Hunstanton Groyne Fields: appraisal of groyne effectiveness

Appendix A. Review of coastal processes and shoreline change

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Appendix A. Review of coastal processes and shoreline change

A.1 Introduction

This appendix provides an up to date understanding of coastal process and shoreline change along the Hunstanton coastline, in support of appraising the effectiveness of groynes across both the Borough Council of Kings Lynn and West Norfolk (BCKLWN) and the Environment Agency frontages. It primarily focuses on the concrete and timber groyne stretches of shoreline but, in terms of coastal processes, has considered the wider coastal zone of The Wash and its outer banks. Findings from this have been taken forward into the main report.

A.2 Coastal setting

The study area frontage stretches from the start of the promenade, at the northern end of Hunstanton, to the end of the timber groyne field at Jubilee Bridge, Heacham. This lies along the north-eastern side of The Wash, within its outer reaches. It can therefore be considered transitional between the estuarine environment of The Wash and the open coast environment of North Norfolk.

Within the Shoreline Management Plan (SMP) (Royal Haskoning, 2010) the study frontage falls within two units (termed Policy Development Zones):

- PDZ2 – Wolferton Creek to South Hunstanton
- PDZ3 – Hunstanton Town

With PDZ4 covering Hunstanton Cliffs, up to the north-eastern end of the cliffs. These units are shown in Figure A-1.

The SMP policies for the units are as follows (Table A-1):

PDZ	Short term (up to 2025)	Medium term 2025-2055	Long term 2055-2105	Intent of plan
PDZ4 Hunstanton Cliffs	No active intervention	No active intervention	No active intervention/ Hold the line	To continue to allow the cliffs to erode naturally and provide sediment to help maintain the beaches to the south, up to the point where the erosion starts to threaten cliff top properties and the B1161. From that time on, the intent is to prevent further cliff erosion to sustain the properties and the road.
PDZ3 Hunstanton Town	Hold the line	Hold the line	Hold the line	To sustain the viability of Hunstanton town as a tourist resort and regional commercial centre, by holding the shoreline defences where they are now.
PDZ2 Wolferton Creek to South Hunstanton	Hold the line	Hold the line/ Managed realignment/ No active intervention	Hold the line/ Managed realignment/ No active intervention	To develop a sustainable long-term solution through cooperation between the partner organisations and people and businesses with an interest in the area. Therefore policies for medium and long term are 'conditional'.

Table A-1 SMP policies (based on information in Royal Haskoning, 2010a).

The subsequent Wash East Coastal Management Strategy (WECMS) (Royal HaskoningDHV, 2015) used the same units, but relabelled these Units A, B and C (Figure A-2):

- Unit A – Hunstanton Cliffs (PDZ4)
- Unit B – Hunstanton Town (PDZ3)
- Unit C – Wolferton Creek to South Hunstanton (PDZ2).

Note that Unit A does not fall within the study area, whilst in Unit C, only Sub-units C1-C3 fall within the study frontage.

Whilst Units A and B are at risk from erosion, Unit C is at risk from flooding. The preferred strategic approaches recommended by the Strategy are as follows:

- Unit A - a Piloting Scheme to determine a '*socially, environmentally and economically acceptable option to reduce, but not stop* erosion'.
- Unit B - to sustain the promenade, sea wall and groynes, and to replace them when needed, currently expected in 15-20 years. At that point, the most likely option is a replacement of the promenade and sea wall, but alternatives could be a rock revetment or beach recharge.
- Unit C - to continue to protect people, properties, caravan parks and environmental assets for the foreseeable future, until a trigger point is reached in terms of environmental impacts, affordability and risk to life. The preferred option includes continued maintenance of the groynes.

A Coastal Management Plan has subsequently been produced for the Hunstanton frontage for BCKLWN (AECOM, 2019). This covers Units A and B (as defined in the WECMS). The preferred management option presented for Unit B is:

- to maintain the existing defences and then in the future to sustain the standard of protection through raising the heights of the defences. This includes refurbishment of the concrete and timber groynes to extend their defence life.

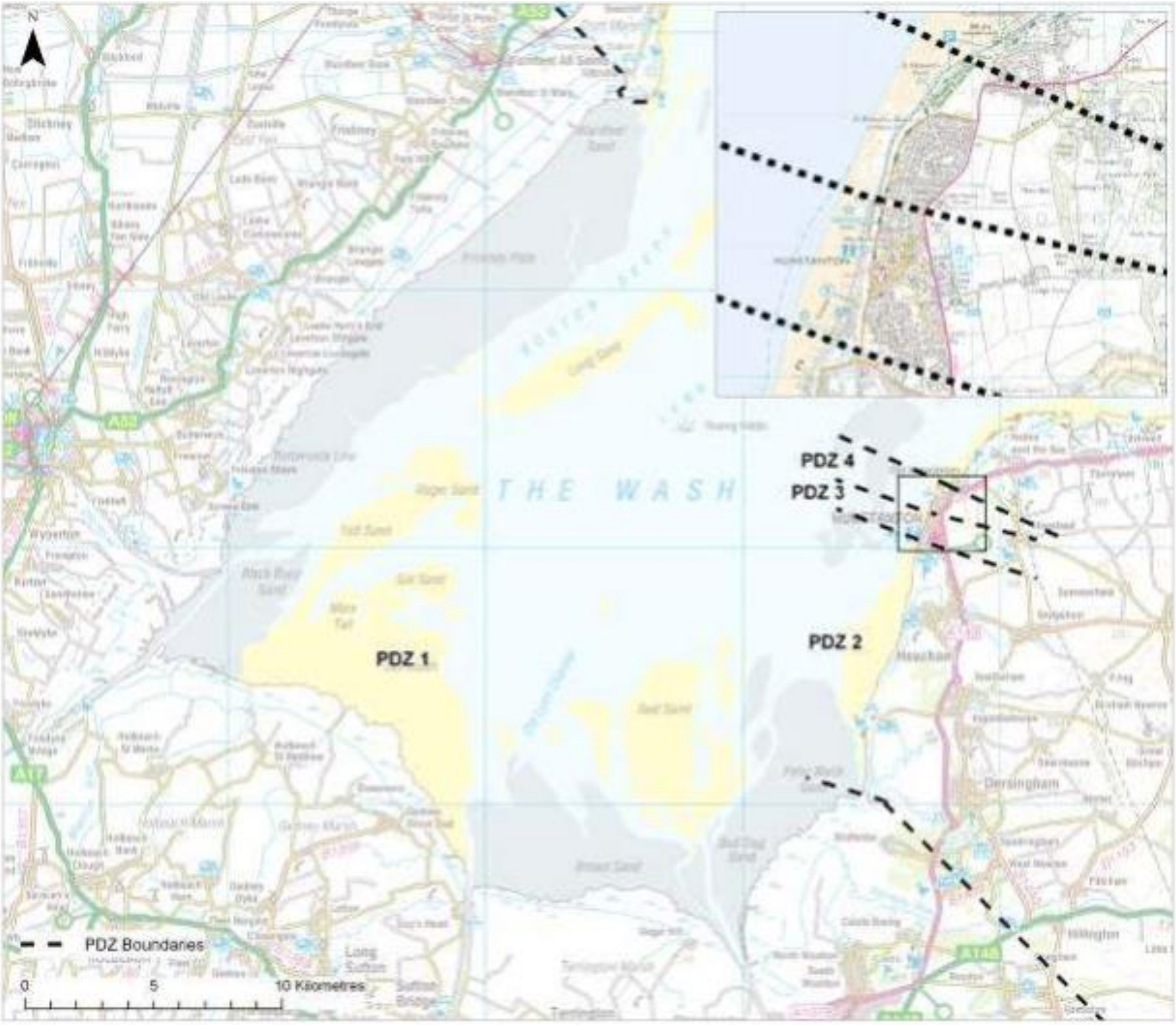


Figure A-1 SMP Policy Development Zones (taken from the SMP, Royal HaskoningDHV, 2010).

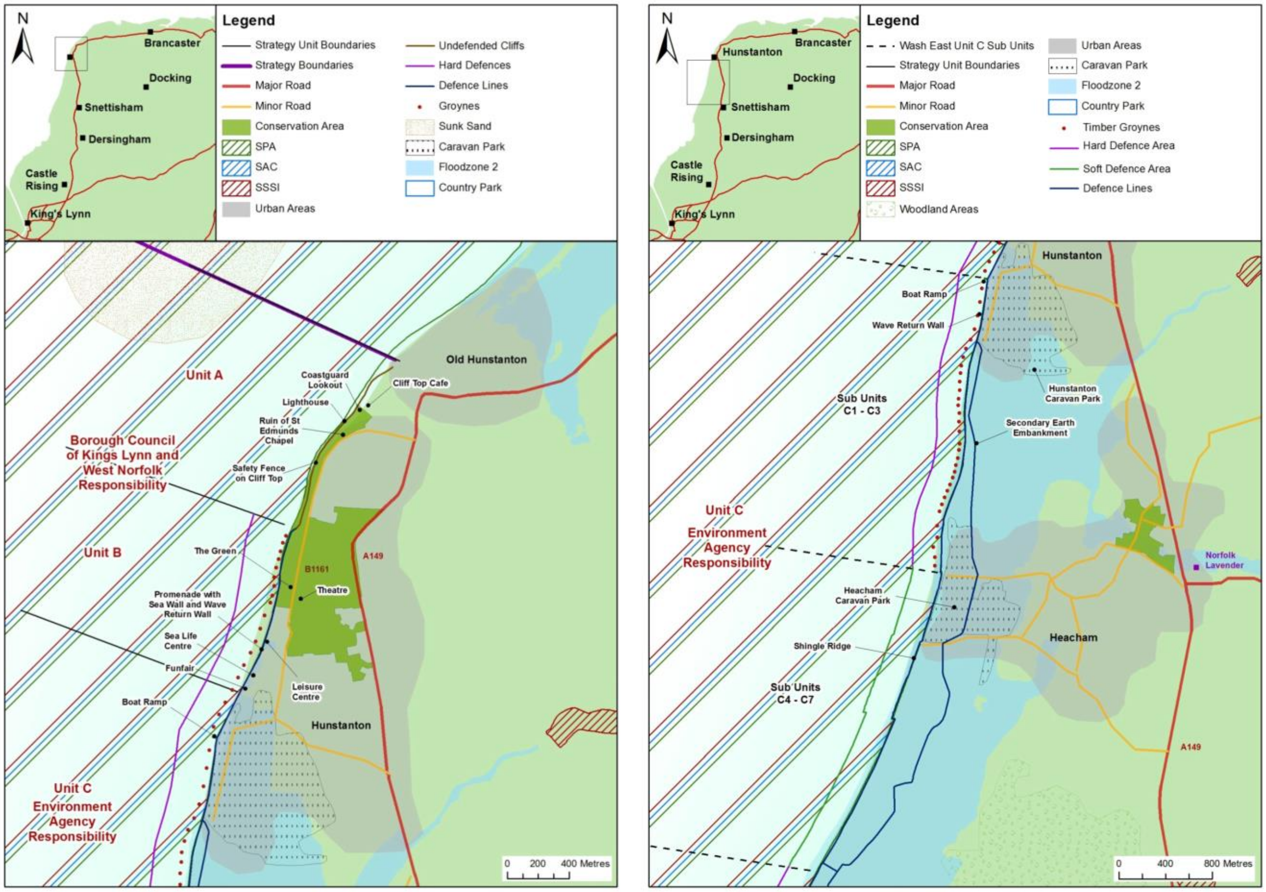


Figure A-2 Units A, B and C (part) as defined in the WECMS, and used in the Hunstanton Coastal Management Plan. Taken from Royal HaskoningDHV (2015).

A.3 Evidence used

A.3.1 Previous studies

The table below summarises the key reports reviewed as part of this study, from the most recent to the oldest.

Report	Produced for	Summary
Beach Survey Annual Report (Jacobs, various years up to May 2021)	Environment Agency	Annual reports produced in support of the Hunstanton & Heacham Beach Management, with particular reference to the annual programme of recycling of beach material. Review of topographic survey data supplied by the Environment Agency for the section of coast between Hunstanton and Snettisham. Includes calculations of beach volume change over time, dating back to 1992. Note that the reports since 2001/2002 have been produced by Jacobs. Previous reports, back to 1992, were produced by Posford Duvivier.
Hunstanton Coastal Management Plan (AECOM, 2019)	BCKLWN	Sets out the 'road map' to deliver the SMP policy for the Hunstanton frontage over the next 100 years; this document considers and costs management approaches for Units A and B.

Report	Produced for	Summary
		The appraisal includes a high level review of coastal processes and analysis of a limited number of beach transects and LiDAR data. Includes limited discussion on the role of the groynes.
Wash East Coastal Management Strategy (WECMS) (Royal HaskoningDHV, 2015)	Environment Agency and BCKLWN	Identifies the preferred strategic approaches for implementing the SMP policy for the frontage between Hunstanton cliffs and Wolferton Creek. Includes a comprehensive review of coastal processes, with the governing coastal process discussed for each of the three coastal units defined. Includes limited discussion on the role of the groynes.
The Wash Shoreline Management Plan: Gibraltar Point to Old Hunstanton (Royal Haskoning, 2010)	East Anglian Coastal Group	Sets out the long term management policies for The Wash, covering the frontage from south of Gibraltar Point up to and including the cliffs at Old Hunstanton. As part of the development of the SMP policies, a full assessment of the coastal processes in The Wash area was undertaken.
Coastal Change Around The Wash: Literature Review (Royal Haskoning, 2004)	English Nature	A literature review that describes Holocene (last 10,000 years) and historical coastal change around The Wash, and its predecessor, the Wash-Fenland embayment. It identifies the geological, sea level and anthropogenic events that have led to the present position of the shoreline.
Southern North Sea Sediment Transport Study (HR Wallingford, 2002)	Partnership including Environment Agency, nine local authorities, BMAPA and English Nature (*now Natural England*)	Regional study to provide a broad appreciation and detailed understanding of sediment transport along the eastern coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent, on the south side of the Thames Estuary.
Shoreline Movement and Shoreline Management in The Wash, Eastern England (Brew D. S. & Williams A., 2002)	Littoral 2002, The Changing Coast. EUROCOAST / EUCC, Porto – Portugal	Short paper providing an overview of coastal processes and management within The Wash up to 2001.
Hunstanton to Heacham beach management. (Nunn R. & Beech N., 1998)	Proceedings of the ICE Coastlines, Structures and Breakwaters Conference, 1998.	Overview and evaluation of beach management approaches prior to 1998, includes an appreciation of coastal processes.
ICE Conference on the North Sea Floods of 31 January and 1 February 1953 (various, 1954)	Institute of Civil Engineers Conference	Review of damage caused to sea defences due to the January 1953 storm surge. Includes description of the coastline before the storms, photographs of the damage and defence cross-sections. A key paper is by W. E. Doran '*Sea defences in the Wash and estuary of the Great Ouse in relation to the tidal surge of the 31st January 1953*'.
Report on Sea Defences (Kirkpatrick & Partners, 1953)	Produced for New Hunstanton Urban District Council.	Report on the condition of Hunstanton North Promenade seawall June 1953 and proposals for renewal/ replacement Provides details on the defences at the time, with maps, and general discussion regarding the issue of erosion.

A.3.2 Site visit

A site visit was undertaken in July 2021. It is expected that the beaches at this time were close to their fullest and therefore observations made may be indicative of the maximum retention of beaches by groynes. As a number of groynes were buried at this time, a subsequent visit was undertaken in November 2021. Appendix B provides further details on observations made during these site visits.

A.3.3 Beach monitoring data

As part of the Anglian Coastal Monitoring (ACM) programme, beach profile data have been collected at one-kilometre intervals along this coastline since 1992. Notably this follows recharge of the beaches in 1990-1991; therefore there is no information from ACM along the recharged frontages of the beach profile. Additional transects were added in 2010 and again in 2013, with transects at roughly 50 m intervals available since 2013. The latest data appraised are from September 2020.

Jacob’s in-house asset management system, SANDS, has been used to plot and analyse the data.

These data sets have also been analysed as part of the Beach Survey Annual Reports (Jacobs and Posford Duvivier, various dates) and used to derive beach volumes above 0 mOD (approximately mean sea level). However, this analysis only covers the Environment Agency frontage, i.e. south of the Power Boat Ramp.

LiDAR data and aerial photography are also collated through the ACM. These are available for the following years:

- LiDAR data: all years 2011 to 2020 (but years 2011, 2013 and 2015 have only partial coverage)
- Aerial photographs: 1992, 1994, 2001, 2004, 2009 and 2020.

A visual analysis has been undertaken of both the aerial photographs and LiDAR data. The LiDAR data has also been used to produce difference plots which highlight key areas of erosion and accretion over time, recognising, however, that these data sets only provide a snapshot in time.

A.3.4 Bathymetric data

No bathymetric data are available covering this area from the Anglian Coastal Monitoring (ACM) programme.

The WECMS (Royal HaskoningDHV, 2015) refers to earlier analysis of historical Admiralty charts by Posford Duvivier (1999), which compared charts for the years 1828, 1871, 1952 and 1971, as well as an Environment Agency seabed survey dated 1995. The results from this analysis have been used within this report, but no further review or analysis of historical charts has been undertaken, nor has the original report been accessed.

A.3.5 Historical maps and photographs

A high-level examination of historical maps of the study frontage has been undertaken to appraise the analysis presented in previous reports. Whilst there are maps of the area dating back to the 1600s, these provide very limited information. The first Ordnance Survey pen and ink drawing was produced in 1815, but it is not until 1886 when the first six-inch maps were produced that the level of detail becomes equivalent to today’s mapping.

The historical Ordnance Survey maps have been used to view changes in the coastline over time, but no GIS analysis has been undertaken at this stage. Maps have been viewed on-line from https://maps.nls.uk/ but due to licence restrictions it is not possible to reproduce these within this report.

There are a number of historical photographs viewable on-line at https://www.francisfrith.com/uk/ and also www.hunstantoncivicsociety.org.uk/; these give a useful insight to how the coast looked in the past. Due to licence restrictions it is not possible to reproduce most of these within this report, but links have been provided.

A.3.6 Coastal data

No new hydrodynamic modelling has been undertaken for this study. Offshore wave data are available for the North Well WaveNet wave buoy (WWB1) located within central channel of The Wash (Figure A-9). This has been deployed since 2006 and provides wave height, direction and period data. Analysis of design nearshore wave parameters was undertaken for the WECMS, which applied a method of wave condition analysis developed for the '*Parameters for Tidal Flood Risk Assessment*' report (Royal Haskoning. 2010b). For the more recent Hunstanton Coastal Management Plan (AECOM, 2019) wave data from the wave buoy was transformed inshore and joint probability analysis undertaken to derive nearshore wave extremes. No further analysis has been undertaken for this study.

AWAC instruments, which record tidal elevations, waves, currents and surge information, have previously been deployed within The Wash, including one just to the west of South Sunk Sand (S8W Sunk Light) (Figure A-9). Two Sea State Reports have been published through ACM covering 2006-2007 and 2007-2008 (Environment Agency, 2009; 2010) and information from these has been incorporated below.

