From: [redacted]
Sent: 01 June 2022 17:07
To: SizewellC <sizewellc@planninginspectorate.gov.uk>; beiseip@beis.gov.uk
Subject: Submission re TR223 and Sizewell B Cessation of Operation

Dear PINS and Gareth Leigh,

I apologise for this additional submission being later than the requested 23:59 on 23 May. It has been prompted by my more recent access to a BEEMS Technical Report (TR223 edition 3) and its relevance to the coastal defence. The issue relates to optimistic modelling and assessments of the Hard and Soft Coastal Defence Features and the lack of a "Plan B" for the Coastal Processes Monitoring and Mitigation Program, should a catastrophic erosion event take place exposing the Hard Coastal Defence Feature.

I have attached a copy of TR223 edition 3, as it is a document that I cannot find on the PINS website for Sizewell C. It may be there as part of some Appendix or concatenated document supplied by the Applicant, as it is heavily referenced in one of their Application documents (referenced in this submission), but so far I have failed to find it.

This copy was sent to me by another Interested Party who accessed it through an FOI request earlier in the Examination process and sent it to me as he knew I was looking at the issue of the Sizewell B salient and its cessation of operation.

I hope you will accept this submission for consideration, given the subject and the Secretary of State's questions to the Applicant.

Kind regards,

Paul Collins.

For the attention of Gareth Leigh, Head of Infrastructure Planning BEIS, ref: Sizewell C.

From: Paul Collins: IP:20026395

RE: Sizewell C— Soft Coastal Defence Feature and the Sizewell B salient.

I apologise for this additional submission being later than the requested 23:59 on 23 May. It has been prompted by my more recent access to a BEEMS Technical Report (TR223 edition 3) and its relevance to the coastal defence. The issue relates to the lack of a Plan B for the Coastal Processes Monitoring and Mitigation Program (CPMMP) (REP10-041), should a catastrophic erosion event take place exposing the Hard Coastal Defence Feature (HCDF), referred to in previous submissions from myself, Theberton and Eastbridge Parish Council et.al. and from Mr Nick Scarr in several of his submissions including one recently submitted but not yet available on the PINS website.

The Applicant has admitted that the cessation of operations at Sizewell B has implications on Sizewell C's Soft Coastal Defence Feature (SCDF) and the underlying HCDF, but it is unclear as to what the actual impact is and, upon closer examination of its submissions, its views are contradictory.

> In TR223 edition 3, page 82 states "*Shorelines immediately north of the salient were eroding until 2000, following which they began to advance, an observation that may be connected to the presence and evolution of the salient.*"
>
> Note TR223 edition 3 is heavily referenced in APP-312, but may not be available in PINS submissions. It was obtained through an earlier Freedom of Information request. It is attached to this submission for completeness.

The shoreline advance of the Sizewell B salient, that this quote refers to, is present across the entire proposed frontage of the SZC site and this can be seen clearly in Figures 2&3 in REP8-280.

Sizewell B may, or may not, receive an extension to its working life. Regardless of this, it will be shut down either, in 2035, at the beginning of, or later during, Sizewell C operation.

The Applicant has acknowledged analysis by Pethick (2004) that Sizewell B cessation of operation will result in loss or depletion of the Sizewell B salient (a shoreline protrusion created by, and in the lee of, the Sizewell B outfall) as follows:

> APP-312 at section 7.3 and in TR223 edition 3: *"The present-day beach salient formed at the Sizewell B Outfall is likely to be maintained until the station ceases to operate, after which the beach is expected to 'relax', eroding locally until the salient has disappeared (as per the Sizewell A salient following cessation of operation)…*
>
> ***Note: The term relaxed used by EDF / CEFAS is a euphemism for a spike in rapid erosion returning the coastline to a more natural shape in better equilibrium.***

In TR223, Pethick continues with the opinion that this will be followed by:

> "*…medium- to long-term erosion rates of 2 m/yr)".*

However, the Applicant disputes this and refers back to:

> *"…analysis of SSMSG and EA beach profile data – our analysis shows that the net shoreline change rates immediately north of SZB are near zero or positive (accreting) for both the medium- and short-term analyses. Significantly, further to the north, shorelines do show erosional trends (Figure 48): up to -1.6 m/yr, 1 to 2 km north of SZB during the short-term period (with near zero net change immediately to the south)."*

Upon my examination of TR223 Figure 48 for the SZC site, I believe it is clear that the decadal plots for both 1999-2008 and 1999-2016 both show erosion in the -1.0 to -3.1 m/yr range, although there is a reduced rate for 2008-2016, which shows +0.25 to -0.5m/yr, due to a short period of accretion in 2013-2014, and little overall erosion between 2013-2016.

Whilst I accept Pethick's estimate may lie on the upper end of erosion rates, the dismissal of this opinion and the claim for near zero erosion or positive accretion in both the short and medium term is unsubstantiated. Also, with erosion rates to the north, towards Minsmere Sluice, showing up to -1.6m/yr, I do not understand why erosion/accretion behaviour should suddenly change at the SZC site position on the coast. This should be assertion should be justified by the applicant.

Furthermore, when examining the Expert Group Assessment (EGA) of the Sizewell frontage against the plan of the HCDF in APP-312 at section 7.2, the focus of the examination was based on an HCDF/SCDF design incorporating a Beach Landing Facility (BLF) which stands proud of the general HCDF profile and the impact of that this "solid BLF block" would have on erosion/ accretion rates across the proposed Sizewell C frontage. This is no longer the case.

In APP-312 the Applicant states, on page 133, that the above design no longer applies. Figures 68, 70 and 71, however, show the former block BLF design and at the southern end of the HCDF in Figure 71, where the defence turned inland towards the existing SZB defences.

The Applicant's current revised design, has a "kick-out" east towards the shoreline starting some 100-200m before the southern end point as shown in REP5-015 and REP8-280 before turning back towards the Sizewell B defences.

In my mapping the Sizewell C HCDF using the grid references provided in REP5-015 I found the eastern edge of the HCDF rests on the existing Sizewell B salient.

So, whilst the various EGA explanations of beach re-charge and sediment bypassing are instructive, the conclusions are, in my view, now obsolete given the changes in design of the HCDF. The focus of any assessment should be on the southern extent of the HCDF with its -1.0m OD toe located on the existing Sizewell B salient, which is predicted to be erode shortly after Sizewell B ceases operation.

The Applicant confirms in their response that the SCDF extent at this point will erode naturally to be some 10m narrower than for the rest of the SCDF. This will result in a significantly steeper SCDF slope to the beach which will inevitably increase the vulnerability of this part of the SCDF to rapid erosion during prolonged north easterly fetches, as have been experienced during the past two winters, or during storms and south easterly fetches.

The most vulnerable part of the coast defence is planned to be protected by the narrowest (weakest) part of the SCDF. The creation of this weak point is a major cause for concern on the integrity of the coast defence structure and the safety of Sizewell C.

Rapid SCDF loss will expose the shallow HCDF toe (-1.0m OD) at this point. Undercutting of the toe will cause a progressive collapse of the HCDF and create a hardpoint on the coast. The ability to mitigate any sudden rapid erosion and HCDF toe exposure/collapse is, in my view, inadequately considered in the CPMMP. In my opinion it is likely that the current CPMMP will be unable to regain control of the defences, following such an episode, rather than the current expectation of regaining control by beach recharge.

The Applicant's attempt to fit two reactors into such a constrained site, requiring such a significant advance seaward of the site and its coastal defence structures, given the susceptibility of this coast to continuous and episodic erosive events, makes the proposal vulnerable to coastal erosion with potential adverse impacts to the coast both north and south.

Given the potential interplay between the Sizewell B outfall, salient, the new Sizewell C HCDF/SCDF structures and the natural tendency of the coast to try to realign to a "smooth curve" bay between the Minsmere Sluice and Thorpeness, the introduction of the SZC sea defence and enhanced beach profile is always going to be one of a confrontation of objectives. The Applicant's assessment of this is optimistic, rather than conservative, and their changes have essentially made the EGA obsolete.

This project has been inadequately assessed and has not adhered to conservative assessments. It is the wrong project in the wrong place and it should be refused consent.

Kind regards

Paul Collins

DOCUMENT DETAILS

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01	25/01/2019	Joe Ribeiro / Will Manning	Data Scientist / Coastal Processes Scientist	Steve Wallbridge / Tony Dolphin	Senior Coastal Processes Scientist / Principal Coastal Processes Scientist	Brian Robinson	Director
02	31/01/2020	Will Manning	Coastal Processes Scientist	Steve Wallbridge	Senior Coastal Processes Scientist	Tony Dolphin	Principal Coastal Processes Scientist

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REVISION STATUS/SUMMARY OF CHANGES

Revision	Purpose	Amendment	By	Date
01	Edition 3	Updated & reinterpreted with recent shoreline change data (2011-2018)	JR / WM	23/01/2019
02	Edition 3	Minor updates following comments from regulators.	WM	31/01/2020

TR223 Shoreline variability and accretion / erosion trends in Sizewell Bay

Edition 3: Updated with 2011 – 2018 data

TR223 Shoreline variability and accretion / erosion trends in Sizewell Bay

Edition 3: Updated 2011 – 2018 data

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Version and Quality Control

	Version	Author	Date
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Edition 2. Draft report including analysis of shoreline change over decadal scales	1.01	Kenneth Pye	22/03/2013
Comments & authorship contributions	1.02	Tony Dolphin	29/03/2013
Revision	1.03	Kenneth Pye	12/04/2013
Additions to discussion including wave modelling, revision and further comments	1.04	Tony Dolphin	13/08/2013
Revision following TD/BR comments	1.05	Kenneth Pye / Simon Blott	11/10/2013
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Executive QC	3.02	Tony Dolphin	31/01/2020
Submission to EDF	4.00		31/01//2020

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Executive summary

This report presents and interprets the results from a systematic analysis of shoreline variability and directional change within the Greater Sizewell Bay (GSB), using all identified and available shoreline change data (save for satellite imagery) spanning the past 183 years (1835 – 2018). Previously, the existing literature for Sizewell has tended to focus on individual data streams that are relevant to a single time-interval, which can be misleading and difficult to interpret, or on selected beach profiles only, which can conceal important spatial patterns between profiles. The comprehensive, modern and historical datasets used to examine the behaviour of shoreline change at Sizewell, include:

- Historical maps and charts (1835 – 2012);
- Orthorectified aerial photographs, including historical aerial photographs and those collected by both the Environment Agency (EA) and the Centre for Environment, Fisheries and Aquaculture Science (Cefas) (1940 – 2018);
- Beach topographic profile surveys, collected by the Central Electricity Generating Board (CEGB), the EA and the Sizewell Shoreline Management Steering Group (SSMSG) (1985 – 2017);
- Light direction and ranging (LiDAR) surveys, undertaken by the EA (1999 – 2017); and
- Bathymetric profiling (1992 – 2007) and swath bathymetry data (2011 – 2017), collected by both the EA and BEEMS.

The main uses of the comprehensive datasets in this report were to characterise the spatial and temporal variability in the historical shoreline and to indicate sections of the coast considered most likely to erode in future, based on the patterns identified. The two main approaches used to assess shoreline change were beach profile and contour analysis, whereby changes in shoreline positions were derived from the various datasets and assessed over different periods – for convenience we label these records relatively as long-, medium- and short-term records. For the purposes of this report, these temporal categorisations were broadly defined according to both the length and resolution of the datasets used in the analysis, as well as prevailing environmental conditions.

“Long-term” patterns were assessed over the whole data record, from 1835 – 2018 (183 years), using historical maps, charts and orthorectified aerial photographs with a decadal to multi-decadal resolution. Due to the transition towards a bi-directional nearshore wave climate between 1925 – 1940, “medium-term” patterns were assessed for the period of 1940 – 2018 (78 years), using orthorectified aerial photographs with a multi-annual to decadal resolution. “Short-term” patterns were assessed at an intra- to multi-annual resolution for the period of 1985 – 2018 (33 years), during which the GSB was subject to extensive and focussed survey effort using a multitude of survey techniques. It should be noted that “short-term” is as much a reference to the resolution of the comprehensive datasets used, as the duration of these records could be considered “medium-“ to “long-“ term in their own right.

Within the broad long-, medium and short-term categorisations, analysis was constrained to the specific datasets being interrogated. For example, whilst the assessment of shoreline trends using the Digital Shoreline Analysis System (DSAS) method of Thieler *et al*. (2009) investigated short-term patterns, the datasets used were limited to the period of 1992 – 2016 due to data availability and the selection of datasets to avoid temporal bias and aliasing.

Whilst subtle variations in shoreline behaviour were observed when analysed over different temporal and spatial scales, other factors of importance are also highlighted and reported herein. Accordingly, the relevance of fixed or relatively stable positive relief features in the nearshore bathymetry (e.g., Coralline Crag, Sizewell – Dunwich Bank, longshore bars) and man-made structures (e.g., Minsmere Sluice) are highlighted, whilst external factors such as sediment supply from eroding cliffs to the north and variability in wave climate (i.e., storminess and the balance between north-easterly and south-easterly wave events), are acknowledged as playing important roles that are difficult to both quantify and forecast.

This assessment thereby provides a detailed and contemporary summary of the existing datasets and the spatial and temporal variability of shoreline position, which could also be used for the calibration and/or validation of numerical models of past, present and future shoreline change.

Conceptual model of historical shoreline behaviour at Sizewell

The GSB shoreline experienced two distinct phases over the last 183 years: (1) prior to 1925, long-term persistent and spatially-coherent erosion and accretion occurred to the north and south of Minsmere Sluice, respectively; and (2) following a reversal of this trend in 1925-1940, the shoreline change rates lowered and became highly spatially and temporally variable. The cause of this change was postulated in Pye and Blott (2006).

Prior to 1925, a high energy uni-directional north-easterly wave climate lead to cliff erosion and the release of large volumes of sediment between Dunwich and Benacre. Along the Dunwich frontage this was exacerbated by a low Dunwich Bank (2 – 4 m lower than present day) that led to high inshore waves and particularly rapid shoreline and cliff erosion. The prevailing uni-directional wave climate advected this material southward, leaving the cliffs prone to ongoing erosion. The eroded sediments accumulated south of Minsmere Sluice, resulting in an advancing shoreline. Accretion in the south is likely to have arisen as a result of a lower energy environment existing in the lee of Sizewell Bank and a change in wave angle at the coast (due to refraction around the bank and a different shoreline orientation). A significant proportion of the sandy material is also believed to have been funnelled offshore by the hard rock ridges of Coralline Crag at Thorpeness and deposited on the bank, causing it to grow and further reduce inshore wave energy in its lee.

The subsequent switch in shoreline behaviour was marked by a change in nearshore wave conditions during the period of 1925 – 1940: the wave climatology became bi-directional, resulting in significantly lower rates of net longshore transport; and the nearshore wave energy was reduced due to sheltering by the higher bank. As a result, the broad erosion and accretion patterns to the north and south of Minsmere sluice respectively, were replaced by lower rates of highly spatially and temporally variable shoreline change and behaviour.

Today, shoreline change all around the GSB coast is a fluctuating patchwork of erosion and accretion. Stretches of coastline with common behaviour are typically only a few hundred metres wide, though zones may be less than 50 m or greater than 1 km. The general patterns of shoreline change are also influenced by variability in the inshore wave climate, longshore transport and offshore bathymetry (the morphology of the Sizewell – Dunwich Bank and longshore bars), although the bi-directional wave climate means zones of higher waves (and potential erosion) vary between individual storm events and their associated direction. In particular, the very low rates of change around the Sizewell power stations coincide with low wave energy and longshore transport (using TOMAWAC wave modelling; BEEMS Technical Report TR420). Thus, net transport over the medium-term and both annual and decadal resolutions is considered to be low and to the south.

Shoreline trends

Over the long- and medium-term, the Sizewell power stations frontage remained relatively stable. Persistent and spatially-coherent accretion with periods of slight erosion occurred prior to the transition towards a bi-directional nearshore wave climate between 1925 – 1940. Subsequently, whilst a steady erosional trend of the shorelines to the immediate north of the proposed Sizewell C (SZC) site has occurred, the Sizewell power station frontage itself has exhibited high variability, but with little net change over the medium-term. Wave modelling suggests that these medium-term trends were due to low longshore sediment transport potential, caused by shoaling and energy dissipation over the Sizewell-Dunwich Bank. In particular, modelling for Flood Risk Assessment has shown that the bank reduces wave energy for infrequent high-energy storms (> 1:10 year interval). The bank's role as a dissipator of high-energy storms is expected to be similar to the present day; that is, it is expected to maintain a similar size due to maintenance or rises in longshore sediment supply that feed the bank (BEEMS Technical Report TR357).

Since 1985, the GSB has been subject to extensive and focussed survey effort and consequently, extensive datasets exist for the assessment of short-term changes. The analysis of beach contour changes identified nine zones of common shoreline response to forces of geomorphological change, that could be broadly characterised according to shoreline change statistics, namely:

- Dunwich Cliffs – relatively stable, with low rates of change, advancing in the north and south (0.0 to 0.7 m/yr (r^2 = 0.5 to 0.8)) and retreating in the centre (-0.1 to -0.6 m/yr (r^2 = 0.4 to 0.8)). The latter resulting in low sediment inputs from cliff erosion in comparison to that reported in the long-term record;
- Minsmere north – highest rates of retreat with a generally persistent trend and large shoreline change envelope (up to -2.2 m/yr (r^2 = 0.9)) observed between Minsmere Cliffs and Minsmere Sluice;
- Minsmere Sluice – an approximately 1 km stretch of coast, centred on Minsmere Sluice, showing highly variable shoreline positions, with a relatively large shoreline change envelope. On average the shoreline was slowly accreting (1.1 m/yr (r^2 = 0.0 to 0.9)), whilst spatially persistent trends were only observed where the shoreline was anchored in position by the sluice itself;
- Minsmere south – high rates of retreat and spatial variation, with a generally persistent trend and moderately large shoreline change envelope (up to -1.4 m/yr (r^2 = 0.6 to 0.9));
- SZC frontage – low rates of shoreline change with no persistent trends (-0.4 to 0.5 m/yr (r^2 = 0.0 to 0.2)), located in a transition zone between eroding areas to the north and stable and/or accreting beaches to the south. Under the present management strategy, the erosion to the north of the site is likely to expose the SZC coastal defences (if unmitigated) to the sea within its life cycle. The reader is referred to BEEMS Technical Report TR403 for further detail on future erosion of the SZC frontage;
- SZB frontage – a short stretch of coast (approximately 200 m) with net shoreline advance but variable and sometimes retreating shorelines. Highest rates of accretion (up to 1.6 m/yr) due largely to post-construction foreshore recovery following the removal of a coffer dam (1992) and beach landing facility (BLF) (1993). Accretion rates are reduced if this recovery period is omitted (1 m/yr (r^2 = 0.2 to 0.8));
- Sizewell gap and south – low shoreline change rates and envelopes with no persistent trend (-0.4 to 0.3 m/yr (r^2 = 0.1 to 0.6));
- Thorpeness north – variable shoreline position, generally stable or slowly retreating, with isolated areas of greater rates of retreat (-0.8 to 0.2 m/yr (r^2 = 0.0 to 0.9)); and
- Thorpeness – highly variable shoreline positions and high rates of change near the tip of the ness (-1.4 to 0.7 m/yr (r^2 = 0.1 to 0.5)).

Most beach volumes along this coastline remained relatively stable over the short-term and, in this sense, can be said to be in dynamic equilibrium. However, there were notable exceptions with temporal trends in beach sediment volume highlighting significant seasonal and inter-annual variation, reflecting changes in wave and longshore drift conditions. For example, a gain in beach sediment volume during the summer months was often observed, with a subsequent reduction during the winter months, indicating sand exchanges between the beach face and longshore bars, although some years did not display this pattern. In addition, individual large storm events had significant but spatially variable effects, depending on the characteristics of the storm itself (e.g., wave direction both during and following storm events). The largest beach volumes were found in the vicinity of the power station (up to 90 $m^3 m^{-1}$ in 2012) but were also highly variable. This was partly attributed to the development of a salient feature opposite the SZB outfall, first observed in 2005 and subsequently prograded with continued sediment accumulation and showed minor longshore migrations.

Short-term patterns in erosion and accretion were assessed over temporal resolutions ranging from seasonal to decadal and corroborated the findings of beach volume and contour analysis. In general, variability in the patterns of erosion and accretion observed could be grouped into four categories: seasonality, cross-shore, long-shore and alternating variability. The cause of these signals was attributed to the cumulative result of: variability in the bi-directional and inshore wave climate (e.g., influences of near- and offshore morphology); individual storm events and their relative characteristics; longshore sediment transport; and the presence of both natural (e.g., Coralline Crag) and man-made (e.g., Minsmere Sluice) stabilising points within the GSB. The latter also played an important role in limiting the spatial extent of the variability observed, with longshore variability being most apparent within sections of the coast that lacked stabilising points that may constrain longshore sediment transport.

Shallow bays and hard points

Observations of the Suffolk coast indicated a shoreline evolving to balance drivers toward longshore or swash alignment i.e., the dominant storm direction and sediment supply pathways from north to south at a given time. In the GSB, the shoreline re-orientation combined anti-clockwise straightening toward a N-S axis in the northern sections and the creation / rotation of bays and sub-bays in the south. The formation of bays between erosion-resistant points (i.e., entrance piers to the Blyth estuary, Minsmere sluice, Coralline Crag at Thorpeness) is promoted because of low longshore transport rates and sediment supply, and re-orientation toward swash alignment.

Minsmere Sluice has acted as a 'hard point' within the coastline since its original construction in 1830 and has provided a "headland" between shallow bays to the north and south. Similar to a groyne structure, the sluice has trapped sediments moving alongshore and promoted net shoreline stability. Under the current bi-directional wave climate, sediment build up typically occurred approximately 500 m to the north and south of the sluice, beyond which net erosional trends are observed. The Minsmere sluice example suggests that the effect of structures that trap longshore sediment on this coast is net stability (there are no signals of persistent downdrift erosion), and decay or removal of the sluice structure (as a hard point, not as an operational sluice) could potentially result in high recession rates at the sluice and between SZC and Minsmere Cliffs, for years to decades, until an equilibrium beach-plan shape is reached, though the behaviour of the shoreline response may differ between that experienced at SZC and Minsmere. In the absence of other control structures between the sluice and SZC, retention of the sluice as a hard point (not an operational sluice) will stabilise the shoreline at this location, whilst influencing the future configuration of the adjacent shoreline as it is forced into alignment with the Minsmere outfall.

Construction impacts on the foreshore

Little information exists about the nature and scale of shoreline change resulting from the construction of SZA, however the scale and longevity of SZB construction impacts (i.e., dredging for cooling water culverts, coffer dam and the BLF) on the beach and nearshore zone is moderately well documented in the shoreline datasets. The dredging and the coffer dam constructed for the cooling water culverts resulted in a 400 m long, 25 m wide indentation in the shoreline, which subsequently infilled naturally over a period of 4 – 5 years. The shoreline positions suggested that, despite the large degree of local change and the lack of active sediment management, impacts were not detectable beyond a few hundred metres from the construction site after a few years. Due to their transmissive nature, the effects of SZC's marine infrastructure are expected to be substantially smaller and shorter lived than those of SZB.

Ongoing shoreline change and coastal processes measurement / modelling

The beach profile monitoring programmes conducted by the SSMSG and the EA provided valuable data on which to document shoreline behaviour, however the methods employed have their (spatial and temporal) limitations. The BEEMS programme is presently augmenting these ongoing programmes using a number of new measurement techniques – X-band radar, digital cameras and remote piloted aircraft (RPA) topographic surveys. The main feature of these techniques is their ability to capture spatial data (e.g., waves and beach, bar and bank position) at a significantly higher frequency (almost continuously for radar and cameras). In doing so, it will be possible to capture important spatial behaviour occurring between beach profiles and in the months between beach profile surveys. It would also enable early detection of any impacts arising from the construction and operation of SZC, shoreline response to individual storms (e.g., Storm Emma (Beast from the East), 2018) and eventually allow longer-term signals to be separated from short-term shoreline responses and active processes.

1 Preface to Edition 3

The first edition of BEEMS Technical Report TR223 was released in 2012 and included shoreline data up to 2011. A second edition was released in 2014 followed by this third edition that provides further updates, extending the analysis of beach profiles and contour positions up to 2018, to provide a more complete baseline for the environmental impact assessment. For the benefit of readers familiar with the second edition, this preface highlights where significant changes to the interpretations and conclusions of the original report have been suggested by the extended analyses.

Changes resulting from the inclusion of an additional seven years of data (2011 – 2018) predominantly relate to the figure updates in Section 6, however minor updates have also been made to figures in Section 7 where necessary. In addition, consideration has been given to the potential interaction between the two Fish Recovery and Return (FRR) outfalls and the Combined Drainage Outfall (CDO) that are to be installed as part of SZC construction. These outfalls will be located on the seaward flank of the outer nearshore bar, which, due to potential changes in morphology and/or position, represents a potential geo-hazard to the outfalls. Elsewhere, small changes to the text have been made where required, however the structure of the report and the bulk of the text is largely unchanged.

Most importantly, figures throughout Section 6 have been updated with additional shoreline measurements up to 2018 and to extend the analyses of shoreline change trends. All descriptions of long-term erosional and accretional trends given in the original report remain unaffected, with the following notable exceptions. The previously eroding north-east corner of the SZC frontage has been stable and unchanging since 2010 (profile P5), however, the central SZC frontage shows an oscillation moving through erosion and accretion phases in the late 1990s and 2000-2010 respectively, and back to erosion in 2010-2018, leading to low net rates of change (by linear regression) over the measurement period (profiles S1B5 and P7 in Section 6). Likewise, the trends at several profile locations (particularly at profiles P1, P3, P7, S1B2, S1B4, S1B5 and S1A1, which cover a range of locations from Dunwich in the north to Thorpeness in the south) up to 2011 were not continued in the subsequent period to 2018. The additional seven years of data suggest a periodic oscillation between erosive and accretive periods over a decadal timescale occurring along the coastline.

Please note that figures that are illustrative or descriptive of historic events have not been updated with the most recent data, as the additional data is not considered to impact on the figure's original interpretation. For example, Figure 59, where data from post 2016 would not be visible due to the temporal scale plotted.

2 Introduction

An understanding of the past, present and potential future variability of the beach and adjoining nearshore morphology is important to the safety cases for Sizewell C (SZC) and the existing Sizewell B (SZB) power station, as well as for assessing the potential effects that the proposed SZC station could have on the adjacent shorelines. The beach and associated dunes (both natural and artificial) form a key part of the coastal flood defence system that protects the Sizewell power stations. Of particular concern are possible longer-term directional changes in shoreline position (erosion or accretion) that might significantly affect the safe and efficient operation of the stations. Changes in sea bed morphology and sediment mobility are also of major importance to nearshore processes and the effective operation of the cooling water intake and discharge systems on which the power stations depend.

Beach and dune systems naturally exhibit variability on a range of time scales, with alternating periods of erosion and accretion due to variations in wind, wave and tidal conditions. They are also affected by human interventions in the coastal zone, including the construction or removal of groynes, jetties, outfalls and other coastal structures, sediment nourishment or sediment removal by dredging. Proximal interventions may induce a rapid change and it may take several years or even decades to reach a new equilibrium depending on the spatial and temporal scale of the intervention. In the case of distal interventions, especially those which influence sediment supply, it may take several decades before the effects become apparent and the beach adjusts to a new equilibrium.

Changes in the Sizewell beach frontage have been monitored since 1985 (Mouchel, 1996), and more intensively since the Sizewell Shoreline Management Steering Group (SSMSG) was set up in 1996 to advise Nuclear Electric and Magnox Ltd on issues related to coastal protection and flood defence (Nuclear Electric and Magnox Electric plc, 1996). The results of SSMSG monitoring have been summarised in a series of quarterly and annual inspection reports (Pethick, 1999a, 1999b, 2000, 2002a, 2002b, 2003, 2004a, 2005, 2006, 2007, 2009, 2010a, 2010b, 2011, 2012, 2013, 2016, 2017, 2018). Critical threshold changes in beach and nearshore morphology have been defined to trigger up to three levels of further investigation (Pethick, 1997a, 1998a). The Sizewell Beach Management Plan (BMP) was revised in 2002 but the key objectives remain the same (Pethick and Taylor, 2002).

Longer-term overviews and supplementary reports have also considered matters such as the effects of dredging, localised dune erosion and flood risk (Pethick 1997a, 1997b, 1998b, 1999b, 2001, 2004a, 2004c, 2010b). This information was recently reviewed in BEEMS Scientific Advisory Report Series SARS018. Aspects of longer-term shoreline and bathymetric change in the area have also been considered in a number of reports commissioned in connection with the proposed development of SZC (e.g., BEEMS Technical Reports TR058, TR105, TR107, TR139) and the RSPB reserves at Minsmere and Dingle Marshes (Pye and Blott, 2005, 2006, 2009). However, the previous reports have not sought to integrate the results obtained from SSMSG monitoring, Environment Agency (EA) strategic coastal monitoring, ongoing BEEMS monitoring and longer-term evidence of coastal change provided by historical maps, aerial photographs and bathymetric data, in order obtain the most robust evidence base possible.

Two main approaches were used in preparing this report:

- Analysis of short-term changes in beach profiles, taken from topographic survey data (1985 – 2017) and supplemented with nearshore bathymetric survey data (1992 – 2017); and
- Analysis of the changes in beach contour positions, taken from; historical maps and charts, orthorectified aerial photographs, beach topographic profile surveys and LiDAR surveys, and assessed over the short- (1985 – 2018), medium- (1940 – 2018) and long- term (1835 – 2018). The assessment of beach contour positions using DSAS (Thieler et al. (2009)), allowed characterization of shoreline changes at a high resolution (alongshore intervals of 50 m), and allowed the identification of localised changes in beach behaviour, that may be missed by beach topographic profile surveys (alongshore intervals of 250 to 1000 m) (i.e., approach 1).

A preliminary analysis of the SSMSG and EA topographic monitoring data was reported in BEEMS Technical Report TR223 first edition. The BEEMS Technical Report TR223 second edition extended the original analysis to include data from additional topographic surveys, historical aerial photographs, historical maps and bathymetric surveys. BEEMS Technical Report TR223 third edition provides further updates, extending the analysis of beach profiles and contour positions up to 2018. The data are used to develop a conceptual model of the spatial and temporal variability and long-term evolution of the shoreline around Sizewell. An initial evaluation on the alongshore variability in wave energy and any potential links to the patterns of shoreline change observed is provided.

This report assembled and interpreted all of the known shoreline position data. As noted, previous investigations have not assembled the complete shoreline datasets, which provide the most detailed and robust evidence available on shoreline behaviour at Sizewell. Having assembled and quality checked the data, this report uses it to:

- Characterise the historical shoreline behaviour including its spatial and temporal variability;
- Characterise how the shoreline reacts to long-, medium- and short-term intervention (coastal structures, construction activities, outfalls);
- Indicate which sections of the coast are most likely to erode in future based on long-term trends and patterns identified;
- Link the observed trends and patterns to nearshore bathymetric configuration (longshore bars, Sizewell – Dunwich Bank and Coralline Crag outcrops) and coastal processes (alongshore gradients in wave energy) to spatial variability in shorelines, where possible;
- Highlight the relevance of fixed or relatively stable positive relief features in the nearshore bathymetry (i.e., Coralline Crag, Sizewell-Bank, longshore bars);
- Indicate the probable role of Sizewell – Dunwich Bank through initial wave modelling and spatial patterns in shoreline behaviour, though it acknowledges that data on the bank itself are sparse and therefore quantitative conclusions cannot be drawn. Given the likely importance of the bank to future flood risk, over topping and coastal erosion, bank monitoring and numerical modelling of geo-scenarios are to be undertaken (for the Flood Risk Assessment exercise);
- Acknowledge that external factors, such as sediment supply from eroding cliffs to the north and variability in wave climate (storminess and the balance between north-easterly and south-easterly wave events) play an important role that is difficult to quantify and forecast; and
- Provide a detailed and up to date comprehensive dataset on the spatial and temporal variability of shoreline position which can be used for calibration/validation of numerical models of shoreline change.

3 Character of the Sizewell frontage within the Suffolk coastal context

3.1 Location and general setting

The proposed SZC new nuclear build (NNB) site is located immediately to the north of the existing SZB power station in a shallow embayment south of Southwold (Figure 1). This area forms part of coastal management cell 3c which extends from Lowestoft Ness to Landguard Point near Felixstowe (Royal Haskoning, 2010).

Most of the Suffolk coast consists of geologically young and relatively 'soft' sedimentary formations that are easily eroded by marine processes (Zalasiewicz *et al*., 1988, Hamblin and Rose, 2012; Mottram, 2012). Significant coastal erosion has occurred during the past several millennia and continues at rates of up to 5 m/yr in some locations, for example at Covehithe Cliffs (Brooks, 2010) to the north of Southwold. Regional cliff erosion is an important process which provides the main supply of sediment via longshore and cross-shore sand transport to beaches, nearshore bars and offshore banks in the area (BEEMS Technical Reports TR139 and TR223 first edition, Lee, 2008; Sear *et al*., 2009, 2010, 2013; Brooks, 2010, Brooks and Spencer, 2010, 2012; Brooks *et al*. 2012; Pye and Blott, 2006).

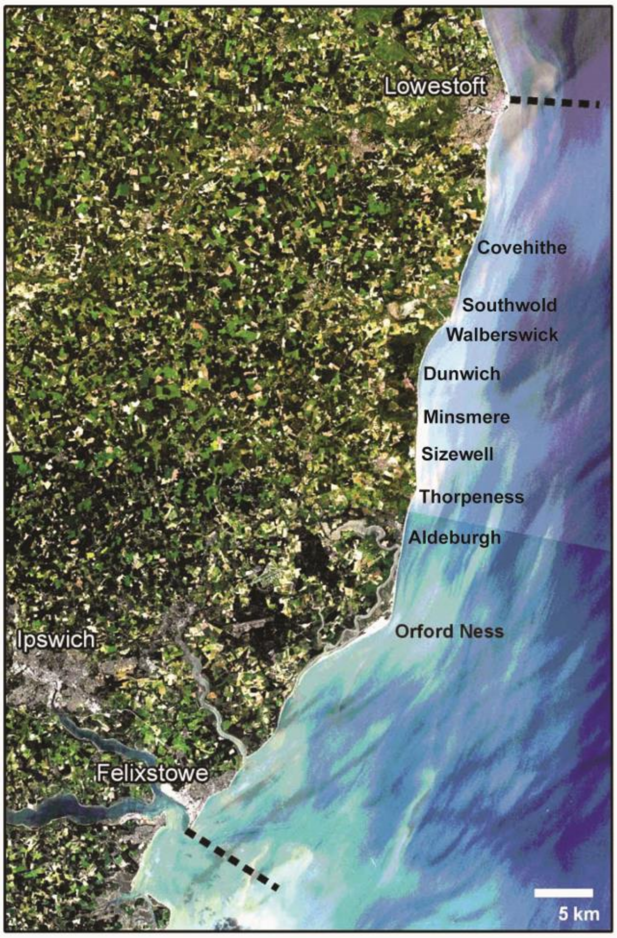

Figure 1: Location of Sizewell within the context of the Suffolk coast, coastal management cell 3c and other principal locations mentioned in the text.

3.2 Role of coastal ‘hard points’

Artificial defences against erosion and flooding have been constructed in a number of places during the past 200 years, creating ‘hard points’ that continue to exert a major influence on coastal evolution. Of particular importance for the GSB are the harbour entrance piers at the mouth of the River Blyth, Minsmere Sluice to the north of Sizewell, and the combination of natural Coralline Crag outcrops and coast protection works at Thorpeness (Figure 2). These ‘hard points’ hold the coastal position, locally interrupt the natural pattern of alongshore sediment transport, and have led to the development of a series of shallow bays in the areas between them.

Figure 2: Coastal ‘hard points’. Formed by (a) the entrance piers to the Blyth estuary, (b) Minsmere sluice, (c) Coralline Crag sub-crop and coastal defences at Thorpeness; photograph (d) shows the beach and artificial dune defences in front of Sizewell ‘A’ and ‘B’ power stations.

3.3 Morphology and sedimentary character of the beach and nearshore area

Along the Sizewell power stations frontage, the subaerial beach generally consists of a gravel-dominated upper beach and a flatter, sand-dominated lower beach. The backshore area above mean high water springs (MHWS) naturally consists of shingle beach ridges capped by thin accumulations of wind-blown sand, but in front of Sizewell A (SZA) and SZB, the natural topography and sediment composition were substantially modified during construction of the power stations and subsequently re-profiled as part of the coastal defences. Seaward of mean low water springs (MLWS) the subtidal part of the beach is sand-dominated, although ephemeral small shingle bedforms and scattered shingle clasts are periodically present on the surface. A sandy inner longshore bar with a crest elevation of -1.0 to -3.0 m OD is typically present between 50 and 150 m seaward of the 3.0 m OD contour. Seaward of the inner bar is a trough, comprised predominantly of sandy sediments but with localised pockets of mud, and an outer longshore sandy bar that lies 150 to 400 m seaward of the 3.0 m OD contour.

The crest elevation of the outer bar varies alongshore and over time, but generally lies at between -2.5 m and -4.5 m OD. BEEMS Scientific Advisory Report Series SARS018 postulates that the seaward nearshore bar has formed in response to long period waves at times of high-water stand, while the smaller and more ephemeral inner bar forms in response to shorter period storm waves.

3.4 Sediment transport pathways

There is good evidence from swath bathymetry surveys and numerical modelling that the nearshore bars play a key role in sediment transport parallel to the coast. Black & Veatch (2005) and BEEMS Technical Reports TR329 and TR420) showed that the direction of alongshore sediment transport between Minsmere Sluice and Sizewell shows considerable intra- and inter-annual variation in response to fluctuations in wave climate, in particular the relative energy of north-easterly and south-easterly waves. The direction of longshore drift of shingle along the subaerial beach also varies in a similar way. However, the evidence from seabed bedform asymmetry and particle size trends suggests that along most of the Dunwich to Thorpeness shore, and in the subtidal area, the long-term net sediment drift is low and towards the south (BEEMS Technical Report TR107).

4 Historical sources of shoreline change data

4.1 General considerations

Several sources of data can provide information relating to past shoreline change:

- Historical maps and charts;
- Orthorectified aerial photographs;
- LiDAR data;
- Ground topographic survey data (typically beach profiles);
- Single-beam echo sounder and Multibeam swath bathymetric profile data;
- Satellite data.

In this study, all sources except satellite data have been used. Most of the available data pertained to the intertidal and subaerial beach, which is typical due to logistical and economic constraints. For example, the EA coastal monitoring programme in East Anglia, which is one of the most comprehensive in Britain, measures the intertidal and subaerial beach at half-yearly (beach profiles) and annual (aerial photography) intervals, but the subtidal beach is only monitored every five years (by single-beam echo sounder until 2007). The SSMSG data also has a terrestrial focus with varying (quarterly – annual) monitoring intervals (plus quarterly visual inspections) and no subtidal monitoring. The exclusion of the subtidal beach is a limitation to the interpretation of shoreline change over the short-term. For example, it is difficult to quantify the seriousness of storm-induced changes in the beach face and berm that occur every winter based on terrestrial beach profiles (SSMSG and EA), as they cannot distinguish sediment loss or gain in the beach system, from sediment exchange between the subtidal and subaerial beach. The latter is part of the normal and regular behaviour of a beach that is of little concern to the station, so long as the primary defences and sediment volumes in the dune system are reasonably maintained. Although there is limited data availability for the subtidal beach, the EA five-yearly profiles across the longshore bar area and selected BEEMS nearshore bathymetric surveys are used to describe the nearshore morphology in Section 5.6.

Assessment of potential future coastal changes can be made on the basis of:

- Extrapolations based on historical changes and trends (historical trend analysis);
- Short-term computer modelling of sediment transport and beach morphological responses, using a range of assumed sediment supply and environmental forcing scenarios;
- Short- to medium- term, broad-scale morphological modelling using coupled erosion, sediment transport and beach morphology models such as SCAPE, GENESIS and UNIBEST; and
- Long-term expert geomorphological assessment (EGA) based on results from the three previous approaches, combined with information from natural analogues in other parts of the world, experimental investigations, and climate and sea level change projections (see BEEMS Technical Report TR403).

This report was primarily concerned with past and present changes. Without this understanding, all attempts to predict future changes are likely to be unreliable.

A central task was to identify the degree of natural beach and nearshore variability on different timescales (monthly, seasonal, annual, decadal, centennial), and to separate short-term fluctuations due to natural environmental variability (which are essentially oscillations around a long-term steady state) from directional erosion or accretion trends. As part of this process, it is important to identify the known extreme conditions which might significantly affect the risk of flooding or affect other operational aspects of the Sizewell power stations (e.g., the lowest or narrowest beach condition, or the minimum sediment volume).

A problem arises from the fact that all aerial photography, LiDAR or ground topographic surveys capture only a ‘snap-shot’ of the beach at the time of survey and the ‘extreme’ conditions and responses may be missed, unless the surveys are undertaken at frequent intervals (e.g., monthly; Smith and Benson, 1997). However, for logistical and economic reasons, surveys at such frequency can rarely be justified. This temporal deficiency in ‘standard’ monitoring techniques can be countered using continuous ground-based remote sensing techniques, such as the radar and video methods being considered for future site monitoring.

4.2 Historical maps

A problem in assessing longer-term shoreline changes from map evidence arises from the fact that most historical Ordnance Survey (OS) maps only showed the levels of mean high water (MHW) and mean low water (MLW), although, OS maps produced on the basis of surveys before 1868 generally showed the position of MHWS, rather than the High Water Mark and Low Water Mark of 'Ordinary' or 'Medium' Tides (taken to be equivalent to MHW and MLW) shown on map editions based on later surveys (Oliver, 1993; Sutherland, 2012). The recommended ground survey procedures used to determine MHWS and MHW varied between surveys. Later published maps often did not include re-surveys of the tidal lines, although other information was updated. From the 1960's onwards, in instances where revisions of the MHW and MLW were undertaken, they were based on aerial photography with limited reference to the exact tidal state and weather conditions at the time of flight. The date of MHW and MLW survey is stated on some, but not all editions of OS Six Inch and 1:2500 scale maps. The MHW and MLW lines are classified by the Ordnance Survey as Category 4 features in terms of priority for revision (Category 1 being the highest, Category 2 no longer being used, and Category 5 the lowest in terms of priority). Category 4 features are not currently programmed for revision in urban, rural or moorland areas, except where affected by changes to features in Categories 1 and 3. The interpretation of historical maps should therefore be undertaken with caution, but if appropriate checks are made, useful information about broad-scale, long-term changes can be obtained.

Table 1 lists a number of historical maps of the Sizewell area from which shorelines have been digitised and used in this study to develop a conceptual model of longer-term coastal evolution.

Table 1: Ordnance Survey maps digitised to extract historical positions of high and low water lines used in this study. Note that the Old Series One Inch maps show High and Low Water Marks of Ordinary Spring Tides (approximately MHWS and MLWS) positions, whereas the County Series Six Inch maps show equivalents MHW and MLW.

Historical Maps	Published	MHW Surveyed	MLW Surveyed
Old Series (One Inch)	1837	1835/36	1835/36
County Series (Six-Inch) First Edition	1883-1884	1881-1883	1881-1883
County Series (Six-Inch) Second Edition	1905	1903	1903
County Series (Six-Inch) Third Edition	1928	1925-1926	1925-1926
National Grid (Six-Inch)	1958	1952-1953	1952-1953
National Grid (1:10,000)	1976-1982	1970-1976	1965-1970

4.3 Aerial photographs

Aerial photography acquired for shoreline management and flood defence purposes is normally specified to be flown at low water of a spring tide, but due to operational constraints, this may not always be achievable, and photographs may be taken at other states of the tide. The 'tide lines' visible on aerial photographs may also be affected by tidal surges (positive or negative) and by wave set-up and wave run-up. In order to minimise such distortions, and to improve image quality, most aerial photography is flown during the summer months, however, this creates a seasonal bias in the data coverage. Any annual monitoring regime will inevitably fail to record the full range of seasonal and shorter-term variability in beach levels.

The quality of aerial photography can also vary greatly, depending on flight height, pixel resolution and light conditions. This has a significant effect on the errors associated with 'tide-line' definitions applied. However, aerial photographs do have a benefit in providing continuous alongshore information, unlike ground surveys along shore-normal transects (i.e., beach profiles). The associated increase in alongshore spatial resolution can aid interpretation along shores like Sizewell's, which exhibit significant spatial variability.

Historical aerial photography was available for the Sizewell area post-1940, whilst annual surveys flown by the EA were available from 1991 (although not all have been rectified / digitised). In addition, intra-annual RPA aerial surveys of the GSB were flown by Cefas as part of the ongoing BEEMS monitoring programme from 2015. Those used in this report to derive digitised tide lines are shown in Table 2.

Table 2: Vertical aerial photography of the Sizewell coast used in this study.

	Flown or commissioned by	Acquired	Orthorectified	Tide lines digitised
08/07/1940	RAF	✓		✓
09/04/1952	RAF	✓		✓
30/04/1965	Meridian Airmaps	✓		✓
14/10/1968	Meridian Airmaps	✓		
07/06/1983	University of Cambridge	✓		✓
1991	EA	✓		
1992	EA	✓	✓	✓
1993	EA			
1994	EA	✓	✓	
1995	EA	✓		
1996	EA	✓		
1997	EA	✓	✓	✓
1998	EA	✓		
1999	EA	✓		
2000	EA	✓		
2001	EA	✓	✓	✓
2002	EA	✓		
2003	EA	✓		
2004	EA	✓		
2005	EA	✓	✓	
2006	EA	✓	✓	✓
2007	EA	✓	✓	
2008	EA	✓	✓	
2009	EA	✓	✓	
2010	EA	✓	✓	
2011	EA	✓	✓	✓
2012	EA	✓	✓	✓
2013	EA	✓	✓	✓
2015	Cefas	✓	✓	✓
2015	EA	✓	✓	✓
2016	Cefas	✓	✓	✓
2016	EA	✓	✓	✓
2017	Cefas	✓	✓	✓
2017	EA	✓	✓	✓
2018	Cefas	✓	✓	✓

4.4 LiDAR

LiDAR data have been available for parts of England and Wales since the late 1990's and at present, there is coverage of approximately 90 % of the country. The horizontal and vertical accuracy of LiDAR varies according to the type of equipment used, the flight height and swath width, the nature of the surface (especially the nature of any vegetation cover), and the nature of any post-collection data processing undertaken. For the purposes of analysing changes in beach profile and contour positions, 0.25 m or higher resolution data are the most useful; errors become increasingly large with 0.5 m, 1.0 m and 2.0 m resolution data. Comparison of 0.25 m data with the results of ground topographic surveys and Ordnance Survey benchmarks has indicated that the vertical accuracy is typically better than +/- 0.1 m and can attain +/- 0.05 m (for flat surfaces with an area greater than the pixel resolution). In this study, EA LiDAR data sets of the power station frontage collected between 1999 – 2017 were used.

4.5 Ground topographic surveys (beach profiles)

Until the 1990's, beach profiles were generally surveyed using a theodolite or total station[1], usually along a limited number of shore-normal transects referenced to temporary bench marks behind the beach. The vertical accuracy of such surveys based on survey closure errors is typically +/ 0.05 to 0.1 m. Since the 1990's, surveys have increasingly been undertaken using global-positioning systems (GPS), either using a fixed base station and mobile receiver or, more recently, combined mobile base station and receivers. The positional accuracy achievable using these systems is typically better than +/- 0.05 m in both the horizontal and vertical dimensions. GPS surveys may be undertaken along fixed shore-normal transects, with measurements recorded at each break of slope or at defining features (e.g., edge of vegetation or ridge crest), at intervals along shore-parallel features (e.g., dune toe, saltmarsh edge or low water mark), or as a multi-point cloud (e.g., the SSMSG surveys are on a 10 x 10 m grid). In many surveys, a combination of the three is employed. Continuous 'on the fly' recording is also possible and is often employed when surveys of large areas are undertaken using a quad bike.

Beach profiles provide no information about shoreline features between transects, meaning that the alongshore extents of shoreline change patterns cannot be easily determined, and localised areas of erosion or accretion may be missed. This problem can be minimised by a detailed multi-point GPS survey, but the accuracy of the profile data derived from the resulting Digital Elevation Models (DEMs) depends on the density and distribution of measurement points. Often this information is not provided by the surveyors and hence the potential errors cannot be assessed. The value of any survey is also dependent on the tidal state at the time of survey, which determines the extent of beach that can be surveyed. Ideally, surveys should always be conducted at low water on a spring tide, but this is frequently not done and many surveys fail to reach below mean sea level (MSL).

4.5.1 EA Anglian Region strategic monitoring

In 1991 the Anglian Region of the National Rivers Authority (NRA) established a strategic shoreline monitoring programme covering the entire east coast between the Humber and the Thames estuaries. Topographic monitoring profile locations were established at approximately 1 km intervals along the coast and have since been monitored twice each year (generally in February or March (post-winter) and September or October (post-summer)). Along this coastline, these strategic profiles have the prefix 'S1'. After the NRA became part of the EA in 1996, additional profile lines, at closer spacing, were added in specific areas of rapid change and where sea defence schemes were being planned. Extra profiles have been surveyed since 2009 along the Minsmere frontage (prefix 'M'), at Walberswick and Sizewell (prefix 'SO') and at Thorpeness (profiles S1B8_A to A1B8_I). Due to their short time span, these additional profiles have not been used in this study, but they will prove useful in future studies, once the timespan exceeds the period of short-term variability. Table 3 lists the topographic surveys which have been used in the present study.

Since 2016, the EA profile naming convention has been changed, giving each profile location a new number with the prefix 'SO' – the old and new names of the profiles used here are presented in Table 4.

[1] A total station is a theodolite with an electronic distance meter, which utilises a microwave or infra-red carrier signal and prism reflectors.

Table 3: Beach topographic surveys by the NRA / EA in the period 1991 – 2018. Numbers indicate the number of surveys conducted in that year, and shading indicates the data used for calculation of beach contour and sediment volume change.

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
S1C5	1	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
S1C6	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
SO39A																				2	1	1						
SO39B																				2	1	1						
SO39C																				2	1	1						
S1C7	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
SO40A																				2	1	1						
SO40B																				2	1	1						
SO40C																				2	1	1						
S1B1	1	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
M1																			1	2	2	1	2	1				
M2																			1	2	2	1	2	1				
S1B1A												1	1	1	1	1	1	2	1	2	2	1						
M3																			1	2	2	1	2	1				
M4																			1	2	2	1	2	1				
M5																			1	2	2	1	2	2	2	2		
M6																			1	2	2	1	2	1				
M7																			1	2	2	1	2	1				
M8																			1	2	2	1	2	1				
M9																			1	2	2	1	2	1				
M10																			1	2	2	1	2	1	2	2		
M11																			1	2	2	1	2	1				
M12																			1	2	2	1	2	1				
M13																			1	2	2	1	2	1				
S1B2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	1
M14																			1	2	2	1	2	1				
M15																			1	2	2	1	2	1				
M16																			1	2	2	1	2	1				
M17																			1	2	2	1	2	1				
M18																			1	2	2	1	2	1				
M19																			1	2	1	1	2	2	2	2		
M20																			1	2	2	1	2	1				
M21																			1	2	2	1	2	1				
M22																			1	2	2	1	2	1				
M23																			1	2	2	1	2	2	2	2		
M24																			1	2	2	1	2	1				
M25																			1	2	2	1	2	1				
M26																			1	2	2	1	2	1				
S1B2A												1	1	1	1	1	1	2	1	2	2	1						
M27																			1	2	2	1	2	1				
S1B2B												1	1	1	1	1	1	2	1	2	2	1						
M28																			1	2	2	1	2	2	2	2		
S1B3	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
M29																			1	2	2	1	2	1				
M30																			1	2	2	1	2	1				
M31																			1	2	2	1	2	1				
S1B4	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
M32																			1	2	2	1						
M33																			1	2	2	1						
S1B4A												1	1	1	1	1	1	2	1	2	2	1						
S1B5	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
SO45A																				2	1	1						
SO45B																				2	1	1						
SO45C																				2	1	1						
SO45D																				2	1	1						
S1B6	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
SO46A																				2	1	1						
SO46B																				2	2	1						
SO46C																				2	2	1						
S1B7	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
SO47A																				2	2	1						
SO47B																				2	2	1						
SO47C																				2	2	1						
S1B8	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	6	2	2	2	2	2	1
S1B8_A																			2	2	2	1						
S1B8_B																			2	2	2	1						
S1B8_C																			2	2	2	1						
S1B8_D																			2	2	2	1						
S1B8_E																			2	2	2	1						
S1B8_F																			2	2	2	1						
S1B8_G																			2	2	2	1						
S1B8_H																			2	2	2	1						
S1B8_I																			2	2	2	1						
S1A1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2	7	2	2	2	2	2	1

Table 4: EA profile names as updated since the BEEMS Technical Report TR223 report, second edition (2014).

2014 Profile name	2018 Updated profile name
S1C5	SO27
S1C6	SO28
S1C7	SO29
S1B1	SO30
S1B2	SO31
S1B3	SO32
S1B4	SO33
S1B5	SO34
S1B6	SO35
S1B7	SO36
S1B8	SO37
S1A1	SO38

4.5.2 Sizewell power stations beach monitoring

The Sizewell shore has been monitored by the power station operating companies at least since 1985 (Mouchel, 1996). A total of 17 cross-shore profiles (P1 to P17) were established in early 1985 on behalf of the CEGB by Clyde Surveying Services Limited (now part of the Halcrow Group) and monitored at least twice a year until 1988 (Table 5). Initial survey height measurements were made at the back of the beach and at 20 m intervals down to the low water mark, which varied throughout the period of each survey (Clyde Surveying Services Ltd, 1985). Some of the early surveys were carried out at higher resolution, with additional height measurements made at visible breaks of slope. Monitoring by Clyde Surveys continued until January 1988. From August 1988 onwards, monitoring surveys were undertaken by the civil engineering departments of National Power and Nuclear Electric. These surveys generally made height measurements at visible breaks of slope between the reference posts and the low water line. In September 1989, three further locations were added, stations 9B, 11A and 12A.

Scanned paper copies of the survey reports for the period February 1985 – January 1994 were provided for examination in this study. Cross-shore position data for the beach contour elevations selected in this study (3.0, 2.0, 1.06 and 0.13 m OD) were read off the scanned paper copies of the cross-shore profiles. A spread sheet was also provided by Prof. J Pethick containing a summary of profile height data for the period May 1993 – August 2006, during which period the beaches were surveyed annually in the summer. Some of these data also appear to have been extracted from plotted cross-shore profiles. Table 5 provides a summary of the Sizewell beach profile data used in this study.

In December 2006, the SSMSG beach monitoring was contracted to Halcrow and methodology changed to multi-point RTK GPS surveys. Additionally, monthly GPS surveys were undertaken between December 2006 – November 2007 in connection to the shut down and decommissioning of SZA. There was one survey in 2008 and since 2009 two surveys per year, generally in February and September (Table 6). Halcrow have produced DEMs based on several of the surveys (August 2008, September 2009, November 2011, February 2012 and October 2012), and extracted cross-shore profiles at the original profile locations (P1 to P17, of which, P4 to P13 are reported in Section 6.1.2.3). For the remaining Halcrow surveys (August 2007, February 2010, September 2010 and February 2011), the original 'xyz' survey data were used in this study to construct new DEMs using kriging interpolation and to extract cross-shore profiles. February 2011 is the last profile for which this processing was necessary, as Geosphere 4D took over surveying when Halcrow was acquired by CH2M in 2011, and cross-shore profiles have been provided at the original profile locations since February 2012. To assess changes along the Sizewell frontage, based on these DEMs, eight additional profiles were inserted between profiles along the Sizewell Power Station frontage (P4 to P13, using a lettered suffix "A" or "B") to provide greater spatial resolution (100 m spacings), giving a total of 18 beach transects in all covering the period December 2006 – September 2017.

4.5.3 Combined beach topographic datasets

From the discussion in Sections 4.5.1 and 4.5.2, three separate Dunwich to Thorpeness beach survey datasets, covering overlapping but different time periods, may be identified:

1) 20 SSMSG profiles (P1 to P17, plus 9B, 11A and 12A) surveyed 1985 – 2017;

2) 19 SSMSG (P1 to P17 digital data) and 12 EA profiles (S1C5 to S1A1) surveyed between at least 1991 – 2018; and

3) 18 SSMSG profiles (P4 to P13) extrapolated from beach DEMs at 100 m intervals, surveyed 2006 – 2017

The epochs 1 through 3 provided increasing spatial resolution, at the expense of a shorter time-period. The cross-shore sampling interval was coarse (20 m) in the earliest surveys (1985 – 1988), whilst some SSMSG surveys failed to survey down to MSL. Nevertheless, despite the differences in sampling methods, it is considered appropriate to combine the data into these three datasets, thereby increasing the temporal coverage to 33 years and allowing a detailed interpretation of the shoreline response over almost three decades, which includes the construction phase of SZB and the decommissioning phase of SZA.

4.6 Bathymetric surveys

As part of the NRA / EA Anglian Region Strategic Monitoring Programme, single beam echo sounder bathymetric surveys were carried out at approximately five yearly intervals since 1992. The survey lines were oriented perpendicular to the shore at each of the beach topographic monitoring locations, spaced at approximately 1 km intervals. The bathymetric profile lines extend approximately 3 km offshore. Survey data for 1992, 1997, 2002, 2007, 2014 and 2017 were provided for analysis in this study to give information about the linkages between the nearshore bars and the subaerial beach morphology.

Single beam and multibeam swath bathymetric surveys were also carried out in 2007, 2008, 2009 and 2011 as part of the BEEMS programme. Data from the last of these surveys extends relatively close inshore along the Sizewell power stations frontage to provide information about the size and position of the nearshore bars.

A number of earlier bathymetric surveys of the nearshore area around Sizewell were undertaken during and shortly after construction of SZB. The original survey data were not available for analysis in this study, but reference has been made to bathymetric maps contained in previous reports and the Sizewell Bathymetry Atlas (CCRU, 1996; Pethick, 1998b; Pye and Blott, 2005; BEEMS Technical Reports TR058 andTR223 first edition (2012)).

Table 5: Beach topographic surveys of the Sizewell frontage commissioned by Nuclear Electric and SSMSG in the period 1985-2017, provided for analysis in this report. ‘g’ indicates that data exist as graphical plots, with survey points at 20 m intervals across the beach; ‘G’ indicates that data exist as graphical plots, with survey points at higher resolution, including breaks in slope; ‘D’ indicates that data has been supplied in digital form, although itself possibly derived from graphical plots. Light grey shading indicates that surveys have been used to measure beach contour movement. Dark grey shading indicates that surveys have been used to measure beach volumes and beach contour movement.

	Feb-Mar 1985	Jul 1985	Feb 1986	Jul 1986	Feb 1987	Jul 1987	Jan 1988	Aug 1988	Feb-Mar 1989	Apr 1989	Jul 1989	Sep 1989	Nov 1989	Feb 1990	Apr 1990	Sep 1990	Feb 1991	May 1991	Nov 1991	Mar 1992	Jun 1992	Nov 1992	May 1993	Aug 1993	Jan 1994	Apr 1995	May 1996	May 1997	Jun 1998	Jun 1999	Jul 2000	Aug 2001	Aug 2002	Jul 2003	Jun 2004	Jul 2005	Aug 2006	Aug 2008	Sept 2009	Feb 2010	Sept 2010	Feb 2011	Nov 2011	Feb 2012	Oct 2013	Feb 2014	Sept 2014	Feb 2015	Sept 2015	Feb 2016	Feb 2017	Sept 2017
P1	g	G	g	g	g	g	g	G	G		G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P2	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P3	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P4	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P5	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D		D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P6	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D		D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P7	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P8	g	G	g	g	g	g	g	G															D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P9	g	G	g	g	g	g	g																D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P9A								G																																												
P9B										G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P10	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P11	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D		D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P11A										G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G																									
P12	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P12A										G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P13	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D		D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P14	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P15	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P16	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
P17	g	G	g	g	g	g	g	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

Table 6: Beach topographic surveys of the Sizewell frontage commissioned by the SSMSG in the period 2006-2017. Area-wide RTK GPS surveys were conducted, and beach profiles interpolated from the resulting digital elevation models. Shading indicates the data provided for use in this project. Note that profiles from the surveys in Aug-2007, Feb-2010, Sept-2010 and Feb-2011 were not supplied but have been interpolated as part of this study. The February 2012 survey (marked in red) was discovered to have some errors after the analysis for this report was conducted. As this report focuses on end point rates that are unaffected, these errors do not affect the results presented in this report.

	Dec-2006	Jan-2007	Feb 1986	Mar-2007	Apr-2007	May-2007	Jun-2007	Jul-2007	Aug-2007	Sep-2007	Oct-2007	Nov-2007	Aug-2008	Sep-2009	Feb-2011	Nov-2011	Feb-2012	Oct-2012	Mar-2013	Oct-2013	Feb-2014	Sep-2014	Feb-2015	Feb-2016	Feb-2017	Sep-2017
Digital Elevation model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Interpolated beach profiles												✓	✓				✓	✓								

5 Data analysis methods

5.1 Shoreline change analysis based on EA and SSMSG topographic survey data

EA beach topographic survey data for all profiles between Dunwich and Thorpeness (EA profiles S1C5 to S1A1) were imported into Microsoft Excel and bench mark positions checked to ensure comparability between survey dates. Visual Basic macros were written to interpolate the x, y position on each profile of selected elevations, including estimated tidal levels for Sizewell (Table 7).

Table 7: Tidal and other levels used to quantify changes in beach contour position and sediment volumes.

Tidal Level	Level (m ODN)	Beach contours 1836-2017	Beach contours 1940-2017	Beach Contours 1992-2017	Beach volumes 1992-2017	Nearshore volumes 1992-2017
Limit of permanent vegetation (LPV)	3.00		✓	✓	✓	
High wave run-up 9HWRU)	2.00		✓	✓	✓	
Highest astronomical tide (HAT)	1.55			✓		
Mean High Water Springs (MHWS)	1.22					
Mean High Water (MHW)	1.06	✓	✓	✓	✓	
Mean High Water Neaps (MHWN)	0.93					
Mean Sea Level (MSL)	0.13		✓	✓	✓	
Mean Low Water Neaps (MLWN)	-0.65					
Mean Low Water (MLW)	-0.86			✓		
Mean Low Water Springs (MLWS)	-1.09					
Lowest Astronomical Tide (LAT)	-1.54					
Crest of landward nearshore bar	~ -1.00 to -2.00					
Crest of seaward nearshore bar	~ -3.00 to -4.00					
Lower limit of volume calculations	-6.00					✓

Up to six beach contour levels were selected for detailed analysis: 3.00 m, 2.00 m, 1.55 m, 1.06 m, 0.13 m, and -0.86 m OD, the relevance of each is described below.

The 3.00 m contour corresponds approximately with the dune toe at the back of the backshore and, where present, the seaward edge of vegetated shingle. The sediments at this level are only mobilized by wave action during severe storms with a significant surge component.

The 2.00 m contour was chosen partly to allow direct comparison with trends reported in the SSMSG Annual Monitoring Reports, which have only considered changes in the 0.00 m and 2.00 m OD beach contours, taken to approximate the 'low tide' and 'high tide' levels, respectively (Pethick, 2012). The 2.00 m OD contour actually lies well above HAT and corresponds approximately with the level of the 1 in 1 year still water level resulting from astronomical tide and surge interaction (BEEMS Technical Report TR139), and the 0.00 m contour is effectively the MSL contour, not MLW.

A larger number of beach contours were considered in this study in order to provide a more detailed understanding of changes in cross-shore beach morphology and to allow assessment of changes in sediment volume between different levels on the beach. The MHW and MLW contours were chosen because these are shown on historical OS maps. MSL was selected because this level on the beach is reached by the majority, although by no means all, of the topographic surveys. Of the SSMSG surveys, a total of 107 surveys over the period 1985 – 2017 (approximately 11 %) failed to reach the MSL contour, presumably due to rising water levels and the large/dense survey area covered during the period of survey. By contrast, only 5 of the EA surveys in the period 1991 – 2018 failed to reach MSL (S1B1 and S1A1 in winter 1995, S1B4 and S1B5 in winter 1996, and S1A1 in winter 2005), representing less than 1 % of all surveys.

For purposes of illustration, Figure 3 shows the selected beach contour and tidal levels superimposed on three beach cross-sectional profiles for EA profile location S1B5 and the adjacent SSMSG Profile 7, surveyed using different methods between January and August 2008.

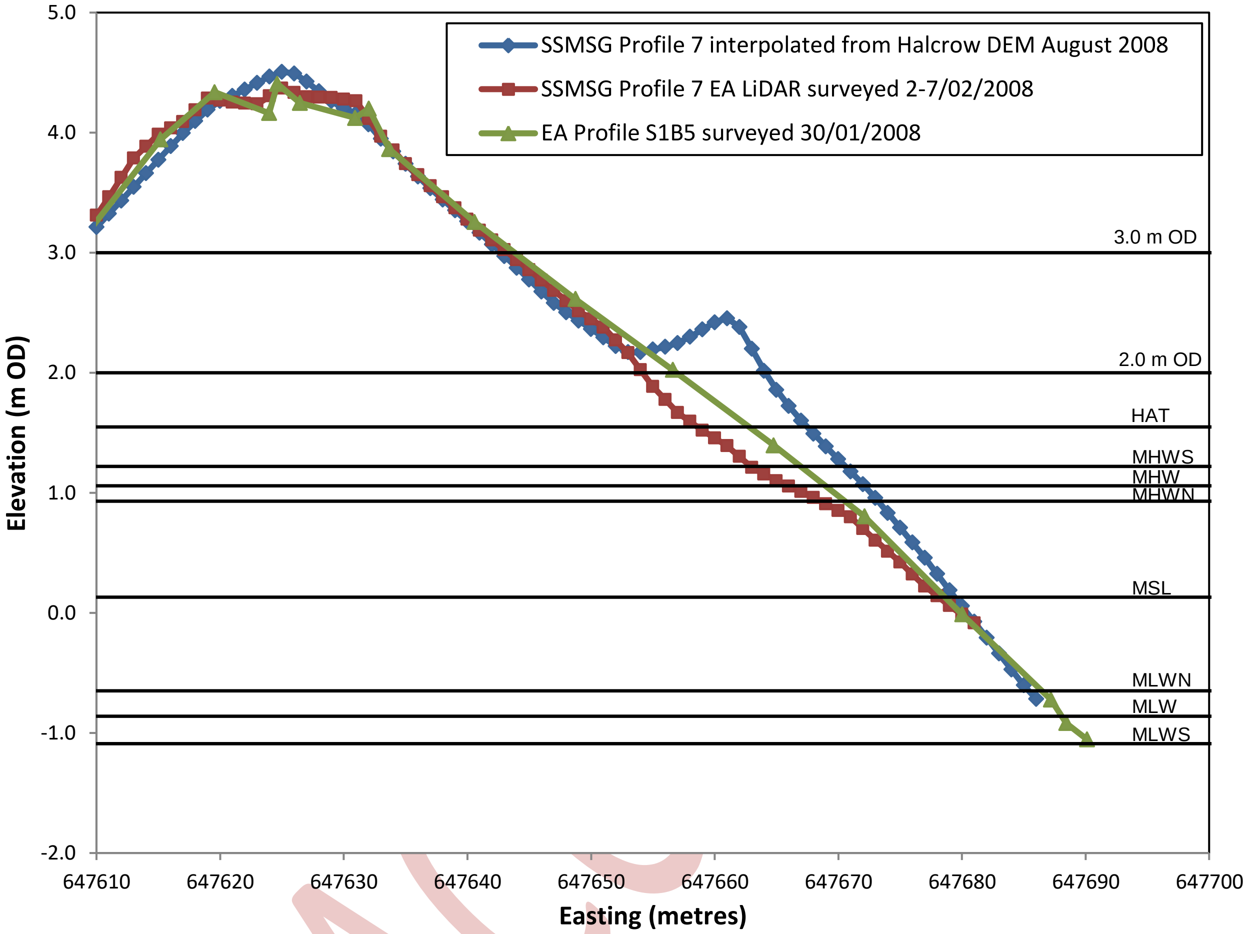

Figure 3: Beach cross-sectional morphology on the northern Power Station frontage at SSMSG Profile 7 and EA Profile S1B5, located 14.6 m further north, indicated by surveys at three different times in 2008. Also shown are the main tidal and beach contour levels referred to in this report.

As discussed in Section 4.5.2, three combined datasets of beach profiles were identified, covering three time periods. For detailed analysis of alongshore variation, it was decided that dataset (2), with 31 profiles covering the period 1991 – 2018 offered the best compromise of temporal and spatial resolution. The slightly longer dataset (1), contained just 17 profiles, whilst dataset (3) contained profiles at 100 m intervals, but only for the power station frontage and beginning in 2006. The movement of six beach contours (3.00, 2.00, 1.55, 1.06, 0.13 and -0.86 m OD) was analysed on 31 profiles (19 SSMSG profiles and 12 EA profiles) covering the period 1993 – 2017 (SSMSG profiles) and 1991 – 2018 (EA profiles).

Four parameters were determined:

- The envelope of beach contour variation (Shoreline Change Envelope, SCE), which defines the most landward and most seaward positions of each contour, along each beach profile transect, during the survey period. The SCE captures the magnitude of positional variability that could result from a beach that has a persistent and strong erosion or accretion trend, or a beach that is highly changeable, oscillating back and forth over large distances without necessarily having a directional trend. When used with net change, the envelope can distinguish beaches which are essentially in condition of fluctuating steady state from those with strong directional trends.
- The net change in position of each beach contour relative to the first baseline year common to both the EA and SSMSG surveys (1993).
- The end point rate of net change (EPR) determined from the 1993 to the last (2017 and 2018) contour positions. This method is adopted by Prof. J Pethick in the SSMSG Annual Monitoring reports. The start of monitoring was 1991 in the case of the EA profiles and 1993 in the case of the SSMSG profiles.
- The directional trend and rate of change of shoreline change determined using linear regression analysis of the contour positions for all surveys between 1993 and 2017/18 (referred to as the linear regression rate of change, LRR).

Changes in the position of each contour over time were also plotted for each profile as time series graphs and superimposed on orthorectified aerial photographs flown in 2011, in order to illustrate alongshore variation in beach contour trends. Inspection of these graphs indicated that some profiles have experienced periods of progradation followed by erosion, or vice versa, over the monitoring period. In such cases, neither the EPR nor the LRR provided a complete picture of the changes which have taken place, hence the inclusion of time-series plots.

5.2 Changes in beach and nearshore sediment volume from EA and SSMSG survey data

Changes in beach sediment volume above selected contour levels were determined from the cross-sectional area of the beach seaward of one of two selected baseline positions (as described in Figure 4): (a) the position of the 3.00 m contour at the time of survey, and (b) the most landward position of the 3.00 m contour observed since 1991 (in the case of the EA data) or 1993 (in the case of the SSMSG data). Sediment volumes at each profile location were determined by multiplying the beach cross-sectional area by one metre width of beach. The first method provides information about changes in the sediment volume of the beach only, as it (and the 3.00 m OD contour at the back of the beach) moves landwards or seawards, whilst the second method provides information about overall changes in sediment volume (found in both beach and dunes) relative to the baseline position of the 3.00 m OD contour since 1991/93.

Nearshore sediment volumes were also calculated for those years where EA survey data were available for both the subaerial and subtidal parts of the beach. The SSMSG profiles were not used for nearshore sediment volume calculations, since they only measure part of the subaerial beach system and can be misleading and difficult to correctly interpret. This follows BEEMS Scientific Advisory Report Series SARS018, which cautioned against using these data for nearshore sediment volume calculations due to the absence of the lower intertidal and subtidal beach.

