

Beach–dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using LIDAR data

S.E. Saye^a, D. van der Wal^b, K. Pye^{a,*}, S.J. Blott^a

^a*Kenneth Pye Associates Ltd., Crowthorne Enterprise Centre, Crowthorne Business Estate, Old Wokingham Road, Crowthorne, RG45 6AW, UK*

^b*Centre for Estuarine and Coastal Ecology (NIOO-CEMO), P.O. Box 140, 4400 AC Yerseke, The Netherlands*

Received 7 August 2003; received in revised form 16 May 2005; accepted 17 May 2005

Available online 10 August 2005

Abstract

The critical relationships between beach and nearshore parameters and the erosion/accretion status of frontal dunes have been investigated using LIDAR data, complemented by data obtained from conventional topographic and bathymetric surveys, at five dune systems in England and Wales. Morphometric parameters calculated from the LIDAR data demonstrate the presence of a general relationship between beach morphology, dune morphology and erosion/accretion. Eroding dunes were found to be associated with narrower, steeper beaches whilst accreting dunes were associated with wider, low-angle beaches. However, the critical beach width/mean slope angle separating eroding dunes from stable or accreting dunes was found to vary between sites. At any given site, changes in beach width/slope over time can be used to provide an ‘early warning’ of changes in frontal dune erosion/accretion behaviour.

© 2005 Elsevier B.V. All rights reserved.

Keywords: LIDAR; Coastal dunes; Beach–dune interaction; Erosion; Morphology

1. Introduction

Sand dunes are a vital component of coastal and flood defences in many parts of the world. On short time scales, dune erosion during and after severe storms acts to naturally replenish beach and nearshore levels. On longer time scales, dune systems can act as mobile flood defence barriers capable of altering position and form in response to varying wind/wave climate, sea level change, and shoreline erosion and

deposition. In addition, dunes have high conservation and recreational value and can assist in the maintenance of freshwater tables against saltwater intrusion. Coastal dunes and beaches, together with adjoining parts of the nearshore zone, form parts of an integrated coastal system which need to be considered together for the purposes of coastal engineering and habitat management. Changes in beach and/or nearshore morphology are likely to be reflected by changes in the erosion/accretion status and morphology of the frontal dunes. Identification of the critical beach and nearshore morphological parameters which define a likely change from frontal dune stability or accretion to

* Corresponding author. Tel./fax: +44 1344 751610.

E-mail address: k.pye@kpal.co.uk (K. Pye).

erosion is therefore important to predict the onset of erosion or accretion before it actually happens, and to inform the process of shoreline management.

Several techniques can be used to obtain topographic data, but vary in terms of their applicability for use at different spatial and temporal scales. Conventionally, topographic data above mean low water mark have been obtained by ground surveys using a theodolite or Total Station (EDM) equipment. Cross-sections across the beach (and sometimes across the frontal dunes) are taken with reference to fixed marker posts and benchmarks at intervals along the coast. Under favourable conditions, surveying accuracy may be as good as ± 1 cm but more typically is of the order of ± 5 cm. More recently, kinematic GPS (Global Positioning System) surveying techniques have been used, often vehicle mounted, to provide both cross-sectional and grid-based spot height data. Under optimal conditions spatial resolution of a few tens of centimetres and vertical resolution of the order of 1 cm can be obtained (Morton et al., 1993). The high accuracy of ground surveys means they are suitable for comparison of sequential surveys, allowing volume change detection of beaches and dunes. However, due to the considerable logistic efforts involved in making the measurements, spatial resolution is usually relatively limited, with data obtained mainly from defined transects. Bathymetric data below the level of mean low water were traditionally obtained by lead line surveys combined with position fixing by triangulation, and more recently by echo sounding or multi-beam (swathe) surveying combined with GPS position fixing. Each method of survey is prone to errors, and accuracy over even quite small areas is still routinely no better than ± 15 cm (e.g., Morang et al., 1997; Hicks and Hume, 1997; Gibeaut et al., 1998; van der Wal and Pye, 2003). Photogrammetry, using stereo air photographs at 1:5000 or 1:10,000 scale, offers a moderately accurate method of obtaining contoured height data from dune and intertidal areas which are difficult to survey on the ground or by boat, but the method is time-consuming and subject to substantial errors in heavily vegetated terrain. Typical vertical accuracy over bare or thinly vegetated surfaces is of the order of 20–25 cm, but may be of the order of metres over wooded ground. Airborne or satellite-borne radar altimetry provides a means of acquiring topographic information over quite wide

areas with vertical resolution of the order of a few tens of centimetres, but spatial resolution is rarely better than 20–30 m and data availability is often poor.

Airborne scanning laser altimetry (LIDAR) offers a useful alternative method of obtaining topographic information for coastal dunes and intertidal areas above low water mark, at least where forest or thick scrub vegetation is not present. A number of different types of airborne system are now available, using either single or multiple return sensor systems to record laser backscatter from the ground surface (and sometimes overlying vegetation cover) (e.g., Cracknell, 1999; Mason et al., 2000). The method has the advantage of being relatively quick, providing data at 1–2 m spatial resolution and 15–20 cm vertical accuracy. In clear waters, some laser systems can also provide bathymetric information, albeit at somewhat lower levels of accuracy (e.g., Irish and White, 1998). However, with all LIDAR surveys ground truthing is essential in order to avoid errors which may arise due to data acquisition or processing deficiencies. Special care needs to be taken when interpreting data from vegetated or wet surfaces (Han, 1995; Huising and Vaessen, 1997; Eleveld, 1999). Only recently have LIDAR surveys begun to be used routinely to map of river environments (Charlton et al., 2003), to define topography for hydraulic and habitat evolution modelling in estuaries (French, 2003; Blott and Pye, 2004), to quantifying beach morphology changes (Sallenger et al., 2003) and to study dune morphodynamics and volumetric changes (Andrews et al., 2002; Woolard and Colby, 2002). In this study high resolution LIDAR data, complemented by data obtained from conventional topographic and bathymetric surveys, were used to investigate the relationships between frontal dune morphology, notably accretion / erosion status, and beach/nearshore morphology. Five dune sites were selected for assessment, representing a range of process environments and morphological types representative of the range found in England and Wales. The principal aim of the work was to determine whether any common quantitative relationships could be established linking beach/intertidal morphology, frontal dune morphology, and dune erosion/accretion status. Such relationships, if established, offer the prospect of predicting future change in dune morphology and erosion/accretion by way of monitoring of the intertidal zone. For reasons of

space, the paper primarily presents data relating to the Sefton coastal dune system in northwest England; data for the other sites are included mainly for comparative purposes.

2. Methods

2.1. Selection of study areas

The five dune systems selected for assessment were: (1) Sefton coast (Merseyside), (2) Spurn Peninsula (Humberside), (3) Brancaster Bay (Norfolk), (4) Studland Bay (Dorset), and (5) Kenfig Burrows (South Wales) (Fig. 1). These sites were chosen to provide wide geographical coverage and contrasting examples of system attributes and process regimes. Despite the differences, there are also similarities: for example, Spurn and Studland are both barrier spit systems, although they occur in different process regimes, whilst Kenfig and Sefton both evolved as open coast transgressive systems (Saye, 2003). Brancaster Bay forms part of a former barrier island dune system which is now attached to the mainland by active and reclaimed salt-marshes. The availability

of LIDAR data also governed site selection. Particular attention was given to the Sefton coast dune system owing to the availability of detailed historical survey information and an extensive literature for this area. The work was undertaken as part of a larger investigation into the geomorphology of coastal dune systems in England and Wales (Pye and Saye, 2005).

2.2. Quantification of beach–dune morphology using LIDAR data

LIDAR works by measuring the direction and propagation time of laser pulses from the aircraft to the ground and back, using a completely digital, integrated multi-sensor system which consists of a satellite-based positioning system (kinematic GPS), INS (Inertial Navigation System), and a laser. In the United Kingdom, LIDAR data normally cannot be obtained below the level of the Lowest Astronomical Tide due to the high turbidity of the coastal waters and because of the type of LIDAR (wavelength) used. Typical quality requirements for LIDAR stipulate a systematic error (mean difference) of 5 cm and average vertical error of 15 cm (Han, 1995). However, this claimed vertical accuracy is not often achieved. The UK Environment Agency calculated that test data for the western Wash contained an average vertical error of ± 19 cm (Mason et al., 2000). Inaccurate positioning of the aircraft by GPS can lead to errors in geo-referencing and data collection can be affected by various interferences. Data processing errors increase with increasing vegetation coverage and height and also with increasing relief (Huising and Vaessen, 1997; Eleveld, 1999). Han (1995) found an accuracy of processed LIDAR data ranging from 5 cm in open terrain to 20 cm in deciduous forest. The reported horizontal (positioning) error is often c. 1 m and most processed data are provided at 2 m grid resolution, although occasionally at 1 m resolution.

LIDAR data were obtained from the UK Environment Agency for each of the five dune systems. Data were collected in March 1998 (Studland), March 1999 (Brancaster and Sefton), May 1999 (Spurn) and November 1999 (Kenfig), respectively. The data were filtered to remove vegetation, but not buildings. Most data were supplied in ArcView ASCII grid format, at

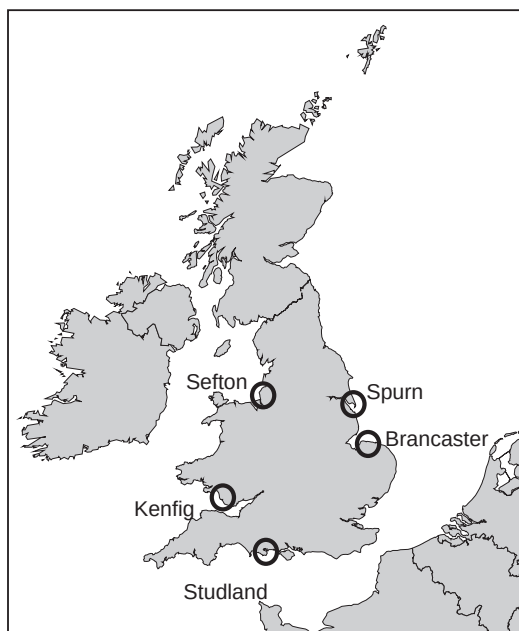


Fig. 1. Location of the study sites.

2 m grid resolution in either 1 by 1 km or 2 by 2 km tile format. Computer programmes were written in Delphi to convert and process the data. The tiles for each area were collated, and an appropriate sub-set defined for each study area. The sub-sets were then converted to a list of X , Y , Z values, with X and Y coordinates relative to the UK National Grid and the height Z to metres above Ordnance Datum Newlyn (ODN). The data were then imported into Golden Software Surfer™ to create contour maps and to extract cross-sectional data. Transects oriented approximately perpendicular to the first frontal dune ridge were obtained, spaced at c. 250 m intervals. Each transect started at the most seaward point covered by the LIDAR data and extended at least 200 m inland of the Highest Astronomical Tide (HAT) level. Data from areas covered by water during the LIDAR survey were eliminated, as they do not reflect the underlying beach topography. Most transects covered the intertidal zone down to about Mean Low Water Neap (MLWN) tide level. Several morphometric parameters were obtained from the cross-sectional data, as follows:

- (i) height of the most seaward frontal dune ridge
- (ii) distance between the HAT contour (in most cases coincident with the dune toe) and the first frontal dune crest

- (iii) frontal dune volume (the sand volume in a 1 m wide strip above HAT level, between the HAT level contour and a point 200 m landwards of HAT)
- (iv) beach volume (the sand volume in a 1 m strip above ODN level, between the ODN contour and the HAT contour measured relative to ODN)
- (v) beach width (a) between ODN and HAT, (b) between ODN and MHW and (c) between MLW and MHW
- (vi) average slope of the beach (a) between ODN and HAT, (b) between MLW and MHW, and (c) between ODN and MHW.

As noted above, a vertical error of c. 15 cm is typically associated with LIDAR data. Relative errors in the sediment volume calculations vary with the sediment thickness, and, assuming an average vertical error in surface height determination of 15 cm, could range from 6% where the beach is 2.5 m ‘thick’ (relative to the datum of survey) to 0.8% where the crest of the frontal dune is 19 m above datum. The various tidal levels used in the calculation of these parameters are listed in Table 1. Tidal levels were assumed to be representative for the whole of each site. All of the sites except Studland can be classified as macrotidal (cf. Davies,

Table 1

Tidal levels and tidal ranges for the five sites, expressed in metres above Ordnance Datum Newlyn (ODN)

Site	HAT	MHWS	MHW	MHWN	MLWN	MLW	MLWS	LAT	MSTR	MTR
Sefton	5.20	4.07	3.22	2.37	−2.03	−2.98	−3.93	−4.93	8.00	6.20
Kenfig	5.60	4.60	3.40	2.20	−2.00	−3.15	−4.30	−5.30	8.90	6.55
Studland	1.20	0.80	0.55	0.30	−0.20	−0.50	−0.80	−1.40	1.60	1.05
Brancaster	4.00	2.73	2.22	1.72	−1.24	−2.00	−2.76	−3.75	5.49	4.22
Spurn	3.80	3.00	2.30	1.60	−1.20	−1.95	−2.70	−3.70	5.70	4.25

Data for Spurn (Spurn Head), Studland (Poole Harbour Entrance), Kenfig (Porthcawl) and Sefton (Formby) taken from Admiralty Tide Tables (Admiralty, 2001); for Brancaster from Halcrow (1988).

