appendix 2

LiDAR error analysis

Table A2.1. Elevations surveyed on the tarmac car park and road at the Ainsdale Discovery Centre with ground RTK-GNSS on 07/05/2021, and differences (in cm) from the same points extracted from airborne LiDAR surveys flown 2010 to 2024.

Ground RTK-GNSS on 07/05/2021			Differences of airborne LiDAR surveys (cm)						
Easting	Northing	Elevation (m ODN)	14/03/2010 (cm)	15/05/2014 (cm)	10/04/2016 (cm)	25/09/2018 (cm)	15/10/2020 (cm)	07/12/2022 (cm)	19/09/2024 (cm)
329797.104	412686.699	8.880	-6.6	-6.9	3.5	7.2	-3.3	-3.7	-1.1
329798.633	412683.293	8.857	-6.7	-8.8	2.7	6.6	-4.0	-5.1	-2.9
329796.103	412678.044	8.808	-5.3	-7.0	3.0	7.2	-2.7	-4.0	-2.2
329794.855	412672.436	8.778	-8.6	-4.2	3.7	7.5	-2.1	-3.1	-0.6
329789.756	412667.378	8.801	-8.2	-6.5	2.3	6.4	-3.3	-3.4	-2.6
329787.275	412659.555	8.804	-9.1	-5.1	2.1	6.7	-2.5	-3.9	-2.1
329781.490	412656.146	8.837	-5.5	-2.8	2.6	7.9	-2.5	-3.8	-0.6
329781.430	412650.277	8.817	-9.6	-6.1	2.5	6.4	-2.4	-3.5	-0.6
329778.427	412643.684	8.763	-10.9	-5.7	3.1	7.1	-2.3	-4.9	-1.4
329772.597	412641.376	8.878	-6.8	-8.0	0.9	5.9	-4.0	-4.9	-1.8
329772.845	412634.750	8.862	-10.6	-4.6	2.2	6.5	-3.4	-4.6	-1.7
329764.418	412636.788	8.980	-8.5	-2.4	0.9	6.5	-3.8	-5.5	-2.6
329767.769	412641.561	8.989	-5.3	-4.2	0.6	4.8	-5.0	-4.4	-2.4
329765.883	412645.608	9.023	-8.8	-4.6	0.6	5.9	-4.6	-5.2	-2.3
329770.638	412647.588	8.944	-6.5	-3.8	-0.5	5.3	-5.1	-5.4	-3.5
329771.323	412651.735	8.901	-6.8	-1.3	0.9	6.0	-3.9	-4.2	-1.8
329761.727	412647.262	9.061	-10.0	-3.5	2.0	6.3	-4.3	-4.0	-2.4
329757.807	412641.744	8.972	-7.8	-2.1	0.2	4.8	-4.8	-4.6	-2.7
329753.449	412646.294	8.981	-7.0	-4.6	1.6	5.6	-3.5	-4.5	-2.8
329750.421	412650.447	8.996	-7.4	-2.6	2.1	6.2	-2.0	-3.1	-1.1
329745.470	412648.556	8.878	-7.1	-4.4	1.3	5.3	-2.6	-4.6	-3.2
329748.150	412642.989	8.796	-6.1	-6.7	2.0	6.5	-4.0	-3.0	-2.0
329802.632	412692.426	8.931	-4.0	-7.1	1.4	7.7	-3.1	-3.7	-2.5
	Mean:	8.893	-7.5	-4.9	1.8	6.4	-3.4	-4.2	-2.0
	StDev:	0.087	1.8	2.0	1.1	0.8	0.9	0.7	0.8

Table A2.2. Elevations surveyed on the tarmac car park at Lifeboat Road with ground RTK-GNSS on 07/10/2024, and differences (in cm) from the same points extracted from airborne LiDAR surveys flown 2010 to 2024.

Easting	Northing	Elevation (m ODN)	14/03/2010 (cm)	15/05/2014 (cm)	10/04/2016 (cm)	25/09/2018 (cm)	15/10/2020 (cm)	07/12/2022 (cm)	19/09/2024 (cm)
327448.841	406547.586	10.060	-5.5	-5.0	2.9	5.8	0.6	-1.4	2.0
327450.757	406552.162	10.103	-5.8	-3.8	3.1	5.2	0.9	-1.6	2.5
327447.940	406556.990	10.086	0.5	-0.2	7.0	9.4	4.7	2.5	6.0
327448.911	406564.006	10.162	-0.8	-2.1	4.8	8.0	3.9	2.0	4.5
327445.514	406568.027	10.187	-2.2	-4.4	4.3	7.4	3.0	1.7	5.6
327447.977	406572.678	10.221	-3.6	-3.6	4.0	6.4	1.9	-1.2	4.0
327447.116	406578.380	10.208	-0.3	-2.5	6.9	8.5	4.0	0.4	5.4
327432.851	406544.676	9.877	-3.2	-5.6	3.2	7.4	2.6	-0.6	4.9
327432.765	406541.416	9.892	-3.9	-6.1	-0.4	4.2	-0.4	-1.5	0.8
327432.368	406534.455	9.925	-8.5	-11.7	-1.5	1.6	-3.6	-5.5	-2.6
327430.570	406530.632	9.921	-10.4	-13.5	-5.5	-1.0	-6.1	-9.5	-5.7
327447.285	406549.342	10.099	-8.6	-9.0	-0.9	1.9	-2.9	-5.0	-0.5
327448.016	406544.014	10.055	-7.7	-9.0	-1.5	0.8	-2.8	-4.8	-2.3
327449.144	406536.680	10.026	-10.5	-10.8	-3.1	-0.4	-5.6	-8.4	-4.6
327446.739	406533.749	9.981	-8.6	-9.0	-1.7	2.0	-3.6	-5.7	-1.4
327448.007	406557.983	10.149	-6.1	-6.4	0.4	4.1	-1.0	-3.2	0.4
	Mean:	10.060	-5.3	-6.4	1.4	4.5	-0.3	-2.6	1.2
	StDev:	0.113	3.5	3.7	3.1	3.1	3.2	3.2	3.5