5.3 Patterns in erosion and accretion

Short-term patterns in erosion and accretion were identified through the comparison of LiDAR and orthorectified aerial photography datasets at the annual and decadal resolution for the period 1999 – 2007. Short-term fluctuations in shoreline position (e.g., storms, seasons) can introduce uncertainty into monitoring programs that only sample at longer intervals. High frequency data can increase confidence in the longer-term signal, thereby compensating for the potential bias or aliasing in annual datasets. Accordingly, successive SSMSG, RPA and LiDAR datasets were also used to identify patterns in erosion and accretion at the intra-annual (monthly) and seasonal resolution along to the Sizewell power station frontage (2007 – 2018).

All of these datasets provide elevation data across the beach face – SSMSG surveys were on a 10 x 10 m grid, LiDAR data had variable resolution between 0.5 and 2 m, and RPA data had a resolution of 0.03 m. A detailed comparative assessment of the three different survey methods is being undertaken separately (BEEMS Scientific Position Paper SPP086), however for the purposes of this study, comparison of these different datasets at the 1 m spatial resolution was considered valid. For this analysis, where data was available, changes in erosion and accretion were calculated through the comparison of beach elevation data, constrained to the area between the most westerly 3.0 m OD contour and the most easterly 0.13 m OD contour for any given northing.

5.4 Beach contour mapping from aerial photographs

The (x, y) co-ordinates corresponding to the position of each beach contour elevation (3.00, 2.00, 1.55, 1.06, 0.13, and -0.86 m OD) on each profile were superimposed as points on orthorectified aerial photographs flown during the summer period of the same year (for the years 1992, 1997, 2001, 2006, 2011 and 2016). The points were then joined by interpolated lines using tide line and EGA of beach morphological features visible on the aerial photographs (Figure 5). The digitised beach contour lines were then exported for analysis using the ArcGIS and DSAS (see Section 5.7).

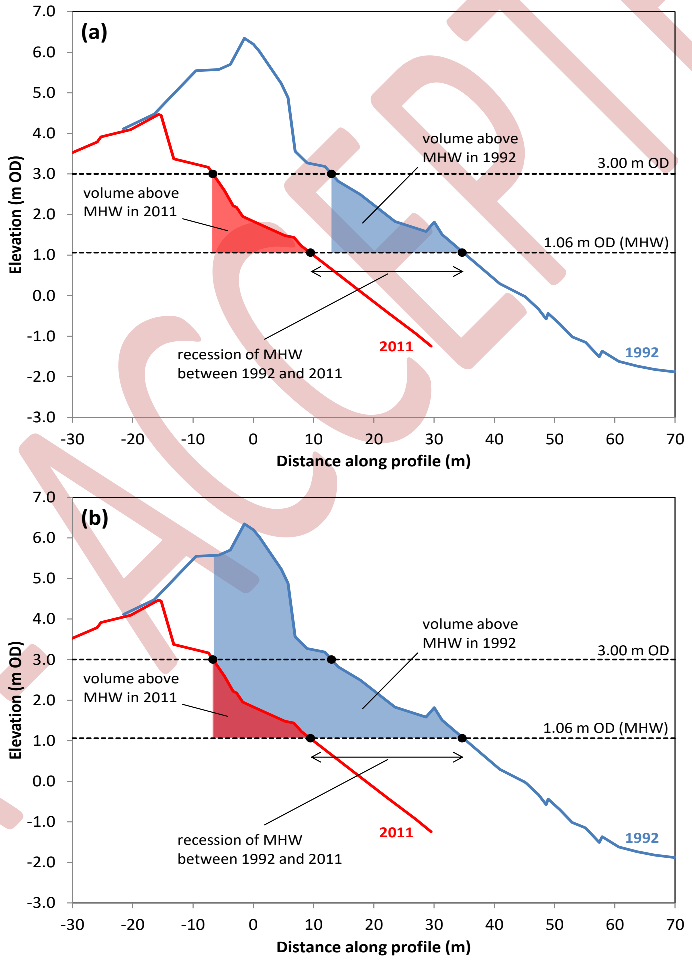

Figure 4: Definition sketches showing method of calculation of beach volume and contour changes based on combined topographic and bathymetric profile data. (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey; (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period 1991 – 2018 or 1993 – 2017 (depending on the dataset being analysed). The example shown is for EA profile S1B4 surveyed in summer 1992 and summer 2011. Similar calculations were made for the 3.0, 2.0 and 0.13 m OD contours.

The positions of the 3.00, 2.00, 1.06 and 0.13 m, OD contours were estimated by interpretation of historical aerial photographs taken in 1940, 1952, 1965 and 1983 (Table 2). Prior to analysis, the photographs were geo-referenced using readily identifiable control points and then combined into a single mosaic. The positions of the beach contours were estimated based on beach width, tide lines and morphological features visible on the photographs. For example, the 1.06 m OD contour (MHW) is often recognised as a tonal contrast between the wetter intertidal beach and the drier supratidal beach (Ruggiero *et al.*, 2007). The July 1985 Sizewell topographic survey was used to cross-check the beach contours identified by interpretation of the 1983 aerial photographs, but no ground survey data were available for comparison with the contours derived from interpretation of the earlier aerial photographs. The errors in upper beach contour position estimated from the pre-1991 aerial photographs are likely to be greater than those for the years after 1991, but are estimated to be smaller than +/- 5 m. This is because earlier aerial photographs were geo-referenced with a small number of points, whereas from 1991, images were orthorectified from film and using ground topography based on LiDAR.

Graphs showing changes in beach contour positions over the period 1940 – 2018 have been plotted on the 2011 aerial photographs to illustrate the alongshore pattern of temporal changes in beach contour movements. The digitised beach contours derived from the photographs were also exported for further analysis using DSAS (see Section 5.7).

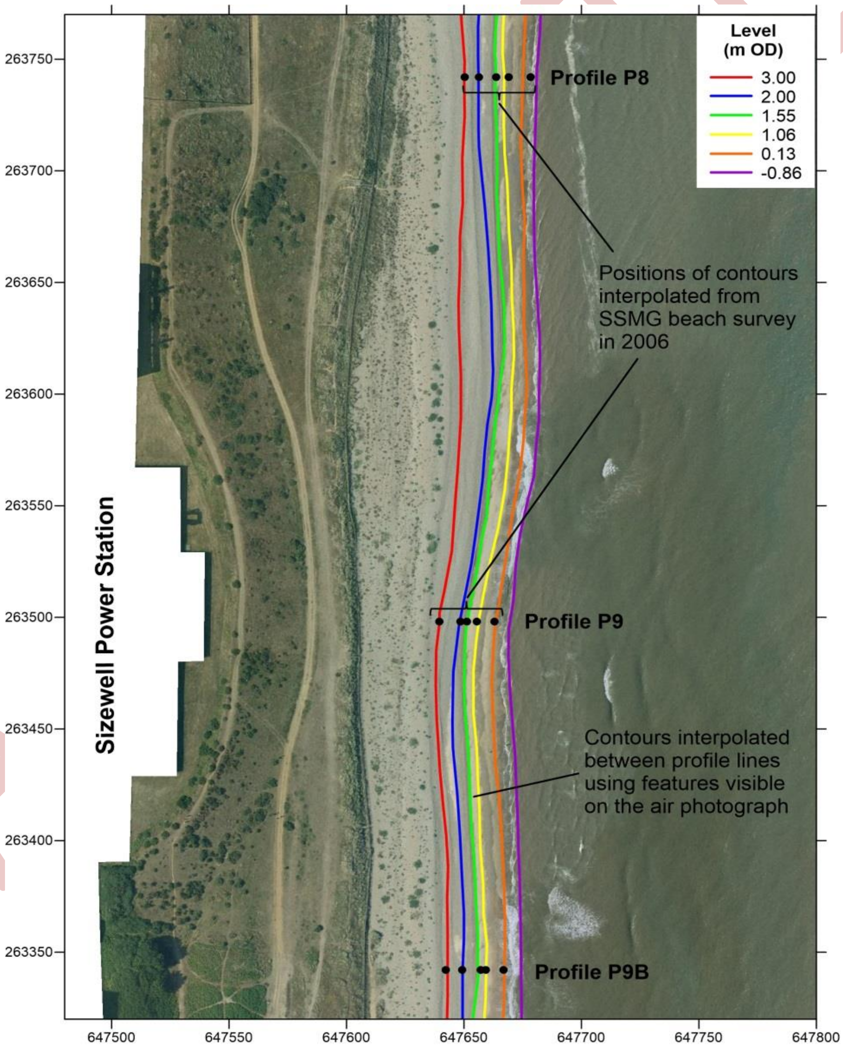

Figure 5: Example of the method used to interpolate beach contour lines using a combination of beach profile data and aerial photographs. The image shows the Sizewell frontage in 2006, with contour positions extracted from beach profile surveys in August 2006. Estimated contour lines have been drawn linking the spot heights using morphological features visible on the aerial photograph.

5.5 Shoreline change analysis from historical maps

Ordnance Survey maps based on surveys in 1835, 1890, 1905 and 1925 were geo-referenced and the positions of the MHW and MLW mark digitised at alongshore intervals of approximately 5 m. In the case of the 1835 One Inch map, the high and low water marks shown correspond approximately with MHWS and MLWS rather than MHW and MLW, as shown on the later Six-Inch County Series maps. However, the lateral distance between the MHW and MHWS tide lines on the modern beach at Sizewell is less than 2 m, and hence the additional error arising from comparison of the 1835 MHWS beach contour with the MHW contour of later surveys is considered to be minor compared with other potential sources of error. These include errors associated with the original surveys, the partial nature of some re-surveys, inconsistencies in cartographic presentation, and inaccuracies associated with digitization, rectification and measurement (Oliver, 1993; Sutherland, 2012). Original survey accuracy is difficult to quantify, but the accuracy associated with map rectification, digitization and measurement is estimated to be better than +/- 3 m in the case of the OS Six-Inch County Series maps and of the order of +/- 5 m in the case of the One-Inch map first edition.

The MHW and MLW positions shown on successive map editions were plotted on the 2011 aerial photographs and measurements made of changes in contour position, relative to the estimated 1835 contour position, at each topographic profile location. The digitised beach contour lines obtained from the historical aerial photographs and maps were also exported for further analysis in DSAS.

5.6 Analysis of EA bathymetric 'long profile' and BEEMS swath bathymetry data

EA 'long profile' bathymetric data for the years 1992, 1997, 2002 and 2007, and swath bathymetry data obtained in 2011, 2014 and 2017 were combined with the beach topographic survey data to provide integrated beach and nearshore profiles at each of the EA profile locations. These results were then used to analyse and interpret variability in the longshore bar and beach volumes.

The volumes of sediment above the -6.00 m OD contour, between -6.00 and 0.13 m OD, and above the 0.13 m OD were then calculated on the basis of the cross-sectional area seaward of the 3.0 m OD contour at the time of survey. As the 2011 swath bathymetry survey did not extend sufficiently close inshore to join up with the subaerial beach surveys, the sea bed elevation between the seaward end of the topographic survey lines and landward end of the swath bathymetry survey was estimated based on examination of the 2007 EA long profile surveys. A judgement was made that less error would arise by making an estimate of the position and height of the inner nearshore bar, rather than by making a linear interpolation. Nevertheless, the sediment volume estimates for 2011 will have a larger error than those for earlier years.

BEEMS swath bathymetry data collected in 2011 were combined with LiDAR data for the subaerial beach flown in 2008 and used to create a bathymetric DEM of the entire Sizewell nearshore frontage. Visual comparison was then made with earlier bathymetric data contained in the Sizewell Bathymetry Atlas (CCRU, 1995) and earlier reports (Pethick, 1998b; Pye and Blott, 2005; BEEMS Technical Report TR058).

5.7 Shoreline analysis and interpretation of beach contour changes

Similar to the method described in Section 5.1, the ArcGIS software extension, DSAS, developed by Thieler *et al*. (2009), was used to determine shoreline change statistics along the GSB at 50 m (northing) intervals. This method requires a pre-determined baseline that mimics the general shape of the coast and a time-series of shorelines as noted above. DSAS finds the intersections of each shoreline with the 50 m spaced shore-normal transects (Figure 6) and calculates the time-series and rate-of-change statistics associated with the shoreline movement along each transect.

Three shoreline change statistics were calculated per transect. These included (as described in Section 5.1):

- SCE, defined as the distance between the two shorelines farthest from and closest to the baseline, regardless of when they occurred (see Figure 7);
- LRR, defined as the rate of change determined by linear regression and used because it incorporates all of the shoreline data to describe the rate of change (Figure 8); and
- LRR trend strength (r^2), defined as the coefficient of determination, r^2, and is the percentage of variance in the data that is explained by the regression, i.e., the r^2 accounts for how well the regression fits the data, with higher r^2 values indicative of a more persistent trend in the rate of shoreline change described by the LRR (see Figure 8).

Additionally, a time series of shoreline intersection distances for each transect and each contour elevation was extracted, to aid the interpretation of temporal variability underlying the shoreline statistics.

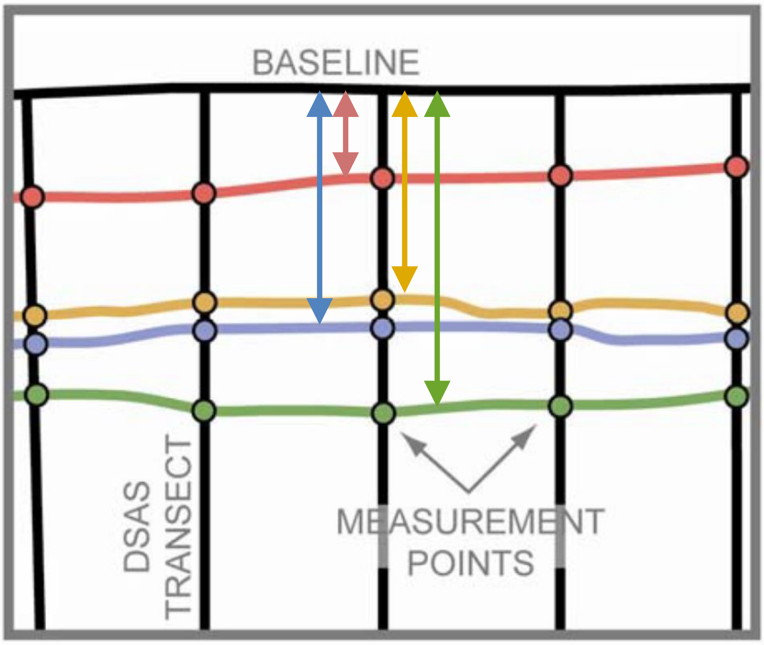

Figure 6: Example of shorelines (coloured lines) and the locations where they intersect cross-shore transects (50 m spacing used in this report). For each transect, the distances of each shoreline from baseline (matching coloured arrows) are used to calculate the shoreline change envelope, rate of change and r2 statistics. (Adapted from Thieler et al., 2009).

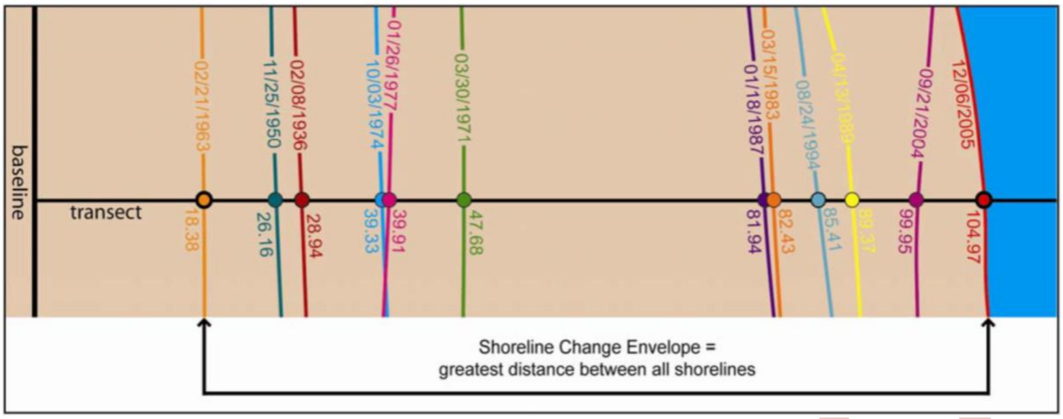

Figure 7: Example of shorelines (coloured lines) intersecting a transect and graphical illustration of the Shoreline Change Envelope statistic (Source: Thieler *et a*l, 2009).

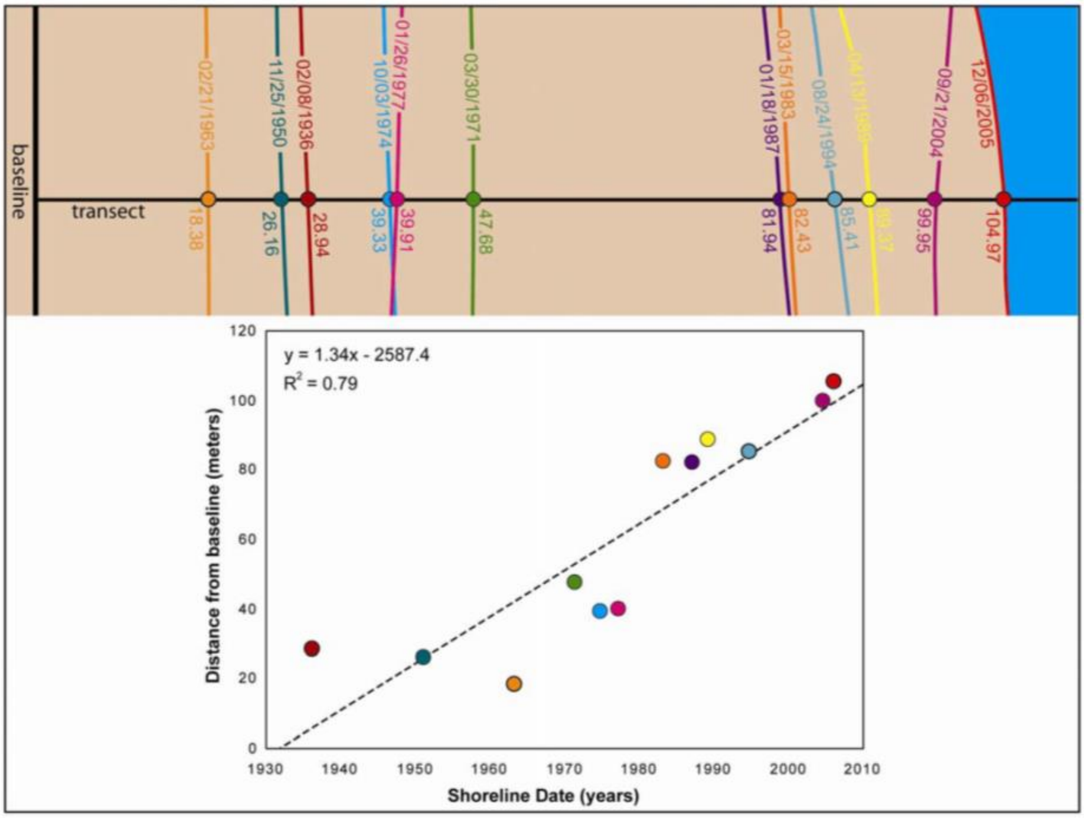

Figure 8: Example of shorelines (coloured lines) intersecting a transect (top panel) and a graph of the corresponding distance from the baseline to each shoreline plotted against time (bottom panel). The Linear Regression Rate (LRR) of change statistic (dashed line) and the coefficient of determination (r2) are calculated from the time-series of shoreline positions. (Source: Thieler et al., 2009).

6 Shoreline analysis results

Change in beach volume and contour positions were assessed using all available beach profile, LiDAR, aerial photography and historical chart datasets. As described previously, short-, medium- and long-term data sets were analysed separately. Short-term changes (1985 – 2018) based on topographic, bathymetric and LiDAR surveys and orthorectified aerial photography are presented in Section 6.1; medium-term changes (1940 – 2016) based on topographic surveys and orthorectified aerial photography are presented in Section 6.2; and long-term changes (1835 – 2017) based on historical maps, topographic surveys and orthorectified aerial photography are presented in Section 6.3.

6.1 Short-term changes, based on topographic, bathymetric and LiDAR surveys and orthorectified aerial photography (1985 – 2018)

For the three short-term datasets described in Section 4.5.2, both EA and SSMSG data were used to obtain the envelopes and rates of beach contour change in Section 6.1.1. Thereafter, as the data sets are not exactly comparable, the analysis of beach shape, volume and nearshore morphology are presented separately for each dataset in Sections 6.1.2., 6.1.3 – 6.1.4 and 6.1.5 respectively.

6.1.1 Short-term changes in beach contour envelope and rates of change, based on topographic surveys (1991 – 2018)

6.1.1.1 Beach contour change envelope

The envelopes of maximum positional variability for the 3.00, 2.00, 1.06 and 0.13 m OD beach contours between 1991 – 2018 (in the case of the EA data), and between 1993 – 2017 (in the case of the SSMSG data), are shown in Figure 9 to Figure 12. Note that the SSMSG profile data have been omitted from the analysis of the 0.13 m OD contour because many surveys fail to reach this level and consequently it is likely that the maximum and minimum contour positions are not captured in the dataset.

The largest envelopes of change in the 0.13 m OD contour (Figure 9) occur near the southern end of Minsmere Cliffs (S1B1) and near Minsmere Sluice (S1B3), while the smallest envelopes of change occur along Dunwich Cliffs (S1C6 and S1C7) and in front of the Sizewell power stations, Sizewell Gap and Sizewell Hall (S1B5 to S1B7).

The envelopes of change for the 1.06 m OD and 2.0 m OD contours (Figure 10 and Figure 11) also show a narrow envelope of change at Dunwich (S1C6 and S1C7) and south of Sizewell (S1B6 and S1B7) but large envelopes of change in front of SZA and SZB power stations due to development of a salient (profiles P8 and P9; see Section 6.1.3 and Section 7.4.1, at the northern end of the Minsmere barrier (S1B1 and S1B2), and at Thorpeness (S1A1).

The envelope for the 3.0 m OD contour (Figure 12), which is determined by storm waves combined with surges, also shows significant change in front of SZA and SZB (P8 and P9), but a lower degree of change along the northern Minsmere frontage (S1B1, S1B2) than that indicated by the 0.13 and 1.06 m OD contours. This reflects the stabilizing influence of man-made sea defences behind the beach in the Minsmere area.

6.1.1.2 Beach contour rates of change

Variations alongshore in the rate of change of each contour between the first and last surveys ('end-point analysis') are shown in Figure 13 to Figure 16. The SSMSG profile data are included in the analysis of the 0.13 m OD contour (substituting 1994 data for 1993 in the very few cases where the profiles did not reach this level). The 0.13 m OD contour shows a net seaward movement between 1991 – 2018 north of Dunwich, around Minsmere Sluice, in front of Sizewell 'B' power station and between Sizewell Gap and Thorpeness, but net landward movement between Dunwich Cliffs and Minsmere Sluice, between SZB and the Sluice, and around SZA power station and Sizewell Gap (Figure 13). A similar pattern is shown by the 1.06, 2.0 and 3.0 m OD contours (Figure 14 to Figure 16).

The average rates of seaward or landward movement of each of the beach contours between 1993 – 2017 (SSMSG) and 1993 – 2018 (EA) indicated by end point analysis are shown in Table 8, while those indicated by linear regression are shown in Table 9. The regression method is considered to be more robust because it takes into account all of the survey data and is less influenced by potentially unusual conditions in the first or last survey years. However, the broad spatial patterns indicated by the two methods are the same.

The main trends over the 1991 – 2018 period emerging from this analysis were:

- seaward movement of all beach contours (accretion) at the southern end of the Walberswick–Dunwich coast (profile S1C5);
- relative stability of the cliff toe and 3.0 m contour, but landward movement of the other beach contours, resulting in beach steepening, along the Dunwich cliffs to Minsmere cliffs frontage;
- landward movement of all beach contours (erosion) between Minsmere cliffs and the former Coney Hill, north of Minsmere Sluice;
- seaward movement of all elevation contours (i.e., accretion of the whole beach), especially between 2006-2012, at S1B3, 100 m south of Minsmere Sluice;
- landward movement of all beach contours (erosion) to the south of Minsmere Sluice and to the north of the proposed SZC site;
- seaward movement of beach contours (accretion) between the SZC site (profile S1B5) and profile P9B just south of SZB; progradation has been greatest at profiles P8 and P9;
- slow landward movement of beach contours (erosion) between SZA (profile P10) and north of Sizewell Hall (profile P13);
- very slow seaward movement of beach contours (accretion) between Sizewell Hall (profile P14) and a point north of Thorpeness (profile S1B7); and
- some landward movement of beach contours (erosion) at Thorpeness (profiles P16, P17 and S1A1), but with localised average accretion at profile S1B8.

The highest average rates of accretion indicated by linear regression are 0.76 to 1.35 m/yr in front of SZB. The highest rates of erosion indicated by linear regression are -1.51 to -2.03 m/yr near the former Coney Hill between Minsmere Cliffs and Minsmere Sluice, and -0.89 to -1.57 m/yr between Minsmere Sluice and the proposed SZC site (Table 9).

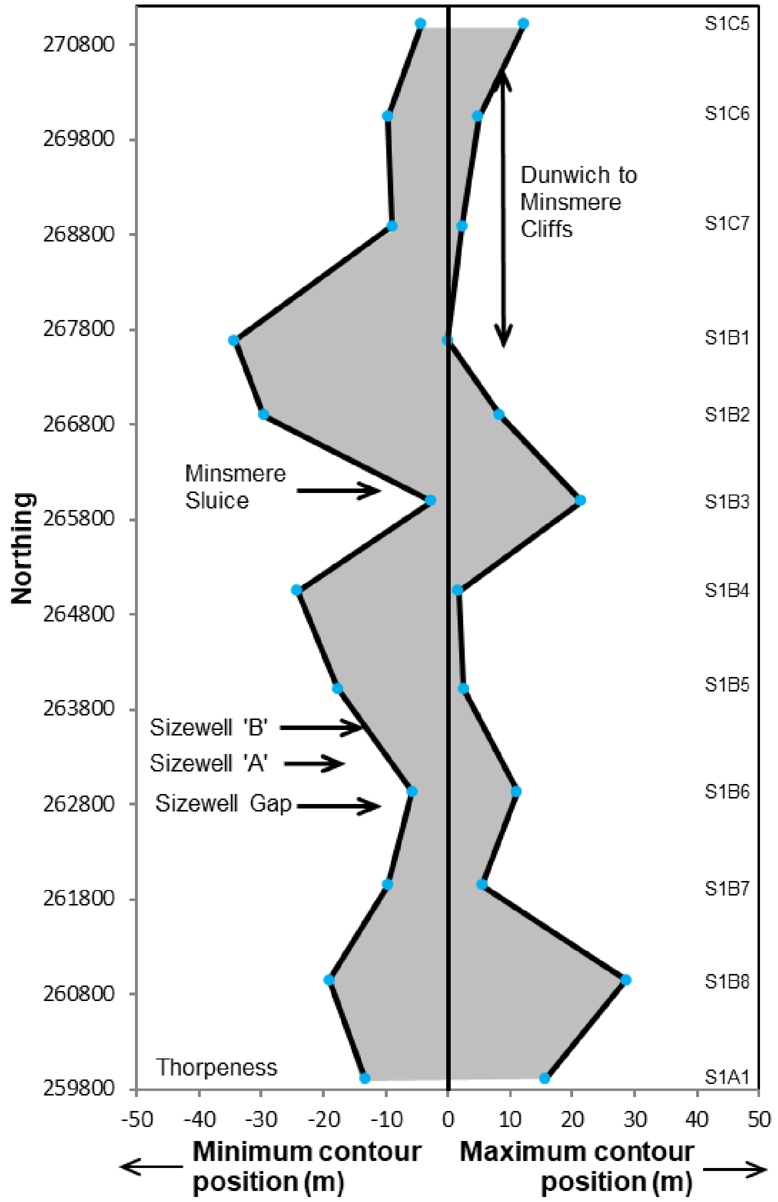

Figure 9: Maximum and minimum positions of the 0.13 m OD contour line recorded by EA surveys between 1991 and 2018 (blue dots).

The envelope of change between 1991 and 2018 is represented by the grey shaded area

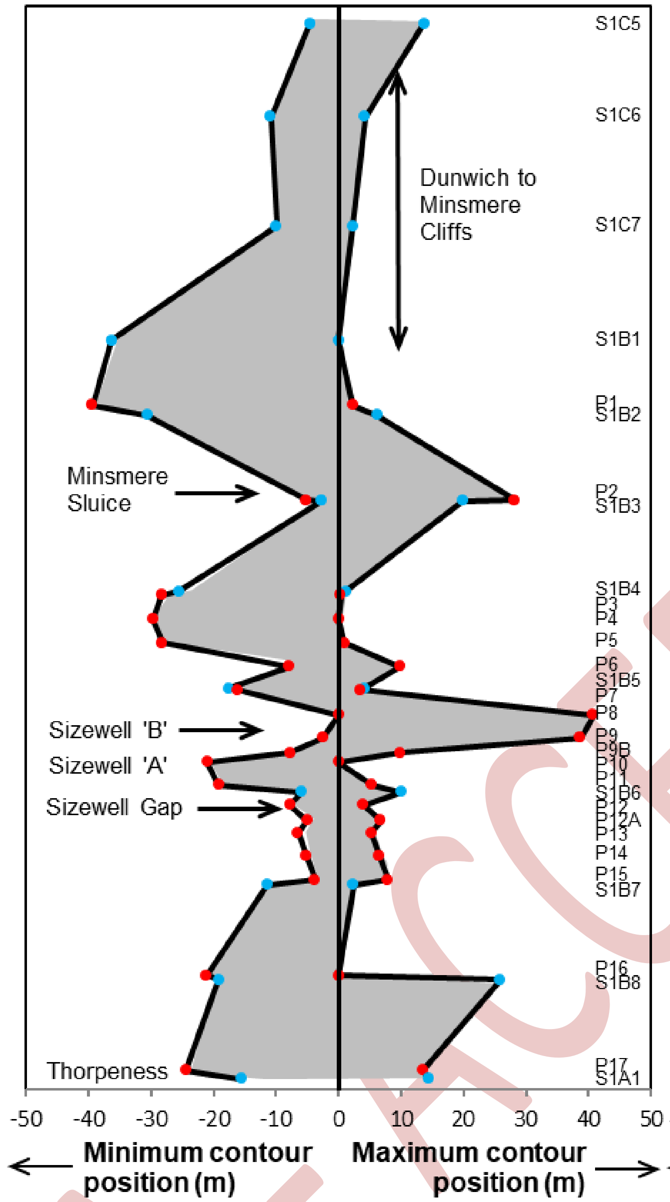

Figure 10: Maximum and minimum positions of the 1.06 m OD contour line recorded by EA surveys between 1991 and 2018 (blue dots) and by SSMSG surveys between 1993 and 2017 (red dots).

The envelope of change between 1991 and 2018 is represented by the grey shaded area. Envelopes are relative to the initial survey of each dataset, in 1991 and 1993 respectively.

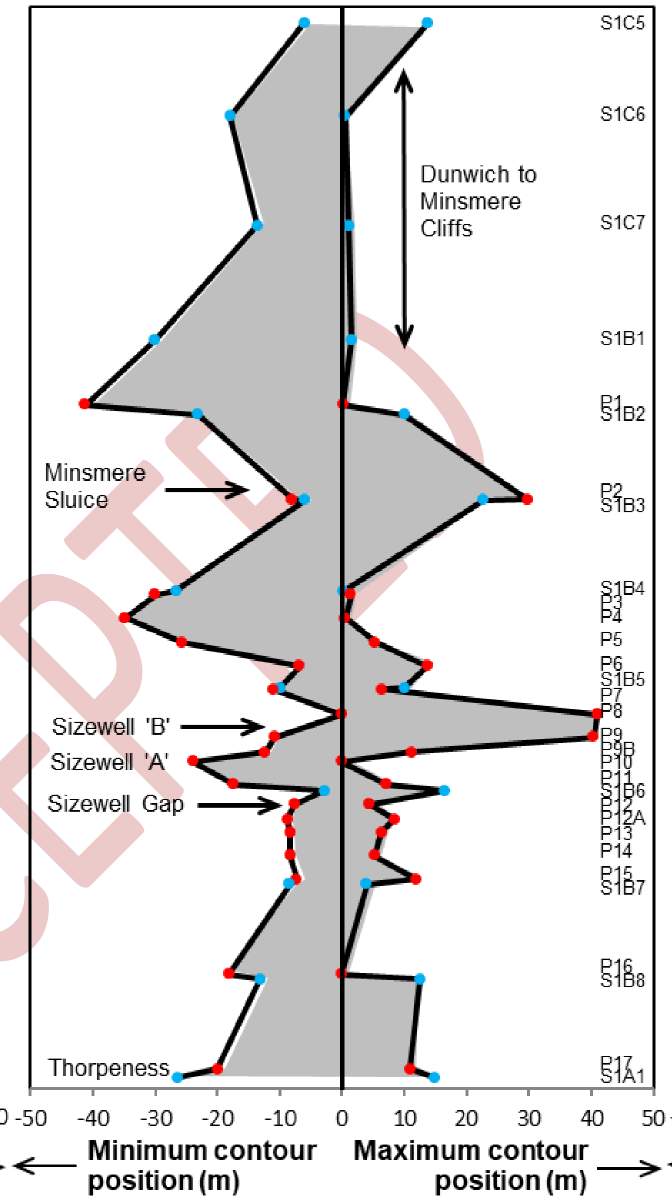

Figure 11: Maximum and minimum positions of the 2.0 m OD contour line recorded by EA surveys between 1991 and 2018 (blue dots) and by SSMSG surveys between 1993 and 2017 (red dots).

The envelope of change between 1991 and 2018 is represented by the grey shaded area. Envelopes are relative to the initial survey of each dataset, in 1991 and 1993 respectively.

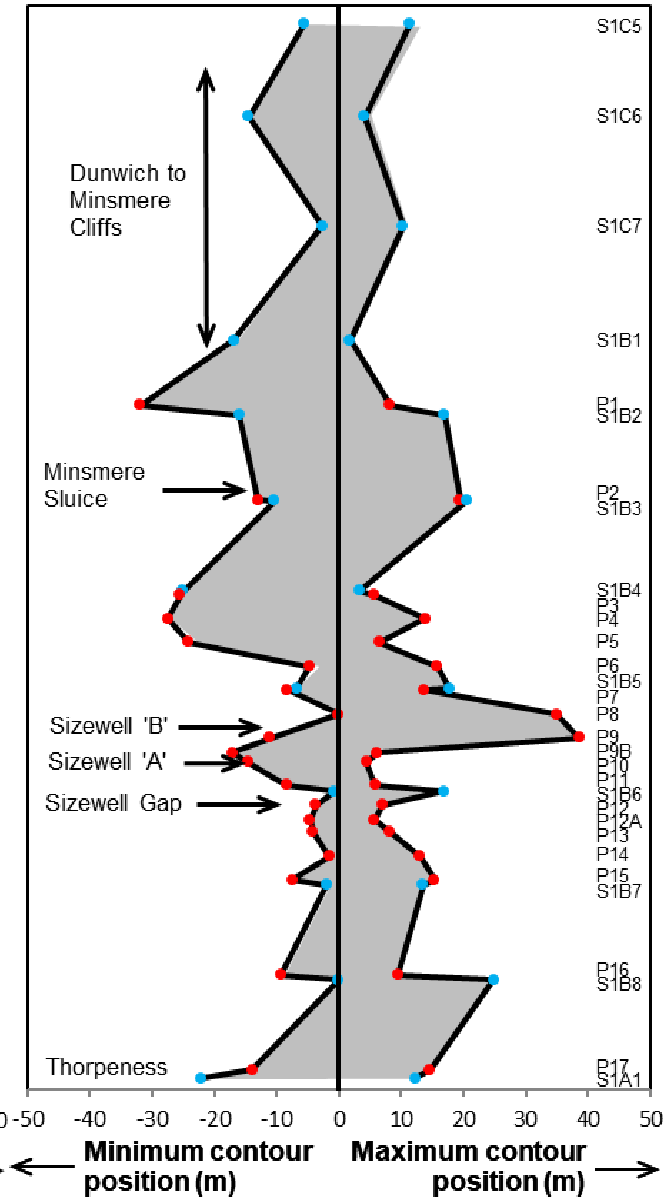

Figure 12: Maximum and minimum positions of the 3.0 m OD contour line recorded by EA surveys between 1991 and 2018 (blue dots) and SSMSG surveys between 1993 and 2017 (red dots).

The envelope of change between 1991 and 2018 is represented by the grey shaded area. Envelopes are relative to the initial survey of each dataset, in 1991 and 1993 respectively.

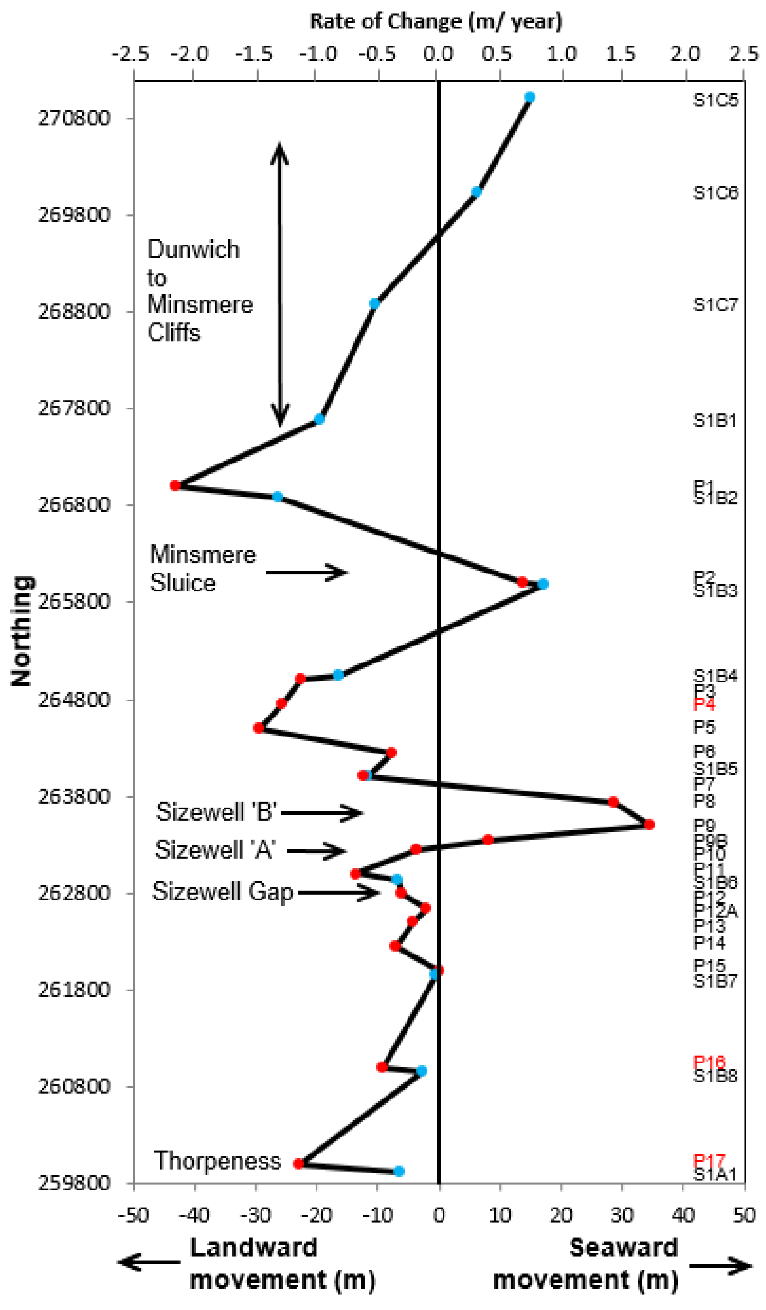

Figure 13: Overall seaward and landward movement of the 0.13 m OD contour between 1993 – 2018 indicated by EA surveys (blue dots) and between 1993 – 2017 indicated by SSMSG surveys (red dots). Red profile labels indicate substituted data where it was not available for the latest year. The 2017 surveys for SSMSG Profiles P4 and P16 did not reach 0.13 m OD and 2011 data has been substituted for these profiles, while 1994 data has been substituted for 1993 data for Profiles P16 and P17. Also, the 1993 EA surveys for Profiles S1C5, S1B4 and S1B5 did not reach 0.00 m OD and 1992 data has been substituted for these profiles. Also shown is the equivalent end point average rate of change since 1993.

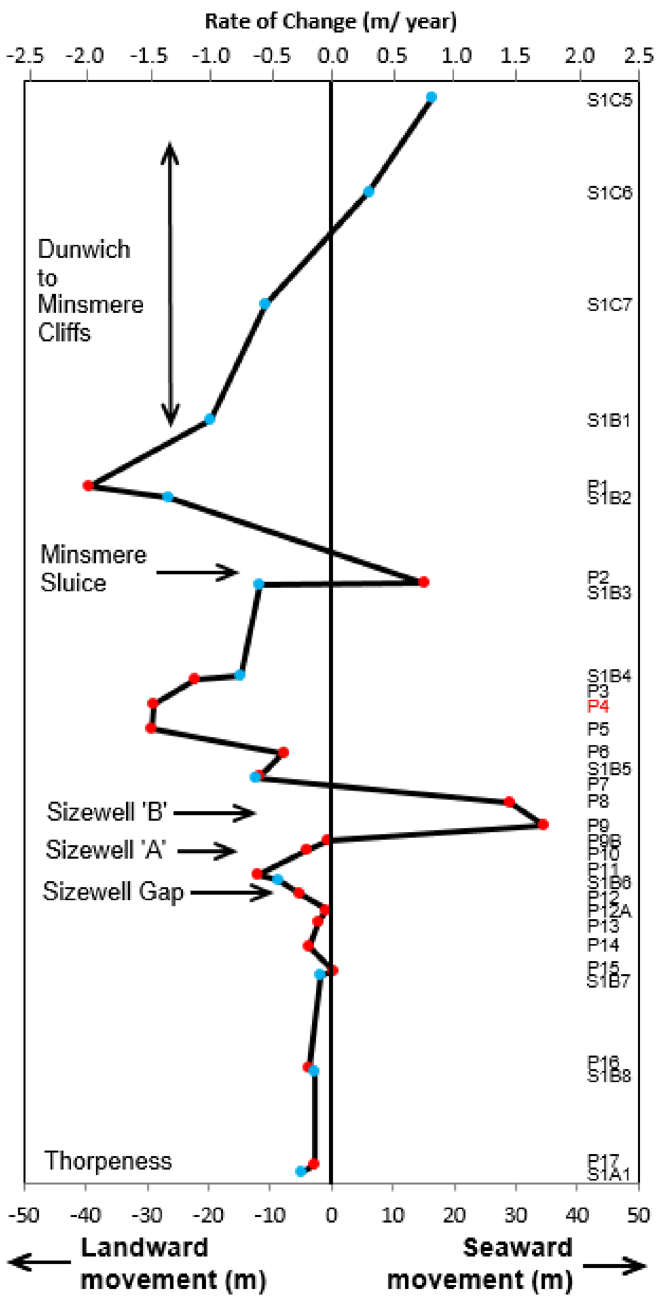

Figure 14: Overall seaward and landward movement of the 1.06 m OD contour between 1993 – 2018 indicated by EA surveys (blue dots) and between 1993 – 2017 indicated by SSMSG surveys (red dots). Also shown is the equivalent end point average rate of change since 1993.

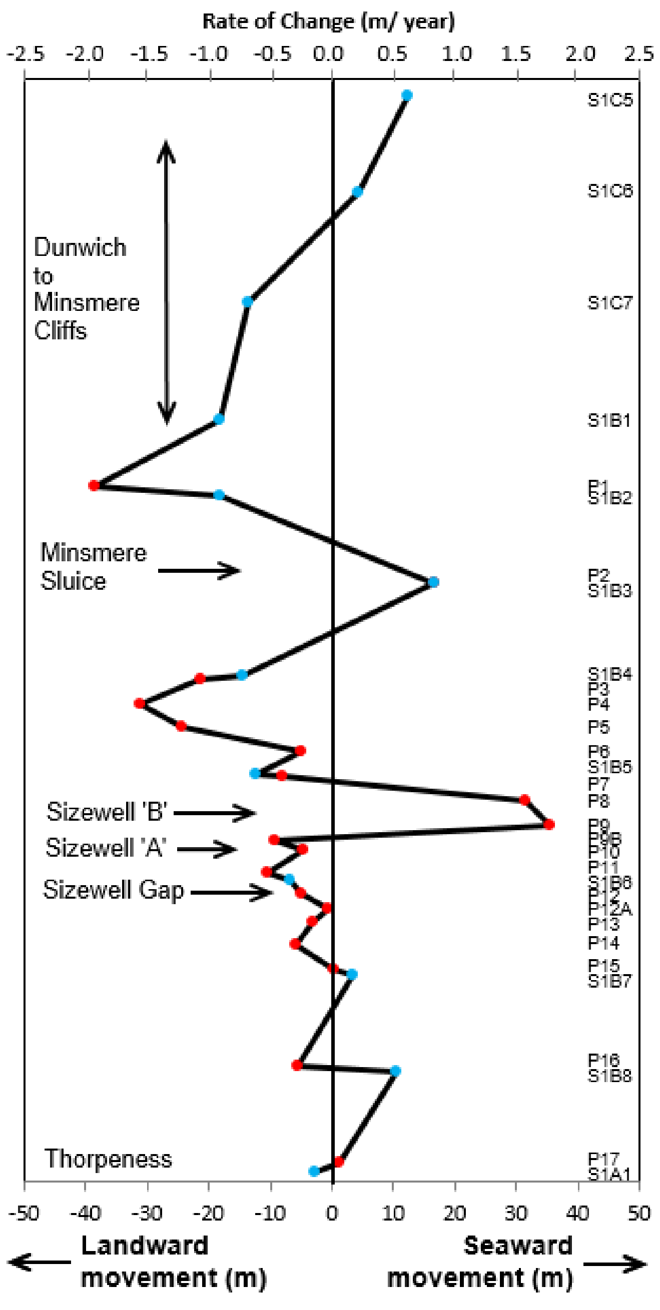

Figure 15: Overall seaward and landward movement of the 2.0 m OD contour between 1993 – 2018 indicated by EA surveys (blue dots) and between 1993 – 2017 indicated by SSMSG surveys (red dots). Also shown is the equivalent end point average rate of change since 1993.

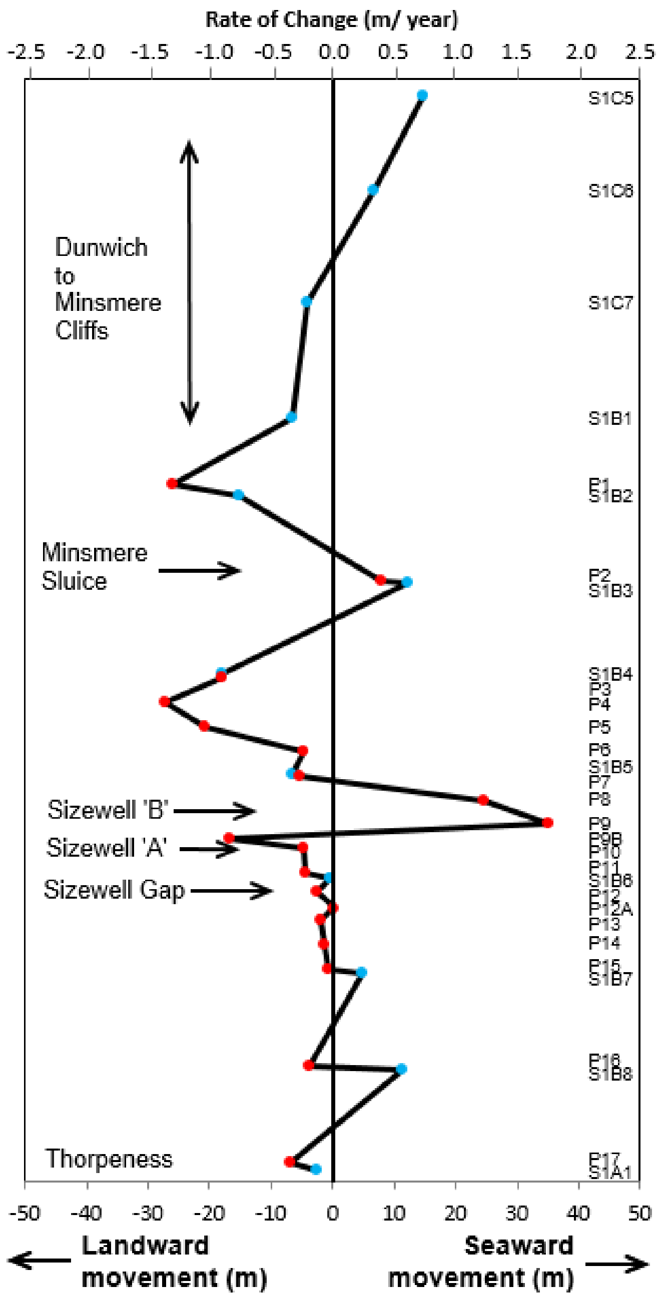

Figure 16: Overall seaward and landward movement of the 3.0 m OD contour between 1993 – 2018 indicated by EA surveys (blue dots) and between 1993 – 2017 indicated by SSMSG surveys (red dots). Also shown is the equivalent end point average rate of change since 1993.

Table 8: Average rates of change in position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours based on time series end point analysis between 1993 – 2018 for EA data and 1993 – 2017 for SSMSG data. Negative and positive rates of change are highlighted in shades of red and green respectively – near-zero values appear white.

Profile	Surveyed by	Position of the 3.00 m OD contour in 1993		End point rate of change over period 1993-2017/18 (m/yr). Positive values indicate seaward movement and negative values indicate landward movement.			
		Easting	Northing	3.00 m	2.00 m	1.06 m	0.13 m
S1C5	EA	648044.2	271020.5	0.61	0.51	0.69	0.62
S1C6	EA	647841.6	270039.2	0.28	0.18	0.25	0.27
S1C7	EA	647760.4	268889.1	-0.17	-0.57	-0.45	-0.44
S1B1	EA	647805.2	267683.1	-0.27	-0.75	-0.82	-0.81
P1	SSMSG	647837.5	267000.0	-1.08	-1.60	-1.64	-1.79
S1B2	EA	647828.1	266893.9	-0.63	-0.76	-1.11	-1.10
P2	SSMSG	647789.0	266000.0	0.33	0.69	0.63	0.58
S1B3	EA	647787.1	265992.1	0.52	0.69	-0.48	0.72
S1B4	EA	647682.6	265042.5	-0.75	-0.61	-0.61	-0.68
P3	SSMSG	647679.7	265000.0	-0.75	-0.89	-0.92	-0.94
P4	SSMSG	647669.3	264750.0	-1.14	-1.29	-1.21	-1.07
P5	SSMSG	647660.4	264500.0	-0.86	-1.02	-1.22	-1.23
P6	SSMSG	647647.1	264250.0	-0.20	-0.20	-0.33	-0.32
S1B5	EA	647641.1	264014.6	-0.28	-0.52	-0.48	-0.48
P7	SSMSG	647641.9	264000.0	-0.22	-0.34	-0.52	-0.52
P8	SSMSG	647624.3	263742.0	1.02	1.32	1.21	1.20
P9	SSMSG	647616.4	263498.0	1.46	1.48	1.44	1.44
P9B	SSMSG	647641.4	263342.0	-0.70	-0.39	-0.02	0.34
P10	SSMSG	647643.5	263244.0	-0.19	-0.20	-0.17	-0.15
P11	SSMSG	647631.1	263000.0	-0.18	-0.43	-0.50	-0.57
S1B6	EA	647612.6	262931.3	-0.02	-0.28	-0.36	-0.28
P12	SSMSG	647611.6	262790.0	-0.11	-0.20	-0.21	-0.26
P12A	SSMSG	647608.1	262630.0	0.01	-0.03	-0.04	-0.08
P13	SSMSG	647605.2	262500.0	-0.08	-0.13	-0.09	-0.17
P14	SSMSG	647606.5	262250.0	-0.06	-0.25	-0.15	-0.29
P15	SSMSG	647613.6	262000.0	-0.03	0.01	0.01	0.00
S1B7	EA	647613.4	261948.5	0.21	0.14	-0.08	-0.02
P16	SSMSG	647693.8	261000.0	-0.16	-0.23	-0.15	no data
S1B8	EA	647695.5	260949.3	0.47	0.43	-0.11	-0.11
P17	SSMSG	647534.0	260000.0	-0.29	0.05	-0.11	no data
S1A1	EA	647507.1	259909.0	-0.10	-0.12	-0.20	no data

Table 9: Average rates of change in position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours based on linear regression analysis between 1993 – 2018 for EA and 1993 – 2017 for SSMSG data. Negative and positive rates of change are highlighted in red and green respectively (near-zero values appear white).

Profile	Surveyed by	Position of the 3.00 m OD contour in 1993		Linear regression rate over period 1993-2017/18 (m/yr). Positive values indicate seaward movement and negative values indicate landward movement.			
		Easting	Northing	3.00 m	2.00 m	1.06 m	0.13 m
S1C5	EA	648044.2	271020.5	0.62	0.70	0.70	0.70
S1C6	EA	647841.6	270039.2	0.15	0.18	0.27	0.32
S1C7	EA	647760.4	268889.1	-0.08	-0.23	-0.20	-0.18
S1B1	EA	647805.2	267683.1	0.29	-0.21	-0.46	-0.51
P1	SSMSG	647837.5	267000.0	-1.51	-1.97	-2.03	-1.80
S1B2	EA	647828.1	266893.9	-1.02	-1.42	-1.61	-1.61
P2	SSMSG	647789.0	266000.0	1.13	0.78	0.66	0.55
S1B3	EA	647787.1	265992.1	1.08	0.79	0.65	0.65
S1B4	EA	647682.6	265042.5	-0.97	-0.99	-1.03	-1.03
P3	SSMSG	647679.7	265000.0	-1.14	-1.26	-1.27	-0.89
P4	SSMSG	647669.3	264750.0	-1.54	-1.57	-1.49	-1.48
P5	SSMSG	647660.4	264500.0	-1.39	-1.35	-1.34	-1.37
P6	SSMSG	647647.1	264250.0	-0.36	-0.39	-0.33	-0.36
S1B5	EA	647641.1	264014.6	0.24	0.10	0.06	0.05
P7	SSMSG	647641.9	264000.0	0.24	-0.04	0.01	-0.18
P8	SSMSG	647624.3	263742.0	0.76	0.88	0.87	0.86
P9	SSMSG	647616.4	263498.0	1.09	1.29	1.25	1.35
P9B	SSMSG	647641.4	263342.0	-0.20	0.18	0.35	0.49
P10	SSMSG	647643.5	263244.0	-0.25	-0.14	-0.13	-0.15
P11	SSMSG	647631.1	263000.0	-0.15	-0.41	-0.46	-0.52
S1B6	EA	647612.6	262931.3	-0.15	-0.31	-0.29	-0.20
P12	SSMSG	647611.6	262790.0	-0.04	-0.07	-0.09	-0.06
P12A	SSMSG	647608.1	262630.0	-0.03	-0.12	-0.13	-0.16
P13	SSMSG	647605.2	262500.0	-0.03	-0.10	-0.13	-0.20
P14	SSMSG	647606.5	262250.0	0.06	0.03	-0.01	-0.08
P15	SSMSG	647613.6	262000.0	0.13	0.07	0.07	0.03
S1B7	EA	647613.4	261948.5	0.32	0.21	0.15	0.20
P16	SSMSG	647693.8	261000.0	-0.20	-0.08	-0.22	no data
S1B8	EA	647695.5	260949.3	-0.01	0.24	0.28	0.28
P17	SSMSG	647534.0	260000.0	-0.49	-0.61	-0.73	no data
S1A1	EA	647507.1	259909.0	-0.33	-0.25	-0.36	no data

6.1.2 Short-term changes in beach contour position, based on topographic surveys (1985 – 2018)

6.1.2.1 *EA and SSMSG datasets between 1991 – 2017/18*

Time series graphs showing changes in the positions of the beach contours at each profile location between 1991 – 2017 (SSMSG) and 1991 – 2018 (EA) are shown superimposed on the 2011 aerial photographs in Figure 17 –

Figure 20.

At most profile locations the trend for accretion or erosion was not constant over this time period. At Profile S1C5, north of Dunwich, there was little net change in any of the beach contours between 1991 – 2003, before a subsequent period of seaward movement. This may be related to erosion of the central part of the Walberswick barrier and movement of sediment towards both its northern and southern ends, forming a more pronounced embayment (Pye and Blott, 2009).

Profile S1C6, south of Dunwich, experienced slight landward movement of the beach contours between 1991 – 2000, since when the mid and lower beach contours experienced only limited variations. The 3.00 and 2.00 m OD contours experienced greater variability, with rapid accretion of the backshore in late 1996 – 1998, severe erosion in 2007, and marked accretion since 2010. This may have been assisted by experimental sediment retention schemes on the upper beach undertaken since 2009.

Profile S1C7 displayed general stability of all the beach contours until 2012, with the exception of the 3.00 m OD contour, which moved seaward in the late 1990's before stabilising and allowing vegetation to spread across the upper storm beach. Between 2012 – 2018, the shoreline at S1C7 has receded 5 – 10m.

Profile S1B1 at the southern end of Dunwich Cliffs experienced landward recession of all contours below the 2.00 m OD contour until 2005, followed by minor progradation. Since the late 1990's, the 3.00 m OD contour moved seawards until 2009, with some regression since, whilst vegetation has increasingly colonised the backshore.

Profiles P1 and S1B2, near the northern end of the RSPB Minsmere Reserve, showed little change or slight seaward movement between 1991 – 2002, after which time, a steady erosion trend set in (up to 40 m retreat over 10 years; i.e., 4 m/yr). This area was severely affected by storms in 2006 and 2007, when waves breached the frontal dune ridge and partially overtopped the secondary earth embankment sea defence behind. Improvements to this defence were made subsequently by the EA as part of the Minsmere Sea Defence Scheme. Since 2012, this section of shoreline exhibited relatively stability.

At Profiles P2 and S1B3, located just south of Minsmere Sluice, the beach contours fluctuated (but with net stability) until 1995. This was followed by a period of net seaward movement. This was associated with a progressive accumulation of sediment on both the southern and northern sides of Minsmere Sluice (see Section 6.1.6), forming a more prominent cuspate feature. Blockage of the sluice has been frequent, requiring periodic clearance by the EA. However, after 2012, seaward movement ceased and the shoreline moved slightly landward.

The northern corner of the SZC site and 550 m to the north (profiles S1B4, P3, P4 and P5) exhibited a pattern of stability in the early 1990's, changing to slow landward recession of all contours between 1993 – 2003. This was followed by more rapid landward movement from 2003 – 2012, before slowing considerably (for profiles P3 and P5) and even reversing (for profiles P3 and S1B4) since 2012. Approximately 200 m further south on the SZC frontage (Profile P6), less net change was observed with the exception of defined landward regression since 2006.

Further south (SZB frontage; Profiles S1B5, P7, P8 and P9), net seaward movement of 250 – 750m occurred until 2012, followed by regression (S1B5 and P7) or stability (P8 and P9) in the years 2012 – 2018. During the construction of SZB, and up until 1992/93, this coastal section was dredged and was occupied by a coffer dam and BLF (BEEMS Technical Report TR105). A 400 m wide shoreline indentation was present for 3 – 4 years following the removal of these structures (see dashed purple line in Figure 19 and Figure 82 – Figure 84 in Appendix A), before a phase of rapid infill and shoreline advance began. P8 and P9 then experienced a phase of relative stability before further rapid seaward movement in 2007 (P8) and 2009 (P9). Just to the north along the SZC frontage (S1B5 and P7) regular reversals of trend have occurred (landward retreat to 2000, seaward advance to 2011, landward retreat to 2018).

Profile 9B is located at the southern extent of the 400 m SZB construction embayment and has shown variability in position but little net change. Profiles P10, P11 and S1B6, in front of SZA and Sizewell Gap experienced the same phases of landward and seaward movement, although the exact timings differ by location. The phases included; seaward movement prior to 1993, landward movement between 1997 – 2000, seaward movement between 2005 – 2009, landward movement between 2008 – 2010 and a period of stability and accretion between 2012 – 2018.

Profiles P12 to P15 and S1B7 at Sizewell and Sizewell Hall were stable with small fluctuations and little net change over the period. P15 shows a period of weak landward movement between 2002 – 2006. At profile P16, to the north Thorpeness, there has been significant inter-annual variability and slow net landward movement of the 2.00, 1.06 and 0.13 m OD contours over the entire monitoring period until 2016, with less variability observed in the 3.00 m OD contour. Profile S1B8, on the northern side of Thorpeness, showed periods of erosion between 1991 – 2000 and 2011 – 2013, but between these years has otherwise shown gradual recovery and a net accretion of all contours since 2013.

Profiles P17 and S1A1 on the south side of Thorpeness, experienced accretion between 1996 – 2003, followed by erosion at all contour levels. Rapid recession of the 2.00 m OD contour occurred at profile S1A1 in 2010 and emergency works were undertaken by the EA. By 2018, most contours had nearly recovered to their 1993 positions.

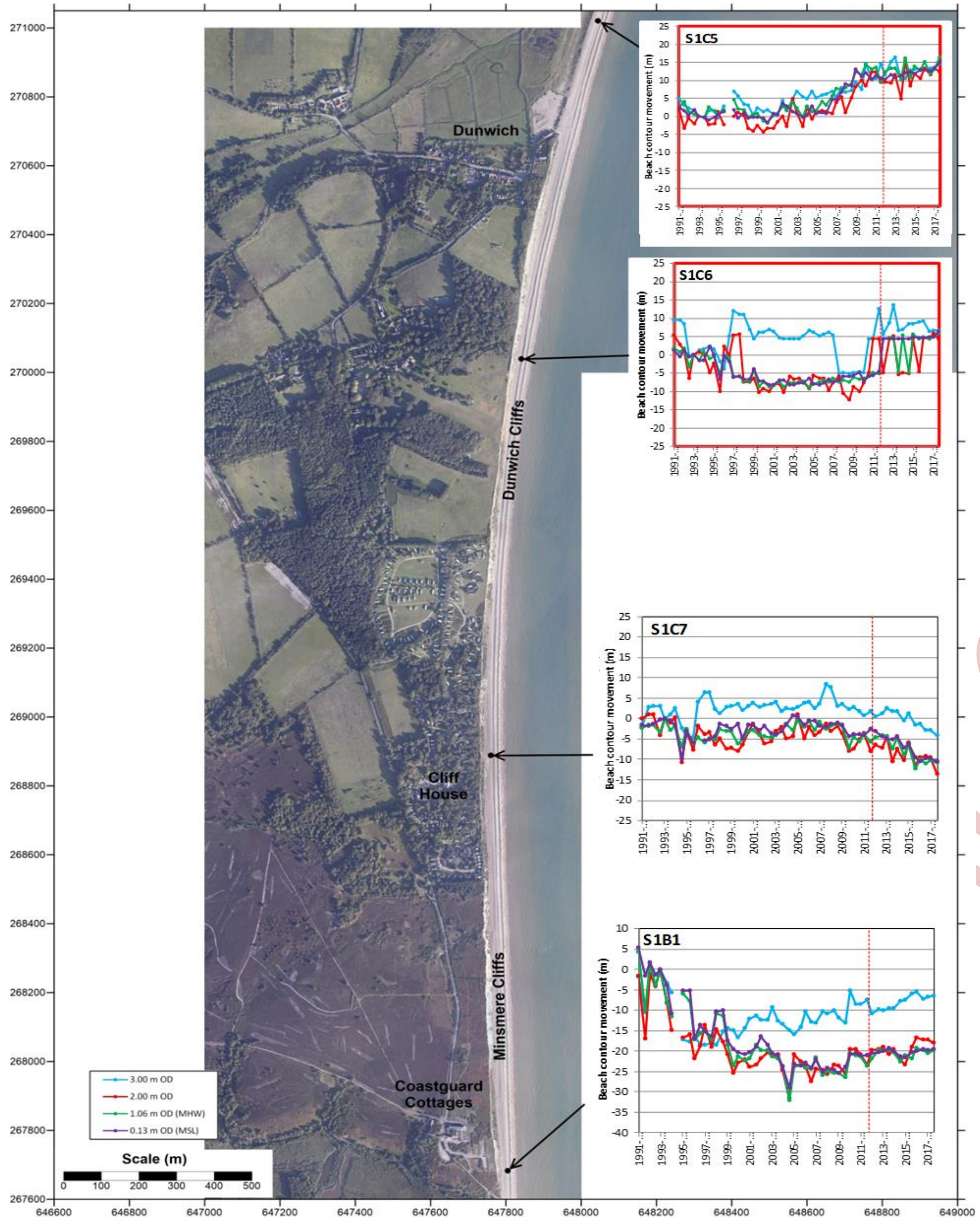

Figure 17: Temporal variation in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on topographic surveys 1991 – 2017/18 (base map aerial photographs flown in 2011): Dunwich to Minsmere Cliffs. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and

data

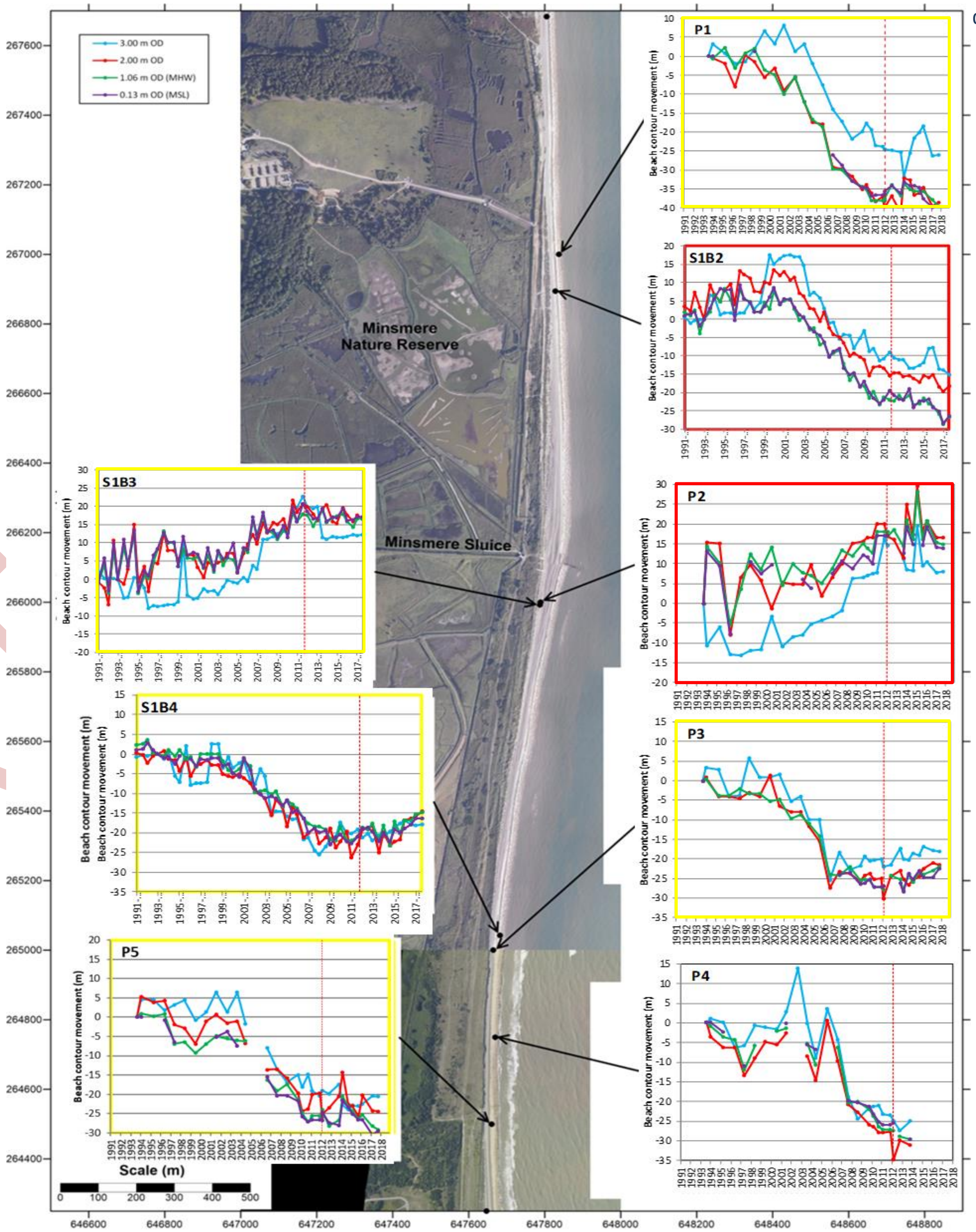

Figure 18: Temporal variation in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on topographic surveys 1991 – 2017/18 (base map aerial photographs flown in 2011): Minsmere Cliffs to Sizewell

North. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in BEEMS Technical Report TR223, second edition (2014).