HAT – Highest Astronomical Tide.

MHWS – Mean High Water Springs.

MHW – Mean High Water.

MHWN – Mean High Water Neaps.

MLWN – Mean Low Water Neaps.

MSL – Mean Low Water.

MLWS – Mean Low Water Springs.

LAT – Lowest Astronomical Tide.

MSTR – Mean Spring Tidal Range.

MTR – Mean Tidal Range.

1964), having a mean spring tidal range (MSTR) of >4 m. Studland Bay is classed as microtidal (MSTR < 2 m).

2.3. Quantification of beach–dune morphology using sequential ground surveys

Sequential topographic beach and dune profile survey data were utilised for Sefton, the only site for which such long-term data were available. The data comprised ground surveys along fixed transects carried out annually by Sefton Council and additional surveys of the frontal dunes along these transects by Jay (1998) obtained using an EDM Total Station. The following parameters were calculated:

- (i) frontal dune volume change (based on the difference in frontal dune volume in October 1996 and August 1998, derived from ground surveys by Jay (1998))
- (ii) upper beach volume change (based on the difference in volume of the upper beach (beach above MHWS) in August 1995 and 1996, derived from ground surveys by Sefton Council, as calculated by Jay (1998))
- (iii) change in the dune foot position (based on the difference in position of the Highest Astronomical Tide (HAT) in 1995 and 2000, derived from ground surveys by Sefton Council)
- (iv) change in beach level (based on the difference in the vertical level of the upper beach, measured relative to fixed bench marks in August 1991 and August 1998, by Sefton Council).

In addition, topographic beach profile survey data for the period October 1997 to March 1999 were obtained for Spurn Peninsula from the East Riding of Yorkshire Council. Similar data for Brancaster relating to the period February 1991 to February 1999, together with nearshore and lower beach bathymetric data obtained by echo sounding in August 1996, were obtained from the Environment Agency Anglian Region. No beach profile or nearshore survey data could be obtained for Studland or Kenfig. These data were used both as a cross-check on the LIDAR data and as indicators of beach morphological change during the 1990s.

3. Relationships between coastal morphology and frontal dune accretion–erosion status

3.1. Sefton coast

The Sefton coast is located between the Mersey and Ribble estuaries in northwest England. This coast is transitional between open coast and estuarine regimes, influenced by processes both in the eastern Irish Sea and in the Ribble and Mersey estuaries (Pye, 1990). The coast is macrotidal, the mean spring tidal range being >8 m. Tidal currents can be strong. The coast is exposed to prevailing southwesterly and westerly winds. Wave climate is moderate, especially due to the shallow and confined nature of the Irish Sea, with restricted wave activity from the southwest due to shelter provided by Anglesey, and the largest waves from the west-northwest. However, storm surges of 2 m or more can produce tidal levels in excess of 6.0 m ODN, and storm waves combined with storm surges result in severe dune erosion (Pye, 1991). The foreshore is characterised by ridge and runnel topography, orientated at a slight oblique angle to the shoreline. The runnels remain wet between tides, restricting aeolian sand transport to the higher parts of the intertidal zone. Several dune morphological types are present in the Sefton system, including foredune ridges, hummocky dunes, blowouts, parabolics and sand sheets. Embryo dunes are present seaward of the foredune where accretion is occurring to the north and south of Formby Point. Blowouts are present both in the foredune and in the dunes behind. Erection of sand fencing on the upper beach between 1880 and 1914 was responsible for the development of multiple parallel ridges, notably at Freshfield/Ainsdale and north of the River Alt mouth. At Ainsdale, the belt of parallel ridges was several hundred metres wide at its maximum, but erosion has since truncated some ridges (Pye, 1990). The foreshore generally becomes wider and flatter towards the Ribble estuary, and southwards towards the Mersey estuary.

Analysis of the morphometric parameters derived from the LIDAR data (Figs. 2 and 3), allowed the Sefton coast to be divided into four sections. The first section (transects 1 to 14) lies to the south of the River Alt, which runs along the foreshore, almost parallel to the coast. The beaches landward of the River Alt channel are about 150 m wide (distance between

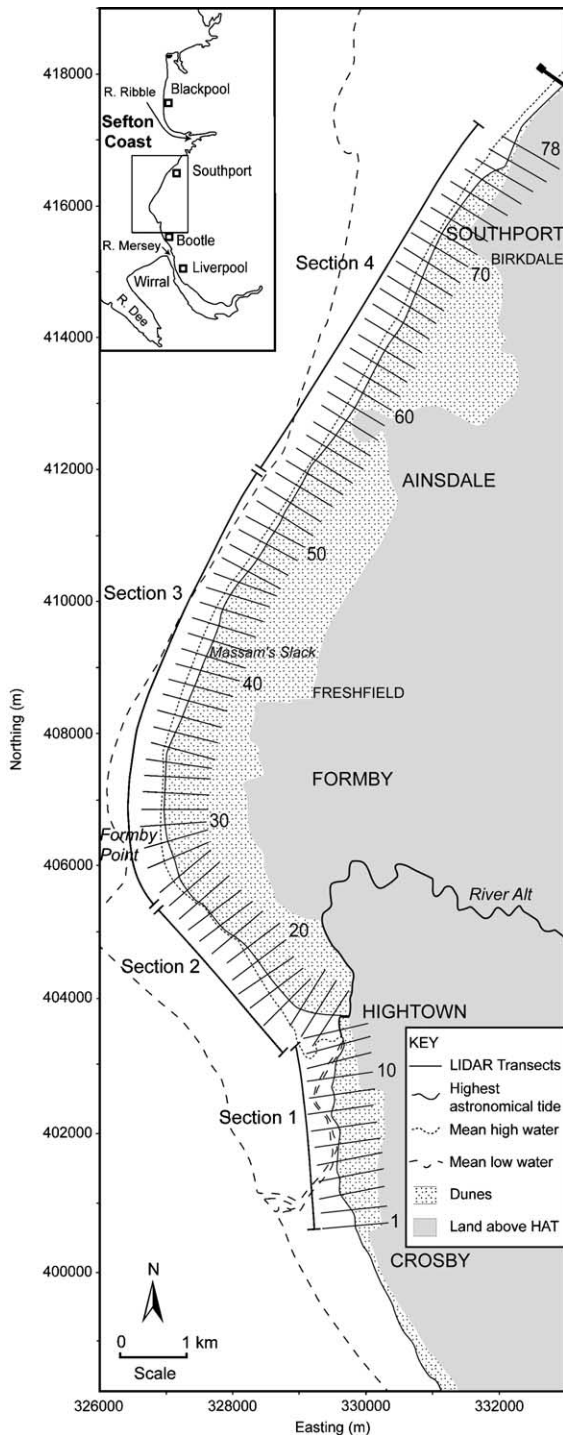


Fig. 2. Location map of the Sefton coast, showing the extent of the dune system and the beach dune transects used in the LIDAR analysis.

ODN and HAT), sloping at an average of 1° to 2° . The frontal dune is 6.5 to 11.4 m ODN in height, although at transect 8 the frontal dune is just 1.3 m above HAT. The second section (transects 15 to 26) lies between section 1 and the south side of Formby Point. The frontal dunes are slightly higher than those along the River Alt section (7.4 to 12.0 m ODN), and are fronted by wide (831 to >1419 m) beaches. The third section (transects 27 to 53) includes Formby Point. The frontal dune is high (up to 18.9 m ODN) and extensively cliffed. However, both the frontal dunes and hind dunes farther inland contain a substantial sand volume. An exception is a blowout at Massam's Slack (transect 42), where the truncation of former artificial shore-parallel ridges has resulted in the formation of a large transgressive sand sheet which is fronted by a frontal dune that had a maximum height of 2.5 m above HAT in 1999, rendering it vulnerable to marine incursion during major storms. However, since 1999 the foredune in this area has grown in height, as sand blown along the beach, mainly from the south, has found its way into the gap and been trapped by vegetation. The beach in this area is 251 to 474 m wide, with an average slope of up to 1° . Along the fourth section (transects 54 to 78), frontal dune volume and maximum crest heights diminish northwards. At transect 76 the maximum frontal dune crest height is low, being only 1.3 m above HAT, although higher dune crests occur farther inland. The beach fronting these dunes is wide (530 to 2131 m) with an average slope (between ODN and HAT) ranging from 0.1° to 0.6° .

Most of the Sefton shoreline prograded during the 19th century, but around 1900 erosion began at Formby Point and has continued to the present (Gresswell, 1937, 1953; Pye and Neal, 1994). The northern erosion limit has extended northwards towards Southport and now lies mid-way between Freshfield and Ainsdale. Much of the dune frontage around Formby Point is cliffed due to wave erosion, and back-barrier silts are exposed on the foreshore. Between transects 26 and 27 the high water mark presently lies 100–200 m seaward of its position in the 1890s, and a zone of well-vegetated hummocky dunes separates a former promenade from the sea.

Several factors probably contributed to the onset of erosion after 1900, including changes in the wind/wave climate and the effects of dredging and training

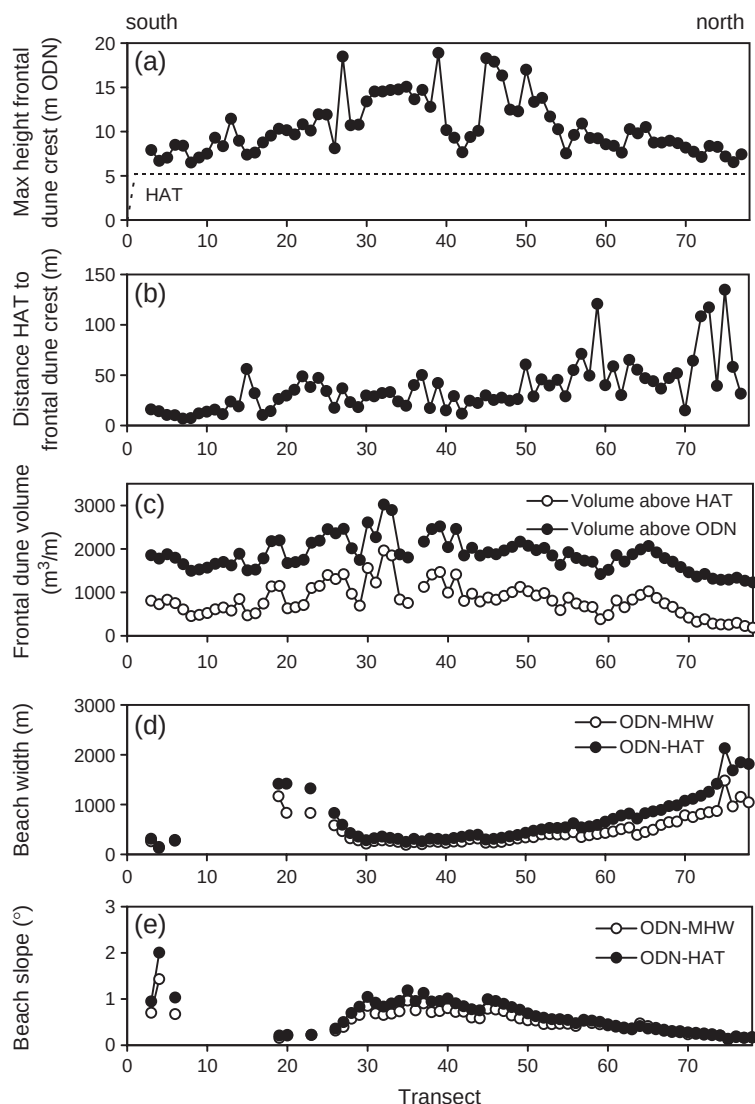


Fig. 3. Longshore variation in selected morphological parameters along the Sefton coast. Transect positions are shown in Fig. 2.

wall construction in the Mersey and Ribble estuaries on sediment transport, bathymetry and wave regime (Pye and Neal, 1994). Foredune erosion was also assisted by the abandonment of beach and foredune management practices implemented in the late nineteenth century, and by increasing visitor pressure from the 1920s onwards. The erosion has been greatest north of Wicks Lane (transect 30), due to wave focusing on this part of the coast, and the coast here has retreated by over 500 m in 100 years. At the centre of Formby Point, the present shoreline lies

almost in exactly the same position as during the late 18th century, having advanced and retreated again by over 300 m.

Changes in foreshore level and frontal dune erosion/accretion have been recorded since 1958 by measurements relative to fixed points. Examples of beach and frontal dune cross sections on both accreting and eroding sections of coast are shown in Fig. 4. Fig. 5 displays the spatial variation in the erosion/accretion status of both the beach and the frontal dune. Fig. 5a shows the net volumetric changes in the frontal dunes.