Table A2.3. Conversion factors between elevations derived from the old OSTN02 transformation (used for LiDAR surveys in 2010 and 2014) and the current OSTN15 transformation (used for LiDAR and RTK-GNSS surveys from 2016 onwards). Data source: https://www.ordnancesurvey.co.uk/gps/transformation/updateOSTN

Location	Conversion factor from OSTN02 to OSTN15
Ainsdale Discovery Centre	2.4 cm
St Josephs	2.5 cm
Cabin Hill	2.6 cm
Mean:	2.5 cm

Table A2.4. Elevation corrections applied to LiDAR surveys in this study to account for differences between OSTN02 and OSTN15, and levels measured on tarmac surfaces with RTK-GNSS (Ainsdale Discovery Centre and Lifeboat Road combined)

LiDAR survey	Conversion factor from OSTN02 to OSTN15	Average correction based on RTK-GNSS	Total correction applied to LiDAR
14/03/2010	+2.5 cm	+6.4 cm	+8.9 cm
15/05/2014	+2.5 cm	+5.7 cm	+8.2 cm
10/04/2016	none	none	none
25/09/2018	none	-5.4 cm	-5.4 cm
15/10/2020	none	none	none
07/12/2022	none	+3.4 cm	+3.4 cm
19/09/2024	none	none	none

Table A2.5 Elevations surveyed on the tarmac cycleway along Clifton Drive with ground RTK-GNSS on 08/10/2024, and differences (in cm) from the same points extracted from airborne LiDAR surveys flown 2010 to 2024. Note that the cycleway was resurfaced in mid 2022

Ground RTK-GNSS on 08/10/2024			Differences of airborne LiDAR surveys (cm)						
Easting	Northing	Elevation (m ODN)	05/02/2010 (cm)	28/02/2014 (cm)	07/04/2016 (cm)	24/09/2018 (cm)	15/10/2020 (cm)	24/09/2022 (cm)	17/09/2024 (cm)
331150.832	430143.228	6.763	-21.4	-8.0	-9.5	-16.5	-13.3	-5.6	-1.2
331146.324	430153.713	6.795	-19.4	-7.7	-9.5	-17.2	-13.9	-6.3	-1.1
331142.003	430165.576	6.838	-22.4	-13.8	-12.8	-20.8	-16.1	-7.6	-1.5
331132.873	430189.695	6.933	-18.7	-9.0	-9.5	-17.0	-13.9	-7.0	-1.5
331121.402	430221.572	6.995	-16.7	-10.6	-10.3	-16.6	-14.4	-6.8	-1.6
331096.114	430294.756	6.788	-24.8	-11.9	-15.5	-21.3	-19.1	-6.3	-2.1
331048.125	430431.868	6.337	-30.9	-14.7	-18.5	-24.3	-22.2	-5.5	-0.7
330963.632	430669.747	5.815	-31.5	-13.5	-19.0	-24.5	-24.1	-5.1	0.5
330929.784	430767.190	5.846	-27.0	-16.2	-20.9	-28.2	-23.8	-3.6	0.4
330896.116	430862.182	6.059	-29.4	-12.6	-20.7	-27.1	-23.0	-4.5	-1.0
	Mean:	6.517	-24.2	-11.8	-14.6	-21.4	-18.4	-5.8	-1.0
	StDev:	0.460	5.3	2.9	4.9	4.5	4.6	1.2	0.8

Table A2.6 Elevations extracted from three tarmac surfaces covering the site at St Annes: at Starr Gate tram station (26 points), North Beach Car Park (176 points) and North Promenade Car Park (170) from the airborne LiDAR survey flown 17/09/2024. Also, differences of the same points extracted from other airborne LiDAR surveys flown 2010 to 2022. Note that areas were selected where the surface was a flat and level as possible, and to avoid parked vehicles. Note that elevations collected in the 05/02/1010 and 28/02/2014 surveys have been transformed to OSTN15