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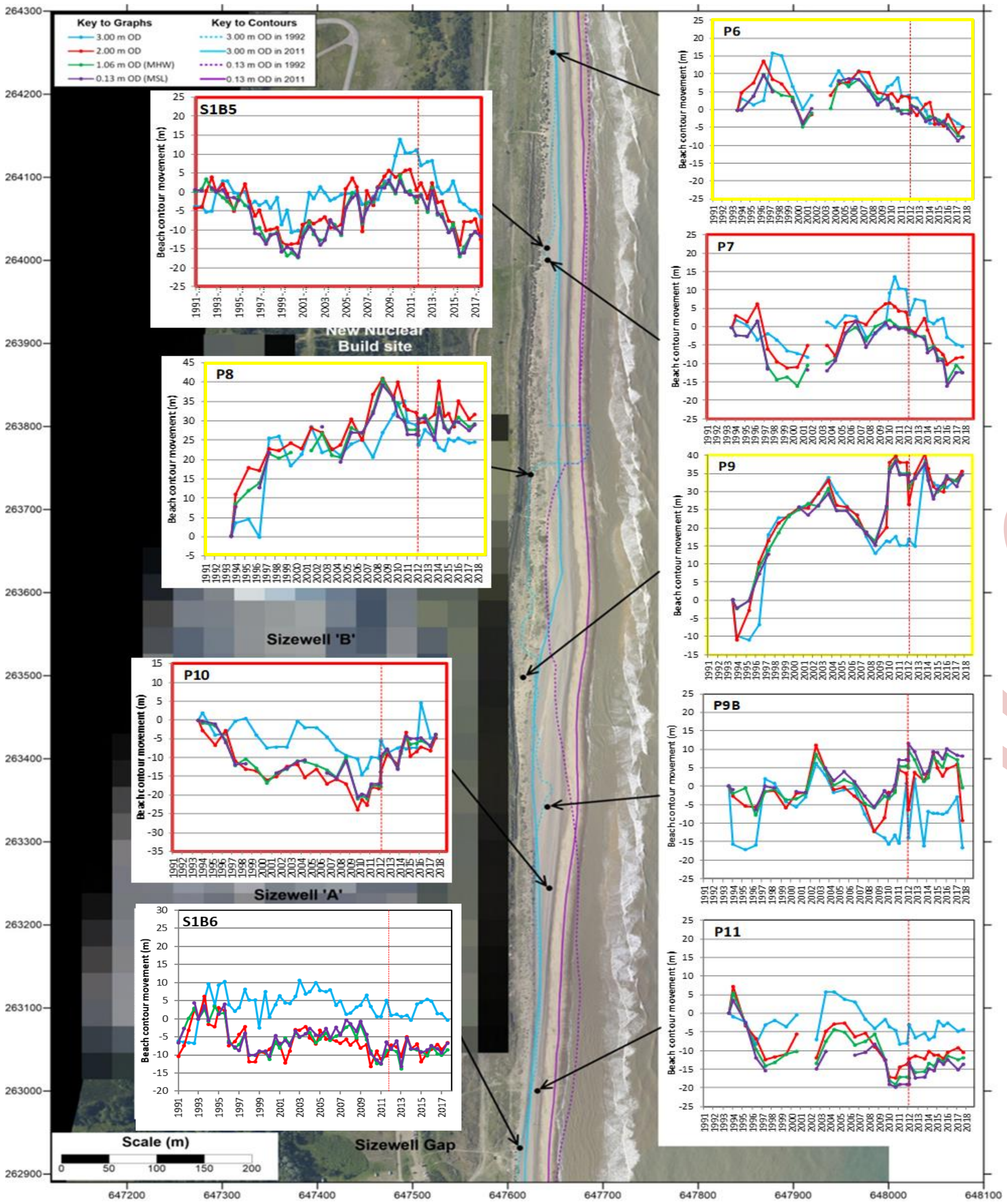

Figure 19: Temporal variation in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on topographic surveys 1991 – 2017/18 (base map aerial photographs flown in 2011): Sizewell power station frontage. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders

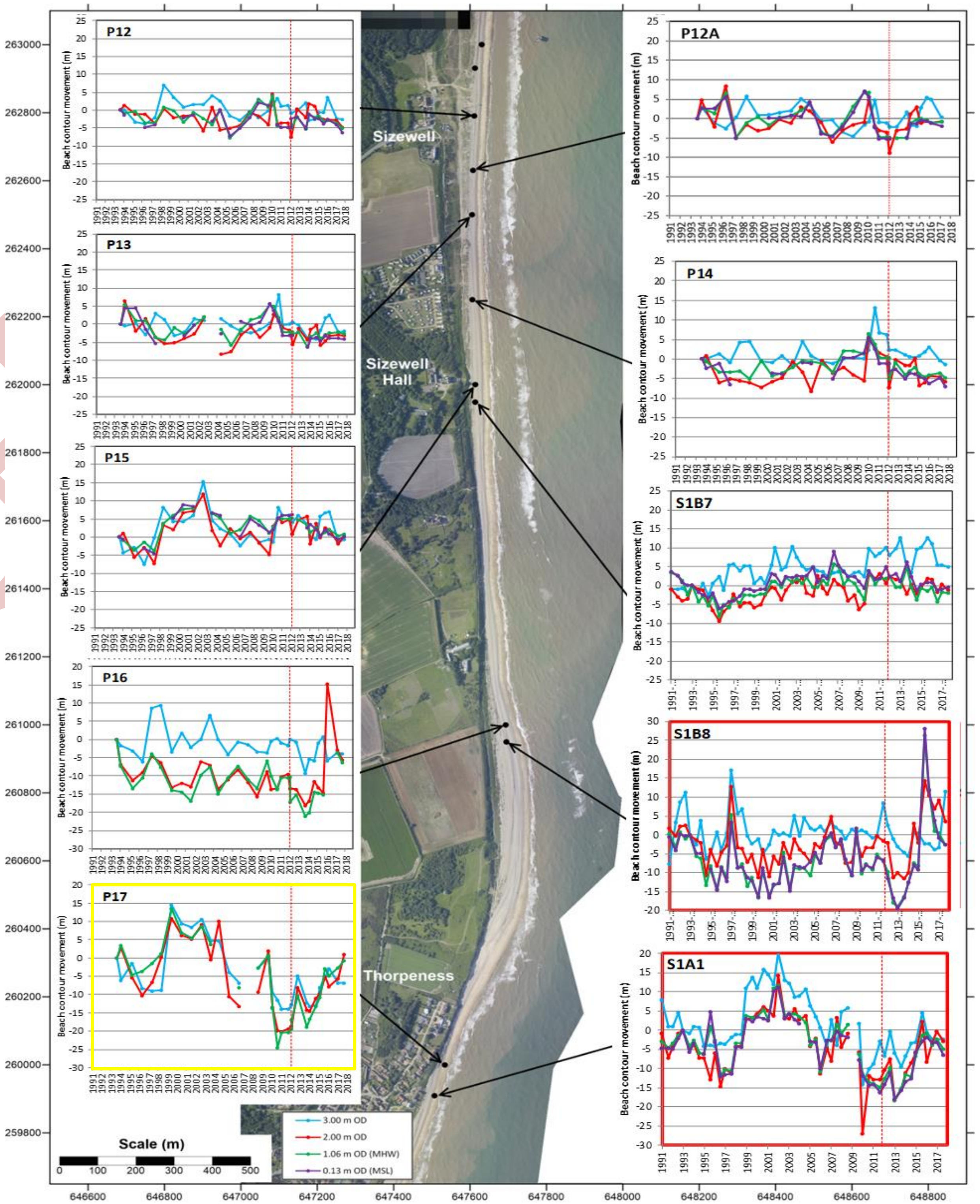

Figure 20: Temporal variation in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on topographic surveys 1991 – 2017/18 (base map aerial photographs flown in 2011): Sizewell to Thorpeness. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in BEEMS Technical Report TR223, second edition (2014).

6.1.2.2 *SSMSG datasets 1985 – 2017*

Figure 21 – Figure 23 differ from Figure 17 –

Figure 20 in that they show the beach contour movements going back to 1985. They also use a different baseline year to map contour movements relative to (1985 instead of 1993). Therefore beyond 1993, they do not provide any further information to that presented above. They are based on monitoring at the Sizewell power stations profiles only, and provide information about changes which occurred during and immediately following the construction of SZB, however for the entire context, the rest of the time series to the present day is provided in Figure 21 – Figure 23. The earlier results were extracted from paper records.

The results show that to the north and south of Minsmere Sluice (Profiles P1, 3, 4 and 5), the period of landward movement of beach contours after 1991 was preceded by a period of seaward advance of the contours of between 5 – 20 m. Immediately south of Minsmere Sluice (Profile P2), the beach eroded by approximately 20 m between 1985 – 1996, followed by approximately 25 m of seaward advance to the present. To the north of the power station (P6 and P7), the beach contours were stable during the period 1985 – 1993. Further south, no monitoring was undertaken at Profiles P8 and P9 between 1989 – 1993 when the beach in front of SZB was heavily disturbed by construction of the BLF and cooling water culverts, but a large indentation was left in the beach following removal of the coffer dam (1992) and BLF (1993). By contrast, to the south of SZB, the beaches in front of SZA and Sizewell village (P10, 11 and 12) experienced 10 –15 m of seaward movement between 1985 – 1993. Further south, the beaches in the front of Sizewell Cliffs and Sizewell Hall (P13, 14 and 15) experienced approximately 10 m of erosion between 1985 – 1993, followed by the general stable condition after the mid-1990's noted earlier, while at Thorpeness (P16 and 17), the contours moved 15 m seaward between 1985 – 1993.

6.1.2.3 *SSMSG datasets 2006 – 2017*

Halcrow/Geosphere 4D (SSMSG) GPS beach monitoring provides greater detail of changes in the positions of the 2.00 and 0.13 m OD contours on the power station frontage since December 2006 (Figure 24 – Figure 25). The data showed a progressive deepening of the bay between profiles P4 and P6 (SZC northern boundary) during the survey period, with a point of zero change to the south near profile P8). At P7 a steady seaward advance (10 – 13 m) switched to steady retreat in the summer of 2010 that continued until 2017. In contrast, only 100 m to the south (profile 7A), a similar but more abrupt advance/retreat pattern was observed. There, rapid seaward advance of 25 m was recorded in the 18-month interval to summer 2008 and was followed by rapid retreat which subsequently slowed following the winter of 2009/10 (20 m). To the south was a point of almost zero change around P8, just north of the B station outfall (Figure 24).

At P9, 150 m south of the B station outfall, stability of beach contours between 2006 – 2009 was followed by a rapid advance of 20 m over the winter of 2009/10, followed by general stability until 2017. The adjacent profiles showed no significant concomitant retreat and it is therefore assumed that the accretion observed at this location over the winter of 2009/10 was caused by sediment moving onto the beach from offshore. Between P9 and P10, in front of the SZB and SZA, the 2.00 m OD contour oscillated, but showed minor net accretion overall. A very similar pattern was seen in Profile 10A. At profile P11, close to SZA outfall, the 2.00 m OD contour moved landwards between 2006 –2010, before subsequently moving gradually seawards, resulting in limited net change. Between P11A and P13A only minor fluctuations occurred (Figure 25). Broadly similar trends were observed in the 0.13m OD beach contour.

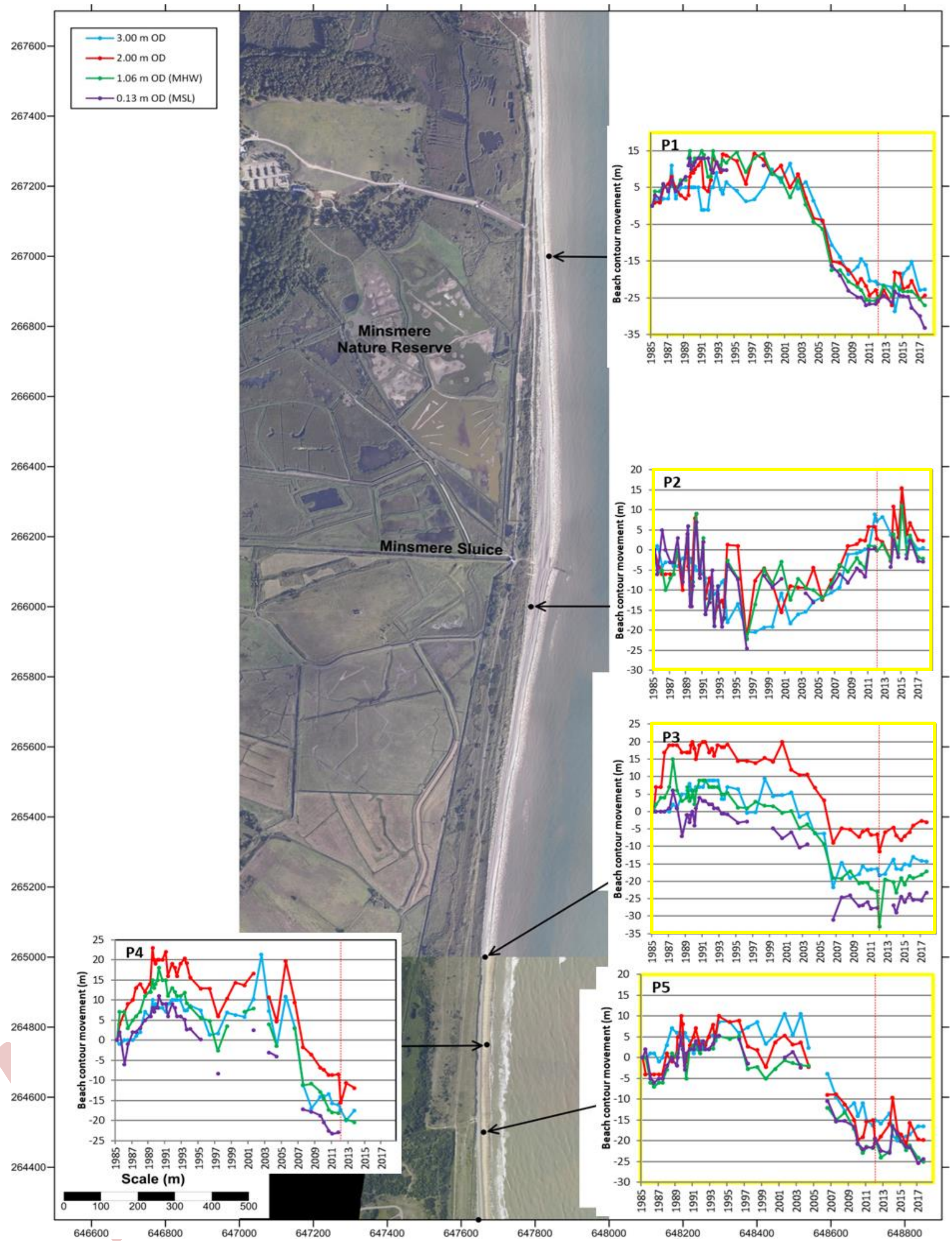

Figure 21: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on Sizewell topographic surveys 1985 – 2017 (base map aerial photographs flown in 2011): Minsmere South to Sizewell North. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

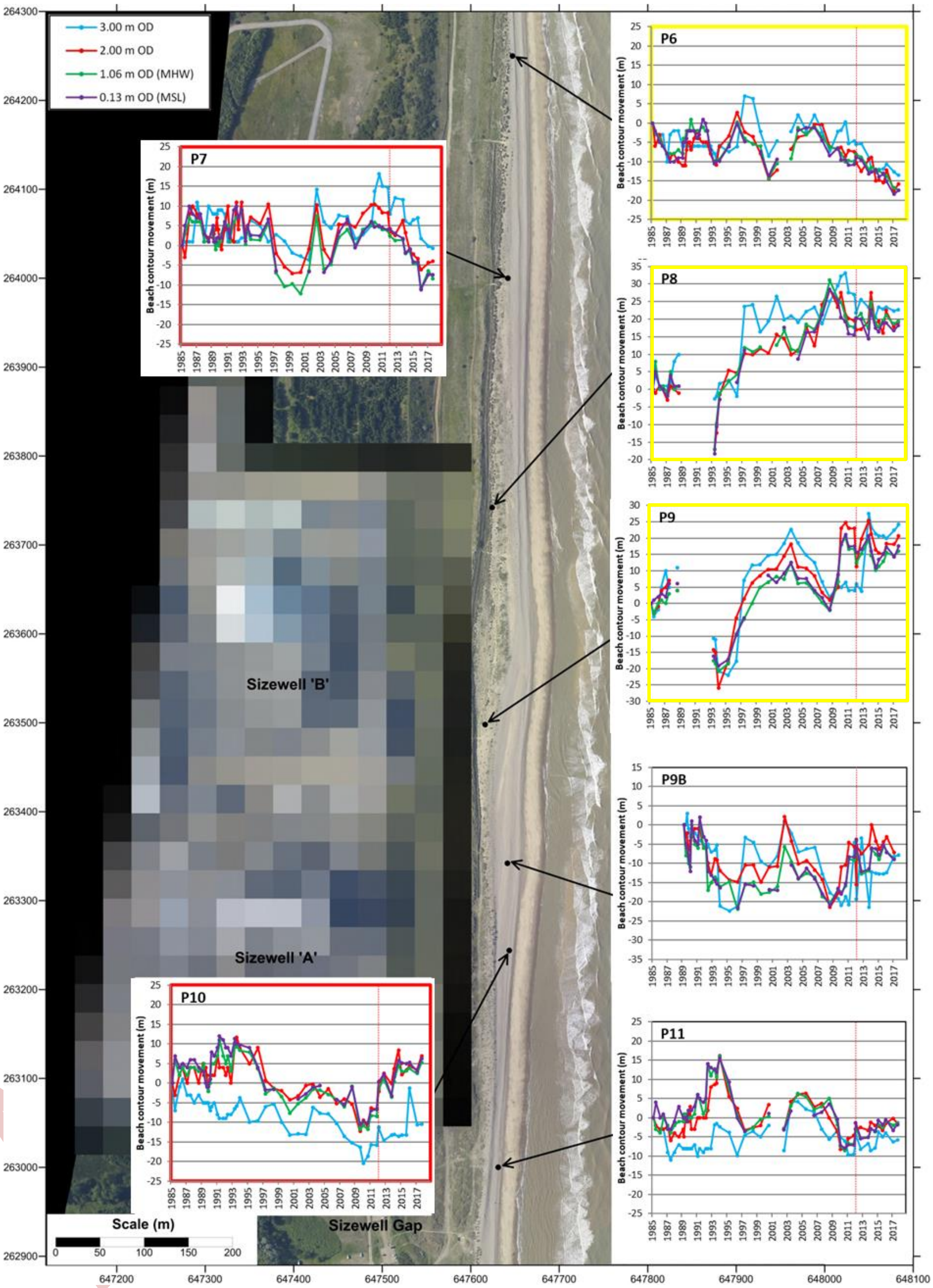

Figure 22: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on Sizewell topographic surveys 1985 – 2017 (base map aerial photographs flown in 2011): Sizewell Power Stations frontage. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

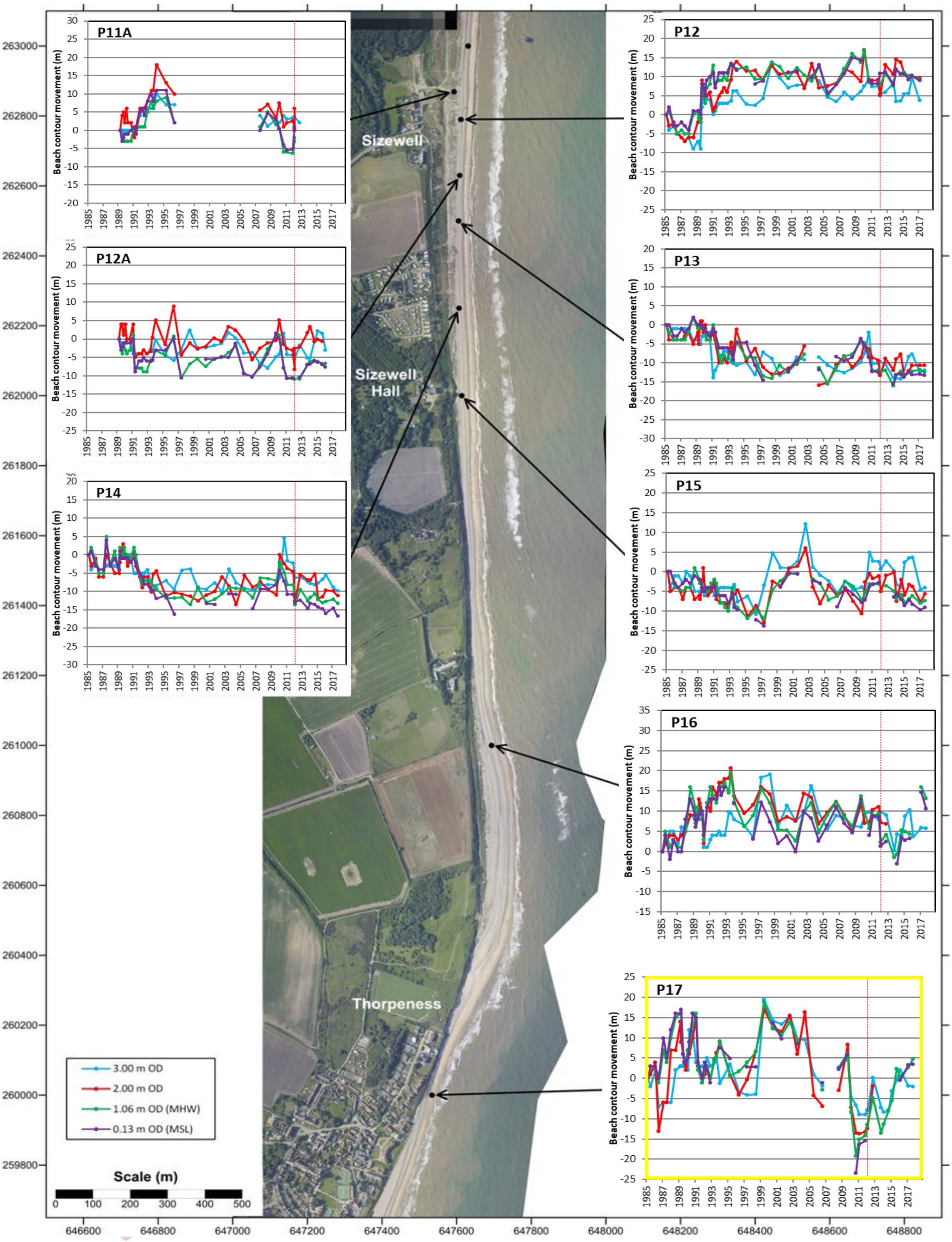

Figure 23: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD beach contours, based on Sizewell topographic surveys 1985 – 2017 (base map aerial photographs flown in 2011): Sizewell to Thorpeness. Positive values indicate seaward shoreline positions relative to the first survey. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

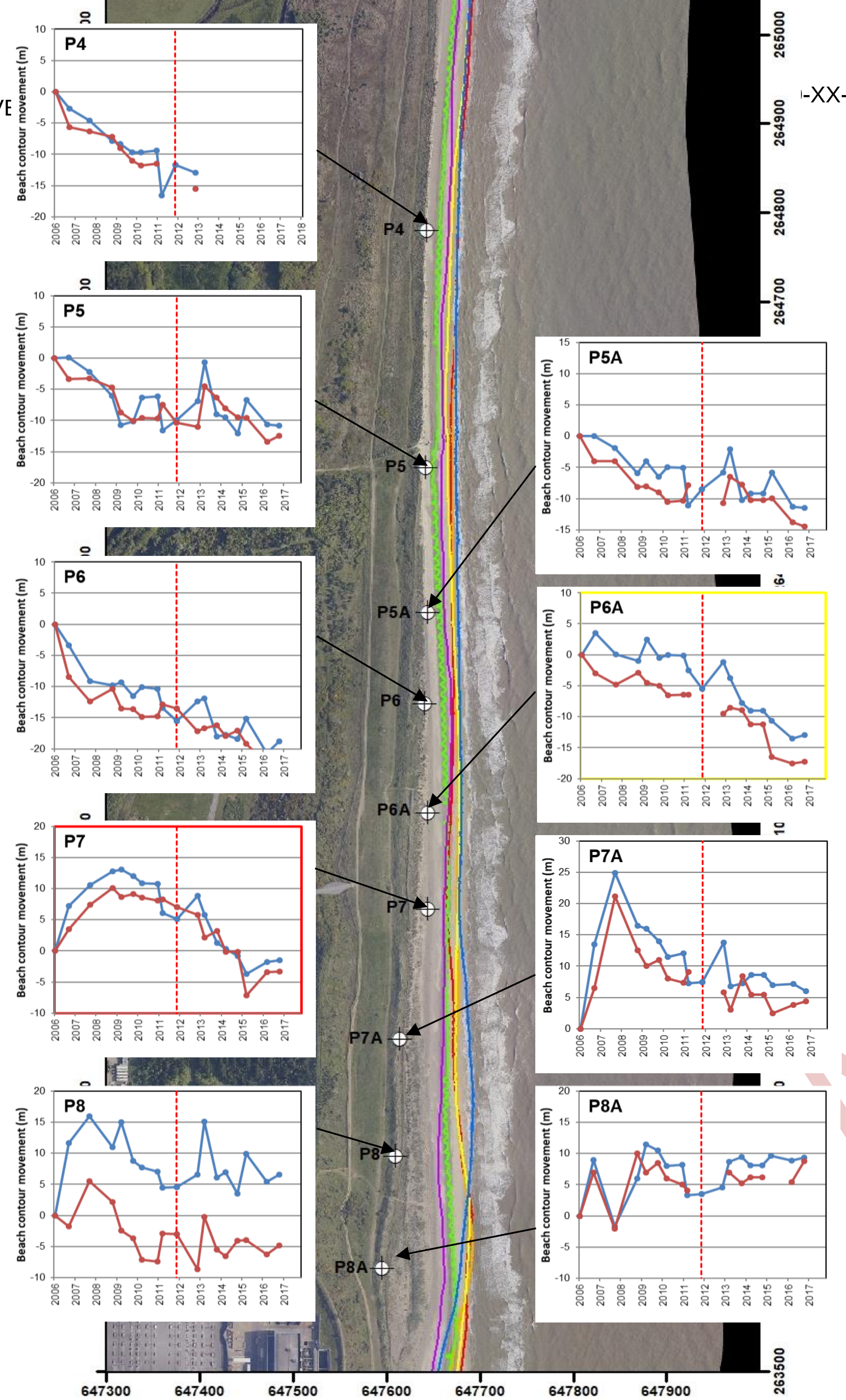

Figure 24: Change in position of the 2.00 m OD beach contours, based on multi-point beach topographic surveys conducted by Halcrow 2006 – 2017: Northern power stations frontage. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

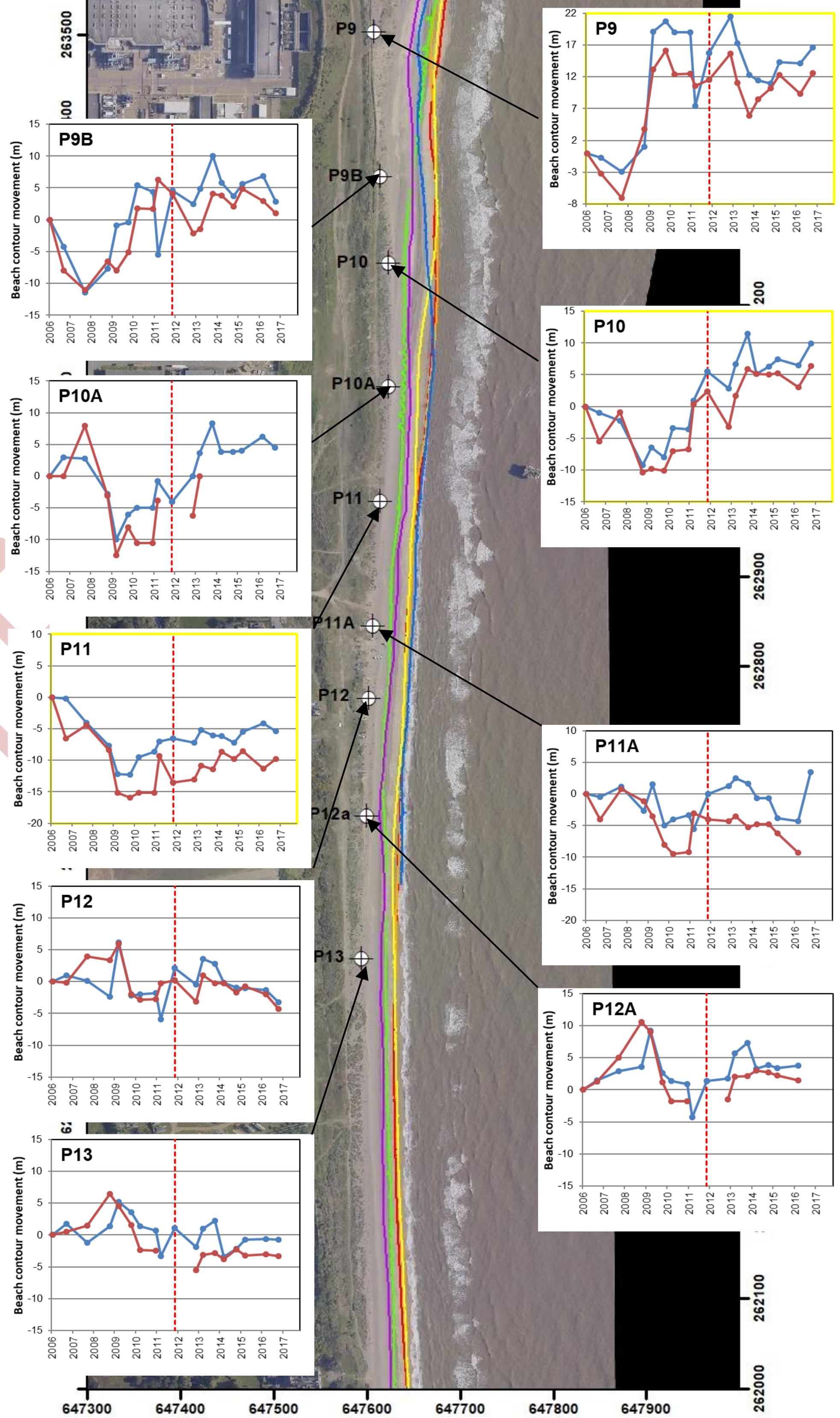

Figure 25: Changes in position of the 2.00 m OD beach contours, based on multi-point beach topographic surveys conducted by Halcrow in between 2006 – 2017: Southern power stations frontage. Plots with red borders indicate large trend or stability changes since 2012 whilst yellow borders indicate lesser trend or stability changes and black borders indicate no trend or stability change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

6.1.3 Short-term changes in subaerial beach sediment volume, based on topographic surveys (1991 – 2018)

The temporal trends in beach sediment volume above each of the selected beach contours for (a) seaward of the 3.0 m OD contour at the time of survey; and (b) seaward of the most landward position of the 3.0 m OD contour during the survey period (as described in Figure 4) are shown in Figure 26 – Figure 32Figure 32. Method (a) indicates changes in beach volumes at the time of survey, regardless of any advance or retreat of the backshore. Method (b) is able to take into account wholesale advance or retreat (accretion and erosion) of the coastline, determining beach volumes relative to a fixed point. Taken together, the two measures can indicate morphological changes such as steepening or flattening of beach profiles, whilst reference to the absolute seaward or landward movement of the beach contours themselves, can indicate the stability or otherwise of each section of the coastline.

The trends in the two complementary volume measures highlight significant seasonal and inter-annual variation, reflecting changes in wave and longshore drift conditions. There is often a gain in beach sediment volume during the summer months and a reduction during the winter months, indicating seasonal sand exchanges between the beach face and longshore bars, although some years do not display this pattern. Individual large storm events, such as those in 1993, 1996, 2005, 2006, 2007, 2013 and 2017 (Table 10, see also Pye and Blott, 2006, 2009, and BEEMS Technical Report TR139), have had significant but spatially variable effects, reflecting the fact that sand[2] is usually moved along as well as across the shore, during and following storm events. The variability in volumes and sediment transport patterns is discussed in Section 7.5.1, and is partly related to wave energy and wave angle.

6.1.3.1 *Beach volumes: method (a)*

Most beach volumes along this coastline have remained fairly stable throughout the period 1991 – 2018 and, in this sense, can be said to be in dynamic equilibrium. However, there are notable exceptions where volume changes have been significant e.g., at Minsmere, where S1B1 and S1B2 beach volumes have dropped (50 % and 30 % respectively), while S1B3 (immediately to the south) initially doubled in volume up to 1998 but then returned to its initial state by 2013, and almost doubled again by 2014. There are also some significant spatial differences along the coast at any one point in time; for example, volumes above mean sea level (MSL) in 2017 increased from 40 $m^3 m^{-1}$ at Minsmere and Sizewell North to 60 $m^3 m^{-1}$ fronting SZA power station. Beach volumes then decreased to 40 $m^3 m^{-1}$ south of SZA. The largest beach volumes were found in the vicinity of SZB (e.g., P8, P9 and P9B) in 2012, but were also changeable: doubling until being reduced by a storm in 1996, then again doubling in volume between 2009 – 2014 before returning to normal by 2017.

6.1.3.2 *Beach volumes: method (b)*

Changes using method (b) indicate general trends in the whole beach, including supratidal areas. Beaches north of Minsmere (S1B1) have largely remained stable or increased in volume. To the south, as far as the SZC site (P7), the beach volumes have mostly decreased, with an exception for the few sites just south of Minsmere sluice. Thereafter, moving south as far as Thorpeness, volumes are generally again relatively stable, with only a few sites showing periods of substantial loss or gain e.g., S1B5 and P10.This again supports the suggestion of a form of dynamic (sediment transport) equilibrium along much of the coastline, with beaches locally maintaining a consistent sediment volume within their full profile even as coastline positions and beach face steepness vary with the fluctuating wave and storm conditions experienced.

[2] The absence of subtidal shingle (BEEMS Technical Report TR238) suggests that only sand is exchanged between the sub- and intertidal.

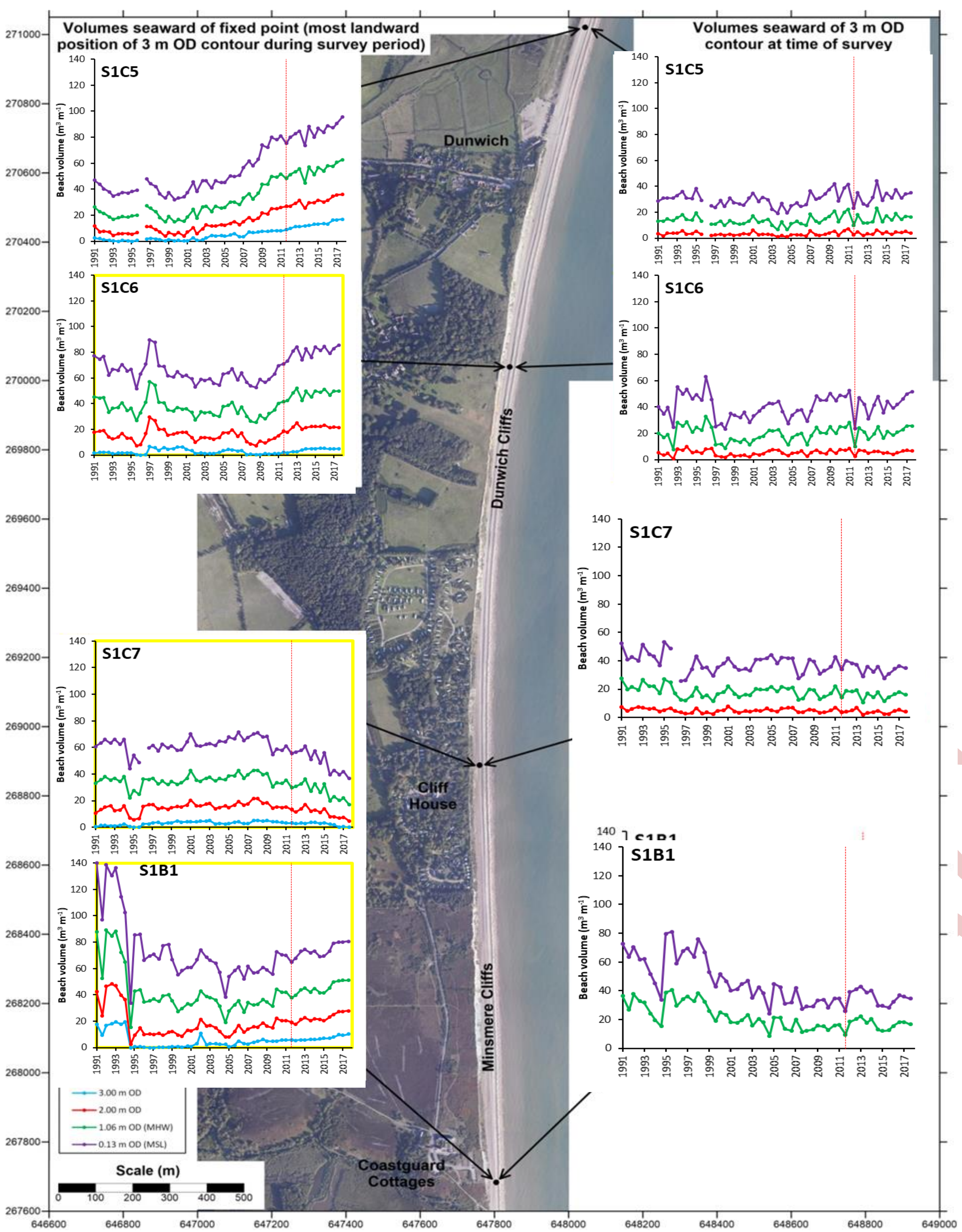

Figure 26: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: Dunwich to Minsmere Cliffs. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

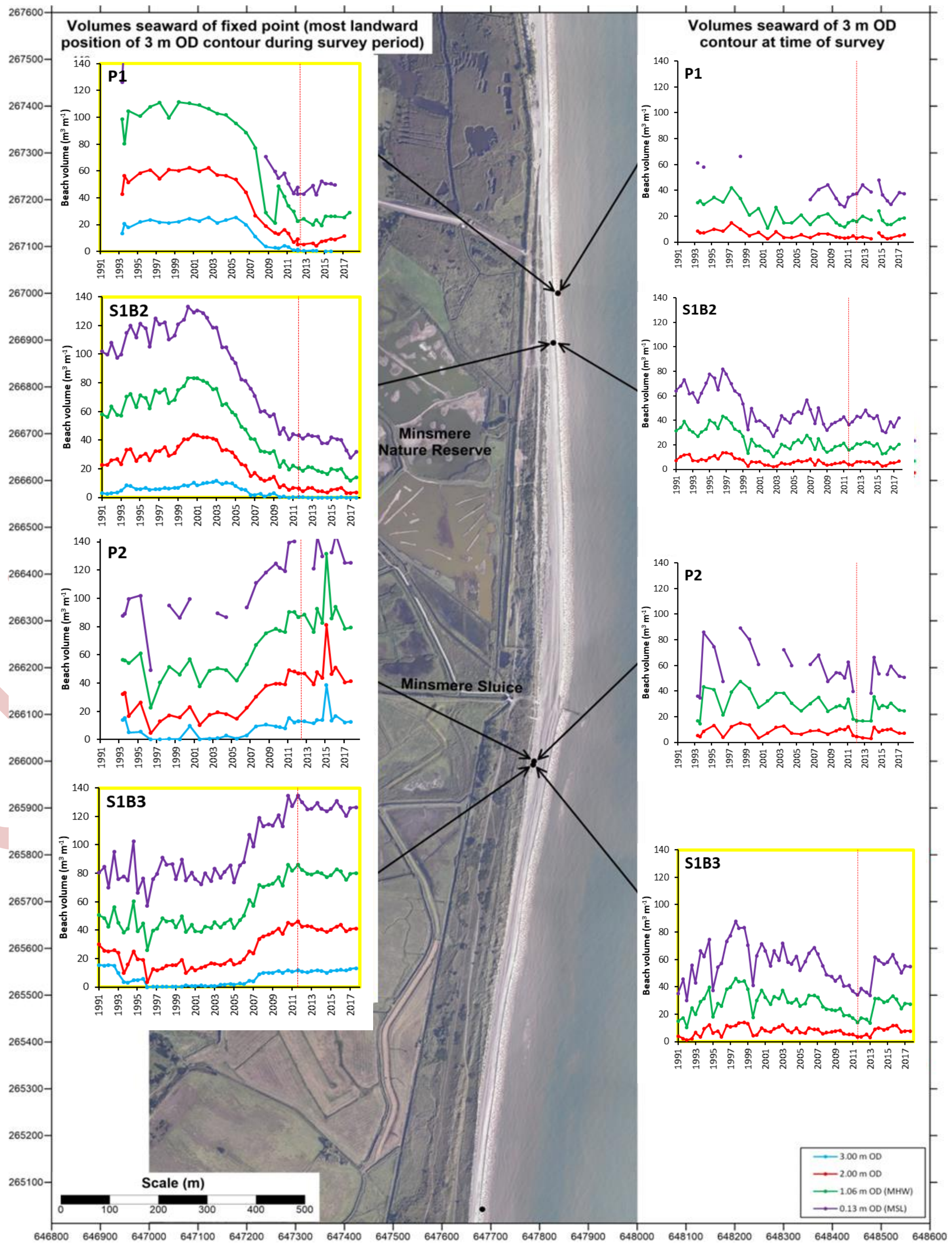

Figure 27: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: Minsmere Cliffs to Sizewell north. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

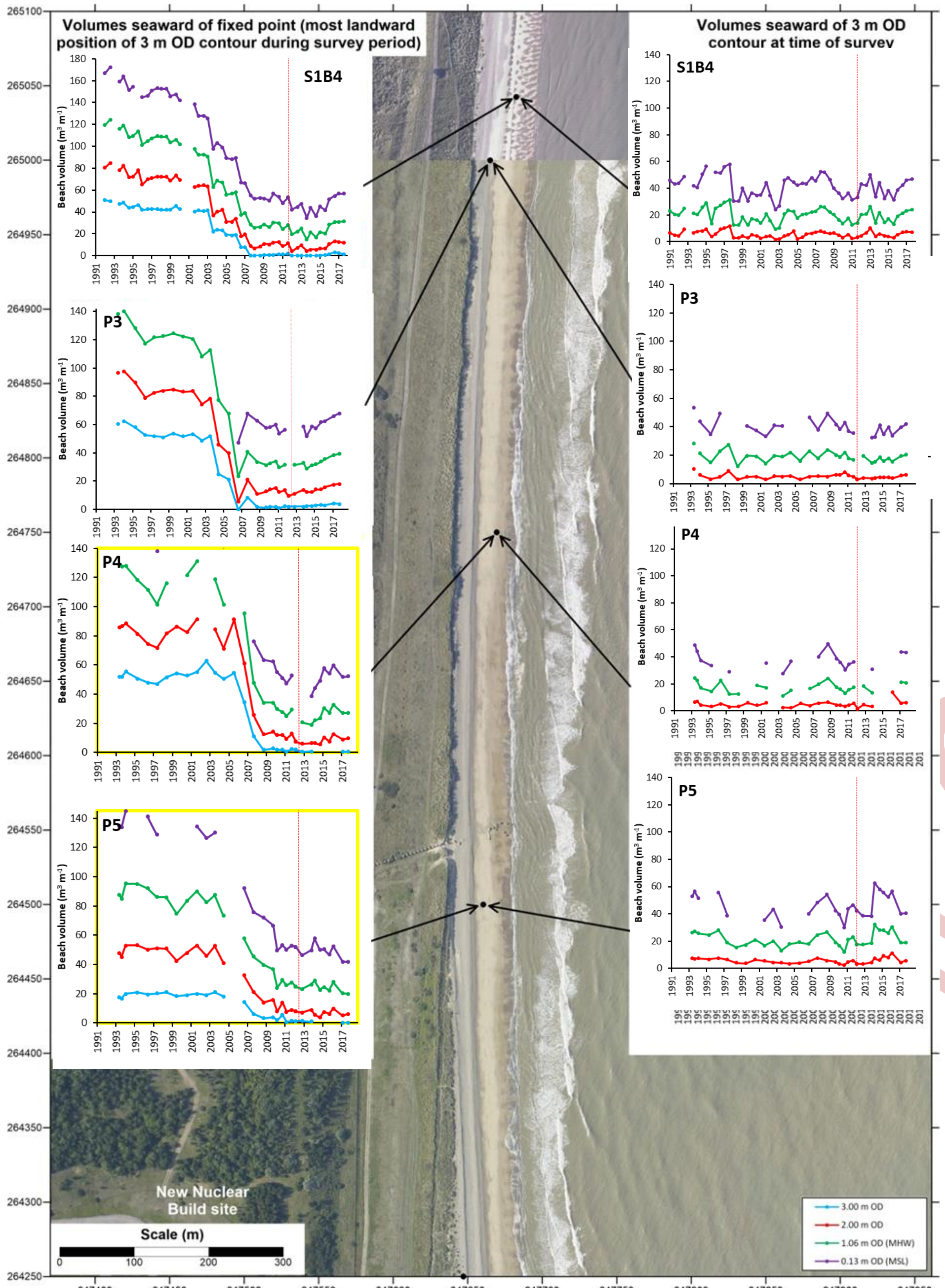

Figure 28: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: Sizewell north. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

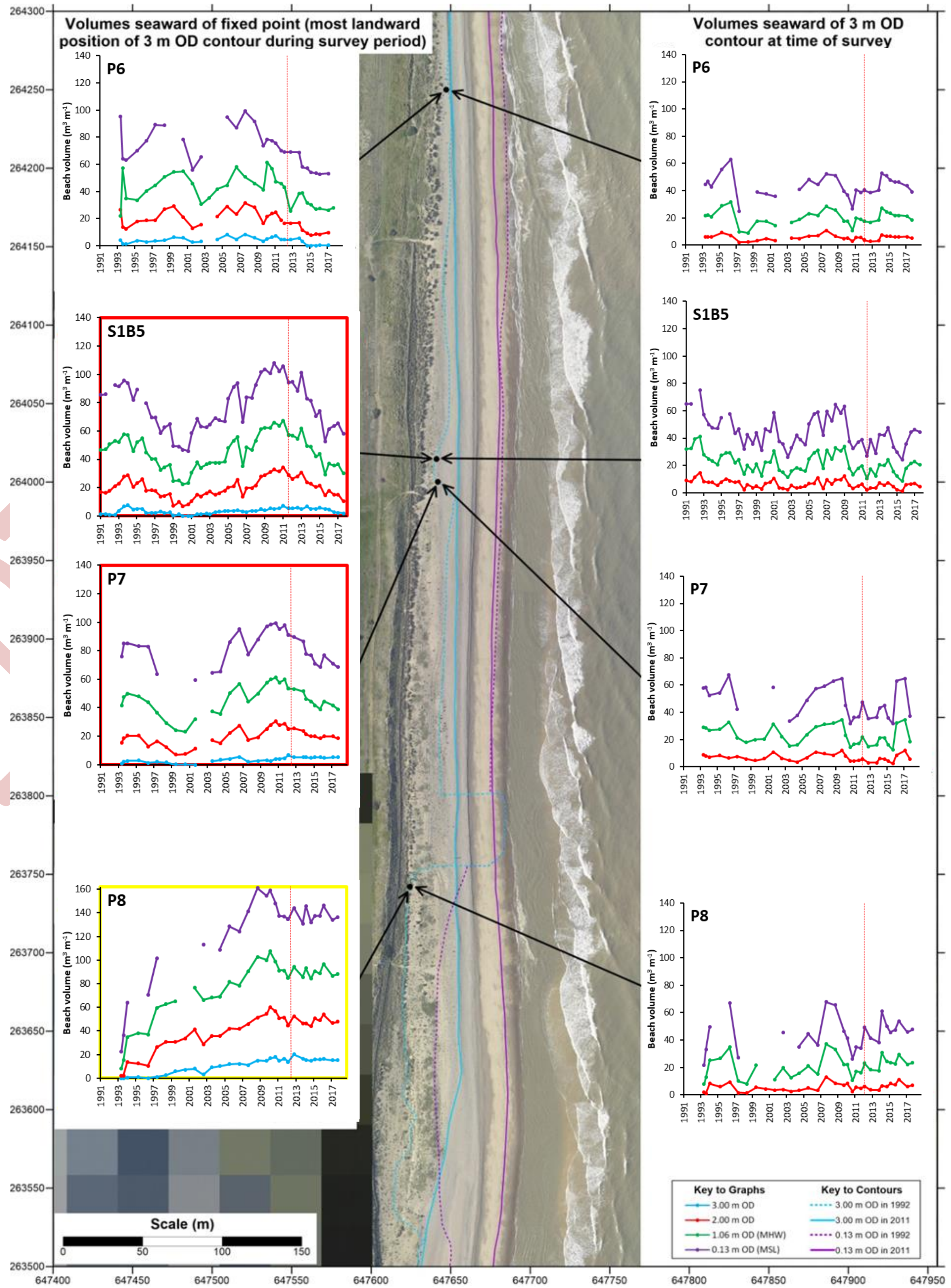

Figure 29: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: SZB. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

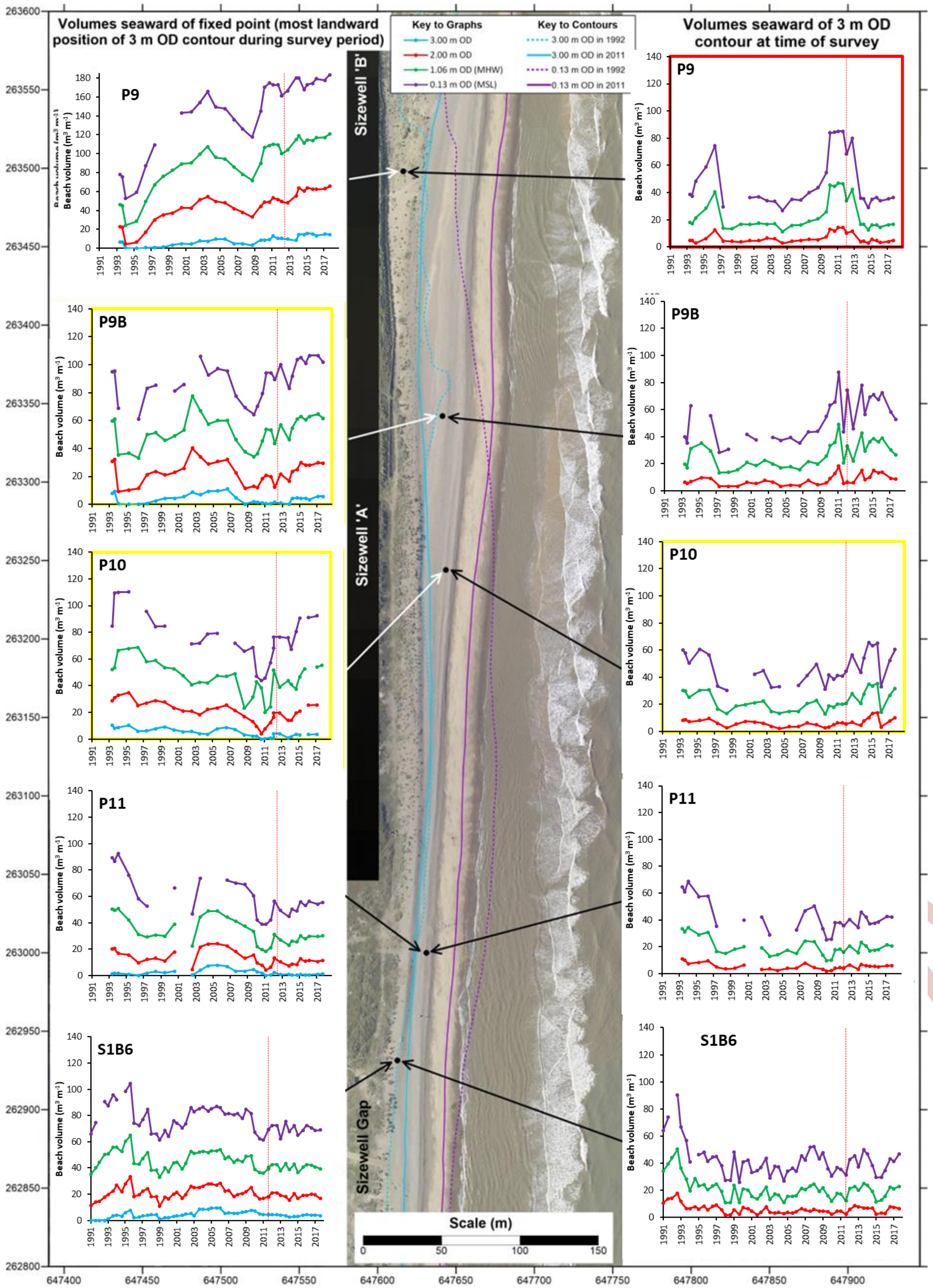

Figure 30: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: SZA. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

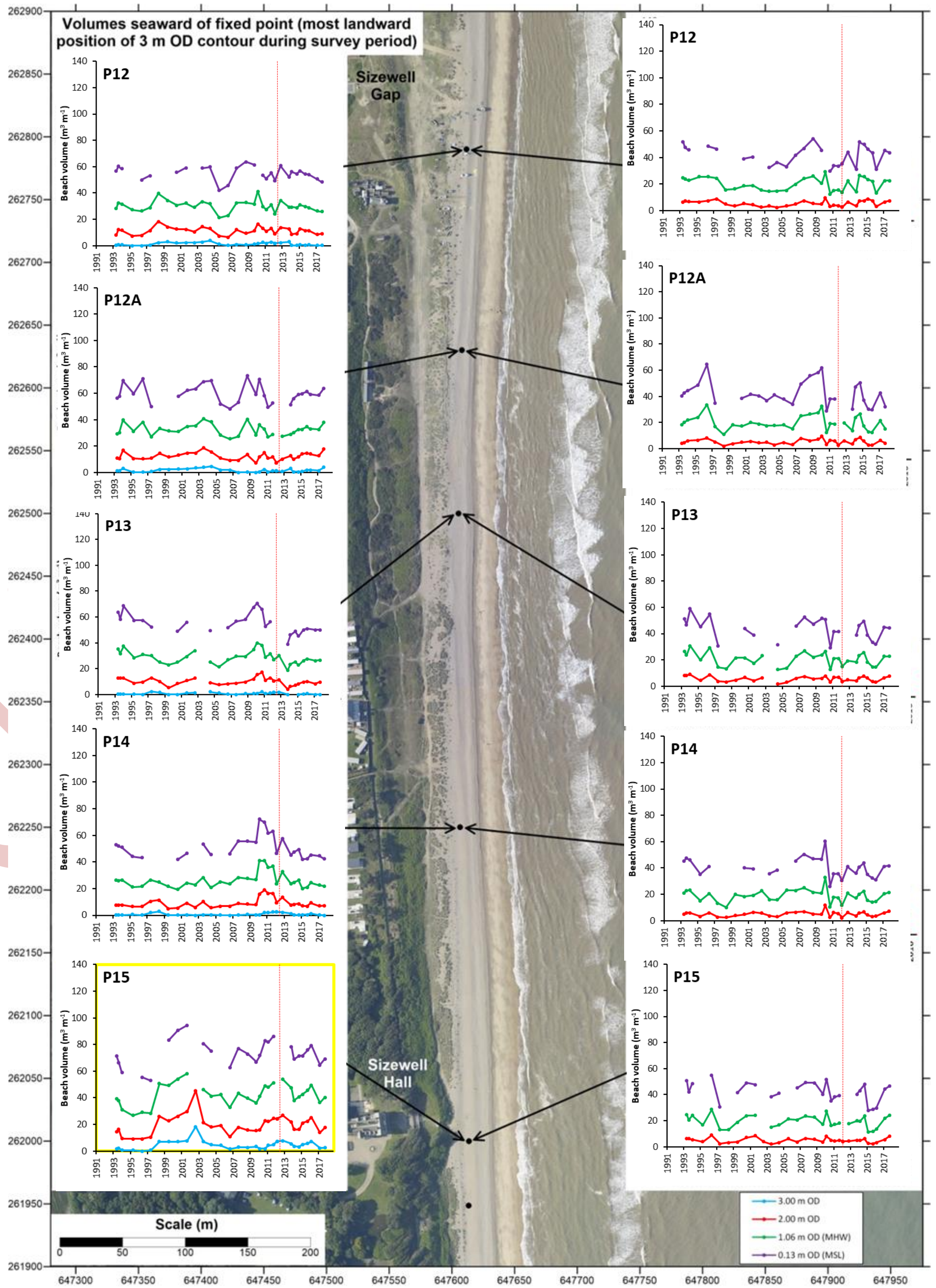

Figure 31: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: Sizewell Gap to Sizewell Hall. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

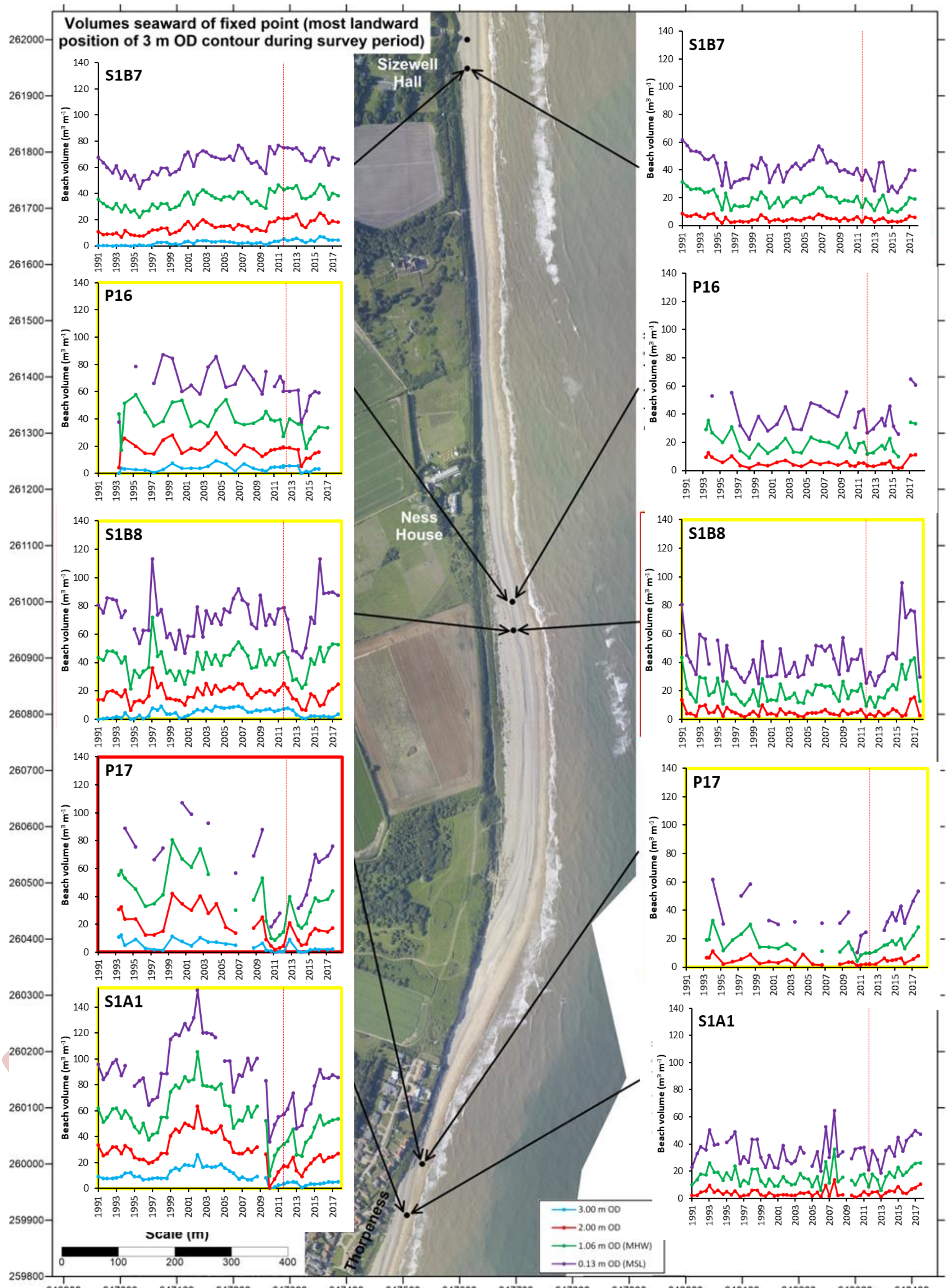

Figure 32: Changes in beach sediment volume above 3.00, 2.00, 1.06 and 0.13 m OD contours, based on beach topographic surveys 1991 – 2017/18: Sizewell Hall to Thorpeness. Calculated using method (a) volume above MHW, seaward of the 3.0 m OD contour at the time of survey (right hand graphs); (b) volume above MHW, seaward of the most landward position of the 3.0 m OD contour during the survey period (left hand graphs). Base aerial photography flown 2011. Plots with red borders indicate large trend or stability changes since 2012, whilst yellow borders indicate lesser trend changes and white borders indicate no trend change. Vertical dashed red lines indicate the date of latest data included in the BEEMS Technical Report TR223, second edition (2014).

6.1.3.3 *Interpretation of beach volume change*

Method (a) shows that the beach volume at the southern end of the Dunwich - Walberswick barrier (S1C5) (Figure 26) fluctuated around a relatively stable beach volume throughout the survey period, losing sediment in a number of storms and surges (see Table 10), followed by periods of slow recovery. Nevertheless, this has been accompanied by a gradual progradation of the upper beach contours and the net effect has been an increase in sediment volume landward of the 1991 3.0 OD position, mostly since 2000 (method (b)).

Method (a) shows that the beach at Dunwich Cliffs (S1C6) (Figure 26) experienced major sediment gain in 1993 and equivalent loss in 1996, followed by recovery until 2010, with a short reversal in the stormy period 2004 – 2007. Following a period of relative stability between 2007 – 2011, fluctuations in beach volume around a relatively stable beach volume were observed. A further sudden reduction in beach volume occurred in 2011. Until 2013, method B indicated that there was no significant change in the sediment volume seaward of the fixed 3.0 m OD contour, after which there was a minor increase in the volumes represented below all contours. Neither method indicated any significant net volume change over the entire period. Taken together with the advance and retreat of the contours (Figure 17) the data indicate a repeated flattening and steepening for the beach profile.

At Cliff House (S1C7) (Figure 26) the 1995 – 1996 storms resulted in less beach volume reduction than on the adjacent beaches, and for the most part, little net change in shoreline position and beach volume (was observed by either method. However, since 2011, method (b) has shown a gradual reduction in beach volumes above all contours.

The beach at Minsmere Cliffs (S1B1) (Figure 26) experienced significant sediment loss during the winter of 1992/93 that continued through 1994, before recovering rapidly in the following year. The 1995/96 storms caused further significant sediment loss, and marked the beginning of period of retreat and net decreasing beach volume that continued up to 2005, with an overall volume loss of 50 % relative to 1992 levels. Subsequently, both methods observed beach volumes move toward stability and minor accretion.

Due to their close proximity, profiles P1 and S1B2 at Minsmere showed similar trends (Figure 27). Method (a) showed net volume losses of approximately 40 % during the period between 1991 – 2000, before stabilising and subsequently fluctuating around a maintained beach volume of approximately 40 m^3 m^{-1} above MSL. In contrast, method (b) showed beach volumes increased during the period 1991 – 2000 as the coastline prograded, before steadily eroding landwards, losing approximately 70 % volumes of sediment. The observed stabilisation in beach sediment volumes for both methods between 2012 – 2017/18 suggests that 30 – 40 m^3 m^{-1} (above MSL) represents the minimum beach volume possible at this location, even during an erosional phase.

Profiles P2 and S1B3 located, just to the south of Minsmere sluice, also showed similar trends due to their close proximity (Figure 27). Method (a) showed pronounced fluctuations, consistent with the highly variable shoreline behaviour observed around Minsmere Sluice (see Section 6.1.6). Overall, sediment volumes doubled during the period of 1991 – 1997, before steadily returning to a volume of approximately 40 m^3 m^{-1} above MSL by 2013. Following an increase in sediment volume up to 70 m^3 m^{-1}, sediment volumes remained relatively stable. Broader patterns identified by method (b) showed a relatively stable beach volume with intra-annual variations of up to 25 %, before a steady increase in sediment volumes during the period of 2005 – 2011, since when, volumes have remained relatively stable.

South of the sluice as far as the northern perimeter of the SZC frontage, profiles (S1B4 (north) to P5 (south)) all showed similar trends for both methods (Figure 28). Method (a) showed a relatively stable each sediment volume of 40 m^3 m^{-1} above MSL, with minor fluctuations. Method (b) showed a gradual decrease in beach sediment volumes at all contours between 1991 – 2003. All profiles experienced a more accelerated (but variable) loss of beach sediment between 2003 – 2009, before subsequently stabilising over the following eight years at 40 to 60 m^3 m^{-1} above MSL, with some minor accretion observed at S1B4 and P3 since 2012.

P6 showed a similar trend for method (a) as S1B4 to P5 (Figure 29). In contrast, method (b) showed a highly variable beach sediment volume that fluctuated between 60 to 100 m^3 m^{-1} above MSL, with some minor decrease in sediment volume since 2011. This highly variable area marks the northern boundary of the proposed SZC site and coincides with the transition zone between erosion to the north (Minsmere South) and accretion to the south (Sizewell power station frontage) as described by beach contour change analysis.

Due to their close proximity, S1B5 and P7 (central SZC frontage) showed similar trends for both methods (Figure 29). Method (a) showed an initial decrease in sediment volume from 70 to 50 m^3 m^{-1} above MSL, before subsequently fluctuating around a beach volume of approximately 50 m^3 m^{-1} above MSL. A stepped decrease in sediment beach volume occurred in 2008/09, with beach volumes since fluctuating around a beach volume of 40 m^3 m^{-1} above MSL. Method (b) indicated a gradual reduction in beach volumes from 80 to 50 m^3 m^{-1} above MSL between 1991 – 2001, before subsequently increasing in sediment volume, up to 110 m^3 m^{-}1 above MSL sediment between 2001 – 2009. Since 2011, a gradual reduction in beach sediment volume was again observed. During this period, the coastline fronting the proposed SZC site neither retreated nor advanced over this period in net terms, rather the beach responded to storms by flattening and steepening in profile.

Profiles P8, P9 and P9B (adjacent to SZB) all showed similar trends (Figure 29 to Figure 30). Method (a) showed an approximate doubling in sediment volumes from 40 to 80 m^3 m^{-1} above MSL between 1993 – 1996 as the beach recovered following the removal of the coffer dam (1992) and BLF (1993), before an equivalent loss of sediment volume occurred as a result of the October 1996 storm event. Steady but minor recovery in sediment volumes was observed between 1997 – 2007, before an accelerated increase up to 80 m^3 m^{-1} above MSL was observed between 2007 – 2011 as the beach prograded. Following the June 2013 storm, P9 experienced a greater volume reduction in comparison with profiles P8 and P9B, which remained fairly resilient, showing periods of erosion and abrupt recovery throughout the 2010 – 2016 period, before showing minor decreases in volume since 2016. Method (b) showed steady and significant increases in sediment volume at P8 and P9 between 1993 – 2009 and subsequently remained stable at approximately 140 to 180 m^3 m^{-1} above MSL. These increases are associated with the development of the aforementioned salient feature. P9B also showed a gradual, albeit comparatively minor increase in sediment volume from 80 to 100 m^3 m^{-1} above MSL throughout the whole period.

Profiles P10, P11 and S1B6 (SZA to Sizewell Gap) all showed similar trends (Figure 30). Method (a) showed a decrease in sediment beach volume as a result of the storm in early 1993 and was most pronounced at S1B6, which showed a decrease in sediment volume from 90 to 40 m^3 m^{-1} above MSL. Subsequently, all profiles remained relatively stable with minor fluctuations around a beach volume of 40 m^3 m^{-1} above MSL until 2011, since when, some minor accretion was observed. Method (b) observed an initial increase in sediment volumes between 1991 – 1994 for all profiles. P10 subsequently experienced a steady decrease in sediment volume to approximately 50 m^3 m^{-1} above MSL in 2010, before recovering to an approximate volume of 90 m^3 m^{-1} above MSL in 2017, similar to the volumes observed in 1993. P11 and S1B6 also showed a gradual decrease in sediment volumes, but then experienced a minor increase in beach volume in 2002, that was subsequently stable at 80 m^3 m^{-1} above MSL between 2002 – 2009. A secondary reduction in beach volumes to 40 and 60 m^3 m^{-1} above MSL respectively occurred in 2010. Some recovery was subsequently observed at both P11 and S1B6 in 2011, which has continued at P11, but stabilised at S1B6. The 3.0m OD contour has remained more stable in this area, but the lower beach contours have retreated, indicating a steepening profile. The secondary reduction in beach volumes relative to 3.0 m OD at the time of survey in 2010 was again due to steepening of the profile, as volumes relative to a fixed-point showed little to no reduction after 2010 (Figure 32).

To the south, between profiles P12 and P16 (Sizewell Gap to Ness House), minor fluctuations were observed, but with little net change was observed between 1991 – 2017 and so might be described as being in dynamic equilibrium (Figure 31 and Figure 32). Method (a) recorded beach sediment volumes being maintained at approximately 40 m^3 m^{-1} above MSL, whilst method (b) showed a volume of approximately 60 m^3 m^{-1} above MSL and was slightly more variable.

Profiles S1B8 to S1A1 (Thorpeness) show similar trends based on both methods, but with slight differences between S1B8 (north of the Ness) and both P17 and S1A1 (to the south of the Ness) (Figure 32). Method (a) indicates that although variable, beach sediment volumes remained relatively stable between 1991 – 2013. This stability continued at S1B8, before rising sharply from 40 to 100 m^3 m^{-1} above MSL in 2015, before returning to 40 m^3 m^{-1} above MSL in 2017. In contrast, P17 and S1A1, experienced a gradual increase in beach sediment volumes between 2013 – 2017, rising from 30 to 50 m^3 m^{-1} above MSL. Method (b) showed a gradual decrease in sediment volume between 1991 and 1996. A sharp increase in beach volume occurred in 1997, before returning to 1996 levels by 1999. Slow beach recovery was observed up until 2005, before stabilising but showing large fluctuations around a sediment volume of approximately 80 m^3 m^{-1} above MSL until 2011. Following a subsequent decrease in sediment volume between 2011 – 2014, the beach showed rapid recovery, up to 110 m^3 m^{-1} above MSL in 2015, before a minor reduction and subsequent stabilisation in sediment volumes at approximately 90 m^3 m^{-1} above MSL. In contrast, method (b) showed a relatively stable beach volume at P17 and S1A1 between 1991 – 1997, followed by progradation between 1997 – 2002, when the beach became much wider and higher in front of Thorpeness village. The beach then entered an erosional phase, with beach volumes decreasing dropping between 2010 – 2012. This decrease in beach levels exposed old sea defences and required the construction of rock gabion defences to protect vulnerable properties. 2011 – 2012 saw some upper beach recovery, but here and at many locations in the vicinity of Thorpeness, sharp reductions in sediment volume were apparent in 2013, possibly due to a storm event in June 2013. Further recovery was then observed up until 2015 and subsequently stabilised at approximately 80 to 90 m^3 m^{-1} above MSL.

Table 10: Observed high tides at Lowestoft exceeding 2.00 m OD (the approximate 1 in 1 year water level at Sizewell, BEEMS Technical Report TR252) in the period January 1964 to December 2017. Significant erosion events, identified from EA beach topographic surveys 1991-2018, are also indicated.

Date	Observed HW (m OD)	Skew Surge (m)	Significant Erosion Events 1991-2012
10/12/1965	2.13	1.17	
29/09/1969	2.71	1.61	
19/10/1970	2.00	1.08	
21/11/1971	2.27	1.35	
02/04/1973	2.19	1.33	
19/11/1973	2.14	1.45	
25/11/1973	2.02	1.08	
06/12/1973	2.06	1.38	
14/12/1973	2.47	1.39	
03/01/1976	2.20	1.35	
03/01/1976	2.68	1.66	
20/01/1976	2.04	0.93	
11/01/1978	2.33	1.15	
24/11/1981	2.01	1.17	
01/02/1983	2.69	1.55	
03/01/1984	2.05	1.12	
14/02/1989	2.31	1.52	
26/02/1990	2.14	1.01	
07/10/1990	2.18	0.92	
12/12/1990	2.02	1.25	
12/12/1990	2.24	1.55	
25/01/1993	2.10	1.33	
21/02/1993	2.68	1.91	Erosion at S1B3
14/11/1993	2.33	1.22	
20/12/1993	2.06	1.12	
28/01/1994	2.41	1.53	
13/03/1994	2.06	1.05	
01/01/1995	2.36	1.27	Erosion particularly bad at
10/01/1995	2.17	1.44	S1C7, S1B1 and S1B8
29/10/1996	2.30	1.17	Erosion at S1B3, S1C6, P1, P2
04/02/1999	2.13	1.07	
30/01/2000	2.18	1.49	
11/02/2000	2.02	1.02	
15/12/2003	2.20	1.29	Erosion at S1B4
08/02/2004	2.00	0.92	
12/01/2005	2.18	1.03	Erosion at S1B1
14/02/2005	2.04	0.90	
31/10/2006	2.04	1.26	Erosion particularly bad
01/11/2006	2.24	1.41	at S1B4 and S1B5, P1, P3, P4
12/01/2007	2.14	1.35	
18/03/2007	2.16	1.09	
08/11/2007	2.04	1.13	
09/11/2007	2.63	1.64	
25/11/2007	2.19	0.96	
01/03/2008	2.11	1.59	
27/11/2011	2.33	1.16	
05/01/2012	2.14	1.37	Erosion particularly bad at
05/12/2013	3.22	2.06	S1A1, S1B1 and S1B8
11/01/2015	2.18	1.22	Erosion at S1B4, S1B5
13/01/2017	2.34	1.20	Erosion at S1B8

6.1.4 Short-term changes in nearshore sediment volumes, based on topographic and nearshore bathymetric surveys (1992 – 2017)

The volume calculations presented in Section 6.1.3 are for the subaerial (terrestrial) part of the beach and are substantial in their spatial and temporal coverage, however, they do not include the subtidal part of the beach. Figure 33 uses the EA long profiles collected every 5 years between 1992 – 2017 (i.e., profiles over the subaerial and subtidal beach) to show the total beach sediment volume above the -6.00 and 0.13 m OD contours (Table 11).