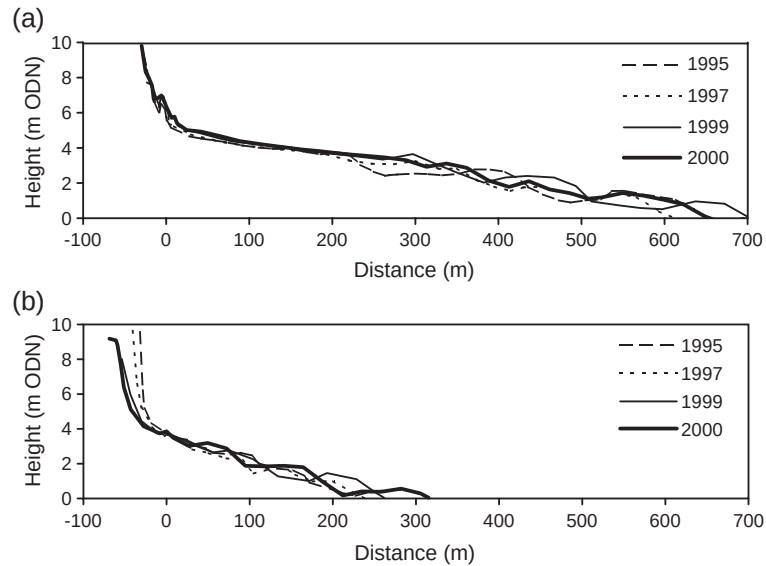


Fig. 4. Selected cross-shore profiles on the Sefton coast, derived from sequential ground surveys in 1995, 1997, 1999 and 2000 by Sefton Council, (a) representing accretion zone at Ainsdale north (transect 64 in Fig. 2), and (b) the erosion zone near Fisherman's Path at Freshfield north (transect 43 in Fig. 2).

The frontal dune is accreting south of Formby Point (i.e., between transects 21 and 25), and erosion is dominant between transects 28 and 48, with the great-

est recent loss to the frontal dunes occurring around transect 40. A second accreting section can be identified to the north, between transects 50 and 78, and a

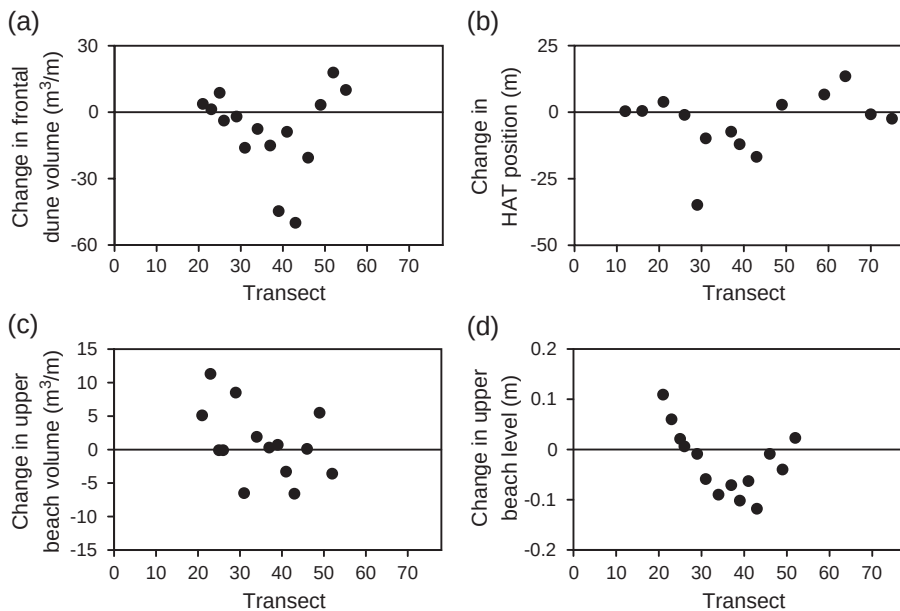


Fig. 5. Comparison of recent erosion/accretion of the frontal dunes and beach at Sefton, derived from sequential ground surveys. Positive values indicate accretion, negative values indicate erosion. Values in (a), (c) and (d) are from data obtained between 1996 and 1998 from Jay (1998). Values in (b) are from data obtained between 1995 and 2000 from Sefton Council.

transitional zone is evident between this section and the eroding section to the south (transects 48 to 52). Early stages of dune development within this section, in front of the foredune between Ainsdale and Birkdale, are evident in the form of ‘green beach’ on the foreshore, which has been initiated by *Puccinellia* colonisation and subsequent invasion by *Leymus ammophila* (Edmondson et al., 2001).

Fig. 5b shows the net lateral retreat or progradation of the position of Highest Astronomical Tide (HAT). The pattern shown in this figure roughly corresponds with the pattern of net frontal dune volume changes, with landward movement of HAT between transects 28 to 45. The position of HAT has recently retreated by 2.4 m a^{-1} near transect 39 and by 3.4 m a^{-1} near transect 43 (close to Fisherman’s Path). The frontal dune erosion/accretion status, as indicated by changes in sand volume, and the position of HAT, show a correspondence with the distribution of frontal dune cliffs (between transects 29 and 51), and uncliffed foredunes (between transects 1 and 28 and between 52 and 78).

Further information relating to the erosion/accretion status of the beach is shown in Fig. 5c, based on surveys by Jay (1998). The changes in the volume of the upper beach (Fig. 5c) again show a general trend of accretion in the south and north and net erosion around Formby Point itself, although the pattern of upper beach values between transects 28 and 35 is complex, with short-term increases in some places. This is related in part to the movement of oblique ridge and runnel systems along the shore. By contrast, erosion/accretion of the frontal dunes corresponds closely to the change in upper beach level (Fig. 5d), with a net reduction of the beach level between transects 29 and 50, and a maximum reduction around transect 42. In general, the pattern is one of a negative beach and foredune budget around Formby Point, and a positive beach and foredune budget both to north and south of Formby Point.

Gresswell (1937, 1953) concluded that the onset of frontal dune erosion at Formby and Ainsdale was preceded by beach narrowing and steepening. A narrowing of the upper beach (especially the backshore above MHW) was identified as being of particular importance since it allowed wave run-up, even during moderate storms, to reach the dune toe. Analysis of topographic beach profile data by Pye and Neal

(1994) subsequently confirmed that changes in beach morphology provide a useful early warning indicator of the onset of frontal dune erosion.

The erosion/accretion status of the beach and frontal dunes on the Sefton coast, displayed in Fig. 5, shows a close relationship with the beach and frontal dune morphometric parameters derived from the LIDAR data (Fig. 3). Statistical tests (an *F*-test and either a two-sample equal variance or an unequal variance *t*-test, $\alpha=0.10$) were performed to ascertain whether the morphometric parameters of the frontal dunes and beach, derived from LIDAR, were different for accreting and eroding sections of the coast. The results showed that cliffed frontal dunes, compared to uncliffed frontal dunes, have:

- (a) a significantly greater maximum frontal dune crest height (on average, 14 m for cliffed frontal dunes compared with 9 m for uncliffed frontal dunes),
- (b) a significantly greater volume of sand in the frontal dunes (i.e. sand volume above HAT is $1116 \text{ m}^3/\text{m}$ width for cliffed frontal dunes versus 700 m^3 for uncliffed frontal dunes),
- (c) a significantly steeper dune front (mean distance from HAT to frontal dune crest is 29 m for cliffed frontal dunes versus 41 m for uncliffed dunes),
- (d) a significantly narrower beach fronting the frontal dunes (i.e. mean width ODN to HAT is 338 m for the beach fronting cliffed frontal dunes compared with 914 m for the beaches fronting uncliffed dunes),
- (e) a significantly steeper beach fronting the frontal dunes (e.g., average beach slope from ODN to HAT is 0.9° for the beaches fronting cliffed dunes and 0.5° for beaches fronting uncliffed dunes).

Similar trends were found when the erosion/accretion status was determined from changes in frontal dune volume, the position of HAT, or the upper beach level, (e.g. as displayed in Fig. 5). A variety of beach width or slope parameters can be used to define the limits of frontal dune erosion. For example, Fig. 6 shows the relationship between upper beach width (distance between MHWS and MHWN contours), changes in the upper beach level, and distribution of

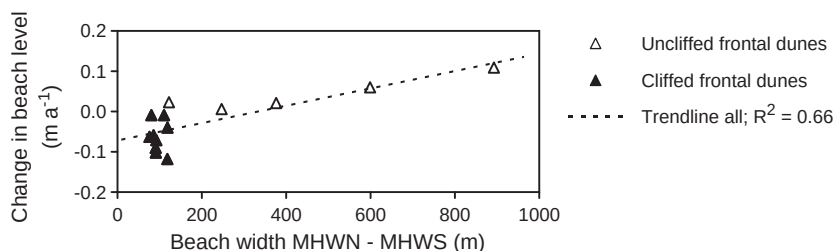


Fig. 6. Comparison of the upper beach width (MHWN-MHWS) derived from LIDAR data versus changes in beach level, derived from sequential ground surveys and the distribution of cliffed and uncliffed frontal dunes.

cliffed/uncliffed dunes. Cliffed dunes are clearly related to falling beach levels and upper beach widths of <180 m.

The spatial transition from frontal dune accretion to erosion (based on morphology and sediment volume change trends) can be used to derive critical values of beach width and slope that result in these changes. Table 2 summarises the relationships between dune erosion/accretion status and beach width and slope, as determined from the LIDAR data. The transitional frontages between erosion and accretion north of Formby Point have an average beach slope (ODN to MHW) of 0.8° , while the transition zone to the south of Formby Point has an average beach slope of 0.3° . These differences can be related to variations in energy conditions on the two sides of the Point.

A similar attempt to determine critical values of average beach width and slope was made using bathymetric chart data, which have the advantage of providing more extensive data below MLW. Table 3 demonstrates temporal change in beach width and slope, derived from bathymetric charts of 1949 and 2002 date (Fig. 7). The southern erosion limit of the frontal dunes on the Sefton coast moved northwards between 1973 and 1998, a trend which can be related

to changes in the width and average gradient of the intertidal profile. The charts clearly illustrate major infilling of the Formby Channel, which formerly ran parallel to the dune front (Fig. 7), between 1949 and 2002. This is seen even more clearly in the cross-sections shown in Fig. 8. These changes in Formby Channel, and Queen's Channel further seaward, are intimately linked to training wall construction and dredging in the Mersey Approaches. Table 3 shows that a reduction in mean beach slope (ODN to MHW) from 0.9° in 1949 to 0.4° in 2002 was more than sufficient to change the frontal dune regime at transect 2 (on Fig. 7) from one of erosion to accretion.

3.2. Kenfig Burrows

Kenfig Burrows is located on the eastern side of Swansea Bay, South Wales (Fig. 9). The area experiences a macrotidal regime, accentuated by the funneling effect of the Bristol Channel, with a mean spring tidal range of 8.9 m. Tidal currents can be strong. Winds are predominantly onshore, especially from the southwest. The site is exposed to swell waves from the Atlantic Ocean and wind-generated waves, but few large waves reach the shoreline because of the shallow nature of Swansea Bay and the Bristol Channel. However, the effect of waves during storms is significant.

The dune system is classified as being of transgressive non-climbing type (Saye, 2003) and comprises a series of dune ridges separated by slacks and parabolic dunes. Near the beach lies one or more shore-parallel dune ridges, widening towards the north, dissected in places by blowouts and incipient parabolic dunes. Further inland are hummock dunes and eighteen large but poorly defined parabolic dunes whose long axes are oriented almost west to

Table 2

Beach width and average slopes (between ODN and MHW) derived from LIDAR data (1998) and the corresponding erosion/accretion status of the frontal dunes between Hightown and Ainsdale

Transect	Erosion/accretion status of frontal dunes	Beach width (m)	Average beach slope (degrees)
60	Accreting	430	0.43
48	Transition	286	0.64
30	Eroding	216	0.85
26	Transition	584	0.32
20	Accreting	832	0.22

Transect positions are shown in Fig. 2.

Table 3

Beach widths and average slopes (between ODN and MHW) derived from bathymetric charts (1949 and 2002) and the corresponding erosion/accretion status of the frontal dunes between Hightown and Formby

Transect	1949			2002		
	Erosion/accretion status of frontal dune	Beach width (m)	Average beach slope (degrees)	Erosion/accretion status of frontal dune	Beach width (m)	Average beach slope (degrees)
1	Eroding	540	0.35	Eroding	410	0.45
2	Eroding	200	0.90	Accreting	460	0.40
3	Accreting	640	0.30	Accreting	690	0.25

Transect positions are shown in Fig. 7.

east, parallel with the resultant wind. Aerial photographs from just after the Second World War show extensive mobile dune areas and many active blow-outs, but at present aeolian processes are mainly confined to the first hundred metres landwards of the dune front (Jones and Etherington, 1989; Jones, 1996).

At the seaward side of the Kenfig system is a foredune system which is widest in the north and has been truncated by recent marine erosion along the central and southern parts. There is a pronounced cliff along much of the dune frontage. In places, there is limited new growth of embryo dunes at the slumped frontal dune toe, but these features are ephemeral. Average rates of shoreline recession are low ($<1 \text{ m a}^{-1}$, Williams and Davies, 2001), however, and large-scale frontal dune ‘rollback’, of the type seen at Formby Point, is not occurring.

Analysis of the cross-sections derived from LIDAR show that the maximum height of the frontal dunes generally increases towards the north (from 8.8 m ODN at transect 2 to 16.1 m at transect 10) (Fig. 10a). The maximum height varies from 3.2 m above HAT (transect 2) to 10.5 m above HAT (transect 10). The width of the zone between HAT and the frontal dune crest fluctuates but shows no significant overall change. Frontal dune sand volume (within 200 m of HAT) also shows no significant longshore trend. The lower beach is generally of very low gradient, separated from a steeper upper beach by a marked break in slope. The width of the beach between ODN and HAT is very uniform, decreasing slightly from c.200 m in the north to c. 160 m in the very south (Table 4). Correspondingly, the average beach slope (both ODN-MHW and ODN-HAT) shows a slight increase in the same direction.