	17/09/2024 elevation (m ODN)	Differences of airborne LiDAR surveys from 17/09/2024 survey					
		05/02/2010 (cm)	28/02/2014 (cm)	07/04/2016 (cm)	24/09/2018 (cm)	15/10/2020 (cm)	24/09/2022 (cm)
Starr Gate tram station (n=26)							
Min:	7.257	-9.5	8.5	-0.7	-4.7	-3.9	-7.2
5%-tile:	7.263	-9.1	7.9	-1.3	-4.3	-4.3	-7.6
25%-tile:	7.284	-8.2	6.3	-0.4	-4.4	-3.5	-6.1
50%-tile:	7.292	**-7.0**	**6.3**	**-0.2**	**-4.2**	**-2.9**	**-5.1**
75%-tile:	7.306	-8.4	5.7	-0.6	-4.6	-3.1	-5.5
95%-tile:	7.327	-7.5	5.1	-0.7	-4.7	-3.7	-6.9
Max:	7.330	-4.8	5.6	-1.0	-4.0	-2.4	-5.6
Mean:	7.295	-7.9	6.3	-0.5	-4.4	-3.2	-6.0
North Beach Car Park (n=176)							
Min:	6.577	-7.5	2.9	2.3	-4.7	-6.5	-3.6
5%-tile:	6.593	-6.1	4.7	1.7	-5.3	-5.8	-4.0
25%-tile:	6.635	-6.3	4.6	1.5	-5.5	-5.2	-4.3
50%-tile:	6.669	**-5.7**	**4.5**	**1.1**	**-5.9**	**-4.8**	**-4.7**
75%-tile:	6.699	-4.7	3.4	1.1	-5.9	-5.4	-4.9
95%-tile:	6.721	-2.9	4.8	1.9	-6.1	-4.7	-4.8
Max:	6.745	-5.3	3.3	0.5	-5.5	-4.3	-4.5
Mean:	6.665	-5.6	4.2	1.5	-5.7	-5.1	-4.5
North Promenade Car Park (n=170)							
Min:	8.226	-5.4	3.5	1.4	-3.6	-6.4	-5.7
5%-tile:	8.265	-5.3	3.2	1.5	-3.5	-5.6	-6.2
25%-tile:	8.346	-4.4	3.6	1.4	-3.6	-5.7	-6.1
50%-tile:	8.408	**-5.6**	**4.4**	**1.2**	**-2.8**	**-5.5**	**-5.5**
75%-tile:	8.475	-6.3	3.4	1.5	-3.5	-5.8	-6.0
95%-tile:	8.521	-3.9	4.0	1.9	-3.1	-5.6	-5.4
Max:	8.553	-3.1	4.9	1.7	-3.3	-5.5	-5.3
Mean:	8.407	-5.1	3.8	1.4	-3.5	-5.7	-6.0
	Mean of D50 values:	**-6.1**	**5.1**	**0.7**	**-4.3**	**-4.4**	**-5.1**

Table A2.7 Conversion factors between elevations derived from the old OSTN02 transformation (used for LiDAR surveys in 2010 and 2014) and the current OSTN15 transformation (used for LiDAR and RTK-GNSS surveys from 2016 onwards). Data source: https://www.ordnancesurvey.co.uk/gps/transformation/updateOSTN

Location	Conversion factor from OSTN02 to OSTN15
Starr Gate tram station	+2.2 cm
North Beach Car Park	+2.2 cm
North Promenade Car Park	+2.2 cm
Mean:	+2.2 cm

Table A2.8 Elevation corrections applied to LiDAR surveys in this study to account for differences between OSTN02 and OSTN15, and levels measured on tarmac surfaces with RTK-GNSS (Clifton Drive cycleway, Starr Gate tram station, North Beach Car Park and North Promenade Car Park combined)

LiDAR survey	Conversion factor from OSTN02 to OSTN15	Average correction based on RTK-GNSS	Total correction applied to LiDAR
14/03/2010	+2.2 cm	+6.1 cm	+8.3 cm
15/05/2014	+2.2 cm	-5.1 cm	-2.9 cm
10/04/2016	none	none	none
25/09/2018	none	+4.3 cm	+4.3 cm
15/10/2020	none	+4.4 cm	+4.4 cm
07/12/2022	none	+5.1 cm	+5.1 cm
19/09/2024	none	none	none

Appendix 3

Selected ground photographs

Formby (Shore Road, Ainsdale to River Alt)

Photograph A3.1 Steeply ramped dunes at Ainsdale North

Photograph A3.2 View north along the frontal dunes at Ainsdale North

Photograph A3.3 View south along the frontal dunes at Ainsdale North, showing notches

Photograph A3.4 Eroded dune frontage north of Fisherman's Path at Ainsdale

Photograph A3.5 Degraded dunes north of Victoria Road, Freshfield

Photograph A3.6 Blowout reaching beach level near Blundell Avenue

Photograph A3.7 Eroding tobacco waste cliffs near Wick's Lane

Photograph A3.8 Advancing parabolic dunes near Blundell Avenue, view seaward

Photograph A3.9 View north from mobile parabolic dunes at Blundell Avenue

Photograph A3.10 Accretionary frontal dune slopes south of Lifeboat Road

Photograph A3.11 Accretionary dune frontage near Albert Road

Photograph A3.12 Accreting embryo dunes and incipient foredunes near Range Lane

Photograph A3.13 View south along slowly accreting dune frontaghe north of Altcar Rifle range

Photograph A3.14 Artifical flood bank at Cabin Hill build in the mid 1970s

Photograph A3.15 Gap in the bank at cabin Hill

Photograph A3.16 Low-lying argicultural land in the Alt flodplain behind Cabin Hill

Appendix 4

Selected ground photographs

Starr Hills / St. Anne's North Beach

Photograph A4.1 View south along dune edge south of North Beach car park; note chestbut paing fencing and rows of placed Christmas trees

Photograph A4.2 View north along dune edge north of North Beach car park; note buried chestbut paling fencing and old Christmas trees

Photograph A4.3 The northern limit of dune progradation works at Starr Hills

Photograph A4.4 The section of slowly eording dune frontage at the northenr end of Starr Hills; note low shingle berm on upper beach and semi-vegetated blowouts in the frontal dunes

Photograph A4.5 Sloping gabion wall at the northern end of Starr Hills

Photograph A4.6 Sand blowing onto the cycleway at the northern end of Cifton Drive; new housing on fomrer Pontins holiday village site to the right