The bathymetric dataset acquired between 03/06/14 – 29/06/14 (and provided on 02/11/2016 by the EA) was combined with EA topographic profiles acquired on 05/08/2014. As well as the temporal mismatch of these datasets, the bathymetric dataset often terminated approximately 50 m seaward of the topographic surveys. In order to calculate volumes for 2014, the ~50 m of missing data was linearly interpolated for the two dates. The resulting 2014 volumes indicate that since 2011 there has been a minor reduction in sediment volume at S1B4, S1B5 and S1B7 and an increase in sediment volume at S1B6, however these changes are small whilst the inaccuracies in this method introduce a large amount of uncertainty. Volumes in 2014 were generally consistent with 2017 volumes, suggesting relative stability since 2011, with the greatest reduction at S1B5 (17 % between 2011 and 2017).

Above the -6.00 m OD contour, there was a net loss in sediment volume of 22 % at profile S1B1 between 1992 – 2011, with most losses occurring between 1992 – 1997, before remaining relatively stable until 2011. No data exists post 2011 at this profile. Similar trends in sediment loss were observed above the 0.13m OD contour.

Above the -6.00 m OD contour, there was a net loss in sediment volume of 31 % at S1B2 between 1992 – 2017, with most losses occurring between 2003 – 2007 with minor losses continuing up to 2017. Similar trends in sediment loss were observed above the 0.13m OD contour.

Above the -6.00 m OD contour at profile S1B3, just south of Minsmere sluice, there was notable variation but a net 5 % gain between 1992 – 2017 (i.e., similar to the shoreline change patterns there). Above the 0.13 m OD contour, a net gain of sediment was also observed, mostly occurring between 2003 – 2011.

Above the -6.00 m OD contour, there was a net loss of sediment volume of 21 % at S1B4 between 1992 – 2017, with most losses occurring between 2003 – 2007. Volumes remained relatively stable between 2007 – 2017, except for a small increase in volume observed in 2011 that subsequently decreased in 2014. Similar trends in sediment loss were observed above the 0.13 m OD contour up until 2011, before relatively small gains in sediment volume were observed between 2011 – 2017.

Above the -6.00 m OD contour at S1B5 (opposite the NNB site), following a gain of sediment between 1997 – 2003, subsequent losses from the subtidal area observed after 2003, attributed to the northward growth of the salient feature opposite the SZB outfall, resulted in a net loss in sediment volume of 13 % between 1992 – 2017. Above the 0.13 m OD contour, sediment volumes showed notable variation with an overall net loss..

Above the -6.00 m OD contour at S1B6 near Sizewell Gap, the temporal pattern was very similar to that of S1B5, with a net reduction in sediment volume of 6 % between 1992 – 2017. Whilst a net loss of sediment volume was also observed above the 0.13 m OD contour, fluctuations were less pronounced than those observed at S1B5.

Above the -6.00 m OD contour at S1B7, near Sizewell Hall, there was a net loss in sediment volume of 8 %, with volume fluctuations observed were relatively small compared with other sites. Low variability was also observed above the 0.13 m OD contour, with a small net gain of sediment.

Table 11: Sediment volumes in the beach and nearshore zone along seven combined topographic and bathymetric EA profiles between Minsmere Cliffs and Thorpeness between 1992 – 2017. Volumes are expressed per metre width of beach and calculated above -6.00 m OD and above 0.13 m OD, to seaward of the most landward position of the 3.00 m OD contour recorded since 1992. Note that volume data calculated for 2014 was calculated using linear interpolation between the extents of EA topographic profiles and EA bathymetric data which were separated by approximately 50m.

Profile	Volume above -6.00 m OD (m^3 / m^{-1})							Change 1992-2017	
	1992	1997	2003	2007	2011	2014	2017	(m^3/m^{-1})	(%)
S1B1	1382	1107	1102	1161	1080			-302	-22
S1B2	1302	1284	1380	1054	968	966	892	-410	-31
S1B3	1245	1152	1334	1268	1308	1303	1313	68	+5
S1B4	1331	1266	1260	1055	1132	1058	1055	-276	-21
S1B5	1196	1075	1306	1235	1217	1113	1040	-156	-13
S1B6	1199	1133	1383	1219	1111	1238	1132	-67	-6
S1B7	1048	956	No Data	1003	1080	906	963	-85	-8

Profile	Volume above 0.13 m OD (m^3 / m^{-1})							Change 1992-2017	
	1992	1997	2003	2007	2011	2014	2017	(m^3 / m^{-1})	(%)
S1B1	139	71	66	62	70			-69	-50
S1B2	108	121	119	71	44	42	31	-77	-71
S1B3	70	79	83	99	127	119	118	48	+69
S1B4	167	151	126	66	48	52	64	-103	-62
S1B5	92	70	65	84	106	81	66	-26	-28
S1B6	91	77	83	82	61	70	73	-18	-20
S1B7	60	57	72	74	77	56	61	1	+2

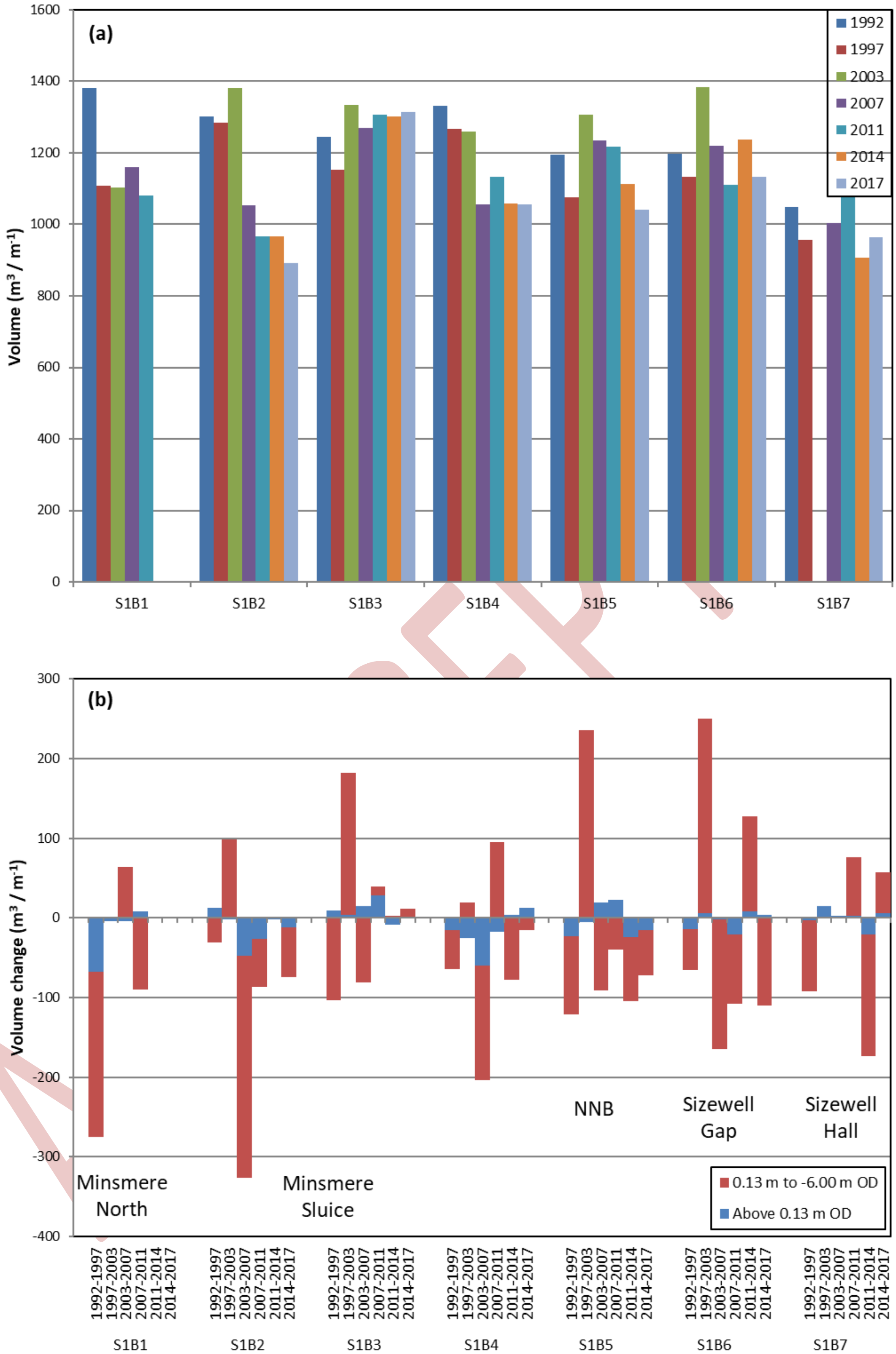

Figure 33: Beach and nearshore sediment volumes changes at EA profile locations between Minsmere Cliffs and Thorpeness between 1992 – 2017. (a) total sediment volume above -6.00 m OD contour and seaward of the most landward recorded position of the 3.00 m OD contour; (b) volume changes between 0.13 and -6.00 m OD contours and above the 0.13 m OD contour. Note that volume data calculated for 2014 was calculated using linear interpolation between the extents of EA topographic profiles and EA bathymetric data which are separated by approximately 50m.

6.1.5 Short-term changes in beach and nearshore morphology, based on topographic and nearshore bathymetric surveys (1992 – 2017)

The combined EA beach topographic and nearshore bathymetric survey data indicated that two nearshore bars are typically present along the Minsmere to Sizewell Hall coastline (Figure 34, Figure 35 and Figure 36), but cease to exist between Sizewell Hall and Thorpeness, (BEEMS Technical Report TR308 second edition). Both of the bars are aligned roughly shore-parallel, orientated north-south between Minsmere cliffs and Minsmere Sluice. For approximately 1 km south of the sluice they are deflected to run NNE to SSW, after which they return to a north to south orientation (with a very slight seaward bulge of the outer bar around the SZB outfall) (Figure 36). The inner bar was usually but not always present north of Minsmere, and from Sizewell Hall to the south there was typically only one bar. The 2014 survey did not extend sufficiently far inshore to measure the inner bar. The nearshore morphology around Thorpeness exhibits a combination of smaller sedimentary bedforms (not bars) and outcrops of Coralline Crag.

Bar crest locations were assessed manually from the profiles shown in Figure 34 and Figure 35, informed also by 2D elevation mapping. Whilst the bars often showed a clear crest peak, the bars become less well defined to the south towards Thorpeness, as small waveforms superimpose and eventually dominate the bars (see Figure 35, S1A1). The last profile for which the bar crest was determined was profile S1B8, however the positions at S1B8 should be interpreted with caution as a clear crest was not always identifiable. Where there was uncertainty about the location of the bar crest due to flat-topping or lack of clarity due to superimposed transverse bedforms (common on the outer bar), an estimate of its position has not been provided. On the few occasions where the peak of the bar falls between transverse bedforms, the peak has been taken to be the highest of the two waveforms.

The crest of the inner bar was usually located 50 to 150 m seaward of the 3 m OD contour, with a crest elevation ranging from -1.25 m OD to -3.0 m OD (Figure 37). There was significant variation in the position and height of the bar on any one survey, and, at some locations, between surveys. However, south of Minsmere Sluice to Sizewell Gap, the bar was consistently high (approximately -1.5 m OD) and close to the shoreline since 1992. This area includes the eroding frontage from the northern boundary of SZC to Minsmere Sluice (S1B4, S1B5).

The outer bar was volumetrically larger with a crest located 150 to 400 m from the 3.0 m OD contour, with a deeper crest elevation ranging between -2.5 m OD to -4.5 m OD (Figure 38). The bar was generally furthest from the 3.0 m OD contour near the SZB cooling water outfall and adjacent to the Dunwich-Minsmere cliffs, and most landward adjacent to the eroding shorelines on either side of Minsmere Sluice and towards Thorpeness, where the bar disappears. BEEMS Scientific Advisory Report Series SARS018 postulates that the outer bar formed in response to long period waves at times of high-water stand, while the smaller and more ephemeral inner bar forms in response to shorter period storm waves.

At profile S1C5 (Dunwich Cliffs), the elevation of the inner and outer bars remained relatively stable at -2.0 and -3.5 m OD respectively, between 1992 – 2017. Whilst the outer bar remained relatively static, the inner bar showed a net movement of approximately 30 m seaward between 2003 -2017 (Figure 34).

At profile S1C7 (Dunwich Cliffs), the inner bar showed fluctuations in both elevation and position. In 1997, the inner bar had an elevation of -1.75 m OD. A definable crest had disappeared by 1997, reappearing in 2007 approximately 25 m seaward and with an elevation of -2.0 m OD. By 2017, the inner profile had returned to a form very similar to that observed in 1992. In contrast, the outer bar had a definable crest with an elevation of -4.5 m OD (deepest point) observed in 1992, before subsequently gaining and maintaining an elevation of -3.75 m OD throughout the survey period. A landward movement of 50 m was observed between 1997 – 2003, before a subsequent secondary movement of 75 m between 2003 – 2007 before stabilising (Figure 34).

Profile S1C7 (Minsmere Cliffs) showed that the inner bar maintained a stable elevations of -1.75 m OD respectively, between 1992 – 2017. Following an elevation gain of 0.5 m between 1992 – 1997, the outer bar subsequently maintained an elevation of 4.0 m OD. Both bars also showed net landward movement. The inner bar moved approximately 30m between 1997 – 2003 before stabilising, whilst the outer bar moved landward 50 m between 1997 – 2003, with a subsequent secondary movement of 100 m between 2003 – 2007 before stabilising (Figure 34).

At S1B1 and S1B2 (north of Minsmere Sluice), both inner and outer bars showed substantial variability in elevation and position. In 1997, the inner bar had an elevation of -1.5 m OD. By 2007, the inner bar had migrated landward by 100 and 50 m at S1B1 and S1B2 respectively, whilst the profile had lost a discernible crest. Between 2007 – 2017, the inner bar had maintained its position and recovered a defined crest with an elevation of -1.5 m OD. At S1B1, the outer bar maintained an elevation of -3.5 m OD between 1992 – 2003, before gaining approximately 0.5 m in height and moving landward 100 m by 2007 where it subsequently stabilised. At S1B2, whilst the outer bar maintained an elevation of -3.25 m OD throughout the survey period, a net landward migration of 100 m was also observed (Figure 34).

Profile S1B3 (immediately south of Minsmere Sluice), the inner bar initially maintained a discernible crest with an elevation 0f -1.25 m OD (shallowest point). Subsequently, the profile migrated landward approximately 50 m, but lost a discernible crest form, reverting to a nearshore shelf with an elevation of -1.0 m OD. The outer bar maintained an elevation of -2.5 m OD (shallowest point) throughout the survey period, but showed fluctuations in its position, with a net landward migration of 50 m (Figure 34).

At profile S1B4 (north of the proposed SZC site), the inner bar maintained a crest elevation of -1.5 m OD, with very little migration throughout the survey period. The outer bar also maintained a well-defined crest throughout the survey period but showed a net landward migration of 75 m and a minor net decrease in elevation from -2.75 m OD to -3.25 m OD between 1992 – 2017 (Figure 35).

At S1B5 (adjacent to the proposed SZC site), the inner bar showed fluctuations between a crest and shelf form, but generally maintained its position and an elevation of -1.5 m OD between 1992 – 2007. By 2017, the crest had become well defined, gaining almost 0.5 m in height and moving approximately 50 m landward. In contrast, the outer bar showed substantial variability. In 1992, the outer bar had a well-defined crest with an elevation of -3.5 m OD and a sharp trough along its landward edge that reached a depth of -6.0 m OD. By 1997, the crest appeared to split, resulting in the infilling of the observed trough as well as a crest form developing approximately 125 m seaward of that observed in 1997. These changes may be associated with beach recovery, following the removal of the coffer dam (1992) and BLF (1993) and associated maintenance dredging. Subsequently, a single crest developed approximately 50 m landward of the 1992 outer bar position and maintained an elevation of -3.0 m OD for the remainder of the survey period (Figure 35).

At S1B6 (immediately south of SZA), the inner bar maintained defined crest with a relatively stable elevation of -1.0 m OD and showed little net migration throughout the survey period. Between 1992 – 2003, the outer bar also maintained a well-defined crest with an elevation of -3.25 m OD and also showed little migration. Subsequently, the outer bar showed fluctuations in its morphology and location, with a net landward migration of 175 m and a minor loss of elevation of approximately 0.5 m (Figure 35).

At S1B7 (adjacent to Sizewell Hall), the bars showed variability as the outer bar begins to merge with the inner bar. Consequently, whilst a defined inner and outer bar was present in 1992, by 2017, the inner bar showed little net change in morphology and position, whilst the outer bar lost a defined crest, instead contributing material to the seaward face of the inner bar resulting in a relatively linear and more stable lower gradient. This variability was also observed at S1B8 (north of the Ness) as both bars continued to merge and lose elevation. By S1A1 (south of the Ness), no nearshore bars are identifiable and the profile showed variability, with an overall gain in depth progressing seaward at a gentle gradient of approximately 1:200 (Figure 35).

The merging of the nearshore bars may be linked to the presence of Thorpeness and/or declining wave energy levels toward the south of the bay (see Section 7.5), as double bar systems are indicative of higher energy levels compared to single and no-bar profiles.

Due to the coarse resolution of these surveys (5 years) it is difficult to determine whether these positional changes represent significant (fluctuating) migrations of the bar in response to (seasonal) storms, or long-term changes (trends) due to sediment budgets. It is possible that bar position and elevation is much more dynamic than represented by the five to six snap-shots shown here. In addition, the 2011 and 2014 swath bathymetric survey data did not cover most of the more inner bar (due to shallow depths), resulting in a 150 m gap between the subaerial LiDAR beach surveys (Appendix B).

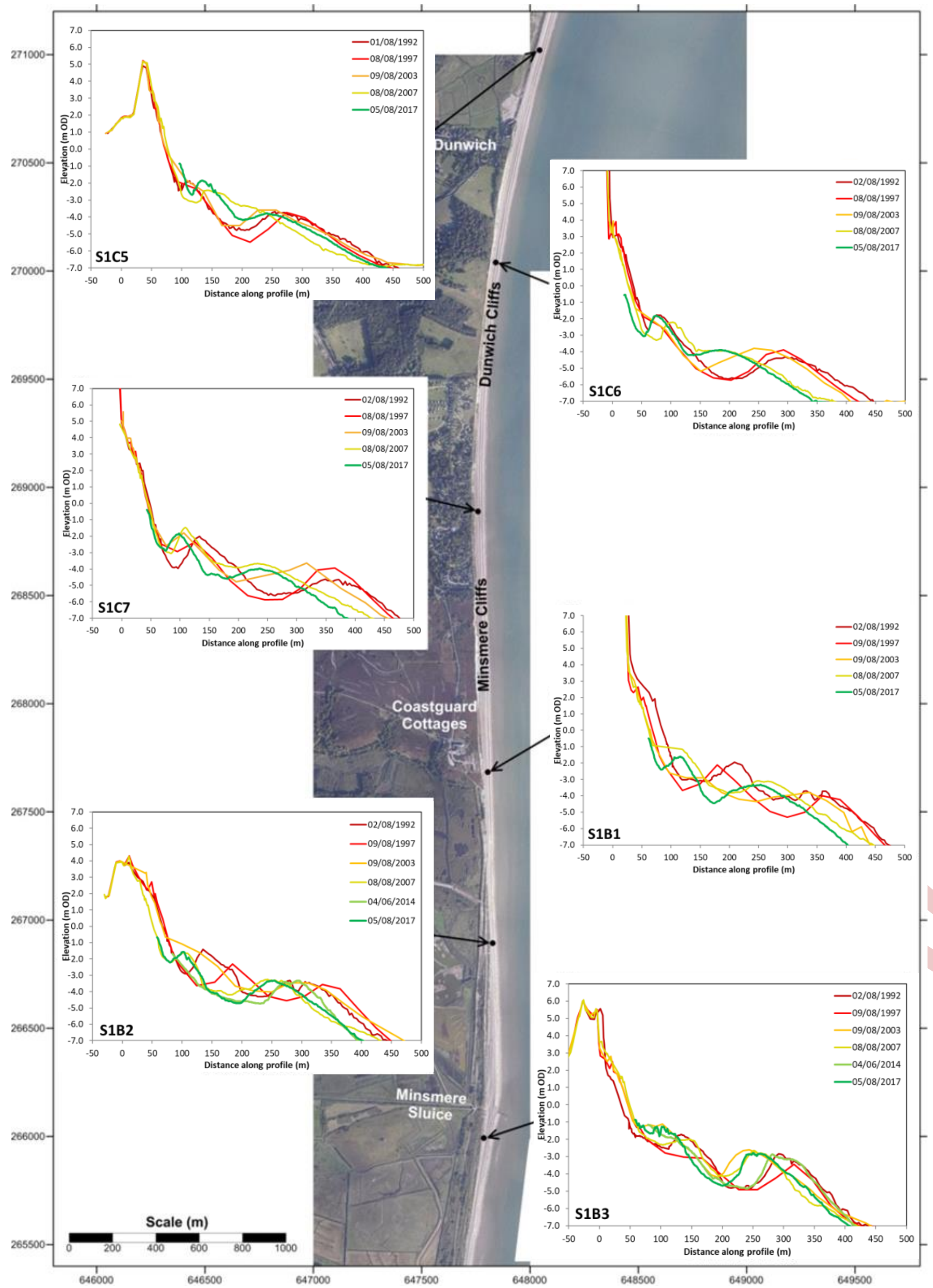

Figure 34: Combined beach and nearshore profiles based on EA topographic and bathymetric surveys in 1992, 1997, 2003, 2007, 2014 and 2017 between Dunwich and Minsmere Sluice.

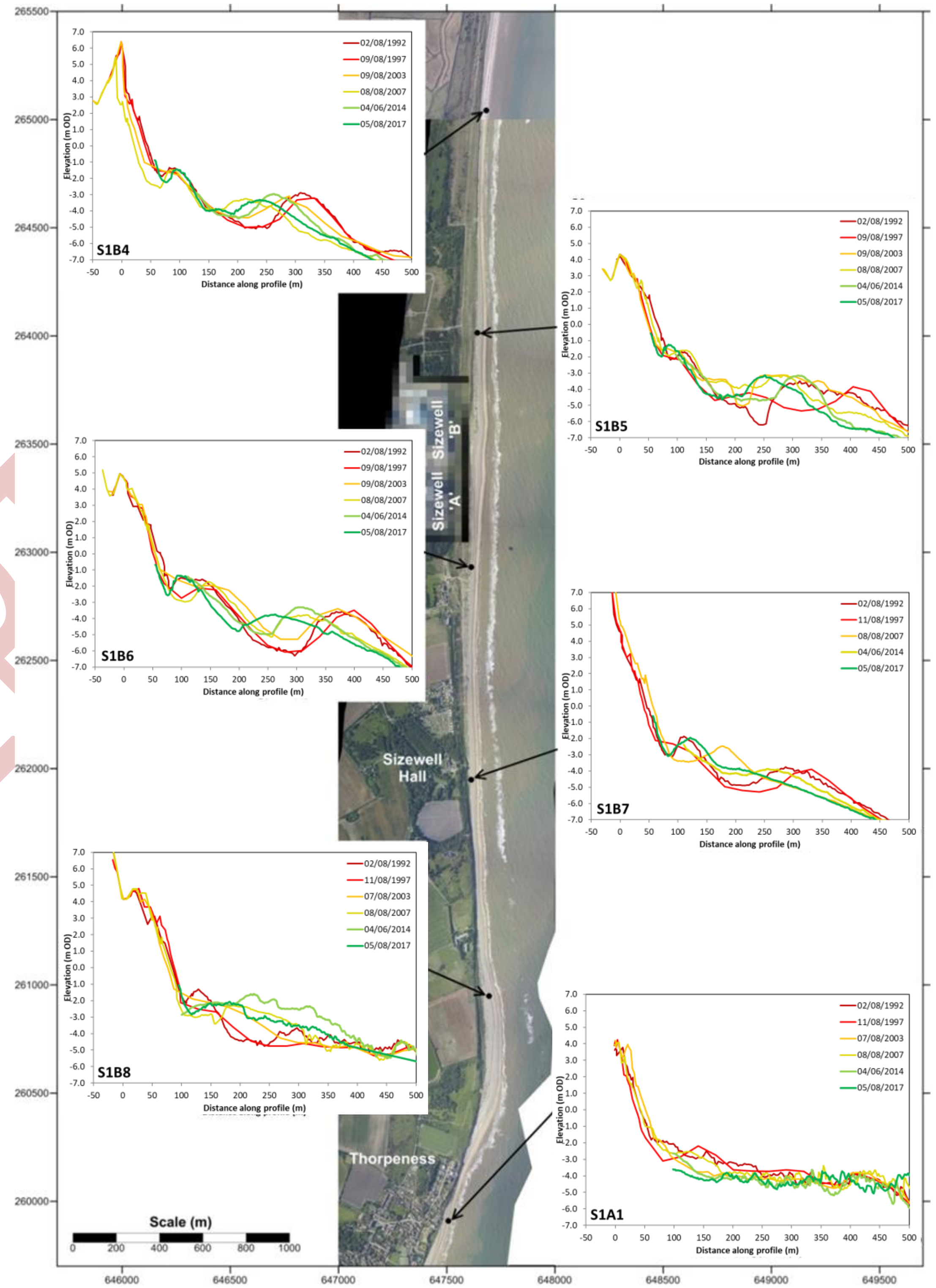

Figure 35: Combined beach and nearshore profiles based on EA topographic and bathymetric surveys in 1992, 1997, 2003, 2007, 2014 and 2017 between Minsmere Sluice and Thorpeness.

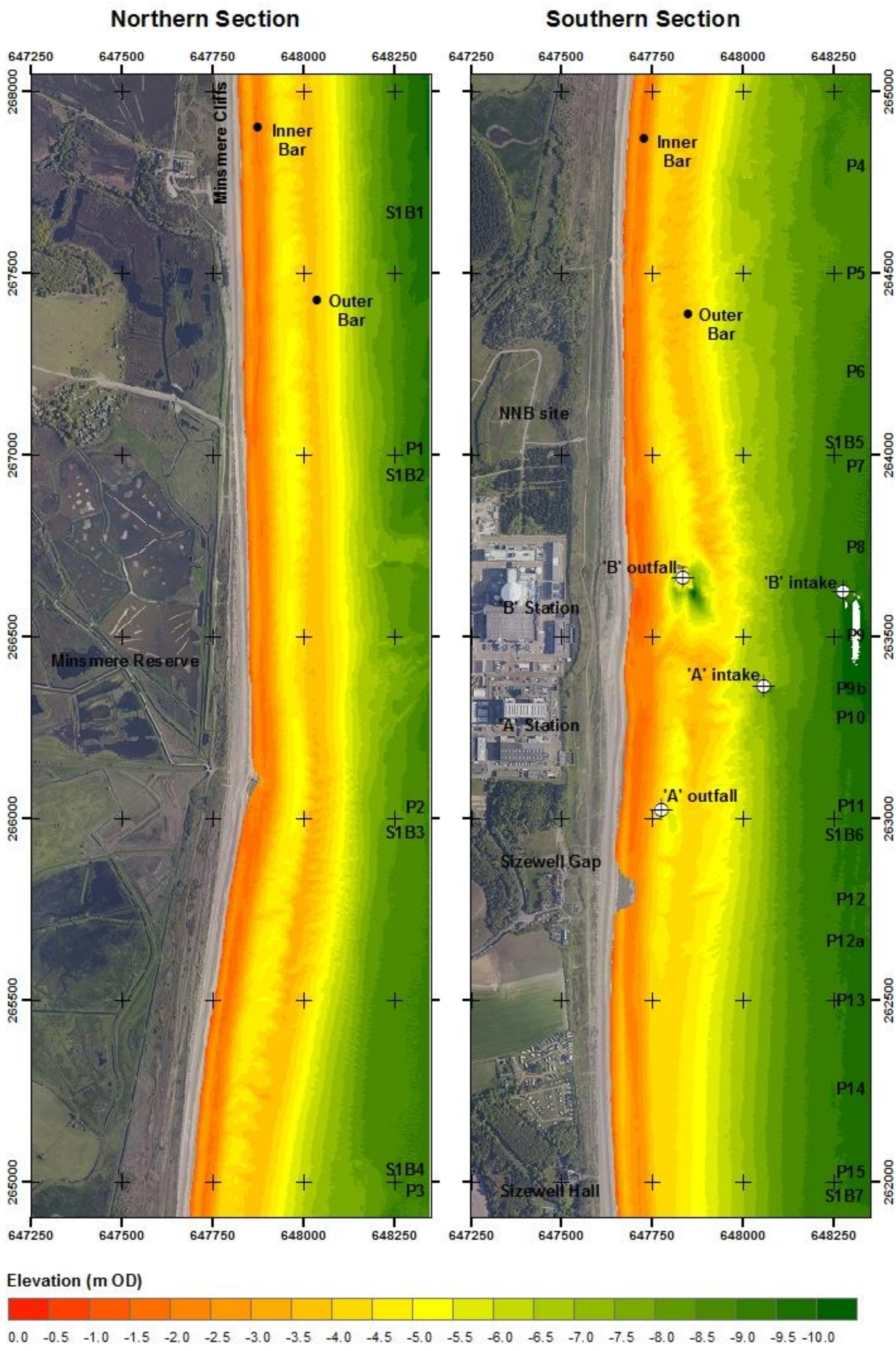

Figure 36: Comparison of subtidal and shoreline morphological features between Minsmere Cliffs and Sizewell Hall (August 2017 swath bathymetry; 2012 aerial photographs).

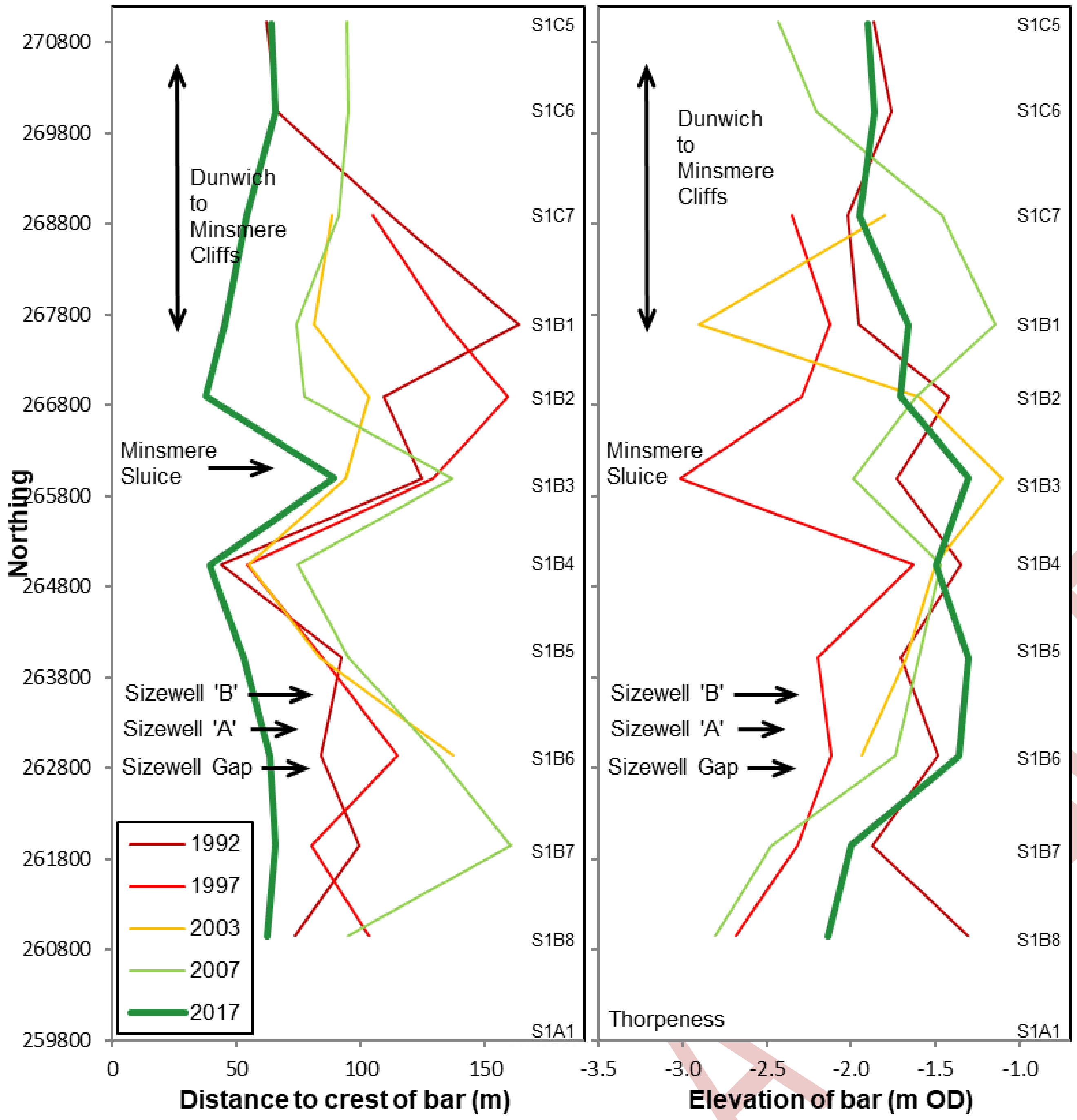

Figure 37: Distance from the 3.0 m OD contour (in 1992) to the crest of the landward (inner) nearshore bar, and crest elevation of the bar. Based on EA topographic and bathymetric surveys between Dunwich and Thorpeness (1992, 1997, 2003, 2007, 2014 and 2017) and BEEMS multibeam survey in April 2011.

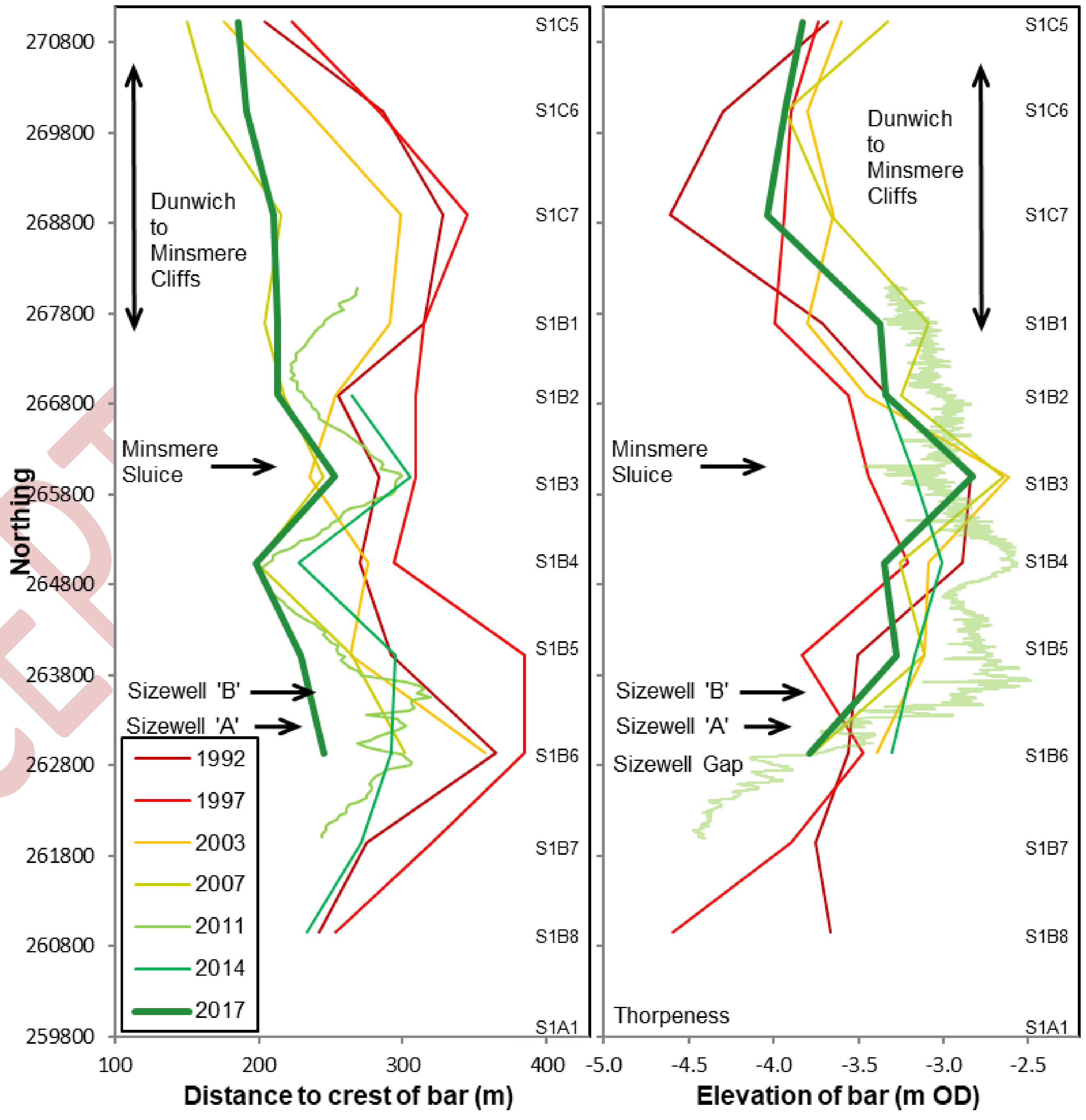

Figure 38: Distance from the 3.0 m OD contour (in 1992) to the crest of the seaward (outer) nearshore bar, and crest elevation of the bar. Based on EA topographic and bathymetric surveys between Dunwich and Thorpeness (1992, 1997, 2003, 2007, 2014 and 2017) and BEEMS multibeam survey in April 2011.

6.1.6 Short-term shoreline analysis (DSAS), based on LiDAR surveys and orthorectified aerial photography (1992 – 2016)

Shorelines digitised from aerial photographs (1992, 1997, 2001, 2006 and 2008) and LiDAR (2011 and 2016) highlighted spatial variability in shoreline behaviour. As described in Section 5.7, digital shoreline analysis followed the method of Thieler et al (2009). Shoreline change statistics were generated using shore-normal transects at 50 m (northing) intervals along the coast and showed strong patterns of spatial variability.

Maps of the SCE, LRR and rate of change trend strength are presented in Figure 39 – Figure 41. Each parameter was plotted against its northing. The easting scale is true for the 3.00 m OD contour, with all other contours manually offset to facilitate visualisation.

In general, the shoreline statistics derived from aerial photographs showed a coastline that exhibits a high degree of spatial variability, with zones of common shoreline response typically spanning just a few hundred metres (Figure 39 - Figure 41). Such spatial variability appears to be common for beaches in the lee of sand banks e.g., EA (2008, 2011), Dolphin *et al.* (2011), BEEMS Technical Report TR105.

Broadly speaking, the studied area can be divided into nine zones, based on the short-term shoreline change statistics (Figure 42):

- Dunwich Cliffs – low rates of change advancing in the north and south, retreating in the centre.
- Minsmere north – highest rates of retreat with a generally persistent trend and large shoreline change envelope.
- Minsmere sluice – highly variable shoreline positions (relatively large shoreline change envelope) with near-zero or slowly advancing net shoreline change.
- Minsmere south – high rates of retreat with a generally persistent trend and moderately large shoreline change envelope. High spatial variation illustrated in Figure 43.
- SZC frontage – low shoreline change rates in between eroding areas to the north and stable/accreting beaches to the south.
- SZB frontage – a short stretch of coast (approximately 200 m) with net shoreline advance but variable and sometimes retreating shorelines; net accretion due largely to post-construction foreshore recovery.
- Sizewell gap and south – low shoreline change rates and envelopes.
- Thorpeness north - variable shoreline position, generally stable or slowly retreating, with isolated areas of greater rates of retreat.
- Thorpeness – highly variable shoreline positions and high rates of change near the tip of the ness. High spatial variation illustrated in Figure 44.

As expected, the 3.00 m OD contour differed most significantly from the other shoreline contours due to the fact that it erodes and accretes under a subset of the conditions experienced on the other lower contours i.e., it is only inundated during storm surges and accretes during slumping at the dune scarp or accretion against its face. As a result, the shoreline position of the 3.00 m contour was observed to be less variable throughout the time-series (not shown due to the large number of plots). For example, a common feature along much of the coast was accretion between 2001 – 2006, and erosion between 2006 – 2008. The latter time interval features two large storm surges (November 2007, March 2008; BEEMS Technical Report TR139) that are known to have eroded sections of the supra-tidal beach.

Similar phases of erosion and accretion were not as clear in the 0.13 m OD contour, due to inundation on every tide facilitating sediment loss and gain over the very short-term via exchange with the subtidal zone, including the longshore bars. These very short-term fluctuations in shoreline position have no direct bearing on the longer-term patterns of shoreline change; however, where they are large, they can introduce uncertainty into the measurement campaigns that only sample at longer intervals, such as the annual and decadal data resolutions used in this report. For logistical and economic reasons, measurements at a higher frequency require automated remote sensing techniques (e.g., radar or cameras fixed to buildings). High frequency data, which is currently being collected and examined, can increase confidence in the longer-term signal as both shorter and longer-term components are measured, thereby compensating for the potential bias or aliasing in annual datasets.

The 0.13 m OD contour showed additional variability along the SZB frontage (Figure 45), which became indented during the period 1989 – 1992, as a result of three activities:

- construction of a vertical coffer dam recessed into the beach face (which will have reflected waves causing localised scour);
- the subsequent dredging to seaward for the installation of intake and outfall tunnels; and
- dredging and construction for the BLF.

The coffer dam and dredging most likely created the initial indentation (BEEMS Technical Report TR105), with the BLF, sited at the north of the indentation, acting like a groyne, interrupting sediment supply and exacerbating or maintaining the indentation by (net) down-drift erosion. By 1997, following removal of the coffer dam (summer 1992) and the BLF (summer 1993), the beach had substantially recovered, with the shoreline subsequently fluctuating, with a net seaward advance approximately opposite the SZB outfall where a subtle salient feature developed (see Section 7.4.1).

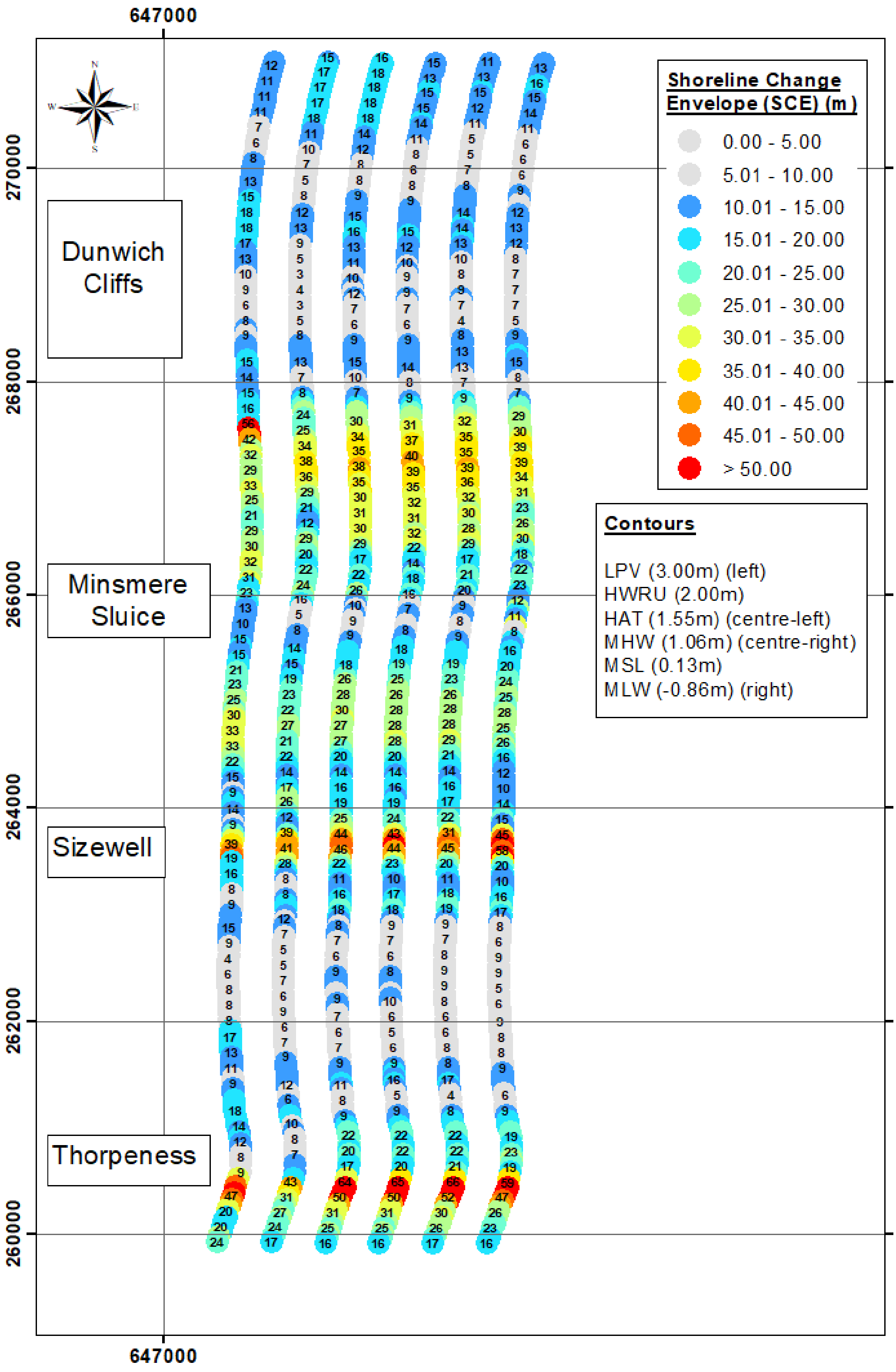

Figure 39: Longshore variability in the shoreline change envelope for six contour elevations, 1992-2016. LPV = Limit of Permanent Vegetation; HWRU = High wave run up; HAT = Highest Astronomical Tide; MHW = Mean High Water, MSL = Mean Sea Level, MLW = Mean Low Water.

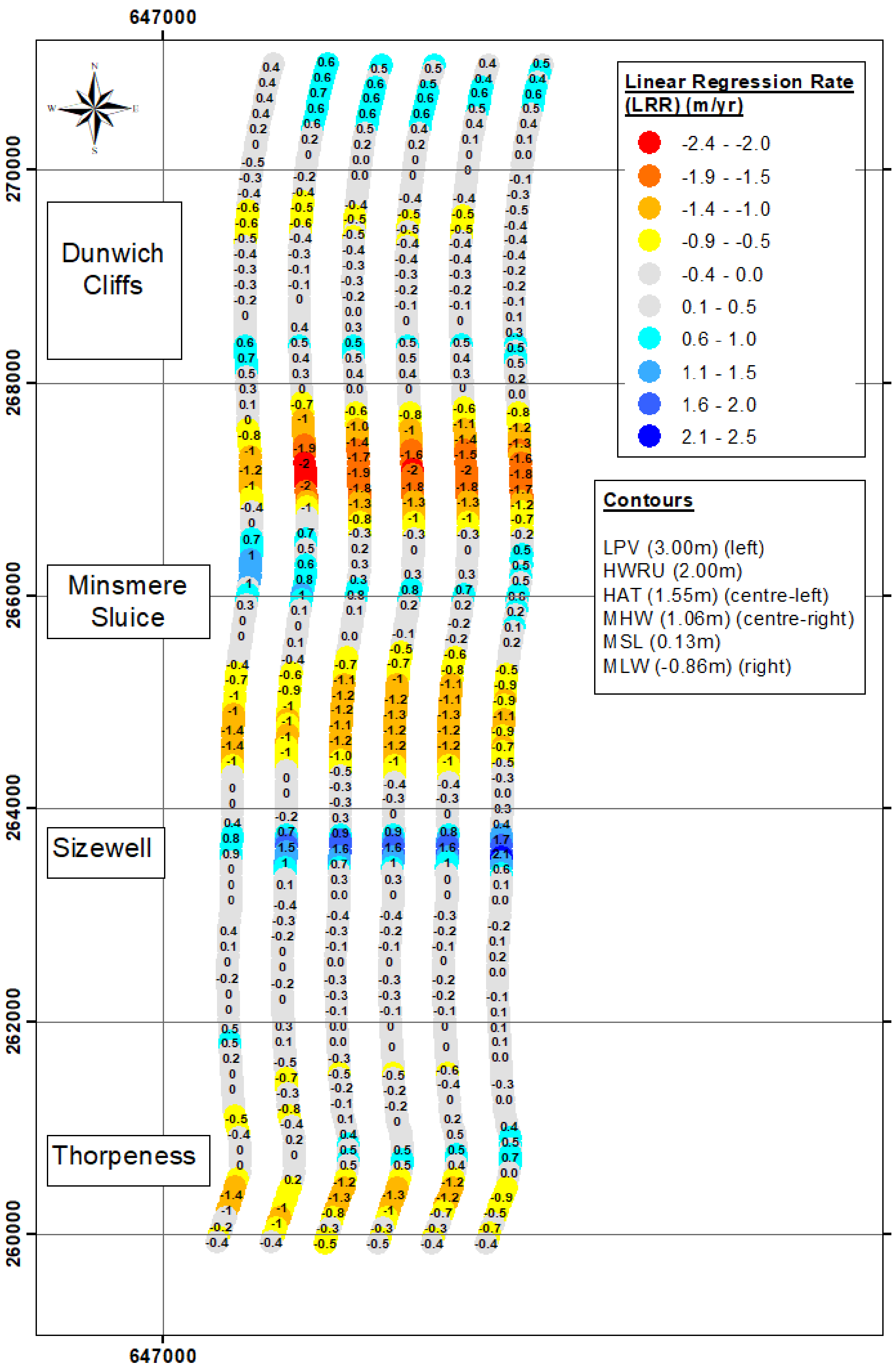

Figure 40: Longshore variability in the shoreline linear regression rate for six contour elevations, 1992-2016. LPV = Limit of Permanent Vegetation; HWRU = High wave run up; HAT = Highest Astronomical Tide; MHW = Mean High Water, MSL = Mean Sea Level, MLW = Mean Low Water.

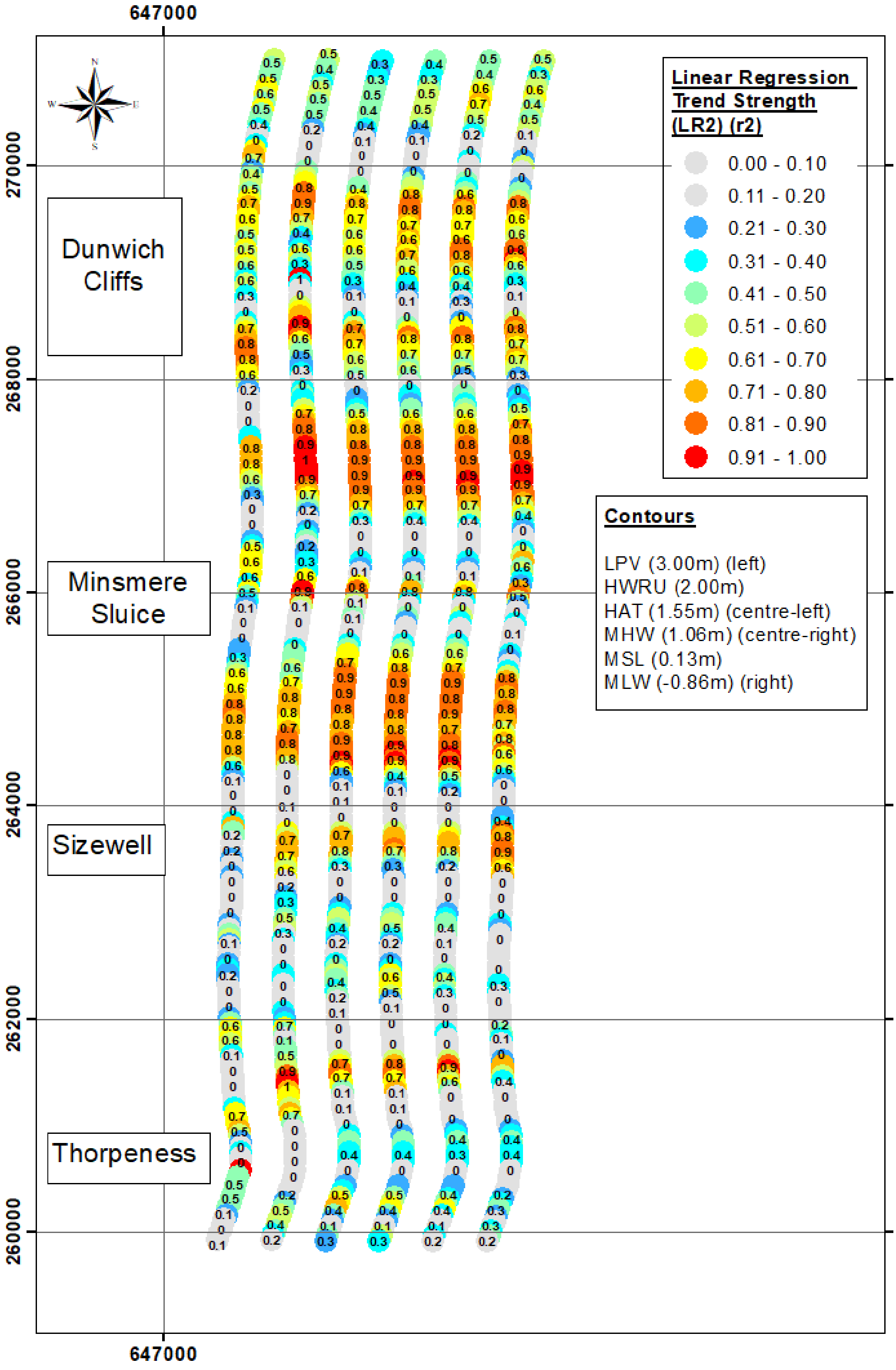

Figure 41: Longshore variability in the shoreline change trend strength (r2) for six contour elevations, 1992-2016. LPV = Limit of Permanent Vegetation; HWRU = High wave run up; HAT = Highest Astronomical Tide; MHW = Mean High Water, MSL = Mean Sea Level, MLW = Mean Low Water.

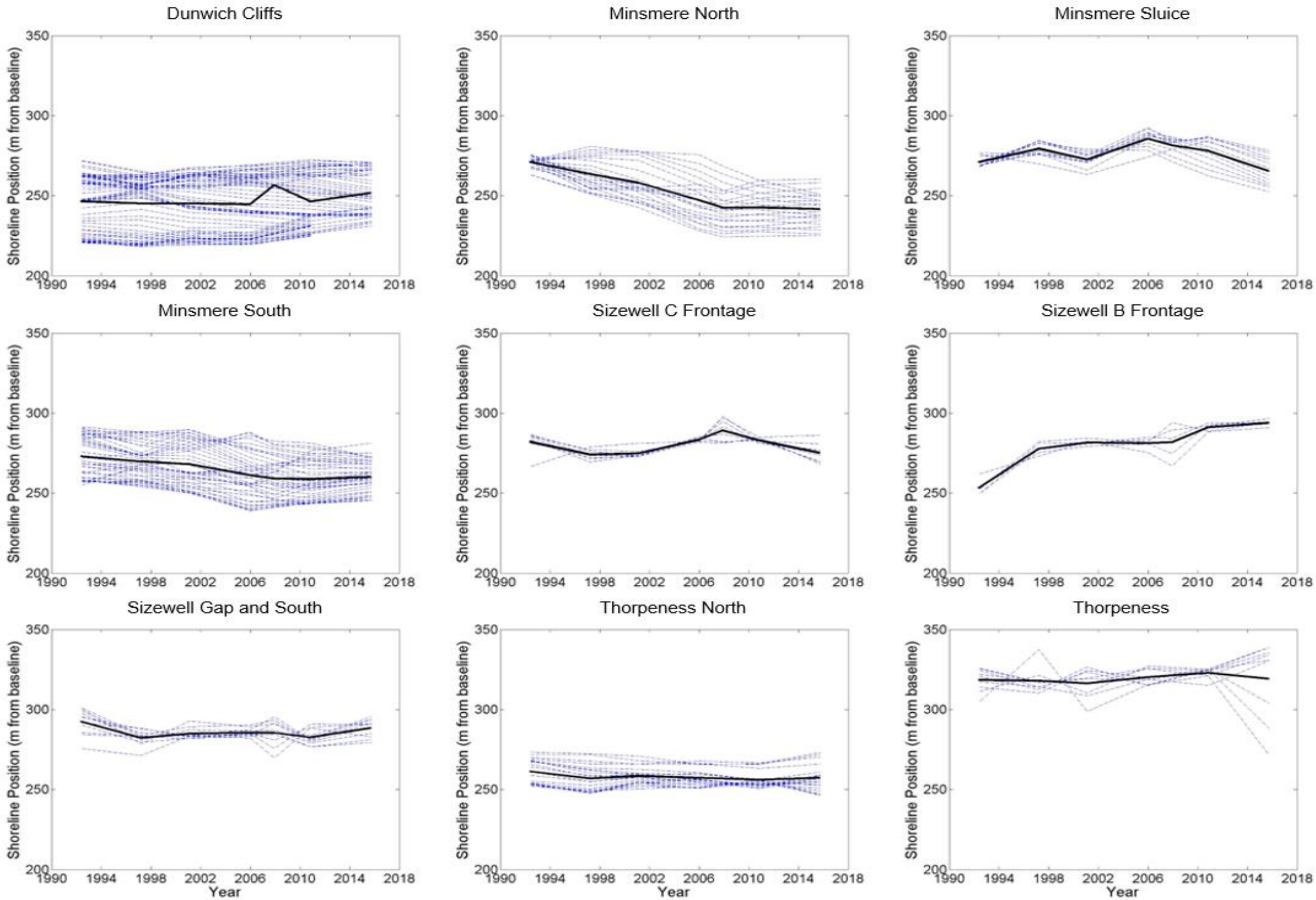
Dunwich Cliffs
Minsmere North
Minsmere Sluice
Minsmere South
Sizewell C Frontage
Sizewell B Frontage
Sizewell Gap and South
Thorpeness North
Thorpeness
Shoreline Position (m from baseline)
Year
350
300
250
200
1990
1994
1998
2002
2006
2010
2014
2018

Figure 42: 0.13 m OD contour (MSL) position time-series for the nine shoreline zones identified by DSAS, where a relatively consistent response is observed based on the 1992 – 2016 orthorectified aerial photography shoreline change statistics.

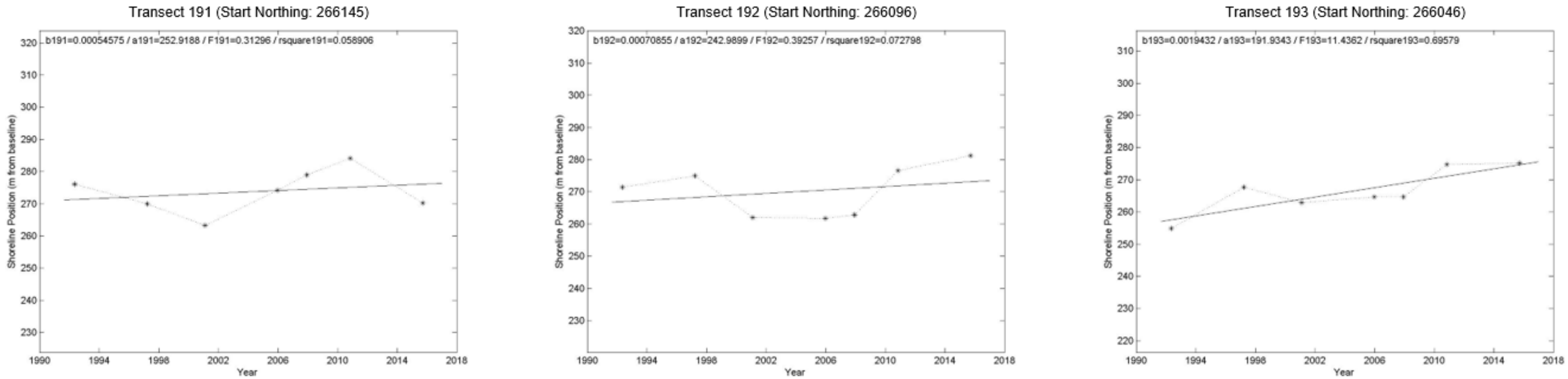

Figure 43: Time-series of the 0.13 m OD contour (MSL) position along three sequential transects from north to south (left to right) at Minsmere Sluice. The plots show that the sluice causes a high degree of spatial variability in shoreline behaviour close to the sluice.

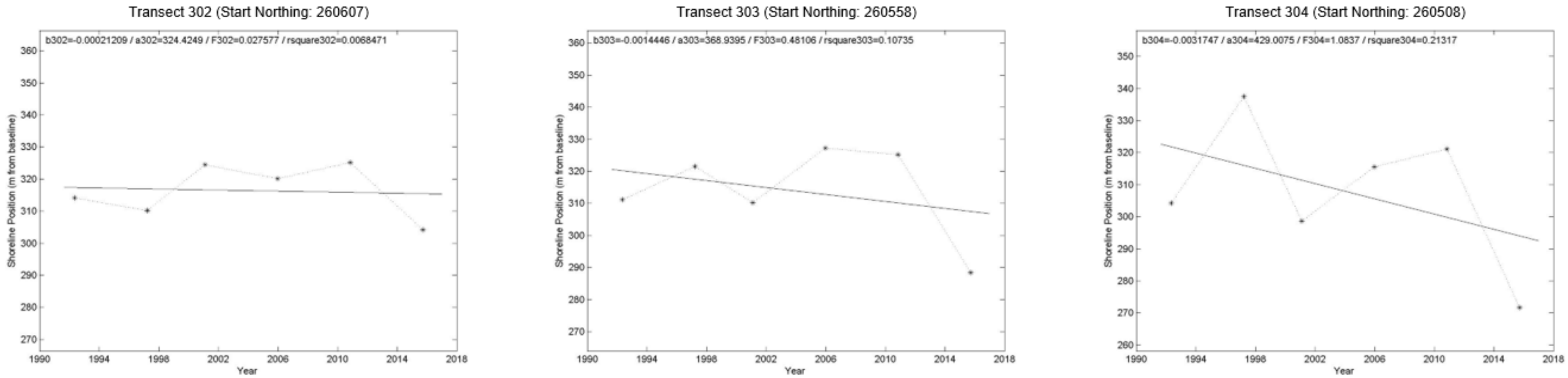

Figure 44: Time-series of shoreline (MSL) position along three sequential transects from north to south (left to right) at Thorpeness. The plots show that shoreline behaviour around the Ness varies on a spatial scale finer than the 50 m transect spacing, as successive transects have a persistently alternating behaviour that tracks the oscillations in the northward and southward movement of the Ness.

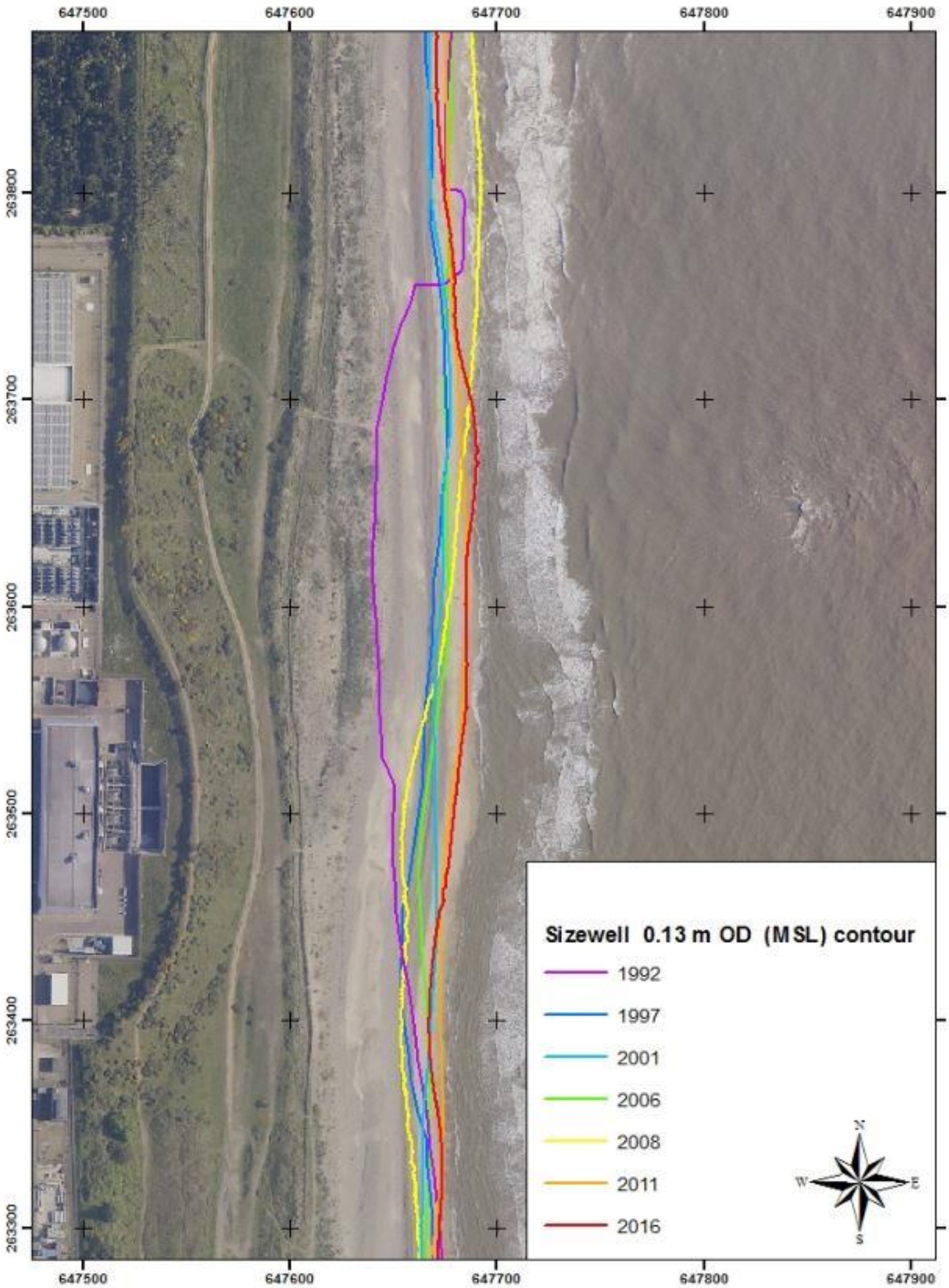

Figure 45: Aerial photograph of the Sizewell B frontage with superimposed 0.13 m OD summer shorelines derived from other aerial photographs, illustrating foreshore recovery following the removal of the coffer dam (1992) and BLF (1993).

The northern and southern sections of the Dunwich-Minsmere Cliffs beaches were generally stable or slowly accreting at a rate of 0.0 to 0.7 m/yr (r^2 = 0.5 to 0.8). In the north, much of the accretion occurred during the recent 2008 – 2016 period, whilst in the south, accretion occurred variably post-1997. In the centre, slow and steady retreat was observed at a rate of -0.1 to -0.6 m/yr (r^2 = 0.4 to 0.8).

The largest rates of shoreline retreat observed within the GSB (up to -2.2 m/yr) occurred approximately 1 km north of Minsmere Sluice and were persistent, as shown by the high r^2 = 0.9.

Around Minsmere Sluice (±500 m), shoreline positions varied significantly with no spatially persistent trend, except where the shoreline was anchored in position by the sluice itself. On average the shoreline was slowly accreting with rates of up to 1.1 m/yr (r^2 = 0.0 to 0.9). The EA and SSMSG profiles S1B3 and P2 located 100 m south of the sluice, observed intense spatial variability in shoreline behaviour, as shown in Figure 43. The DSAS transect T193 (i.e., S1B3 and P2), and the two transects to the north (T191 and T192), all exhibited different shoreline behaviour. Analysis of aerial imagery corroborated the beach profile results (i.e., both show an accreting shoreline), but the results from the beach profiles cannot be used to infer behaviour to the north[3].

Further south, as far as the northern extent of the proposed SZC station, the shorelines at all elevations retreated at rates of up to -1.4 m/yr. A moderate erosion trend was persistent over the entire active beach face (r^2 = 0.6 to 0.9). The upper beach differed in that the shoreline position was stable from 1992 – 2006 but retreated by 20 to 25 m between 2006 – 2008, possibly due to the previously mentioned storm surges that occurred during this period (Table 10). This result highlights the importance of severe storm events during which the upper beach can retreat by tens of metres.

The frontage of the proposed SZC station lies between a persistently eroding area to the north and a stable, possibly accreting shoreline to the south, adjacent to the existing SZA and SZB stations. Low rates of change with no persistent trends typified this area (-0.4 to 0.5 m/yr, r^2 = 0.0 to 0.2). Whilst the 3m contour retreated by 25 to 30 m between 2006 – 2008, it was stable prior to this period.

At SZB, the shoreline change rates were positive and large over a short 200 to 300 m section. The high rates of up to 1.6 m/yr are largely due to beach recovery (1993 – 1997) following the cessation of the dredging and subsequent removal of the coffer dam (summer 1992) and the BLF (summer 1993). In the centre of the indentation, the shoreline advanced by up to 30 m to 1997, before stabilising. The rate of advance falls to less than 1 m/yr if the post-construction recovery is omitted. A relatively subtle beach salient on the SZB frontage (made more obvious by the indentation to the south) had its apex just north of SZB in 2008 but had moved 200 m south by 2011. Shorelines immediately north of the salient were eroding until 2000, following which they began to advance, an observation that may be connected to the presence and evolution of the salient.

The shoreline at Sizewell Gap, just south of the power station experienced variable shoreline behaviour (-0.4 to 0.3 m/yr) with no consistent trend. Further south the shore was stable, with near-zero rates of change. The shoreline change envelope was small, typically less than 10 m for the 24 year dataset.

Approximately 800 m north of Thorpeness a section of coast showed net retreat of up to -0.8 m/yr of the 3.0 m OD contour. The net erosion rate was largely the result of retreat during the period 2001 – 2006. Shorelines between MLW (-0.86 m OD) and MHW (1.06 m OD) showed lower net erosion rates and were accreting at a rate of up to 0.2 m/yr in some locations due to beach recovery between 2006 – 2011.

Shorelines at Thorpeness itself were spatially variable (Figure 44), being stable in the north and eroding towards the south with rates of change ranging between -1.4 to 0.7 m/yr. Movement of the apex of the Ness resulted in fluctuating shoreline positions (shoreline change envelopes of up to 52 m), with low net change rates.

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[3] This highlights that, in areas where alongshore variation in beach behaviour is high, caution must be used in interpreting beach profile data in the absence of shorelines derived from other sources, such as orthorectified aerial photography, LiDAR, drone DSMs and continuous shorelines from radar or video. The use of spatially continuous data allows greater confidence in the spatial patterns described and in the conclusions drawn.