The observed minimal alongshore variation in the morphometric parameters of the beach corresponds with a relatively consistent frontal dune morphology along much of the frontage (Fig. 10a; Tables 5 and 6). However, a slight trend can be observed with higher frontal dunes associated with wider, low-angled beaches. Owing to the relatively uniform beach morphology, rates of erosion are uniformly low and the entire beach/frontal dune system is retreating landwards at a similar low rate.

3.3. Studland Bay

The Studland Bay dunes form part of the South Haven Peninsula, a spit-like feature on the southern side of the entrance to Poole Harbour, Dorset (Fig. 11). Dunes on the South Haven Peninsula have formed mainly by wind deflation of beaches on the Studland Bay (eastern) side, but there are also foredunes backing Shell Bay which faces northeast. Landward of the modern foredune ridge in Studland Bay are three shore-parallel dune ridges which are separated from each other, and the higher land composed of Tertiary sediments behind, by marshy depressions and shallow lakes. Since the initiation of dune development in the seventeenth century (Diver, 1933) the system has prograded eastwards, but in recent decades erosion has affected parts of the system.

This coast experiences a microtidal regime (MSTR=1.6 m). The relative shelter of Studland Bay to storm waves from the south and south-west, provided by Handfast Point, has caused Studland to form an important sink for sandy sediments, with some material transported southwards into Swanage Bay (Bray et al., 1991). Lateral accretion of the frontal dune occurs towards the northern end of Studland Bay, and opposite the northern end of the Little Sea,

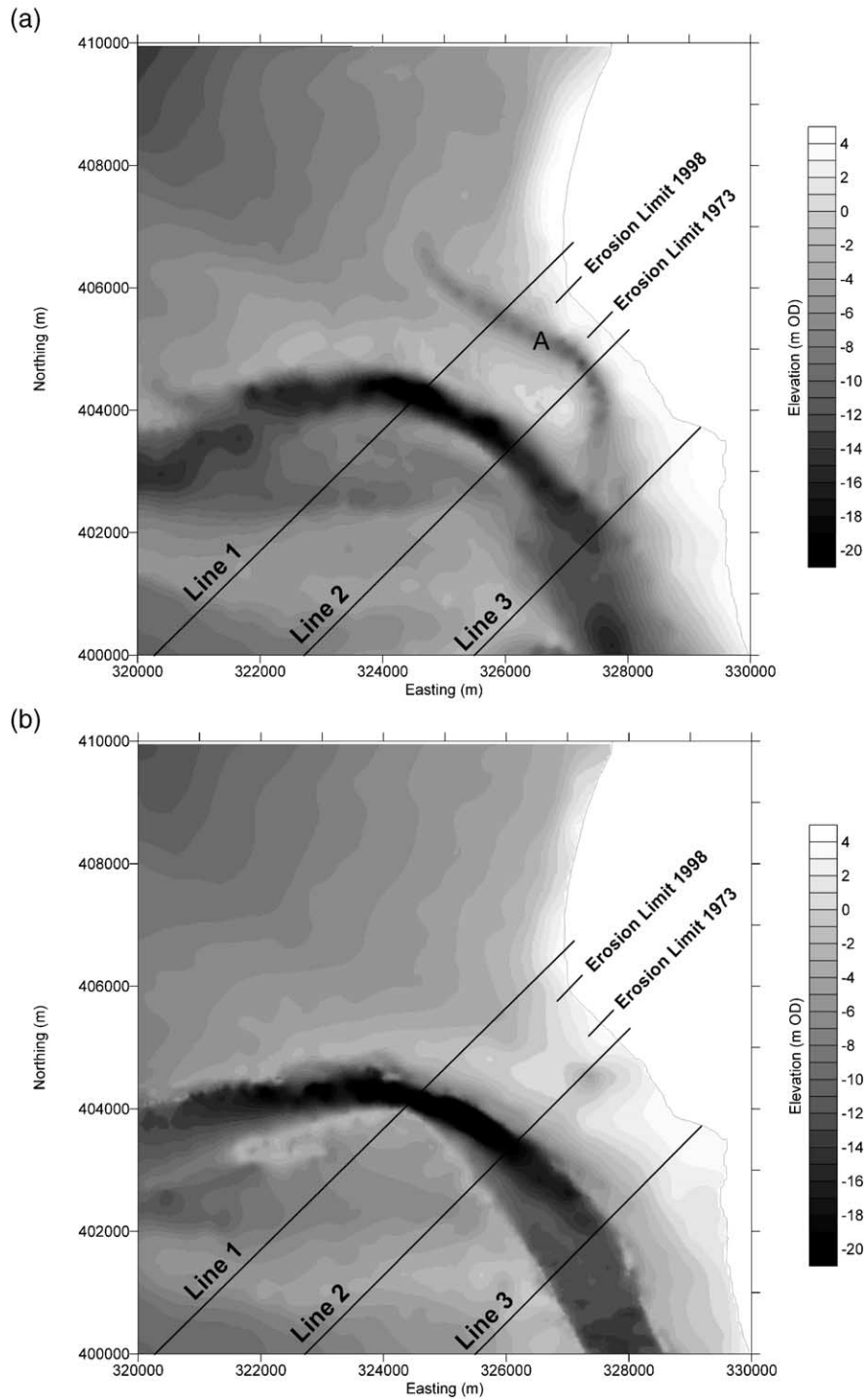


Fig. 7. Simplified bathymetry of eastern Liverpool Bay dated (a) 1949 and (b) 2002, based on Admiralty charts. The southern limits of the eroding dune section in 1973 and 1998 are shown. Note that Formby Channel (A) has been completely infilled since 1949. Intertidal widths and slopes have been calculated for Transect lines 1 to 3 (see [Table 3](#)).

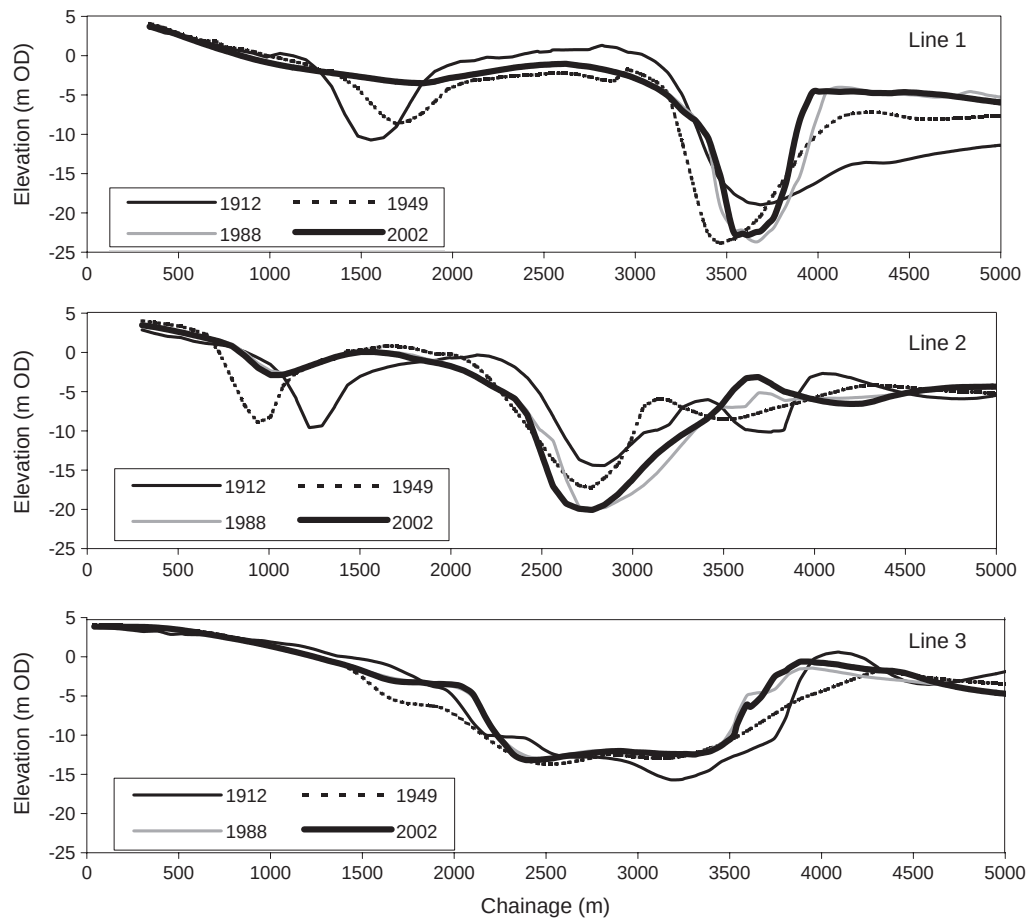


Fig. 8. NE-SW cross-sections of the Outer Mersey Estuary obtained from bathymetric charts dated 1912, 1949, 1988 and 2002. See Fig. 7 for the position of the surveylines.

as denoted by the presence of embryonic dune ramps. Nevertheless, there are two areas that suffer erosion: Shell Bay in the north (transects 11, 12 and 13 in Fig. 11) and the area south of Knoll Beach (near and south of transect 1 in Fig. 11) in the south. High recreational pressure has led to vegetation destruction and blowout development in the latter area.

Analysis of profiles derived from the LIDAR data shows that the frontal dune ridge is relatively low (4.2 to 6.5 m ODN), but is still 2.9 m (transect 6) to 5.3 m above the level of HAT (Table 5). The height of the frontal dune ridge decreases northwards from transect 1 to 6, and is variable but generally higher between transects 6 and 13 (Fig. 10b). The width of the beach between ODN and HAT generally increases from Knoll Beach car park (17 m at transect 1) towards

the north (70 m at transect 12). The relatively wide and flat beach at transects 8, 9 and 10, and frontal dune accretion, may be associated with lower energy wave conditions in the lee of a training bank that fronts these transects. Frontal dune volume is relatively constant along the shore but shows a slight tendency to increase between profiles 5 and 9.

With the exception of transect 9, the beach width increases and beach slope decreases towards the north. Beaches in Shell Bay are notably wider and less steep than those in Studland Bay: beach angles range from 4.1° (transect 1) to 1.0° (transect 13). The beaches often have a distinct berm formed by swell waves, especially in Studland Bay.

Frontal dune accretion at the northern end of Studland Bay (transects 9 and 10) corresponds with wider,

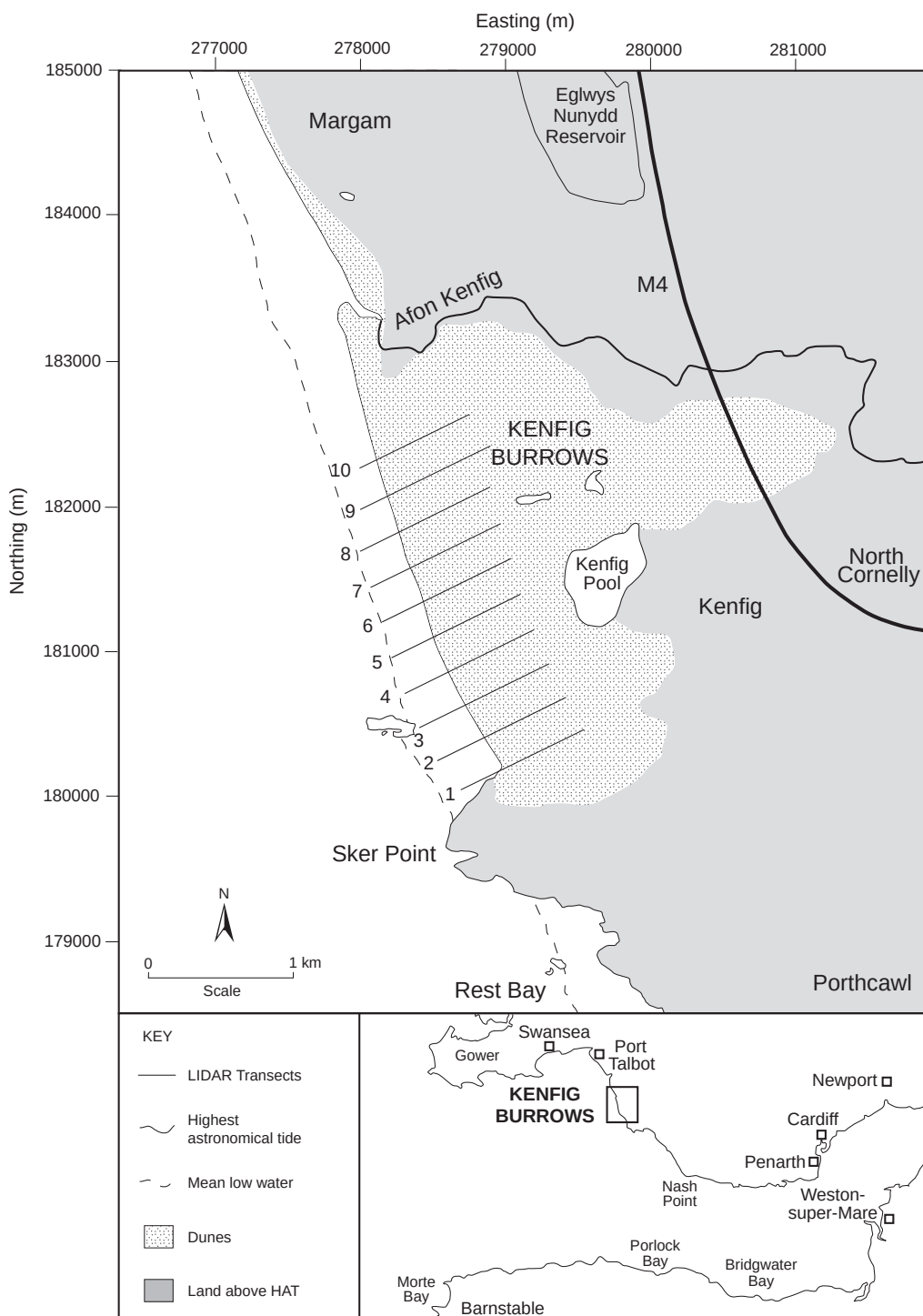


Fig. 9. Location map of Kenfig Burrows, showing the extent of the dune system and transects used in the LIDAR analysis.