Photograph A4.7 View south along the northern part of Clifton Drive shosing mobile sand incursion from degraded dunes to the right

Photograph 4.8 Geotextile mattting and marram planting used in attempts to control sand movment at th enorthenr end of Starr Hills

Photograph 4.9 Controlled access from the cycleway into the northern part of Starr Hills

Photograph 4.10 Thickly vegetated inland dunes just north of New Thursby Nursing Home

Photograph 4.11 Information hut at the entrnce to the St Anne's Dunes Local nature Reserve

Photograph 4.12 View north along the cycleway / Starr dunes boundary to the south of New Thursby Nursing Home

Appendix 5

Change in beach contour positions from LIDAR analysis

Formby (Shore Road, Ainsdale to River Alt)

Table A5.1 Changes in distance to the HAT contour (5.30 m ODN) since the baseline LiDAR survey on 14/03/2010.

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Shore Road	112	10	22	27	29	29	34
	111	6	11	14	16	18	21
	110	6	12	14	17	22	22
	109	8	8	9	16	19	18
	108	6	9	17	23	29	27
	107	13	18	25	31	37	39
	106	17	23	30	34	42	45
	105	17	23	29	35	40	46
	104	13	19	26	32	41	42
	103	16	21	29	34	43	42
	102	12	16	22	27	34	33
	101	8	13	19	25	28	26
	100	8	13	19	21	26	27
	99	7	12	18	19	25	25
	98	7	11	16	17	24	24
	97	5	8	13	13	20	20
	96	5	7	12	12	18	19
	95	6	6	14	12	18	18
	94	6	5	13	12	19	19
	93	6	5	14	12	18	18
	92	5	5	12	10	15	15
	91	5	4	10	8	13	14
	90	5	3	7	5	9	11
	89	1	-1	2	0	4	3
Ainsdale Boundary	88	1	-1	1	-1	3	3
	87	0	-2	-1	-2	0	-1
	86	1	-3	-3	-2	-1	-6
	85	2	-4	-3	-4	-4	-8
	84	1	-6	-5	-6	-9	-12
	83	0	-10	-10	-12	-14	-17
	82	-5	-11	-14	-18	-23	-24
	81	-7	-14	-16	-21	-26	-27
	80	-14	-22	-23	-25	-29	-30
	79	-7	-13	-17	-21	-24	-24
	78	-8	-18	-22	-22	-25	-27
	77	-10	-16	-16	-20	-19	-21
	76	-5	-13	-15	-20	-19	-22
Fishermans Path	75	-4	-12	-13	-19	-18	-20
	74	-2	-8	-8	-15	-18	-19
	73	-3	-9	-9	-15	-21	-20
	72	-6	-11	-11	-19	-25	-24
	71	-9	-15	-14	-19	-24	-25
	70	-10	-15	-13	-20	-24	-28
	69	-10	-14	-12	-19	-23	-24
	68	-12	-15	-15	-21	-24	-29
	67	-10	-16	-17	-23	-28	-31
	66	-8	-18	-19	-26	-31	-36
	65	-11	-21	-22	-31	-35	-37
	64	-12	-21	-22	-30	-33	-38
	63	-14	-19	-22	-28	-29	-33
	62	-11	-18	-22	-26	-28	-34
	61	-7	-18	-21	-26	-30	-34
	60	-9	-17	-21	-28	-33	-38
Victoria Road	59	-10	-17	-21	-24	-25	-26
	58	-11	-19	-19	-21	-22	-23
	57	-12	-21	-19	-29	-32	-33
	56	-16	-23	-19	-29	-33	-32
	55	-13	-24	-24	-34	-40	-44
	54	-11	-23	-27	-36	-44	-48
	53	-7	-17	-20	-28	-36	-44
	52	-7	-16	-20	-29	-37	-43
	51	-8	-18	-24	-30	-37	-40
	50	-9	-16	-20	-27	-34	-38
	49	-12	-17	-18	-21	-27	-28
	48	-10	-15	-14	-21	-21	-25
Wicks Lane	47	-7	-10	-10	-15	-16	-20

Table 5.1 cont. Changes in distance to the HAT contour (5.30 m ODN) since the baseline LiDAR survey on 14/03/2010 (continued)

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Wicks Lane	46	-3	-7	-8	-10	-9	-11
	45	2	-5	-4	-8	-9	-17
	44	1	-2	-2	-5	-6	-8
	43	5	3	2	3	4	2
	42	3	3	3	3	6	3
	41	4	3	6	5	8	8
	40	6	3	6	9	10	12
	39	4	3	5	7	11	11
Lifeboat Road	38	6	7	8	11	16	16
	37	6	7	10	14	17	17
	36	3	4	6	10	14	17
	35	4	6	10	12	17	17
	34	5	8	11	12	15	16
	33	8	8	12	15	19	22
	32	8	11	16	19	25	27
	31	9	14	19	21	28	30
	30	12	16	21	23	30	34
Albert Road	29	16	19	24	27	31	36
	28	16	19	27	31	34	37
	27	11	15	21	24	28	32
	26	7	12	17	21	25	28
	25	6	8	11	14	19	22
	24	7	9	13	16	21	23
	23	7	10	14	16	23	26
	22	7	10	13	17	22	25
	21	4	7	11	15	21	24
	20	5	8	12	15	22	25
	19	6	8	12	16	21	24
Range Lane	18	5	10	13	13	21	25
	17	5	8	12	15	19	22
	16	4	7	11	14	19	23
	15	5	9	13	17	21	25
	14	6	10	14	19	22	26
	13	5	10	14	17	20	23
	12	5	9	12	14	17	19
	11	4	7	9	10	12	12
	10	3	4	6	5	7	7
	9	1	0	2	1	1	1
	8	1	-1	1	-1	0	-1
	7	1	0	0	1	1	1
	6	-1	-2	-2	-2	-1	-1
	5	-1	0	0	1	3	5
	4	1	4	7	7	12	15
	3	5	11	14	14	19	22
	2	8	12	16	17	20	22
Alt Estuary	1	1	11	12	14	18	18