Despite the deployment of AWACs, there does not appear to be any recent information on tidal currents. No reference to tidal currents is made in the Hunstanton Coastal Management Plan, and the WECMS only refers to 'typical' current speeds in the Old Lynn Channel taken from the Admiralty Chart. Similarly, no additional data sets on currents were reported in the Sea State Reports.

A.4 Review of evidence

A.4.1 Introduction

The intention of this study has been to appraise the effectiveness of groynes. A key part of this has been to understand how this coastline has changed over time and the key drivers of this change. There has already been significant work undertaken to look how the various components of this coast interact and the interdependencies between them. As such work has not been unnecessarily repeated but has been used, together with additional analysis of beach profile data, to build up a picture of current shoreline behaviour and influences on this.

A.4.2 Coastal characteristics

A.4.2.1 Morphology

At the large scale, this frontage sits within the wider area of The Wash. This is the largest embayment in the UK and both its natural configuration, which makes it a generally sheltered, low-energy environment, and the human modifications through extensive land claim, has made the embayment a significant sink for sediments.

In terms of morphology, however, the Hunstanton-Heacham coastline is distinctly different from the south or west coasts of The Wash, where there are extensive saltmarshes. Instead, the frontage is characterised by the dramatic Hunstanton chalk cliffs to the north (Figure A-3) to the low-lying plain of Heacham to the south, fronted by beaches consisting of gravels and sands and lower sandflats.


Figure A-3 Hunstanton cliffs

Figure A-4 Carstone platform showing distinctive jointing formation.

Along the base of the Hunstanton cliffs, and exposed across the foreshore extending south of the cliffs, is an outcrop of red-brown Carstone (Figure A-4). Carstone is an iron-rich sandstone and is generally around 5 m thick (although it reaches up to 18.9 m thickness as recorded in the Hunstanton Borehole at TF64SE11; BGS Lexicon). Where the Carstone is exposed on the foreshore it has been weathered to form a distinctive jointing pattern.

Across the lower sandflat there are also features known as ‘scalps’; these are biogenic reefs formed by mussels, which bind together to form dense clumps. During the site visit, it was observed that there were locations where deposits of mussel shells have accumulated against the groynes. These may relate to storm events.

The intertidal area along the Hunstanton frontage is constrained by low water channels exiting The Wash and is narrower than to the south, which allows higher energy waves to reach further up the beach (Royal HaskoningDHV, 2015). Along the concrete groyne frontage, the beaches typically are characterised by a narrow gravelly-sand upper beach, which is fronted by sand beach and Carstone outcrop, beyond which lies a sandflat.

Figure A-5 Differential beach levels across the groynes.

The Strategy (Royal HaskoningDHV, 2015) reports that the thickness of sediment on the Hunstanton beaches is generally unknown; although it is noted within the Hunstanton Hard Defences Design Report (Babtie Brown & Root 2005) that the beach level varies between 2.50 and 3.35 mOD the depth to the toe of the pile on the existing defences was reported as unknown. Given the exposure of Carstone across the concrete groyne frontage, the gravelly-sand can, however, be assumed to be a superficial veneer of limited thickness.

At the time of the site visits (July and November 2021) it was evident that the upper gravelly-sand beach was constrained to the top of the concrete groyne bays and whilst there was only minor differential in beach level evident at some of the more northern groynes (up to groyne 5), this was typically less than half a metre at its maximum in July (and even less in November) and only extended up to 20 metres from the seawall (Figure A-5). The build-up of sediment in November 2021 was generally over a metre below the top of the groynes. Between Groyne 5 and Groyne 9 the beaches were observed to be lower, with gaps beneath the groynes evident. Cobbles derived from erosion of Hunstanton cliffs form a linear deposit along the toe of the upper beach. The position of this interface does not appear to be much influenced by the groynes.

Figure A-6 BCKLWN timber groyne frontage, looking north.

Moving south, along the BCKLWN timber groyne frontage, south of Groyne 12 the morphology of the beach changes, characterised by a wider upper gravelly sand beach which transitions to a lower sand beach, fronted by a sandflat below - 1 mOD (beyond the end of the groynes) (Figure A-6). At the time of the site visits the upper sections of the groynes were buried, with generally around 50 to 65 m of the groyne length still exposed.

Along much of the frontage the upper coarse mixed beach is around 35 to 40 m in width, but tapers considerably north of Groyne 12. At the time of the November site visit, across the lower sandy beach there was limited build up at the groynes evident and as a result little or no differential in beach level across the groynes, along most of the frontage: only where larger stones have become trapped is any differential evident. As to the north, cobbles originally derived from Hunstanton cliffs form a deposit along the toe of the gravelly-sand beach, below which extends the lower sand beach and then the sandflat.

Figure A-7 Environment Agency timber groyne frontage

To the south of the Power Boat Ramp, along the Environment Agency frontage, the morphology of the beach varies along shore, which is likely to relate changes in the alignment of the coast, the nearshore and also beach management (Figure A-7). Along some stretches, the beaches are similar to those along the BCKLWN timber groyne frontage; characterised by an upper sand and gravel beach, fronted by a more gently sloping lower sand beach and sandflat. Elsewhere the distinction between upper and lower beach is not so evident and the sand-shingle beach transitions directly to a lower sandflat. The state of the beach has, however, changed over time. Exposure of the groynes also varies alongshore, with greatest exposure around Groyne 12 and Groyne 13, but a general observation made during the sites visits was the lack of height differential at the groynes. The cobble deposits evident further north are no longer present (or exposed) along the toe of the upper beaches (Figure A-8).

A narrow strip of low vegetated dunes has developed at the toe of the seawall in the slight embayment that exists just north of Heacham, between Groyne EA15 and Groyne EA26. Historical aerials show that prior to 1999 there were no dunes here. The latest aerials and observations from the site visit indicate, however, that there has been some erosion of these in recent years.

(a) BCKLWN frontage (Groyne 16)

(b) Environment Agency frontage

Figure A-8 Comparison of beaches at groynes along the BCKLWN and Environment Agency frontages

There is more information on sediment thickness available for the beaches south of Heacham: the Strategy records that The Heacham Dam and Snettisham Scalp investigations (AEG Investigations 1998) reported that at Heacham, loose sandy silt, and medium to very dense sand is present down to just over 6.5 m, and below that there is stiff silty clay with sand beds. Whilst to the south of Snettisham Scalp, the borehole data indicate dense to very dense sand, with bands of silt and clay, down to the limit of the borehole (approximately 10 m deep).

The Strategy reports that previous studies have indicated that the intertidal area between Shepherd's Port and Hunstanton is primarily fine sand (0.125 – 0.185mm) and very fine sand, whereas south of Snettisham Scalp the sediment are more typically poorly sorted muds and very fine sands. Whilst the 2001 PAR (Posford Duvivier 2001) noted that there is a significant decrease in sand content from the northern to southern end of the Hunstanton-Heacham frontage (Unit C), the Strategy suggested that this had become less noticeable since 1992, possibly as a result of the Environment Agency's management operations, which will obscure some of the natural sediment trends.

A.4.2.2 Bathymetry

The average depth of The Wash is less than 10 m, with the deepest areas located within the central part, with depths of up to 40 to 50 m recorded in the Well and Lynn Deeps (Royal Haskoning, 2004). These deep water channels are incised into the underlying geology and are relict fluvial channels that would have originally drained the Wash-Fenland plain; they are therefore relatively immobile features.

Sand is the dominant subtidal surface sediment, with mud and shells in the inner channel bottoms and coarser materials around the deepest parts. The Wash features a complex series of sand banks (Figure A-9), which lie parallel to the axis of main tidal flow and tend to separate flood and ebb-dominant tidal flows and the associated sediment transport. These are also likely to affect nearshore waves and therefore influence patterns of erosion and accretion at the shoreline (Royal Haskoning, 2015). Lying offshore of the Hunstanton-Heacham shoreline is the offshore bank of Sunk Sand, which extends around four kilometres from the coast. Royal HaskoningDHV (2015) suggest that the western and eastern edges of Sunk Sand are likely to be constrained by the flood and ebb channels respectively, and that therefore the bank is unlikely to move onshore. To the south of this is a shore-attached sand bank, known as Stubborn Sand.

Hydraulics Research Station (1975a) (cited in Royal Haskoning, 2004) looked at changes in the bathymetry of The Wash between 1828 and 1971 and found that the major banks of The Wash had not changed in general position, but had changed in size. Of relevance to this study, Sunk Sand was found to have increased significantly in size in south-west and south-east directions and experienced erosion (about 1.5 km) of their northern ends.

More recently, Posford Duvivier (1999; cited in Royal Haskoning, 2015) have analysed historic Admiralty charts for the area adjacent to Hunstanton for the years 1828, 1871, 1920, 1952 and 1971, as well as an Environment Agency sea bed survey dated 1995. The assessment concluded that Sunk Sand was mapped as a very small sea bed feature in 1828 but between 1871 and 1920 increased significantly in size and spread south, with erosion of its northern end. By 1952, Sunk Sand was in its current position. Stubborn Sand to the south started as a build-up of sand along the shoreline and was first shown on the 1920 survey. Since then, it has grown out from the shore and joined with sand banks that had formed just offshore. The mapping suggests it moved back onshore between 1971 and 1995. There is, however, no data available on recent changes to the bathymetry.

There does not appear to have been analysis of the consequences of these changes on changes at the shoreline, although it could be inferred that:

- Development of Sunk Sand as a more substantial feature may have constrained tidal flows between the bank and the shoreline, potentially increasing tidal (ebb) energy along the Hunstanton shoreline.
- In contrast, the expansion of Stubborn Sand further south would be expected to have wave energy at the shoreline (during normal conditions) and potentially created an environment more conducive to sediment accumulation.

A.4.3 Physical setting

A.4.3.1 Tides

The Wash is macro-tidal, with a spring tidal range of around 6.3 m and neap tidal range of around 3 m (Table A-3); this is the largest occurring range on the east coast of England (Nunn & Beech, 1998). As a result, tidal currents can be strong, particularly in the main channels. Admiralty charts shows the Old Lynn Channel peak flood spring tide to be 1.20 m/s, and a 1.02 m/s peak ebb spring tide (Environment Agency, 2010).

The central part is flood dominated, whilst the margins are ebb-dominated but weaker, with north-eastern residual flows along the study frontage (Royal HaskoningDHV, 2015). This means that at Hunstanton and Heacham the net tidal currents flow run from south to north, in contrast to the wave-driven littoral transport (see below).

Location	Tidal level (mOD)			
	MHWS	MHWN	MLWN	MLWS
Hunstanton	3.65	1.85	-1.25	-2.85
King’s Lynn	3.77	1.97	-1.23	-2.03

Table A-2 Tidal levels at Hunstanton and King’s Lynn (UK Hydrographic Office; taken from Royal HaskoningDHV, 2015).

It is reported within the Strategy (Royal HaskoningDHV, 2015) that offshore at Hunstanton, spring tidal current velocities are close to a maximum to the north approximately two hours after high tide with slightly lower velocities to the south two hours prior to high tide (Mott MacDonald, 2005).

Surges are an important factor in driving change along the coast. The vulnerability of this coastline to surge events is due to both the funnelling effect of The Wash embayment and the shape of the North Sea itself, which is relatively shallow (the average depth of the North Sea is in the region of 40 m) and is open to the North Atlantic at its northern end but effectively forms a closed basin at the southern end (HR Wallingford, 2002). External surges result from pressure gradients travelling from the deep North Atlantic waters onto the shallow continental shelf and by strong winds to the north of Scotland causing an increase in tidal levels (Pugh, 1986). In addition, the North Sea basin is also prone to the generation of 'internal surges'. These events usually occur in response to north or north-west winds produced by low pressure over the continent and areas of high pressure to the west of Ireland (Pratt, 1995). They are less common than external surges, but can produce more severe events (HR Wallingford, 2002).

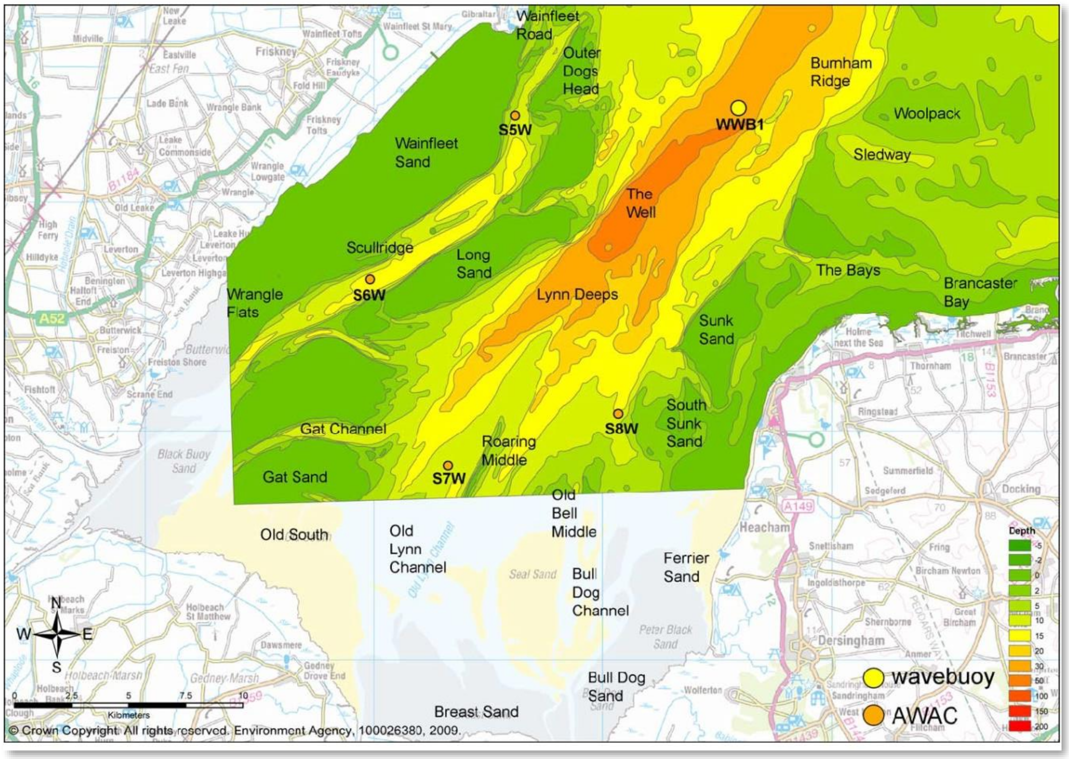


Figure A-9 Bathymetry plot showing water depths and the location of instruments in The Wash. Taken from Environment Agency (2010).

A.4.3.2 Waves

Figure A-10 shows wave roses for significant wave height (Hs) and wave period (Tp) for North Well WaveNet buoy, and Figure A-11 shows wave roses from the deployed AWACs (covering one year of data).

Whilst much of The Wash is sheltered from significantly wave energy, the Hunstanton-Heacham shoreline is exposed to waves predominately from the north-north-east sector (000 – 030°) (Royal HaskoningDHV, 2015, Posford Duvivier 1996a; cited in Royal Haskoning, 2004). Nunn & Beech (1998) report that waves within The

Wash can be generated in two ways: externally generated from the North Sea, which tend to be the greater in magnitude, and locally generated within the embayment itself.

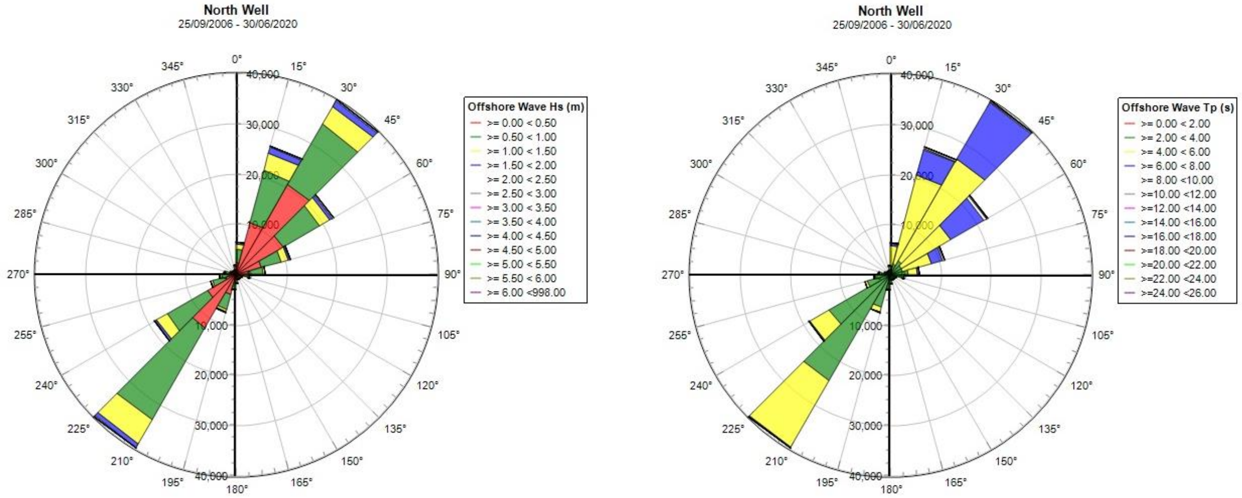


Figure A-10 Offshore wave rose generated for data from North Well wave buoy: left - significant wave height (Hs), right - wave period (Tp).

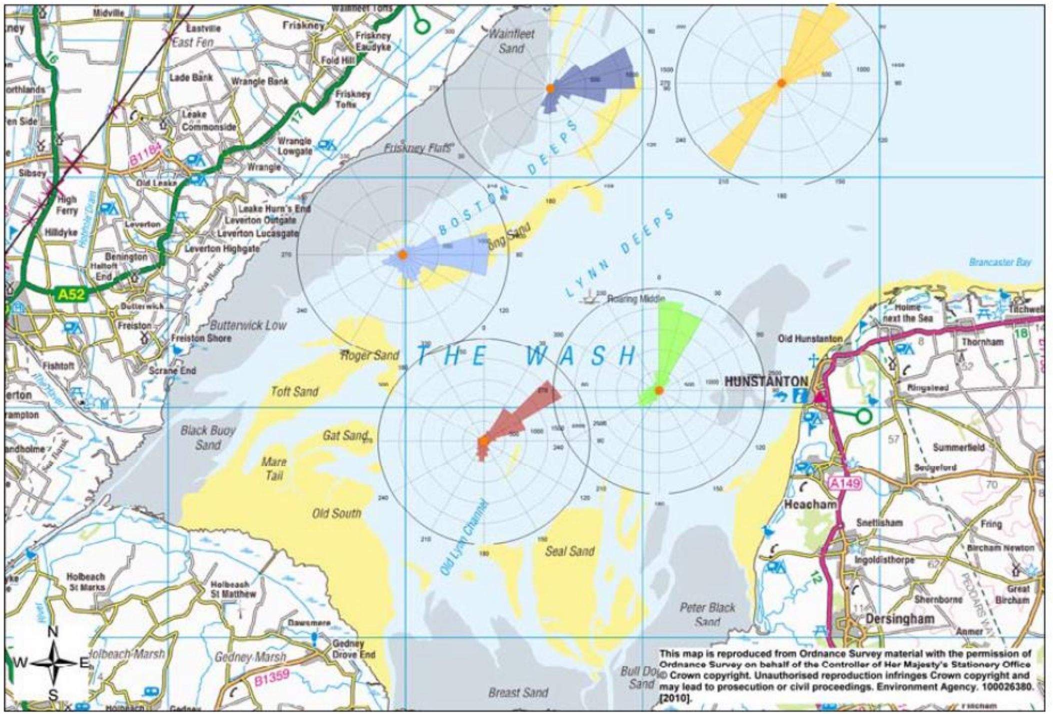


Figure A-11 Wave roses for The Wash AWACs and the North Well Waverider buoy (shown in yellow), from October 2007 to September 2008. Taken from Environment Agency (2010).