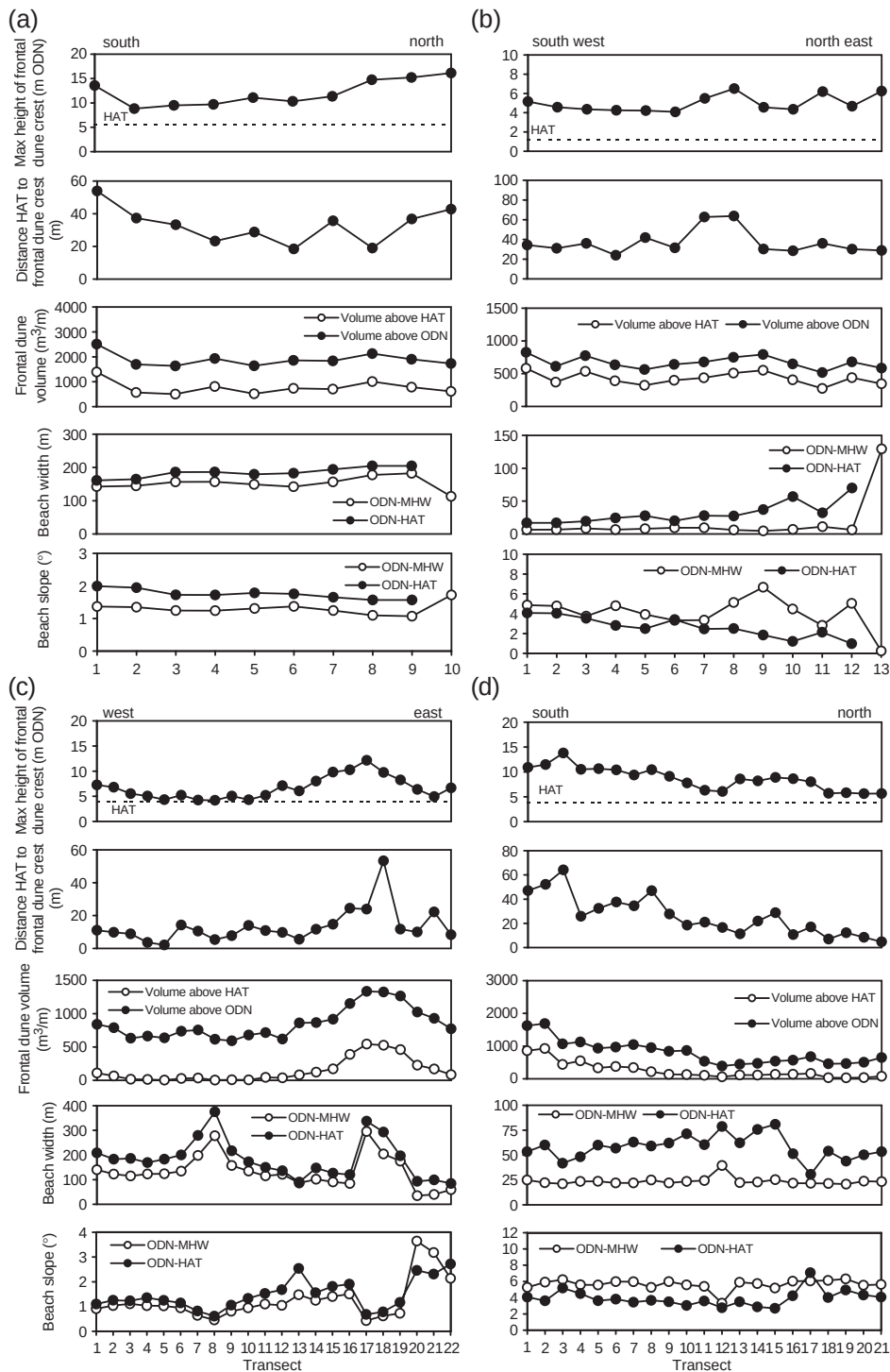


Fig. 10. Longshore variation in selected morphological parameters of the beach and frontal dunes derived from LIDAR data at (a) Kenfig Burrows, (b) Studland, (c) Brancaster Bay and (d) Spurn. Transect positions are shown in Fig. 9 and 11 12 13.

Table 4
Comparison of morphological parameters of the intertidal zone at the five study sites

Morphological parameter		Sefton	Kenfig	Studland	Brancaster	Spurn
Beach width		Wide	Wide	Narrow	Moderate	Moderate
MLW–MHW (m)	Min	–	–	10	–	43
	Max	–	–	35	–	124
	Mean	–	–	18	–	86
	SD	–	–	8	–	25
	<i>N</i>	–	–	8	–	20
ODN–HAT (m)	Min	149	161	17	84	31
	Max	2131	205	70	375	81
	Mean	690	185	31	184	58
	SD	466	15	16	79	12
	<i>N</i>	59	9	12	22	21
ODN–MHW (m)	Min	129	113	5	35	21
	Max	1481	182	129	295	40
	Mean	475	152	17	133	24
	SD	287	19	34	66	4
	<i>N</i>	59	10	13	22	21
Beach slope		flat	moderate	steep	moderate	steep
MLW–MHW (°)	Min	–	–	1.7	–	2.0
	Max	–	–	6.0	–	5.6
	Mean	–	–	3.8	–	3.1
	SD	–	–	1.3	–	1.0
	<i>N</i>	–	–	8	–	20
ODN–MHW (°)	Min	0.1	1.1	0.2	0.4	3.3
	Max	1.4	1.7	6.7	3.6	6.3
	Mean	0.5	1.3	4.1	1.3	5.6
	SD	0.2	0.2	1.5	0.8	0.6
	<i>N</i>	59	10	13	22	21
ODN–HAT (°)	Min	0.1	1.6	1.0	0.6	2.7
	Max	2.0	2.0	4.1	2.7	7.1
	Mean	0.6	1.7	2.6	1.5	3.9
	SD	0.4	0.1	1.0	0.6	1.0
	<i>N</i>	59	9	12	22	21
MLWN–MHWN (°)	Min	0.3	0.9	2.9	0.3	1.8
	Max	0.5	1.1	5.7	1.2	6.5
	Mean	0.4	1.0	4.0	0.7	4.7
	SD	0.1	0.1	0.9	0.3	1.3
	<i>N</i>	5	8	10	11	21
MHWN–MHWS (°)	Min	0.1	1.8	0.6	0.4	1.6
	Max	8.4	5.3	5.3	7.2	7.2
	Mean	1.0	2.9	3.4	1.8	4.8
	SD	1.5	1.1	1.3	1.4	1.9
	<i>N</i>	70	10	13	22	21
Beach type (terminology of Short and Hesp, 1982)		Dissipative	Intermediate-dissipative	Intermediate-reflective	Intermediate	Intermediate-effective

low-angled beaches (ODN–HAT is 37 m wide with a slope of 1.9° at transect 9 and 57 m and 1.2° at transect 10), whereas dune erosion occurring at transect 1 at the southern end of the bay is associated with a narrower, steeper beach (ODN–HAT is 17 m wide and 4.1° slope) (Table 6). More stable dune frontage is

associated with intermediate beach width and slope values. The same relationship between dune erosion/accretion status and beach morphology is evident when the distance between MHW and HAT is considered, but the relationship is less evident with the distance between ODN and MHW, indicating the

Table 5

Morphological parameters and features of the frontal dunes at the five study sites

Morphological parameter		Sefton	Kenfig	Studland	Brancaster	Spurn
Frontal dune crest height (m ODN)	MIN	6.50	8.82	4.09	4.21	5.62
	MAX	18.90	16.13	6.51	12.15	13.80
	MEAN	10.52	12.04	4.97	6.67	8.66
	SD	3.14	2.65	0.86	2.23	2.27
	N	75	10	13	22	21
Frontal dune volume above HAT (m ³ /m)	MIN	186	505	274	3	31
	MAX	1962	1389	582	544	927
	MEAN	822	762	428	143	254
	SD	366	268	93	176	256
	N	75	10	13	22	21
Frontal dune volume above ODN (m ³ /m)	MIN	1227	1633	518	593	389
	MAX	3022	2510	826	1335	1688
	MEAN	1866	1887	670	851	801
	SD	369	266	94	234	369
	N	75	10	13	22	21
Dune types		Foredune ridges	Single foredune	Low multiple	Single foredune	Multiple foredune
		Transgressive dune sheets (Formby Point)	ridge Parabolic dunes, blowouts	foredune ridges	ridge (centre)	ridges (more ridges in the south)
		Parabolic dunes, blowouts (Formby Point)	Hummock dunes		Recurves (notably in the east)	Embryonic dunes (mainly in the south)
		Hummock dunes (Formby Point)				
		Embryonic dunes (north and south)				
		Beach ridges (north)				

importance of the beach morphology (width and height) above MHW as a determinant of frontal dune erosion/accretion status. The relationship between frontal dune erosion/accretion status and morphology in Shell Bay is less clear as beach width and slope vary considerably.

3.4. Brancaster Bay

Brancaster Bay is situated on the coast of North Norfolk (Fig. 12). The mean spring tidal range is 5.5 m. Wave energy is low to moderate and dominant waves are from the north-northeast (corresponding with the greatest fetch), whilst the predominant wind direction is south-westerly and thus offshore or along-shore (Pye, 1992; Bristow et al., 2000). The level of HAT is almost 4 m ODN, but the southern North Sea is susceptible to storm surges, which may result in water levels well in excess of 5 m ODN (Steers et al., 1979). The Brancaster Bay dune system is classified as an open coast barrier island system (Saye, 2003), although it is attached to the mainland by active and

reclaimed marsh. The system consists of a single foredune ridge in the western and central parts and up to twelve recurves in the east. There is a small tidal inlet in the centre of the bay and two larger tidal inlets leading into Thornham Harbour in the west and Brancaster Harbour in the east.

There is substantial spatial variability in the morphology and frontal dune erosion/accretion status within Brancaster Bay. Dunes are prograding slowly in the west (transects 1 to 3), at a rate of 1 to 2 m a⁻¹ (Halcrow, 1988), and are stable to slowly eroding farther east (transects 4 to 10). In the 1980s dunes were eroding in the centre of the Bay (transects 12 to 17), at a rate of 1 to 2 m a⁻¹ (Halcrow, 1988), but this section is now largely protected. Beach profiles indicate that for most of this area, the low water mark is retreating landwards with an accompanying lowering and steepening of the fore-shore. Retreat of the foredunes, coupled with coastal defence works near the golf clubhouse (transect 13), has caused the clubhouse to form a promontory. On the east side of Brancaster Bay there has, in recent

Table 6

Beach width and average slopes (a) between ODN and MHW, (b) between ODN and HAT, and (c) MHW and HAT derived from LIDAR data (1998) for eroding, accreting and transitional/stable frontal dunes at the five study sites

Site	Eroding/protected		Transitional/stable		Accreting	
	Beach width (m)	Average beach slope (°)	Beach width (m)	Average beach slope (°)	Beach width (m)	Average beach slope (°)
<i>(a)</i>						
Sefton	216 (T30)	0.85 (T30)	583 (T26) 286 (T48)	0.32 (T26) 0.64 s(T48)	832 (T20) 430 (T60)	0.22 (T20) 0.43 (T60)
Kenfig	142 (T1) 182 (T9)	1.37 (T1) 1.07 (T9)	—	—	—	—
Studland	6 (T1)	4.87 (T1)	9 (T7)	3.35 (T7)	7 (T10)	4.48 (T10)
Brancaster	86 (T13) 175 (T19)	1.48 (T13) 0.73 (T19)	115 (T11)	1.10 (T11)	140 (T1) 40 (T21)	0.91 (T1) 3.18 (T21)
Spurn	22 (T16)	6.03 (T16)	22 (T7)	5.39 (T7)	22 (T2)	5.92 (T2)
<i>(b)</i>						
Sefton	358 (T30)	1.05 (T30)	831 (T26) 361 (T48)	0.36 (T26) 0.82 (T48)	1419 (T20) 646 (T60)	0.21 (T20) 0.45 (T60)
Kenfig	161 (T1) 205 (T9)	1.99 (T1) 1.57 (T9)	—	—	—	—
Studland	17 (T1)	4.08 (T1)	28 (T7)	2.46 (T7)	57 (T10)	1.21 (T10)
Brancaster	90 (T13) 197 (T19)	2.54 (T13) 1.16 (T19)	150 (T11)	1.53 (T11)	208 (T1) 99 (T21)	1.01 (T1) 2.31 (T21)
Spurn	51 (T16)	4.23 (T16)	63 (T7)	3.45 (T7)	60 (T2)	3.62 (T2)
<i>(c)</i>						
Sefton	68 (T30)	1.66 (T30)	247 (T26) 75 (T48)	0.46 (T26) 1.52 (T48)	587 (T20) 225 (T60)	0.19 (T20) 0.50 (T60)
Kenfig	19 (T1) 22 (T9)	6.77 (T1) 5.60 (T9)	—	—	—	—
Studland	10 (T1)	3.59 (T1)	19 (T7)	2.01 (T7)	50 (T10)	0.75 (T10)
Brancaster	4 (T13) 22 (T19)	24.27 (T13) 4.63 (T19)	35 (T11)	2.95 (T11)	69 (T1) 59 (T21)	1.49 (T1) 1.72 (T21)
Spurn	30 (T16)	2.90 (T16)	41 (T7)	2.09 (T7)	38 (T2)	2.27 (T2)

Transect positions are given in brackets.

years, been net accretion and flattening of the beach, at a rate of 1 to 3.5 m a⁻¹ (Bristow et al., 2000).