Table A5.2 Changes in distance to the MHWS contour (4.07 m ODN) since the baseline LiDAR survey on 14/03/2010.

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Shore Road	112	8	17	23	22	41	41
	111	13	16	41	28	38	43
	110	12	17	19	46	36	48
	109	6	14	24	21	34	35
	108	12	14	18	31	30	31
	107	7	11	15	27	29	47
	106	4	6	12	18	24	34
	105	13	12	15	20	30	40
	104	16	17	18	30	33	42
	103	6	8	7	25	19	33
	102	9	12	23	24	20	33
	101	11	11	32	24	29	30
	100	12	15	16	26	24	31
	99	19	16	19	27	29	35
	98	27	19	22	27	33	62
	97	27	19	26	26	32	43
	96	21	16	17	23	29	39
	95	21	13	17	22	32	38
	94	22	15	19	23	30	40
	93	19	12	17	18	24	30
	92	20	11	10	16	21	27
	91	14	8	4	10	13	18
	90	8	6	7	7	10	16
	89	3	3	-1	2	7	5
Ainsdale Boundary	88	4	3	-3	4	12	7
	87	-18	-17	-9	-19	-11	-13
	86	-7	-8	-9	-7	-5	-11
	85	-8	-12	-7	-14	-12	-11
	84	-3	-6	-3	-10	-8	-7
	83	-12	-18	-14	-20	-25	-22
	82	-18	-21	-21	-25	-34	-26
	81	-16	-22	-18	-24	-33	-28
	80	-17	-23	-23	-25	-30	-28
	79	-18	-21	-30	-28	-32	-29
	78	-11	-16	-24	-21	-24	-24
	77	-10	-16	-14	-19	-16	-22
	76	-6	-11	-13	-20	-18	-19
Fishermans Path	75	-4	-8	-3	-18	-4	-16
	74	-5	-8	-5	-16	-11	-14
	73	-5	-10	-11	-13	-21	-20
	72	-4	-7	-4	-15	-11	-21
	71	-9	-13	-9	-17	-14	-25
	70	-8	-15	-7	-16	-14	-21
	69	-1	-6	-3	-13	-17	-18
	68	0	-5	-6	-14	-19	-17
	67	-7	-14	-16	-22	-23	-26
	66	-18	-25	-27	-34	-34	-39
	65	-22	-25	-28	-37	-35	-35
	64	-14	-17	-23	-29	-26	-25
	63	-13	-19	-23	-25	-24	-26
	62	-11	-19	-21	-26	-26	-31
	61	-12	-20	-22	-27	-31	-33
	60	-12	-20	-19	-29	-32	-36
Victoria Road	59	-14	-19	-21	-29	-32	-29
	58	-16	-22	-23	-28	-26	-27
	57	-13	-16	-18	-28	-26	-24
	56	-13	-21	-20	-29	-33	-29
	55	-16	-23	-27	-35	-40	-40
	54	-14	-24	-26	-32	-38	-40
	53	-8	-19	-21	-26	-34	-39
	52	-8	-19	-21	-28	-34	-35
	51	-11	-19	-24	-31	-32	-38
	50	-10	-18	-19	-29	-33	-33
	49	-12	-16	-21	-24	-29	-27
	48	-5	-11	-11	-18	-21	-20
Wicks Lane	47	-1	-6	-4	-13	-12	-12

Table A5.2 cont. Changes in distance to the MHWS contour (4.07 m ODN) since the baseline LiDAR survey on 14/03/2010 (continued)

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Wicks Lane	46	3	-5	2	-6	-9	-3
	45	5	-6	-3	-1	-4	1
	44	3	0	-2	2	-5	5
	43	4	3	0	5	1	6
	42	7	7	14	10	9	11
	41	8	8	19	9	13	15
	40	5	4	7	11	13	17
	39	5	4	8	12	12	17
Lifeboat Road	38	2	3	5	10	14	24
	37	11	10	19	24	26	32
	36	12	11	18	34	28	51
	35	16	8	23	31	33	58
	34	39	20	12	29	33	44
	33	11	32	14	36	50	58
	32	7	19	22	41	57	67
	31	5	4	11	39	56	61
	30	2	-1	9	36	55	64
Albert Road	29	-1	-10	4	29	57	61
	28	3	-9	1	20	49	56
	27	-4	-7	-2	15	40	49
	26	0	2	4	20	41	56
	25	12	6	11	23	21	53
	24	6	11	13	26	33	57
	23	7	22	19	39	47	63
	22	1	18	15	34	45	61
	21	0	20	23	34	40	66
	20	-6	15	12	31	38	55
	19	4	21	22	38	53	56
Range Lane	18	6	25	15	46	52	57
	17	11	49	48	71	78	76
	16	13	33	32	81	85	90
	15	11	45	38	88	81	85
	14	6	36	35	72	76	74
	13	10	42	38	67	57	59
	12	11	31	28	46	52	48
	11	11	23	20	38	41	44
	10	10	29	19	33	33	41
	9	7	25	11	26	34	38
	8	-1	18	8	22	28	38
	7	0	9	7	15	18	23
	6	-2	7	3	14	11	14
	5	3	6	-1	11	8	17
	4	3	5	9	14	16	17
	3	10	12	13	17	16	24
	2	6	10	12	19	13	19
Alt Estuary	1	1	2	3	5	7	8

Table A5.3 Changes in distance to the MHWN contour (2.37 m ODN) since the baseline LiDAR survey on 14/03/2010.