From the North Sea, waves enter The Wash primarily through the central main channel, and then tend to radiate out into The Wash embayment (Environment Agency, 2010). The shallow bathymetry of The Wash means that wave heights and energy are reduced due to shoaling, with further reduction at the shoreline due to attenuation by intertidal sandflats. Waves generated internally tend to be of much shorter period, creating choppy conditions (Environment Agency, 2010).

Although the North Well buoy also shows a high proportion of south westerly waves (Environment Agency, 2010), data from the from Sunk Light AWAC for 2007-8, which lies closer to the shoreline show the dominance of waves from the North to North-east sector. The Sunk Light AWAC for 2007-8 data also indicate that the mean significant wave height typically ranges from 0.3 m to 0.7 m (Environment Agency, 2010), but in the south-eastern Wash, strong or gale force NE-NW winds may produce wave heights of about 1 m, with up to 2 to 3 m waves generated during severe gales. Wave period data collected through the AWACs generally shows that the dominant waves are locally generated waves within The Wash, with the majority of waves between 2 and 5 seconds, but the data for Sunk Light, offshore of Hunstanton, does show a second peak created by slightly longer period waves, likely to be waves entering The Wash from the north east (Environment Agency, 2010). The North Well wave buoy, located within the outer central channel, records more waves with a longer peak wave period, with waves typically between 2 and 7 seconds. Notably, wave periods and wave heights vary throughout the tidal cycle as an increase in water depth allows longer period waves to reach the shorelines that are protected by banks (Environment Agency, 2010).

The Hunstanton Coastal Management Plan (AECOM, 2019) made a high-level assessment of nearshore wave extremes for various return periods, by transforming the North Well offshore wave data to six nearshore locations along the BCKLWN frontage using a 1D model (Figure A-12). The results suggest that there is some small variation along the BCKLWN shoreline, with typically larger waves experienced at location NH016, which is located midway along the concrete groyne frontage. AECOM's calculations were found to compare well with the results from WECMS (Royal HaskoningDHV, 2015) for events below a return period of 1 in 50 years, but for return periods greater than 1 in 50, results from WECMS were higher by almost 0.5 m in places.

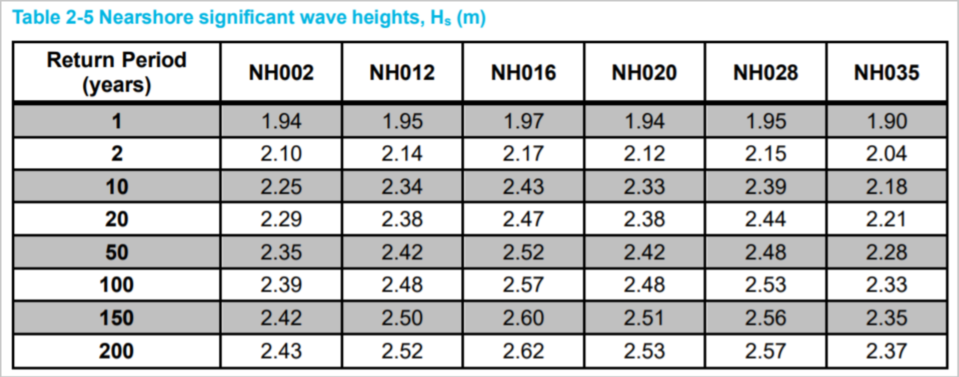


Table 2-5 Nearshore significant wave heights, H_s (m)

Return Period (years)	NH002	NH012	NH016	NH020	NH028	NH035
1	1.94	1.95	1.97	1.94	1.95	1.90
2	2.10	2.14	2.17	2.12	2.15	2.04
10	2.25	2.34	2.43	2.33	2.39	2.18
20	2.29	2.38	2.47	2.38	2.44	2.21
50	2.35	2.42	2.52	2.42	2.48	2.28
100	2.39	2.48	2.57	2.48	2.53	2.33
150	2.42	2.50	2.60	2.51	2.56	2.35
200	2.43	2.52	2.62	2.53	2.57	2.37

Figure A-12 Nearshore significant wave heights calculated by AECOM (2019). Note NH002 is at the southern end of the BCKLWN frontage and NH035 is in the vicinity of the lighthouse, along Hunstanton cliffs. Note that these are for current conditions, i.e. do not include allowance for sea level rise.

Waves at the shoreline drive a north to south littoral drift. Potential rates of sediment transport along the frontage vary, both due to subtle changes in orientation (Royal HaskoningDHV, 2015) and also the attenuation of waves across the sandbanks. Incoming waves can also be affected by the strong currents within The Wash. Reported rates are in the region of 6,000 to 8,000 m^3/year (Royal HaskoningDHV, 2015; Nunn & Beech,1998); these are likely to be potential rather than actual rates, i.e. rates that would occur if sediment were available to be transported, and much lower rates have been reported by others (see Royal HaskoningDHV, 2015 for a review).

The wave-driven littoral transport is opposite to that generated by tidal currents, which is directed from south to north along the frontage (Royal HaskoningDHV, 2015), but Nunn & Beech (1998) report that along the upper part of the beach the wave driven transport is sufficient to overcome the northward drift generated by the residual tidal currents.

A.4.3.3 Sediment supply

Fine sediment is supplied in suspension into the larger body of The Wash mainly from the north, through the northern extremity of Boston Deep, with the subtidal channels acting as the main conduits. It has been estimated that The Wash receives an annual deposition of about 6.8 million tonnes of suspended sediments from offshore areas (Ke et al., 1996). Some of this is subsequently deposited on the sandbanks, sandflats and saltmarshes around the margins of The Wash. As such the offshore zone is understood to provide the largest input of sediment to the frontage (Royal HaskoningDHV, 2015).

In terms of the coarse sediment (coarse sand and gravels), which constitutes the beaches of the study frontage and barrier beach to the south, the original source of much of this is likely to have been erosion and subsequent onshore transport of fluvio-glacial or glacial sediments occupying parts of the deeper and outer parts of The Wash embayment and North Sea (Royal HaskoningDHV, 2015).

The Strategy reports that Halcrow (1988) described the quantity of material forming the beach as being finite as the supply is not replaced from the north by natural means. Conversely, as reported in the Strategy, Mott MacDonald (2005) estimated that approximately 5,200 m^3/year of material enters the coastal system from the approximate 1.3 kilometre length of Hunstanton Cliffs. They proposed that the majority of this material is Carstone and as such the eroding cliffs provide a significant contribution to maintaining beach levels in Hunstanton. The Strategy noted that the volume of 5,200 $m^{3/}$year is a similar order of magnitude as the average annual recycling and calculated that if this volume was spread evenly across the foreshore of Units B and C, the overall vertical accretion would be only 0.25mm and therefore insignificant. If it remained in Unit B, this volume would equate to around 20 mm/year.

At the time of the site visit, cobble-sized deposits were present along the Hunstanton beaches, which clearly originate from the cliffs. These will be broken down over time and eventually will contribute to the fine components of the beach system: the time for this process to occur is not certain. The beaches also contain gravel-sized flints, which are likely to have originated from fluvio-glacial or glacial sediment and therefore do not have a source from the cliffs and in places there is a high proportion of shell (mussels). Therefore, although the cliffs clearly do contribute to the beaches, this process is likely to be only significant over longer, rather than shorter, timescales in terms of contributing to maintaining or building beaches. This concurs with conclusions of the Strategy which reported that chalk is not present in large amounts in the beach deposits, with observations from key stakeholders also suggesting that the presence of both grey and red chalk within Unit B is only superficial and in relatively small amounts. The Strategy concluded that sediment supply from the eroding cliffs is not significant in terms of maintaining beach levels along the Hunstanton to Wolferton Creek frontage (Appendix K2; Royal HaskoningDHV, 2015).

A review of coastal processes by Posford Duvivier (1999) identified no link between sediments of the nourished (upper) beach along the Snettisham-Heacham frontage and the offshore sandbanks, but proposed a possible link between the sandbanks and the lower foreshore. No further quantification of this link was, however, made.

A.4.4 Historical morphological change and shoreline management

A.4.4.1 Geological past

Whilst the chalk of the Hunstanton cliffs and sandstone of the Carstone date from the Cretaceous period (around 145 to 66 million years ago), the superficial geology is more complicated; seas and ice sheets came and went over this part of Norfolk many times in the Pleistocene period, leaving a complex sequence of marine and terrestrial sediments which includes many gaps in the record (Norfolk Coast Partnership, 2011). The last glaciation to affect the area was in the Devensian period (around 27,000 years ago) when the large ice sheet that covered the north of England extended to this frontage. As this retreated it deposited till and outwash sediments known as the Holderness Formation between Heacham and Morston (Norfolk Coast Partnership, 2011). At this time Norfolk was part of the North Sea plain, but around 12,000 years ago the world climate warmed significantly and global sea level began to rise, rapidly at first and then slowing after about 6,000 years ago (Royal Haskoning, 2004). The sea is believed to have entered the Fenland around 7,800 years ago, quickly flooding the central and eastern sectors, with the western and southern sectors being flooded around 4,400 years ago (Brew et al., 1999; Royal Haskoning, 2004). This marine incursion led to the deposition of sand and gravels, transported by tidal currents into the embayment from the North Sea (Holt, 1999; cited in Royal Haskoning, 2004).

In more recent history, human modification to The Wash, through land claim and construction of defences, has had a significant impact on its morphological evolution. Beginning in the Roman period, land claim has enclosed around 32,000 hectares of land, with the natural response of The Wash to this land-claim being for accretion seaward of the new embankment (Royal Haskoning, 2004). This has been predominately along the western and southern shores of The Wash, with a narrow strip of land claim undertaken between Snettisham and Heacham.

A.4.4.2 Historical change and shoreline management (1890s to 1990s)

Evidence from historical Ordnance Survey maps and photographs provide some insight into how the coastline has changed over the past century or so. There has been previous analysis of these and a visual examination has also been undertaken as part of this review.

Along the undefended Hunstanton cliffs, it is estimated that the cliffs have retreated by up to 30 m in a series of failures of varying size and nature since 1885 (Royal HaskoningDHV, 2015). There is, however, no detailed quantitative information before 1991 about the variability in time of these erosion rates.

Major cliff failure events are caused by undercutting of the lower Carstone, leading to stress on the upper Carstone due to the weight of overhanging Red and Grey Chalk, and can potentially result in erosion of between 10 and 30 m across and between 3 and 5 m deep (Royal HaskoningDHV, 2015). Mott MacDonald (2005) reported that changes are cyclical with a short term periodicity and therefore reflect pulses of beach sediment being transferred southwards, rather than a general long term trend. During these pulses, there is a tendency for a build-up of beach material at the southern end of any subtle bay features whilst the northern end of bay features acts as a source area. Smaller cliff failures can also occur, which are typically 3 to 6 m across and between 1 and 2 m deep.

South of the cliffs, evolution of the study frontage over the past 150 years has been constrained, in part, by the construction of defences. Posford Duvivier (1997; cited in Royal Haskoning, 2004) analysed the changing position of the low water mark (mean low water spring tide) of The Wash between 1828 and 1995, and between 1971 and 1995, noting however that this analysis will not pick up changes in the upper beach. Between 1828 and 1995, the shoreline at Heacham was the only location where there was a landward movement of the low water mark, although the same report concluded a seaward movement between 1971 and 1995. At Hunstanton the low water mark was reported to have been relatively stable, whilst to the south, between Snettisham Scalp and Wolferton Creek, there has a seaward movement of the low water mark, which Posford Duvivier (1997) attributed to the onshore migration of Stubborn Sand. The Strategy (Royal HaskoningDHV, 2015) notes that the damage caused by the 1978 storm event is likely to have contributed to the trend identified by Posford Duvivier (1997a).

A much earlier study (Kirkpatrick & Partners, 1953) compared Ordnance Survey maps from 1885 to 1927 and concluded that these indicate a landward movement of the lower water mark by around 120 m (400 feet). This report concluded that this erosion of the lower beach was supported by the 1899 report '*The Geology of the Borders of The Wash*', which stated that at the time Carstone was only exposed on the beach for short periods of time, whereas in 1953 the Carstone was noted to always be visible on the lower portion of the beach. This does not, however, concur with historical photographs from the 1890s, which show exposure of the Carstone across the foreshore along the cliffs and Hunstanton North Promenade.

The seaside resort of Hunstanton has only existed since the 1840s, when Henry Styleman Le Strange came up with a proposal for a coastal holiday village on a previously undeveloped part of his estate, with the original village becoming 'Old Hunstanton'. The coastal holiday village quickly expanded and Hunstanton Pier was built in 1870. The 1904 Ordnance Survey map shows that by this time a promenade had been constructed at the northern end of Hunstanton, extending out to the high water mark, but the map does not suggest the presence of groynes along the Hunstanton frontage, apart from a timber 'breakwater' just south of the Pier (which is also illustrated in https://www.francisfrith.com). As shown on an early photograph of Hunstanton (Figure A-13), there was no beach exposed at high tide along the promenade frontage. A photograph from 1893 (https://www.francisfrith.com) at low tide illustrates widespread exposure of Carstone in front of the North Promenade, suggesting there was no upper beach cover at this time.

Further south, there was a short stretch of undefended cliff along the site of the former railway station (now the Central car park) and beyond this, to the current Power Boat Ramp, there were no defences.The coastal strip in front of Heacham was undeveloped at this time, with the village boundary of Heacham located over 500 m inland from the coast.

South of the Power Boat Ramp, there were some timber groynes were in place by 1904, together with Y-shaped structures referred to as breakwaters, and the mapping indicates an embankment ran sub-parallel to the shoreline for part of the frontage. This was presumably associated with previous land claim for agriculture. The mapping suggests a strip of dunes or scrub lay between the embankment and the gravel-sand beach. South of Jubilee Bridge, the channel referred to as Heacham Harbour ran roughly parallel to the shoreline, enclosed by a sand-gravel spit and outflowed to the sea around 1.5 km north of Shepherd's Port.

Photographs from the early part of the twentieth century show that as this time wider beaches were present to the south of the Pier, compared to the north, but the images suggest that beaches were coarser in nature, with a photograph from 1907, in front of the former Sandringham Hotel (which was located in the vicinity of the Central Car Park), illustrating a fairly steep interface between an upper gravel-rich beach and lower sandflat (https://www.francisfrith.com).

Figure A-13 Hunstanton at high tide: date of photograph not known but assumed to be early twentieth century. Source: http://www.hunstantoncivicsociety.org.uk.

By the 1920s, a few more timber groynes had been constructed, along the frontage south of the Pier, and the Hunstanton promenade had been extended southwards to the current funfair (Figure A-14). This was built slightly out from the coast, as illustrated in a photograph from 1927 (https://www.francisfrith.com). One report suggests that this was constructed in two stages coinciding with the opening of the swimming pool in 1928 and the boating lake in 1932 (https://www.lynnnews.co.uk). Along the remainder of the frontage, it appears that much of the beach remained open, with groynes limited to a stretch to the north of Heacham.

Photographs show that there were holiday bungalows along the Hunstanton-Heacham frontage from at least the turn of the twentieth century (Figure A-15). These were built along the back of the beach and photographs from this period show the proximity of these to the high tide mark (https://www.francisfrith.com and https://www.francisfrith.com/heacham. The photographs do not suggest any groynes were present along this part of the frontage at this time. The level of the beach crest pre-1953 storm was around 5.3 mOD, just less than a metre above high spring tides (Doran, 1954). The sediment composition of the crest was noted to be increasingly gravel-rich from south to north and the early photographs also show this to be the case. The 1954 report also records that there were significant quantities of shingle excavated for construction purposes during the second world war, although it is not clear whether this was from the beach or from the area inland.

Figure A-14 Hunstanton Pier, 1920, illustrating some of the groyne structures in place by this time. Source: www.britainfromabove.org.

Figure A-15 Heacham Beach. Date unknown, but assumed to be around the 1930s/1940s. Source: M Rouse (2013).

The coastline between Hunstanton and Wolferton Creek remained undefended (with the exception of short lengths of timber groynes and breastwork; see Figure A-16) until the 1930/1940s, when Heacham South Beach wall, Heacham North Beach wall and Hunstanton South Beach wall were constructed.

The January 1953 storm had a significant impact on this coastline, resulting in a total of 66 deaths in Hunstanton, Heacham and Snettisham. The account by Doran (1954), records the following:

- There were three major breaches between Hunstanton and Wolferton, which was lowered to beach level, and more than 40 breaches in the earth embankment behind. The low level of both the shingle barrier and the earth embankment contributed to their failure.
- The Heacham South wall was destroyed and the parapet of the Heacham North Beach wall was demolished over a third of its length (Figure A-16). The shingle-fill behind the wall was also heavily scoured out.
- Between the northern end of Hunstanton South Beach wall and the southern end of Hunstanton Beach promenade (Hunstanton Gap), where there was a break in the defences, the shingle barrier beach was breached resulting in significantly flooding of the area behind.
- Restoration of the shingle barrier beach as a defence was considered impossible and it was therefore decided to improve and adopt the secondary earth bank as the main line of defence.

Figure A-16 Damage to Heacham North Beach Wall following 1953 storms, noting the timber groynes that were present at this time. Taken from ICE Conference on the North Sea Floods (1954).

In the years following, works were undertaken to reinforce the secondary embankment south of Heacham North Beach, reinstate Heacham North Beach wall and reconstruct Hunstanton South Beach wall. A stepped wall was constructed between the southern end of Hunstanton Beach promenade and Hunstanton South Beach wall.

The 1953 report by Kirkpatrick & Partners (1953) also reported that the Hunstanton North Promenade wall was also seriously damaged during the 1953 event, with the coping dislodged for most of its length. Works were undertaken to improve defences along this stretch between 1955 and 1956. The authors note that at this time there were six precast reinforced concrete groynes along the North Promenade wall and records that these were built in 1943. The report goes on to recommend that two further groynes be constructed along the South Promenade; it is uncertain whether this was undertaken. It is understood that the groynes were subsequently reinforced or rebuilt in 1980 (based on 'Concrete Groynes Details'; a report from 1980), and it is assumed these works were undertaken on the same alignment of the existing groynes.

Figure A-17 is an aerial photograph of the frontage post-war (exact date unknown), which shows the six original groynes. At the time, these appear to be retaining a beach, but it appears that a consequence is very low beach levels to the north and south of the pier (the Amusement Arcade today). The second photograph (Figure A-18 is from 1956; it is, however, uncertain whether this pre or post-dates Figure A-17. This shows exposure of Carstone at the norther end of the promenade and also possibly just north of the pier. Beaches to the south of the pier were, however, fuller at this time compared to Figure A-17.

