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A new perspective on meso-scale shoreline dynamics through data-driven analysis

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ABSTRACT

The twin ambits of climate change and coastal development have raised public awareness of shoreline management. Simultaneously, they have highlighted a gap in our understanding of sediment transport and morphodynamic processes at time and space scales appropriate for shoreline management purposes. Here, we analyse an exceptional set of beach surveys gathered over a period of twenty-two years along the Suffolk coast, eastern UK, that extends over approximately 80 km to investigate the meso-scale shoreline variations. The surveys have been made biannually along fixed transects spaced at approximately 1 km intervals as part of a strategic monitoring exercise undertaken by the coastal authorities to assist in shoreline management planning. Changes in beach volume, foreshore slope and shoreline position have been computed to investigate both spatial and temporal changes. The analysis reveals some distinct responses to the physical processes of tides and waves, anthropogenic interventions and geological controls. Neither a clear relationship between the presence of sea defences and beach response nor an ordered regional-scale shoreline movement are evident. Temporal variations in beach volumes and position provide a similarly complex picture with recessionary, accretionary and stable behaviour all apparent within the study site. There is evidence of quasi-cyclic behaviour at some locations as well as a reduction in variability over time-scales beyond approximately five years.

1. Introduction

Our shorelines are an inherently dynamic place where waves and tides provide the driving mechanism to move sediment, changing the shape of the surface of the nearshore and foreshore. Tides are driven by gravitational forces and are essentially deterministic, being predictable to a good degree from Newtonian equations of motion. Surges and waves, on the other hand, are driven by turbulent atmospheric conditions and have a much more intermittent behaviour, behaving for practical purposes as random events. The shoreline that faces these physical processes has a natural variation in geological composition, morphology and exposure that encompasses a range of spatial scales from individual sand grains to countries and continents. The time scales of variation associated with tides and waves exhibit a similarly large range from the period of an individual wave to intervals over which climate change is discernible and beyond. It is therefore not surprising that shorelines exhibit a multitude of scales of response. For clarity in the following, we define four scales of change: Micro; Synoptic; Meso and Macro. These correspond respectively and approximately to: sand ripples to small coastal schemes; individual coastal schemes; shoreline management planning; and continental and geological changes. These scales map quite neatly onto different categories of model that are available for predicting shoreline response to tides and waves, with some well-known exceptions detailed below. Fig. 1 encapsulates the relationship between the morphodynamic scales and the different types of models available. Thus, computational models that solve the detailed equations of motion are available to describe the hydro- and morpho-dynamics at the smallest scales. The use of these models at larger scales is limited by computational cost and lack of data to specify boundary conditions and for testing. At the very largest scales empirical models that describe the profile or plan-shape of the shoreline under equilibrium conditions are available (e.g. Silvester and Hsu, 1997; Moreno and Kraus, 1999; Bruun, 1962, 1983, 1989; Dean, 1977, 1991; Rosati et al., 2013). These have also been used at synoptic scale to design coast and flood protection schemes, (Fleming and Hamer, 2000). Between these two extremes there is a knowledge gap and a plethora of modelling approaches, (Hanson et al., 2003; Nicholls et al., 2015).

A consensus on the best approach or approaches has yet to emerge, and there remain unanswered questions regarding the consistency and validity of model projections when transferring from one scale to another. The models fall into two broad categories: data-driven modelling and reduced physics/reduced complexity/hybrid models. The former combines statistical analysis of observations to identify patterns of behaviour with an extrapolation algorithm as a means of projecting into

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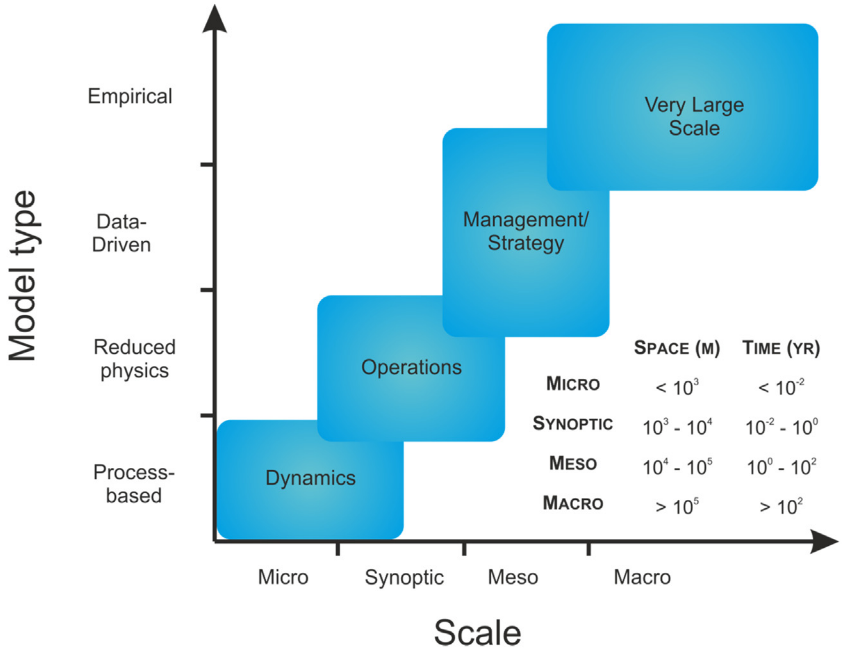