6.1.7 Short-term patterns in erosion and accretion, based on topographic and LiDAR surveys and orthorectified aerial photography (1999 – 2018)

In support of the beach sediment volume and contour positional analysis described previously, short-term patterns of erosion and accretion across the GSB were assessed at an annual and decadal resolution (1999 – 2017) (Figure 46 to Figure 49), and between Minsmere Sluice and Sizewell Gap, encompassing the Sizewell power station frontage at an intra-annual and seasonal resolution (2007 – 2018) (Figure 50 to Figure 53). This was done using the 3D datasets, which provide more detail on the nature of beach change however the data are not as temporally consistent until post-2007, especially when LiDAR only data are considered. The advent of small drones facilitates regular survey of this nature and the method has been shown to be sufficient for coastal surveys (Turner *et al.*, 2016 and BEEMS Scientific Position Paper SPP086).

Short-term patterns of erosion and accretion observed at the decadal resolution, were broadly consistent with the zones of common shoreline behaviour identified by DSAS, as described in Section 6.1.6. In contrast, at the finer temporal resolution (<1 year), areas of common shoreline behaviour were typically limited to just a few hundred metres – this important point highlights the potential deficiency of beach profile data due to the short and moving zones of a particular trend, which could fall between profiles for a period of time and remain undetected. Areas of high variability observed at the intra-annual resolution were consistent with zones of common shoreline behaviour (as described in Section 6.1.6) that have a characteristically high variability, as indicated by low trend strengths (r^2) in the LRR calculated (Figure 40 and Figure 41). The three main areas of high variability were:

- Approximately 500 m of shoreline centred on Minsmere Sluice;
- Approximately 1000 m of shoreline adjacent to Sizewell; and
- Approximately 1500 m of shoreline centred on the ness at Thorpeness.

In general, variability in the patterns of erosion and accretion observed could be grouped into four categories: seasonality, cross-shore, long-shore and alternating variability. Evidence of seasonal patterns in erosion and accretion, were observed between Minsmere Sluice and Sizewell Gap. For example, the 2015/16 and 2016/17 winters highlighted greater variability in comparison to the relatively stable 2016 summer (Figure 52 and Figure 53). However, this general seasonality was not consistent, with reduced winter changes constrained to the lower shore over the 2012/13 winter (Figure 51), whilst the summer of 2015 exhibited greater variability, comparable with that observed during most winters (Figure 52). Seasonal patterns in erosion and accretion are a contributory factor to the shoreline variability observed across the GSB, but the seasonal signal is partially obscured by the impact of individual storm events and/or periods of relatively persistent environmental conditions (e.g., wind and wave direction), coupled with the irregular timings of the survey datasets used in the comparison.

Cross-shore patterns in erosion and accretion were also evident. Consistent with the beach contour analysis reported in Section 6.1.6, the backshore experienced relatively little change over all temporal resolutions, as a result of elevation and the associated infrequency of tidal inundation and erosive forcing (Figure 46 to Figure 53). Regardless of elevation, cross-shore profile changes typically associated with intra-annual and seasonal trends were also observed, whereby the redistribution of sediment resulted in a steepening or flattening of the beach profile.

These patterns presented themselves as adjacent bands of erosion and accretion, orientated north to south (Figure 50 to Figure 53). For example, Minsmere South showed erosion of the backshore with corresponding accretion across the foreshore, indicative of beach flattening during the 2007/08 winter, followed by a reversal during the 2008 summer. This in fair agreement with the variations in beach contour positions observed during topographic surveys, as reported in Section 6.1.2 (see profiles S1B4 and P3 in

Figure 18). Similar trends were also observed along the SZB frontage during the 2009/10 and 2017/18 winter (Figure 50 and Figure 53 respectively), and adjacent to the proposed SZC site during the 2012 autumn (Figure 51), representing beach flattening and steepening respectively.

Longshore patterns of accretion were observed, primarily at an annual resolution (Figure 46 to Figure 49), and were expressed as bands of erosion or accretion that moved alongshore and generally to the south over successive years, with the extent of the movement likely associated with the predominant wave strength and direction during that period. For example, alternating bands of erosion and accretion were observed migrating south between Sizewell Gap and Thorpeness during the period 2011 – 2016, whilst over the whole period (1999 – 2016), relatively limited change was observed, except for a localised area of variable cross-shore patterns of erosion accretion at Thorpeness (Figure 48 and Figure 49). This is consistent with the common shoreline behaviour described previously for this area. Typically, the bands observed at an annual resolution were larger in extent than the bands of common shoreline behaviour observed at the intra-annual scale, but smaller than those observed at the decadal scale.

At the intra-annual resolution, the longshore variability signal was less discernible, whilst it was absent over the decadal scale. The reduced intra-annual signal was attributed to the low longshore sediment transport rates observed along the GSB (BEEMS Technical Report TR357), resulting in minor banding and only subtle differences in longshore patterns of erosion and accretion between the individual surveys assessed.

For example, a minor band of erosion followed by a minor band of accretion, was observed migrating approximately 1 km south between Minsmere South and the Sizewell power stations frontage during the period 06/11/2014 – 01/09/2015 (Figure 52). In contrast, the lack of a decadal signal was attributed to the more persistent zones of common shoreline behaviour described in Section 6.1.6, that are relatively static due to geomorphic (e.g., Coralline Crag) and man-made influences (e.g., Minsmere Sluice). Accordingly, any longshore variability signal that was observed, was most apparent within sections of the coast that lacked stabilising points that may constrain longshore sediment transport.

The characteristics of the alternating patterns of erosion and accretion differed to the seasonal, cross-shore and longshore patterns described above. Alternating bands showed well-defined contrasting areas of erosion and accretion, that were separated by and fluctuated around, the distinct bands of limited net change associated with these relatively static influences. The extent and direction (i.e., erosion or accretion) of these bands was attributed to the size and zone of influence of the stabilising point and the predominant environmental conditions (e.g., wave direction and longshore transport rates) experienced at that location.

For example, a large but ill-defined alternating band was observed at Thorpeness and was associated with Coralline Crag (Figure 49). In contrast, banding around Minsmere Sluice was limited in size (varying with the bi-directional wave climate) but clearly defined (e.g., Figure 48, Figure 51 and Figure 53), whilst banding along the Sizewell power station frontage was similar in extent to that of Minsmere Sluice, but less well defined and may be due to the postulated effects of the SZB outfall (e.g., Figure 48 and Figure 51). Due to the role of static stabilising points in the formation of these alternating patterns of erosion and accretion, they are observed over all temporal scales and also play an important role in the spatial separation of zones of common shoreline behaviour along GSB (including the longshore patterns in erosion and accretion described previously), particularly Minsmere Sluice, as has been previously discussed.

The temporal and spatial patterns in erosion and accretion observed and described above, are the cumulative result of variability in the bi-directional and inshore wave climate (e.g., influences of near- and offshore morphology and individual storm events and their relative characteristics), longshore sediment transport and the presence of both natural and stabilising points within the GSB. The result is a fluctuating patchwork of erosion and accretion, but whilst short-term changes at the seasonal, intra- to inter-annual resolution contribute towards this highly dynamic shoreline, only persistent trends observed at the decadal scale, relating to the wider wave climate and longshore drift conditions, resulted in longer-term erosion and accretion patterns that were consistent with the main zones of shoreline change identified through the DSAS.

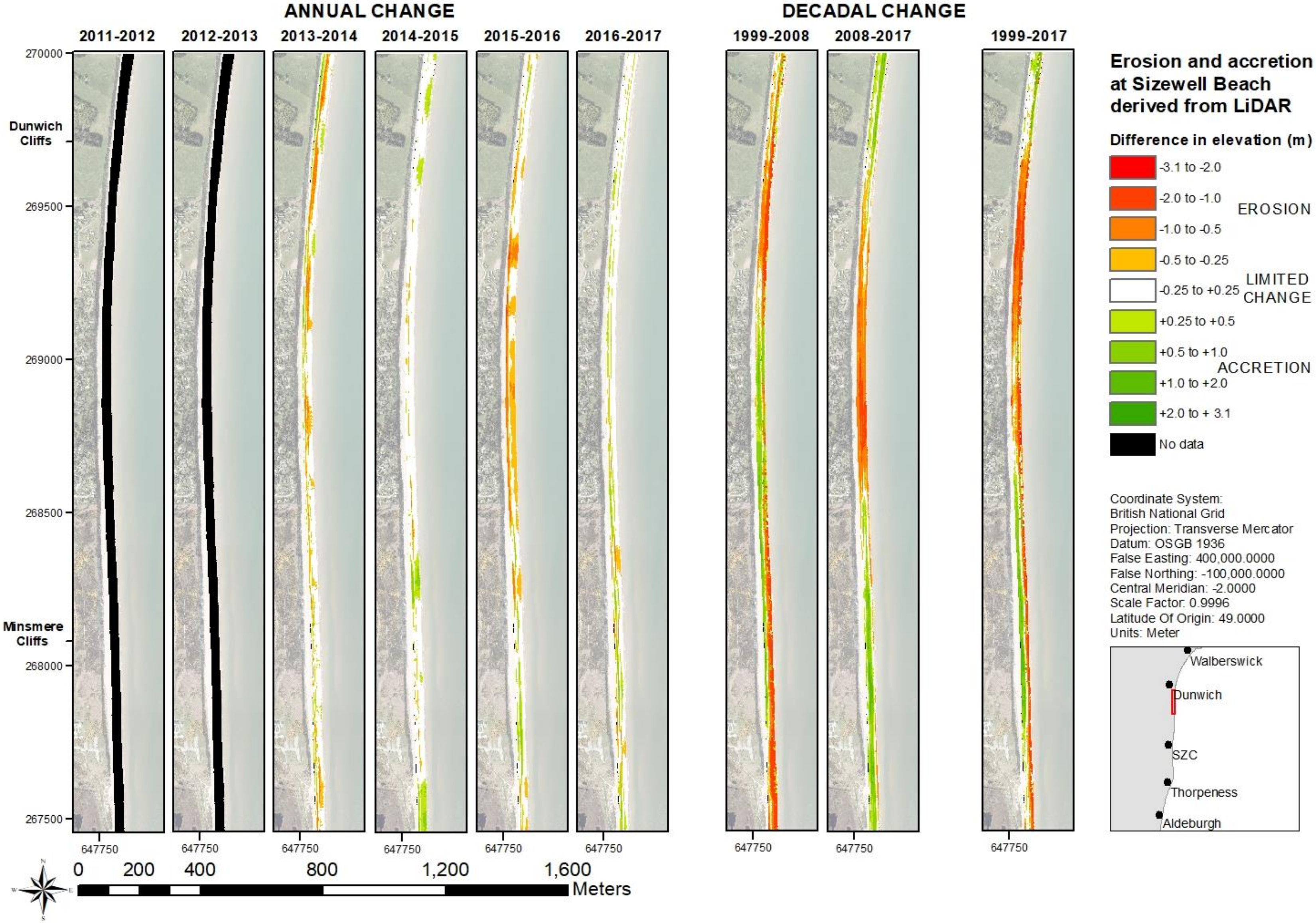


Figure 46: Short-term changes in beach elevation over annual and decadal temporal scales, between 1999 and 2017: Dunwich to Minsmere Cliffs.

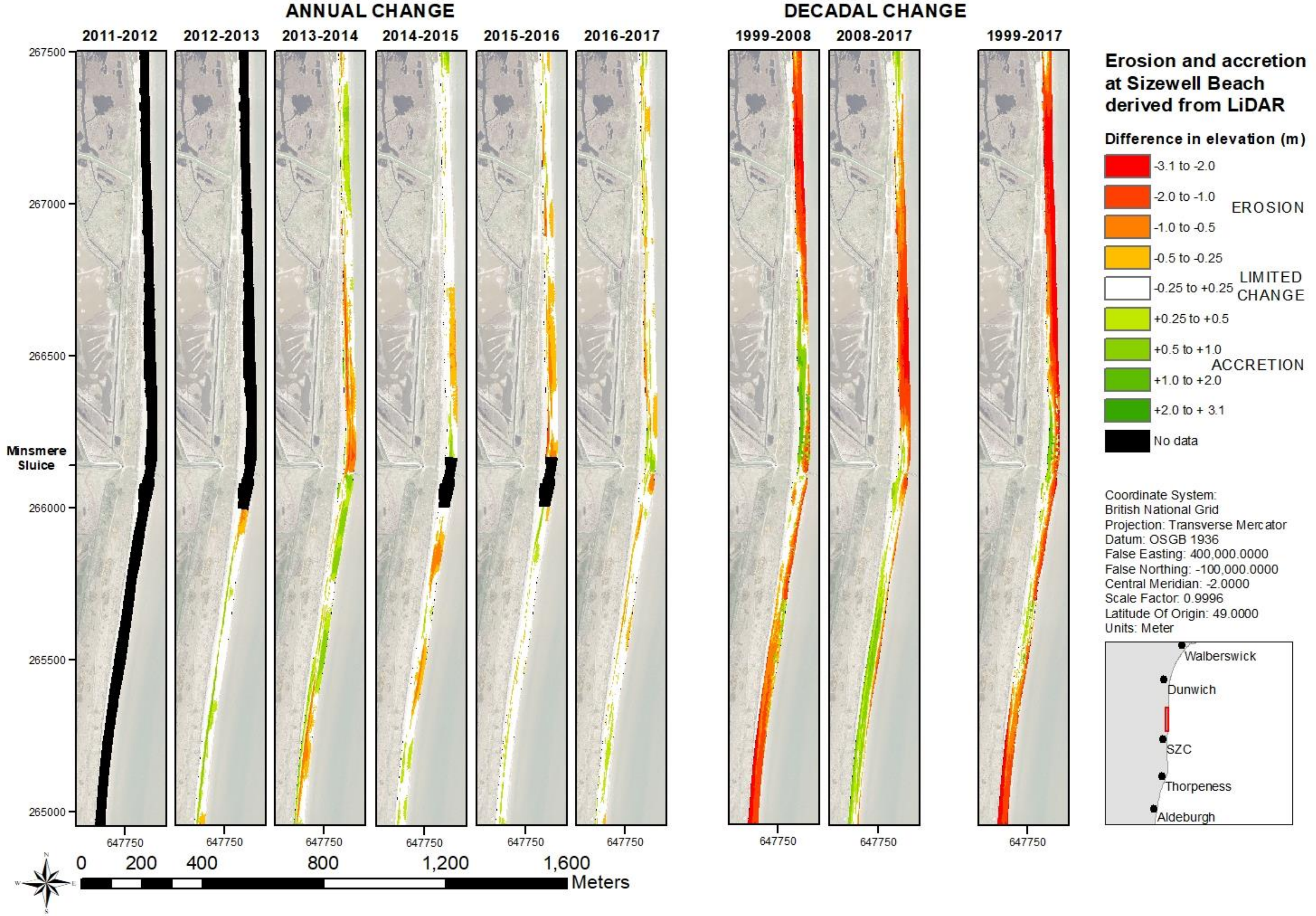

ANNUAL CHANGE
2011-2012
2012-2013
2013-2014
2014-2015
2015-2016
2016-2017
DECADAL CHANGE
1999-2008
2008-2017
1999-2017
267500
267000
266500
Minsmere Sluice
266000
265500
265000
647750
0
200
400
800
1,200
1,600
Meters
Erosion and accretion at Sizewell Beach derived from LiDAR
Difference in elevation (m)
-3.1 to -2.0
-2.0 to -1.0
-1.0 to -0.5
-0.5 to -0.25
EROSION
-0.25 to +0.25
LIMITED CHANGE
+0.25 to +0.5
+0.5 to +1.0
+1.0 to +2.0
+2.0 to + 3.1
ACCRETION
No data
Coordinate System: British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936
False Easting: 400,000.0000
False Northing: -100,000.0000
Central Meridian: -2.0000
Scale Factor: 0.9996
Latitude Of Origin: 49.0000
Units: Meter
Walberswick
Dunwich
SZC
Thorpeness
Aldeburgh

Figure 47: Short-term changes in beach elevation over annual and decadal temporal scales, between 1999 and 2017: Minsmere Cliffs to Sizewell north.

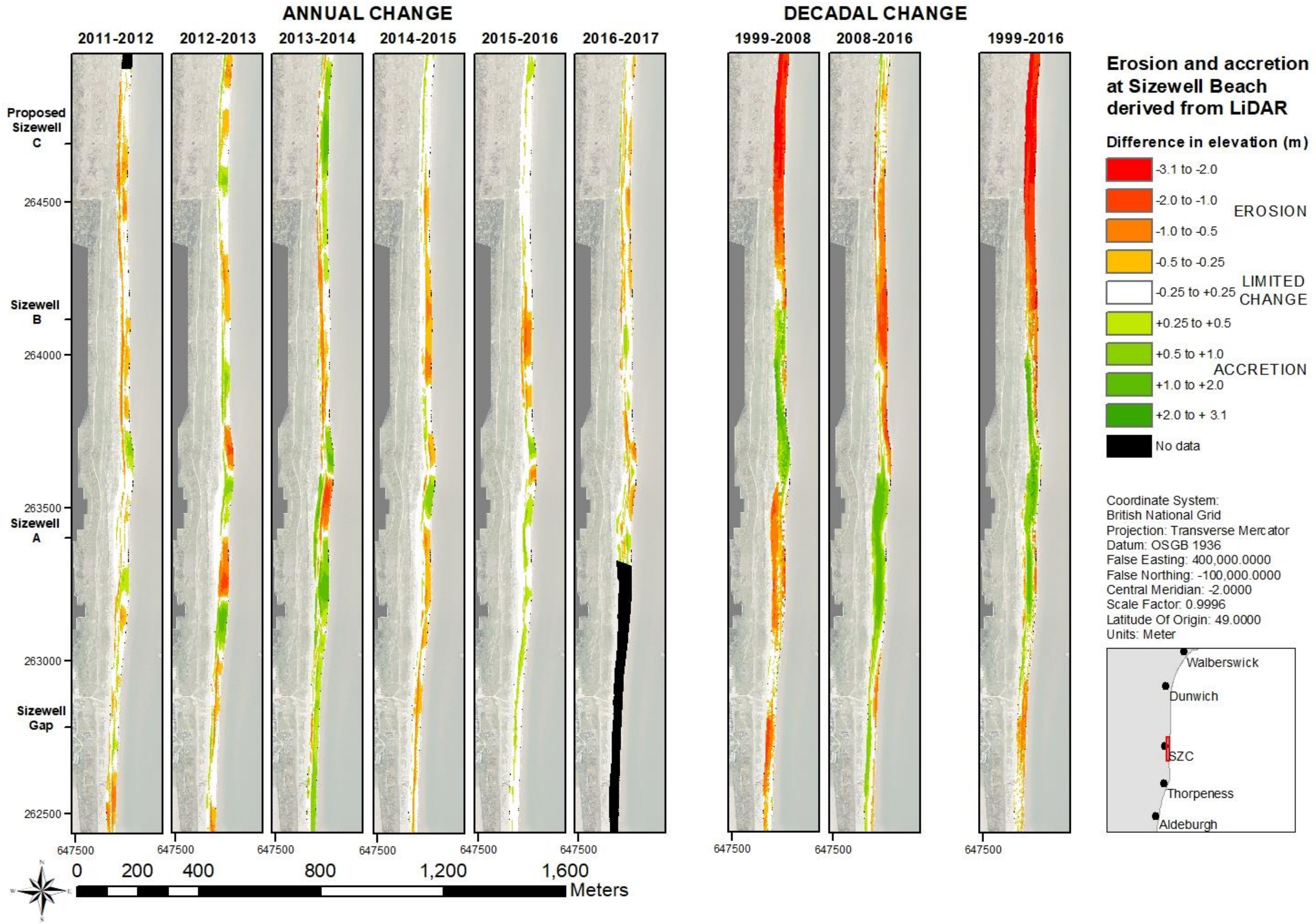


Figure 48: Short-term changes in beach elevation over annual and decadal temporal scales, between 1999 and 2017: Sizewell power station frontage.

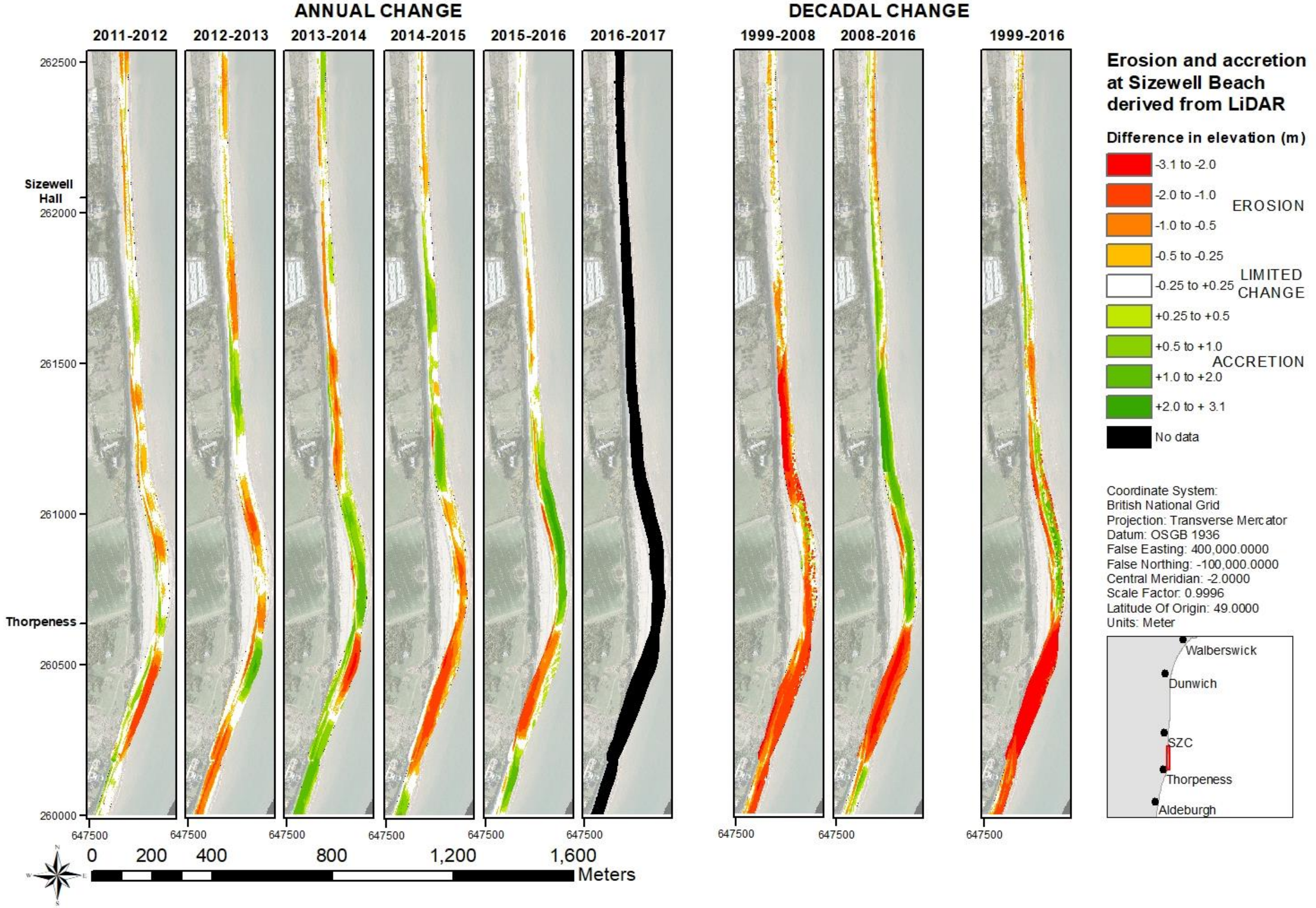


Figure 49: Short-term changes in beach elevation over annual and decadal temporal scales, between 1999 and 2017: Sizewell to Thorpeness.

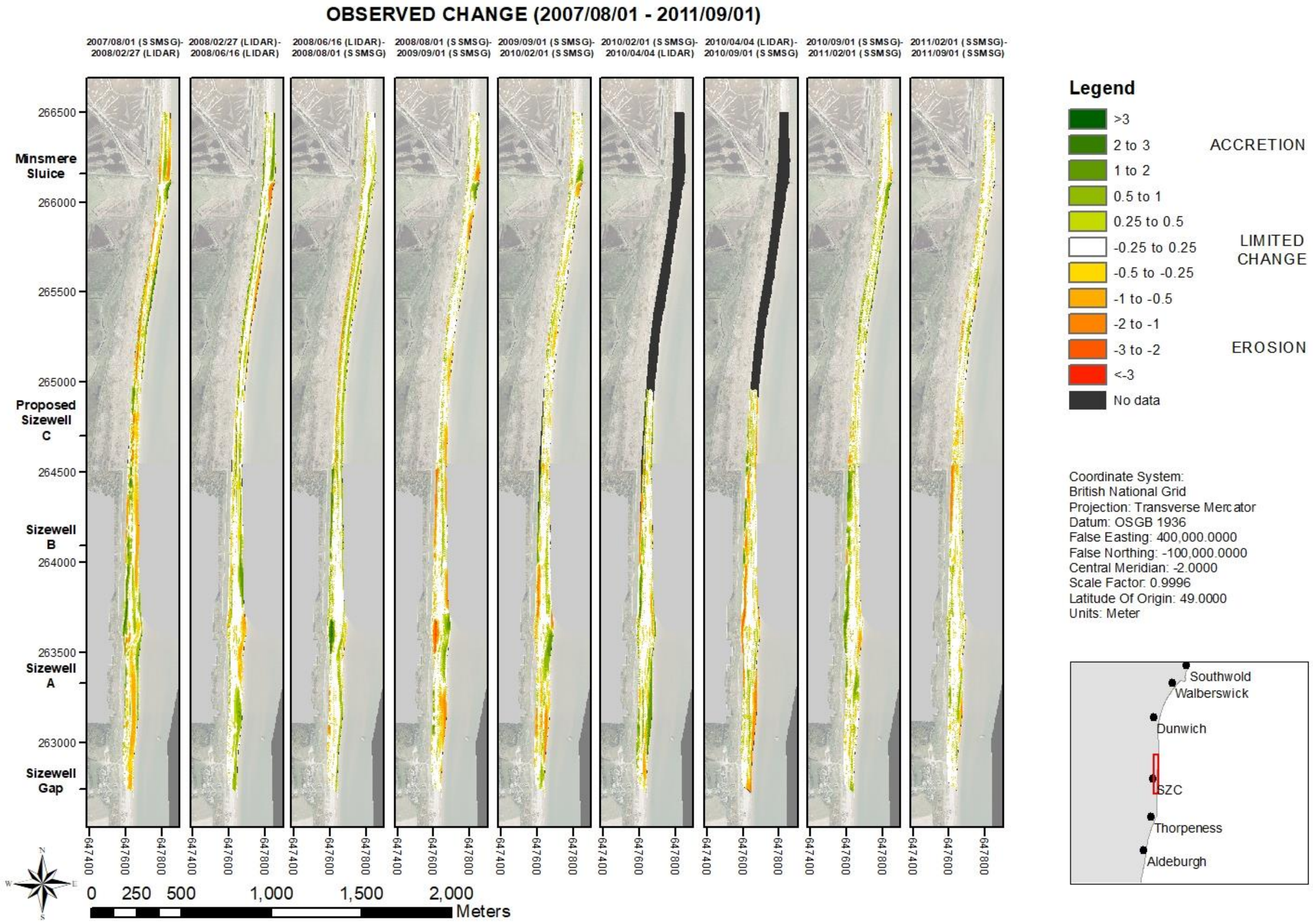


Figure 50: Intra-annual short-term changes in beach volume between Sizewell Gap and Minsmere north, between 01/08/2007 and 01/09/2011.

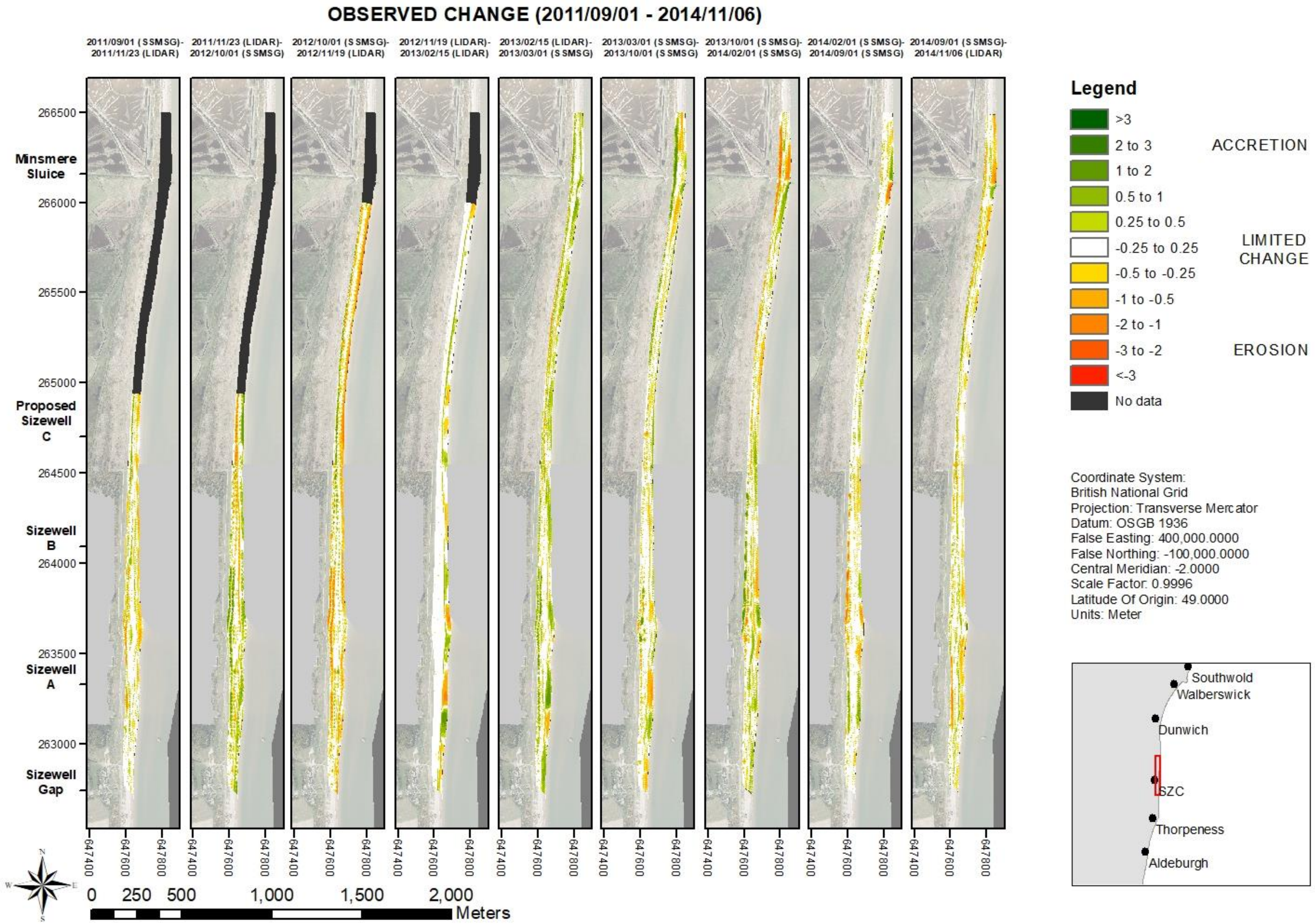

OBSERVED CHANGE (2011/09/01 - 2014/11/06)
2011/09/01 (SSMSG)- 2011/11/23 (LIDAR)
2011/11/23 (LIDAR)- 2012/10/01 (SSMSG)
2012/10/01 (SSMSG)- 2012/11/19 (LIDAR)
2012/11/19 (LIDAR)- 2013/02/15 (LIDAR)
2013/02/15 (LIDAR)- 2013/03/01 (SSMSG)
2013/03/01 (SSMSG)- 2013/10/01 (SSMSG)
2013/10/01 (SSMSG)- 2014/02/01 (SSMSG)
2014/02/01 (SSMSG)- 2014/09/01 (SSMSG)
2014/09/01 (SSMSG)- 2014/11/06 (LIDAR)
266500
Minsmere Sluice
266000
265500
265000
Proposed Sizewell C
264500
Sizewell B
264000
263500
Sizewell A
263000
Sizewell Gap
647400
647600
647800
0 250 500 1,000 1,500 2,000 Meters
Legend
>3
2 to 3
1 to 2
0.5 to 1
0.25 to 0.5
-0.25 to 0.25
-0.5 to -0.25
-1 to -0.5
-2 to -1
-3 to -2
<-3
No data
ACCRETION
LIMITED CHANGE
EROSION
Coordinate System:
British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936
False Easting: 400,000.0000
False Northing: -100,000.0000
Central Meridian: -2.0000
Scale Factor: 0.9996
Latitude Of Origin: 49.0000
Units: Meter
Southwold
Walberswick
Dunwich
SZC
Thorpeness
Aldeburgh

Figure 51: Intra-annual short-term changes in beach volume between Sizewell Gap and Minsmere north, between 01/09/2011 and 06/11/2014.

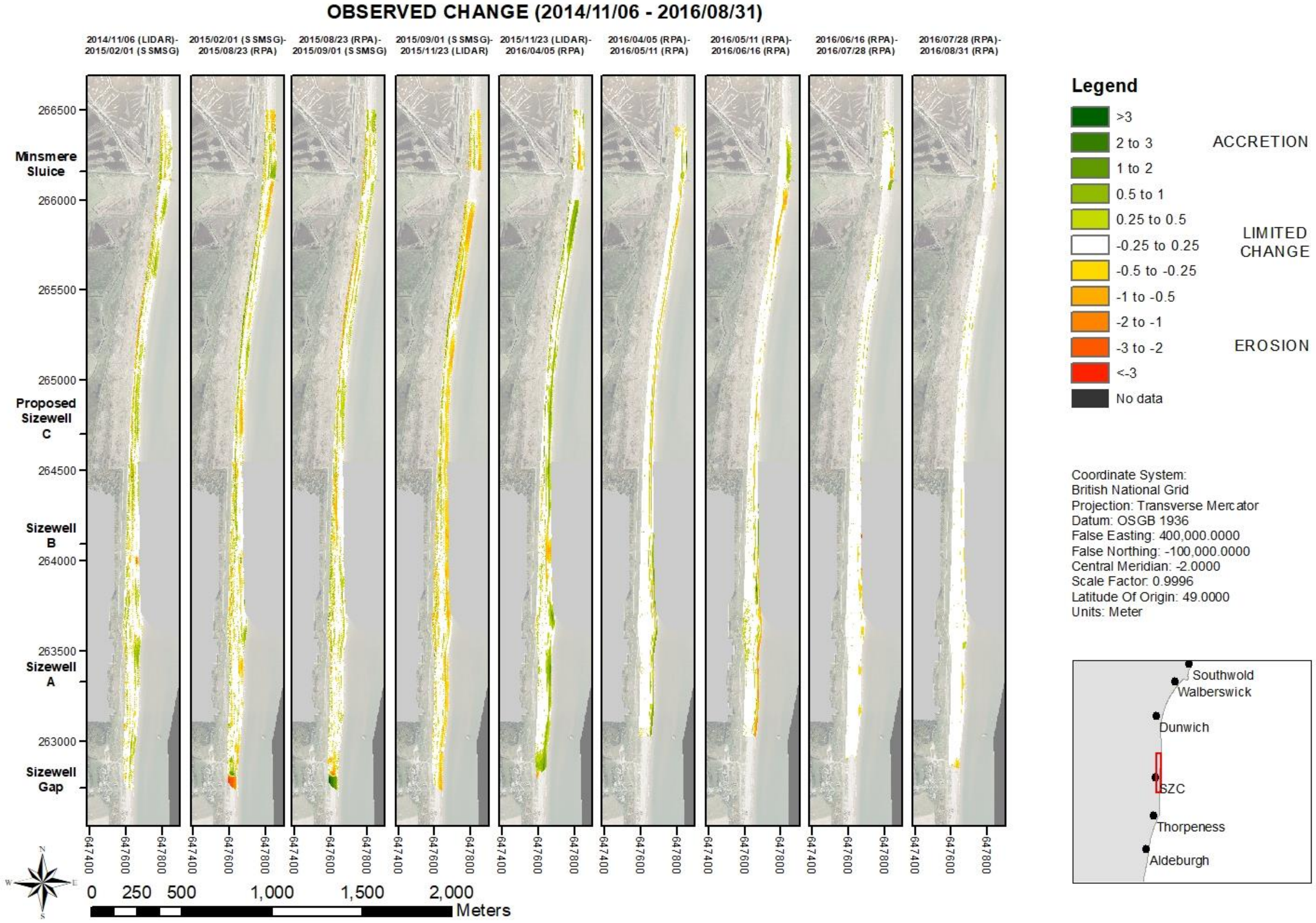


Figure 52: Intra-annual short-term changes in beach volume between Sizewell Gap and Minsmere North, between 06/11/2014 and 31/08/2016.

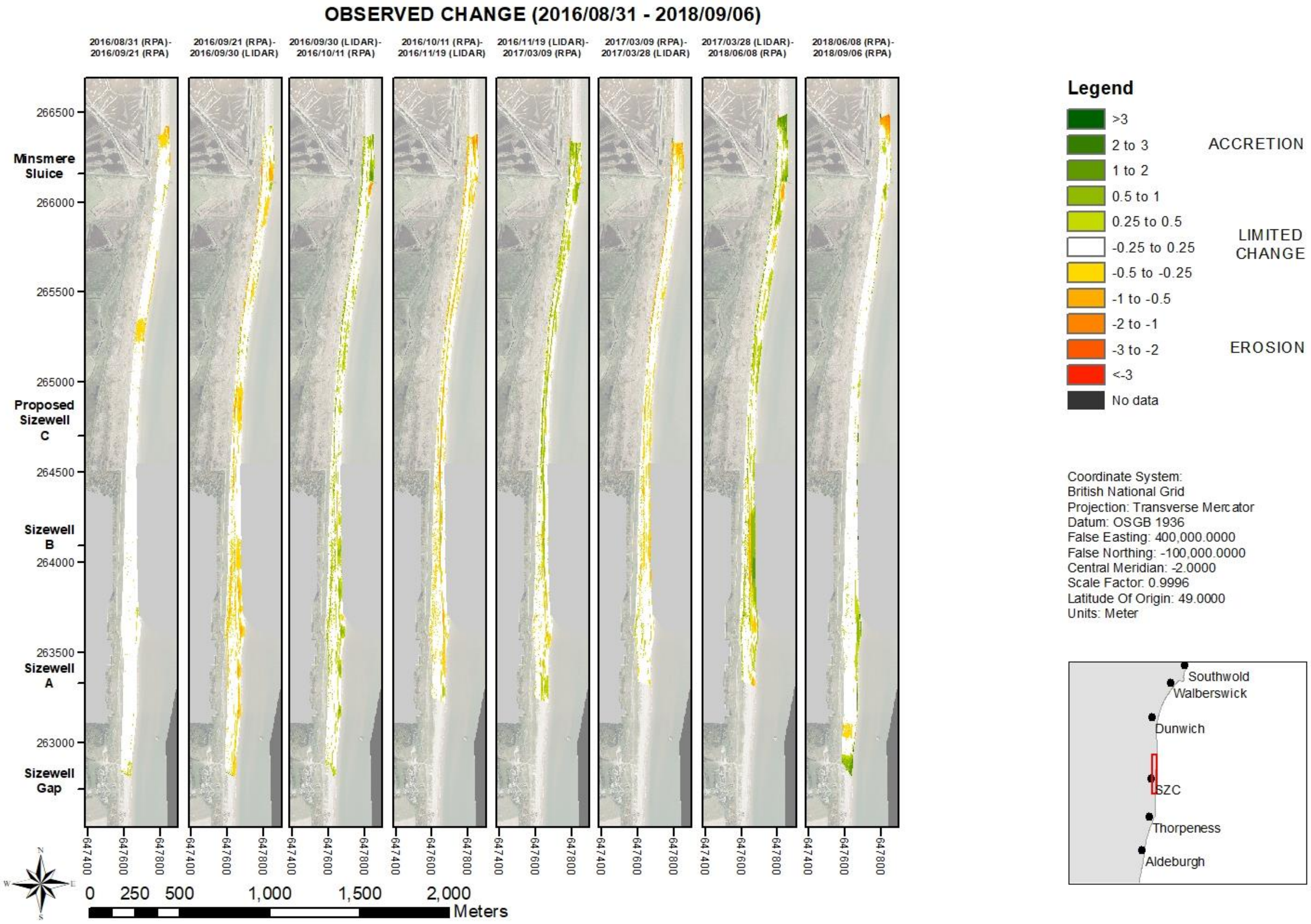

OBSERVED CHANGE (2016/08/31 - 2018/09/06)
2016/08/31 (RPA)-2016/09/21 (RPA)
2016/09/21 (RPA)-2016/09/30 (LIDAR)
2016/09/30 (LIDAR)-2016/10/11 (RPA)
2016/10/11 (RPA)-2016/11/19 (LIDAR)
2016/11/19 (LIDAR)-2017/03/09 (RPA)
2017/03/09 (RPA)-2017/03/28 (LIDAR)
2017/03/28 (LIDAR)-2018/06/08 (RPA)
2018/06/08 (RPA)-2018/09/06 (RPA)
266500
Minsmere Sluice
266000
265500
265000
Proposed Sizewell C
264500
Sizewell B
264000
263500
Sizewell A
263000
Sizewell Gap
647400
647600
647800
0 250 500 1,000 1,500 2,000 Meters
Legend
>3
2 to 3
1 to 2
0.5 to 1
0.25 to 0.5
-0.25 to 0.25
-0.5 to -0.25
-1 to -0.5
-2 to -1
-3 to -2
<-3
No data
ACCRETION
LIMITED CHANGE
EROSION
Coordinate System: British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936
False Easting: 400,000.0000
False Northing: -100,000.0000
Central Meridian: -2.0000
Scale Factor: 0.9996
Latitude Of Origin: 49.0000
Units: Meter
Southwold
Walberswick
Dunwich
SZC
Thorpeness
Aldeburgh

Figure 53: Intra-annual short-term changes in beach volume between Sizewell Gap and Minsmere North, between 31/08/2016 and 06/09/2018.

6.2 Medium-term changes, based on topographic surveys and orthorectified aerial photography (1940 – 2016)

6.2.1 Medium-term changes in beach contour position, based on topographic surveys (1940 – 2016)

Graphs showing the changes in beach contours since 1940, based on historical aerial photographs and topographic surveys, are shown in Figure 54 – Figure 57.

At the southern end of the Dunwich – Walberswick barrier (Figure 54), the beach contours moved seawards between 1940 – 1952, possibly aided by the erection of anti-invasion structures on the beach. The beach remained stable until 1965, after which the beach receded approximately 20 m. Post-1997, the beach and ridge system grew seaward, likely fed mainly by sediment transported alongshore from the central part of the barrier, which has experienced pronounced sediment loss (Pye and Blott, 2009).

At Dunwich Cliffs, the beach contours moved landwards 28 m between 1940 – 1965, and at Cliff House they receded 32 m by 1983. There was some beach recovery at Cliff House between 1983 – 1991, since when the beach was relatively stable. At Minsmere Cliffs, the beach accreted between 1940 – 1952, remained fairly stable until retreating approximately 25 m in 1991 – 2000 and was subsequently stable.

At profiles P1 and S1B2 on the northern Minsmere barrier (Figure 55), net beach accretion occurred between 1940 – 1997, followed by rapid erosion. The 1953 storm surge event appeared to have no significant long-term effect (several years to decades) on the shoreline position in this area. Although significant over-washing of the back-barrier area occurred during the 1953 storm, the earth embankment inner line of defence was rebuilt and vegetation planted on the backshore area to encourage the growth of a new dune ridge outer sea defence (Figure 58). The southern beach erosion limit appeared to move southwards from the southern end of Minsmere cliffs in 1991 (S1B1), reaching the North Wall area by 1997 and profile S1B2 by 2000. Falling beach levels after 2000 led to erosion of the outer barrier ridge and allowed the trough between the outer and inner sea defences to be filled by seawater and sediment during storm surges in 2006 and 2007.

To the north of Minsmere Sluice, the beach contours moved seawards between 1940 – 1965, landwards between 1965 – 1983, and seawards again after 1983. A similar pattern occurred on the southern side of the Sluice, except that landward movement continued between 1983 – 1991, after which time there was net progradation.

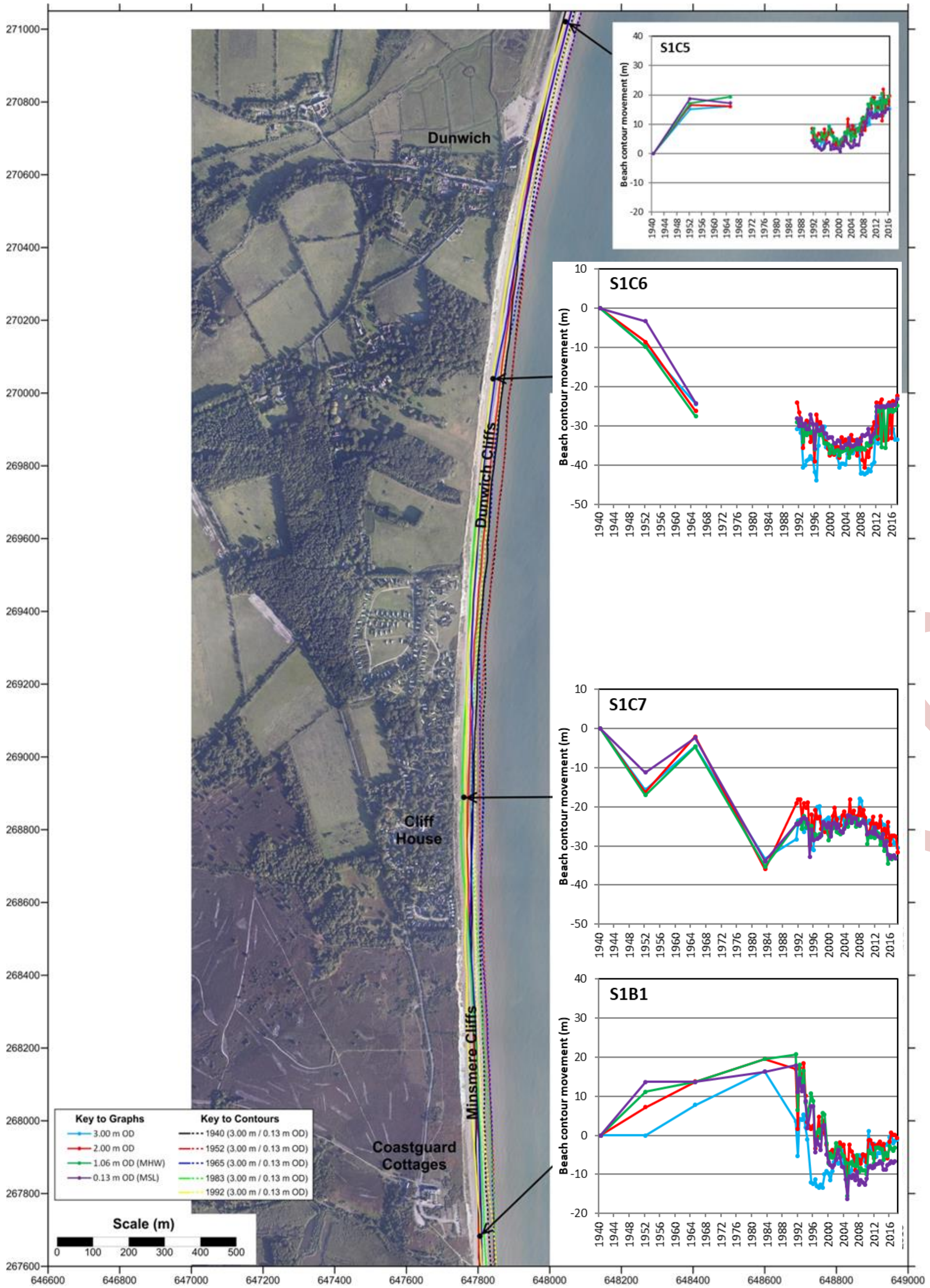
The aerial photographic evidence shows that the beach south of Minsmere Sluice has been receding landwards since 1940, with periods of relative stability between 1952 – 1965 and between 1983 – 1996. At profiles S1B4 and P3 there has been a maximum beach recession of 60 m since 1940, with the fastest recession occurring after 2000 (approximately 20 m in 10 years). Since 2011, S1B4 has accreted and since 2005 P3 has been stable.

At P4 and P5 a similar recession occurred in the post-2000 period, but the overall recession was much less due to the pre-2000 period in which P4 experienced relatively slow recession and P5 advanced. Both profiles also showed stability in the last 6 – 8 years. The total amount and average rate of recession declined southwards from profile P3 to P6 (just north of SZC; Figure 54), where there was no net change since 1940. Further south from P6 there was net beach progradation since 1940, amounting to 20 m at profile P7 and 30 m at profiles P8, P9, and P9B in front of SZB and the northern end of SZA. Although net accretion was observed, shoreline positions varied significantly (envelope of up to 46 m) and a phase of accretion occurred after 1993. This frontage experienced major disturbance during the construction of SZB and the artificial dune sea defences and again during beach restoration works following removal of the coffer dam (1992) and BLF (1993). At the northern extent of the SZC site (S1B5 and P7), shoreline retreat of up to 20 m occurred during and post-construction (1991 – 2002) but was followed by an almost equal advance during 2002 – 2011, before a similar degree of retreat to 2017.

At profile P10, in front of SZA, the beach contour positions did not change greatly between 1940 – 1965, but seaward movement of almost 30 m occurred between 1965 – 1993. This was followed by recession post SZB construction, before stabilisation and recovery since 2000.

The positions of the beach contours near Sizewell Gap (Figure 55) have not changed greatly since 1940, but to the north and south of Sizewell Hall (P12 – S1B7), significant beach erosion occurred between 1965 – 1991 (30 – 70 m), since when the beach experienced relative stability.

Just 800 m south at Thorpeness North (profiles P16 and S1B8), the beach contours showed little change between 1940 – 1952, landward recession between 1952 – 1965, renewed seaward movement between 1965 – 1991, and relative stability thereafter. Small net change (and the stark contrast with large net change to the north) could be related to the Coralline Crag that outcrops just offshore from P16 and S1B8. At Thorpeness South (profiles P17 and S1A1), beach accretion between 1940 – 1952 was followed by erosion until 1983. Fluctuations in erosion and accretion have continued in this area of high variability, with further accretion between 1983 – 2003, slight erosion until 2012 and subsequent accretion over the last 3 – 4 years.


S1C5
S1C6
S1C7
S1B1
Dunwich
Dunwich Cliffs
Cliff House
Minsmere Cliffs
Coastguard Cottages
Beach contour movement (m)
Key to Graphs
3.00 m OD
2.00 m OD
1.06 m OD (MHW)
0.13 m OD (MSL)
Key to Contours
1940 (3.00 m / 0.13 m OD)
1952 (3.00 m / 0.13 m OD)
1965 (3.00 m / 0.13 m OD)
1983 (3.00 m / 0.13 m OD)
1992 (3.00 m / 0.13 m OD)
Scale (m)

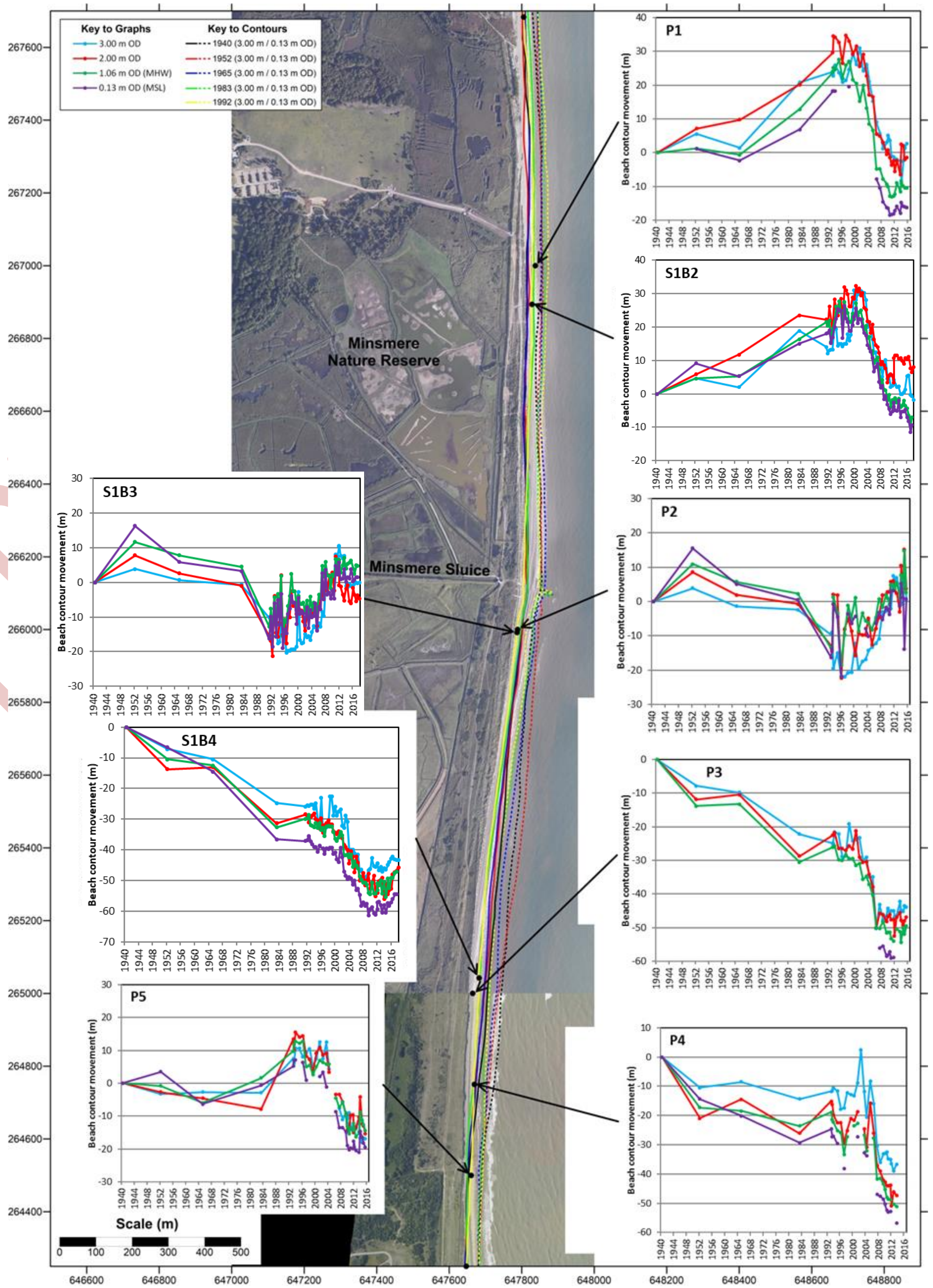

Key to Graphs
3.00 m OD
2.00 m OD
1.06 m OD (MHW)
0.13 m OD (MSL)
Key to Contours
1940 (3.00 m / 0.13 m OD)
1952 (3.00 m / 0.13 m OD)
1965 (3.00 m / 0.13 m OD)
1983 (3.00 m / 0.13 m OD)
1992 (3.00 m / 0.13 m OD)
P1
S1B2
P2
P3
P4
S1B3
S1B4
P5
Minsmere Nature Reserve
Minsmere Sluice
Beach contour movement (m)
Scale (m)

Figure 54: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD contours, based on aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2012): Dunwich to Minsmere Cliffs.Base aerial photographs flown in 2011. Note that aerial photographs did not cover profiles S1C5 and S1C6 in 1983, producing a data gap on these graphs.

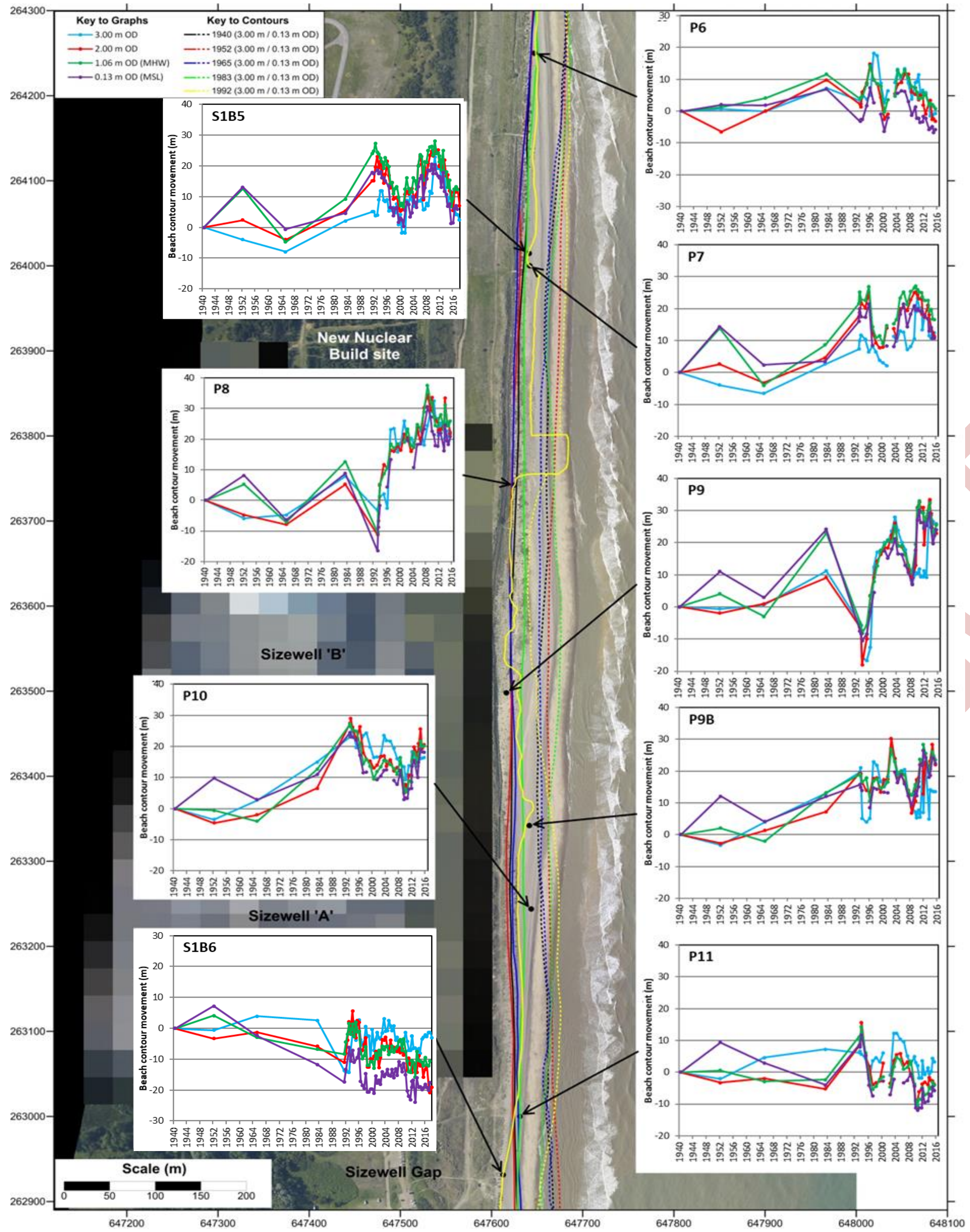


Figure 55: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD contours, based on aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2012): Minsmere Cliffs to Sizewell north.Base aerial photographs flown in 2011. Note that aerial photographs did not cover profiles S1C5 and S1C6 in 1983, producing a data gap on these graphs.

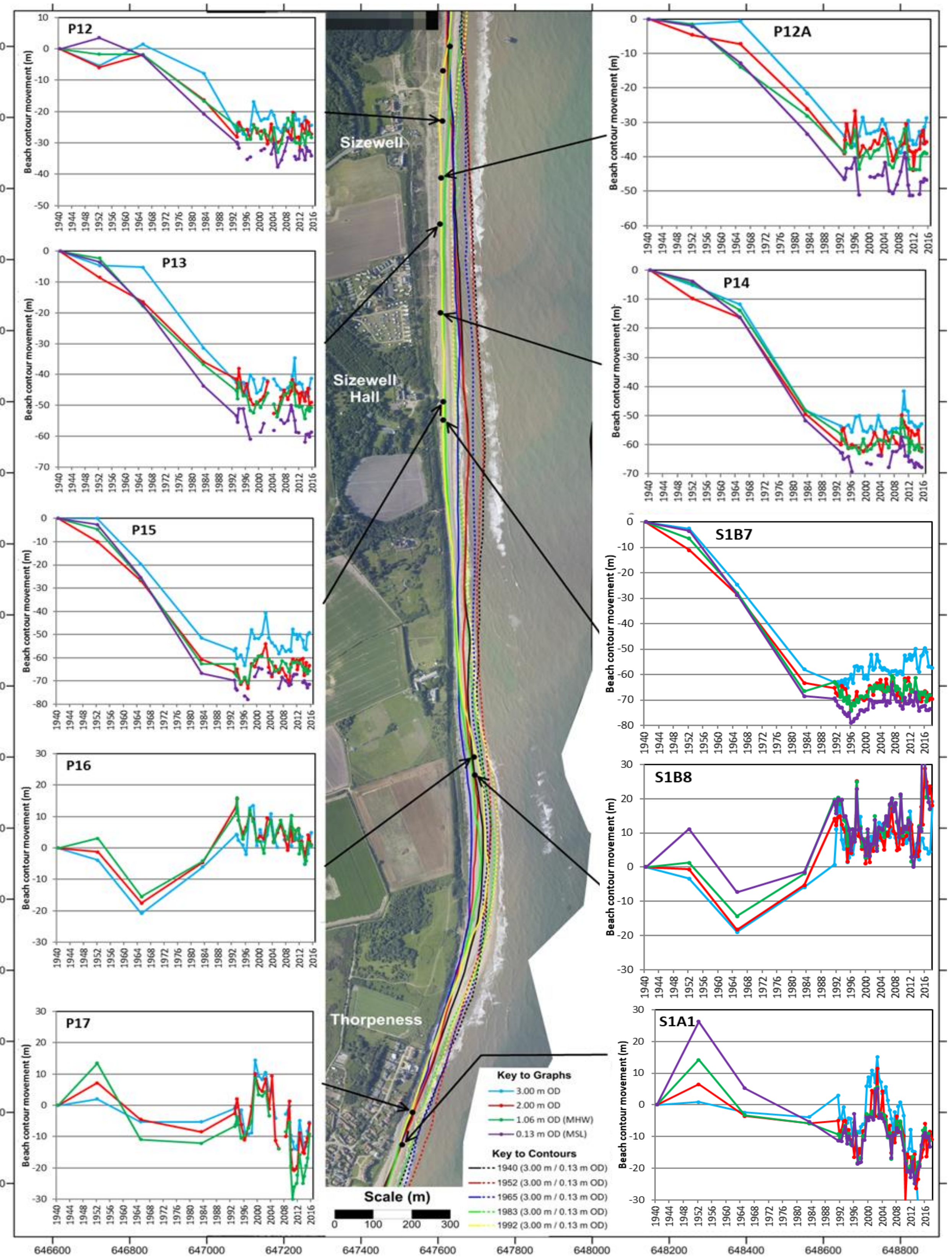


Figure 56: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD contours, based on aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2012): Sizewell Power Station frontage. Base aerial photographs flown in 2011. Note that aerial photographs did not cover profiles S1C5 and S1C6 in 1983, producing a data gap on these graphs.

Figure 57: Changes in the position of the 3.00, 2.00, 1.06 and 0.13 m OD contours, based on aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2012): Sizewell to Thorpeness. Base aerial photographs flown in 2011. Note that aerial photographs did not cover profiles S1C5 and S1C6 in 1983, producing a data gap on these graphs.

Figure 58: Marram planted on the backshore at Minsmere in 1954, following the 1953 storm surge (from Steers, 1960).

6.2.2 Medium-term changes in beach contour position, based on orthorectified aerial photography (1940 – 2011)

Beach contours derived from historical (1940, 1952, 1965 and 1983) and modern EA (1992, 2000 and 2011) aerial photos were used to investigate the spatial patterns of shoreline change over 71 years. Only selected modern EA aerial photos were used, to maintain an approximately decadal time step and so to avoid bias toward the most recent decades (for which there are more frequent data). The analysis of shoreline positions utilised the same transects discussed in Sections 5.7 and 6.1.6, which are spaced at 50 m intervals. The SCE and r^2 trend strength plots (Figure 59 and Figure 61) utilise the same symbol colours as the 1992 – 2016 analysis (Figure 60), but the Linear Regression Rate uses a finer (0.25 m/yr step) colour scale to highlight spatial patterns that are otherwise not evident.

The decadal interval shoreline change rates showed alternating bands of retreat (Dunwich, south of Minsmere, Sizewell Hall) interspersed by sections of stability or slight seaward movement (north of Dunwich, north of Minsmere, Sizewell, north of Thorpeness). As might be expected in multi-decadal time series, most of the underlying data showed phases of erosion and accretion, much of which has been described previously.

There were three coastal sections that have high r^2 values indicating persistent trends over the 71 year period:

- At Dunwich high r^2 values of 0.7 – 0.9 reflected slow but steady retreat at rates of -0.3 to -0.6 m/yr, with occasional short phases of seaward movement (e.g., Figure 62, top panel).
- 400 m south of the Minsmere sluice, a 1300 m section of persistently retreating coast extended to the northern edge of the proposed SZC site. Very high r^2 values of 0.8 to 1.0 and retreat rates of -0.6 to -0.8 m/yr were common over this section (e.g., Figure 62, centre panel). The rates within this area are greater in post-1992 (-1.7 m/yr) as shown in Figure 55 (S1B4 and P3) and Figure 60. This section exhibted the second largest SCE (50 – 65 m), 70 – 100 % of which was due to shoreline retreat (net landward movements of 44 – 62 m).
- A 1500 m stretch around Sizewell Hall (extending approximately 900 m north and 600 m south) had a very large SCE, with retreat rates of up to -1.2 m/yr and r^2 values ranging between 0.8 – 1.0, despite very little change since 1992 (e.g., Figure 62, bottom panel). The short-term stability, as shown by a low SCE of 5 – 8 m and very low rates of change in this area (see Figure 55), was not reflected in the medium-term statistics, because the signal was dominated by high rates of retreat (up to -2.1 m/yr) during 1952 – 1983. This long coastal section identifies an important feature of the GSB, in that shoreline behaviour can alternate between phases of stability and rapid change. Accordingly, it highlights the value of assessing changes in shoreline behaviour over variable temporal and spatial scales.

In contrast to the persistent trends described above, much of the 2km frontage from Cliff House to Minsmere Sluice was typified by near-zero r2, as a result of such alternating phases of erosion and accretion. Near Cliff House (P1 and S1B2), gradual seaward movement prior to 1992 subsequently changed to a trend of rapid erosion (see Figure 55). This pattern was reversed 1750 m to the south (500 m north of Minsmere Sluice), with gradual landward movement prior to 1992 and seaward movement thereafter. These patterns appeared to be a result of the southward migration of a bulge in the shoreline, as indicated by the yellow triangle in Figure 63.

Minsmere sluice shorelines were generally stable over the 71 year period but exhibited higher rates of seaward movement in the post-1992 period, especially on the northern side (in between beach profiles S1B2 and S1B3). On the southern side, up to 400 m south of the sluice (see P3 and S1B2 on Figure 55), the low net rate of change is due to a balance between slow retreat prior to 1992 and high rates of seaward movement after 1992.

The SZB frontage of a few hundred metres, showed a consistent seaward trend in the pre- and post-1992 periods with relatively large SCE (up to 43 m), but was characterised by low rates of change (0.2 – 0.4 m/yr) and variable r^2 values (0.2 – 0.8). This implied that this short section of stable shoreline is in dynamic equilibrium. A component of the spatial and temporal variability here was the growth and movement of the salient that is seen as a slight bulge in the shoreline since 2005 (see Section 7.4.1).

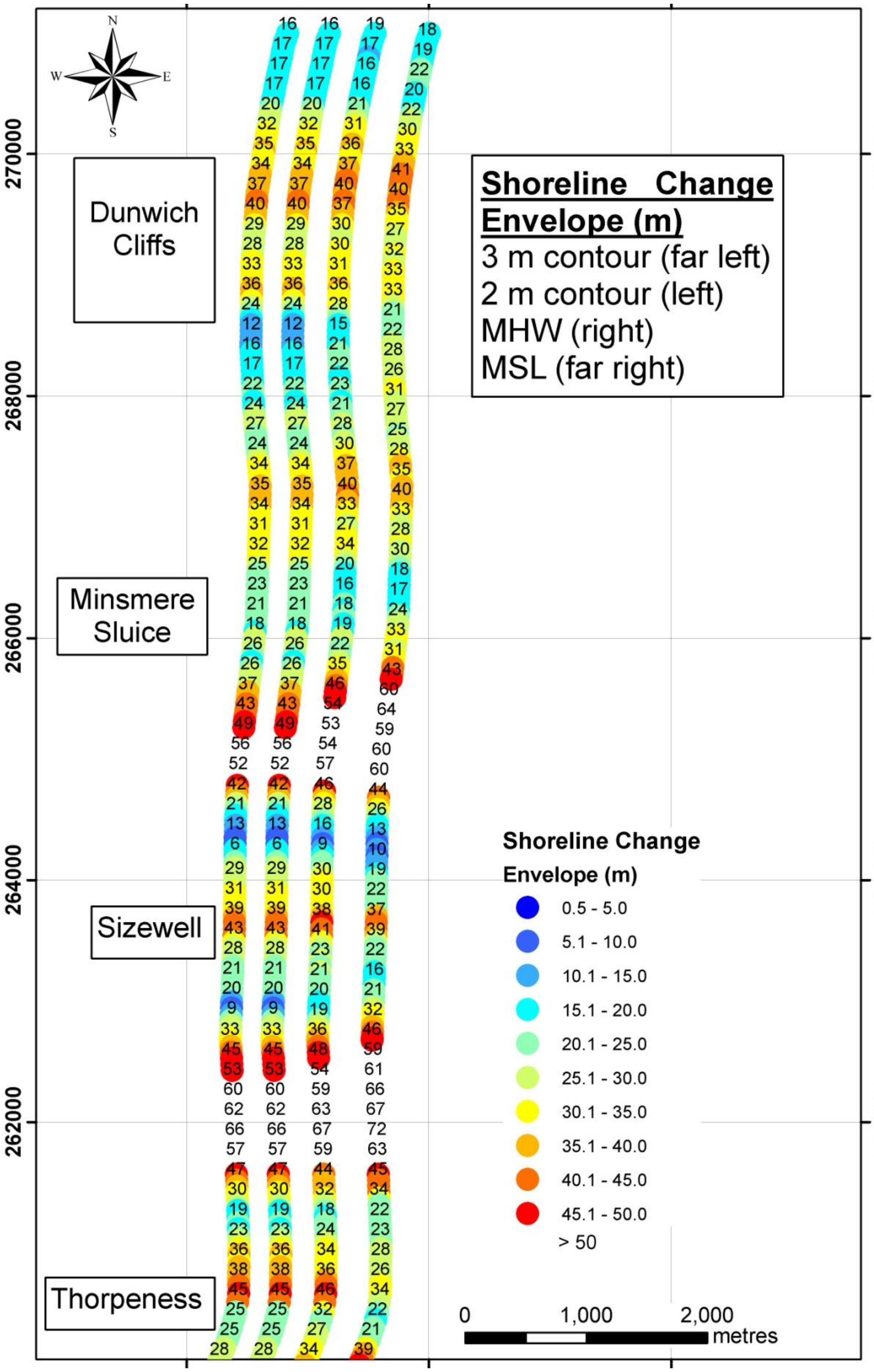


Figure 59: Longshore variability in the shoreline change envelope for four contour elevations, 1940-2011.