Figure A-17 Aerial photograph of the concrete groynes frontage. Exact date of the photograph is unknown, but taken between 1945-6 and 1960-1965. Crown Copyright, source: http://www.historic-maps.norfolk.gov.uk

Figure A-18 Hunstanton in the 1950s. Exact date of photograph is unknown. Source: https://www.kingslynn-forums.co.uk

The coastline was hit by a further storm surge in January 1978. This resulted in higher water levels that during the 1953 storm in The Wash, due to funnelling on winds and waves onshore (Steers et al., 1979), and caused breaches in the shingle barrier south of Heacham and in the Heacham South wall (Figure A-19), and resulted in most of Hunstanton Pier being destroyed. This storm prompted further repair work, including an additional wave return wall added to the Hunstanton sea wall, at the front of the promenade at the north and at the rear of the promenade to the south (Royal HaskoningDHV, 2015) and construction of a stepped concrete seawall at Heacham in 1981/2. This seawall stopped just north of North Beach Heacham, but a report by HR Wallingford (1987) records that '*despite the installation of additional timber groynes, the shingle ridge continued to erode rapidly … in February 1983, a freak surge tide caused severe erosion*'. This prompted the construction of a block revetment along the 418 m stretch of coast north of Jubilee Bridge, which was completed in June 1984.

Figure A-19 Damage caused by breach of sea defences at Heacham in 1978. Source: Environment Agency (date unknown, but possibly 1998).

The construction date for the current zig-zag timber groynes along the Hunstanton-Heacham frontage is not known. Anecdotal information suggests that they were constructed in the 1980s, and a survey of the Heacham Revetment by HR Wallingford (1987) refers to '*Three fairly new zigzag groynes (circa) 1982*', with design drawings also dating from this time. However, Figure A-19 shows the Heacham frontage in 1978 and indicates that zig-zag groynes were present at this time. It is also not known, however, whether subsequent reinforcement of these groynes incorporated any materials from the early groynes that were present along this shoreline.

Due to continued issues of beach erosion it was decided in 1990 to implement a beach recharge scheme (Nunn & Beech, 1998) along the Hunstanton-Heacham frontage. This is discussed further in section A.4.5 below. This was also the point at which regular beach profile monitoring commenced, through what is now the Anglian Coast Monitoring programme. In the 1990s an additional wave return wall was added to the sea wall, at the front of the promenade at the north, and at the rear of the promenade to the south and in the early 2000s re-facing works were undertaken to sections of the sea wall (Royal HaskoningDHV, 2015).

A.4.5 Recent morphological change and shoreline management (since 1990s)

A.4.5.1 Shoreline management

Along the Environment Agency frontage, south of the Power Boat Ramp to Snettisham Scalp, coastal change in recent years has been highly modified by beach nourishment and sediment recycling.

Between 1990 and 1991, around 400,000m^3 of sand and gravel dredged from the mouth of the Humber was placed on the beaches between Hunstanton and Snettisham (Nunn & Beech, 1998). Whilst beaches were originally designed to a 1:4 slope this was revised to 1: 5.5 following a storm in November 1990 that led to flattening of the profile and severe cliffing (Nunn & Beech, 1998). The material used had a D50 of approximately

8 mm (i.e. pebble size), but came from two offshore areas which meant that whilst the material fell within the envelope of the design grading curve it was actually bi-modal in character (Nunn & Beech, 1998). A review found that as a result the beach had a natural tendency to form a much shallower slope (between 1: 12 and 1:15) than the revised design slope of 1:5.5. Since completion of the original nourishment scheme in 1991, the Environment Agency has undertaken annual recycling of sand and gravel together with beach reprofiling works. Material is currently taken from Snettisham Scalp and placed on the eroding beaches to the north.

Following a review of the scheme performance, a revised strategy was adopted in 2001/2 and led further improvement works comprising (Jacobs, 2021; Royal HaskoningDHV, 2015):

- Improvements to defences at Snettisham (south of the Scalp and near Heacham Dam) in 2002 (Zones 14 and 9, shown in Figure A-34).
- Improvements to defences at Heacham (between the former Kala Juga ramp and Jubilee ramp) in 2003 (Zone 4, shown in Figure A-34).
- Improvements to defences at Hunstanton South Beach (Zone 1) and extension to River Heacham Outfall in 2005 (boundary of Zones 5 and 6).
- Further beach nourishment campaign between August and November 2005 where material was placed in front of South Hunstanton, in front of Heacham(Zones 5 to 8), and directly to the north of Heacham Dam (Zones 5 to 8 and 10 to 12).
- Continued annual recycling, with the aim of achieving a beach crest level of 6.35 mOD, a minimum beach crest width of 5 m and a revised seaward slope of 1 in 13.

There was significant erosion of the beach as a result of the January 2013 storm surge, which resulted in beach volume loss (above 0 mOD) across the frontage between the Power Boat Ramp and Wolferton Creek of around 19,900 m^3 (Jacobs, 2014). Repair works, including additional recycling and import of sediment, were undertaken in the December following the event; it is not clear, however, whether this included any repairs to the groynes. Material was added to the beaches at Snettisham (Zones 8 to 12 shown in Figure A-34).

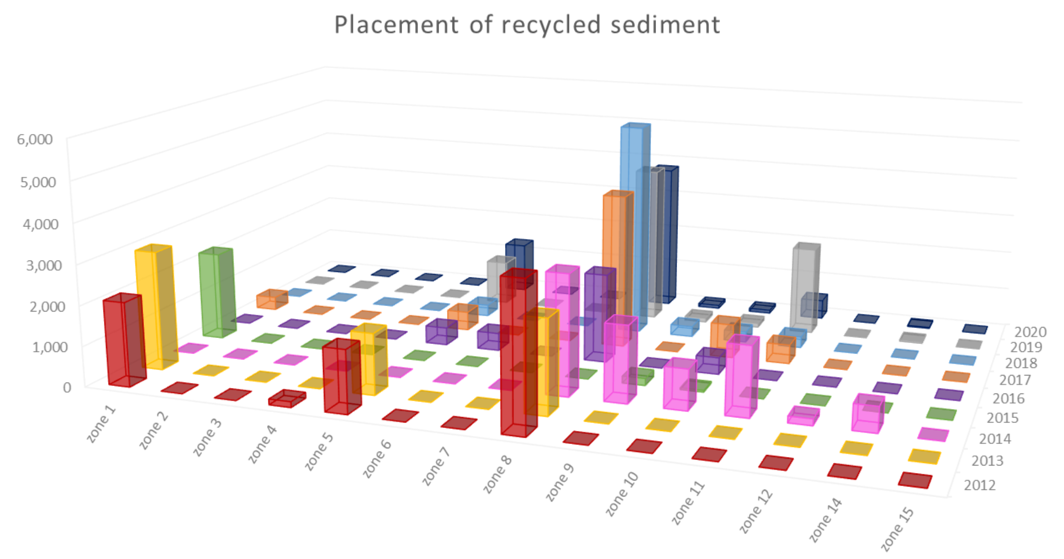
Currently the annual recycling volumes are based on analysis of both beach losses along the frontage and beach gains at Snettisham Scalp and Table A-3 shows the recycling volumes involved since 1993; this shows that following the recycling of large volumes in 1993 to 1995, extraction from Snettisham Scalp was reduced. This was in order to maintain the volume of material held at Snettisham Scalp and thus limit the environmental impact of the recycling programme (Jacobs, 2021). A more substantial campaign was undertaken in 2004 and volumes have varied since. Despite the recent changes in recycled volumes, the volume of material on the Scalp has reportedly remained relatively constant (Jacobs, 2021).

Year	Recycling volume m^3
1993(1)	58,000
1994	33,700
1995	31,600
1996	7,000
1997(2)	6,600
1998	9,620
1999	8,992
2000	8,016
2001	5,988
2002	3,570
2003	6,396
2004	18,465
2005	5,422
2006	10,374
2007	5,184
2008	12,672
2009(3)	4,972
2010(4)	7,265
2011	9,867
2012	7,381

Year	Recycling volume m^3
2013	6,811
2013	5,425
2014	2,988
2015	2,453
2016	3,556
2017	6,075
2018	6,538
2019	7,630
2020	5,768

Table A-3 Annual recycling volumes. (Notes: (1) 1993 was a double campaign, (2) 1997 was in autumn and winter, (3) 2009 included 2,486m^3 from Heacham frontage (Zone 3), (4) 2010 included 2,464m^3 from Heacham frontage (Zone 3).

The majority of material is extracted from Snettisham Scalp (in Zone 13), but placement, in terms of both volumes and location, varies slightly from year to year, as shown in Figure A-20. There have been two years where material has been taken from Zone 3, along the north Heacham frontage: 2009 and 2010. Placement tends to be in February/ March of each year, following a scheduled beach survey. The majority of the recycled sediment is placed to the south of the groyne frontage, but there have been a number of years when sediment has been placed in Zone 1, i.e. immediately south of the Power Boat Ramp, or just to the south of the groyne frontage in Zone 5.



	zone 1	zone 2	zone 3	zone 4	zone 5	zone 6	zone 7	zone 8	zone 9	zone 10	zone 11	zone 12	zone 14	zone 15
2012	2,090			143	1,551			3,597						
2013	2,970				1,518			2,321						
2014								2,988	1,900	1,010	1,720	165	630	
2015	2,233								176	44				
2016					448	448		2,240		420				
2017	345				480			3,915		855	480			
2018					294			5,432	266	266	280			
2019					1,134			4,004	105	105	2,240		42	
2020					1,302			3,780	84	84	490		28	

Figure A-20 Placement of recycled sediment since 2012, by year. Data extracted from Annual Beach Survey Monitoring Reports (e.g. Jacobs, 2021). Figure A-34 shows location of zones: Zone 1 starts at the Power Boat Ramp, with Zone 15 ending at Wolferton Creek.

A.4.5.2 Analysis of beach monitoring, LiDAR and aerial data

For discussion purposes within this report, the frontage has been considered in the following sections:

a) Hunstanton cliffs (undefended stretch between the Lighthouse and the start of Hunstanton promenade) – southern part of Unit A (PDZ4).

b) Concrete groynes along BCKLWN frontage (between the start of North Promenade and South Promenade) – part of Unit B (PDZ3).

c) Timber groynes along BCKLWN frontage (between the start of South Promenade and the Power Boat Ramp) – part of Unit B (PDZ3).

d) Timber groynes along Environment Agency frontage (between the Power Boat Ramp and Jubilee Bridge, Heacham) – a small section of Unit B (PDZ3) and part of Unit C (PDZ2)

a) Hunstanton cliffs

Whilst outside of the study frontage, beach data for this frontage have been reviewed to look at the potential evidence for pulses of sediment moving onto the groyne frontage to the south.

There are nine beach transects covering this frontage that include data back to 2010 (from 2d01328 to 2d01312), one of which includes data dating back to 1992 (2d01320). Figure A-21 shows the beach profile for 2d01320 (which is located near Queen's Drive). This profile is fairly typical for the frontage and shows that over time the recorded beach level has fluctuated by around 0.4 to 0.8 m. Whilst within these fluctuations it is difficult to identify a clear trend, at this location it is noticeable that the last few years of surveys generally lie below the mean profile. Some of the recorded changes relate to the difficulty of surveying a beach where there are fallen boulders, as this can result in false peaks in beach level being recorded. From the beach profiles, there is no evidence for significant influxes of sediment into this frontage, from either the north or south. The presence of cobbles along the beaches at Hunstanton indicates that material has previously been moved southwards, but it is not known how contemporary this material is.

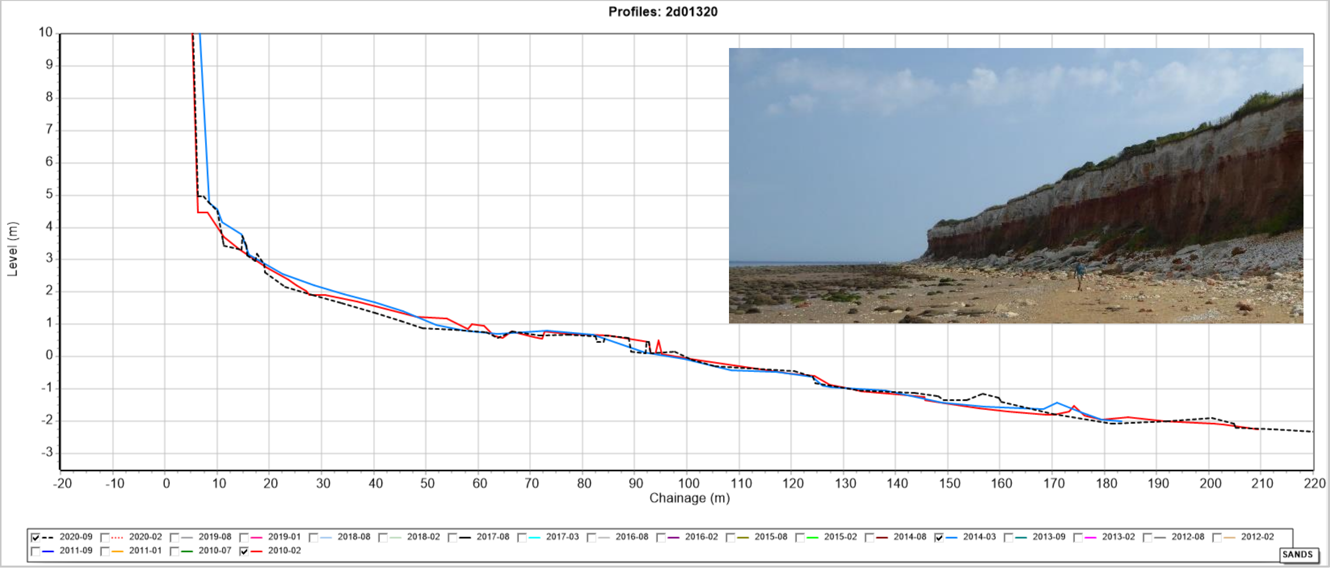
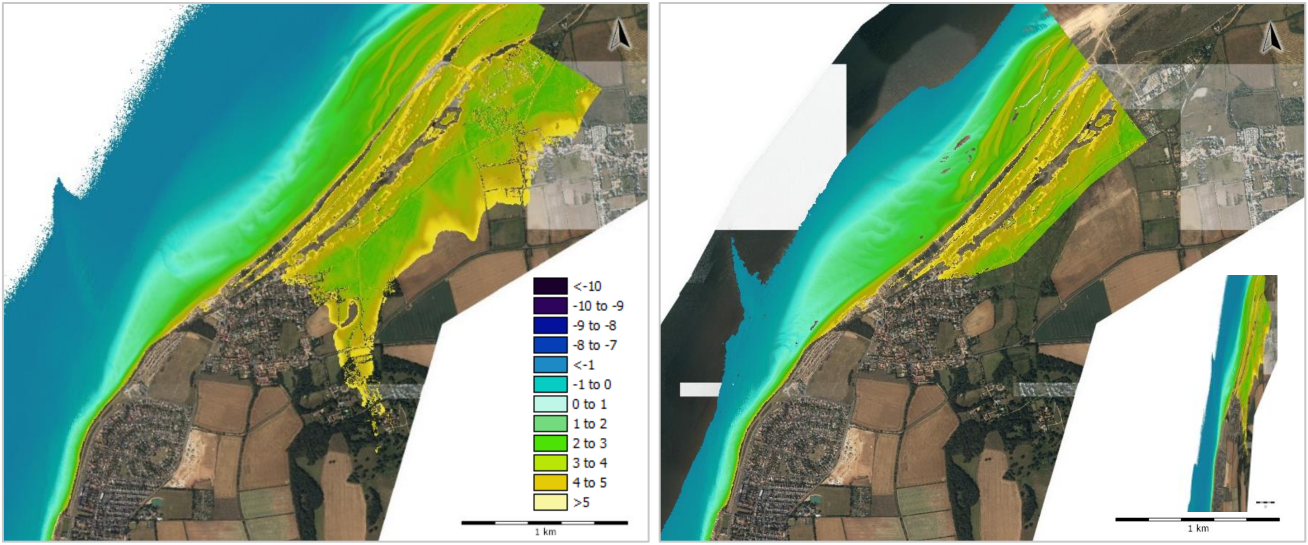


Figure A-21 Typical changes in beach shape along the Hunstanton Cliff frontage. Selected beach survey dates shown: Sept 2020 (black dashed), Mar 2014 (blue) and Feb 2010 (red).

LiDAR data for this frontage also indicate very little change between surveys (Figure A-22). At the larger scale, both aerial images and LiDAR data show the movement of sediment (assumed to be sand) southwards from Holme, which has contributed to the build-up of beaches and dune growth to the north of the cliffs. It is possible that this sediment could be moved further south and start to contribute to the beaches at Hunstanton, but it is also possible that the southwards movement may be inhibited due to the increasing influence of northward tidal flows when moving into the mouth of The Wash.

Comparing the LiDAR in 2020 to that in 2011 (Figure A-23) accepting that this only represents two snapshots in time), shows that along the beach changes in level between these two dates are typically less than a metre. Greater changes are recorded at the base of the cliffs.

There is also some evidence that beaches at the southern end of this frontage have decreased slightly in level. Intervening years do show that levels do fluctuate slightly over time, but this picks up the more recent trend observed from the beach profile data of recent beach levels lying towards the lower end of the profile envelope.



2011 LiDAR (provided by ACM) 2020 LiDAR (provided by ACM)

Figure A-22 LiDAR data covering Hunstanton Cliffs and Hunstanton golf club to the north. Illustrating the southward growth of a spit, but with build-up to the north of the cliffs. LiDAR provided by ACM.

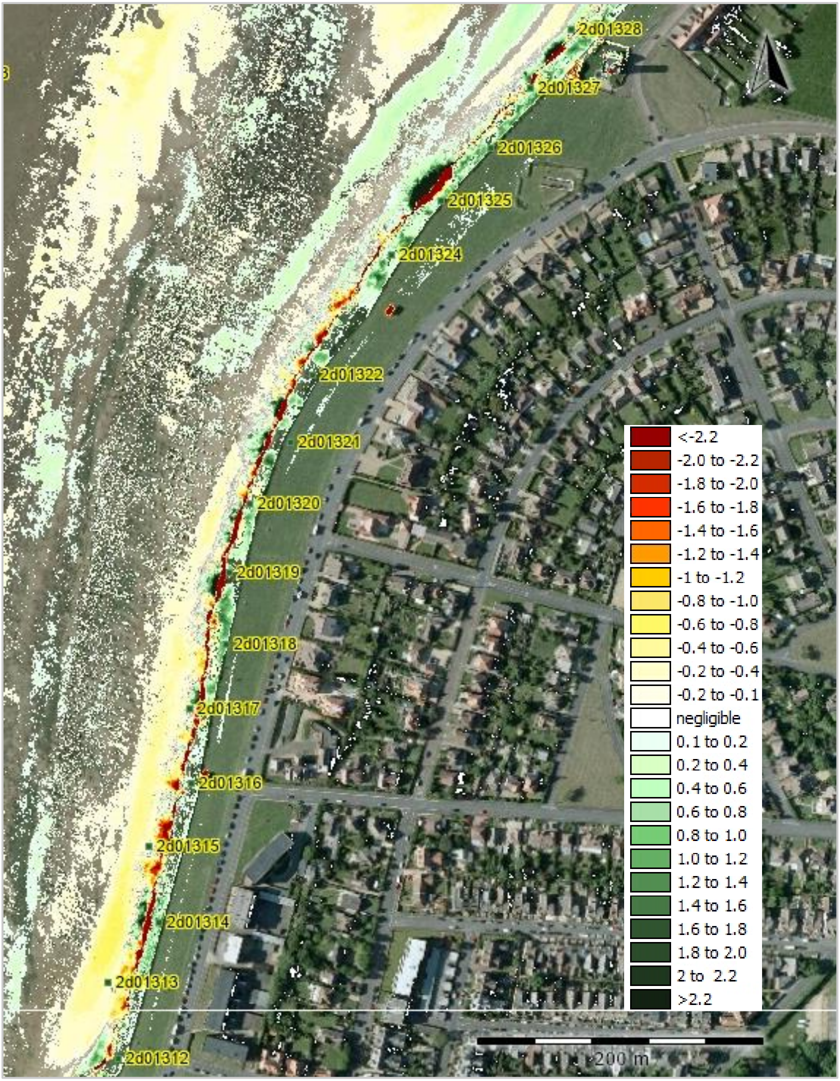


Figure A-23 Difference plot for the Hunstanton cliff frontage, generated from LiDAR data from 2020 and 2011, with change in beach level in m. (data courtesy of ACM).