Analysis of the cross-sections derived from LIDAR shows a difference in morphology between the foredunes west of the inlet and the eroding foredunes in the centre of the eastern part, in particular. Western Brancaster Bay (transects 1 to 8) has a foredune which decreases in height from 7.3 m to 4.2 m ODN towards to the east (Fig. 10c). The dunes in the far west (transects 1 and 2) are fronted by a relatively wide beach (ODN-HAT width 180 to 200 m). Towards transect 5, where the foredune is ‘rolling’ back, the distance between HAT and the frontal dune crest decreases and the

dunes are fronted by a slightly narrower beach (Fig. 10c). The dunes between transects 5 and 10 are only slightly higher than HAT (at transects 7 and 8 just over 20 cm above HAT, respectively), making them vulnerable to storm overwash. At the inlet (between transects 8 and 9), beach width increases up to 375 m, reflecting the existence of a small ebb-tidal delta.

Between transects 13 and 17 the foredune increases in height (to over 12 m at transect 17), and the dune front becomes less steep as the backshore and dune toe sand accumulations get wider (Fig. 10c). The beach is narrowest (90 m in places) and steepest (2.5°) at transect 13 fronting the golf club house. At this point, the foredune is only 2.1 m above HAT and

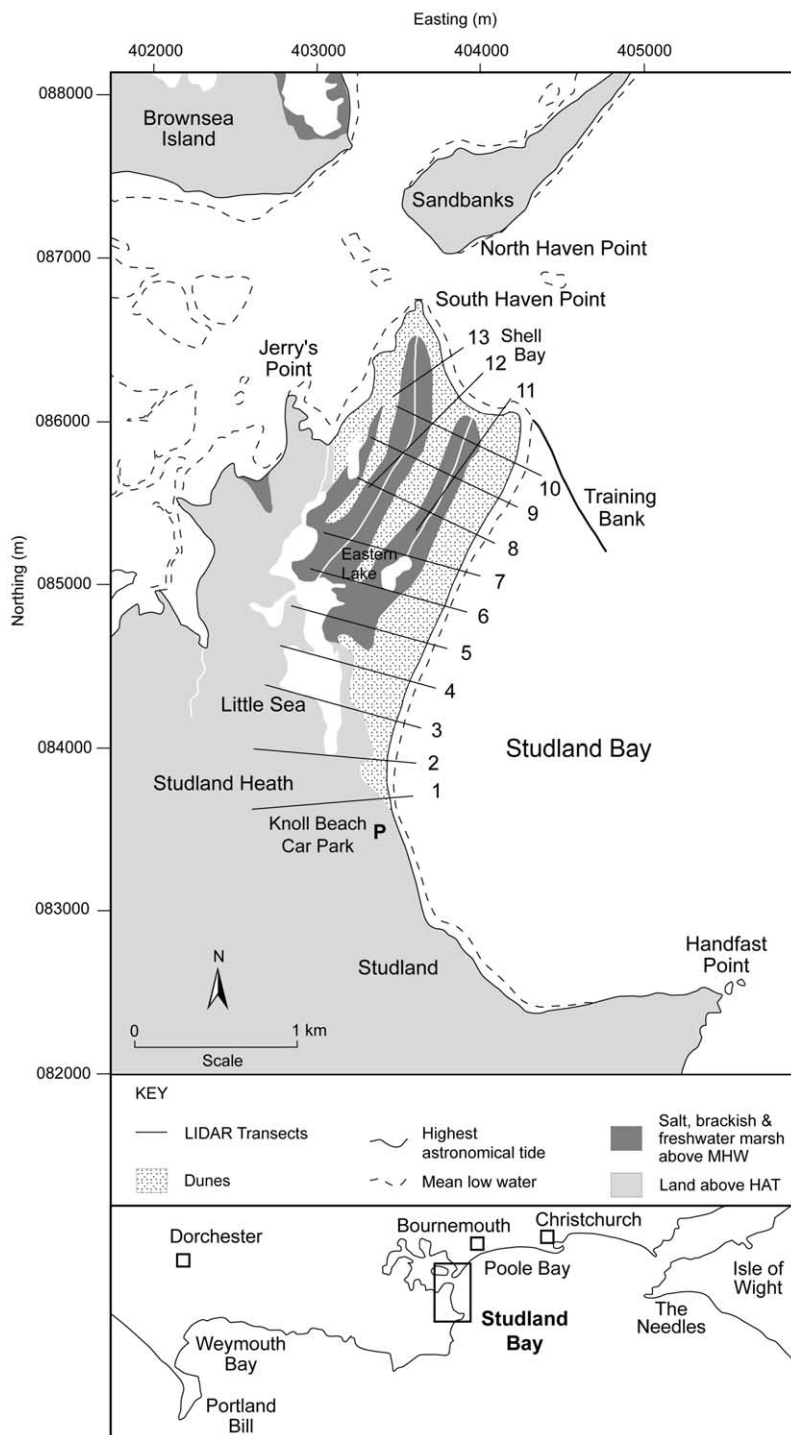


Fig. 11. Location map of Studland, showing the extent of the dune system and transects used in the LIDAR analysis.

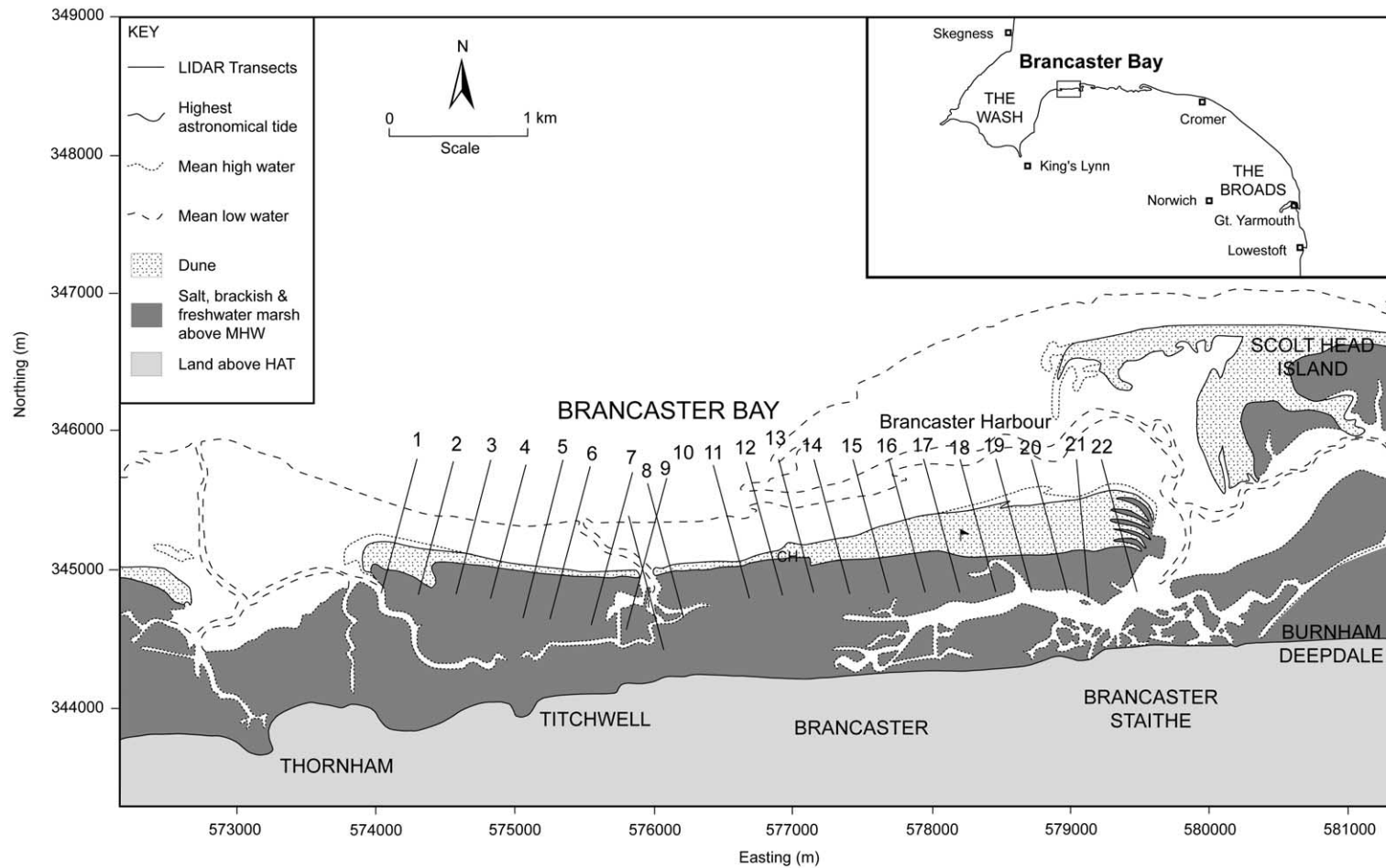


Fig. 12. Location map of Brancaster Bay, showing the extent of the dune system and transects used in the LIDAR analysis.

is protected by rock armour. Surveys between 1991 and 1996 showed that at this point the MLW retreated at a rate of about 50 m a^{-1} . The dune volume increases eastward of this point, reaching a maximum between transects 16 and 18, as the foredune ridge is not only higher but the dune belt is also wider. East of transect 17, foredune crest height and dune volume again decrease, and the beach becomes increasingly narrower (84 m at the eastward tip) and steeper (up to 2.7°) towards the entrance to Brancaster Harbour. This area has experienced rapid lateral progradation over the past 100–150 years due to the growth of successive dune-capped recurves and intervening marshy depressions.

The relationship between beach morphology and the erosion/accretion status of the frontal dunes is complicated in Brancaster Bay, as shown in Table 6. Dunes which are now protected in the centre of the bay generally coincide with narrower, steeper beaches (e.g., ODN-MHW distance is 86 m wide and the average slope 1.48° at transect 13), and dune height and volume are also greater along this section. By contrast, accreting dunes at the western end of the system are associated with wider, low-angled beaches (e.g., ODN-MHW distance is 140 m and the average slope 0.91° at transect 1). However, as shown in Table 6, the reverse relationships can be observed at the eastern end of the bay with frontal dune erosion associated with wider, low-angled beaches whilst accretion is associated with narrower, steeper angled beaches. The same trends are evident when the beach widths between ODN and MHW are considered. However, the relationship is more consistent when considering the beach morphology between MHW and HAT, with wider, low-angled beaches fronting the accreting dune sections in comparison to the eroding or protected sections (Table 6c).

3.5. Spurn peninsula

The Spurn Peninsula extends southwards from Holderness across the mouth of the Humber estuary (Fig. 13). The mean spring tidal range is 5.7 m. Wave energy is moderate to high and the wind direction is variable, although the predominant direction is south-westerly, causing formation of foredune ridges on both the eastern and western sides of the spit. The beaches on the North Sea side experience moderate

to high energy, and are composed of sediments ranging from sand to gravel and pebbles in the north to sand in the south (Ciavola, 1997). The northern part of the spit is vulnerable to overwash (De Boer, 1964), but a variety of hard defences protect the coastline, including groynes and revetments. A consequence of the defence works is that the central part of the spit has been fixed in position, and sediment transported southwards by longshore drift has been partially intercepted by the groynes.

Ground surveys between 1997 and 1999 show a relatively stable beach in the north. The beach is backed by a dune system, with a cliffed frontal dune now fronted by protection works. Near transect 13 the beach has become concave, indicating erosion has occurred. Further south, the lower beach is subject to erosion, while there is accumulation on the higher beach and dune front, as demonstrated by a convex profile at transect 7. Further south still, the beach is relatively stable, with alternating small-scale erosion and accretion. Around Spurn Head, there has been recent net accretion of the upper beach and dune toe, with additional accretion on the lower beach of the south and west-facing parts of Spurn Head.

Analysis of the cross-sections derived from the LIDAR data shows that dune development on the Spurn Peninsula is relatively small-scale. The North Sea side can be divided into two sections with different erosion/accretion status: an eroding section in the north, featuring protection works, and a more stable and locally accreting section in the south. The protected stretch in the north (transects 12 to 21) is characterised by low frontal dunes (maximum height of the frontal dune crest is 5.6 to 8.9 m ODN), with a steep dune front (as indicated by the distance between HAT and the maximum frontal dune crest) (Fig. 10d). Between transects 18 to 21 the dunes are less than 2 m above HAT. The beach is relatively narrow and steep in the north (the distance ODN to HAT is 30 to 54 m, with a slope of up to over 7° for transects 17 to 21) and wider in the central part of the Peninsula, close to Chalk Bank (with a width of nearly 80 m at transect 11). Further south, the maximum frontal dune height increases (up to 13.7 m ODN) and the dune front becomes less steep. The dunes become wider, and sediment volume increases.