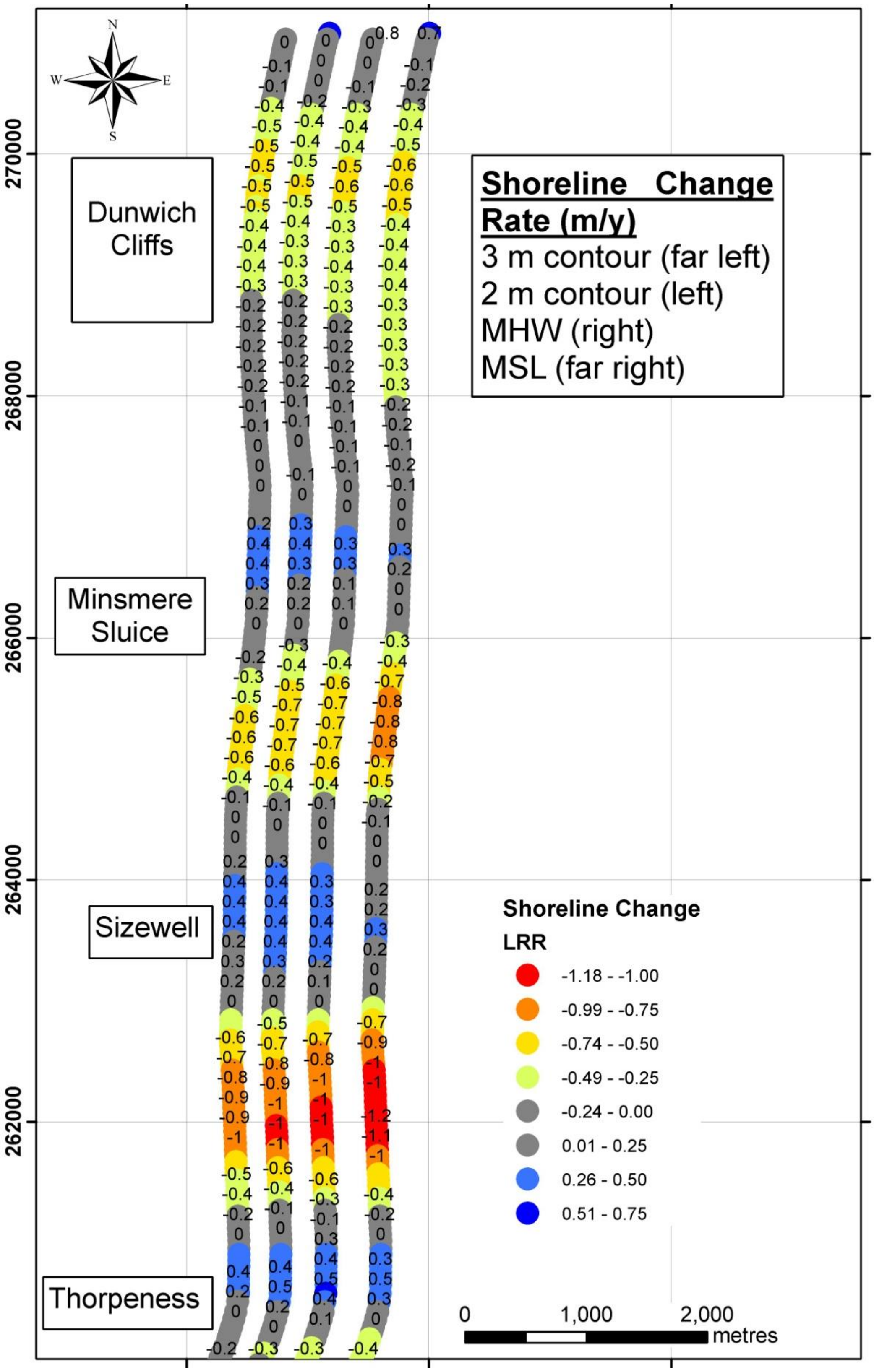


Figure 60: Longshore variability in the shoreline change rate for four contour elevations, 1940-2011.

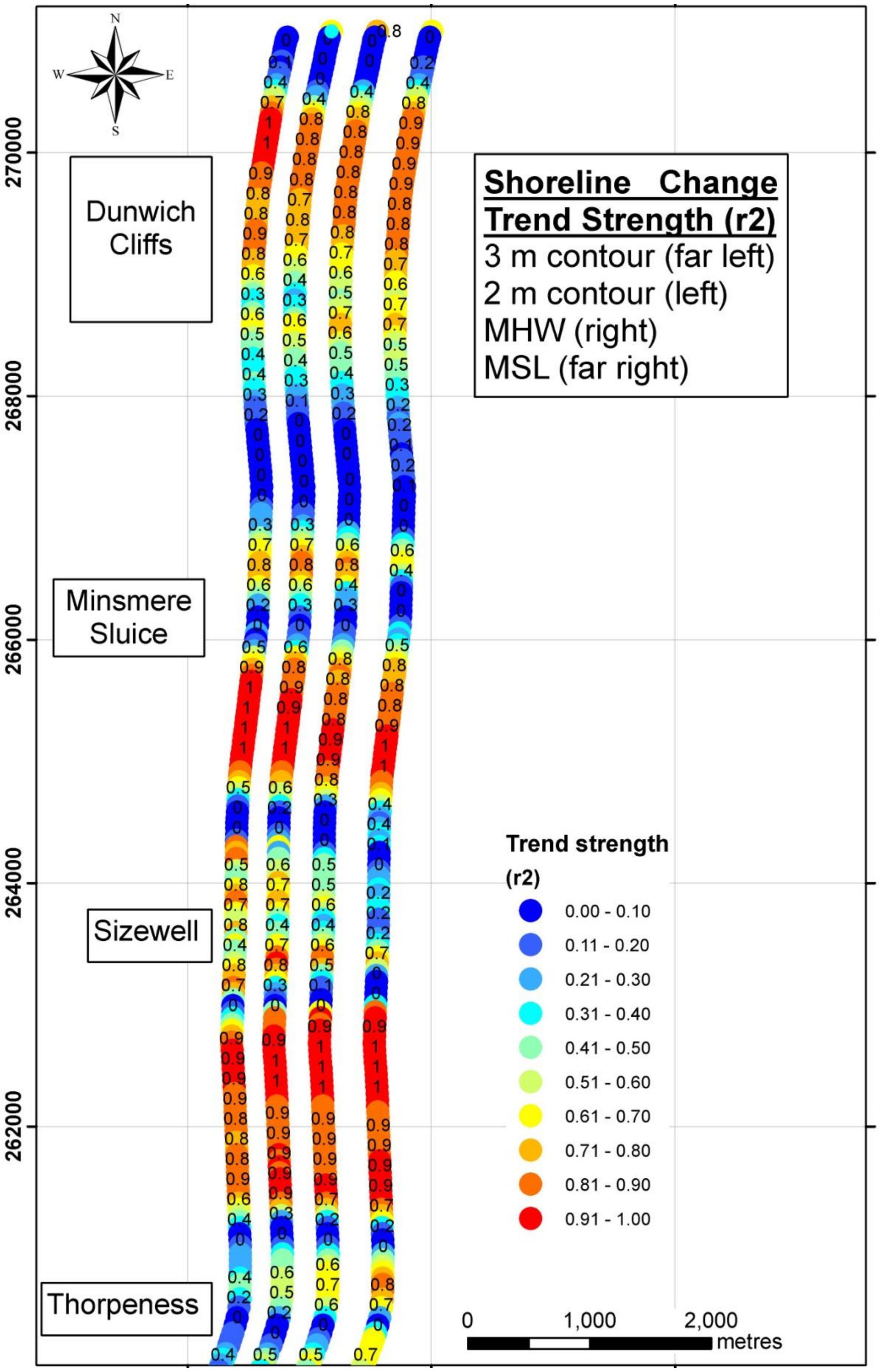


Figure 61: Longshore variability in the shoreline change trend strength (r^2) for four contour elevations, 1940-2011.

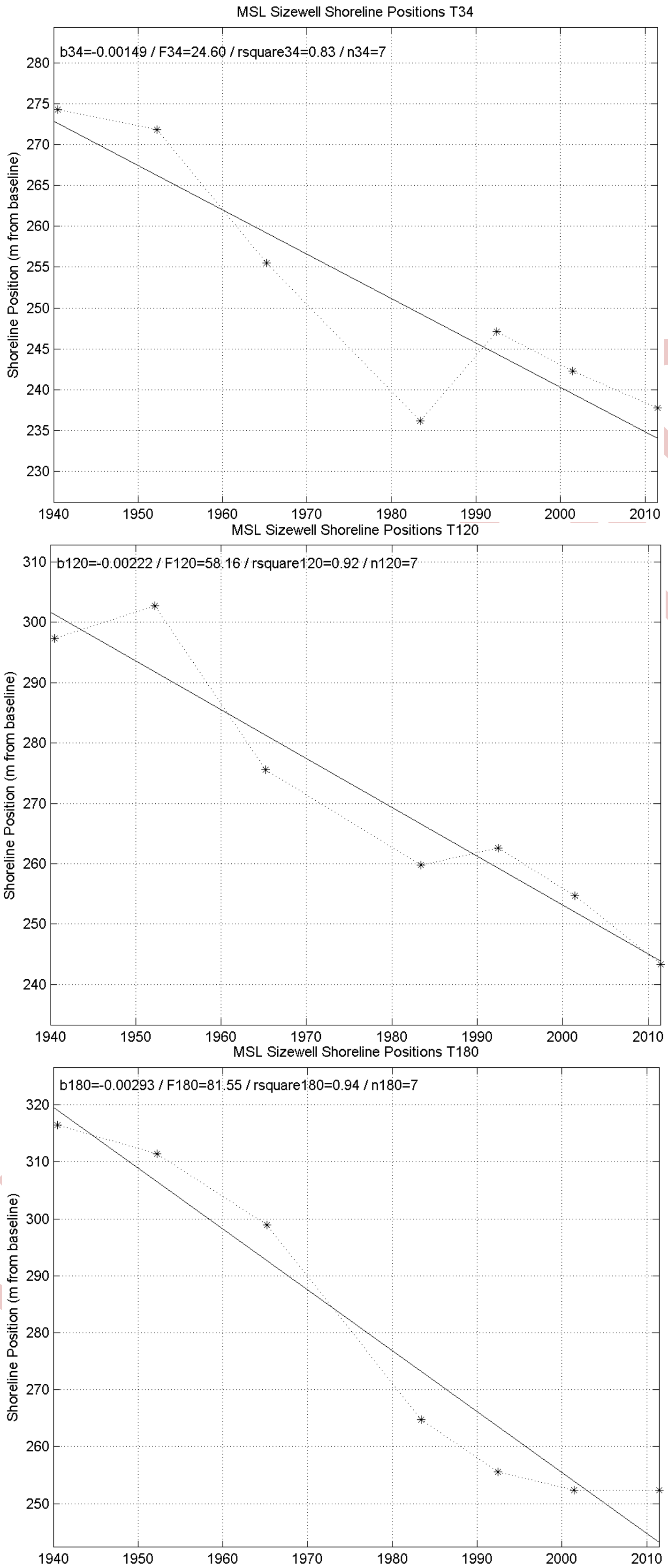


Figure 62: Time-series of the 0.13 m shoreline positions from near the centre of zones of relatively persistent behaviour at Dunwich, between Minsmere and SZC, and Sizewell Hall. The straight line is the linear regression rate of change (LRR).

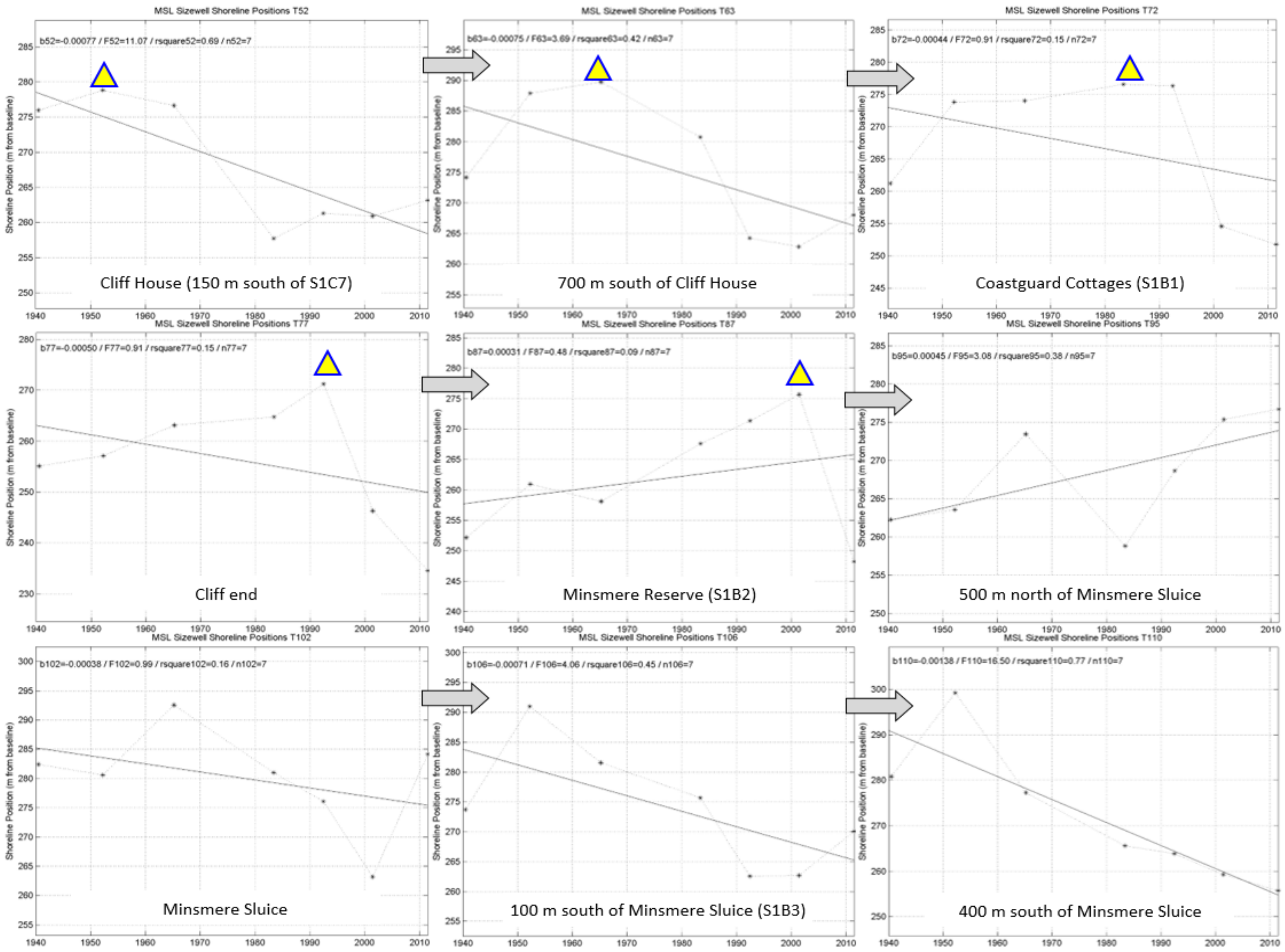

MSL Sizewell Shoreline Positions T52
b52=-0.00077 / F52=11.07 / rsquare52=0.69 / n52=7
Cliff House (150 m south of S1C7)
MSL Sizewell Shoreline Positions T63
b63=-0.00075 / F63=3.69 / rsquare63=0.42 / n63=7
700 m south of Cliff House
MSL Sizewell Shoreline Positions T72
b72=-0.00044 / F72=0.91 / rsquare72=0.15 / n72=7
Coastguard Cottages (S1B1)
MSL Sizewell Shoreline Positions T77
b77=-0.00050 / F77=0.91 / rsquare77=0.15 / n77=7
Cliff end
MSL Sizewell Shoreline Positions T87
b87=0.00031 / F87=0.48 / rsquare87=0.09 / n87=7
Minsmere Reserve (S1B2)
MSL Sizewell Shoreline Positions T95
b95=0.00045 / F95=3.08 / rsquare95=0.38 / n95=7
500 m north of Minsmere Sluice
MSL Sizewell Shoreline Positions T102
b102=-0.00038 / F102=0.99 / rsquare102=0.16 / n102=7
Minsmere Sluice
MSL Sizewell Shoreline Positions T106
b106=-0.00071 / F106=4.06 / rsquare106=0.45 / n106=7
100 m south of Minsmere Sluice (S1B3)
MSL Sizewell Shoreline Positions T110
b110=-0.00138 / F110=16.50 / rsquare110=0.77 / n110=7
400 m south of Minsmere Sluice
Shoreline Position (m from baseline)

Figure 63: (including previous page). Time-series plots highlighting the progression of a bulge (marked by triangles) in the coast from Cliff House to Minsmere Reserve over 48 years and the opposite patterns at each end of the section.

6.3 Long-term changes, based on historical maps, topographic surveys and orthorectified aerial photography (1835 – 2017)

Long-term changes (1835 – 2017) in the MHW contour derived from Ordnance Survey maps[4], topographic surveys and orthorectified aerial photography are shown in Figure 64 – Figure 67. Average rates of change in the position of MHW between different epochs are compared in Table 12. Table 12 also provides the net rates of change for 1835 – 2017 and 1883 – 2017 separately because of higher uncertainty in the 1835 maps.

At the southern end of the Dunwich - Walberswick barrier (S1C5, Figure 64) the position of MHWS and MHW was relatively stable between 1835 – 1883, but the MHW retreated landwards by approximately 70 m between 1883 – 1925. Seaward movement of approximately 30 m occurred between 1925 – 1952, followed by landward movement. Although sea level rise of up to 60 mm may have contributed to this landward movement, most of the change is likely to be attributable to beach erosion.

At Dunwich Cliffs (profile S1C6), the MHWS and MHW mark (and cliffs behind) receded by 145 m between 1835 – 1983, since when there has been relative stability. Erosion was most rapid (-1.91 m/yr) between 1903 – 1925 (Table 12). Some cliff erosion at Dunwich and Cliff House continued until 1983. Since the mid-1980's, wave conditions and longshore sediment drift favoured the build-up of beaches in front of Dunwich cliffs.

At Cliff House (profile S1C7), erosion of over 240 m occurred between 1835 – 1983, since when there has been little change. The rate of erosion was most rapid (-2.7 m/yr) between 1883 – 1903 and began to decline after 1903.

At the southern end of Minsmere Cliffs (profile S1B1), the MHW mark receded by 158 m between 1835 – 1940. Erosion was most rapid (-2.95 m/yr) between 1883 – 1903. Since 1940, the MHW position fluctuated but overall, receded only an additional 5 m.

Profiles P1 and S1B2, located just south of the former Coney Hill, experienced rapid erosion (-1.4 m/yr) between 1835 – 1883 (Figure 65), followed by a period of beach accretion lasting until the late 1990's when erosion set in again, reaching a maximum of -2.5 m/yr between 2001 – 2012. Groynes, artificial embankments, erection of brushwood fences and planting of beach grasses were employed at different times in this area to slow the erosion and provide stronger flood defences for the Minsmere Levels.

Hodskinson's map of 1783 suggests that the Minsmere River entered the sea through a gap in the northern end of the barrier near Coney Hill. Following an Act of Parliament in 1810, a new cut was made through the central part of the Minsmere Levels and thereafter, the river entered the sea via a sluice in the mid part of the barrier. The former discharge point became blocked and drainage of the North Marsh was diverted southwards into the main river. Although the sluice and drainage outlet on the seaward side of the barrier were subsequently improved, its position changed very slightly.

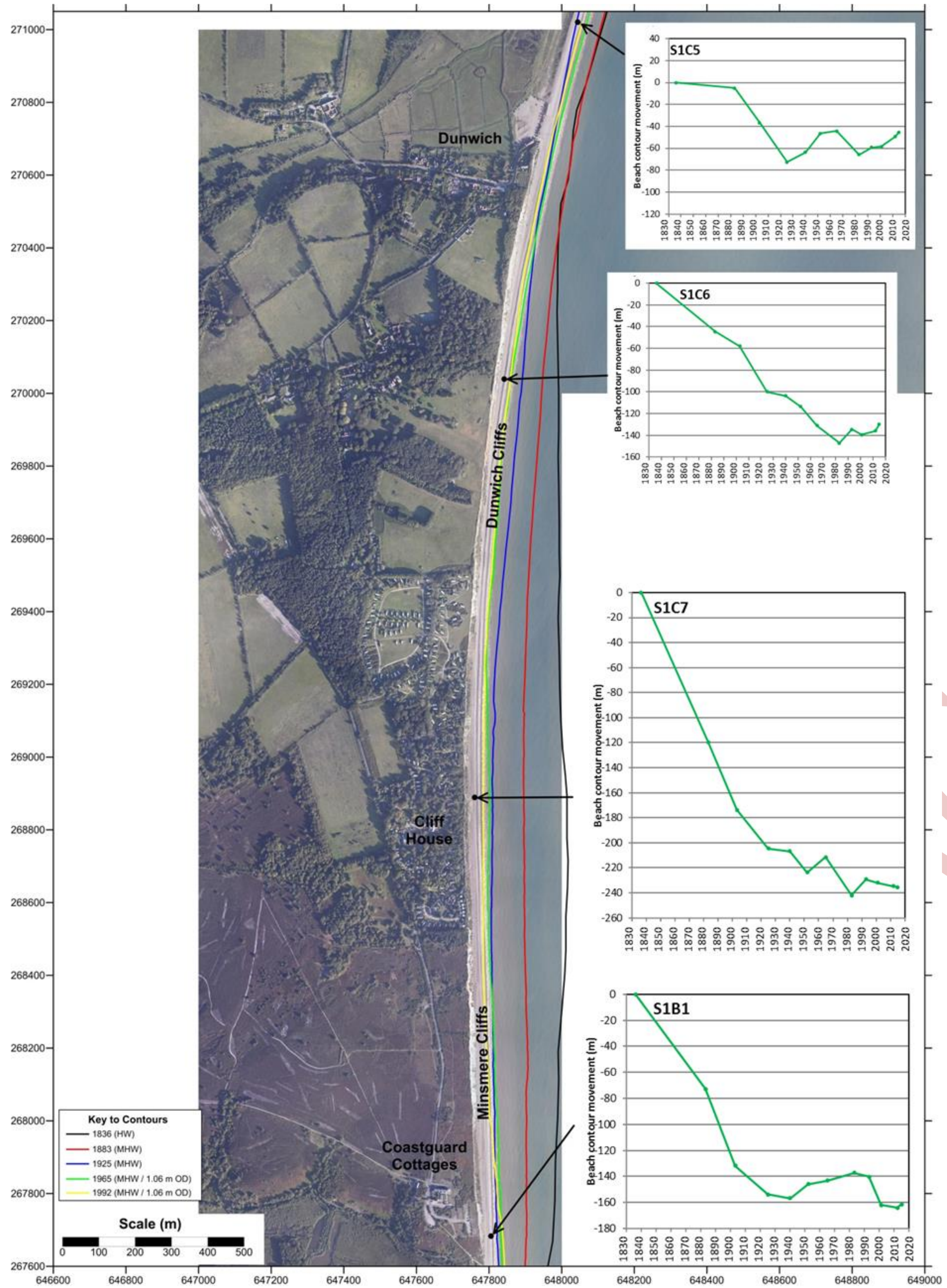
In 1835, the MHWS mark 250 m north of the Sluice (marked Minsmere Sluice North on Figure 65) lay approximately in the same position as today. The MHWS and MHW mark at this location receded landward by approximately 38 m between 1835 – 1903, since when it moved seawards again by approximately 35 m.

On the south side of the sluice (Profiles P2 and S1B3) there was erosion of up to 5 m between 1835 – 1883, since when there was accretion of 25 to 30 m (Figure 65). This may be attributable, at least in part, to improvement works which have raised and lengthened the sluice since its original construction, thereby increasing its sediment trapping potential.

[4] The back of the beach is approximately equivalent to MHWS position in the case of the 1835/36 survey.

The frontage between Minsmere Sluice and Thorpeness prograded by up to 140 m between 1835 – 1940. A series of beach ridges, capped by low dunes, grew seawards within a shallow bay south of the sluice. The First Edition One Inch map surveyed in 1835 (Figure 74 in Appendix A), showed a slight salient in the 'MHWS' contour opposite the southern end of Sizewell Cliffs and Sizewell Gap. Consideration of other elevation data for the area suggests this salient represented a sedimentary accumulation (the beach had a wider backshore compared with adjoining areas to the north and south). Progradation was most rapid (2.52 to 2.66 m/yr) at profiles P4 to P7 (from SZC to Minsmere), but between 1835 – 1883 all beaches as far as Thorpeness were prograding. (Figure 66 and Figure 67). Progradation continued along almost all of this frontage until 1925, and at profiles S1B4 to P4 until 1940 (Table 12). This phase of beach progradation corresponded with the period of rapid erosion of the Dunwich to Minsmere cliffs, suggesting that beach progradation at Sizewell may have been promoted by high rates of sediment supply from the north, which are also believed to have contributed to the development of the offshore Sizewell Bank (Carr, 1979), though it is not possible to ascertain if the higher bank came before or after shoreline accretion.

After 1940, progradation along this stretch was replaced by a general shoreline retreat. In the northernmost stretch (from Minsmere to profiles P3 and S1B4, 1 km south of Minsmere sluice), the shoreline retreated after 1940 by up to 62 m (Figure 65). Retreat of approximately 47 m was evident at profiles P3 and S1B4. Further south, along the power station frontage, the beach contours were generally stable since 1940. However, south of Sizewell all profiles showed a trend of erosion after 1925, for example, the MHW retreated by 80 to 90 m between 1925 – 2016 at profiles P13, P14, P15 and S1B7. Retreat of approximately 40 m since 1925 has occurred on all profiles as far as Thorpeness, although with greater variability at the Ness itself.


Dunwich
Dunwich Cliffs
Cliff House
Minsmere Cliffs
Coastguard Cottages
S1C5
S1C6
S1C7
S1B1
Beach contour movement (m)
Key to Contours
1836 (HW)
1883 (MHW)
1925 (MHW)
1965 (MHW / 1.06 m OD)
1992 (MHW / 1.06 m OD)
Scale (m)

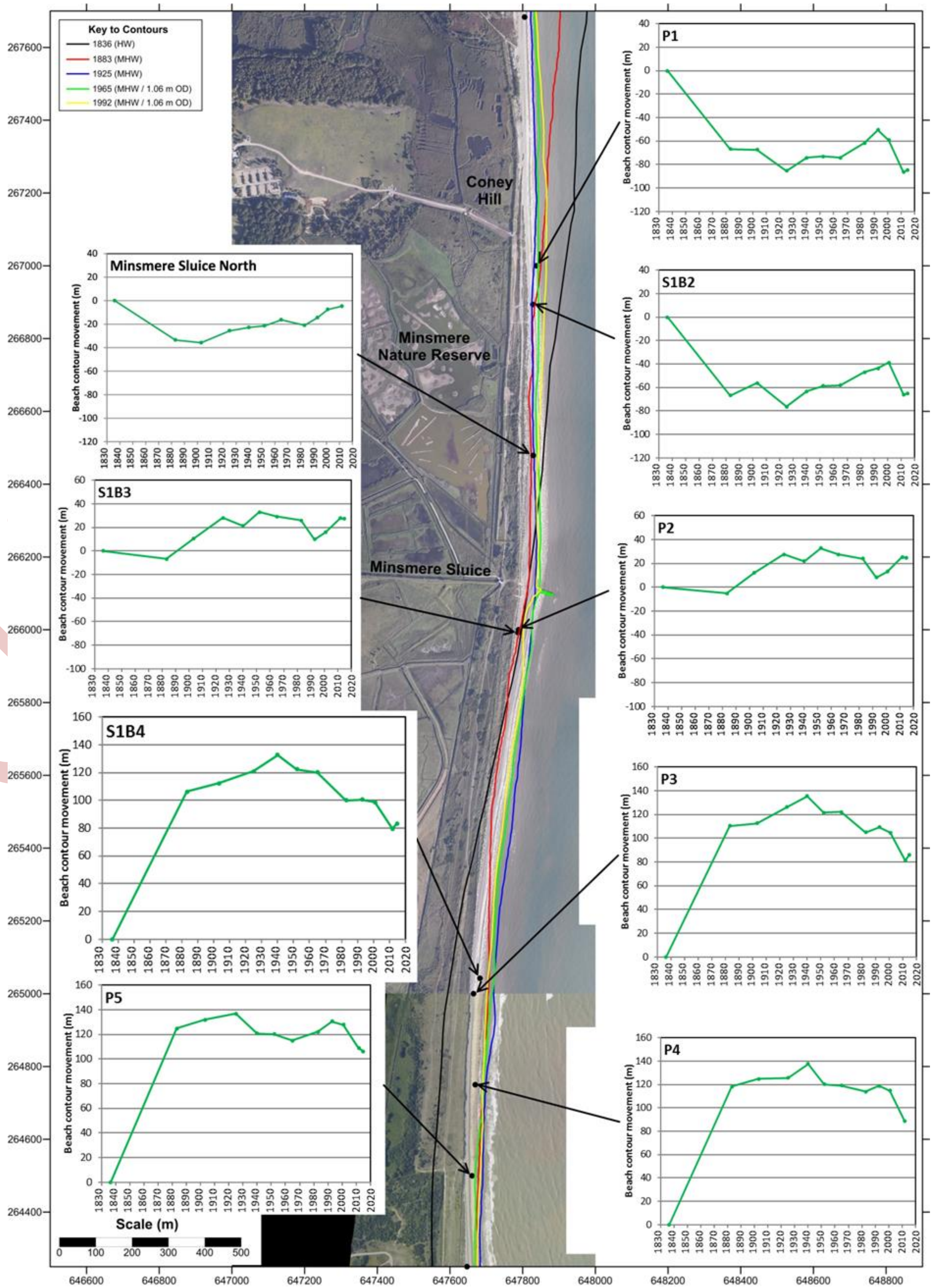
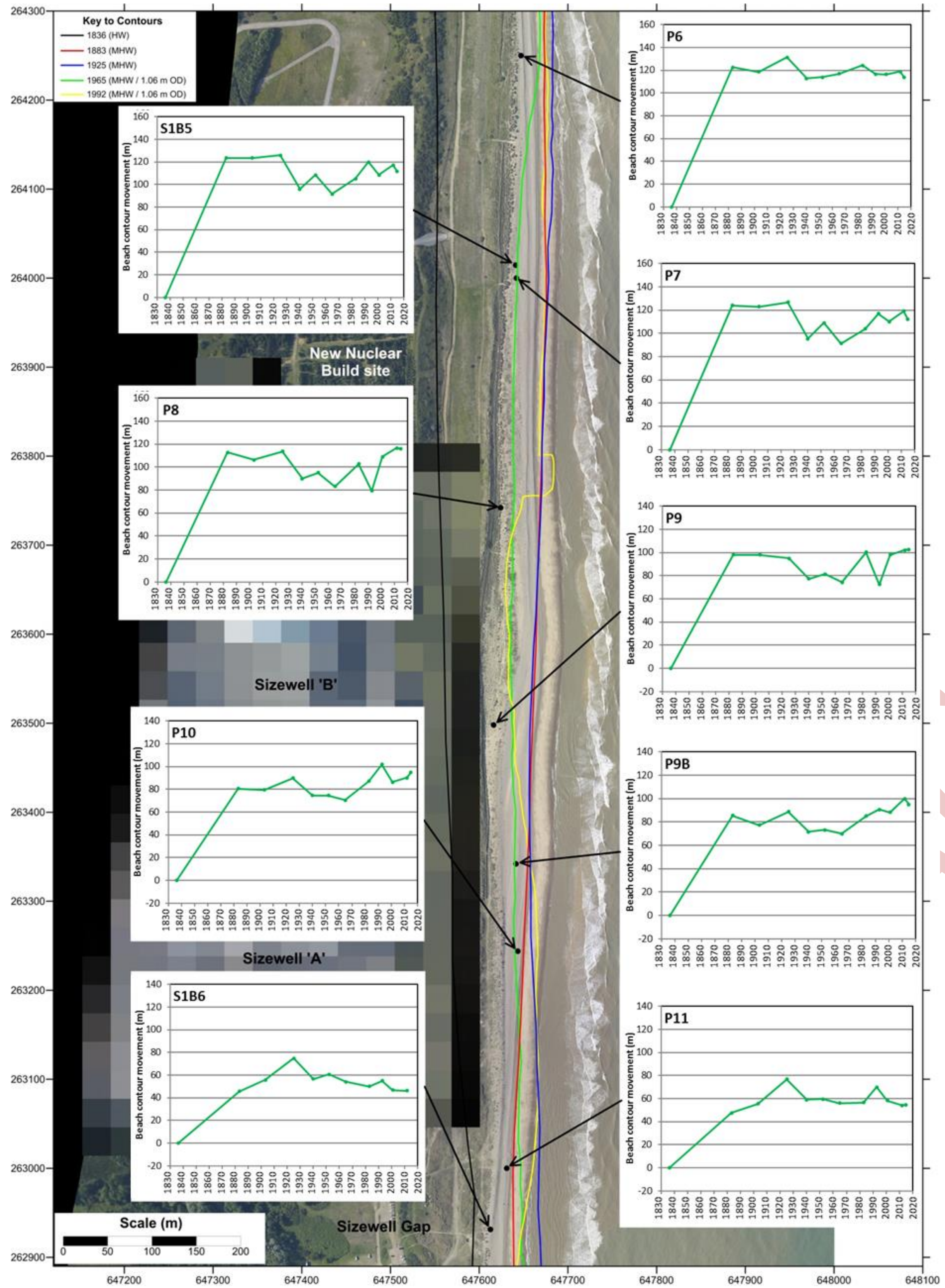

Key to Contours
1836 (HW)
1883 (MHW)
1925 (MHW)
1965 (MHW / 1.06 m OD)
1992 (MHW / 1.06 m OD)
Coney Hill
Minsmere Nature Reserve
Minsmere Sluice
Minsmere Sluice North
S1B3
S1B4
P5
P1
S1B2
P2
P3
P4
Beach contour movement (m)
Scale (m)

Figure 64: Changes in position of the MHW contour indicated by historical OS maps (MHWS contour in the case of the 1836 One Inch map), aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2016): Dunwich to Minsmere Cliffs. Base aerial photography flown in 2011.

Figure 65: Changes in position of the MHW contour indicated by historical OS maps (MHWS contour in the case of the 1836 One Inch map), aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2016): Minsmere Cliffs to Sizewell north. Base aerial photography flown in 2011. NB Minsmere Sluice North is an additional location identified in the GIS analysis performed in this study.


Key to Contours
1836 (HW)
1883 (MHW)
1925 (MHW)
1965 (MHW / 1.06 m OD)
1992 (MHW / 1.06 m OD)
S1B5
P6
P7
P8
P9
P9B
P10
P11
S1B6
New Nuclear Build site
Sizewell 'B'
Sizewell 'A'
Sizewell Gap
Scale (m)
0 50 100 150 200
Beach contour movement (m)

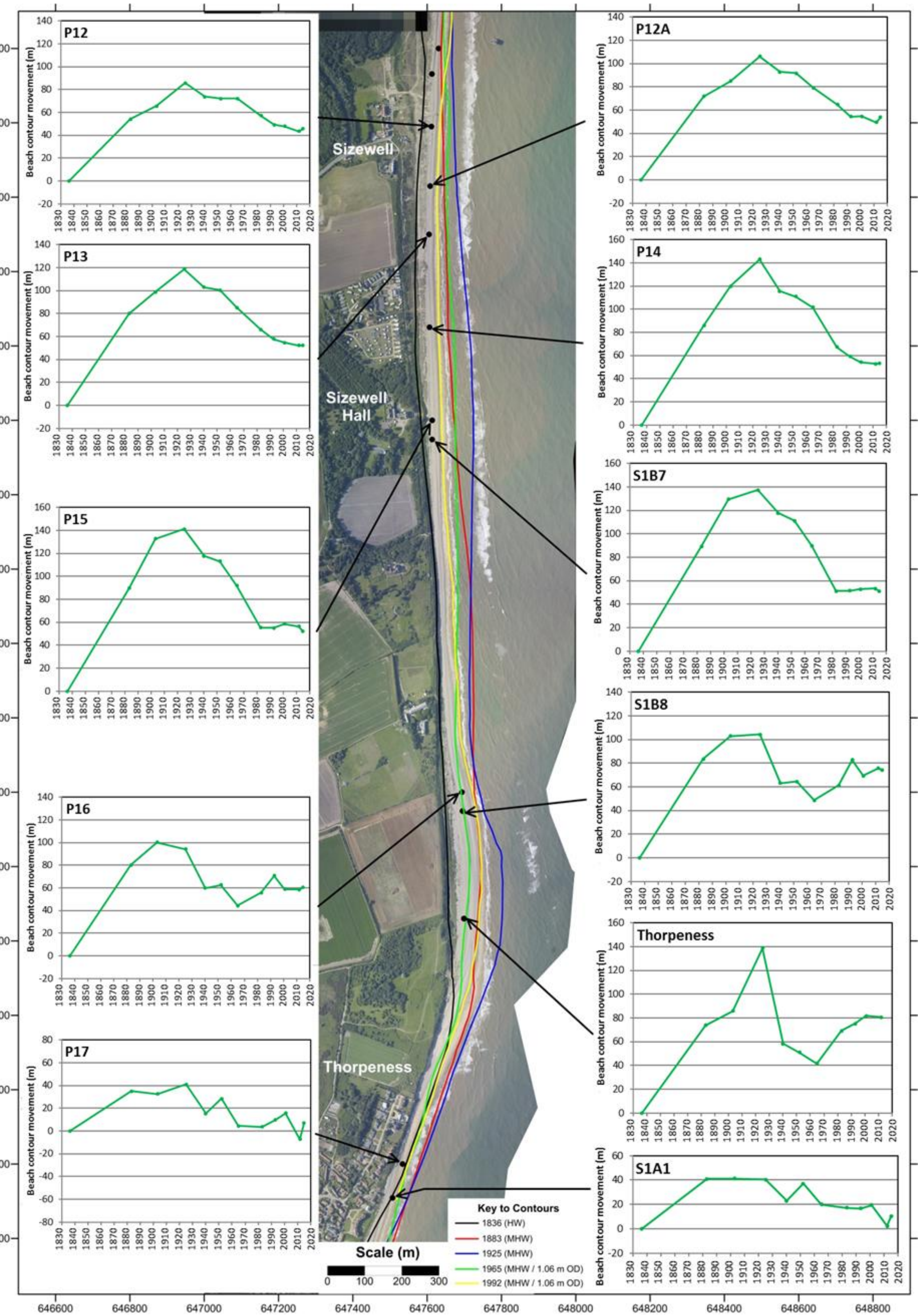

P12
P12A
P13
P14
P15
S1B7
P16
S1B8
P17
Thorpeness
S1A1
Sizewell
Sizewell Hall
Thorpeness
Key to Contours
1836 (HW)
1883 (MHW)
1925 (MHW)
1965 (MHW / 1.06 m OD)
1992 (MHW / 1.06 m OD)
Scale (m)
0 100 200 300
Beach contour movement (m)

Figure 66: Changes in position of the MHW contour indicated by historical OS maps (MHWS contour in the case of the 1836 One Inch map), aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2016): Sizewell Power Station frontage. Base aerial photography flown in 2011.

Figure 67: Changes in position of the MHW contour indicated by historical OS maps (MHWS contour in the case of the 1836 One Inch map), aerial photographs (1940, 1952, 1965 and 1983) and topographic surveys (1991-2016): Sizewell to Thorpeness. Base aerial photography flown in 2011. NB Thorpeness is an additional location identified in the GIS analysis performed in this study

Table 12: Rates of seaward movement (positive values) and landward movement (negative values) of the MHW contour. Back of beach, approximately equivalent to MHWS in the case of the 1835/36 survey. Data based on historical maps, aerial photographs and ground topographic surveys. Seaward movement (progradation) is highlighted in green; landward movement (erosion) is highlighted in red. Values are calculated at each EA and SSMSG profile line, and at two additional lines, Minsmere Sluice North (northing 266480) and Thorpeness (northing 260660).

Profile	Rates of change between dates (metres per year)											
	1836 1883	1883 1903	1903 1925	1925 1940	1940 1952	1952 1965	1965 1983	1983 1993	1993 2001	2001 2017	1836 2017	1883 2017
S1C5	-0.10	-1.59	-1.64	0.62	1.42	0.17	-1.20	0.65	0.10	0.42	-0.24	-0.28
S1C6	-0.95	-0.67	-1.91	-0.26	-0.82	-1.36	-0.89	1.26	-0.61	0.41	-0.71	-0.63
S1C7	-2.55	-2.70	-1.41	-0.14	-1.41	0.95	-1.70	1.29	-0.34	-0.32	-1.33	-0.90
S1B1	-1.55	-2.95	-0.99	-0.21	0.92	0.20	0.33	-0.30	-2.72	0.25	-0.88	-0.65
P1	-1.43	-0.02	-0.82	0.75	0.10	-0.09	0.70	1.11	-1.08	-0.12	-0.49	-0.16
S1B2	-1.42	0.53	-0.93	0.89	0.38	0.05	0.62	0.31	0.64	-0.28	-0.39	-0.03
Sluice N	-0.71	-0.12	0.46	0.19	0.12	0.39	-0.26	0.65	0.87		0.00	0.00
P2	-0.11	0.86	0.70	-0.38	0.91	-0.40	-0.19	-1.57	0.60	-0.12	0.13	0.21
S1B3	-0.15	0.86	0.80	-0.44	0.98	-0.30	-0.18	-1.61	0.75	-0.09	0.15	0.25
S1B4	2.26	0.30	0.40	0.78	-0.87	-0.15	-1.12	0.04	-0.23	0.39	0.47	-0.15
P3	2.35	0.12	0.61	0.62	-1.15	0.05	-0.96	0.44	-0.60	0.38	0.48	-0.17
P4	2.52	0.32	0.04	0.78	-1.44	-0.09	-0.29	0.47	-0.49		0.00	0.00
P5	2.66	0.35	0.23	-1.07	-0.05	-0.40	0.38	0.86	-0.35	-0.32	0.57	-0.16
P6	2.61	-0.21	0.59	-1.24	0.10	0.22	0.42	-0.77	-0.04	-0.58	0.60	-0.10
S1B5	2.63	0.00	0.11	-1.99	1.03	-1.30	0.76	1.48	-1.44	-0.56	0.60	-0.11
P7	2.64	-0.06	0.17	-2.09	1.15	-1.37	0.70	1.30	-0.85	-0.68	0.60	-0.12
P8	2.40	-0.32	0.34	-1.58	0.43	-0.93	1.08	-2.33	3.71	-0.06	0.64	0.02
P9	2.09	0.00	-0.13	-1.19	0.34	-0.53	1.44	-2.78	3.22	0.24	0.59	0.06
P9B	1.82	-0.40	0.51	-1.14	0.14	-0.27	0.83	0.57	-0.31	-0.65	0.49	0.03
P10	1.72	-0.06	0.47	-1.02	0.00	-0.31	0.92	1.46	-1.91	0.42	0.53	0.12
P11	1.01	0.40	0.97	-1.19	0.05	-0.27	0.03	1.34	-1.49	0.10	0.31	0.06
S1B6	0.97	0.52	0.86	-1.21	0.33	-0.50	-0.22	0.48	-1.01	0.01	0.26	0.01
P12	1.15	0.57	0.92	-0.80	-0.14	0.00	-0.83	-0.80	-0.14	0.00	0.24	-0.08
P12A	1.53	0.65	0.97	-0.88	-0.10	-0.97	-0.80	-1.05	0.04		0.00	0.00
P13	1.70	0.94	0.90	-1.05	-0.19	-1.19	-1.05	-0.85	-0.38	0.00	0.29	-0.21
P14	1.83	1.69	1.06	-1.84	-0.38	-0.71	-1.92	-0.81	-0.63	0.02	0.29	-0.25
P15	1.91	2.16	0.38	-1.56	-0.38	-1.63	-2.04	-0.02	0.45	-0.30	0.28	-0.28
S1B7	1.90	2.01	0.36	-1.30	-0.54	-1.66	-2.14	0.03	0.14	-0.23	0.27	-0.30
P16	1.71	0.99	-0.27	-2.30	0.24	-1.41	0.64	1.51	-1.50	0.68	0.38	-0.08
S1B8	1.78	0.97	0.07	-2.75	0.11	-1.20	0.69	2.15	-1.66	0.26	0.44	-0.03
Thorpeness	1.57	0.59	2.41	-5.35	-0.62	-0.72	1.54	0.60	0.81	0.00	0.00	0.00
P17	0.75	-0.13	0.38	-1.71	1.10	-1.86	-0.04	0.58	0.75	1.05	0.05	-0.19
S1A1	0.87	0.02	-0.04	-1.16	1.19	-1.33	-0.15	-0.05	0.33	0.60	0.07	-0.22

7 Discussion

7.1 Long-, medium- and short-term shoreline response of the Greater Sizewell Bay

As described previously, the shoreline change datasets assembled and analysed are from different sources and for the purposes of this report, were broadly defined according to both the length and resolution of the datasets used in the analysis, as well as prevailing environmental conditions.

- Long-term patterns were assessed over the whole data record, from 1835 – 2018 (183 years), using historical maps, charts and orthorectified aerial photographs with a decadal or greater resolution;
- Medium-term patterns were assessed for the period of 1940 – 2018 (78 years), following the transition towards a bi-directional nearshore wave climate between 1925 – 1940, using orthorectified aerial photographs with a multi-annual to decadal resolution; and
- Short-term patterns were assessed for the period of 1985 – 2018 (33 years), during which the GSB was subject to extensive and focussed survey effort using a multitude of techniques, at an intra- to multi-annual resolution. It should be reiterated that "short-term" is as much a reference to the resolution of the comprehensive datasets used, even though the duration of these records could be considered "medium-" to "long-" term in their own right.

Within the broad long-, medium- and short-term categorisations, analysis was constrained to the specific datasets being interrogated. As the duration and temporal resolution differ, each of the long-, medium- and short-term data sets provide different details on shoreline behaviour in the GSB. Due to the relatively long (decadal or greater) intervals between measurements, the long- and medium-term data can only be used to investigate broader patterns of change and are not likely to include the responses to individual storms, as beach recovery usually occurs over the short-term (intra- to multi-annual). However, long- and medium- term datasets can highlight shoreline evolution, including responses due to extended phases of stormy weather, different wave climates and changes in sediment supply. Short-term signals tend to be noisier as they pick up some of the fluctuations that result from individual storm events or storm sequences with subsequent beach recovery.

As expected, the long-term patterns in the shoreline change envelope differed significantly from the medium-term for the majority of the GSB coastline. Two major exceptions occurred at (i) Minsmere sluice, where the long-term change envelope was only 2 to 3 times larger than the medium-term, and (ii) at Sizewell where the statistics were similar and, in some cases, the medium-term was larger. The reader is reminded that the medium-term data are not a subset of the long-term data, and the two are derived from different data sources.

This study has clearly demonstrated that using data over different time periods and resolutions may lead to different conclusions if each data set is considered in isolation. Initially, short-term data assembled for this report showed that the area around Sizewell Hall was very stable with no net change in the past 20 years (as reported in BEEMS Technical Report TR223, first edition). However, the medium-term data used in Edition 2 (2014) (and included in this edition) revealed overall erosion of up to 72 m (1940 – 2011), occurring prior to the short-term records. Also, short-term records showed a longshore trend south of Dunwich in which accretion gave way to a 1250 m long zone of shoreline retreat (Figure 48) near the northern end of Minsmere Reserve. However, the medium-term record indicated low rates of change, because in the north, the short-term accretion was balanced by preceding erosion, and further to the south recent rapid erosion was balanced by preceding accretion.

Interpretation of shoreline change data must therefore take place within a conceptual regional model that accounts for trends in all three perspectives (and any new data), in order to justify confidence in the conclusions drawn. The following discussions address the key features of the shoreline change results in the context of very long-term trends and the geomorphological importance of specific natural and constructed features of the shoreline around the Sizewell site (Sections 7.2 to 7.5). This is then fed into a review and development of previous conceptual models of the GSB coast (Section 7.6).

7.2 Very long-term shoreline evolution (centuries)

A large body of documentary evidence testifies to erosion of the Suffolk coast during the past 2000 years, and the trend has probably continued since sea level approached its present level around 5000 years ago. The pattern and rates of erosion have varied spatially and temporally, largely in response to variations in storminess and configurational changes in the size and position of offshore and nearshore banks, but the overall trend has been recession of most of the coastline at an average rate of approximately 1 m/yr over the past 1000 years (Pye and Blott, unpublished data). There are no grounds to believe that this long-term erosion trend will change in the next 100 to 200 years; indeed, an acceleration of erosion in unprotected locations may be expected if there is a significant rise in sea level, as currently forecast by global and regional climate models.

Documentary records suggest that, prior to the 16th century a salient of relatively low-lying land (the 'Westwood') lay to the east of Dunwich (Pye and Blott, 2006; Sear *et al*., 2009, 2010, 2013). To the north of this area lay a broad bay (Sole Bay) that extended north towards another promontory at Easton Ness, north of Southwold. Within the southern part of Sole Bay lay a sand and shingle barrier spit (Kingsholme) which extended from Southwold towards Dunwich. In the mid-13th century, the entrance to the combined estuary of the Blyth and Dunwich rivers lay close to Dunwich. The estuary mouth provided a sheltered haven for shipping and allowed Dunwich to develop as a prosperous city and port between the 8th and 14th centuries (Comfort, 1994). The position of the Blyth and Dunwich river mouths fluctuated over time due to drifting shingle and as new outlets were forced to the sea during times of flood, or artificially cut to maintain entrance to the ports of Dunwich, Walberswick and Blythburgh. The estuary mouth became fixed in its present position only after an artificial cut and harbour entrance piers were built in the 17th century to provide secure navigation access (Pye and Blott, 2006).

To the south of the slight promontory at Dunwich, a second shallow bay extended south as far as Thorpeness, a 'hard point' created by the outcrop of relatively erosion-resistant Coralline Crag which is overlain by Norwich Crag and glacial deposits. The southern part of this shallow bay, between Sizewell and Thorpeness, was backed by eroding cliffs and a narrow sand and shingle beach. Between Sizewell Cliffs and Minsmere Cliffs lay another sand and gravel barrier that was broken by the entrance to the Minsmere estuary. Documentary and historical map evidence suggests that the position of the estuary entrance also fluctuated over time in response to shingle drifting and storm flood breaching. The Minsmere River outlet was only fixed in its present position after the creation of the New Cut and Minsmere Sluice following an Act of Parliament in 1810 (Pye and Blott, 2005, 2006; Robb, 2009).

Prior to construction of the hard structures at the Blyth entrance and Minsmere Sluice, the shore would have formed a relatively smooth curve between Easton Ness and Thorpeness, interrupted for a time by the Westwood to east of Dunwich. Since construction of the Blyth entrance piers and Minsmere Sluice, a series of smaller shallow sub-bays formed by continuing erosion, centred at Easton Bavents, Walberswick, Cliff House and Sizewell North.

Bay development occurred as a result of faster erosion in the central parts of the bays and longshore drifting of sediment towards their southern and northern ends. This pattern of development is essentially continuing at present, although it may slow and eventually stabilise as an equilibrium bay depth is reached.

The sediment released by coastal erosion has been transported by marine processes principally in two directions: (a) in a southerly direction along the beach and nearshore zone, with some (mainly gravel and medium to coarse sand) passing Thorpeness towards Aldeburgh, and (b) very likely offshore (mainly fine sand) towards the Dunwich – Sizewell Banks at Thorpeness (BEEMS Technical Report TR357), which could explain the larger size of Sizewell Bank since the early 19th century (Carr, 1979; Pye and Blott, 2005; BEEMS Technical Report TR058). Superimposed on this long-term pattern of change have been fluctuations in erosion and sediment deposition within the sub-bays, in response to fluctuations in local wave energy, nearshore and offshore morphology, longshore sediment transport rate and the intrusive development of engineered structures.

7.3 Long-term shoreline evolution 1835 – 2012

The historical maps and aerial photographs that pertain to this section can be found in Appendix A (Figure 74 – Figure 93).

The OS First Edition One Inch map surveyed in 1835 (Figure 74) shows a low hill on the site of SZA and a reed (ozier) bed on lower ground now occupied by SZB. Seaward of a low cliff cut into the Crag deposits, was a sand and gravel beach that was slightly wider opposite the power station than to the north and south.

The OS First Edition County Series map, surveyed in 1881 – 1883, shows that the beach ridge system had grown to more than 150 m wide. In front of the old cliff line was a wide belt of vegetated shingle, occupied by a rifle range. The MHW and MLW lines lay very close to their 2016 positions (Figure 75). Sediment accumulation within the GSB during the late 19th and early 20th centuries is likely to have been favoured by a high rate of sediment supply from Dunwich and Minsmere Cliffs, which were rapidly eroding at that time, and by the creation of Minsmere Sluice which reduced the longshore sediment transport rate. Growth of the Sizewell – Dunwich Bank during the same period was probably also driven by high sediment supply from the cliffs (Carr, 1979; Pye and Blott, 2006; BEEMS Technical Reports TR058 and TR357; Brooks and Spencer, 2010). Subsequent growth of the bank system (height, width and extent) is very likely to have reduced wave energy at the shoreline, further reducing the longshore sediment transport rate and favouring beach progradation.

Landward recession of the MHW line along the Sizewell power stations frontage began pre-1903, leading to a reduction in the width of vegetated shingle and relocation of the rifle range between 1903 – 1925 (Figure 76 and Figure 77). Rapid erosion occurred along the Sizewell power station frontage between 1925 – 1940, by which date, the MHW line lay approximately 20 m landward of its 2016 position (Figure 54).

The change from accretion to erosion at Sizewell in the early- to mid-20th century could have been due to one or more of the following factors:

- reduced sediment supply from Dunwich and Minsmere cliffs;
- reduced southerly longshore sediment transport due to the growth of the offshore banks;
- reduced wave energy and sediment transport along the shoreline and nearshore bars;
- a change in the pattern of wave refraction and wave focusing due to changes in the morphology of the offshore banks;
- a reduction in the size or position of the nearshore bars as sediment moved out of the system to the south but was not replenished from the north; and
- a regional increase in storm wave energy, leading to transfer of sediment from the subaerial beach to the nearshore bars.

By 1930 a saddle (lowered crest elevation) had developed in the crest of the Sizewell – Dunwich Bank, centred just north of the NNB site (Pye and Blott 2006; BEEMS Technical Report TR058), and this basic configuration has been maintained to the current day. If the 1868 bathymetry (Figure 68) is taken as broadly realistic, then the development of the saddle is likely to result from the raising of the Dunwich end of the bank, rather than lowering in the bank's centre (BEEMS Technical Report TR058)[5]. The lowering of the crest at the saddle would be expected to modify the pattern of wave refraction significantly, and to allow greater penetration of wave energy towards the shore south of Minsmere Sluice and North of NNB site (see Section 7.5), although with a bi-directional wave climate any zones of higher energy would be expected to migrate from one storm to the next. Indeed, the greater extent of the erosion between 1925 – 1965, affecting the entire shore between Minsmere Sluice and Thorpeness (Table 12), suggests that other factors were primarily responsible.

[5] The wide use of black and white bathymetric contour maps in the literature (necessitated for publishing formats of the day) can be misleading and caution should be exercised in the interpretation of such maps. For example, the charts presented in Robinson (1980) and Pye and Blott (2006) suggest two features not connected and a lowering that simply isn't the case

The 1940 aerial photograph (Figure 78, Appendix A) shows disturbance to the dune and shingle vegetation around Sizewell village and Sizewell Gap arising from visitor pressure during the 1930's and military activities following the outbreak of World War II. There was limited change between 1940 – 1952 (Figure 80, Appendix A), followed by further erosion between 1952 – 1965 at a slightly slower rate than 1925 – 1940 (Table 12).

Construction of SZA began in 1961. The power station site was levelled and a concrete raft foundation constructed with a surface elevation of approximately 8.5 m OD. The lower lying area to the north was raised and levelled using imported fill to allow erection of buildings used during the construction phase (Figure 81, Appendix A). The beach and nearshore area in front of the power station experienced further disturbance during construction of the cooling water intakes and outfalls, although detailed information about the construction process and its effects are not available. The beach and dunes were restored following construction. An oblique aerial photograph taken in the mid 1960's shows a slight beach salient close to the cooling water outfall tower (Figure 69), but no possible causal connection can be established.

The support site north of SZA was cleared of buildings after commissioning of the power station, although a large area of bare sandy ground and a track network remained in 1983 (Figure 81, Appendix A). By this date the small beach salient feature near the SZA cooling water outfall was no longer visible, but a relatively wide beach had developed as a result of accretion to the north of the A station water intake.

7.3.1 Shoreline behaviour before and after 1925 – 1940

The long-term record highlights two distinctly different phases of shoreline behaviour that are not evident in the medium-term and short-term records. During the mid-late eighteenth century and the early nineteenth century, the Sizewell shorelines did not exhibit the localised spatial variability typical of the subsequent medium- and short-term periods – instead, all shorelines north of the sluice showed significant and persistent erosion, whilst to the south, all shorelines show significant and persistent accretion. This phase of anticlockwise movement of the coastline about Minsmere Sluice coincides with stormier sea conditions dominated by N – NE winds (as deduced by Pye and Blott (2006) from Lamb's (1995) interpretation of patterns in climate data). Furthermore, Dunwich Bank was a less effective dissipater of wave energy due to its arrangement in two small and low elevation banks (see Figure 68), Together, the increased N – NE storms combined with the lowered bank, would have led to higher inshore wave energy and an increase in storm surge magnitude and frequency, which most likely drove the persistent shoreline recession shown in Figure 54 and Figure 55.

High volumes of sediment supplied by Dunwich cliff erosion between 1836 – 1925, did not translate into wide local beaches that might then have protected the cliffs. Instead the beaches and cliffs retreated landward and the freshly supplied sediments appear to have moved toward Sizewell, indicating a strong longshore transport system driven by the N – NE dominant wave climate, as proposed by Pye and Blott (2006). The last 2 to 3 decades of strong erosion at Dunwich were not, however, matched by ongoing accretion in the south (Table 12), suggesting either bypassing of the southern beaches, offshore transport or northerly transport. A large part of the eroded Dunwich cliff sediment may have accumulated on the Sizewell – Dunwich Bank (Carr, 1979), which was significantly larger by 1940 (Figure 68). The shallower bed over the Thorpeness Coralline Crag by 1940 suggests probable offshore transport with the potential to reach the bank (BEEMS Technical Reports TR107 and TR357). It is also possible that some fine sands could reach the northern part of Sizewell – Dunwich Bank directly from the erosion at Dunwich or from sources north of Southwold as postulated in BEEMS Technical Report TR107.

It is hypothesised that, as the wave climate transitioned to one with fewer strong north easterly storms and a greater balance between NE and SSE wave conditions towards the mid-twentieth century, the persistent erosion in the north and accretion in the south gave way to the current medium-term phase of relatively high spatial and temporal variability in shoreline behaviour, which is seen in both the beach profile and contour change results.

Between 1868 – 1940, the two low bank features at Dunwich merged into a single bank 2 to 4 m higher and more clearly connected to Sizewell Bank (Figure 68). The reduction in the magnitude and frequency of N – NE storms, together with the higher bank, will have acted to reduce inshore wave energy and the strong southerly directed longshore drift, leading to the end of the persistent phase of shoreline retreat and cliff erosion between Dunwich and Minsmere (Robinson, 1980; Pye and Blott, 2006). The inshore wave climate is affected by the bank, in particular large infrequent storms with return intervals greater than 1:10. As suspected by Carr (1981) and Tucker et al (1983), numerical modelling has shown that the most substantial role of the bank is to impose a spatially varying cap (due to different water depth along its north-south axis) on inshore wave height BEEMS Technical Report TR319.

The Sizewell end of the bank has also changed shape over time but retains a similar position and elevation through the bathymetric record, probably as a result of the underlying Coralline Crag giving positional stability to Thorpeness and Sizewell Bank. Dyer and Huntley (1999) suggested Sizewell Bank is a classic example of a geologically-controlled headland-associated bank. The shorelines close to Sizewell Bank tend to exhibit a greater degree of net stability, probably as a result of bank-induced reductions in inshore wave energy and drift rates (see Section 7.5). Such conditions favour convergence in the longshore sediment flux, promoting the accretion observed during the increased sediment supply phase from Dunwich cliffs (1836 – 1925) and general net stability since that supply was lost. Subsequent variable patterns in shoreline response with low rates of net change are likely to be the result of the development of a bi-directional wave climate, reduced supply of sediment in the longshore transport system, and low wave energy and drift rates due to shoaling and/or breaking processes over Sizewell Bank.

7.3.2 The role of Minsmere Sluice

Although Minsmere Sluice marks the transition between eroding and accreting beaches of the 1836 – 1925 period, its effect on shoreline change is only likely to be localised due to its small size, as shown by the spatially detailed DSAS (Section 6.1.6). That is, it is likely that the sluice acted to anchor shorelines approximately 500 m either side of it (Pye and Blott, 2005, 2006); however, it is not the reason that sediment accumulated over the 5 km section to the south. There, conditions favourable for deposition would have required lower inshore wave energy and/or low rates of longshore drift, which are not related to the sluice. Given the hypothesised high energy wave climate of the late 1800's and early 1900's, accumulation of sediments and widening of beaches would have required convergence in the longshore sediment flux. This is likely to have been achieved by a lower inshore wave climate due to dissipation on the shallower Sizewell Bank (Figure 68), combined with reduced wave angle to the shore (caused by a combination of bank- and bar-induced wave refraction and anticlockwise re-orientation of the shoreline).

7.3.3 Geographical trends in shoreline change

Shoreline change rates and directions were fundamentally different before and after 1925 – 1940. At Dunwich, long-term erosion was replaced by stability and low rates of change. Accretion and stability just north of the SZC frontage gave way to steady retreat post-1940. An understanding of the recent trend for erosion near the SZC frontage is of interest as continued retreat at this rate could result in exposure of the northern boundary within the life-span of the proposed SZC station (see BEEMS Technical Report TR403).

The shorelines north of Minsmere Sluice were also variable, with high erosion rates prior to 1883, stability and accretion to 1965 and subsequent erosion (up to -1.7 m/y) over the last 20 years. If such high and persistent retreat continues, more frequent breaching of the gravel barrier would be expected. Near the sluice however, the rate of change is similar in the medium- and long-term. Given that larger storms are likely to have occurred in the long-term, the similar statistics for these two data sets suggest that this shoreline is likely to respond well to other hard points along the coast. Stabilising shores approximately 500 m either side of a structure penetrating approximately 50 m into the subtidal beach.

South of the sluice, persistent long-term retreat was marked by high r^2 values in the medium- and long-term, but the short-term rate of retreat there is twice that for the medium-term period. The cause of this long-term erosion has yet to be identified, but detailed wave modelling (BEEMS Technical Report TR232) is being used to explore the driving mechanics and the role of the lower saddle between Sizewell – Dunwich Bank. The persistent retreat along this frontage suggests a degree of shoreline insensitivity to the different historical configurations of the Sizewell – Dunwich Bank (see BEEMS Technical Reports TR058 and TR139 for details).

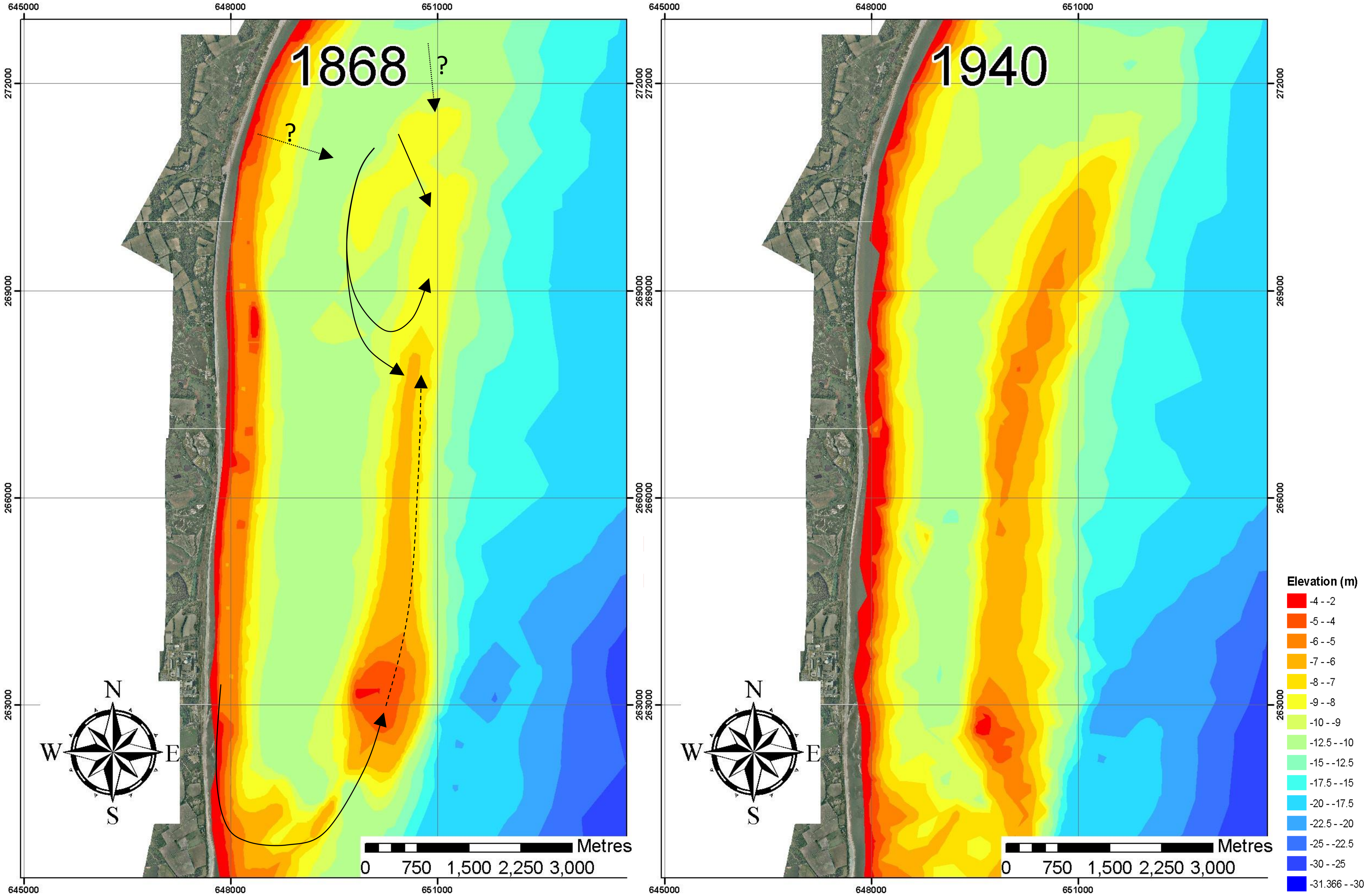

1868
?
?
1940
N
S
W
E
Metres
0 750 1,500 2,250 3,000
645000
648000
651000
272000
269000
266000
263000
Elevation (m)
-4 - -2
-5 - -4
-6 - -5
-7 - -6
-8 - -7
-9 - -8
-10 - -9
-12.5 - -10
-15 - -12.5
-17.5 - -15
-20 - -17.5
-22.5 - -20
-25 - -22.5
-30 - -25
-31.366 - -30

Figure 68: Bathymetry of the Sizewell – Dunwich Bank evident during the stormier mid-late eighteenth and early nineteenth centuries (1868) and less stormy period post 1925 (1940). The arrows on the 1868 bathymetry show potential pathways that may have led to the growth in the bank, especially at the Dunwich end. Postulated direct paths (with little modern evidence) are marked with question marks. Adapted from: BEEMS Technical Report TR058.

7.4 The effect of building Sizewell B

SZB was constructed and commissioned between 1989 – 1995 on the made ground to the north of SZA. The general platform level on which the single pressurised water reactor sits was raised to an elevation of approximately 6.5 m OD. During construction a number of heavy loads were brought to site by sea. A BLF was built in 1989 to allow berthing of large vessels. This consisted of a concrete platform built across the intertidal zone and a 56 m long mooring jetty (Figure 82). A channel was dredged to a depth of -5.5 m OD across the nearshore zone, cutting across the outer and inner nearshore bars, to provide vessel access to the jetty. Approximately 83,000 m^3 of sediment was removed in the initial capital dredge, and a further 132,339 m^3 removed by maintenance dredging between June 1990 – November 1991 (Pethick, 1998b).

A considerably larger volume of sediment (640,000 m^3) was dredged to allow construction of the cooling water culverts. At the landward end of these culverts, a 150 m wide sheet pile coffer dam was constructed. The 1991 aerial photograph shows the coffer dam was exposed to the sea (i.e., there is no beach; Figure 82, Appendix A) and so it would have reflected incoming waves resulting in increased turbulence and scour. Following removal of the coffer dam in the summer of 1992, a 400 m long embayment remained (see shoreline indentation in Figure 19 and Figure 45) south of the BLF (between profiles P8 and P9, Figure 84). The concrete BLF platform was removed in August 1993 (Figure 70; taken just prior to BLF removal) but the embayment in the beach was still present in summer 1994 (Figure 84) and of a similar size, though it had moved 100 to 200 m to the south. By summer 1997, the embayment had been completely filled by sediment, giving a recovery period of 2 to 4 years, during which there was a general increase in beach width along the Sizewell stations frontage (Figure 85).

A narrative on the dredging volumes and backfill can be found in BEEMS Technical Report TR105. Although the channels dredged for cooling water culverts were backfilled, the BLF approach channel was not. The dredged BLF approach channel instead infilled naturally (Pethick, 1998). Aside from placement of 5,250 m^3 inland derived sediments on the beach face following a storm in 1993, no further interventions were known to be made.

The coffer dam and BLF embayment size corresponded closely with these structures and the construction zone on the beach. Dredging for culverts and the presence of the coffer dam (which will have acted as a wave reflector increasing turbulence and inhibiting sediment settling) was considered to be the primary disturbance that lead to the development of the embayment. A reduction in supply of beach face material (shingle) due to the presence of the BLF was likely to have been minor because the longshore drift rates are very low and because the BLF did not interrupt sediment supply within the subtidal beach, as shown by the presence of the inner longshore bar that ran continuously along the coast and passed underneath the BLF mooring jetty (Figure 70).

Despite heavy re-engineering of the shoreline and nearshore system (BLF, coffer dam, nearshore dredging) the impact duration and length of coast affected by SZB's construction was 2 to 4 years and 400 m respectively (see beach profile results in Figure 19). Beyond these spatial and temporal scales there were no discernible patterns due to construction in the shoreline data. The likely reasons for this are related to the naturally low shoreline change and longshore transport rates at the Sizewell stations frontage. The stability of this shoreline over the short-, medium- and much of the long-term, as shown in Section 6, suggests that the shoreline has tended to hold its position and may be relatively insensitive to construction related disruptions on time scales of just a few years. There was no evidence of downdrift impacts beyond approximately 200 m of the construction site, which is also likely to be a result of low longshore transport rates there (see Section 7.5).