(b) Concrete groynes along BCKLWN frontage

There are 11 beach transects covering this frontage that include data back to 2011 (from 2d01311 to 2d01301), one of which includes data dating back to 1992 (2d01304). Figure A-24 shows the beach profile for 2d01304, which is located in the vicinity of the Amusement Arcade (near Groyne 6).

The location of transects within the groyne bays means that at times the recorded beach response differs for the same survey date due to movement of sediment from one side of the groyne bay to the other. Despite this, the following generic observations can be made:

- There is a distinct change in beach slope around -1 to -1.5 mOD, which is approximately mean low water neaps. This represents the interface between the Carstone/lower sand beach and the fronting sandflat.
- In profiles where the Carstone is exposed close to the seawall, there is also a change of slope evident around +1 mOD to +1.5 mOD which is indicative of the extent of the upper coarse mixed beach.

- North of profile 3d01305 (Groyne 5), the recorded beach level at the seawall is typically up to +2.5 to +3 mOD, which is approximately mean high water. To the south, beach levels can reach up to +3.5 to +4 mOD, which is above mean high water springs. The southern profiles also demonstrate greater volatility, which is likely to be due to the greater volume of sand and gravel than along the beach further north.
- The fluctuation in beach level tends to be greater at the base of the seawall than elsewhere along the profile and the upper beach (above -1 mOD) is more volatile than the sandflat, although in places some scour is evident at the interface of the Carstone and sandflat. At the base of the seawall, the variation in beach level is around 1 to 1.5 m.
- Typically when beach levels at the seawall are highest, the upper beach slope is steeper, whilst lower levels at the seawall are associated with a flatter beach, suggesting that there is a wedge of sediment that tends to be moved across-shore.
- Notably, transects north of profile 3d01305 (Groyne 5) do not indicate any net trend in terms of beach lowering or growth. In contrast, transects to the south indicate a net lowering trend over time – this is illustrated in Figure A-24 (profile 2d1304, near Groyne 6) where beach levels over the past few years have been some of the lowest recorded (since 1992) and surveys from 2012 onwards have generally been below the mean profile.

Although aerials are only snapshots in time, images for this frontage do suggest that exposure of Carstone has increased over the past few years along this frontage.

LiDAR data, together with aerial images and observations made during the site visit, indicate that the groynes do have some localised influence on sediment movement at the base of the seawall, with build-up of sediment against the groynes evident on occasions. This influence increases in a southwards direction (as illustrated in the 2016 LiDAR; Figure A-26), but is restricted to the very upper part of the beach, within 20 to 30 m of the seawall. Difference plots generated from the LiDAR data shows that there are small changes in beach level beyond the end of the groynes, inferring that sediment transport takes places in this area; however, this is also where the Carstone crops out, which can introduce discrepancies between surveys due to the difficulty of surveying this surface.

Using the LiDAR data the positions of the +1 mOD, 0 mOD and -1 mOD contours have been plotted and Figure A-25 shows the data for 2012 and 2020. The 2012 is the earliest complete LiDAR survey for the study frontage whilst 2020 is the more recent survey. The 0 mOD contour represents the approximate position of mean sea level, which also roughly corresponds with the interface between the lower sandflat and upper coarse beach, whilst -1 mOD contour is the lowest beach level that is covered by the majority of beach profiles. The data show that along this frontage there has been very little change in the position of either the -1 mOD or 0 mOD contours north of the Amusement Arcade, with a slight seaward movement of the +1 m contour recorded. South of the Amusement Arcade there has been a net landward movement of all three contours, indicating that the shore profile is translating landwards, resulting in a narrowing upper beach.

Figure A-27 shows the difference plot comparing the latest (2020) data with the earliest available (2011), noting that this only represents two snapshots in time. Positive change (in green) shows where there has been an increase in beach level between 2011 and 2020 data, whilst a negative change (in yellow and red) indicates a drop in beach level. The data illustrate some build up on the northern side of Groyne 1, which may indicate some input of sediment from further north. Also illustrated is the drop in beach level south of profile 2d01305 (Groyne 6) identified from the beach profile data.

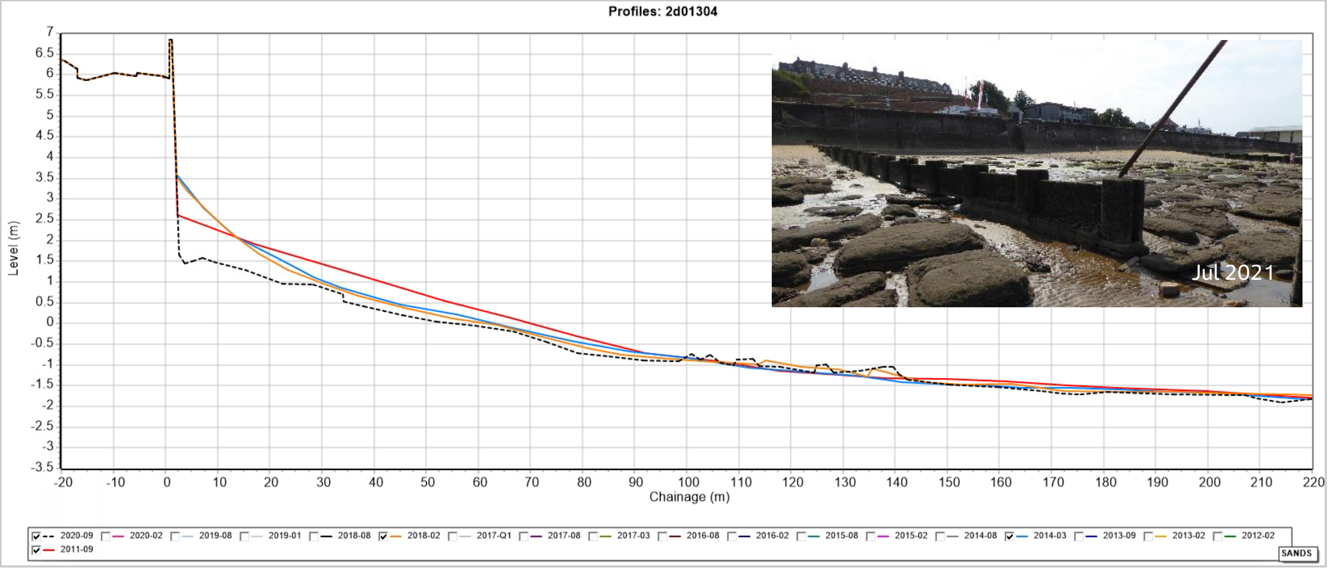


Figure A-24 Typical changes in beach shape along the BCKLWN concrete groyne frontage (Groyne EA3). Selected beach survey dates shown: Feb 2020 (black dashed), Feb 2018 (orange), Mar 2014 (blue) and Sept 2011 (red).

Figure A-25 BCKLWN concrete groynes frontage, with the position of the 0 mOD, +1 mOD and -1 mOD contours generated from 2012 (light blue) and 2020 (blue) LiDAR data. Also shown are the beach transect locations.

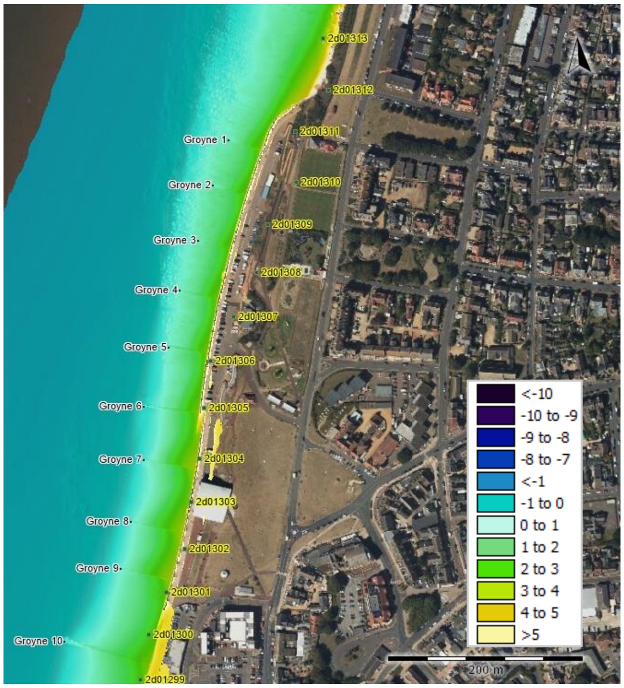


Figure A-26 LiDAR data from 2016, illustrating the influence of the concrete groynes on upper beach sediment movement. Beach levels in metres OD. *(Data courtesy of ACM).*

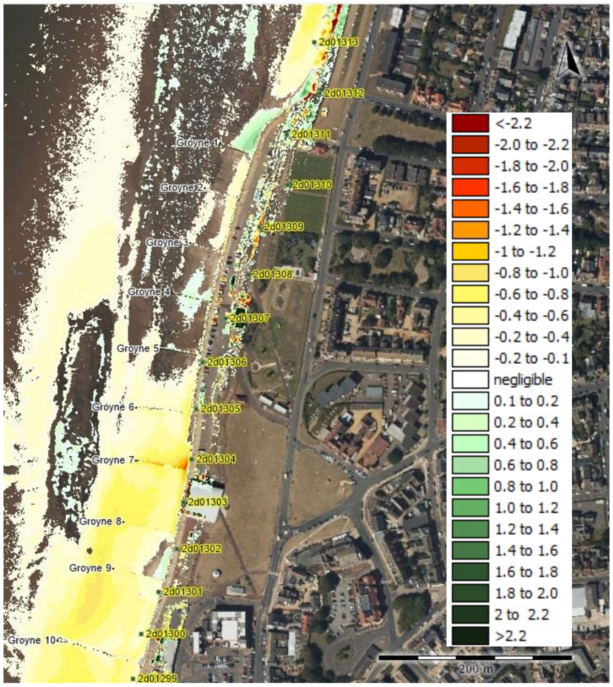


Figure A-27 Difference plot for the concrete groyne frontage, generated from LiDAR data from 2020 and 2011, with change in beach level in m. *(Data courtesy of ACM).*

A simple calculation of ‘beach’ volume above 0 mOD has been undertaken using a function within SANDs; this calculates a cross-section area for each transect and extrapolates between adjacent transects to derive an estimated volume. It should be noted that this does not equate to the actual volume of mobile sediment on the beach, as no assessment has been made of the underlying bed level. Figure A-28 illustrates this data and shows the change in calculated volume relative to the earliest common survey date of September 2011; also shown are sparklines illustrating the relative change between each transect.

The data show that across the whole frontage there has been a net reduction in calculated beach volume over this period indicating an overall loss of sediment and reduction in beach level. The data suggests that the loss is less than 1,000 m^3/year. Whilst volumes have fluctuated across the northern-most transects, the southern transects suggest a progressive loss of sediment. Given that the location of these transects relative to the groyne bays varies, there is always a risk that this type of analysis does not pick up the overall trend for the frontage; however, profiles 2d01306 and 2d01305 are at either end of the same groyne bay and the data for these show a similar trend of progressive sediment loss. A similar calculation was also undertaken, to look at beach volumes changes above +1 mOD; this showed very similar trends.

This suggests that whilst the groynes do exert some influence on sediment movement, as evidenced by the occasional and localised accumulation of sediment at one end of a bay, they are not currently effective in preventing the net loss of sediment from the frontage, particularly along the southern part of this frontage. It is also critical to recognise that the residual volume of mobile coarse sediment, which makes up the upper beaches, is also low along this frontage. Therefore changes in volume would be expected to be low and are not therefore representative of the potential rates of sediment movement; i.e. if more sediment were available it is possible that greater volumes of change would be recorded.

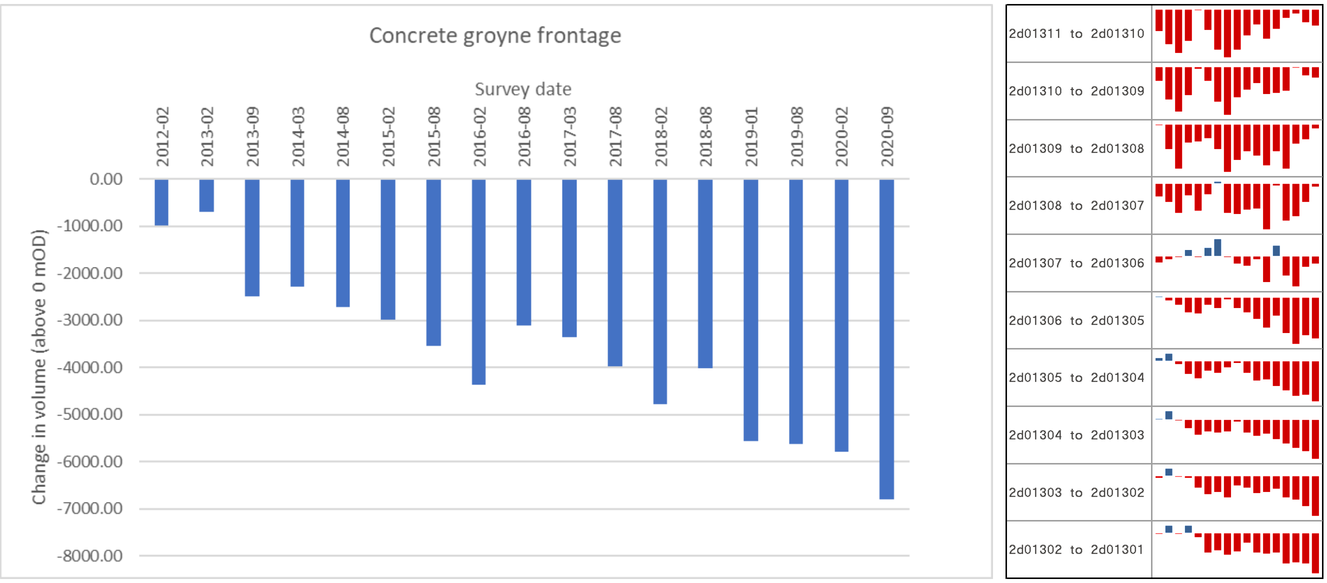


Figure A-28 Change in calculated beach volume above 0 mOD, along the concrete groyne frontage relative to September 2011. The sparklines to the right illustrate the same data for each set of beach transects, moving from north to south.

(c) Timber groynes along BCKLWN frontage

There are 19 beach transects covering this frontage that include data back to 2011 (from profile 2d01300 to 2d01282), one of which includes data dating back to 1992 (2d01282). There are typically two profiles within each groyne bay. The longer term data set (back to 1992) is, however, located immediately north of the Power Boat Ramp and reflects local fluctuations in beach level associated with the influence of this structure and is therefore not considered to be representative of the frontage. Instead the data for 2d01298 (between Groyne 10 and Groyne 11) and 2d01293 (Groyne 13) are shown in Figure A-29, for selected dates.

From the profile data for September 2011 to September 2020, the following observations can be made:

- There is a distinct change in beach slope around -0.5 to -1 mOD, which represents the interface between the lower sand beach and sandflat. The upper sand-gravel beach typically lies above +1 to +1.5 mOD.
- The fluctuation in beach level tends to be greater at the base of the seawall than elsewhere along the profile and the upper beach (above +1 mOD) is more volatile than the sandflat.
- At the base of the seawall, beach levels can vary by up to a metre and typically lie between 3 and 4.5 mOD, i.e. between mean high water springs and HAT, although at profiles 2d01297 and 2d01296 (either side of Groyne 11) the beach level at the seawall in January 2019 was 1.5 m below the recorded maximum. Beach levels at the seawall are generally higher along the southern part of this frontage, south of Groyne 13.
- In terms of profile change the frontage can be considered in three sections: north of profile 2d01295 (which is in the vicinity of the Leisure Centre, Groyne 12), between 2d01295 and 2d01290 (Groyne 12 to Groyne 15) and south of 2d01290 (Groyne 15 to Groyne 19). North of profile 2d01295, there has been a net drop in beach levels over time, which is a continuation of the trend observed along the adjacent section of concrete groynes, and the most recent available survey (September 2020) recorded the lowest beach levels over the past decade. Between Groyne 12 and Groyne 15, beach levels have

tended to fluctuate over time and the latest survey lies around the mean profile for the data set. South of Groyne 15, there has been progressive growth across the upper beach since 2011.

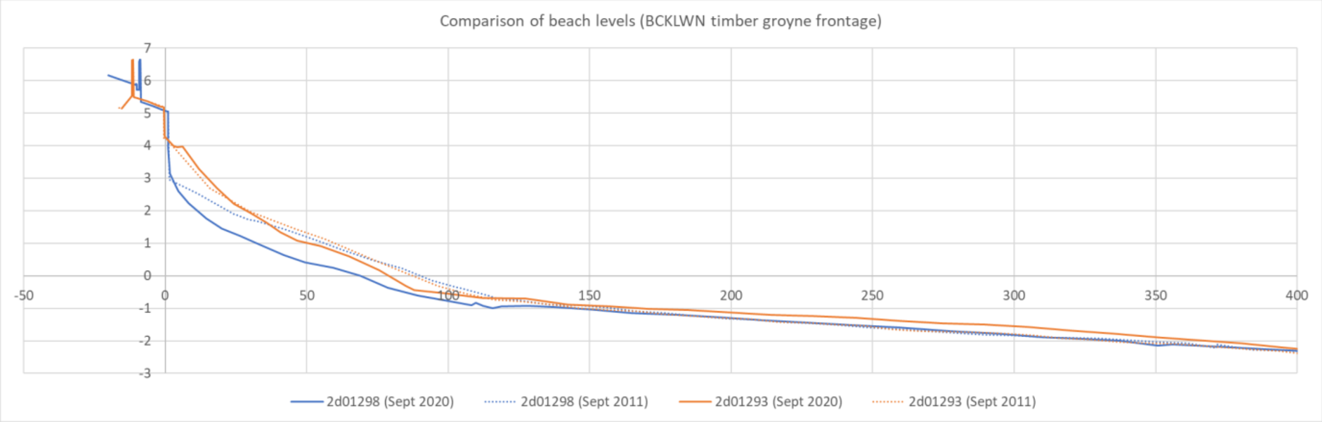


Figure A-29 Typical beach profiles showing the contrast in beach response along the northern (shown by 2d01298, Groynes 10-11) and southern end (shown by 2d01293, Groynes 13 - 14) of the BCKLWN timber groyne frontage between 2011 and 2020.