The width of beach between MLW and MHW is up to 124 m in the north, with an average slope of 2.0°

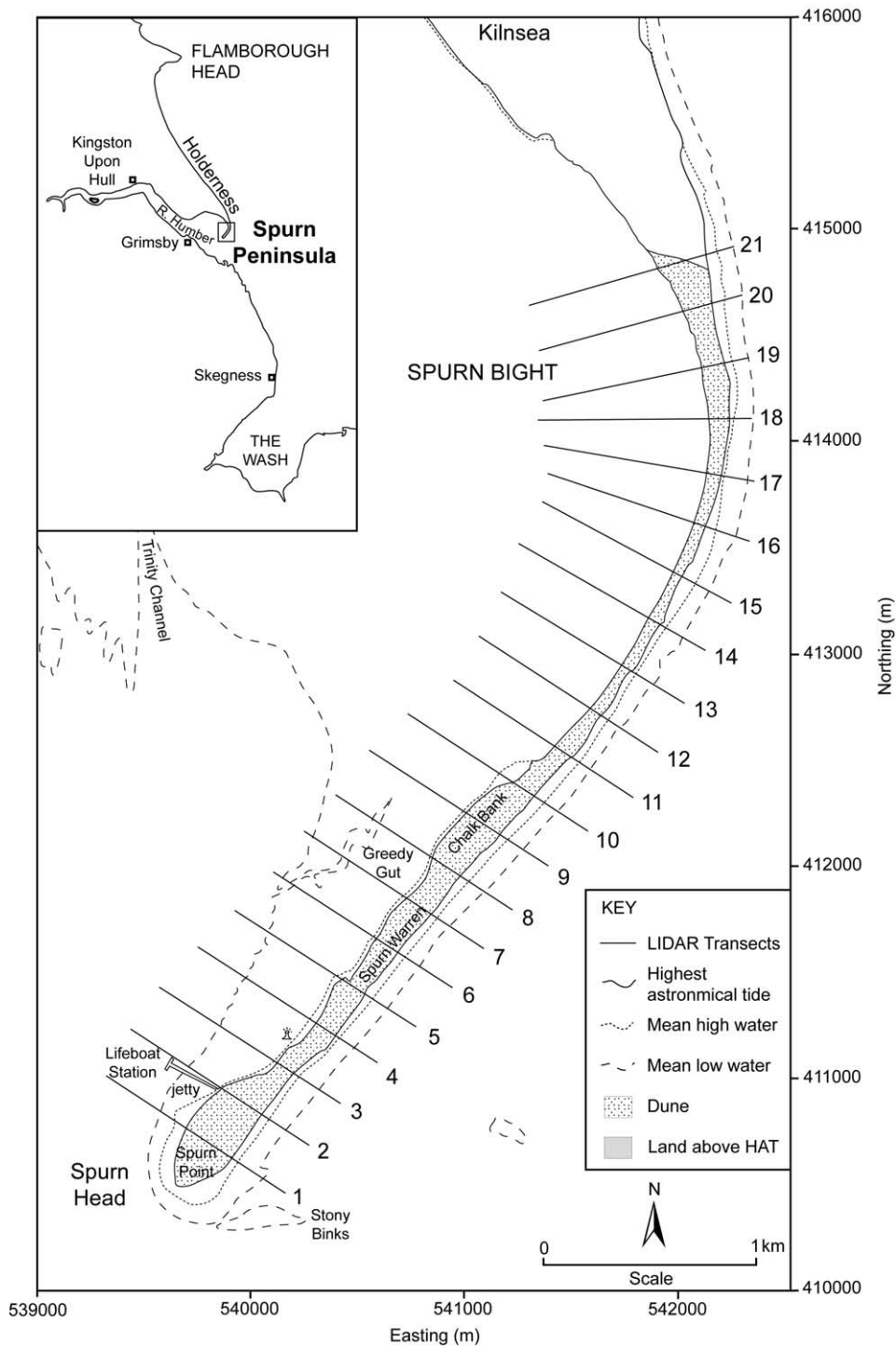


Fig. 13. Location map of Spurn Peninsula, showing the extent of the dune system and transects used in the LIDAR analysis.

(transect 21), decreasing to 43 m in the south (transect 3), with an average slope of 5.6° (Table 4). The form of the upper beach, backed by dunes, both on the North Sea and the Spurn Bight side, is convex. A strong negative relationship was found between frontal dune height and beach width, expressed as the distance between MLW and MHW. However, no clear relationship was found between frontal dune height and the width of beach between ODN and HAT.

There is little along-shore variation in beach width and slope between ODN and MHW indicating that these parameters do not strongly influence the erosion/accretion status of the frontal dunes (Fig. 10d; Table 6). However, longshore differences are evident in the beach widths between ODN and HAT and between MHW and HAT, the beach being narrower and steeper along the protected, eroding northern section than along the accreting dune frontage along

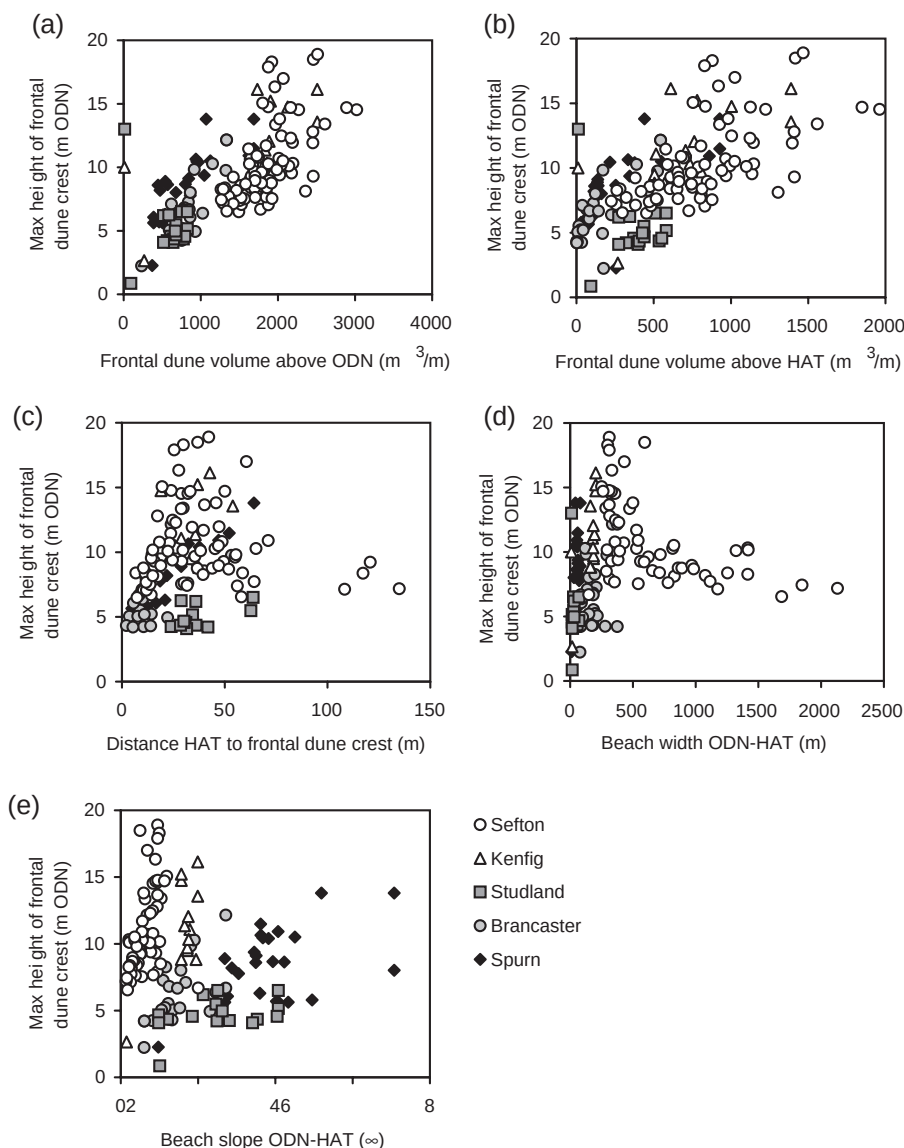


Fig. 14. Comparison of morphometric parameters for the beaches and frontal dunes at the five study sites.

the southern part of the spit. These differences indicate that it is the beach morphology above the level of MHW which primarily influences the erosion/accretion status of the frontal dunes.

3.6. Comparison of different dune systems

The morphometric parameters derived from LIDAR data for each dune site are tabulated in [Tables 4 and 5](#), and compared graphically in [Fig. 14](#). In general, frontal dune heights are lowest at Studland, followed by Brancaster and Spurn, Kenfig and Sefton ([Fig. 14a](#)). Frontal dune sand volume, expressed as the volume of sand above ODN per metre width, and extending up to 200 m inland of HAT, ranges from a minimum of c. 500 to 750 m³/m on the Studland Peninsula to c.1250 to 2500 m³/m at Sefton ([Fig. 14a](#)). However, if the volume of dune sand above HAT is considered ([Fig. 14b](#)), which represents the reserve of sand that can serve as a buffer during major storm events, the dunes at Brancaster Bay and Spurn are smallest, indicating high vulnerability during storms, with Studland intermediate and Kenfig and Sefton still the largest. The differences in distance between HAT and the maximum frontal dune crest height position ([Fig. 14c](#)) are not so distinct; only the dune front at Brancaster Bay is relatively steep (<20 m), but most sites have a fairly wide range (typically 20 to 60 m).

Beach width (width of beach between ODN and HAT) shows no general correlation with frontal dune height ([Fig. 14d](#)), but it is closely related to the tidal range, beach slope and wave energy. Defined in this way the beach width is smallest at Studland (<30 m), intermediate at Spurn (about 40 to 80 m), and widest at Brancaster (80 to 380 m), Kenfig (160 to 200 m), and Sefton (generally over 250 m). Spurn has the steepest beaches (3° to 7°) (considering the average slope between ODN and HAT) ([Fig. 14e](#)), followed by Studland, whereas average beach slopes at Brancaster, Kenfig and Sefton are low angle (0.1° to 2°). However, these average slope values do not reflect the fact that some of the beaches consist of two components, a steeper upper beach and a more gently sloping lower beach. For example, Kenfig has a steep upper beach and (mean slope between MHWs and HAT=7°) and a flatter lower beach, whereas Studland has a flat upper beach (2°).

The narrowest beaches at Sefton and Spurn are associated with the highest frontal dunes. [Table 6](#) summarises beach morphology parameters for different dune frontage status types at the five study sites. Eroding, cliffed frontal dunes are generally fronted by narrow, steep beaches, whilst accreting dunes are associated with wider, low angled beaches. This relationship is most evident and consistent between the five sites for the beach between MHW and HAT, indicating that beach morphology above MHW is critical for the erosion/accretion status of the frontal dunes. However, no universal association between beach width and dune recession could be identified: beaches fronting eroding dunes at Sefton and Kenfig are much wider than those at Brancaster, reflecting the higher wave energy regime at the two west coast sites. However, where the frontal dunes are eroding or protected the beach between MHW and HAT is generally less than 30 m wide with an average gradient of >2.9° at all sites except Sefton ([Table 6](#)). Where the frontal dunes are accreting the beach slope between MHW and HAT is 2.3° at all sites.

4. Discussion

Despite the observed associations between frontal dune morphology, erosion/accretion status and beach/nearshore morphology at sites such as Sefton, it is evident that at some localities dune morphology does not always closely reflect beach morphology. For example, on the Spurn Peninsula variation in dune volume and erosion/accretion status do not appear to be related to beach width as the accreting southerly section is fronted by a beach of similar width to the eroding section. Other possible influences include sediment supply rates and the grain size of the beach distribution of the beach sediments. In the north, the beach sediments are coarser and more poorly sorted; consequently rates of aeolian transport is limited and the potential for dune development is reduced. Southward littoral drift of the finer sediments is significant and the beach sediment budget lies close to a state of dynamic equilibrium in which longshore transport is much greater than onshore transport. Further south, the beach sediment budget becomes positive, the beaches are composed of better sorted, finer sediments, and the potential for aeolian transport and

dune building is increased compared with the area further north.

In general terms, extent and form of dune development are linked to several broad-scale factors, including sediment supply, wind/wave climate, sediment properties (principally grain size), vegetation characteristics and human influence. A number of conceptual models have been proposed which relate the morphology of dunes to shoreline dynamics and dune forming factors. For example, Psuty (1992) developed a model based on sediment budget, which identified four possible situations:

- (a) negative beach and foredune budget, associated with washover, or foredune attenuation (featuring blowouts, parabolic re-entrants or hummocks)
- (b) negative beach budget, positive foredune budget, associated with foredune development, with maximum foredune height occurring where the beach is slightly erosional
- (c) positive beach budget, negative foredune budget, associated with beach ridge topography
- (d) positive beach and foredune budget, associated with multiple dune ridge topography.