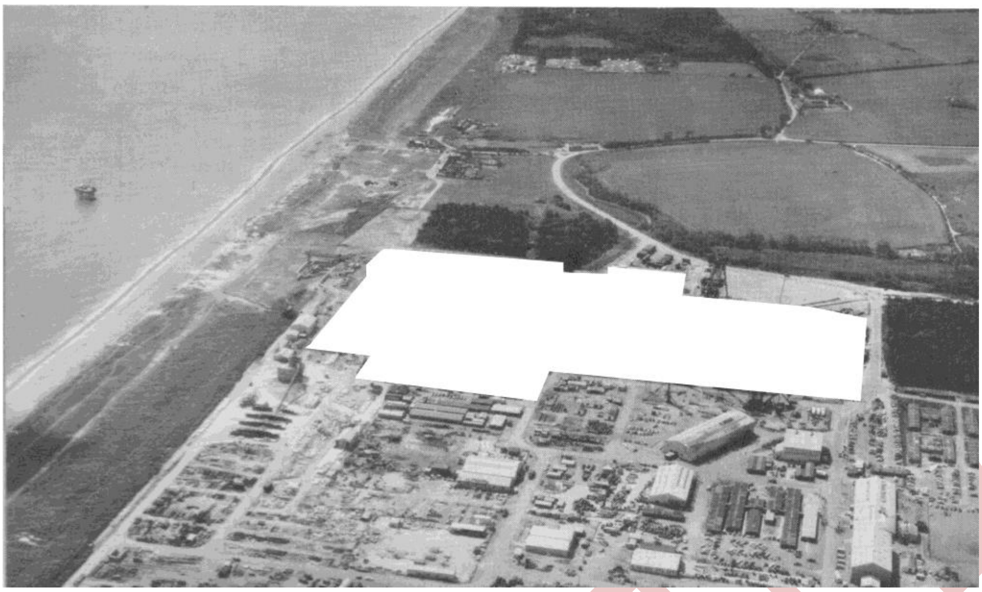


Figure 69: Oblique aerial photograph of Sizewell A (1960's). South facing, showing two phases of beach ridge development in front of the old cliff line and a slight salient in the beach to the southwest of the cooling water outfall platform (Source: National Parks Commission (1968)).

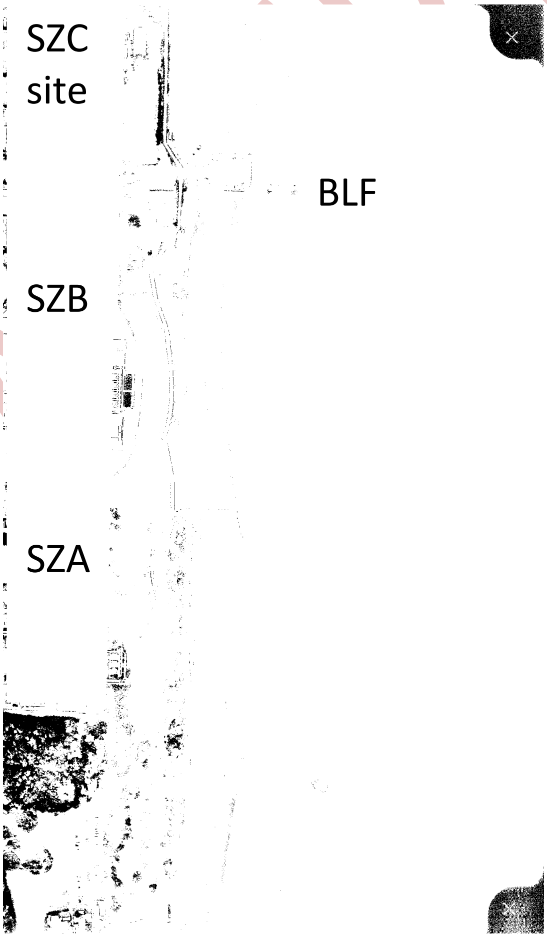


Figure 70: Aerial photography of the Sizewell B frontage (August 1993). Shows the BLF and embayment due to the coffer dam (removed 1 year earlier) and potential sediment transport blockage by the BLF. Note the presence of the exposed inner longshore bar that runs continuously along the coast and passes underneath the BLF mooring jetty, indicating that transport of sediment along the bar did occur even though the jetty was present. This image is not orthorectified.

7.4.1 The effect of cooling water outfalls on shoreline position

The 1994 aerial photograph (Figure 71 and Appendix A) shows the remains of the embayment caused by the coffer dam, dredging and the BLF. By 1997 a relatively wide beach had developed between the SZB cooling water outfall and a point just to the south of the SZA intake, separated by a slight embayment between profiles 9 and 9B (Figure 71). No beach salient features are evident near either of the cooling water outfalls in the first 2.5 years of operation. By 2001 this embayment had completely filled with sediment and a wide beach had developed between the SZA outfall, and a point just north of the SZB outfall. The 2001 aerial photograph shows a relatively straight beach with no obvious salient features. The 2005 aerial photograph also shows a relatively straight beach but with a small salient feature opposite the SZB outfall (Figure 71 and Appendix A). These images suggest that the salient did not develop for the first 6 – 10 years of SZB operation, bringing into question the cause of its formation.

By summer 2006, a small embayment had again formed between profiles P9 and P9B, opposite the SZA intake, and a small salient had formed to the south of the SZB outfall (Figure 71 and Appendix A). The salient on the northern end of the bay had grown larger by summer 2007 and remained a prominent feature since. The northern progradation limit moved north towards profile P6, whist the southern limit of progradation moved southwards from Profile P9 to profile P9B (also shown in Section 6.1.1), and the elevation of the backshore increased due to accumulation of shingle and wind-blown sand. Surface sediment stability encouraged the spread of vegetation in this area. By contrast, between profile P9B and Thorpeness, the MHW contour showed net landward movement over the same period.

After the cooling water discharge from SZA was turned off at the end of 2006, beach monitoring showed that a small-scale landward movement of the subaerial beach contours occurred in the first two quarters of 2007, attributed by Halcrow (2008) to the shut-down of the SZA cooling water discharge (Figure 25). EA and BEEMS bathymetric surveys suggest that a significant volume of sediment was lost from the subtidal nearshore zone near SZA between 2007 – 2011. However, this was not associated with a major and lasting landward movement of the subaerial beach contours, which have showed some recovery post-2010. Given the magnitude of monthly, seasonal and inter-annual variability observed before and since the SZA shut-down, there was insufficient evidence to conclude that the straightening of the shoreline in the first half of 2007 was caused by the SZA shut-down. This conclusion is in accordance with that previously reached in BEEMS Technical Report TR105.

Pethick (1999a) observed that waves passing over the SZA and SZB outfalls appeared to lose energy and suggested that the cooling water discharges were acting as a hydraulic wave break. He noted that the outer longshore bar was displaced seaward in the region of the SZB outfall, which was best shown by the 2017 bar positions (Figure 29 and Figure 36), however it is also noteworthy that the bar position was similar from the SZB outfall to Sizewell Gap. The historical data from EA surveys were too widely spaced to assess how the plan shape of the bar may have changed between 1992 – 2011, but they did show positions ranging from 85 to 220 m seaward of the outfall. Pethick (1999a) suggested that the seaward displacement of the bar was due to a seaward displacement of the nearshore sediment transport pathway by the cooling water outfall. He hypothesized that reduced wave energy, and/or a lower longshore sediment transport rate in the lee of the outfall is responsible for the development of the beach salient in this area. Although he noted that the magnitude and position of the salient varied from year to year after 2000. Pethick (2007, 2010b) concluded that the salient had approached a state of relative equilibrium, forming a point of shoreline stability which separates two deepening sub-bays to the north and south.

An EGA of the beach salients considered four possible mechanisms which might be responsible for their formation:

- reduction of the wave field by the outfall discharges;
- interruption to the currents by the outfalls and the discharge plumes;
- effect on the waves of the disruption to the bar during dredging; and
- changes to the wave patterns by refraction and diffraction round the offshore banks.

The EGA considered the first two mechanisms recognised by Pethick (2007, 2010b) to be potentially viable formation pathways. The third possible mechanism was considered not to be relevant to the development of the salient in the recent past or at present, since the integrity of the bar has now been largely re-established. The fourth mechanism was also judged to be viable and supported by the results of SWAN wave modelling described in BEEMS Technical Report TR068 and more recently by the results from the BEEMS validated TOMAWAC model (see Section 7.5). These modelling studies, which consider wave refraction over the offshore banks and the effect of longshore variations on nearshore wave height and potential sediment transport capacity, indicated the Sizewell power station frontage to be one of relatively low wave energy where the direction of transport could be variable depending on the offshore wave approach direction.

The analysis of shoreline change in the present study confirms that the beach near profile P9 experienced rapid progradation after 1993 (Figure 72), which represented infilling of the coffer dam embayment. By 1998 the shoreline there had straightened but recovered only to its 1988 position (see P9, Figure 72). Further accretion occurred until 2003, after which time, a period of erosion set in until 2009. It is perhaps significant that discharge from the SZB outfall did not prevent erosion and landward movement of the beach contours after 2003 at profiles 9 and 9B (Figure 72). The beach contours in this area reached their most landward point in August 2008 following a stormy period (2005 – 2008), after which there was another change to accretion until 2010. The nature and timing of these changes suggests that variations in local wave conditions, driven either by fluctuations in wind and wave climate or sea bed bathymetry (e.g., the nearshore outer bar), are more important than the hypothesised hydraulic groyne effect associated with the SZB cooling water outfall.

On the basis that the salient is caused by the SZB outfall, Pethick (2004b) raised concerns that the station frontage would fall into rapid recession following cessation of discharge when SZB is decommissioned, followed by medium- to long-term erosion rates of 2 m/yr. The conclusions of BEEMS Scientific Advisory Report Series SARS018, and the evidence of shoreline change (this report) and alongshore variability in wave energy (BEEMS Technical Reports TR068, TR232 and Section 7.5), suggests that there are many processes at play making it difficult to determine the role of the outfall in salient development and/or behaviour. The high rates of erosion following decommissioning suggested by Pethick (2004b) are not well founded as the rates of shoreline change prior to SZB construction were low, with much of the subsequent change being due to recovery from the coffer dam and BLF rather than outfall related accretion. The stated "*average 2 m per year immediately north of the B station*" (Pethick, 2004b) does not concur with our analysis of SSMSG and EA beach profile data – our analysis shows that the net shoreline change rates immediately north of SZB are near zero or positive (accreting) for both the medium- and short-term analyses. Significantly, further to the north, shorelines do show erosional trends (Figure 48): up to -1.6 m/yr, 1 to 2 km north of SZB during the short-term period (with near zero net change immediately to the south).

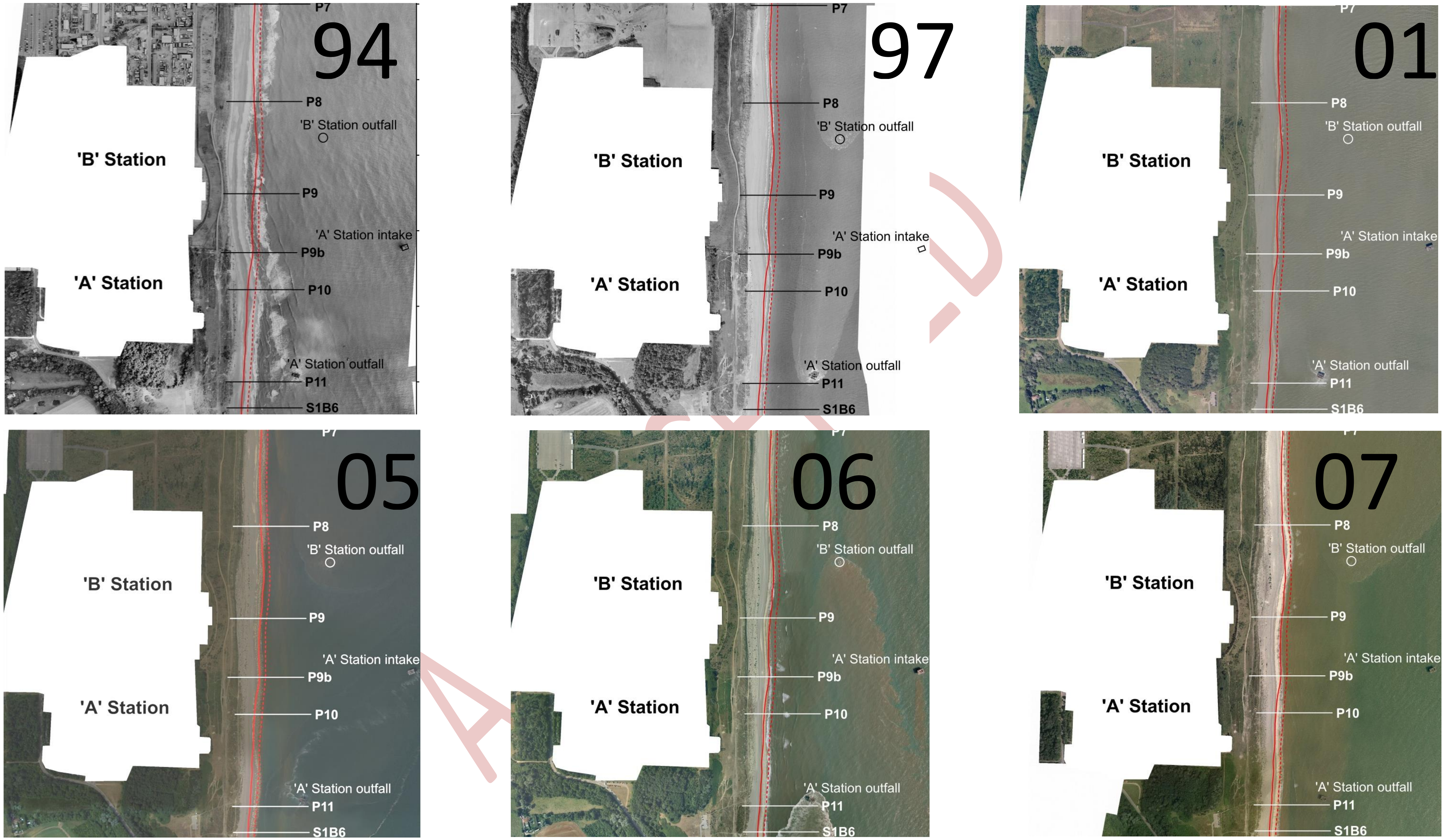


Figure 71: Aerial images showing recovery of the Sizewell power stations frontage following SZB construction. The solid and dashed red lines are the 2011 MHW and MLW shorelines, respectively.

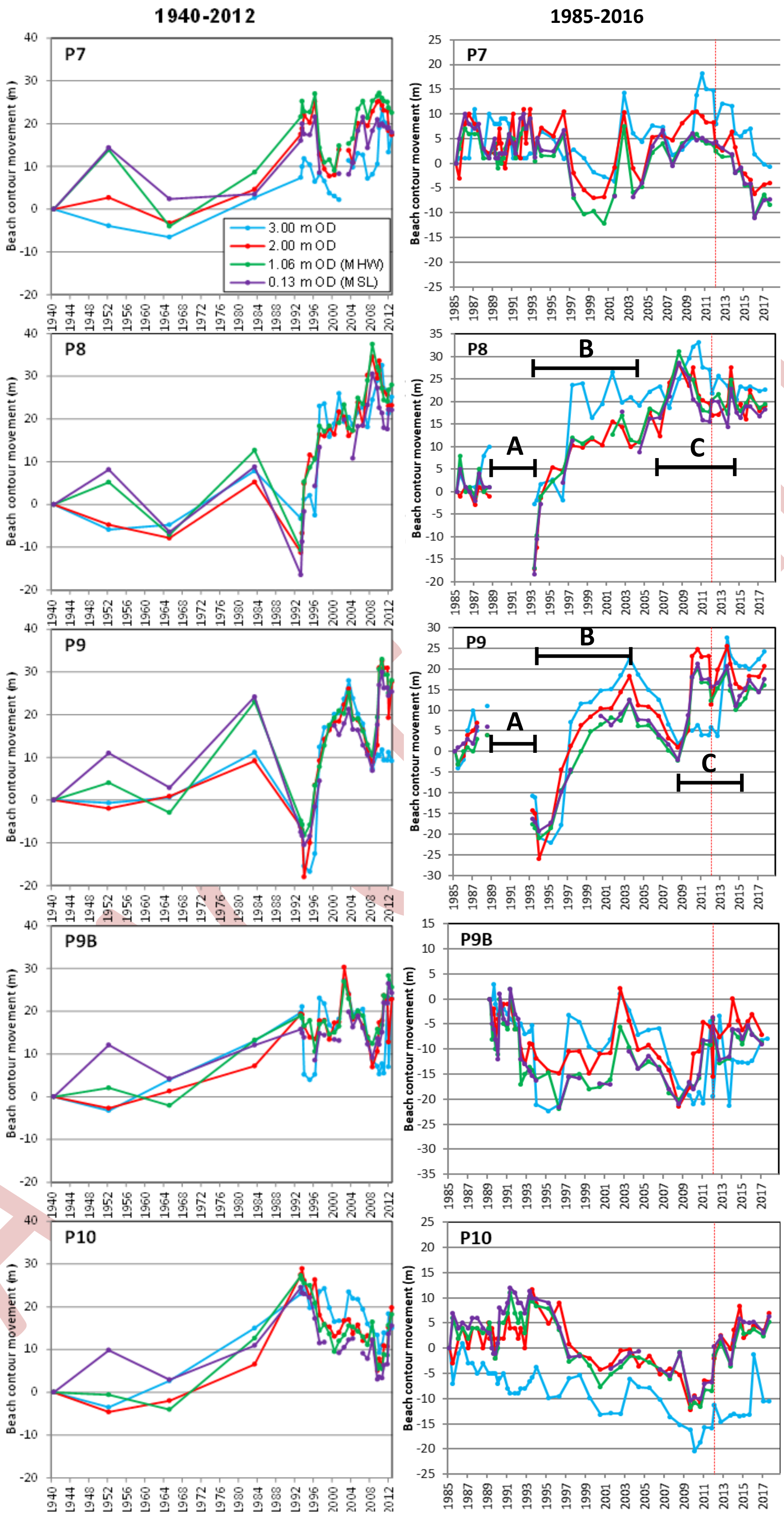


Figure 72: Shoreline position adjacent to the Sizewell power stations since 1940 (left) and 1985 (right). (A) indicates the impact of dredging, (B) indicates the period of recovery, (C) indicates the development of a salient.

7.4.2 The potential longshore bar geo-hazard for station outfalls

The outer longshore bar is a potential geo-hazard to the operation of the existing SZB outfall. It is no longer a potential hazard to SZC's outfall as that has been relocated offshore of the Sizewell – Dunwich Bank, however this section does give consideration to the two smaller Fish Recovery and Return (FRR) outfalls and the Combined Drainage Outfall (CDO) that would be located on the seaward flank of the outer bar. Migration of the bar is a 'potential' geo-hazard because there are two important unknowns with respect to the risk of smothering and sediment ingress at the outfall: scour processes and bar behaviour.

The SZB outfall is presently situated in a trough landward of the outer longshore bar (Figure 29). Sea bed elevations in the trough to the north are similar to that at the outfall head, but to the south a 3m deep, 400 m long, scour tail is observed. Its orientation indicates that the scour is due to turbulence generated by tidal currents interacting with the outfall structure and (probably) its jet (discharge rate of 52 m^3/s). Whilst self-scouring processes around the outfall are likely to protect it from smothering, it is not known whether outages, during which discharge is minimal, would reduce turbulence and scour leaving the outfall more vulnerable to smothering by a migrating longshore bar.

The variability in position and elevation of the longshore bar is very poorly understood because of the mismatch between the time-scales over which it fluctuates (hours – weeks) and the measurement time scale (5 yearly). The existing data do, however, show that variability can be large. For example, the envelope of outer bar positions just north of the SZB outfall (S1B5) was approximately 130 m wide.

At SZB in 2017, the bar crest was 85 m seaward of the outfall and had an elevation equal to 1.5 m higher than the outfall heads (-4.5 m OD). The 2017 position was the most landward recorded at SZB, however there are insufficient data to assess whether the bar fluctuates and was at a landward extreme or whether it has been migrating landward to its present location. If the bar migrated further landward towards the outfall, it is likely to hold a similar (or higher) crest elevation and could infill the scour pit and smother the outfall (if scour around the outfall is unable to clear the migrating longshore bar sediments). Landward migration as far as the outfall could occur during a prolonged period of low swell waves or following shoreline recession. Alternatively, the outfall discharge could prevent shoreward migration of the bar or it could disrupt the bar and thereby affect bar integrity, longshore transport and potentially shoreline position. Indeed, this may have already occurred as the bar tends to curve seaward of the outfall.

The proposed positions of the SZC FRR heads and the CDO at the time of writing this report have an easting of 647980E and respective northings of 264000N, 264300N and 264340N (BEEMS Technical Report TR311 Edition 2), slightly seaward of the crest of the outer bar. During the measurement period, the bar was relatively stable in its position, with some landward migration (within a 40 m envelope) between 2003 – 2007 (Figure 38). Again, the lack of data on bar positions makes it difficult to accurately assess bar positions relative to the proposed outfalls. However, there are a number of factors that make smothering of the proposed nearshore outfalls by the longshore bar significantly less likely:

- the structures would be placed close to the crest;
- the structures would be 4.5 m tall, requiring bar growth to a similar level, which compares to bar crest variation of around 0.5 m (elevation); the greatest range in bar crest elevations observed is just over 1 m (near S1B5); and
- sea bed elevations typically fluctuate less in deeper water and there is a limit to which longshore bars can migrate offshore.

7.5 Inshore wave energy and shoreline behaviour

Wave direction and alongshore gradients in wave energy at the coast drive longshore currents and influence net sediment transport patterns, so are likely to be key near-field processes (i.e., within the GSB) controlling shoreline response. Geological inheritance and coastal engineering interventions (Minsmere sluice) have also been shown to influence shoreline position and response. In comparison, sediment supply is both a near-field (e.g., potential inputs from Dunwich Cliffs, Walberswick barrier, net cross-shore sand transport) and far field (e.g., regional supply from cliffs to the north) factor influencing shoreline behaviour.

The longshore variability in wave characteristics inshore of sand banks is a function of the offshore wave conditions and the sand bank morphology (elevation, width, extent, shape), which modifies the waves that shoal across it (e.g., Kuang and Stansby, 2006; Coughlan *el al.*, 2007; Dolphin *et al.*, 2007; BEEMS Technical Reports TR319, TR232 and BEEMS Scientific Advisory Report Series SARS018). Medium-term variability in bank morphology may explain the localised and variable nature of beach erosion during storms. However, little is known about the wave climatology along shores landward of sandbanks as 1) wave measurements landward of banks are rare and usually restricted to a single-point short-term series (i.e., they are not able to reveal spatial patterns in the wave field); and 2) numerical model simulations typically lack detailed calibration and/or validation, consider only a few storm cases and do not usually investigate the spatial variability in nearshore wave parameters and the associated sediment movement and shoreline response.

Future work in the BEEMS project will investigate the spatial variability in nearshore wave conditions using data and modelling. The aim will be to quantify the role and importance of the Sizewell – Dunwich Bank to nearshore coastal processes.

7.5.1 Inshore wave energy modelling

Exploratory wave modelling (BEEMS Technical Report TR062) highlighted longshore gradients in wave energy due to the presence of the bank. BEEMS has since developed and validated a TOMAWAC wave model, which uses an unstructured triangular element grid to give significantly higher resolution on the bank (30 m compared to the 50 m regular grid used in BEEMS Technical Report TR062) where the factors influencing the inshore wave climate – wave shoaling and energy dissipation – are most important. The TOMAWAC model also features new and more detailed nearshore bathymetry, including the first swath measurements of the outer longshore bar. The key leads identified in the TOMAWAC validation cases (BEEMS Technical Reports TR232 and TR319), namely spatial gradients in wave energy in the lee of the bank, were broadly similar to those of BEEMS Technical Report TR062.

This section makes an initial comparison between variability in the driving wave conditions revealed by modelling and the patterns of shoreline and longshore bar behaviour at Sizewell. Based on a limited number of cases, it is intended only to give initial, general insight to how the bank influences nearshore processes and whether these are related to the observed zones of erosion and accretion.

7.5.1.1 *Case study - storm characteristics*

Wave data representative of the two principle directions of wave approach (NE and SSE) were obtained from the Sizewell wave buoy (seaward of Sizewell Bank; 52°12.62’ N, 001°41.12’ E) for two storms used in TOMAWAC validation (Table 13). The significant wave heights in both cases were just over 3 m at the wave buoy. Wave statistics were extracted inshore of the bank along the -7 m OD contour (i.e., just seaward of the surf zone).

The variability in nearshore wave energy in the GSB (Figure 73) reflected wave energy dissipation (bottom friction and wave breaking) and wave refraction over the topographic highs and lows of the Sizewell – Dunwich Bank. That is, lower energy in the lee of topographic highs at each end of the Sizewell – Dunwich Bank, and higher energy inshore of the lower and narrower saddle between the two. This broad pattern was retained for both storm cases, but its features are offset by 750 m – 1500 m due to the different storm directions. Relative to the SSE (case F) storm, the NE storm (case H) had an energy low at Dunwich displaced 750 m to the south, an energy high in the lee of the saddle 1100 m to the south and a second energy low inshore of Sizewell – Dunwich Bank 1500 m to the south.

Table 13: Characteristics of two storms at the Sizewell wave buoy as modelled in BEEMS Technical Report TR232 using TOMAWAC.

Case	**Sizewell wave buoy observations**		
	H_{m_0} (m)	Tp(s)	Direction (°N)
F	3.15	7.14	165
H	3.11	7.69	68

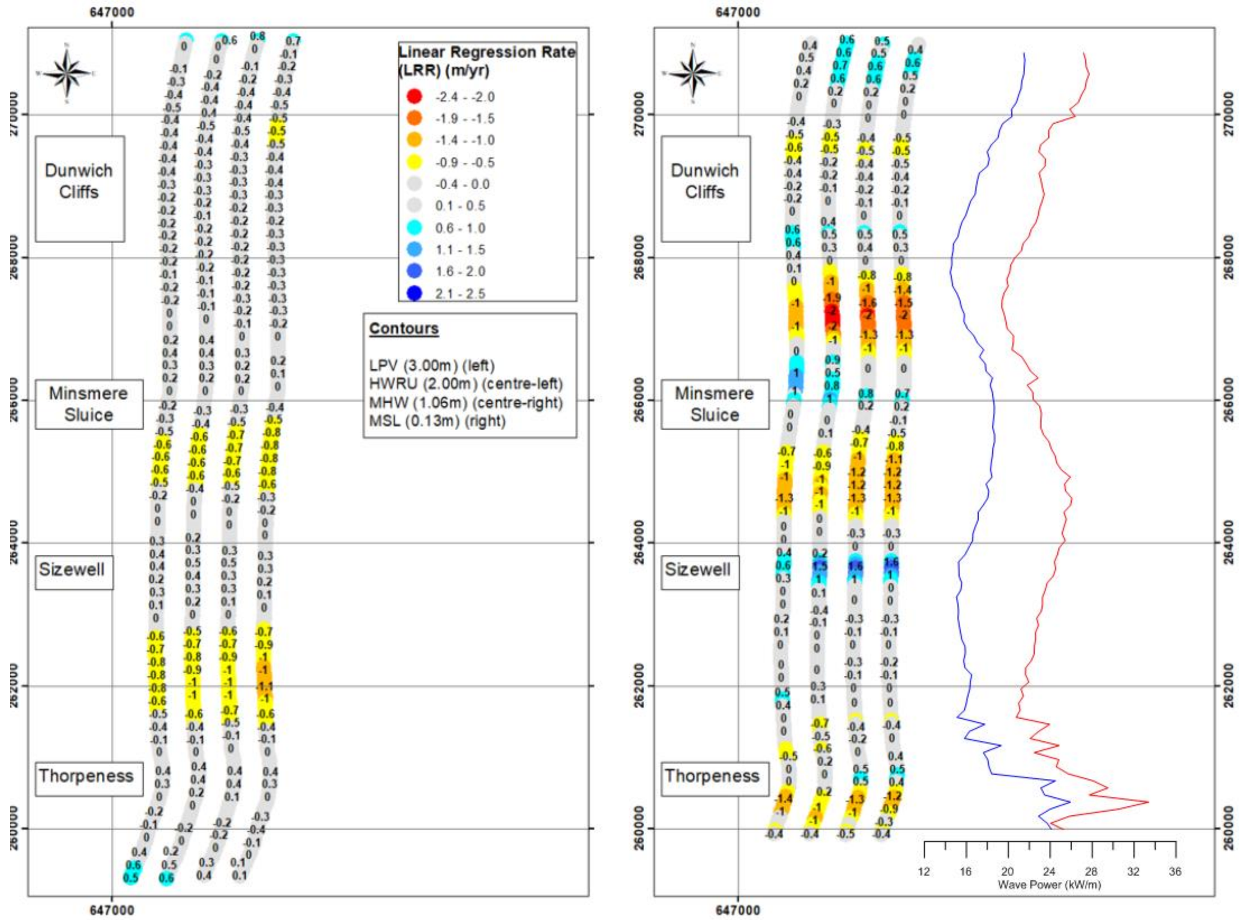


Figure 73: Comparison of alongshore temporal patterns in shoreline change and nearshore wave power. South of south-easterly (case F; blue line) and north easterly storm (case H; red line), with the medium-term (76 years, 1940 – 2016) (left panel) and short-term (24 years, 1992 – 2016) (right panel) shoreline change rates derived from aerial photos. The LRR change rates shown are for the 3 m, 2 m, MHW and MSL contours (left to right); see Figure 40 and Figure 60. The nearshore wave results were extracted outside of the breaker zone on the -7 m (ODN) contour.

7.5.1.2 *Comparison of wave energy with shoreline change patterns*

The alongshore wave energy distribution was compared to the short- and medium-term shoreline change rates in Figure 73. The reader is reminded that the two cases of modelled alongshore wave energy use the sand bank morphology, which maintained the same basic form over the medium-term since the transition to a bi-directional wave climate, (i.e., a higher Sizewell – Dunwich Bank, separated by a narrow saddle that is approximately 3 m lower than Sizewell Bank), with moderately subtle changes in bank morphology and position when compared to the long-term record (see BEEMS Technical Report TR058). Work is ongoing in order to further quantify any changes in the Sizewell – Dunwich Bank observed.

The peak in wave energy at Dunwich corresponded to waves penetrating north of Dunwich Bank (i.e., where there is no bank) and stable shorelines for the short- and medium-term records. Further south, a sheltered zone in the lee of Dunwich Bank corresponded to stable shorelines with near-zero or slow rates of change. Pre-1925, both areas were erosional. The high rates of retreat between Minsmere Sluice and Cliffs coincided with the lowest wave energy for the NE storm and relatively low energy from the SSE storm. These observations run counter to the notion that high wave energy equates to high rates of shoreline retreat. Low retreat around the sluice was due to its ability to trap longshore sediment transport, as previously noted.

Despite its co-location with the peak wave energy for SSE storms and relatively high energy from the NE, the Minsmere Sluice beaches experienced very low rates of net change. It was long considered that the sluice head acts as a long groyne that traps longshore drifting sediments on both sides (e.g., Figure 43). The aerial photograph and beach profile evidence over the medium-term shows a strong trend of shoreline retreat along the Minsmere sluice to SZC frontage (Figure 55 – Figure 56, Figure 60 – Figure 61), which is greatest toward the centre but has wider extents and faster retreat rates in the last 25 years. North of the SZC site, beach sediment volumes decreased by 15 % between 2003 – 2007, but this lost volume has shown some recovery over since 2012 (Figure 27 to Figure 29). This persistent erosion over both the medium- and short-term datasets aligns with the peak energy for NE storms and moderate energy for SSE storms, suggesting that stretch of coastline has a moderately high integrated exposure to waves. The Minsmere sluice to SZC frontage could be sensitive to storm direction and bank lowering around the juncture between the saddle and Dunwich Bank. A shift toward more easterly NE storms would displace the energy peak to the north and increase the wave energy on this shoreline, whilst a shift toward more northerly storms would have the opposite effect. Hypothetical lowering near the bank-saddle juncture by 1 to 2 m (no such lowering has been observed in modern surveys) would extend the zone of peak nearshore wave energy to the north, resulting in an energy increase of approximately 10 %. It is worth noting that, pre-1940, the Minsmere sluice to SZC frontage was accreting, probably due to high sediment supply from the eroding Dunwich Cliffs and potentially aided by lower levels of nearshore wave energy as a result of the higher saddle (2 to 3 m) at that time (see BEEMS Technical Report TR058).

Long-term stability of the Sizewell power station frontage corresponded closely with low wave energy in the lee of Sizewell Bank for SSE storms. However, it is reasonably exposed to NE storms, being half-way between the peak energy associated with the bank's saddle and the energy low near Thorpeness. Despite this, the Sizewell power station frontage remained the most stable shoreline, with low rates of change and small shoreline change envelopes. The frontage south of Sizewell has been stable over the short-term but did experience significant erosion during 1940 – 1980. This erosive phase may have been an initial response to increased wave exposure as the saddle began to deepen and parts of Sizewell Bank lowered (BEEMS Technical Report TR058). The nearshore wave energy is low for NE storms, but a slight peak in inshore SSE sourced wave energy suggests penetration through the gap between Thorpeness and Sizewell Bank could occasionally lead to periods of higher waves, especially if Sizewell Bank migrates northwards, leading to a deeper and wider gap (e.g., BEEMS Technical Report TR058).

The patterns described above showed no clear connection between energy levels and shoreline behaviour. This is probably because of differences in the energy arriving at the beach face (compared to the energy on the 5 m OD contour shown in Figure 73) and the wave angle (both of which will be affected by the size and shape of the longshore bars), local sediment supply (e.g., from barrier erosion), longshore sediment supply, and restrictions to supply caused by barriers in the longshore transport system (e.g., Minsmere sluice).

7.5.2 The key shoreline: Minsmere sluice to Sizewell C

The trends and behaviour of the coastal section between Minsmere sluice and the proposed SZC power station are of great significance because prolonged erosion there could expose the northern site boundary.

7.5.2.1 Future of Minsmere sluice

Although the EA have stated that the sluice would be maintained for at least 50 years and possibly much longer, at the end of its life there are two possibilities – natural decay or removal.

Natural decay

At present, the beaches to each side of the sluice outfall are of a relatively large volume and only a few tens of metres of the outfall are exposed to the waves – the rest being buried in the beach. If the outfall were left to decay naturally, it is reasonable to expect the exposed portion of the outfall to collapse within a decade or so. This may provide a pathway for increased transport of beach material around the sluice location (in both directions, as wave directions vary, but with a net southward transport expected). However, at present the outfall itself (as a single, shore-normal structure) does not provide substantial protection to the beach material against direct erosion (e.g., beach levelling and scarping of the shoreface) nor a substantial barrier to net longshore transport rates, which are, in addition, low (particularly for beach material). As a result, slow realignment of the shoreline may be expected, gradually exposing a further section of the outfall, which in turn will eventually collapse, and the process will repeat. As such, decay of the sluice is not expected to lead to rapid changes in shoreline position and longshore processes.

Sluice removal

The shoreline around the present sluice is in a form of dynamic equilibrium with the wave and longshore transport processes which maintains a substantial beach at this location, but the longer the sluice remains in place (apparently anchoring the shoreline at this location), the greater the disruption it represents to longshore processes either side of the sluice. Accordingly, removal of the sluice is likely to leave the location exposed to increased erosion pressure. Given its wave exposure, it appears reasonable to expect that removal of Minsmere sluice would lead to retreat instead of stability at the sluice locale.

The highest erosion rates might be expected immediately following loss of the sluice, as the shoreline attempts to reach a natural equilibrium with the nearshore wave conditions (see Dolphin et al., 2012, for example). Removal of the 'fixed point' constraint on shoreline change may also reduce the rate of erosion to the shorelines around 1 km north and south of the outfall, as the system adjust to a more natural form. Nevertheless, the present dynamic stability of the beach at this location suggests that the shoreline form may be at least partly self-sustaining and that the present equilibrium will adjust gradually even without the outfall in place – there is no mechanism for the present wave climate to rapidly accelerate the rate of sediment removal from this location above its present rate.

7.5.2.2 Geomorphology in the nearshore

The persistent double longshore bar is a key feature of the Sizewell beach system as it induces wave breaking, reduces wave angle at the shore (which is important for longshore sediment transport) and further dissipates storm wave energy seaward of the beach face. Bar mobility (see Section 6.1.5) indicates that both bars are active and will experience high levels of suspended sand during storms. The outer bar is likely to be the primary sand transport conduit (BEEMS Scientific Advisory Report Series SARS018), however it is inactive under low wave conditions due to its greater depth.

The outer bar is often further from the coast at Minsmere sluice, where the localised shoreline projection also forces the bar seaward (Figure 38). A similar seaward deflection is observed around the Sizewell B outfall structure, which may have contributed to the building and maintenance of the shoreline salient. Deviation of the bar implies that longshore transport of sand is not significantly interrupted by these structures. The accompanying accumulation of less mobile shingle beach material may be a secondary response to very localised changes in wave action in the lee of the bar deviation. These observations suggest that any attempt to stabilise the stretch from Minsmere sluice to SZC with a similar structure will have an impact on the system.

Given the dissipative properties of the longshore bars, the volume of beach sediment they hold and their likely function as a conduit for longshore sand transport (BEEMS Scientific Advisory Report Series SARS018), the bars should be included in consideration and monitoring of beach condition. It is acknowledged that this can be costly and logistically difficult using traditional techniques (i.e., echo-sounder), which is reflected in the fact that the SSMSG monitor the shallow subtidal beach once every 10 years and the EA only measure it every 5 years. Consequently, the discussion presented here is based on just a few datasets (four EA long profiles and two swath bathymetry surveys) spread over 20 years. The bar location (and presence/absence) aspect of this problem is being investigated by novel use of x-band radar, video and overhead aerial mapping with RPA.

7.5.3 Future measurements and modelling in BEEMS

The future behaviour of this coastal section will be determined by sediment supply, the presence/absence of the sluice structure and any new hard points, wave climate and the morphology of the Sizewell – Dunwich Bank and the longshore bars. Potential deepening and widening of the bank's saddle, which is likely to expose a wider area of coast to higher inshore waves (due to deeper water and less dissipation) is particularly relevant as it may increase exposure of parts of the SZC frontage. Equally, shallowing or narrowing of the saddle would afford more protection to the coast. Other factors that may alter the present pattern of shoreline stability include an increase in the frequency or magnitude of NE events and/or lowering of the northern end of Sizewell – Dunwich Bank, as increased inshore wave energy, sediment mobility and southerly longshore transport would result; although it is worth noting that climate change predictions suggest no change in the Southern North Sea wave climate and bank lowering is not considered likely due to increases, not decreases, in sand supply.

The stability of the shoreline along the Sizewell power stations frontage suggests that it is relatively insensitive to the scale of changes that have occurred on Sizewell Bank during the historical period covered by this report, although erosive phases lasting a decade or more have been observed (Table 12). This may allow an estimate to be made of the magnitude of the change in bank elevation that would be of relevance to shoreline change. New measurements of bank morphology, shoreline and longshore bar change, inshore wave climate are expected to shed further light on this subject.

The importance of the inshore wave climate change to nearshore processes and shoreline change features in the BEEMS measurement and modelling plan. Hydrodynamic models have been run as a feed to EDF's Flood Risk Assessment, to assess the alongshore component of wave power driving shingle transport (BEEMS Technical Report TR420) and for prediction of the effects caused by marine components of the proposed development (e.g., scour, dispersal of dredged material etc.). This models the 10 year Sizewell wave buoy and radar and video data will be used to investigate the sensitivity of the inshore wave climate to:

- gross changes in bank morphology (e.g., based on historical observations from BEEMS Technical Report TR058 and future geo-scenarios from BEEMS Technical Report TR105);
- localised changes in Sizewell – Dunwich Bank morphology (e.g., on the saddle); and
- storm directions (for change in wave climate).

7.6 Conceptual models of shoreline development

7.6.1 Pethick (2004, 2010b)

Only those elements of Pethick's (2004c, 2010b) conceptual models which are pertinent to the results in this report are described here - the full models should be sought in the original references.

From an analysis of EA bathymetric profile data 1992 – 1997, Pethick (2004c) concluded that the Suffolk coast and nearshore zone is developing as a series of shallow bays, separated by headlands formed by natural geological outcrops, seabed promontories backed by cliffs, sedimentary 'ness' accumulations and hard coastal defences. Pethick (2004c) suggested that the bays are slowly orienting to face NE wave approach angles, through redistribution of sediment by erosion from the north of each bay and accretion in the south. This is interpreted as a typical progression from a predominantly drift-aligned shore to a swash alignment, indicating that a regional sediment deficit is affecting the Anglian coast. Ultimately, redistribution of existing sediment would form a wide asymmetric bay between the two headlands of Thorpeness and Dunwich cliffs, with the bay head approximately at the present location of Minsmere Sluice, where the river would form a tidal delta. Pethick (2004c) estimated that the bay would take 175 to 325 years to attain a stable form, with the bay head eroding up to 22 to 30 m by 2010, by 72 to 87 m by 2035 and up to 260 m by 2100. He noted the significant influence of the distribution, nature and age of coastal defences on shoreline form, and the retardation of recession caused by Minsmere sluice (the anticipated 30 m erosion to 2010 has not been observed) but considered that this would be unsustainable in the longer-term. Hard defences here would cause the location of maximum erosion to move south toward the Sizewell frontage.

In Pethick (2010b), the model is revised (as described in the rest of this section) to identify two distinct sediment cells: one between Benacre Ness and the Blyth estuary, which is relatively straight and with no offshore banks; and a second between the Blyth estuary and the present crag outcrop at Thorpeness, which has been developing over several centuries into a relatively deep asymmetric bay ('Minsmere Bay') with offshore banks. The revised concept assumed a significant ebb-tide delta on the Blyth/Dunwich rivers, to the north of Dunwich, around 1000 yrs before present (BP). The coast north of the ebb tide delta was relatively straight, stable and drift-aligned, fed by a high rate of sediment supply from cliff erosion further north. South of the Blyth and Dunwich ebb tide delta, the coast formed a shallow bay, more than 1 km seaward of the present shoreline. Longshore sediment transport rates would have been relatively high in the northern part of Minsmere Bay due to the high angle of the shoreline relative to the dominant NE waves, leading to a negative sediment budget and sustained erosion of the Dunwich Cliffs. The more swash-aligned coastal orientation and reduced longshore transport rate between Sizewell and Thorpeness, together with generally lower energy conditions in the lee of Sizewell Bank, would have encouraged sediment accretion in this area. According to Pethick (2010b) "*the sediment accreted immediately north of Thorpeness would have been moved north during south to southeasterly storms forming banner banks within the Minsmere Bay - the Sizewell – Dunwich Banks. Sediment movement around these banks, now agreed to be a clockwise circulation (e.g. Lees, 1980) was moved north along the landward flank of the Bank and subsequently moved south along the seaward flank*."

Pethick (2010b) went on to propose that the southern end of Minsmere Bay is not fully swash aligned, and so must maintain a drift alignment sufficient to balance sediment inputs with outputs. Hence, as longshore input from the north decreases, the Minsmere sediment cell rotates anticlockwise toward a swash alignment, while the artificial headlands in the bay (Minsmere sluice and the cooling water outfalls) sub-divide the larger system into a series of *en echelon* sub-cells. The decreased sediment input might be explained by a change in wave climate, but more likely by a decrease in external sediment sources or by the diversion of sediment offshore. Sediment passing the Blyth is diverted southerly to the seaward flanks of the Sizewell – Dunwich Banks, facilitated by the landward movement of the banks, thus forming part of their clockwise circulation pattern. Less sediment enters the Minsmere Bay than formerly, increasing the disparity between potential and actual sediment transport and leading to continued erosion of the Dunwich cliffs (despite their anticlockwise re-orientation) and an increasing length of the Minsmere Bay shoreline as it deepens. Hence, the Sizewell shore, formerly accreting, has become largely erosional over the past 50 years. The model concludes that, as the Minsmere Bay deepens further, so the discontinuity in orientation of the sediment pathway south from the Blyth increases and sediment is increasingly diverted away from the nearshore into the offshore. This positive feedback means that, ultimately, external inputs to the nearshore pathway will decrease to zero and the bay will eventually become fully swash aligned.

7.6.2 Assessment and modification of the conceptual models

A number of elements of Pethick's conceptual models require careful scrutiny in the light of available evidence assembled in this report. The configuration of the Suffolk coast 1000 years ago is conjectural, but from archival records it is clear that the general line of the coast lay 0.2 to 2 km east of its present position. Several early maps and charts show the existence of a promontory (Easton Ness) just to the north of Southwold, in the mid-16th and 17th centuries (Pye and Blott, 2005), reportedly the most easterly point on the English landmass until it was progressively eroded in the 17th and 18th centuries. To the south of this was Sole or Southwold Bay, defined by a slight promontory on its southern side at Dunwich. Saxon to Medieval period accounts suggest that much of the town of Dunwich was then located on relatively low ground to the east of the present cliffs (Comfort, 1994; Sear *et al*., 2010). Within this bay lay the combined estuary of the Blyth and Dunwich Rivers, the position of which varied over time in response to the growth and breaching of a large shingle barrier south of Southwold (Pye and Blott, 2006).

The Domesday Book records that over half the taxable farmland at Dunwich was lost to the sea between 1066 and 1086 (Gardner, 1755), whilst severe storms in the late 13th and early 14th centuries destroyed numerous properties in the eastern part of the town (Gardner, 1755). Episodic erosion caused further significant land loss at Dunwich in the 16th, 17th and 18th centuries, and Easton Ness disappeared as a recognizable feature during this time. This erosion reduced the depth of Sole Bay, as did the construction of the first dredged harbour and harbour pier at the entrance to Southwold Harbour in the 17th century. The structures at the harbour mouth were subsequently improved and extended on a number of occasions between the 18th and 20th centuries, creating a 'hard point' which has helped to impede the deepening of the bay (Pye and Blott, 2005, 2006). Much of the Blyth estuary was embanked and reclaimed for agriculture in the 16th and 17th centuries, significantly reducing the tidal prism. However, the relatively small size of the Blyth and Dunwich estuary, and the small tidal range, suggests it is unlikely that a large ebb tidal delta existed in the past in the manner envisaged by Pethick (2010b).

The chart of 1824 clearly shows that a smaller sub-bay had developed between the Blyth entrance and the high ground at Minsmere Cliffs. Rapid erosion of the Dunwich and Minsmere Cliffs occurred within this sub-bay during the 19th century. To the south of Minsmere cliffs, erosion affected the cliffs at Sizewell and between Sizewell Gap and Thorpeness before 1835 but, since that time, maps indicate no further cliff recession. The 1837 edition One Inch OS map clearly shows that the southern end of Minsmere cliffs formed a slight promontory, with shallow bays to the north and south. After construction of the first Minsmere Sluice shortly after 1810, creating a further hard point, erosion slowed, and two further sub-bays have been developed on either side of the sluice.

Historical maps also show that the southern part of Minsmere bay did accumulate large quantities of sediment between 1835 – 1925, but this process reversed around 1930. The slow erosion trend between Sizewell Gap and Thorpeness has continued to the present, with fluctuations, but since 1965 the frontage between a point north of the SZC site and Sizewell Gap fluctuated but with no significant net trend (Table 12), evidently independent of the construction of the Sizewell power stations and their outfalls. The spatial variability of erosion and accretion trends from the data assembled in this report also demonstrates that shoreline dynamics are more complex than envisaged in the Pethick model.

Investigations of sea floor bedforms and particle size trends (BEEMS Technical Report TR107) provide little support for Pethick's (2012) suggestion of a strong northerly sediment transport pathway from Thorpeness up the landward side of the Sizewell – Dunwich Bank, or southerly transport along its eastern flank. BEEMS Technical Reports TR098, TR107, TR233 and TR357 instead show southerly dominance inshore of the bank. There is also some evidence for northerly movement along the south-eastern flank of Sizewell Bank (BEEMS Technical Reports TR139 and TR357), which together with the probable southerly transport, suggest a potential localised anti-clockwise circulation at Sizewell Bank, which is counter to Lees (1980) and Pethick (2010b).

There is, however, some evidence (Pye and Blott, 2006 and BEEMS Technical Report TR139) supporting the transport of sand from northerly cliff and/or beach sources onto the northern end of Dunwich Bank, and southerly transport in the deeper water to the east of Dunwich Bank. Although the principal net sediment transport direction inshore of the bank system is evidently southerly (driven primarily by tides), transport on the subaerial beach and in the shallow subtidal zone shows reversals in response to short-term changes in wave approach.

Between 1835 – 1930 the northern part of the Sizewell – Dunwich Bank system grew significantly in size, possibly as a result of transport of large quantities of cliff-eroded and possibly beach sediments from the coast to the bank. This coast to bank transport pathway is supported by geomorphic indicators as well as sediment transport modelling (see BEEMS Technical Report TR357). Stormy conditions considered to characterise the late 19th and early 20th centuries would have favoured longshore (southerly) and possibly offshore transport of beach sediment. Beach levels would have remained low along much of the coast for long periods, providing little in the way of a protective buffer against cliff erosion when storms occurred. As documented in BEEMS Technical Report TR139, a reduction in the frequency of severe storms from the 1930's onwards has generally favoured the maintenance of high, wide beaches, albeit with short-lived exceptions. The increase in size of the Sizewell – Dunwich Bank, and its inshore movement, has also contributed to a reduction in overall wave energy at the shoreline (Pye and Blott, 2006; BEEMS Technical Reports TR068 and TR232). As a result of these changes, rates of cliff erosion and sediment supply at Dunwich and Minsmere have progressively slowed. The relative stability of the Sizewell power station frontage over the past 50 years is likely related to low net rates of longshore sediment transport in the lee of the bank, with southerly transport under the influence of NE waves being more or less balanced by northerly transport during periods of SSE waves. Further south, between Sizewell Gap and Thorpeness, slow net sediment loss is taking place and is probably due to the rate of supply of new sediment from the north being less than the transport rate of sediment towards the south. Although some of the sediment may be finding its way onto the southeast side of Sizewell Bank, a significant proportion of the sand and virtually all of the gravel appears to be moving around Thorpeness towards Aldeburgh. Further testing of these hypotheses using numerical models is required.

8 Conclusions

This report has updated the previous edition, which presented the first integrated analysis of all identified and available shoreline change data (save for satellite imagery) covering the GSB during the past 183 years. These datasets (including historical maps and charts 1835 – 2012, orthorectified aerial photographs 1940 – 2018, beach topographic surveys 1985 – 2017, LIDAR surveys 1999 – 2017, bathymetric profiling 1992 – 2007 and swath bathymetry data 2007 – 2017), provide a wide range of spatial and temporal resolutions. While different measurement techniques reveal processes operating over different time and length scales, findings may still be complementary (e.g., whilst analysis of shorelines mapped from aerial photographs gives more information about localised changes (and highlights spatial variability), beach profile data from topographic surveys help to identify beach contour levels and features that can be mapped on the aerial photographs).

8.1 Conceptual model of historical shoreline behaviour at Sizewell

The Sizewell shoreline has experienced two distinct phases in the past 183 years: (1) prior to 1925 long-term persistent and spatially-coherent erosion and accretion occurred to the north and south of Minsmere Sluice, respectively; and (2) following a reversal of this trend in 1925 – 1940, the shoreline change rates lowered and became highly spatially and temporally variable. The cause of this change was postulated in Pye and Blott (2006). Prior to 1925, a high energy uni-directional north-easterly wave climate (Lamb, 1995; Pye and Blott, 2006) and a low Dunwich Bank (2 to 4 m lower than present day; Figure 68) led to inshore waves that attacked the coastline causing rapid shoreline and cliff erosion, and the release of large volumes of sediment (e.g., Dunwich and the Southwold to Benacre coast to the north; Brooks, 2010). The then prevailing uni-directional wave climate advected this material to the south within the longshore transport corridor and thereby prevented the build-up of beaches that might have otherwise protected the cliffs. However, south of Minsmere Sluice divergence in longshore sediment flux promoted high rates of accretion fed by the high volumes of sediment supplied from the north. The probable causes for accretion there are lower energy in the lee of Sizewell Bank, and a reduction in wave angle at the coast due to refraction around the bank and the more easterly shoreline orientation. In addition to historical accretion, sediment in the longshore transport system is considered to have continued south passed Thorpeness (shingle) or to have been funnelled offshore and onto the bank at the Coralline Crag ridges (sand). Given that banks are tidally maintained bedforms, sediments supplied from the shore would have circulated and accumulated causing the bank to grow. There is some tentative evidence to suggest that sand may also reach the bank directly from Southwold to Dunwich (BEEMS Technical Report TR107).

The subsequent switch in shoreline behaviour across the bay post-1925 was marked by a change in nearshore wave conditions: the wave climatology became bi-directional, resulting in a substantial reduction in net longshore transport; and the nearshore wave energy will have reduced due to sheltering by the higher bank. A cap on maximum inshore wave height (approximately 2 to 4 m) due to wave breaking (Lees, 1983 and BEEMS Technical Report TR058) will have lessened the impact of larger storms; this cap means that the shoreline is relatively insensitive to extreme events (high magnitude, low return interval) of varying magnitudes as the high energy component of the wave spectrum is cut off due to extensive wave breaking on the bank (BEEMS Technical Report TR319). As a result, the erosion and accretion patterns to the north and south of Minsmere sluice respectively, were replaced by lower rates of highly spatially and temporally variable shoreline change.

Today, shoreline change all around the GSB is a fluctuating patchwork of erosion and accretion. Stretches of coastline with common behaviour are typically only a few hundred metres wide, though zones may be less than 50 m or greater than 1 km. Similar findings have been reported elsewhere for the East Anglian coast (e.g., EA 2008, 2011; Dolphin *et al.* 2011) and such behaviour seems to be a characteristic of recent (last 20 – 30 years[6]) shorelines in the lee of banks. The general patterns of shoreline change also appear to be linked to variability in the inshore wave climate (as modelled by BEEMS Technical Report TR232), longshore transport and offshore bathymetry (the morphology of the Sizewell – Dunwich Bank and longshore bars). In particular, the very low rates of change around the Sizewell power stations coincides with low wave energy and longshore transport, as shown in various modelling outputs (BEEMS Technical Reports TR068, TR232, TR329 and TR420). Thus, over periods of years to decades the net transport is considered to be low and to the south (Royal Haskoning, 2010; BEEMS Technical Reports TR329 and TR420).

8.2 Shallow bays and hard points

Pethick's regional scale description of the Suffolk coast is of a shoreline evolving in order to balance the drivers toward longshore or swash alignment (i.e., the dominant storm direction and sediment supply pathways from north to south at a given time). The shoreline re-orientation combines anti-clockwise straightening toward a N-S axis in the northern sections (Brooks, 2010) and the creation and/or rotation of bays and sub-bays in the south. The formation of bays between erosion resistant points (i.e., entrance piers to the Blyth estuary, Minsmere sluice, Coralline Crag at Thorpeness) is promoted because of low longshore transport rates and sediment supply, and re-orientation toward swash alignment. The bays may deepen and re-align toward an equilibrium shape, but severe erosion is likely should Minsmere sluice or the Blyth estuary piers decay or be removed (for an example of rapid erosion following removal of coastal structures see Dolphin *et al*., 2012).

Minsmere Sluice has acted as a 'hard point' within the coastline since its original construction in 1830, that is, the sluice acts in the same way as a groyne, trapping sediments moving alongshore. Under the current bi-directional wave climate, sediment build up typically occurs on both sides of the sluice over a distance of approximately 1 km, beyond which net erosional trends are observed, resulting in shallow erosional bays to the north and south. It is likely that these erosion rates are lower than they would otherwise be if the sluice were not present. Wave modelling indicates that the relative stability of this shoreline at present is in defiance of the inshore wave energy and erosion potential, which are high along this section of the coast. The Minsmere sluice example suggests that the effect of structures that trap longshore sediment on this coast is net stability (there are no signals of persistent downdrift erosion), and decay or removal of the sluice structure (as a hard point, not as an operational sluice) is likely to result in very high recession rates between SZC and the Minsmere cliffs, for years to decades, until an equilibrium beach-plan shape is reached, though the behaviour of the shoreline response may differ between that experienced at SZC and Minsmere. In the absence of other control structures between the sluice and SZC, retention of the sluice as a hard point (not an operational sluice) will stabilise the shoreline at this location, whilst influencing the future configuration of the adjacent shoreline as it is forced into alignment with the Minsmere outfall.

8.3 Sizewell shorelines

Since 1940, the shorelines to the immediate north of SZC (almost as far as Minsmere sluice) have been eroding, with the highest rates observed in the 2001 – 2012 period (up to -2.36 m/yr; Figure 65 and Table 12). Extrapolation of recent and longer-term trends suggests that the SZC coastal defences would be exposed to the sea (i.e., direct wave impacts and the potential for defences to affect longshore shingle and sand transport) within the operational lifetime of the proposed SZC station. The likely plausible future shoreline (50 – 60 years into the future) that, if unmitigated, could affect longshore transport and coastal processes, is investigated in BEEMS Technical Report TR403.

[6] These patterns may have been present for a longer period, back to the 1940's, but the survey interval prior to 1985 is insufficient to draw conclusions about annual fluctuations in the shoreline

The coastal erosion north of SZC, combined with accretion at SZB since 2007, can be seen to shape a shallow bay that Pethick (2010b) identified. Beach profile P6, immediately north of the SZC site, currently represents the transition point between the eroding and accreting zones (see Table 12). It is important to note that the shoreline behaviour in these two zones is occurring independently: the area north of SZC began slowly eroding in 1940 and accelerated in 2001, whilst the accretion and salient at SZB is a relatively recent response. Although potential mechanisms have been postulated (i.e., Pethick, 2010a), the exact cause for salient development remains unclear (BEEMS Scientific Advisory Report Series SARS018). However, as the salient was not an obvious and persistent feature until 2005 (Figure 71 and Figure 72), it seems that it may not have been formed in response to the operation of the outfall, or at least not for the first decade of the stations operation (before the outer bar migrated into the outfalls zone of influence).

Whether the salient's recent formation is related to the SZB outfall discharge could be assessed by detailed shoreline measurements during future planned outages, however they would need to be sufficiently long for geomorphic response to be observed. For example, the Cefas radar deployed at SZA could track the response of the longshore bar during such periods and RPA[7] aerial overflights could map the 3D beach topographical response. It seems likely that analogy of the SZA salient and subsequent shoreline relaxation following shut down (2007), is relevant to the SZB salient – that is, once SZB begins decommissioning localised recession and shoreline straightening is expected. Such an event is rather minor in comparison to the erosion trends to the north of SZC and, in particular, the likely shoreline response should Minsmere sluice degrade or be removed in the future.

The Sizewell power station frontage remained very stable both pre- and post-1925, with intermittent periods of accretion and slight erosion, since 1830. Wave modelling and shingle tracer measurements (BEEMS Technical Reports TR068, TR232, TR329 and TR420) suggest that this is due to low longshore sediment transport potential caused by shoaling, refraction and energy dissipation over Sizewell – Dunwich Bank and the longshore bars. As the evidence suggests that long-term stability of the Sizewell frontage is dependent on the dynamics of the Sizewell – Dunwich Bank, the future bank morphology is likely to play an important role on future shoreline behaviour. Although changes to the Sizewell – Dunwich Bank over the next century may well remain within its historical 'envelope' (because of the stabilising effect of the Coralline Crag formations and the expected increase in sand supply), the saddle and Dunwich Bank show higher variability and are distal to the fixed 'geological aids', so are perhaps more liable to change and affect parts of the SZC frontage as far north as Dunwich. EGA, drawing upon modelled and measured data, has been used to consider the future Sizewell shoreline (see BEEMS Technical Report TR403).

The longshore bars are an integral part of the beach system, and act as longshore sand transport corridors, a repository for eroded beach sediments during storms (making correct interpretation of terrestrial-only beach profile results difficult), and lines of natural coastal defence through refraction and dissipation of wave energy during storms. However, their dynamics are poorly understood because of a lack of data (the subtidal beach is more difficult to measure than the terrestrial beach). Fixed cameras and radar (deployed in 2013/14) are being used to study the dynamics of the bars, including their interaction with the SZB outfall.

8.4 Construction impacts on the foreshore

Little information exists about the nature and scale of shoreline change resulting from the construction of SZA, however this report gives clear evidence of the scale and longevity of SZB construction impacts (i.e., dredging for cooling water culverts, coffer dam and the BLF) on the beach and nearshore zone at Sizewell. In particular, dredging and the coffer dam resulted in a 400 m long, 25 m wide indentation in the shoreline, which subsequently infilled naturally over a period of 4 to 5 years. The shoreline positions suggest that, despite the degree of local change and the lack of active sediment management, impacts were not detectable beyond a few hundred metres from the construction site. The observed SZB impacts are expected to be substantially more severe than those of the current SZC designs (as reported in BEEMS Technical Report TR311 Edition 2) because there will be no large structures in the beach face (i.e., SZB coffer dame for cooling water culverts and BLF block), no dredging of the beach face, very minor dredging near the longshore bars (4,600 m^3 around four times per year during construction compared to SZB 855,000 m^3) and SZC will use transmissive structures in the intertidal and subtidal zones.

[7] Remote Piloted Aircraft

8.5 Ongoing shoreline change and coastal processes measurement / modelling

The beach profile monitoring programmes conducted by the SSMSG and the EA have provided valuable data on which to document shoreline behaviour, however the methods employed have their (spatial and temporal) limitations. The BEEMS programme is presently augmenting these ongoing monitoring programmes with a number of measurement and modelling techniques to answer a range of questions on coastal process and shoreline change at Sizewell. The main feature of these additional methods is their ability to capture spatial data (waves, and beach, bar and bank positions) at a significantly higher frequency. In doing so, it will be possible to examine important spatial behaviour occurring between topographic survey profiles and in the months between surveys, as well as the driving conditions. They could also enable earlier detection of impacts from SZC construction and operation, as well as detection of significant trends and (eventually) robust long-term signals based on virtually continuous measurements. The instrumentation being employed includes x-band radar, fixed (oblique) digital cameras and RPA topographic surveys.

The x-band radar[8] and digital cameras have been installed to detect the shoreline and longshore bar position. Shoreline and bar detection algorithms have been developed previously for both video and radar images, and similar detection methods will be employed here. RPA aerial overflights are also being investigated for regular mapping of the 3D beach topography and could include storm-response surveying as needed. Detailed coincident measurements of the bar and the shoreline were previously recommended in the BEEMS Scientific Advisory Report Series SARS018 report on the salient feature near SZB. Detection of the key receptors used to assess the baseline and impacts of the development will be an essential component of any conditions attached to the SZC Development Consent Order and Marine Licence (if approved).

Details of the inshore wave climate (including wave angle that drives longshore transport) will also be examined. This work will include the effects of gross changes in bank configuration (which have already been investigated for the purposes of Flood Risk Assessment; BEEMS Technical Report TR319) as well as the more likely subtle changes in the Sizewell – Dunwich Bank saddle area.

[8] In addition to shoreline and longshore bar detection, the radar data is being explored for its potential to measure the position and elevation of Sizewell Bank, and the wave and surface currents between the land and just seaward of the bank.

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Appendix A Historical maps and aerial photographs

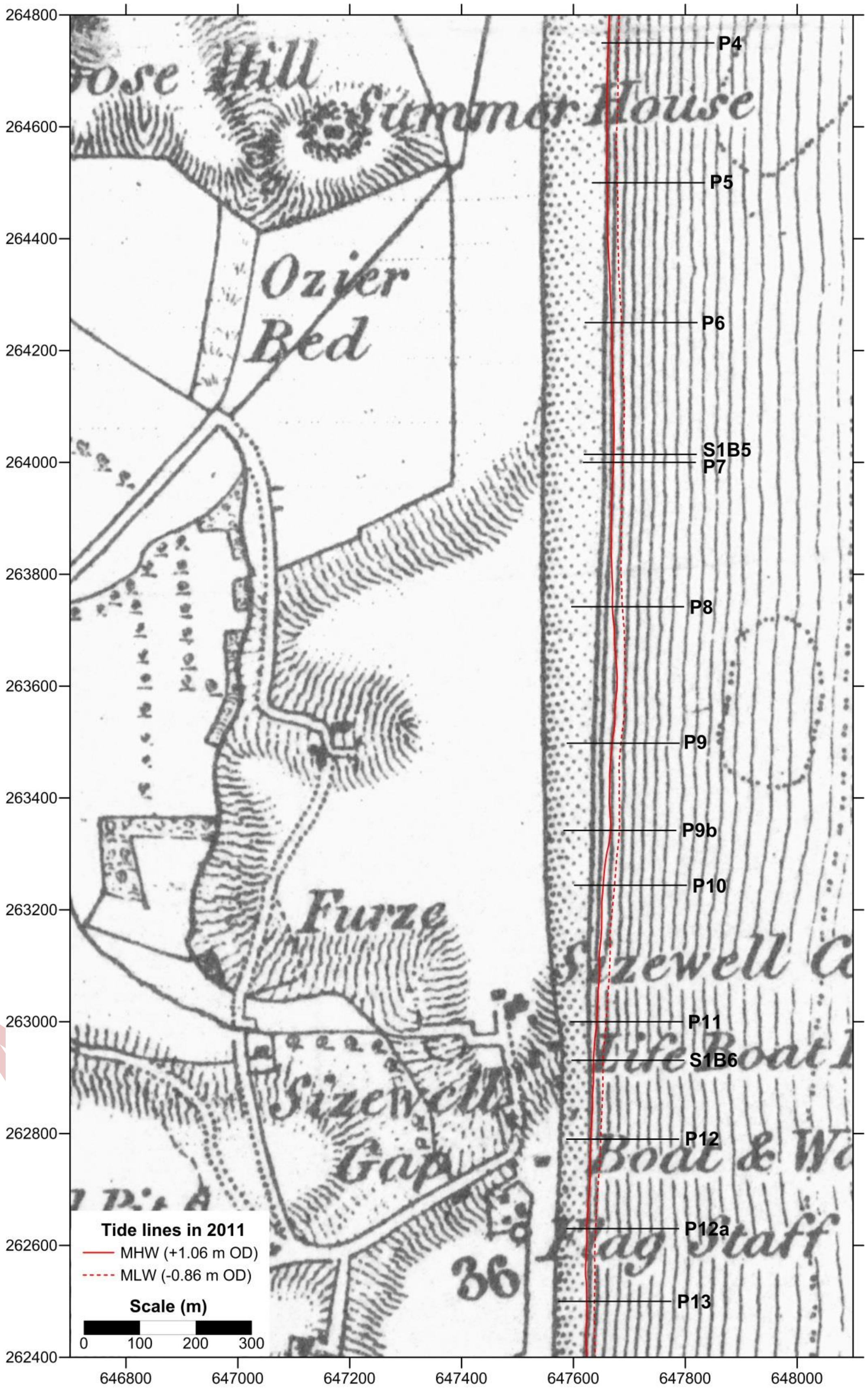

Figure 74: Ordnance Survey One-Inch ‘Old Series’ map, surveyed 1835/36, with superimposed profile monitoring positions.

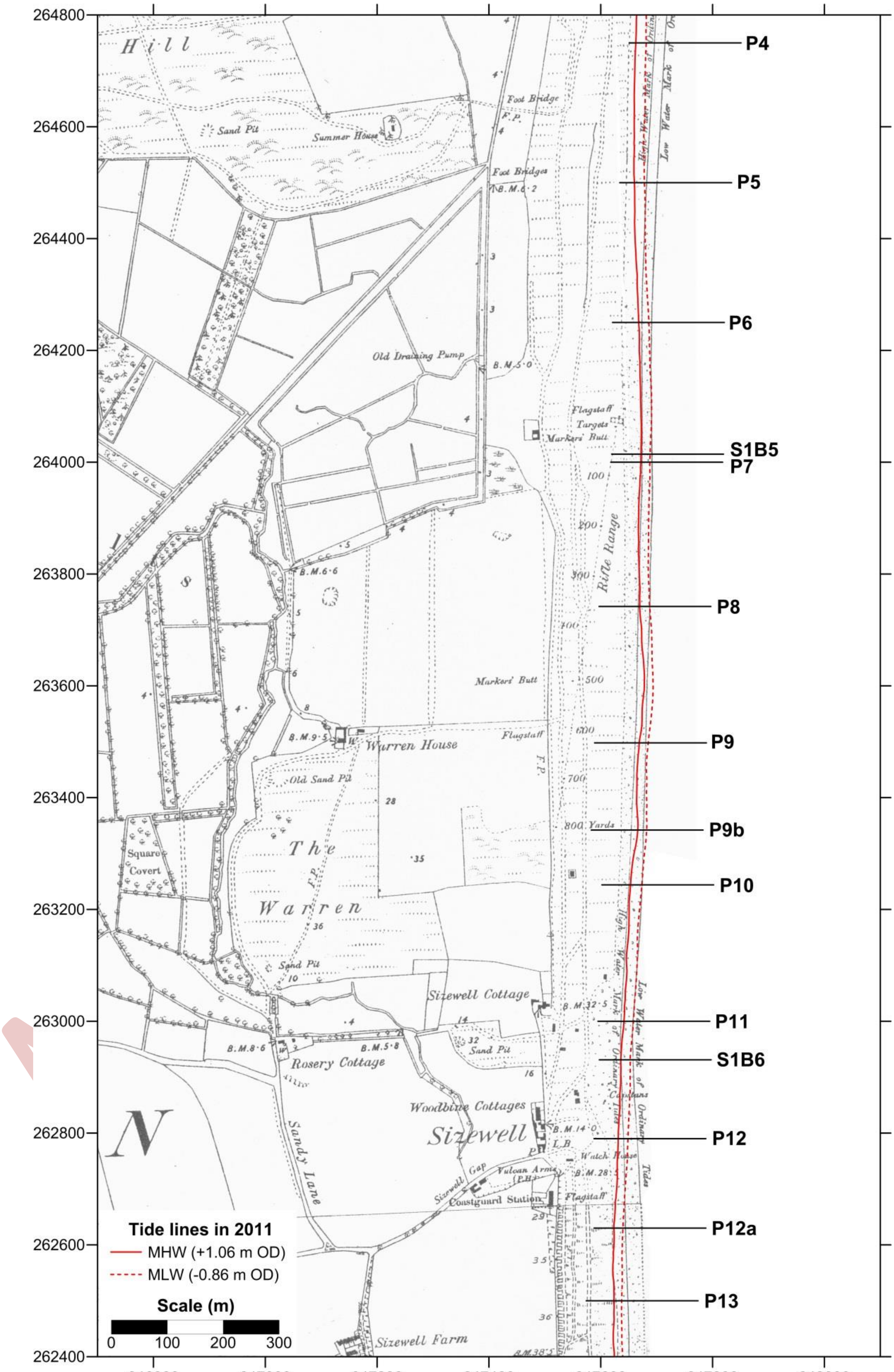

Figure 75: Ordnance Survey Six-Inch 'County Series' map, surveyed 1881 – 1883.