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Shore Road	112	112	68	95	13	66	66
	111	105	63	83	27	76	62
	110	62	81	99	41	85	81
	109	86	89	80	56	115	85
	108	72	78	55	193	87	93
	107	59	54	68	182	83	72
	106	55	44	26	74	62	62
	105	19	11	0	7	10	21
	104	-88	-88	-117	-52	-87	-53
	103	-71	-72	-119	-69	-72	-71
	102	-67	-31	-105	-53	-44	-47
	101	-66	-29	-97	60	-84	-67
	100	-64	-39	-96	11	-91	-52
	99	-59	-16	-94	63	-81	-38
	98	-49	-17	52	52	-61	-29
	97	-59	-29	36	42	-66	-37
	96	-67	-20	24	3	-71	-38
	95	-36	-17	27	-36	-64	-29
	94	-22	2	50	-17	-29	89
	93	-112	-101	-63	-118	2	-129
	92	8	-100	-55	-120	-23	-132
	91	0	-122	-52	-123	-50	-128
	90	-1	-116	-51	-114	1	-137
	89	-9	-112	-49	-82	16	-7
Ainsdale Boundary	88	-11	19	-39	50	23	-14
	87	-4	23	-18	51	32	-18
	86	-34	0	-52	35	17	-25
	85	-30	0	-36	32	-50	-24
	84	-11	8	46	43	-54	-21
	83	-19	-7	-42	33	35	-24
	82	-14	-2	-32	36	35	-37
	81	-9	-5	-43	21	32	-39
	80	-84	-65	-105	-51	-31	-75
	79	14	-59	-97	-76	-29	-97
	78	47	-28	-61	-47	13	35
	77	54	-33	28	-53	12	30
	76	94	7	76	0	65	69
Fishermans Path	75	13	-68	-85	-98	-35	-10
	74	-2	-78	-4	-109	-38	-21
	73	-6	-86	9	-92	-47	-25
	72	4	-71	19	14	-45	-21
	71	5	-98	23	21	-42	-20
	70	8	-89	19	37	-46	-10
	69	16	16	9	36	-42	-66
	68	-3	6	17	40	49	2
	67	33	-10	16	-72	32	19
	66	-39	-23	27	26	35	33
	65	-22	-19	38	37	72	37
	64	29	-64	-2	4	25	-1
	63	9	-71	-9	3	-20	-29
	62	-12	-3	-16	-17	-38	-24
	61	5	16	23	2	1	-2
	60	1	21	4	8	17	-6
Victoria Road	59	1	24	-19	9	8	-10
	58	1	23	-42	18	-2	-22
	57	6	20	22	12	3	25
	56	7	16	6	5	2	-34
	55	-5	4	-10	-11	5	-37
	54	-35	-29	-54	-26	-45	-63
	53	-17	2	-32	-1	-24	-25
	52	-17	14	-21	4	-13	-14
	51	-8	31	-11	-51	-1	7
	50	1	-29	-6	-35	5	13
	49	17	-12	-12	-7	12	17
	48	-14	20	1	11	20	-20
Wicks Lane	47	7	13	-5	13	-50	-19

Table A5.3 cont. Changes in distance to the MHWN contour (2.37 m ODN) since the baseline LiDAR survey on 14/03/2010 (continued)

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Wicks Lane	46	11	26	-2	32	-13	0
	45	44	-2	34	-27	3	44
	44	44	-19	40	-23	6	58
	43	34	-29	-13	50	25	61
	42	6	-58	-45	-40	-3	36
	41	19	-43	-26	-5	1	-46
	40	35	-15	12	2	22	-24
	39	-80	-1	12	-10	27	-38
Lifeboat Road	38	-109	8	22	-5	32	-48
	37	-39	43	17	65	-8	26
	36	-28	31	29	47	35	30
	35	-5	44	11	46	-44	46
	34	-22	-19	11	19	56	43
	33	-32	-115	-43	5	48	56
	32	-43	11	-72	-42	-38	-67
	31		29	-32	-9	9	80
	30		202	143	185	165	257
Albert Road	29		-23	-1	-5	77	77
	28		-1	28	-25	-51	31
	27		-11	21	-51	-75	-15
	26		-11	-88	-53	-81	-14
	25		60	-25	-14	-8	59
	24		-93	-115	-68	-103	-144
	23		-40	-113	-63	-129	-151
	22		2	-49	-111	-85	-96
	21	102	112	62	-20	42	9
	20	37	76	73	-31	59	-9
	19	-32	-25	-67	-34	-35	-89
Range Lane	18	55	68	40	56	32	13
	17	-20	54	38	48	-55	25
	16	40	-35	-70	-54	-46	25
	15	-55	-18	-16	-26	-84	-2
	14	-38	-35	10	0	-31	-46
	13	-45	-49	-86	-64	-39	-73
	12	-61	-52	-48	-27	-27	-43
	11	-12	-28	-15	3	-4	-35
	10	-33	-22	-25	16	-88	-30
	9	-30	-31	-1	23	6	-19
	8	-52	-41	-46	-102	-28	-37
	7	-65	-33	-37	-52	-76	-26
	6	-39	-25	-5	-80	-60	-18
	5	42	43	60	0	46	-45
	4	-3	13	-29	-18	13	17
	3	37	-14	19	26	-25	-16
	2	18	-9	-2	15	-32	-18
Alt Estuary	1	27	30	23	20	-36	-11