Other conceptual models consider additional factors. Short and Hesp (1982) suggested that, all other factors being equal, the potential for aeolian sand transport is highest on wide, low angle, dissipative beaches which often have fine, well sorted sediments, and lowest on narrow, steep, reflective beaches which often have coarser grained sediments. Dissipative beaches were found to be frequently backed by large transgressive dune sheets, intermediate beaches by parabolic dunes and blowouts, and reflective beaches by minimal dune development. The latter were relatively immobile, but showed rapid recovery after erosion events. Based partially on data for the Sefton

coast, Pye (1990) proposed a model which related dune morphology to coastal sediment budget, shoreline dynamics and degree of human disturbance. Where sediment supply is high but wind erosion is low, a series of beach ridges can be expected to develop whereas parallel foredune ridges (or irregular hummock dunes if vegetation is discontinuous) are more likely where wind energy is higher. High foredune ridges should develop where the sediment budget of the beach and dune are in balance, and the position of the shoreline remains constant. Parabolic dunes with blowouts and transgressive dune sheets will form where there is net shoreline erosion and high wind energy and/or high levels of human disturbance. However, the conditions for dune formation frequently change over time. For example, the morphology of the dunes on the Sefton coast has been profoundly influenced by changes both in natural processes and human interferences over the course of the past 150 years (Pye, 1990). Hesp (2002) recently developed such ideas in a model that relates the morphological development of foredunes on eroding, stable and accreting coasts to sediment budget, changes in sea level and vegetation cover.

There is considerable variation in the beach and frontal dune morphometry both within and between the five sites considered in this study. However, the following generalisations can be drawn. In general, higher and more developed dunes are fronted by wider beaches, corresponding with a larger tidal range (Table 7). The largest dune system, with the highest frontal dunes, is found at Sefton, which has a large tidal range, a generally wide, low angle beach, and high exposure to onshore winds. By contrast, development of high dunes is inhibited at Studland, where sediment supply is low, beach width is narrow and aeolian processes are inhibited by a microtidal regime and restricted exposure to the prevailing southwesterly winds. However, within individual

Table 7
Comparison of controlling environmental variables at the five study sites

	Sefton	Kenfig	Studland	Brancaster	Spurn
Wind/wave climate	moderate	moderate-high	low-moderate	low-moderate	moderate-high
Tidal range (m)	macro-tidal	macro-tidal	micro-tidal	macro-tidal	macro-tidal
Beach sediment characteristics	sand	sand-pebbles	sand	sand	sand-pebbles
Sediment supply	moderate	low	low	low	moderate

sites, the highest frontal dunes are often associated with the narrowest beaches, as on the central Formby coast. This is due to the fact that on slowly retreating and stable shores dunes have an opportunity to grow vertically, either in a stable position or as the frontal dune slowly moves landwards through a process of ‘rollover’ (Pye, 1990). Exceptions to this pattern occur where the sand cover on the beach is thin and/kept permanently wet by a perched groundwater table on top of the underlying Holocene silts, and where sand is funnelled inland through low gaps in the dune topography. This is most notably the case near Massam’s Slack and Dale Slack Gutter between Victoria Road and Fisherman’s Path. The accretion to the north and south of Formby Point reflects the longshore transfer of sand from the eroding section at Formby Point towards the north and south. On accreting sections of coast, new dune ridges progressively form, the maximum crest height of each ridge being limited by the rate of beach accretion and shoreline progradation.

5. Conclusions

LIDAR provides a rapid and effective method of obtaining three-dimensional topographic data at relatively high resolution for large areas covering both beach and dunes. On bare sand surfaces, vertical accuracy is typically of the order of ± 15 cm. On dunes covered by grass and scrub this may be reduced to ± 20 – 50 cm and particular problems arise in forested areas and intertidal zones covered by standing water. However, the effect of such errors is relatively small when the purpose is to obtain quantitative relationships between broad aspects of beach and dune morphology. The data obtained can be used to derive a variety of morphometric parameters that can be compared with those derived from topographic and bathymetric surveys and used to monitor and predict trends in frontal dune and beach erosion/accretion status.

The results obtained in this study demonstrate a clear relationship between beach morphology and dune morphology and erosion/accretion status along the Sefton coast, with eroding dunes associated with narrower, steeper beaches whilst accreting dunes are associated with wider, low-angled beaches.

The relationship between beach morphology and dune erosion/accretion status at other dune systems was generally found to exhibit the same pattern, although there is inevitably some variation due to local factors. In particular, beach morphology between MHW and HAT was found to strongly influence the accretion/erosion status of the frontal dunes. As might be expected, a universal association between beach width and dune accretion/erosion could not be identified, reflecting the differences in the process regime between the various beach–dune systems. Other factors which can have a locally important effect on frontal dune erosion/accretion status include sediment supply and grain size characteristics, wind/wave climate, vegetation characteristics and management practices. Consequently, ‘critical’ values for beach morphology parameters are largely site specific. However, regular monitoring using lidar provides a useful means of identifying both local critical parameters and of identifying beach changes which may provide ‘early warning’ of the onset of frontal dune erosion.

Acknowledgements

The work presented in this paper was partly carried out as part of a study funded by DEFRA (formerly MAFF) Flood and Coastal Defence with Emergencies Division. Data were made available by a number of institutes and persons. In particular, we would like to thank Paul Wisse, John Houston and Graham Lymberry for provision of data relating to the Sefton coast, Julie Richards, formerly of the Environment Agency Anglian Region, for help with data for Brancaster Bay, and Marieke Eleveld, Marie-Helen Ruz and Bernard Bauer for comments on an earlier version of the manuscript.

References

- Admiralty, 2001. Admiralty Tide Tables. Volume 1. United Kingdom and Ireland, Including European Channel Ports. NP 201-02, 2002. United Kingdom Hydrographic Office, Taunton.
- Andrews, B.D., Gares, P., Colby, J.D., 2002. Techniques for GIS modeling of coastal dunes. *Geomorphology* 48, 289–308.
- Blott, S.J., Pye, K., 2004. Application of lidar digital terrain modelling to predict intertidal habitat development at a managed

- retreat site: Abbots Hall, Essex, UK. *Earth Surface Processes and Landforms* 29, 893–903.
- Bray, M.J., Carter, D.J., Hooke, J.M., 1991. Coastal sediment transport study. Volume 1; Methods, Synthesis and Conclusions. Report. Portsmouth Polytechnic, Portsmouth.
- Bristow, C.S., Chroston, P.N., Bailey, S.D., 2000. The structure and development of foredunes on a locally prograding coast: insights from ground-penetrating radar surveys, Norfolk, UK. *Sedimentology* 47, 923–944.
- Charlton, M.E., Large, A.R.G., Fuller, I.C., 2003. Application of Airborne LIDAR in river environments: The River Coquet, Northumberland, UK. *Earth Surface Processes and Landforms* 28 (3), 299–306.
- Ciavola, P., 1997. Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK). *Catena* 30, 369–389.
- Cracknell, A.P., 1999. Remote sensing techniques in estuaries and coastal zones— an update. *International Journal of Remote Sensing* 20, 485–496.
- Davies, J.L., 1964. A morphogenic approach to world shorelines. *Zeitschrift für Geomorphologie* 8, 127–142.
- De Boer, G., 1964. Spurn Head: its history and evolution. *Transactions of the Institute of British Geographers* 34, 71–89.
- Diver, C., 1933. The physiography of South Haven Peninsula, Studland Heath, Dorset. *Geographical Journal* 81, 404–427.
- Edmondson, S.E., Traynor, H., McKinnell, S., 2001. The development of a green beach on the Sefton Coast, Merseyside, UK. In: Houston, J.A., Edmondson, S.E., Rooney, P.J. (Eds.), *Coastal Dune Management: Shared Experience of European Conservation Practice*. Liverpool University Press, pp. 48–58.
- Eleveld, M.A., 1999. Exploring Coastal Morphodynamics of Ameland (The Netherlands) with Remote Sensing Monitoring Techniques and Dynamic Modelling in GIS. ITC Publication 70. PhD Thesis. University of Amsterdam, Amsterdam.
- French, J.R., 2003. Airborne LIDAR in support of geomorphological and hydraulic modelling. *Earth Surface Processes and Landforms* 28 (3), 321–335.
- Gibeau, J.C., Gutierrez, R., Kyser, J.A., 1998. Increasing the accuracy and resolution of coastal bathymetric surveys. *Journal of Coastal Research* 14, 1082–1098.
- Gresswell, R.K., 1937. The geomorphology of the southwest Lancashire coastline. *Geographical Journal* 90, 335–349.
- Gresswell, R.K., 1953. *Sandy Shores in South Lancashire*. Liverpool University Press, Liverpool.
- Halcrow, 1988. The Sea Defence Management Study for the Anglian Region. Supplementary Studies Report. Anglian Water, Sir William Halcrow and Partners, BMT and Hydraulics Research, Swindon.
- Han, C.S., 1995. Vliegtuig-laserscanning. *NGT Geodesia* 2, 89–93 (in Dutch).
- Hesp, P.A., 2002. Foredues and blowouts: initiation, geomorphology and dynamics. *Geomorphology* 48, 245–268.
- Hicks, D.M., Hume, T.M., 1997. Determining sand volumes and bathymetric change on an ebb-tidal delta. *Journal of Coastal Research* 13, 407–416.
- Huising, E.J., Vaessen, E.M.J., 1997. Evaluating laser scanning and other techniques to obtain elevation data on the coastal zone. *Proceedings of the Fourth International Conference on Remote Sensing for Marine and Coastal Environments*, March 1997, Orlando, pp. 510–517.
- Irish, J.L., White, T.E., 1998. Coastal engineering applications of high-resolution LIDAR bathymetry. *Coastal Engineering* 35, 47–71.
- Jay, H., 1998. Beach–Dune Sediment Exchange and Morphodynamic Responses: Implications for Shoreline Management, The Sefton Coast, NW England. PhD Thesis. University of Reading, Reading.
- Jones, P.S., 1996. Kenfig National Nature Reserve: a profile of a British west coast dune system. In: Jones, P.S., Healy, M.G., Williams, A.T. (Eds.), *Studies in European Coastal Management*. Samara publishing Limited, Cardigan, pp. 255–267.
- Jones, P.S., Etherington, P.S., 1989. Autoecological studies on the rare orchid *Liparis loeselii* and their application to the management of dune slack ecosystems in South Wales. In: Carter, R.W.G., Curtis, T.G.F., Sheehy-Skeffington, M.J. (Eds.), *Coastal Dunes. Geomorphology, Ecology and Management for Conservation*. Proceedings of the Third European Dune Congress, Galway Ireland, 17–21 June 1992. A.A. Balkema, Rotterdam, pp. 299–312.
- Mason, D.C., Gurney, C., Kennett, M., 2000. Beach topography mapping— a comparison of techniques. *Journal of Coastal Conservation* 6, 113–124.
- Morang, A., Larson, R., Gorman, L., 1997. Monitoring the coastal environment: Part III. Geophysical and research methods. *Journal of Coastal Research* 13, 1064–1085.
- Morton, R.A., Leach, M.P., Paine, J.G., Cardoza, M.A., 1993. Monitoring beach changes using GPS surveying techniques. *Journal of Coastal Research* 9, 702–720.
- Psuty, N.P., 1992. Spatial variation in coastal foredune development. In: Carter, R.W.G., Curtis, T.G.F., Sheehy-Skeffington, M.J. (Eds.), *Coastal Dunes; Geomorphology, Ecology and Management for Conservation*. Proceedings of the Third European Dune Congress, Galway Ireland, 17–21 June 1992. A.A. Balkema, Rotterdam, pp. 3–13.
- Pye, K., 1990. Physical and human influences on coastal dune development between the Ribble and Mersey estuaries, north-west England. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), *Coastal Dunes: Form and Process*. Wiley, Chichester, pp. 339–359.
- Pye, K., 1991. Beach deflation and backshore dune formation following erosion under storm surge conditions: an example from Northwest England. *Acta Mechanica. Supplementum* 2, 171–181.
- Pye, K., 1992. Saltmarshes on the barrier coastline of north Norfolk, eastern England. In: Allen, J.R.L., Pye, K. (Eds.), *Saltmarshes. Morphodynamics, Conservation and Engineering Significance*. Cambridge University Press, Cambridge, pp. 148–178.
- Pye, K., Neal, A., 1994. Coastal dune erosion at Formby Point, north Merseyside, England: causes and mechanisms. *Marine Geology* 119 (1–2), 39–56.
- Pye, K., Saye, S.E. 2005. Sand Dune Processes and Management for Flood and Coastal Defence. Unpublished Report to DEFRA, London, 5 volumes.
- Sallenger, Jr., A.H., Krabill, W.B., Swift, R.N., Brock, J., List, J., Hansen, M., Holman, R.A., Manizade, S., Sontag, J., Mer-

- edith, A., Morgan, K., Ynkel, J.K., Frederick, E.B., Stockton, H., 2003. Evaluation of airborne topographic LIDAR for quantifying beach changes. *Journal of Coastal Research* 19, 125–133.
- Saye, S.E., 2003. Morphology and Sedimentology of Coastal Sand Dune Systems in England and Wales. PhD Thesis. University of London, UK.
- Short, A.D., Hesp, P.A., 1982. Wave, beach and dune interactions in southeastern Australia. *Marine Geology* 48, 259–284.
- Steers, J.A., Stoddart, D.R., Bayliss-Smith, T.P., Spencer, T., Durbidge, P.M., 1979. The storm surge of 11 January 1978 on the east coast of England. *Geographical Journal* 145, 192–205.
- van der Wal, D., Pye, K., 2003. The use of bathymetric charts to assess morphological and sediment budget change in estuaries. *Geographical Journal* 169 (1), 21–31.
- Williams, A.T., Davies, P., 2001. Coastal dunes of Wales; vulnerability and protection. *Journal of Coastal Conservation* 7, 145–154.
- Woolard, J.W., Colby, J.D., 2002. Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LIDAR: Cape Hatteras, North Carolina. *Geomorphology* 48, 269–287.