LiDAR data for the frontage (Figure A-30) clearly show the change in coastal orientation at profile 2d01295 (Groyne 12) and also illustrates the increase in beach width south of this point. Figure A-31 shows the change in beach level based on comparing LiDAR data from 2020 and 2011.

The LiDAR data have also been used to plot the position of the 0 mOD, +1 mOD and -1 mOD contours for 2012 and 2020 (Figure A-32). This shows that along the northern half of this frontage there has been landward movement of the +1 mOD and 0 mOD contour, indicating narrowing of the upper beach. Along the southern part of the frontage, the degree of change in both the +1 mOD and 0 mOD contour diminishes, but there is seaward movement of the -1 mOD contour. This indicates that there has been less change along the beach, but widening and therefore flattening of the sandflat. The degree of change diminishes towards the Power Boat Ramp.

This confirms the trend identified from the beach profile data of general beach loss to the north of Groyne 12 and gains to the south. As such the planform of beach has rotated clockwise over time. The LiDAR data (Figure A-31) shows that losses across the beach (above MSL) along the northern part of this frontage are across the whole beach profile, whilst gains to the south are predominately at the top of the beach, along the seawall.

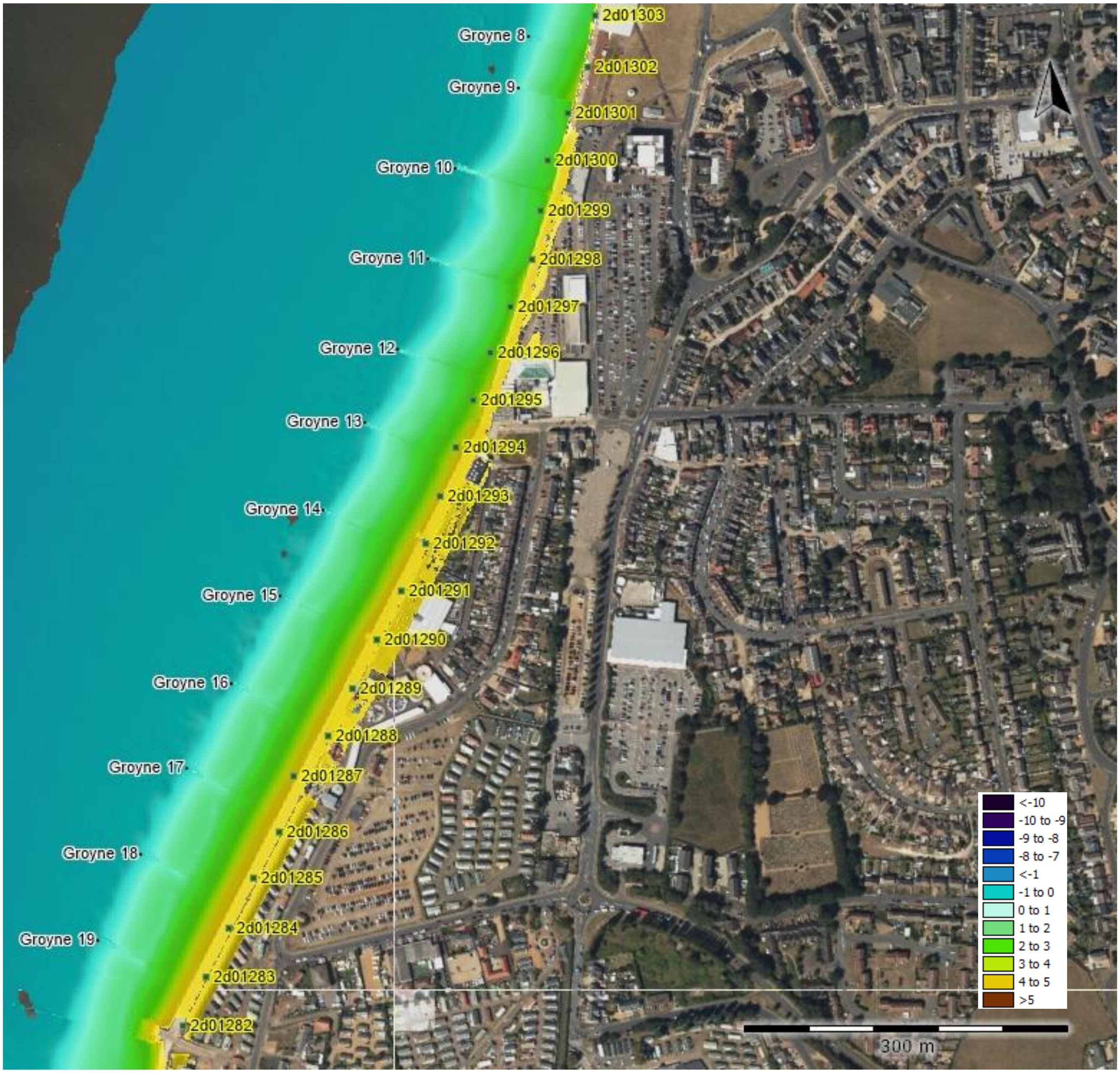


Figure A-30 2020 LiDAR data for the BCKLWN timber groyne frontage, with beach levels in mOD (data courtesy of ACM).

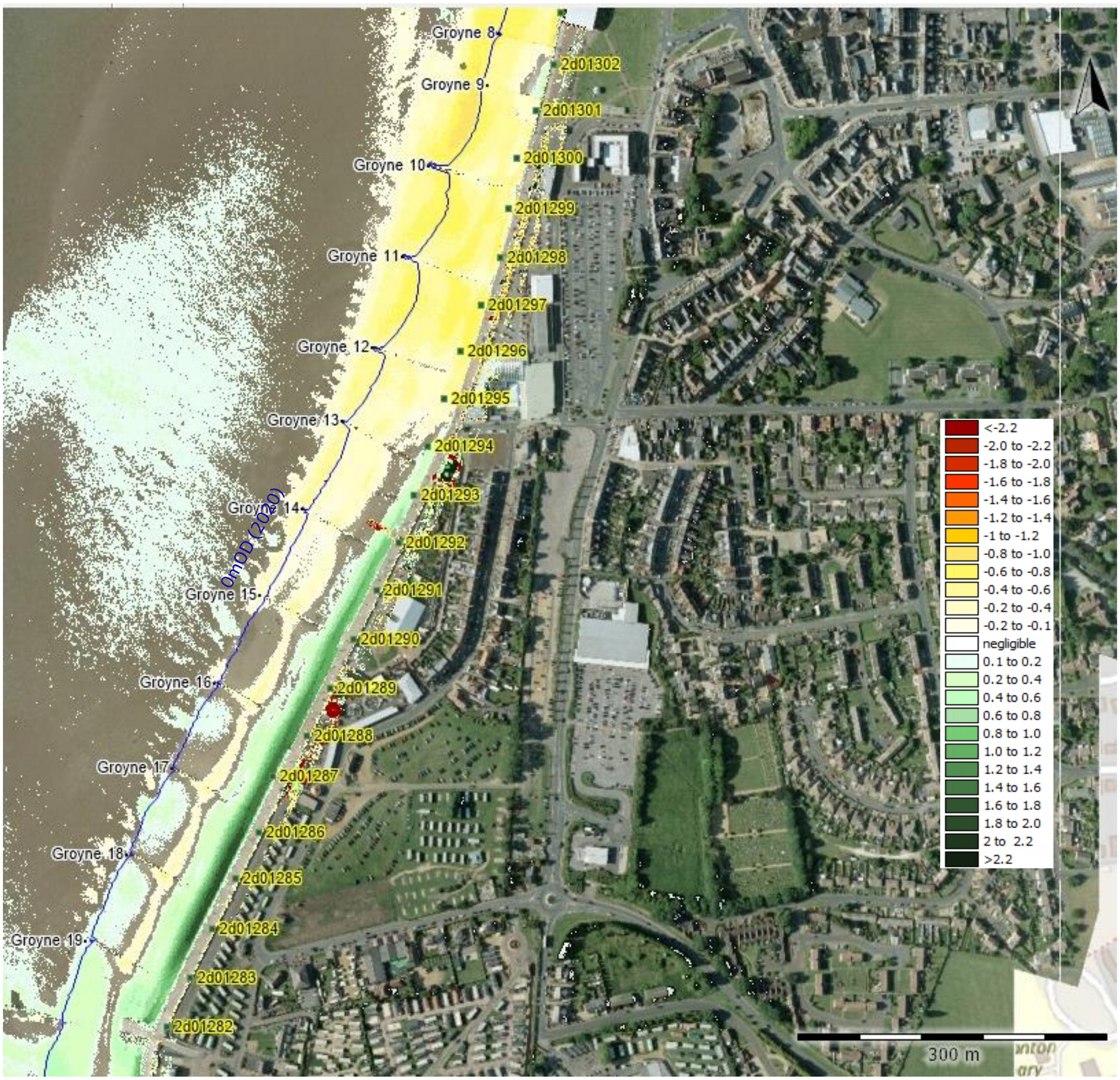
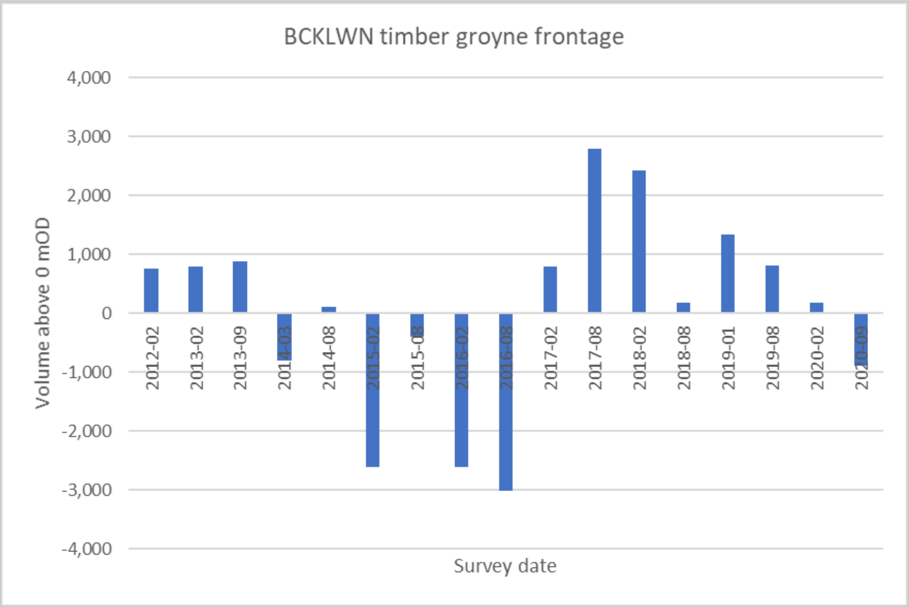


Figure A-31 Difference plot for the BCKLWN timber groyne frontage, generated from LiDAR data from 2020 and 2011, with change in beach level in m. (data courtesy of ACM). Negative values (green) mean that there has been a drop in level in 2020, and positive values (red and yellow) indicate an increase in level.

Figure A-32 BCKLWN timber groynes frontage, with the position of the +1 mOD, 0 mOD and -1 mOD contours generated from 2012 (light blue) and 2020 (blue) LiDAR data. Also shown are the beach transect locations. 2020 aerial image courtesy of ACM.

As for the concrete groyne frontage, a simple calculation of beach volume above 0 mOD has been undertaken using SANDS. Figure A-33 illustrates this data and shows the change in calculated volume relative to the earliest common survey date of September 2011; also shown are sparklines illustrating the relative change between each transect.

These data show that when considering the frontage as a whole, the change in volume over time has fluctuated, with no clear trend evident; this can be attributed to the differing beach behaviour to the north and south of Groyne 12 (2d01295), as discussed above, which is evident from the sparklines. When volumes have been lower, this has typically coincided with lower volumes adjacent to the southern end of the frontage, at the Power Boat Ramp.



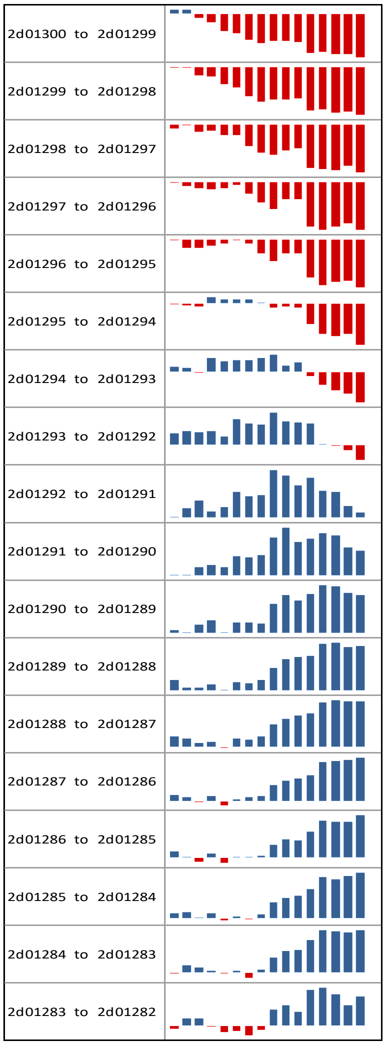


Figure A-33 Change in calculated beach volume along the BCKLNW timber groyne frontage relative to September 2011. The sparklines to right illustrate the same data for each set of beach transects, moving from north to south, illustrating the net gain along the southern beaches within this frontage, compared to the net loss along the northern beaches. .

(d) Timber groynes along Environment Agency frontage

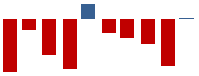
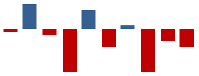
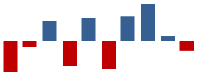
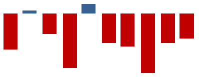
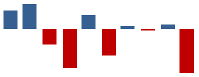
An analysis of beach volumes is already undertaken as part of the Beach Survey Annual Reports (e.g. Jacobs, 2021) that consider the Environment Agency frontage south of the Power Boat Ramp; therefore this has not been repeated as part of this study.

The analysis for the Beach Survey Annual Reports uses Surfer software to generate a gridded interpolated surface from the beach transects and from this calculates changes in beach volumes, above 0 mOD (approximately mean sea level). The Beach Survey Annual Reports split the frontage between the Power Boat Ramp and Wolferton Creek into 15 zones for analysis purposes (Figure A-34), with Zone 1 starting at the Power Boat Ramp. The Environment Agency timber zig-zag groynes considered by this study lie within Zones 1 to 4.

Table A-4 summarises the calculated changes in 'natural' beach volume over time for Zones 1 to 6, i.e. removing any contribution to volume from recycling or nourishment, with sparklines showing the net changes within each zone. The data show that across the frontage the loss of volume over time exceeds any gain, this is particularly the case in Zone 2 and Zone 3 (which cover the stretch between Groyne EA5 to Groyne EA23. Zone 4, which includes the frontage where works were undertaken at Heacham in 2002-3, shows variable trends of volume loss and gain. Notably this lies just to the north of where recycled sediment is frequently required to replenish beaches (Zone 5), which may suggest that material is potentially moved northwards onto this frontage from Zone 5. Zone 5 is also the frontage that has experienced the greatest loss in volume of the six zones considered by this study.

The data also illustrate the impact of the December 2013 storm, which resulted in substantial volume losses across Zones 1 to 6 (and the majority of the frontage between the Power Boat Ramp and Wolferton Creek). There was subsequent recovery of beaches, with a net natural gain of sediment recorded in the 2014-2015 Annual Beach Survey Report (Jacobs, 2015). 2015 – 2016 was also a year of significant loss across the frontage, whilst in more typical years, losses or gains across Zones 1 to 4 tend to be in the region of 2,000 to 4,000 m^3 each year.

Table A-4 Total overall natural gain/loss of sediment above 0 mOD calculated by the Beach Survey Annual Reports for Zones 1 to 6 (i.e. gross volume change - volume imported - volume recycled). Red indicates net loss. The shaded boxes indicate where recycled sediment was added to the beach during the period.

	2010-2011	**2011-2012**	**2012-2013**	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**	***Net change***	
zone 1	1,490	-4,254	1,443	-4,925	-58	-3,684	2,708	2,513	396	-68	*-4,439*	
zone 2	-2,205	-484	-1,513	-2,059	638	-561	-759	-1,022	-1,968	33	*-9,900*	
zone 3	-224	2,484	-498	-4,108	1,825	-1,717	371	-4,162	-1,162	-1,771	*-8,962*	
zone 4	-2,095	-430	1,467	-1,623	1,689	-1,851	1,727	2,609	343	-547	*1,289*	
zone 5	-3,610	403	-2,029	-5,502	966	-3,018	-3,304	-6,054	-3,051	-2,620	*-27,819*	
zone 6	732	1000	-689	-1,658	525	-1,106	93	-1	165	-1,823	*-2,762*	

Sum zones 1 to 4	-3,034	-2,684	899	-12,715	4,094	-7,813	4,047	-62	-2,391	-2,353

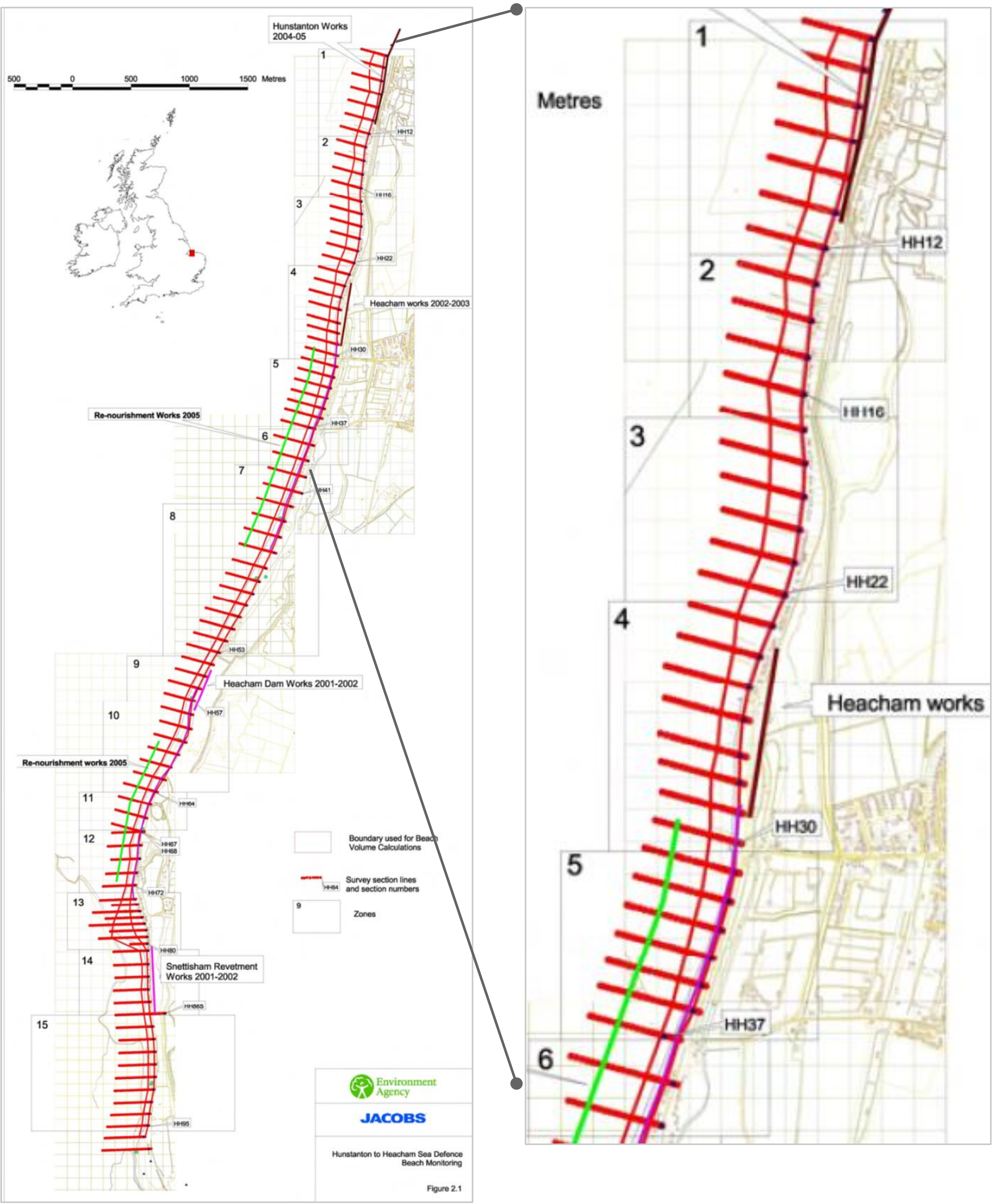


Figure A-34 Zones 1 to 15 defined in the Beach Survey Annual Reports (e.g. Jacobs, 2021), and zoomed in location showing the groynes frontage considered by this study, which lies within Zones 1 to 4. The green line shows were nourishment works were undertaken in 2005.