Table A5.4 Changes in distance to the MLWN contour (-2.90 m ODN) since the baseline LiDAR survey on 14/03/2010 and/or the bathymetry survey July-September 2010 (source: Channel Coast Observatory)

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Shore Road	112	17	-39	0	148	9	-7
	111	-14	1	-20	-19	18	-16
	110	-7	-38	5	18	8	-13
	109	34	-14	-16	1	13	7
	108	-13	-32	-16	8	-18	-14
	107	21	-38	-26	9	8	8
	106	9	-15	1	-5	-29	-16
	105	12	0	-4	6	-5	-1
	104	16	-39	27	16	-9	3
	103	12	31	29	17	12	12
	102	-18	-52	0	-24	-47	-27
	101	-14	-35	-15	-27	-13	-6
	100	-1	-26	2	-10	-33	-24
	99	-6	-29	-38	-70	-51	-24
	98	13	-10	30	-45	7	-20
	97	15	-40	-8	19	-13	3
	96	-31	-31	-18	10	-25	2
	95	-27	11	5	7	-31	-20
	94	-51	14	-3	6	-21	-17
	93	4	15	3	-2	-29	-21
	92	-32	8	-16	-8	-44	-90
	91	-14	15	-59	-30	-41	-98
	90	15	21	-1	-19	-18	10
	89	16	25	8	-18	-24	5
Ainsdale Boundary	88	-26	-9	-11	-5	-24	-13
	87	29	9	6	7	-6	-5
	86	-22	-2	-11	-4	-22	-18
	85	25	-11	-19	-14	-18	-24
	84	3	-30	-30	-26	-31	-51
	83	9	-38	-31	-34	-33	-59
	82	-1	-35	-16	-35	-31	-64
	81	-7	-37	-20	-30	-34	-47
	80	11	-18	-10	-20	-21	-27
	79	24	-10	-5	5	-17	-53
	78	-3	-38	-25	-17	-36	-87
	77	31	8	17	26	18	38
	76	51	-4	15	31	10	46
Fishermans Path	75	-41	-73	-60	-47	-65	-66
	74	-33	-78	-41	-56	-71	-33
	73	-22	-12	-60	-62	-85	-21
	72	-26	-84	-37	-60	-90	-38
	71	-6	-18	-24	-41	-93	-4
	70	-59	-22	-54	-84	-61	-45
	69	-54	-2	-49	-91	-18	-56
	68	-18	-39	-44	-98	-13	-54
	67	-14	-8	13	-40	52	14
	66	34	48	16	-30	62	13
	65	36	49	-3	-11	72	11
	64	57	51	-8	25	71	21
	63	46	49	8	45	81	32
	62	29	32	-12	26	24	0
	61	-9	-17	-50	-16	-68	-45
	60	-11	-18	-39	-13	-49	-32
Victoria Road	59	-24	-34	-35	-8	-21	-19
	58	-33	-59	-38	-55	-37	-2
	57	-52	-39	-53	-64	-46	-14
	56	-47	-38	-75	-61	-43	-77
	55	-45	-26	-74	-64	-16	-67
	54	-39	-19	-12	-73	-13	-64
	53	-22	-7	0	-60	-11	-44
	52	-3	-10	22	-54	7	-18
	51	-6	-21	23	-49	20	-4
	50	-3	39	-4	-62	-48	-23
	49	-24	9	-30	-97	-72	-24
	48	-6	19	-24	-33	-69	-18
Wicks Lane	47	-7	47	-29	0	-78	-30

Table A5.4 cont. Changes in distance to the MLWN contour (-2.90 m ODN) since the baseline LiDAR survey on 14/03/2010 and/or the bathymetry survey July-September 2010 (source: Channel Coast Observatory) (continued)