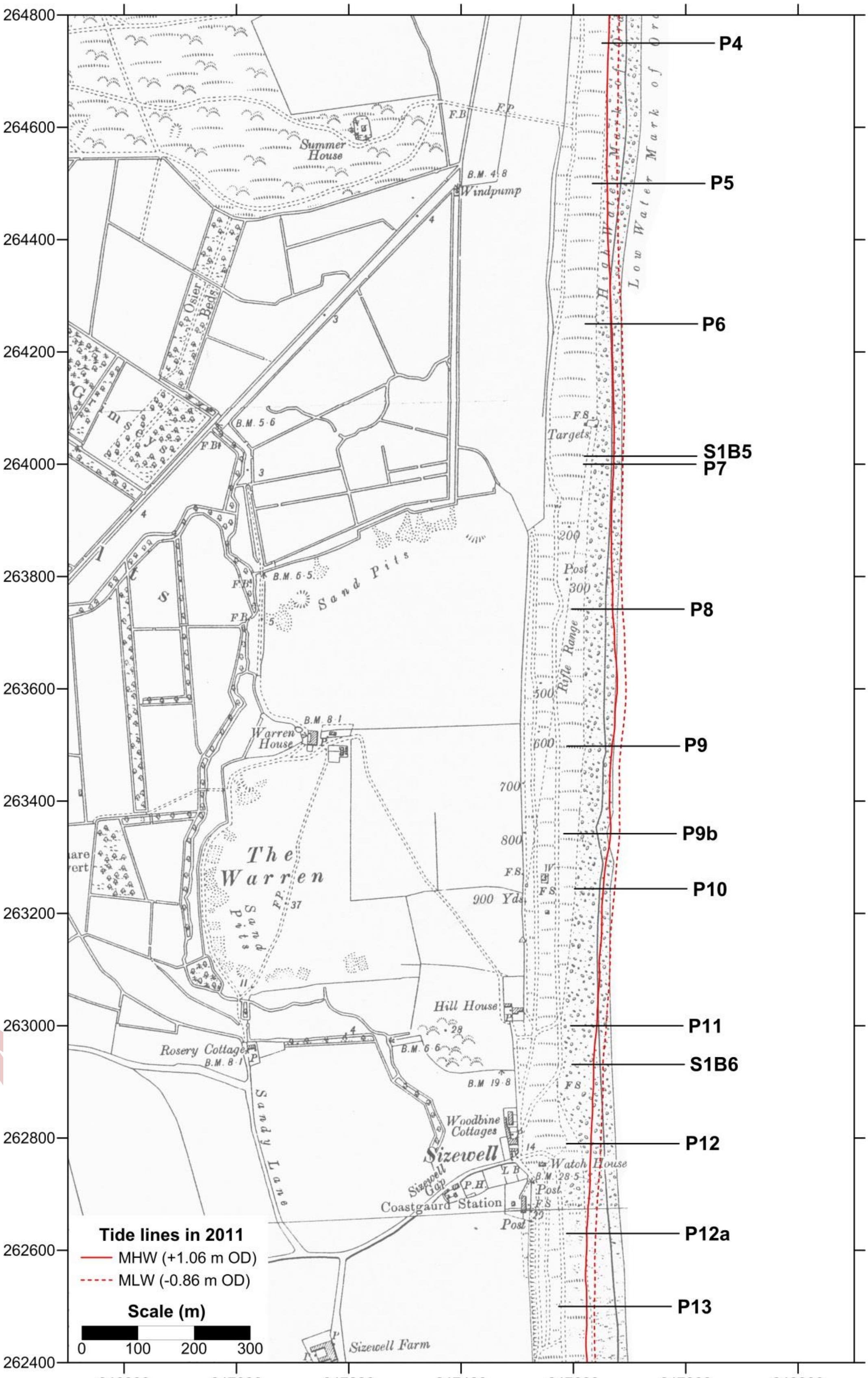

Figure 76: Ordnance Survey Six-Inch 'County Series' map, revised 1903.

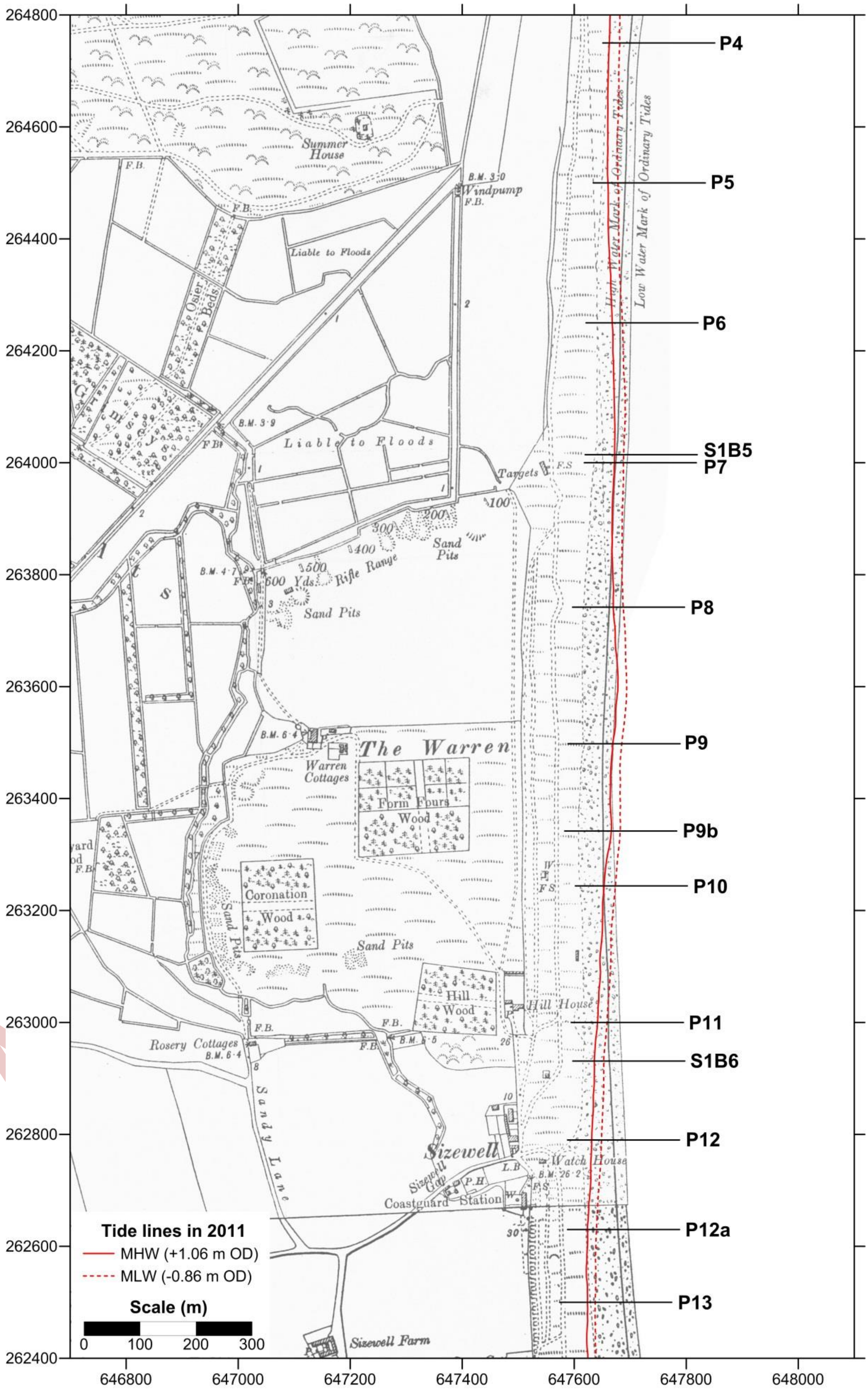

Figure 77: Ordnance Survey Six-Inch 'County Series' map, revised 1925 – 1926.

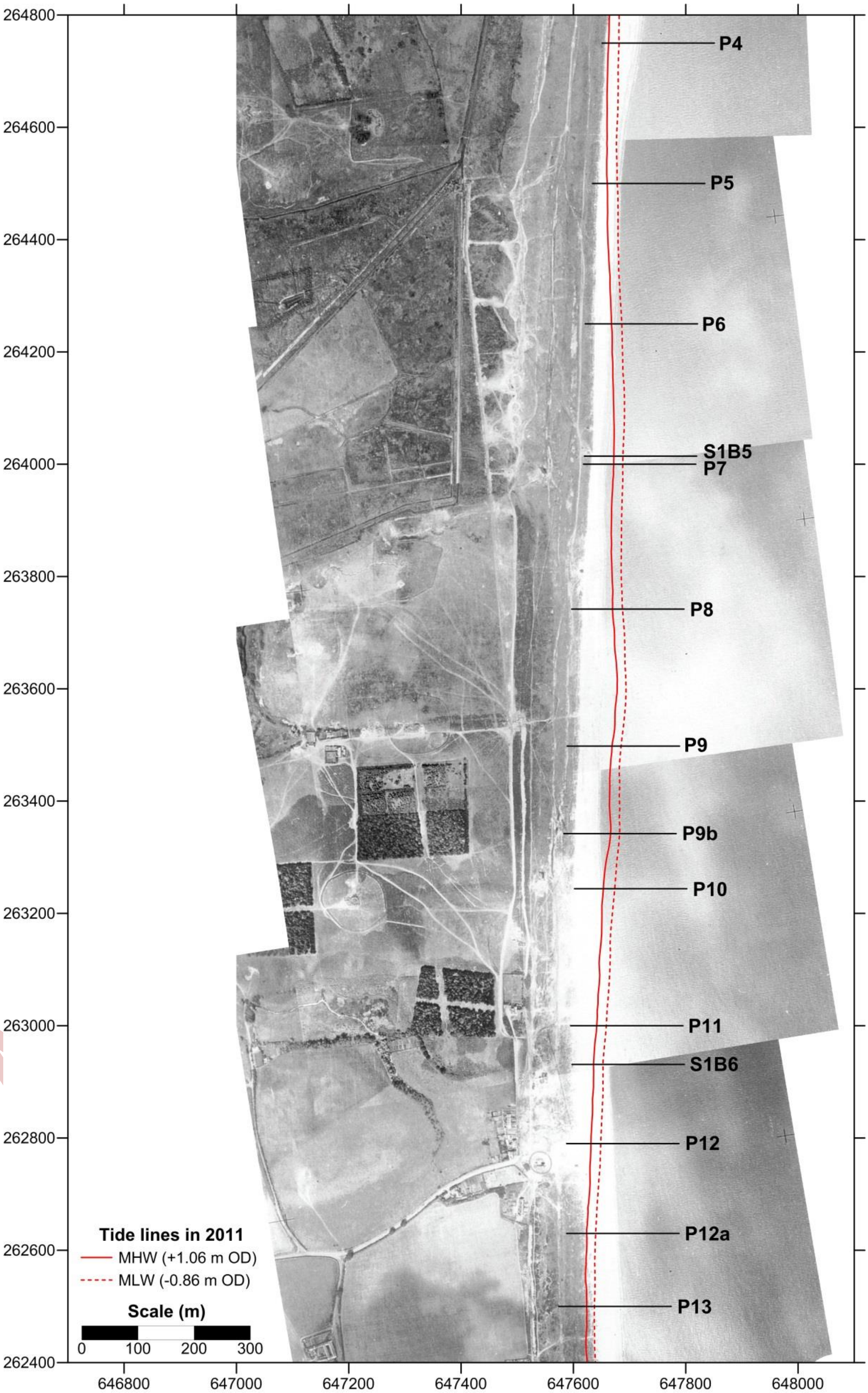

Figure 78: Aerial photography flown summer 1940.

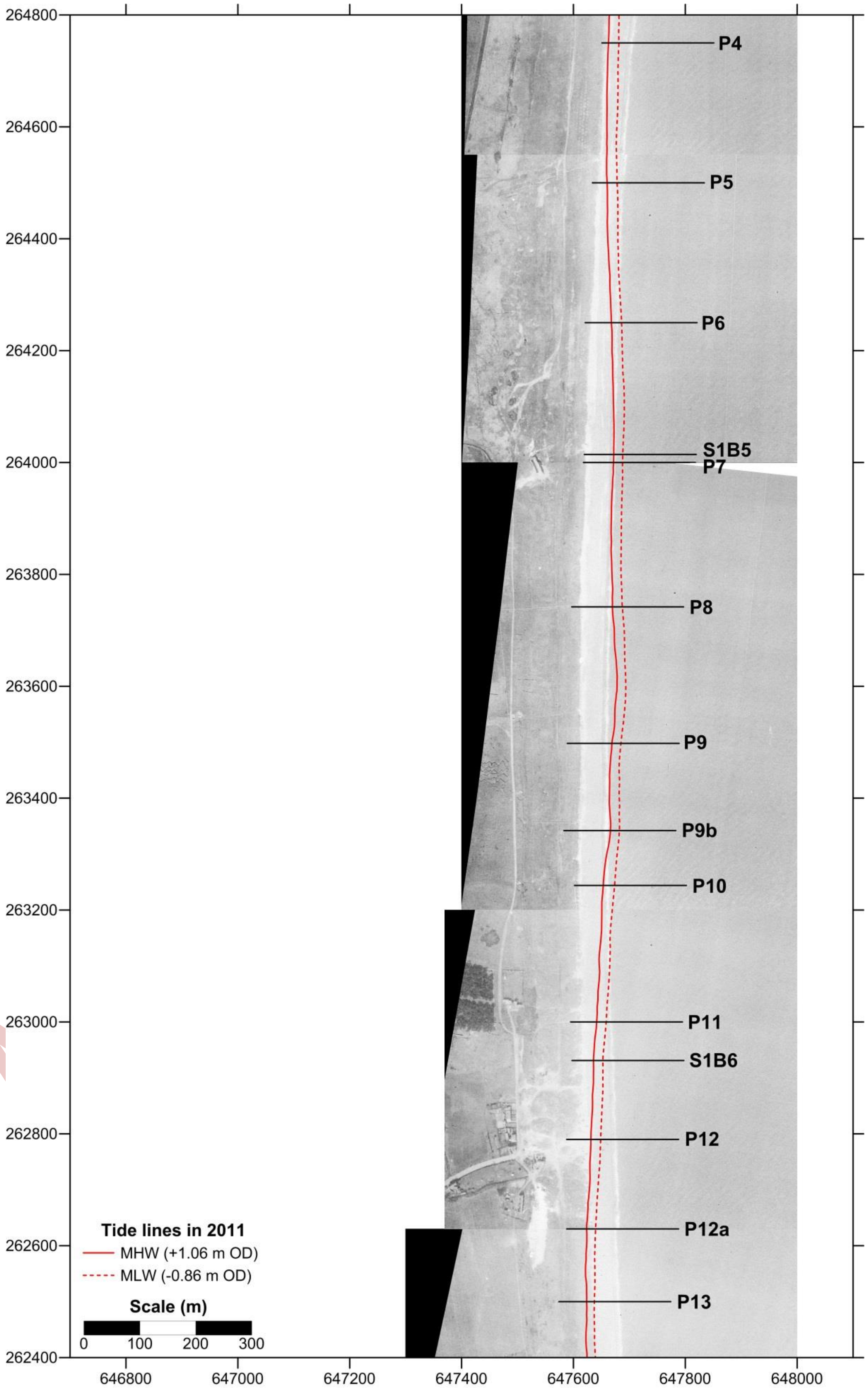

Figure 79: Aerial photography flown spring 1952.

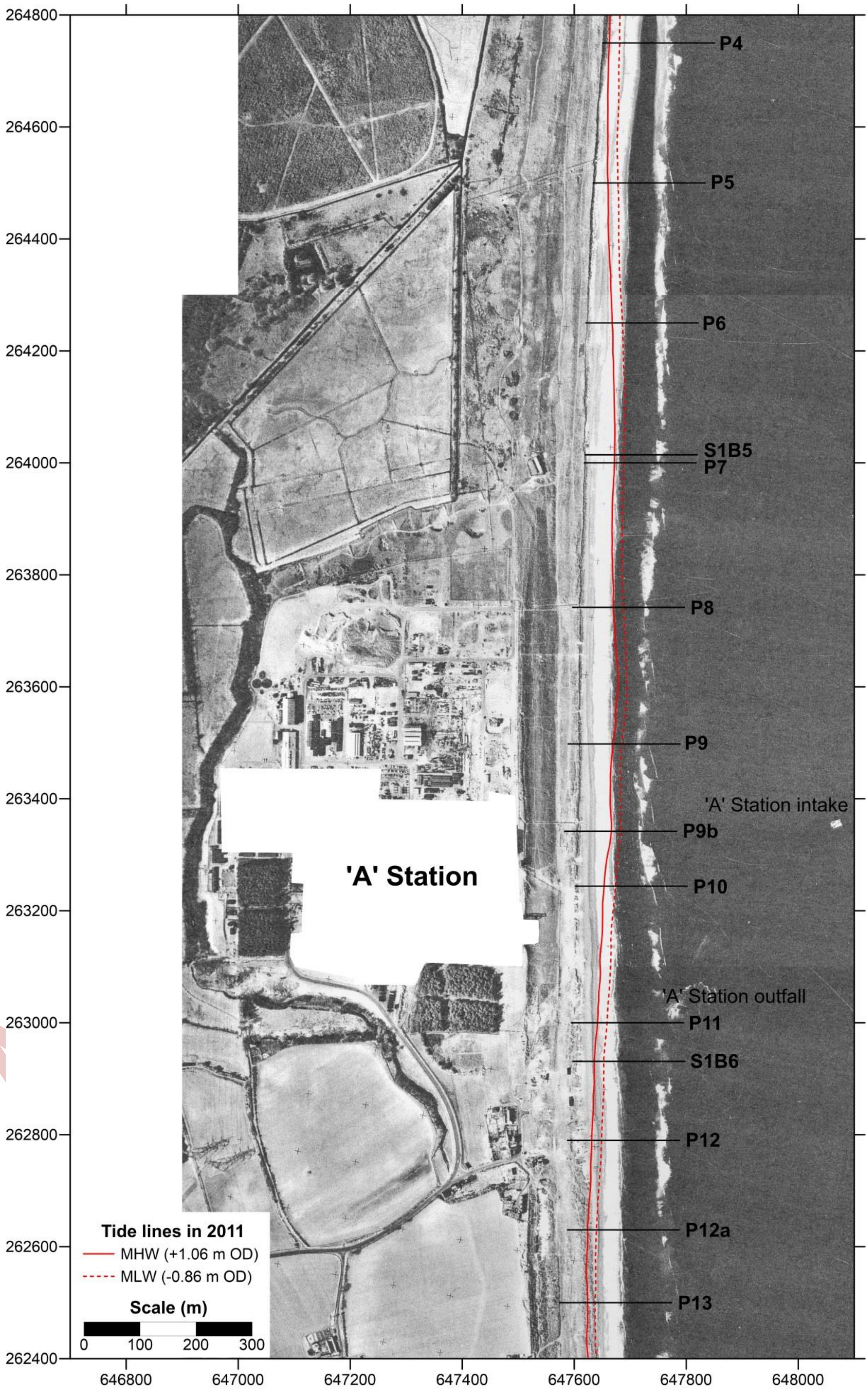

Figure 80: Aerial photography flown spring 1965.

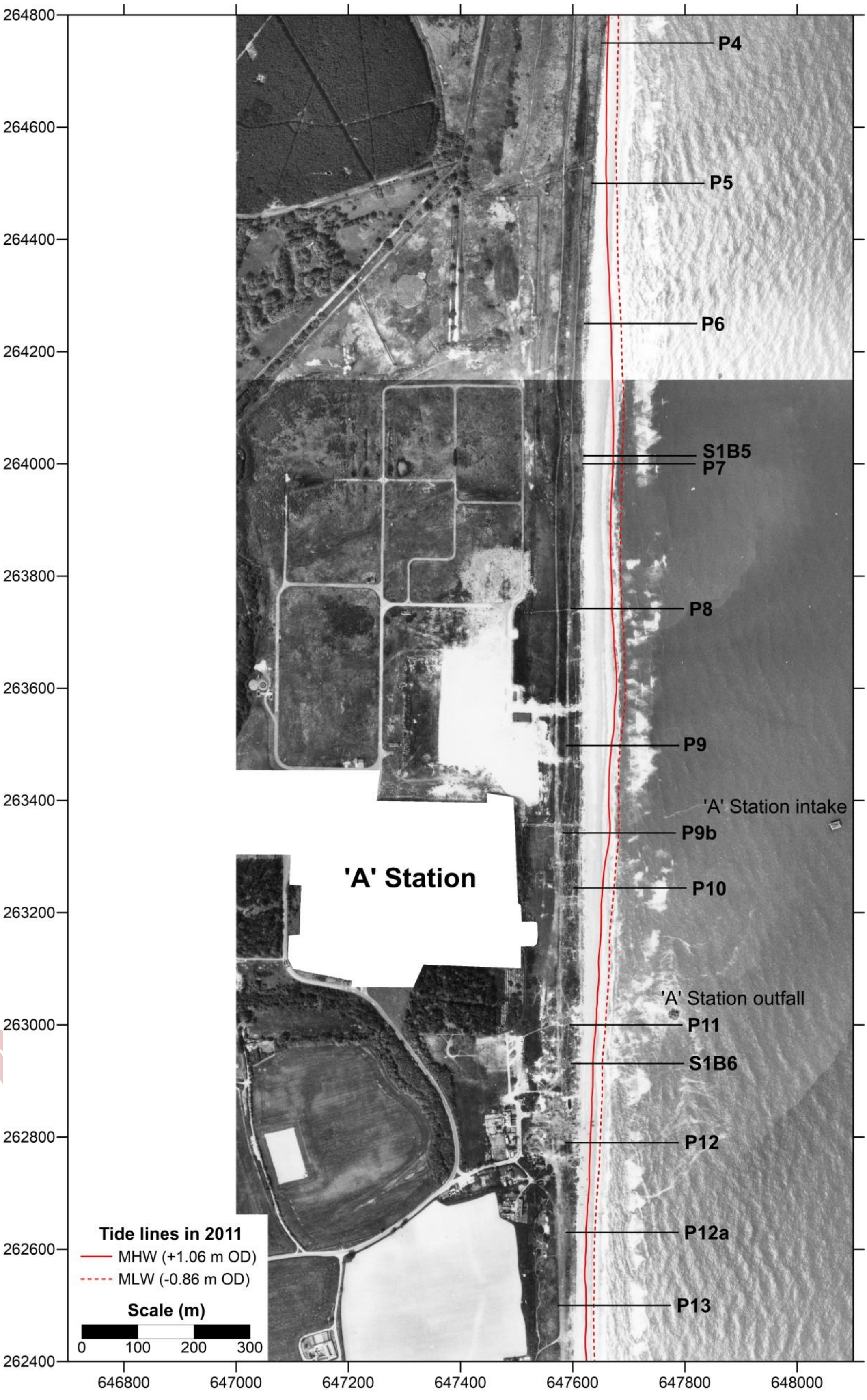

Figure 81: Aerial photography flown summer 1983.

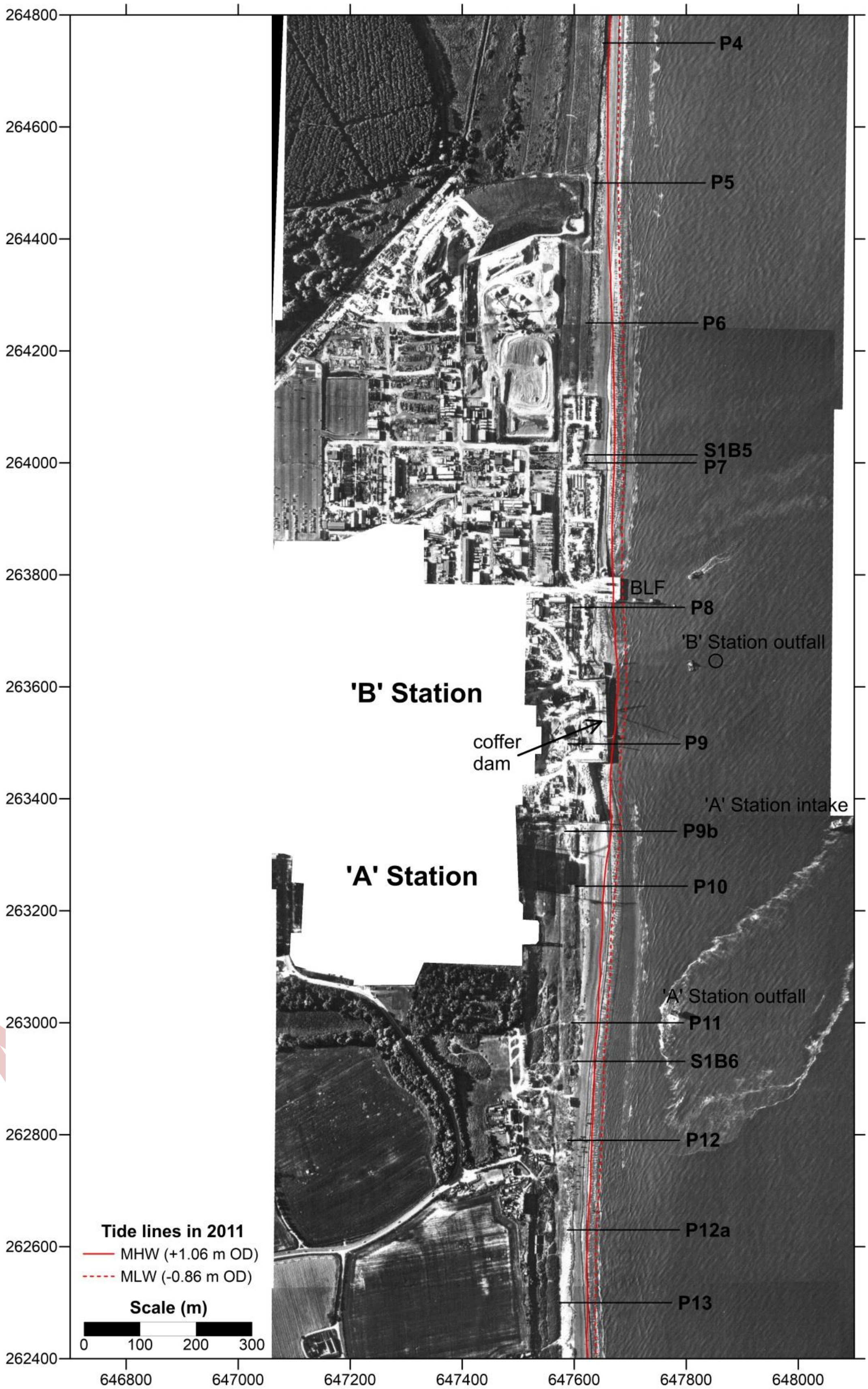

Figure 82: Aerial photography flown summer 1991.

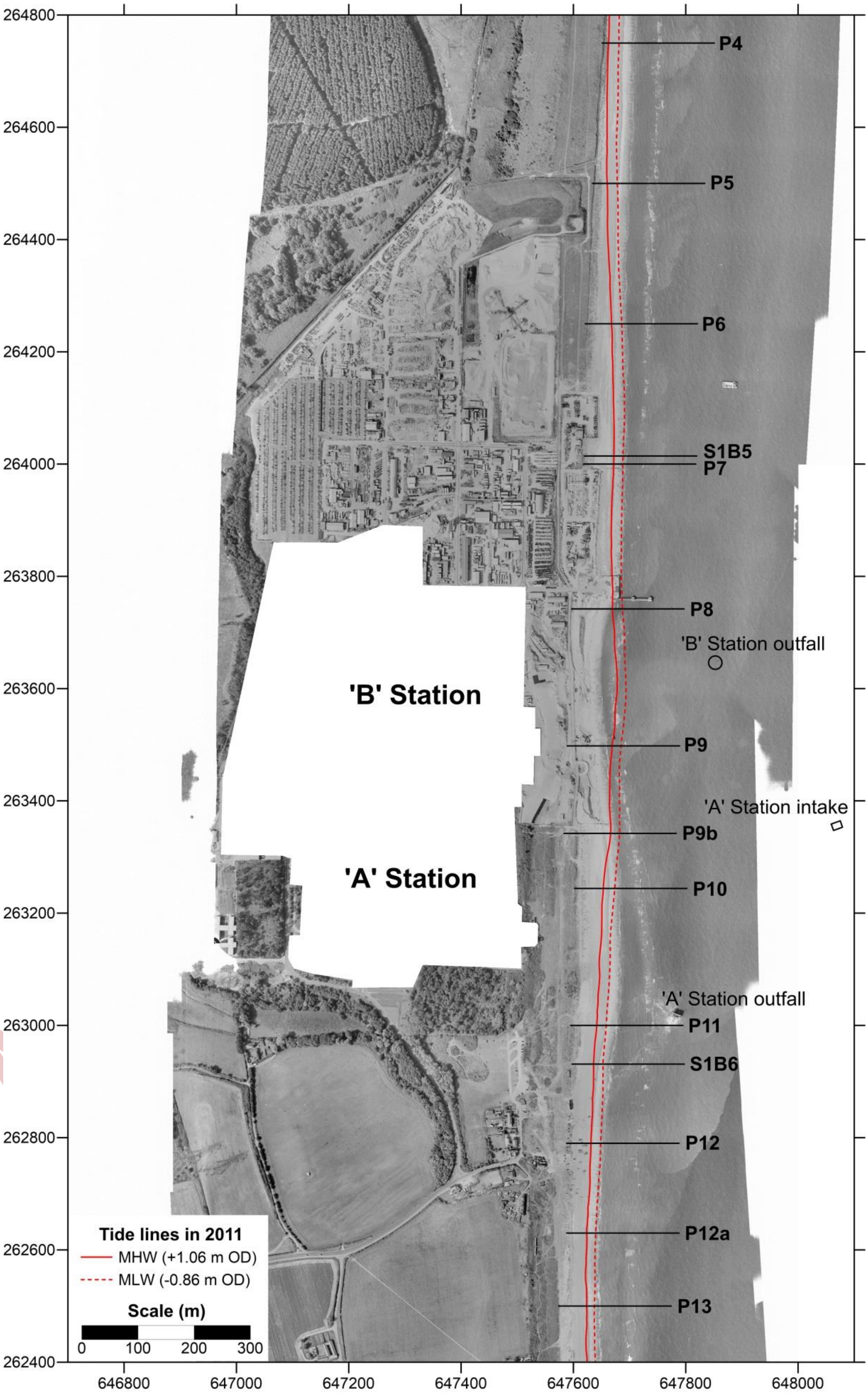

Figure 83: Aerial photography flown summer 1992.

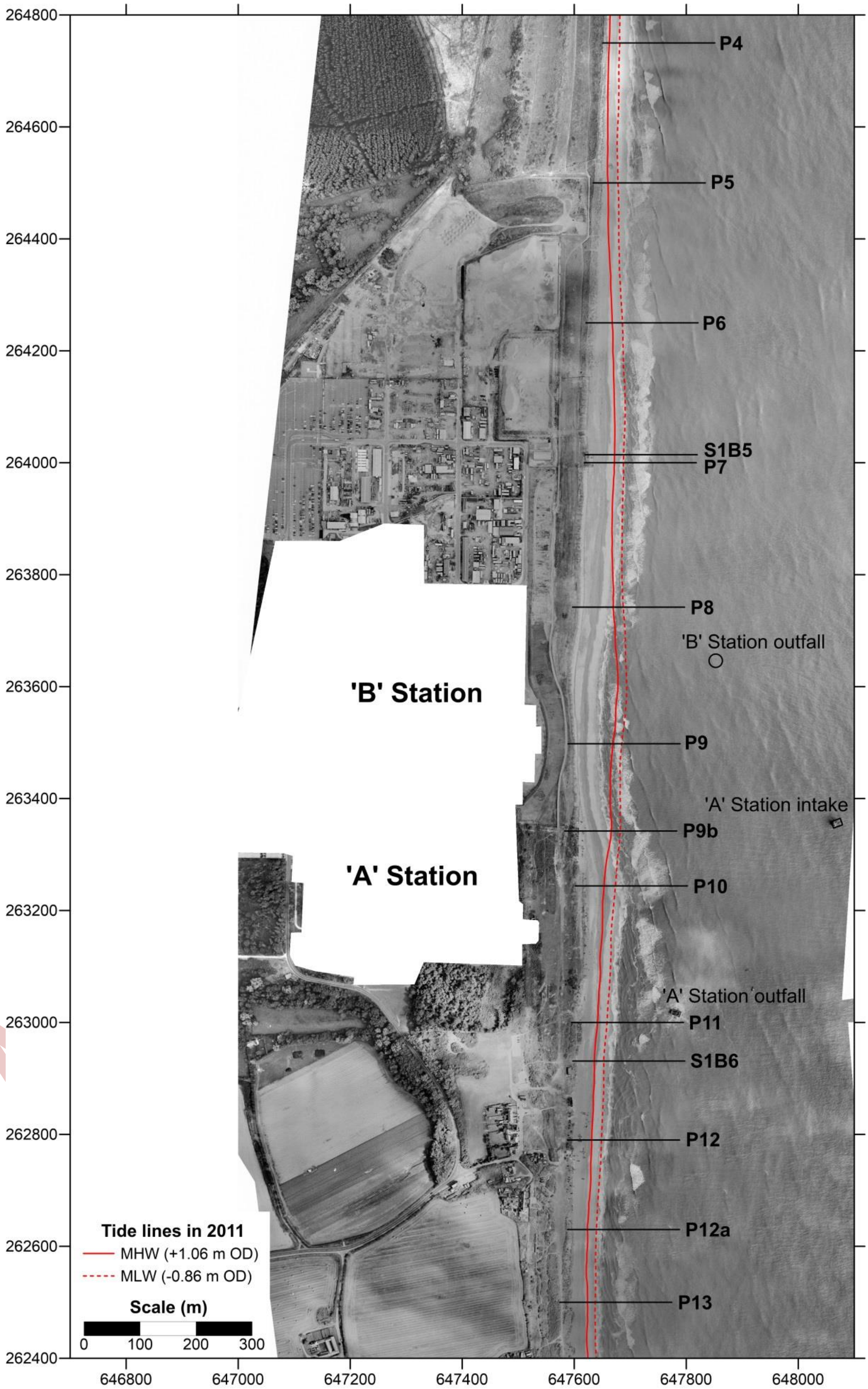

Figure 84: Aerial photography flown summer 1994.

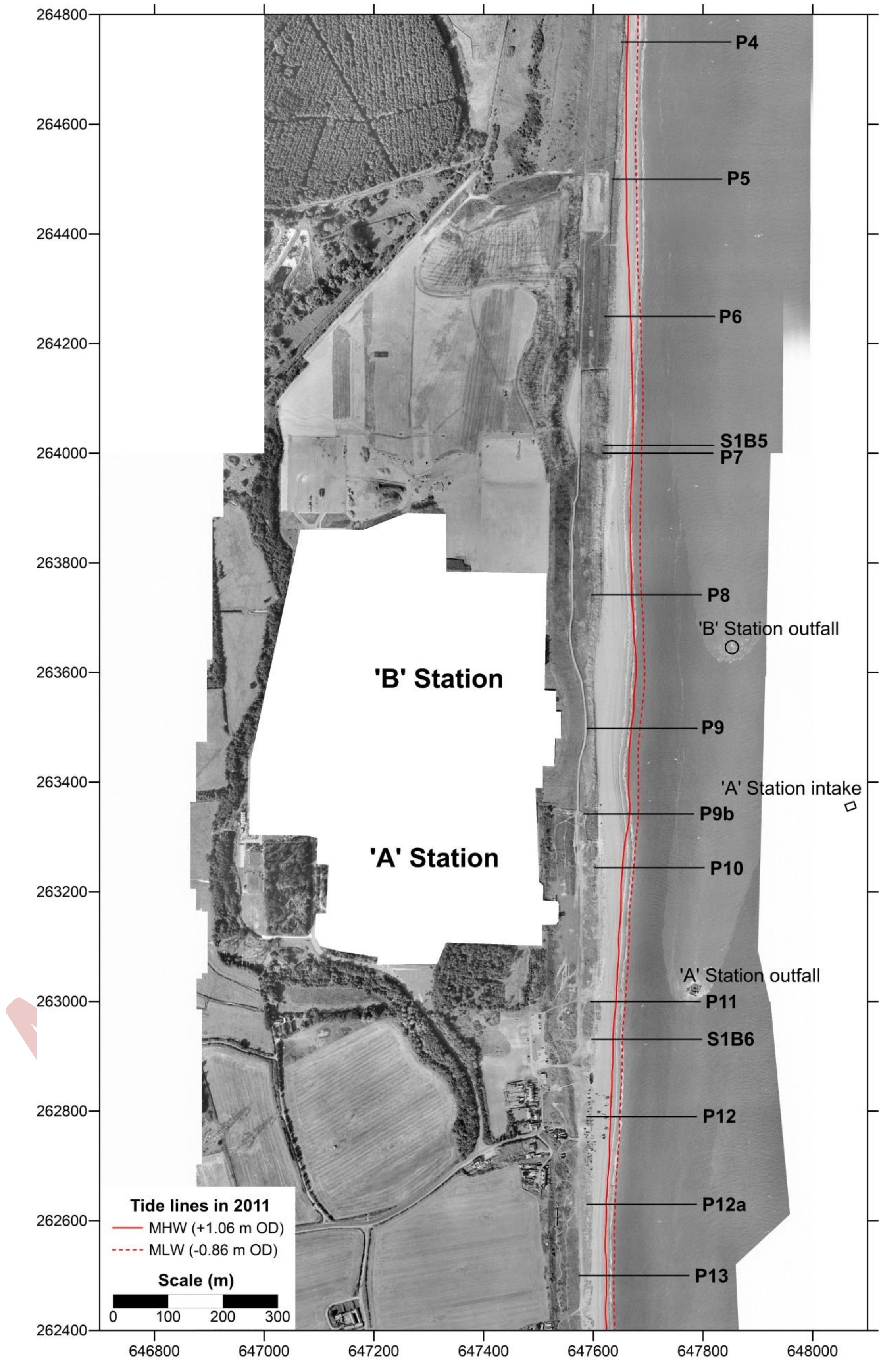

Figure 85: Aerial photography flown summer 1997.

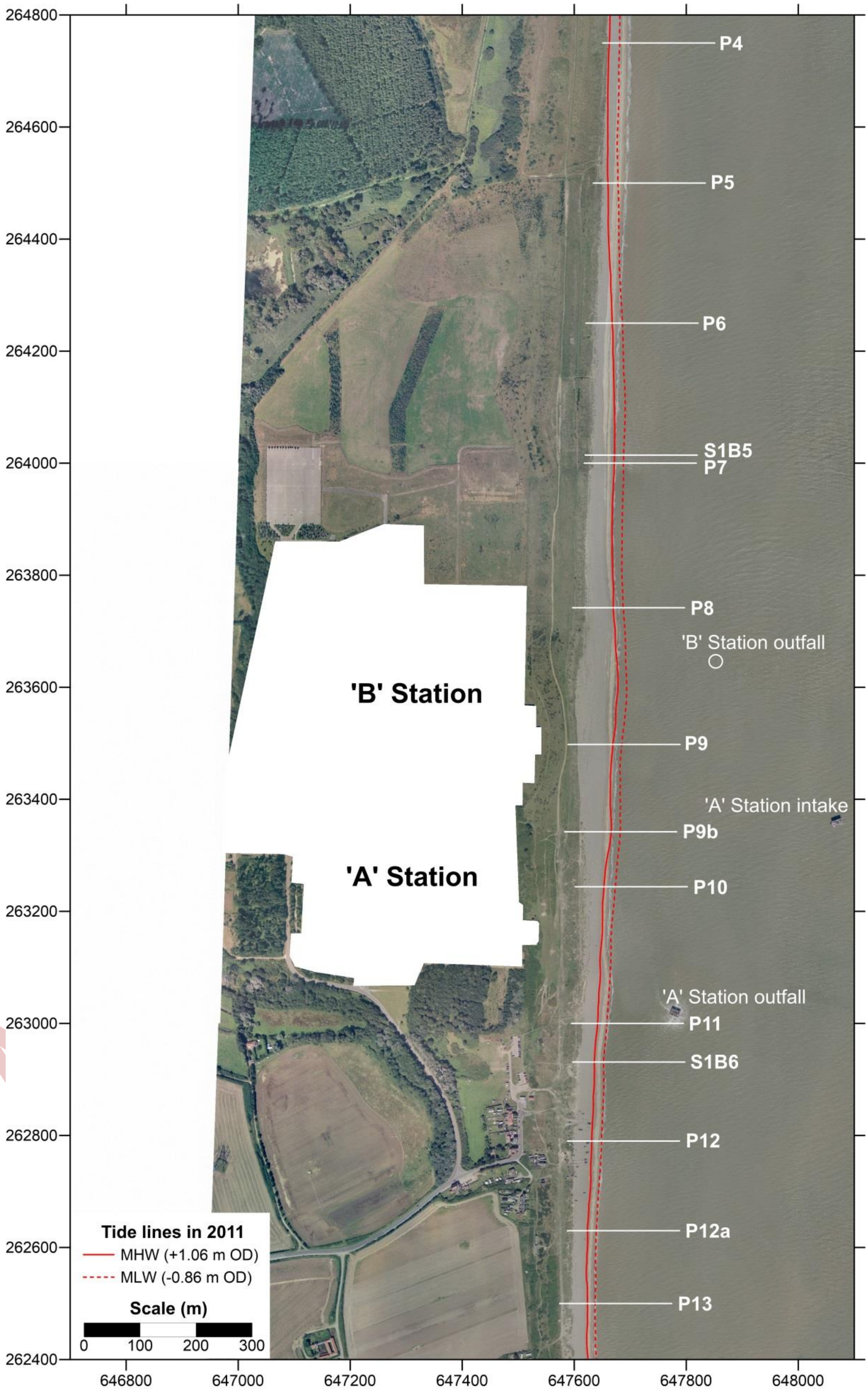

Figure 86: Aerial photography flown summer 2001.

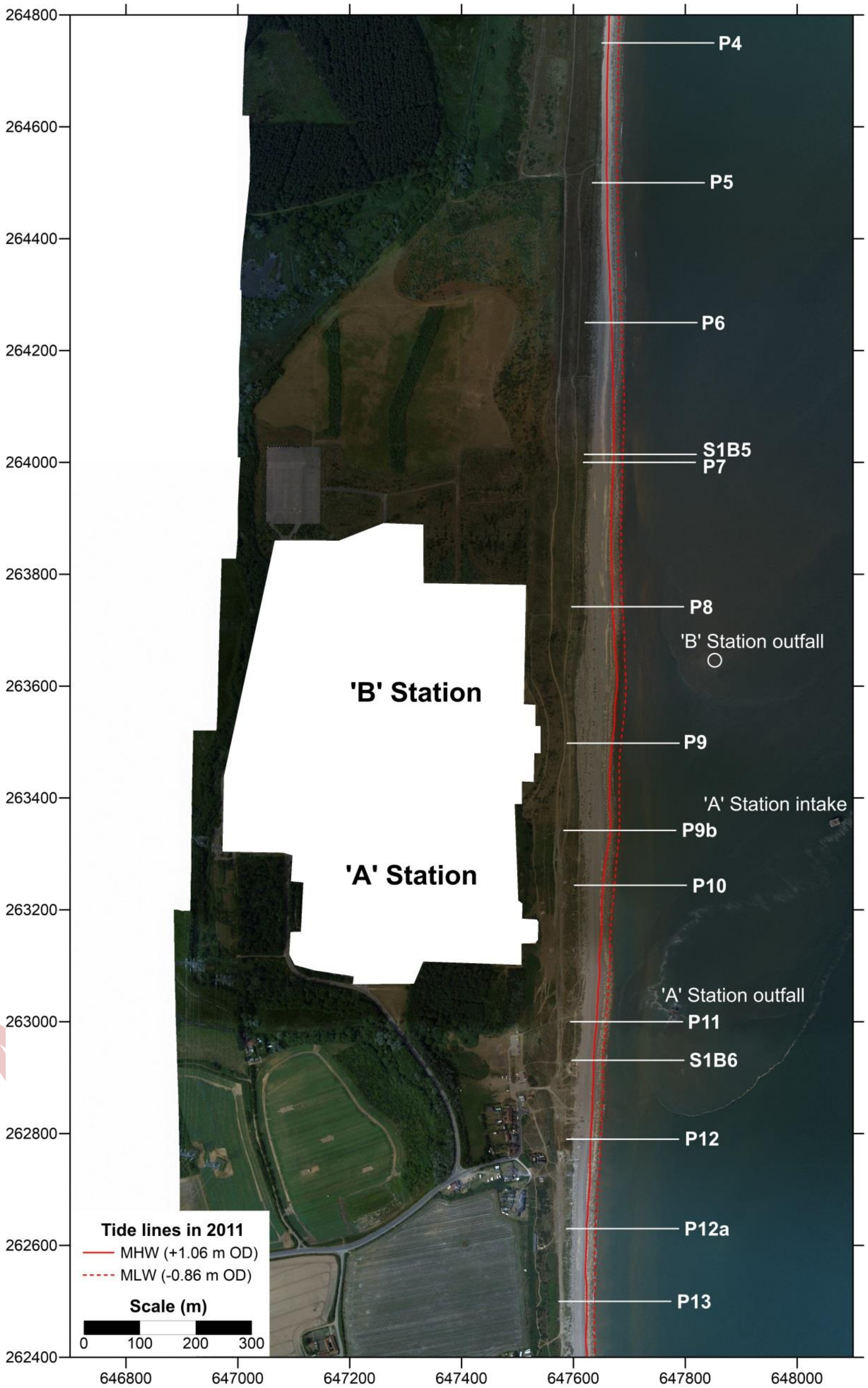

Figure 87: Aerial photography flown summer 2005.

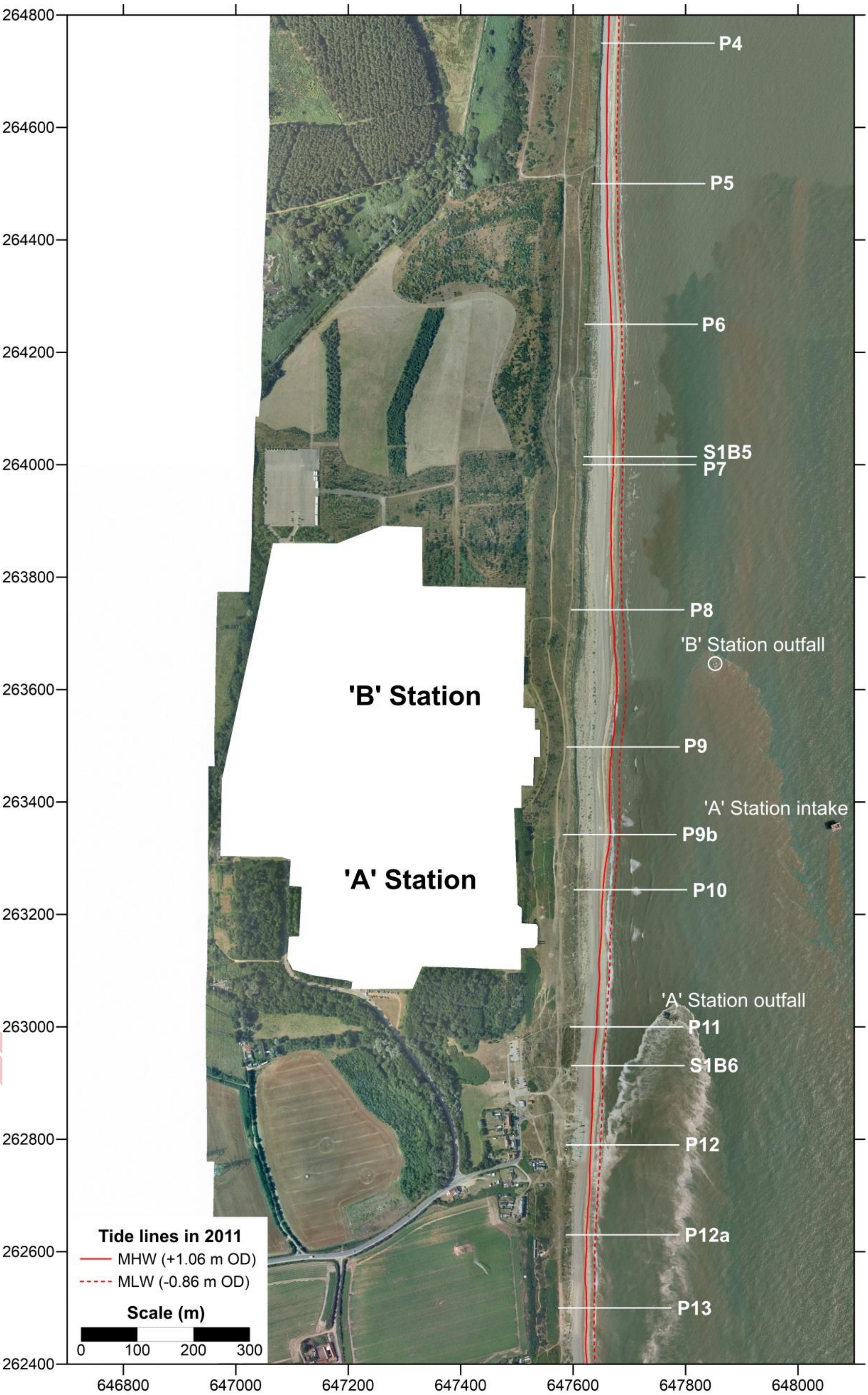

Figure 88: Aerial photography flown summer 2006.

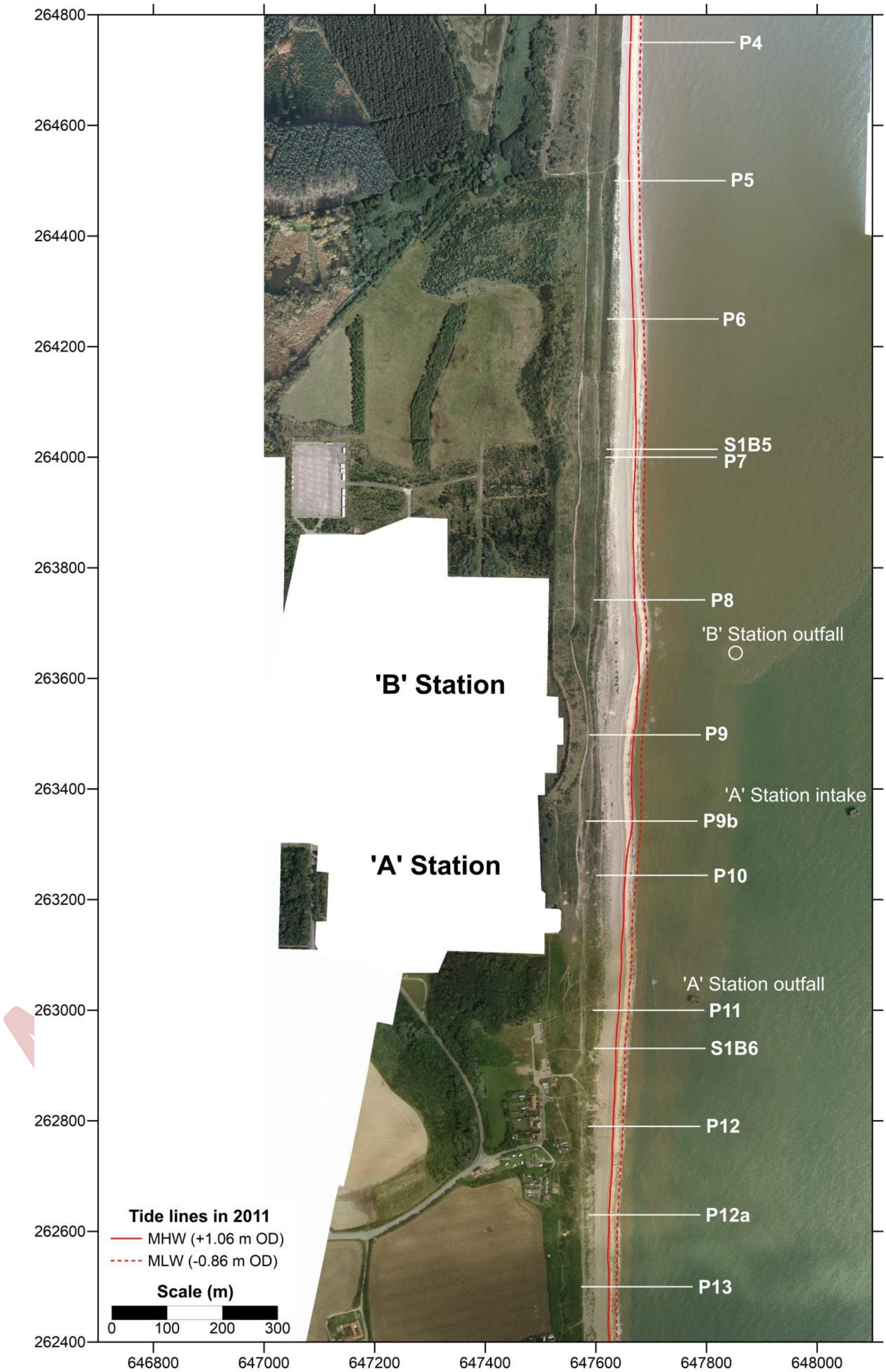

Figure 89: Aerial photography flown summer 2007.

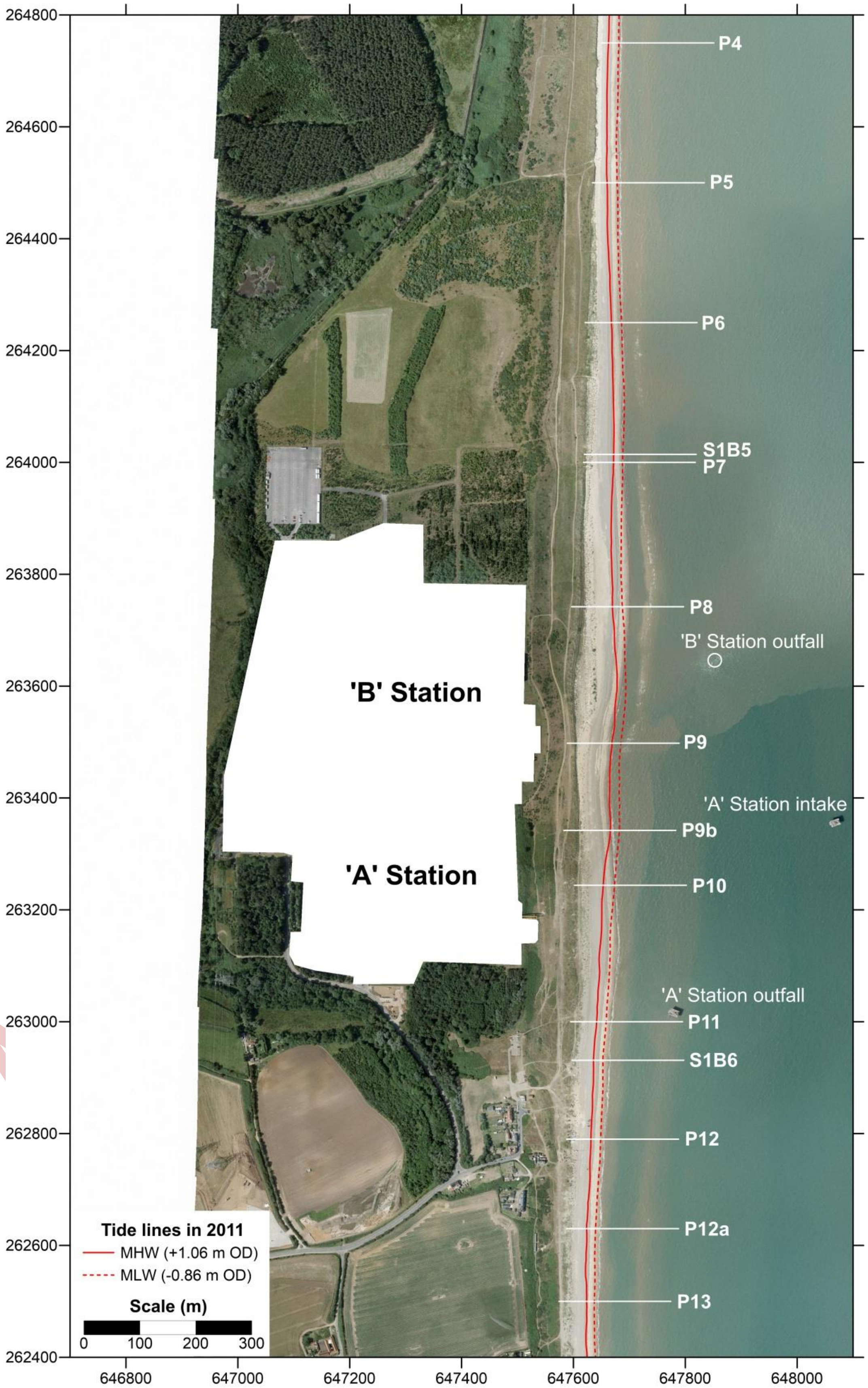

Figure 90: Aerial photography flown summer 2008.

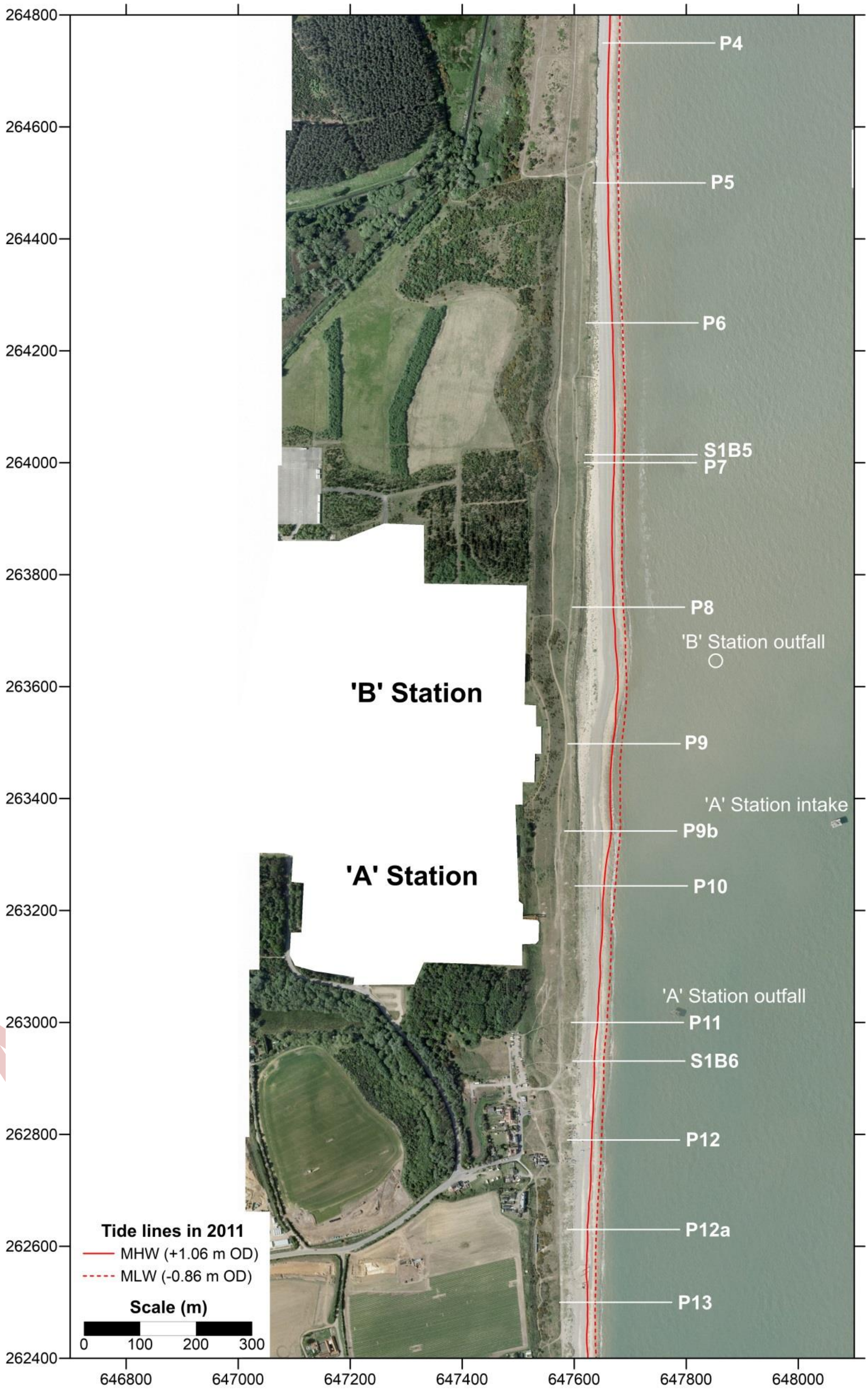

Figure 91: Aerial photography flown summer 2009.

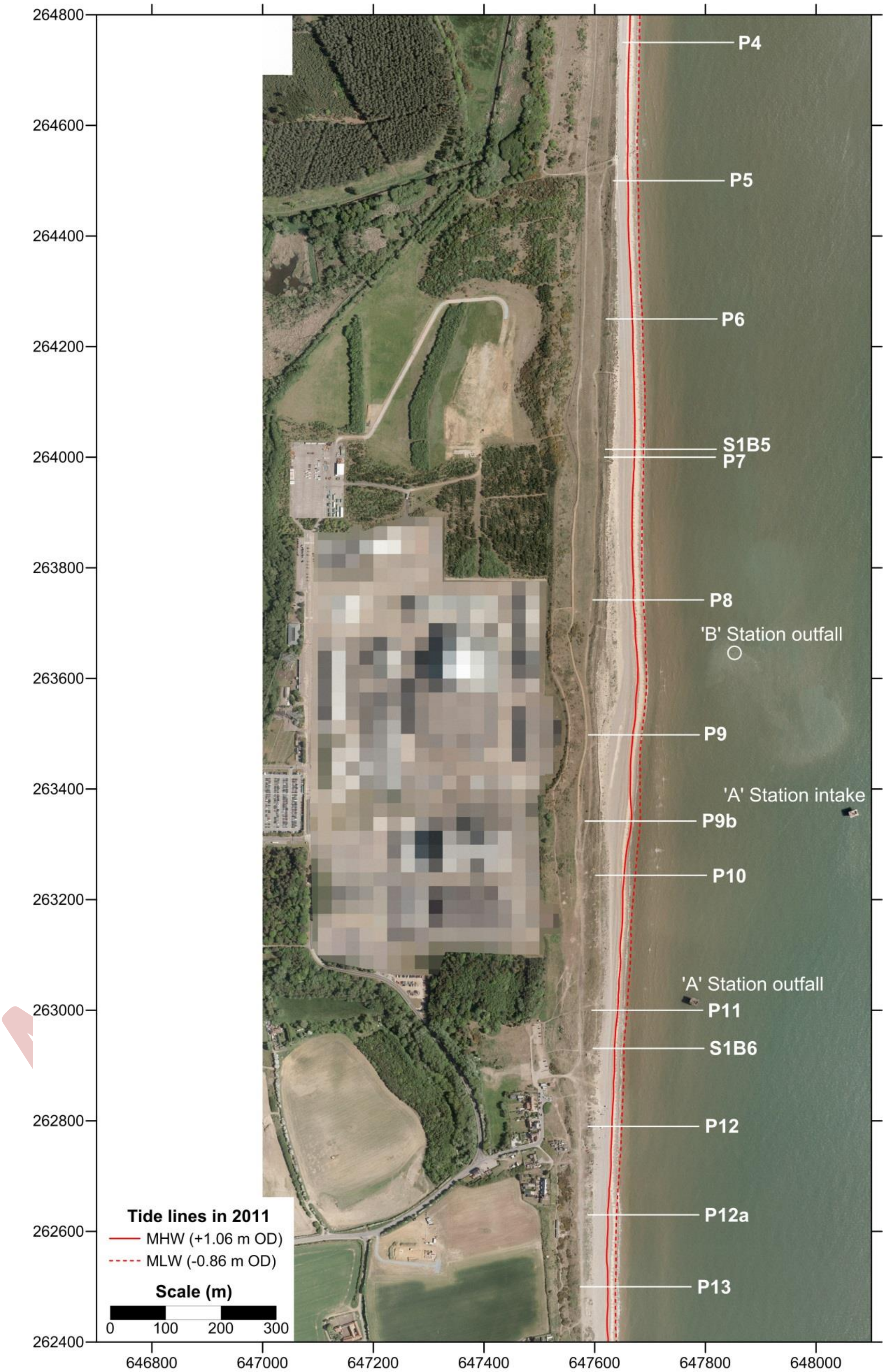

Figure 92: Aerial photography flown summer 2010.

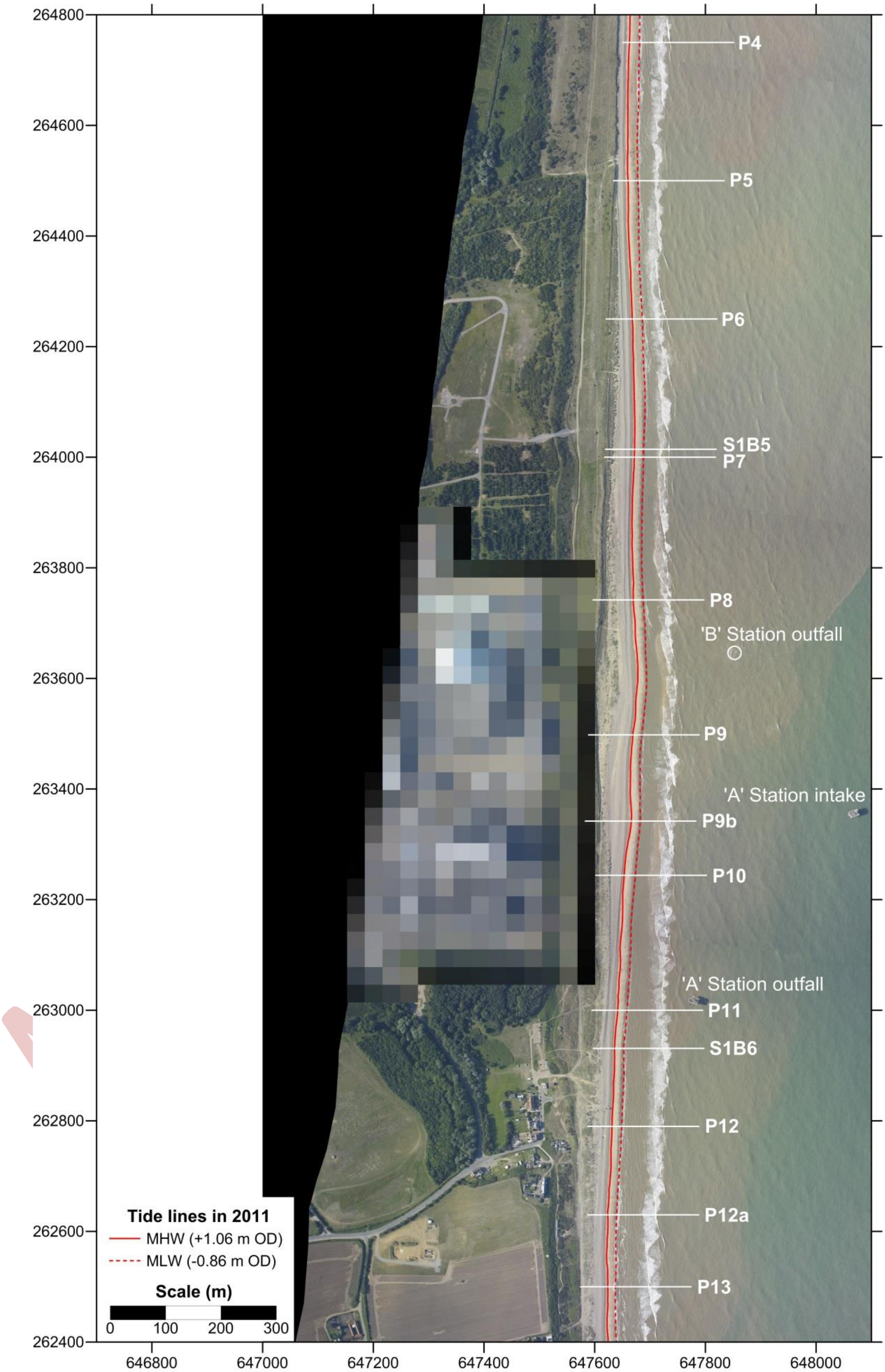

Figure 93: Aerial photography flown summer 2011.

Appendix B Longshore bar and terrestrial topography

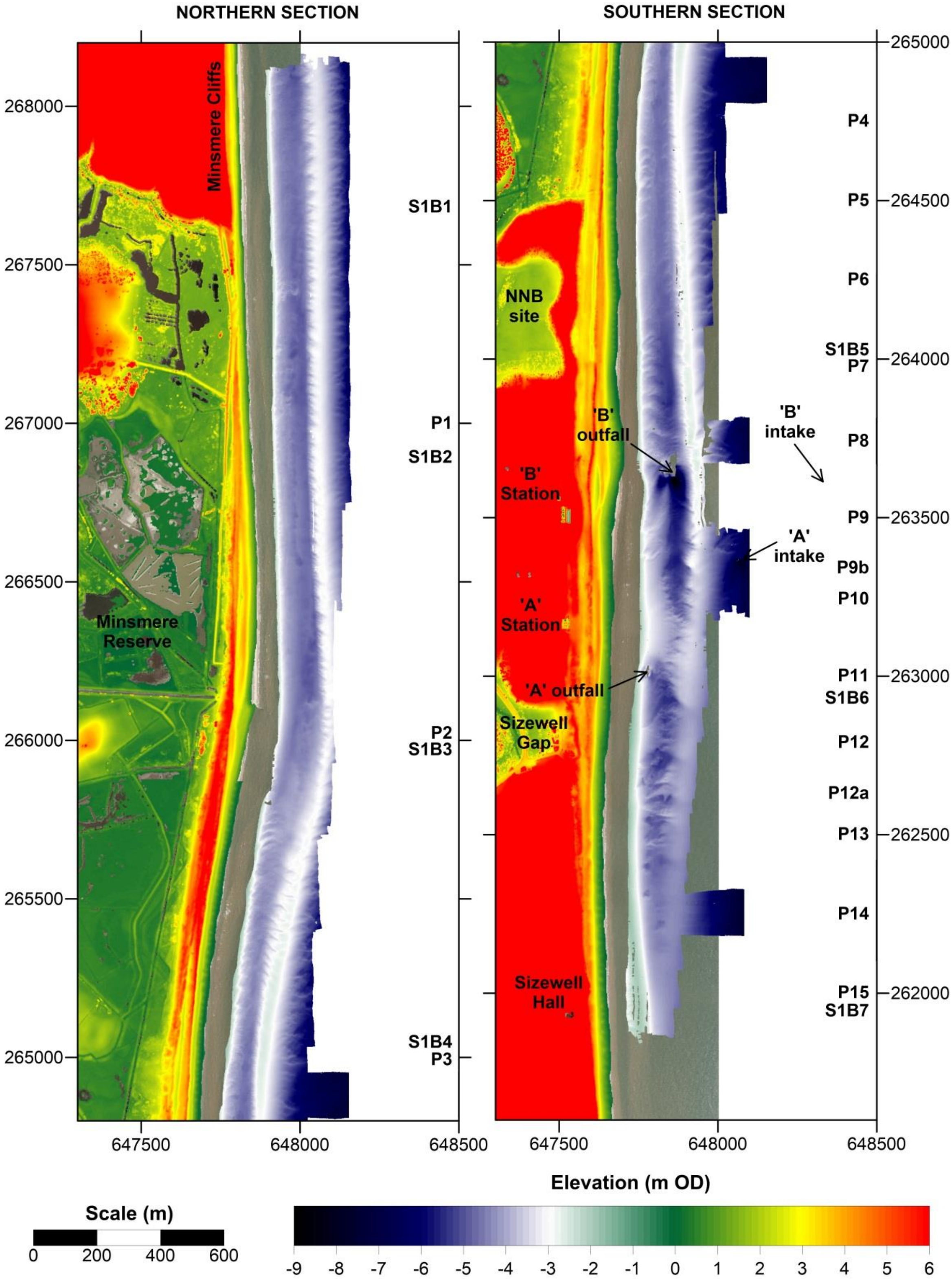

Figure 94: Composite DEM of the Minsmere Cliffs to Sizewell Hall frontage based on June 2008 LiDAR and April 2011 swath bathymetry.