Due to the difference in length and area between the zones, it is not possible to directly compare the zones. To address this, changes in average beach level have been appraised within the Beach Survey Annual Reports; calculated by dividing the volume change by the beach planar area. The results of this analysis for Zones 1 to 6 are illustrated in Figure A-35, which shows:

- In Zone 1 (Groynes EA1 to EA4), whilst there has been variable changes over time, the trend has been for a slight increase in average beach level since 2010. This frontage has received recycled sediment in some years, which is likely to have contributed to this trend.
- Zones 2 (Groynes EA5 to EA13), 3 (Groynes EA14 to EA23) and 6 show very similar trends, with a net decrease recorded over time. Notably whilst Zones 2 and 3 have groynes, Zone 6 does not.
- Zone 4 (Groynes EA24 to EA 31) shows a very slight increase over time, at a similar rate in recent years to that recorded in Zone 1.
- Zone 5 shows the greatest decrease, which appears to have accelerated since 2016. This is also a zone which has regularly received recycled sediment.

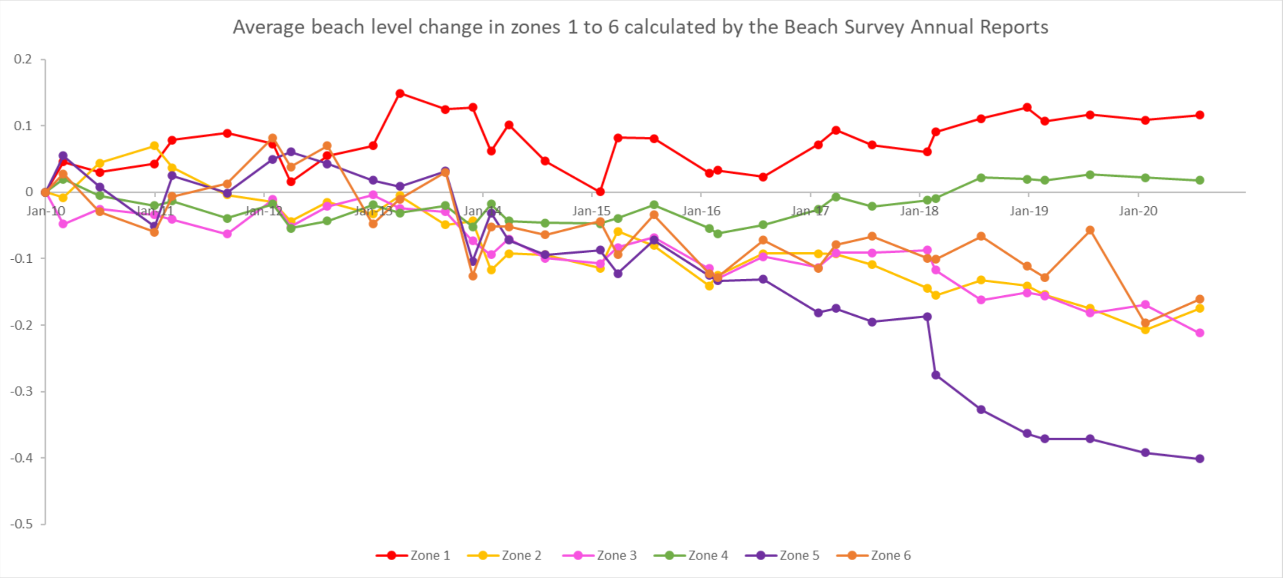


Figure A-35 Average beach level changes in each zone since 2010, as calculated by the Beach Survey Annual Reports. The data includes any contribution from recycling. Note that the reports themselves include data back to 1992. Generated from data from Jacobs (2021).

Using the gridded surfaces, difference plots are produced by the Beach Survey Annual Reports, which illustrate where losses and gain of beach sediment have occurred across the beach, both cross-shore and alongshore. Data from the latest report (Jacobs, 2021) are shown in Figure A-36 as an example, data for other years are provided within each Beach Survey Annual Report. The data show that Zone 3 is particularly dynamic with a greater change in level, both increase and decrease, recorded here than in Zones 1, 2 and 4. The cross-shore location of this change is also interesting, as it effectively continues the shoreline alignment to north and south, cutting across the face of the slight embayment that is present here.

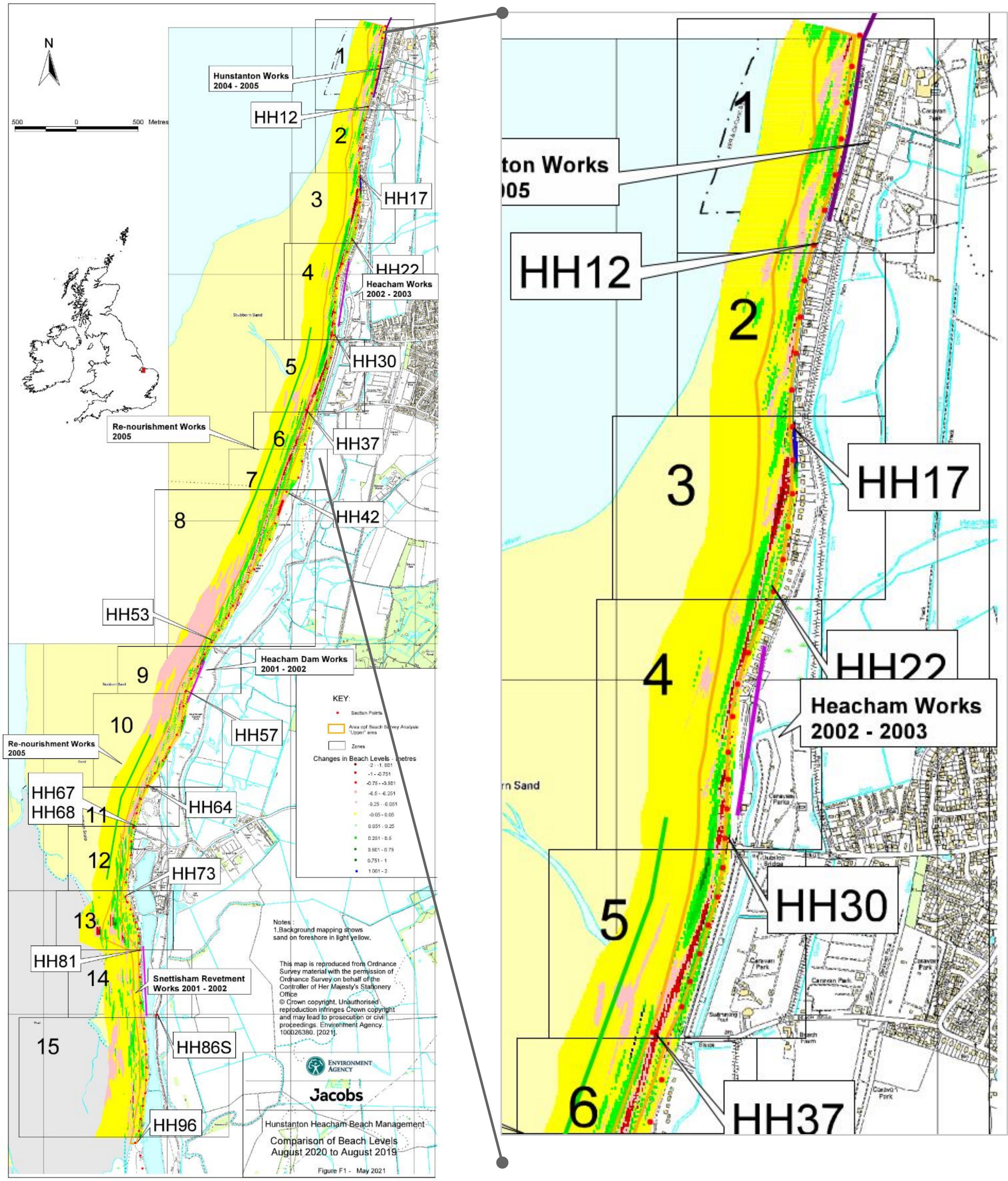


Figure A-36 Comparison of beach levels August 2019 – August 2020. Red and pink areas indicate a drop in level, green and blue areas indicate an increase in level. Taken from Jacobs (2021).

As for the other frontages, beach profile and LiDAR data have also been analysed to assess changes in the cross-shore morphology over time. For consistency with the Beach Survey Annual Reports, findings from this are discussed for each zone in turn, focusing on Zones 1 to 4.

Zone 1 (Groynes EA1 to EA4)

Six transects (from profile 2d01281 to 2d01272) cover this frontage that include regular data back to 1992 (with the exception of 2d01281, which only includes data back to 2011). Other transects are available, but these only include a few surveys. The beaches were recharged between 1990 and 1991, therefore there is no information on pre-nourishment beach condition. The transects do not follow the same alignment as the groynes, so often cut across them.

The data show that the initial nourishment profile, recorded by the 1992 survey, was fairly quickly reworked, with material removed from the upper beach, i.e. about around 1 mOD, resulting in a much shallower beach slope. Subsequent data illustrate the nourishment of the beaches in spring, followed by loss of nourishment sediment from the groyne bays, which appears to typically occur by the subsequent January survey. The 1997 survey suggests a slight change in behaviour; prior to this the profile data indicate very little change in beach level seaward of +0.5 mOD, but from 1997 onwards recorded beach levels between +0.5 and -1.5 mOD have remained higher, with a general trend of growth evident (Figure A-37). This is just at the toe of the groynes along this section. Prior to 1997, there was a distinct change in beach slope around 0 and -1 mOD, but since 1997 the change in slope lies around +1.5 mOD due to accretion of the lower beach.

Beach levels typically fluctuate in level by a metre, although the difference in recorded level at the base of the defences can be much greater than this, up to two metres. Some profiles pick up localised beach lowering, due to the formation of small channels from the toe of the groynes.

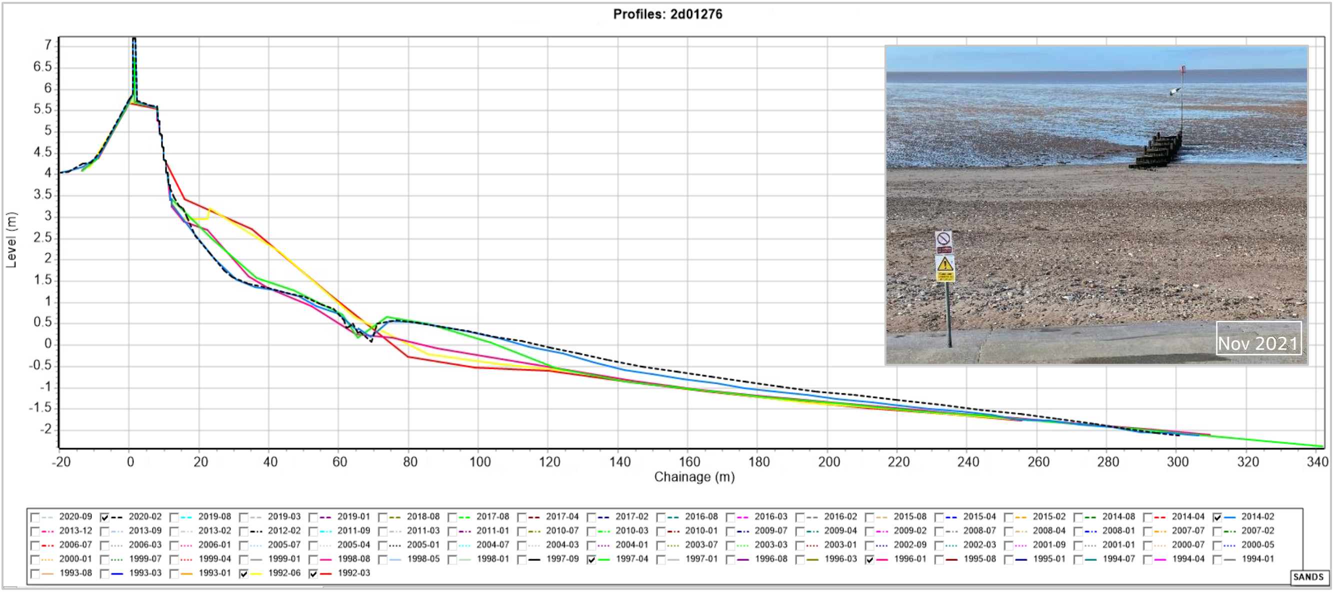


Figure A-37 Typical changes in beach shape along the EA timber groyne frontage: Zone 1 (Groyne EA3). Selected beach survey dates shown: Feb 2020 (black dashed),Feb 2014 (blue), April 1997 (green), June 1992 (yellow) and Mar 1992 (red).

Zone 2 (Groynes EA5 to EA13)

Six transects cover this frontage that include regular data back to 1992 (from 2d01270 to 2d01262). Other transects are available, but these only include a few surveys.

A comparison of beach levels in March 1992 to February 2020 shows a similar trend to that observed along Zone 1, with a notable change in beach cross-shore shape over time.

Figure A-38 shows typical observed changes, which illustrate the change in beach profile shape. There was a drop in upper beach levels (above MSL) from around 1997 and since this time levels have tended to fluctuate within a fairly small margin. As observed in Zone 1, the upper beach has narrowed and steepened over time; this represents the coarser mixed sediments which are constrained to the top of the beach. In contrast there has been accretion of the lower sandy beach. The loss of upper beach material is also shown by the increasing exposure of groynes captured by aerial photographs (Figure A-39). It is not thought that this frontage has received any direct nourishment from recycling.

From the data it is possible to identify small influxes of sediment to the beaches, which is likely to be related to a feed of material following nourishment of beaches within Zone 1.

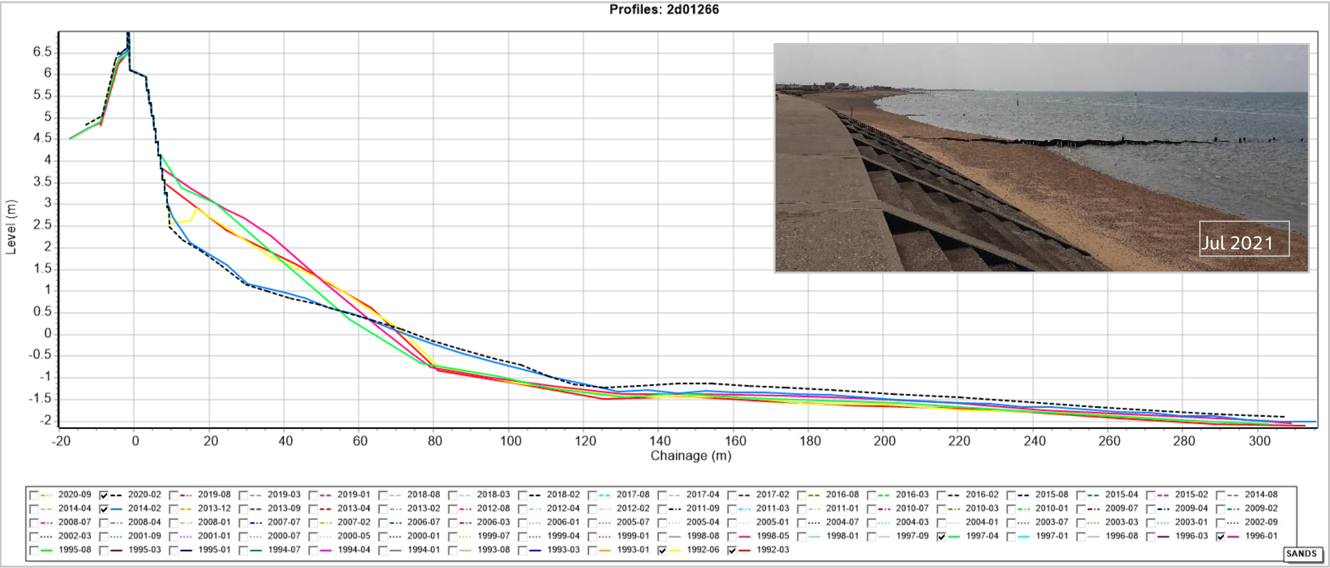


Figure A-38 Typical changes along the EA timber groyne frontage: Zone 2 (Groyne EA10). Selected beach surveys dates shown: Feb 20 (black dashed), Feb 14 (blue), April 97 (green), June 92 (yellow) and Mar 92 (red).

Figure A-39 Change in groyne exposure illustrating the change in the upper beach over time: left is 2020, right is 1992. Aerial images courtesy of ACM.

The length of the groynes varies along this frontage, with Groynes EA6 to EA10 substantially longer that those further south (Groynes EA11 to EA13). A comparison of the February 2020 survey data does not however, indicate a significant difference between profiles (Figure A-40).