Location	Profile	15/05/2014	10/04/2016	25/09/2018	15/10/2020	07/12/2022	19/09/2024
Wicks Lane	46	-5	29	-30	15	-22	-17
	45	4	-89	-27	35	-52	-31
	44	9	-51	-25	47	-51	-17
	43	-16	-64	-41	25	-69	-52
	42	-45	-72	-47	20	-77	-59
	41	-53	-73	-57	-150	-94	-94
	40	-2	-22	-20	-90	-56	-57
	39	-31	-127	-107	-158	-172	-187
Lifeboat Road	38	-122	-102	-94	-194	-179	-194
	37	-47	-153	-111	-243	-189	-297
	36	-49	-195	-154	-243	-317	-282
	35	-15	42	118	-1759	-1877	-1931
	34	162	-36	316	290	-84	343
	33	-35	31	60	-66	17	-6
	32	-17	10	18	-23	22	36
	31	7	22	7	-10	34	15
	30	24	21	20	7	54	35
Albert Road	29	30	33	29	20	47	69
	28	29	33	30	21	40	44
	27	27	46	35	35	47	41
	26	19	42	40	43	52	41
	25	24	47	48	57	68	62
	24	29	35	43	37	71	67
	23	25	41	26	36	66	76
	22	19	22	19	27	57	60
	21	8	12	4	20	21	40
	20	17	15	1	13	-1	29
	19	21	19	-3	17	0	34
Range Lane	18	19	19	-1	11	11	13
	17	9	6	-10	-2	-4	-4
	16	7	6	-9	-10	-5	-21
	15	18	13	2	-11	1	-5
	14	-2	-10	-25	-19	-14	-26
	13	-12	-23	-29	-30	-27	-26
	12	-9	-19	-29	-26	-22	-21
	11	-5	-17	-27	-22	-26	-20
	10	-14	-16	-34	-36	-31	-30
	9	-14	-23	-27	-38	-33	-28
	8	-12	-27	-26	-31	-29	-31
	7	-16	-33	-31	-46	-28	-30
	6	-12	-28	-25	-39	-36	-26
	5	-13	-22	-18	-30	-27	-33
	4	-15	-23	-19	-27	-19	-32
	3	-13	-18	-32	-32	-21	-32
	2	-10	-19	-30	-23	-22	-22
Alt Estuary	1	-7	-17	-24	-24	-22	-30

Appendix 6

Changes in beach contour positions from LIDAR analysis

Starr Hills / St Anne's North Beach

Table A6.1 Changes in distance to the HAT contour (5.30 m ODN) since the baseline LiDAR survey on 05/02/2010.

Profile	28/02/2014	07/04/2016	24/09/2018	18/10/2020	24/09/2022	17/09/2024
A	-3	-3	-3	-3	-4	-4
B	5	10	15	17	19	26
C	8	15	21	25	28	34
D	10	16	22	36	39	46
E	12	17	41	52	52	58
E2	6	9	15	17	23	25
F	8	11	18	22	28	31
G	2	5	13	18	19	22
G2	-6	-3	-3	-4	-4	-2
H	0	0	0	0	0	0

Table A6.2 Changes in distance to the MHWS contour (4.02 m ODN) since the baseline LiDAR survey on 05/02/2010.

Profile	28/02/2014	07/04/2016	24/09/2018	18/10/2020	24/09/2022	17/09/2024
A	5	-2	-4	-3	-3	-3
B	5	-6	-4	5	-3	5
C	5	-10	-17	-3	-15	-7
D	2	3	33	19	6	4
E	-2	13	6	36	39	41
E2	-10	12	11	47	43	44
F	3	21	30	34	48	56
G	19	37	57	55	76	72
G2	11	43	60	65	92	105
H	13	46	54	67	102	108

Table A6.3 Changes in distance to the MHWN contour (2.10 m ODN) since the baseline LiDAR survey on 05/02/2010.

Profile	28/02/2014	07/04/2016	24/09/2018	18/10/2020	24/09/2022	17/09/2024
A	-16	-14	-20	-45	-13	-13
B	21	11	-6	-2	23	-16
C	-5	-44	-10	10	-5	12
D	-59	-83	-44	-42	17	49
E	-36	-89	-178	-122	81	34
E2	46	11	-129	-33	-94	47
F	51	114	71	-7	19	27
G	23	71	62	60	36	128
G2	20	15	49	19	219	111
H	-7	67	-47	-23	-54	71

Table A6.4. Changes in distance to the approximate MLW contour (-2.90 m ODN) since the LiDAR survey on 28/02/2014 (the baseline survey on 05/02/2010 did not extend to cover the -2.90 m ODN contour).

Profile	07/04/2016	24/09/2018	18/10/2020	24/09/2022	17/09/2024
A	25	-2	13	5	7
B	42	30	48	-22	-15
C	-76	-61	-34	-75	-73
D	45	-46	-44	-14	-115
E	-76	-57	-73	-122	-116
E2	-83	-74	37	-107	-125
F	62	4	21	-50	-155
G	nd	nd	nd	nd	nd
G2	nd	nd	nd	nd	nd
H	nd	nd	nd	nd	nd

Table A6.5. Horizontal differences in the position of four beach contours at St Annes caused by hypothetical 5 cm and 10 cm vertical errors in the LiDAR data, measured at each of the profiles where data exist for the LiDAR survey on 17/09/2024

Profile	5 cm vertical error				10 cm vertical error			
	5.30 m ODN	4.02 m ODN	2.10 m ODN	-2.90 m ODN	5.30 m ODN	4.02 m ODN	2.10 m ODN	-2.90 m ODN
A	0.6	0.9	3.1	2.0	1.2	1.7	6.2	4.0
B	0.7	2.6	1.6	2.6	1.5	5.1	3.2	5.3
C	0.8	10.4	3.1	5.5	1.5	20.9	6.1	10.9
D	0.5	6.5	5.3	2.6	1.0	13.0	10.6	5.1
E	0.9	17.7	4.2	6.0	1.8	35.4	8.4	12.0
E2	0.8	5.2	0.8	3.2	1.5	10.3	1.6	6.4
F	0.3	11.1	2.1	6.3	0.6	22.3	4.2	12.5
G	0.5	16.8	4.2	nd	0.9	33.5	8.3	nd
G2	0.9	16.0	2.2	nd	1.8	32.0	4.4	nd
H	nd	13.8	nd	nd	nd	27.7	nd	nd
Mean:	0.7	10.1	2.9	4.0	1.3	20.2	5.9	8.0