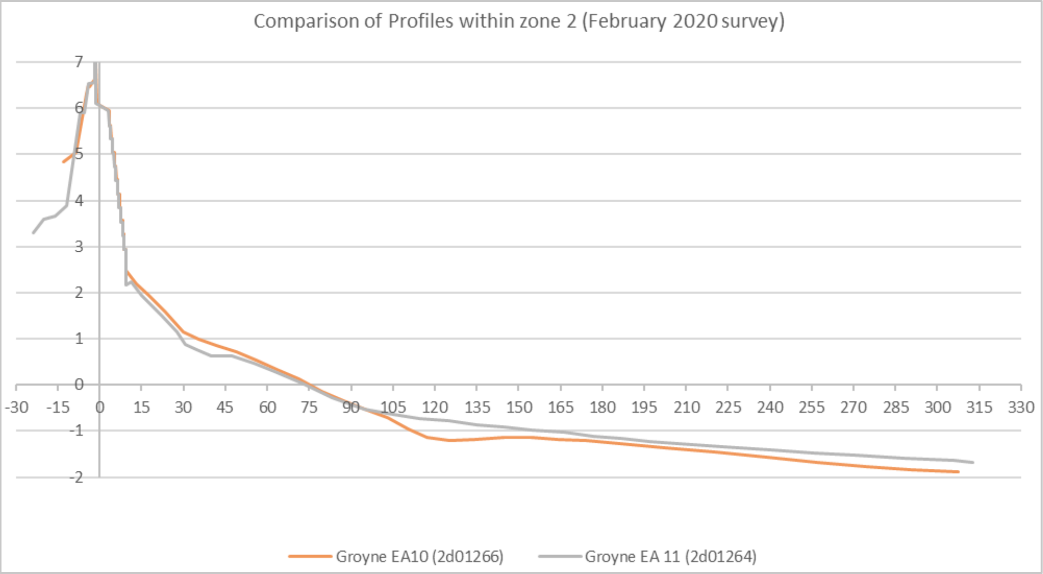


Figure A-40 Comparison of profiles along the longer groyne frontage (represented by Groyne EA10) and the shorter groyne frontage (represented by Groyne EA11) within Zone 2.

<u>Zone 3 (Groynes EA14 to EA23)</u>

Six transects cover this frontage that include regular data back to 1992 (from profile 2d01260 to 2d01250). Other transects are available, but these only include a few surveys. In contrast to Zone 1 and Zone 2, observed trends vary across this frontage.

The northern-most profiles (2d01260 and 2d01258, Groynes EA15 and EA16) show a net loss of beach volume over time, and follow a trend of cross-shore profile change comparable to that observed in Zone 2 (Figure A-41).

In contrast, the southern-most four profiles (Groynes EA17 to EA23) indicate net growth over time since 1992, with the greatest gain observed furthest south (Figure A-42). There has therefore been a rotation in shoreline orientation, similar to that observed along the BCKLWN timber groyne frontage (around Groyne 12). Notably there is little build up across the sandflat area, unlike frontages in Zone 1 and Zone 2.

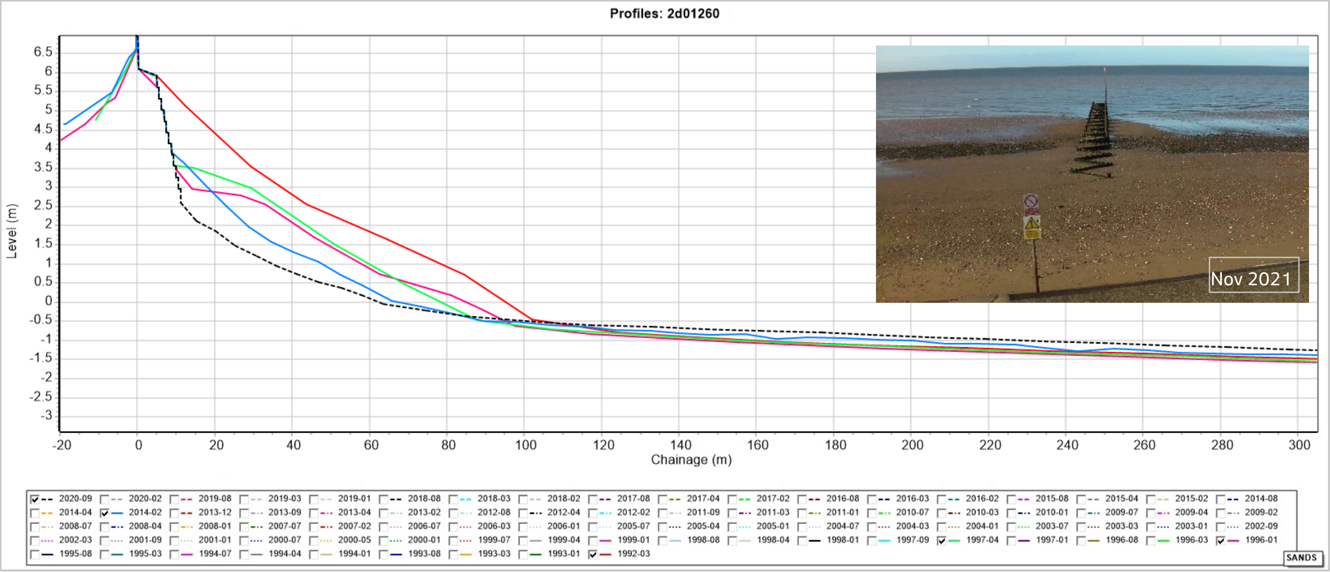


Figure A-41 Changes along the EA timber groyne frontage: northern part of Zone 3 (Groyne EA15). Selected beach surveys dates shown: Sept 20 (black dashed), Feb 14 (blue), April 97 (green), June 92 (yellow) and Mar 92 (red).

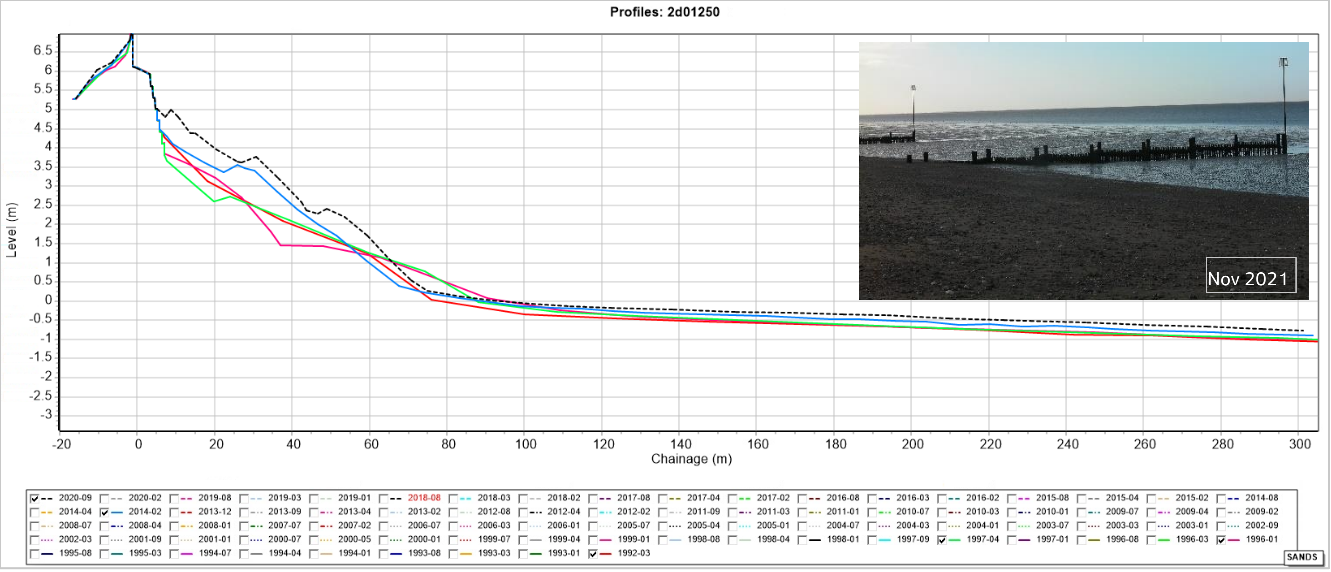


Figure A-42 Changes along the EA timber groyne frontage: southern part of Zone 3 (Groyne EA22). Selected beach surveys dates shown: Sept 20 (black dashed), Feb 14 (blue), April 97 (green), June 92 (yellow) and Mar 92 (red).

Zone 4 (Groynes EA24 to EA31)

Eight transects cover this frontage that include regular data back to 1992 (from profile 2d01248 to 2d01234). Other transects are available, but these only include a few surveys.

A comparison of beach levels in March 1992 to February 2020 indicates that across most of the frontage beach levels (above MSL) are lower than they were in 1992 (following the 1990-1991 nourishment scheme), but levels below MSL are slightly higher.

Following nourishment in 1990-1991, beach levels subsequently dropped and, similar to frontage further north, there appears to have been a change in beach response around 1997/1998, when accretion of sediment across the sandflat starts to be recorded. Upper beach levels continued to drop up to around 2006 and then stabilised slightly, although the lowest levels were recorded in 2012. Since then there has been some slight improvement in beach levels, although the upper beaches have not returned to their early 1990s levels.

There is some evidence that this frontage occasional receives an influx of sediment, which accumulates as a small ridge around +1 mOD (shown in Sept 2020 profile in Figure A-43); this is subsequently eroded. This could explain the fluctuation in beach levels observed, and changes in the calculated volume (see above).

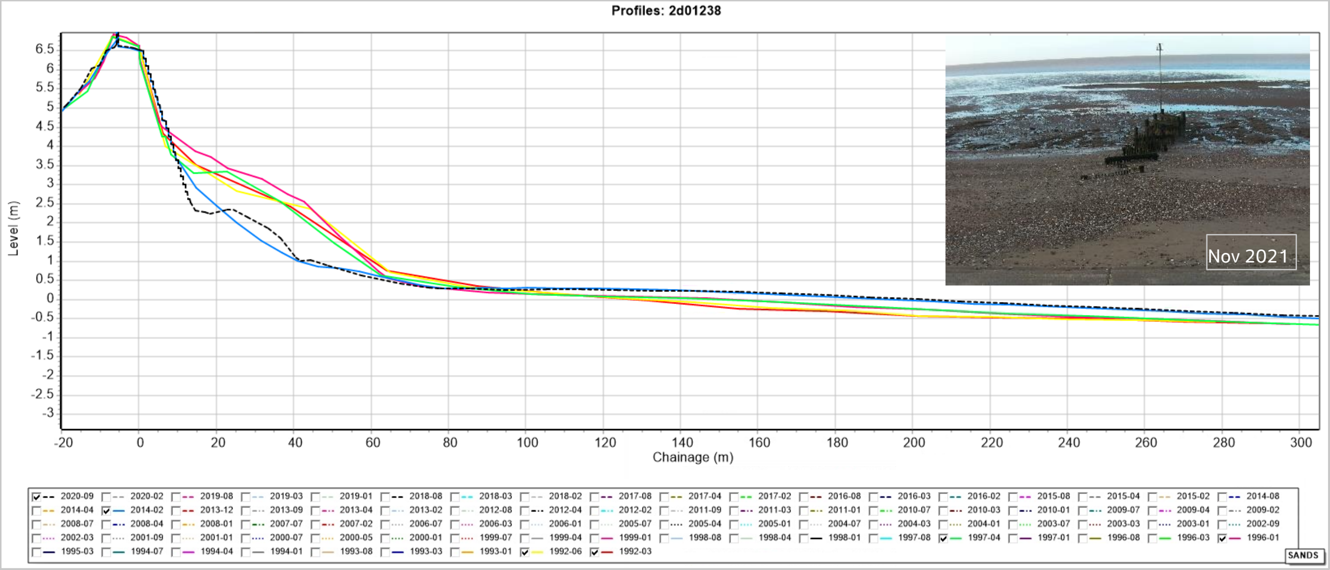


Figure A-43 Typical changes along the EA timber groyne frontage: Zone 4 (Groyne EA29). Selected beach surveys dates shown: Sept 20 (black dashed), Feb 14 (blue), April 97 (green), June 92 (yellow) and Mar 92 (red).

Zone 5

Along this non-groyne stretch, there are six transects that include regular data back to 1992 (from 2d01248 to 2d01234). Following nourishment in 1991-1992 and subsequent receipt of recycled sediment, there was a fluctuation in beach levels between the design beach and reworked form. Further nourishment was undertaken along this stretch in 2005, and again following this, it is apparent that the beach slope was reworked to achieve a more stable form.

The profiles show a distinct change in slope around 0.5 mOD, and below this there has been a general accumulation of sediment, as observed in Zone 4, although levels have fluctuated over time with particularly low beach levels recorded following the December 2013 event.

As for frontage to the north, the LiDAR data have been used to plot the position of the 0 mOD, +1 mOD and - 1 mOD contours for 2012 and 2020 (Figure A-44 and Figure A-45). These plots show the following trends:

- In Zone 1 (Groynes EA1 to EA4), the position of all three contours has shifted seawards by around 10 to 20 m indicating a translation of the beach profile and therefore net accretion. This concurs with Figure A-35, noting that this early graph only considers the beach above 0 mOD. Both 0 mOD and -1 mOD contours lie seaward of the groynes at this location.
- In Zone 2 (Groynes EA5 to EA13), changes are smaller but at the northern end of the frontage the data show a slight seaward movement of both contours (as observed in Zone 1), but at the southern end of the frontage the dominant trend is for landward movement of the +1 m contour, which suggests steepening of the upper beach, whilst there has been a seaward movement of both the 0 mOD and - 1 mOD contours, indicating a widening and flattening of the lower beach.
- In Zone 3 (Groynes EA14 to EA23), the data indicate a seaward movement of -1 mOD, indicating flattening of the lower beach and accretion. At this location the sandflat widens in southerly direction (forming Stubborn Sand), such that this contour lies seaward of the groynes. There is little recorded change in the position of the 0 mOD contour, but along the northern half of this zone there has been net landward movement of the +1 m contour suggesting steepening of the upper coarse beach, but

flattening of the lower sand beach. Both here, and in Zone 2, this concurs with the volume calculations for the frontage and observations made from the beach transect data.

- In Zone 4 (Groynes EA24 to EA31), the sandflat is wider still and beach levels are generally higher across the flat, meaning that the position of 0 mOD contour lies seaward of the groynes. The data indicates a seaward movement of the -1 mOD contour, indicating flattening of the lower beach and accretion. There is also some evidence that the 0 mOD contour line has also moved seawards. Changes in the +1 mOD contour are smaller, but do suggest a slight widening of the upper beach along this stretch.

In summary, the data show that whilst upper beaches have narrowed in Zone 2 and the northern half of Zone 3, there has been expansion of the intertidal flat across part of Zone 1 and more notably across both the very southern part of Zone 3 and Zone 4.

Figure A-44 Environment Agency timber groynes frontage Zones 1 and 2, with the position of the 0 mOD, +1 mOD and -1 mOD contours generated from 2012 (light blue) and 2020 (blue) LiDAR data. Also shown are the beach transect locations. 2020 aerial image courtesy of ACM.

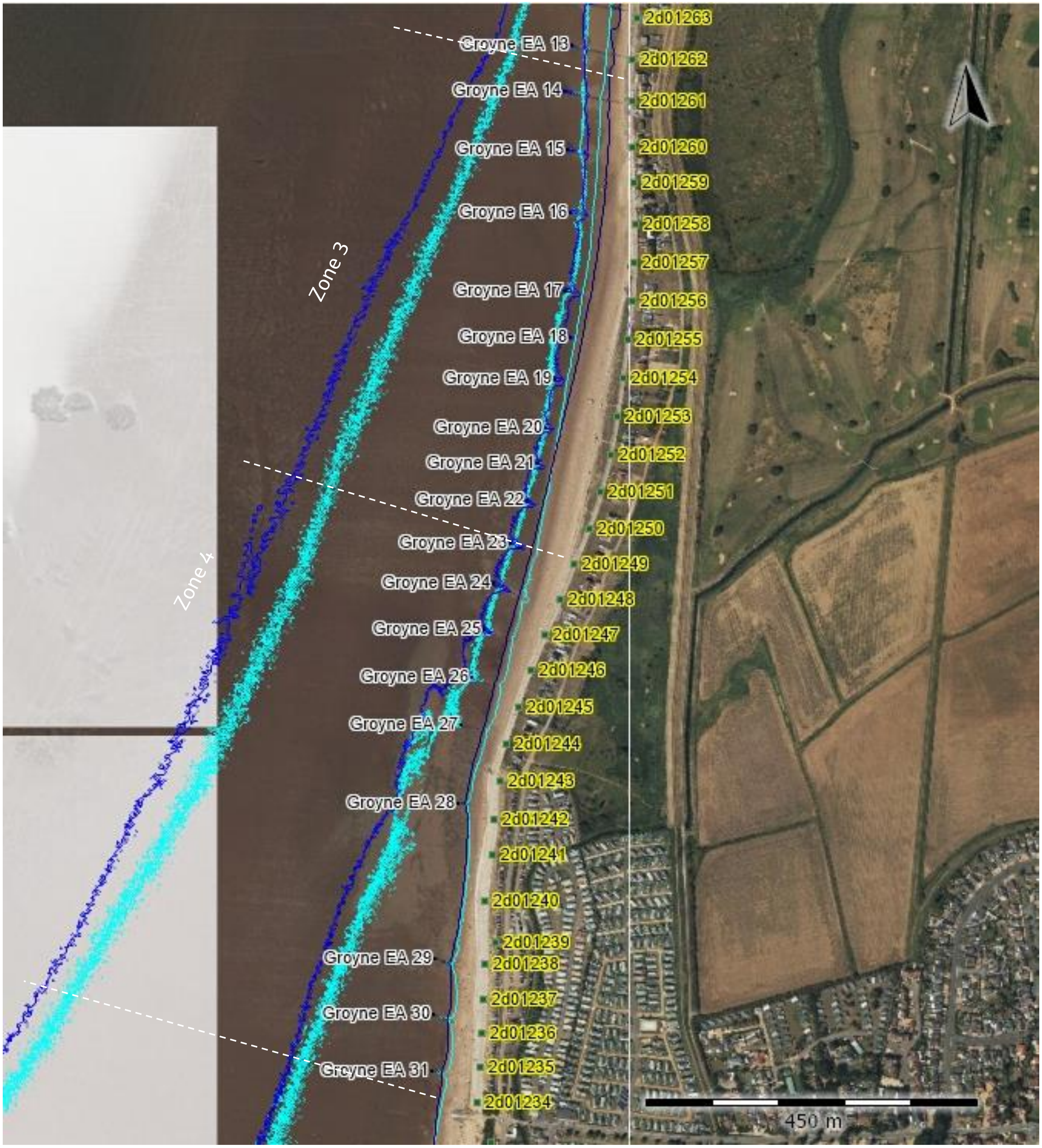


Figure A-45 Environment Agency timber groynes frontage Zones 3 and 4, with the position of the 0 mOD, +1 mOD and -1 mOD contours generated from 2012 (light blue) and 2020 (blue) LiDAR data. Also shown are the beach transect locations. 2020 aerial image courtesy of ACM.

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