Fig. 1. Model types relating to morphodynamic scales.
(After Cowell and Thom, 1994).

the future. Winant et al. (1975), Larson et al. (2000), Różyński (2003) and Reeve et al., (2016) provide examples of purely statistical analysis of coastal observations while Reeve et al. (2008), Horrillo-Caraballo and Reeve (2010) and Alvarez and Pan (2016) explore different means of extrapolation. The latter type of model is epitomised by a range of approaches such as: simplifying the equations of motion by ignoring certain processes, for example, the 1-line model and recent variants (Pelnard-Considère, 1956; Hanson and Kraus, 1989; Ashton et al., 2001; Hurst et al., 2015); assuming a particular form of governing equation for the morphology (Stive et al., 1991; Stive and De Vriend, 1995; Karunarathna et al., 2008, 2009; Davidson et al., 2010; Reeve and Karunarathna, 2011; Pender and Karunarathna, 2013; Splinter et al., 2014); mapping expert opinion onto a logical framework that guarantees mathematical consistency (Karunarathna and Reeve, 2008; Reeve and Karunarathna, 2009); sediment budget and tracking 'reservoir' procedures (Stive et al., 1998; Kraus, 2000; Cowell et al., 2003; Van Maanen et al., 2016; Kinsela et al., 2017). The ad hoc nature of many reduced physics or reduced complexity models and the site-specific nature of data-driven methods means that there is less generality and confidence placed in the results obtained from them than from process-based and equilibrium models.

There remains a gap in our predictive abilities and capabilities at the larger synoptic and meso-scales, synonymous with coastal planning and management. This deficiency is critical because reliable forecasts of shoreline evolution are a necessity for shoreline management and crucial for designing coastal defences. Notwithstanding this gap in modelling ability, the introduction of national and regional coastal or shoreline planning frameworks has helped incubate a more integrated approach to shoreline management (Cooper and Hutchinson, 2002; Pontee, 2005; Pontee and Parsons, 2012). In the UK shoreline management plans have been in place for over twenty years. A key part of these plans has been to identify missing data needs; which has led to the implementation of long-term coastal monitoring (DEFRA, 2002; SCOPAC, 2004; Royal Haskoning, 2009).

Here, we focus on an unprecedented set of beach profile measurements gathered along the Suffolk coast over a period of 22 years (1991–2013). This section of shoreline has been closely managed and much of it is not 'natural' and free to evolve in response to the physical forces of tides and waves. Numerous structures and controls on sediment movement constrain both the movement of the shoreline and the release of sediments. In response to sea-level rise a natural shoreline would recede, freeing sediments that were once in the hinterland. Doody (2004) has argued that where defences are in place that prevent this natural recession the beach will narrow, leading to the phenomenon of 'coastal squeeze'. Also evident may be beach lowering, whereby the beach profile translates downward due to the loss of sediment, and beach steepening, where material from the lower beach is preferentially removed (Morris, 2012). Some evidence of this occurring at a macroscale along the eastern coast of the UK has been presented by Townend et al. (1990) and at a national level by Taylor et al. (2004). A detailed evaluation of the meso-scale coastal response in this region has yet to be reported, although there is a substantial literature on meso-scale coastal barrier behaviour at other sites (Cooper, 2013; Clarke et al., 2014; Cooper et al., 2018). In this paper a new perspective on the mesoscale shoreline evolution of the Suffolk coast is presented. We do this through a combination of statistical analyses and foreshore classification. The main objectives are: to examine the evidence for coastal squeeze, beach lowering and beach steepening and their potential links with hard defences; to investigate whether the temporal and spatial changes in the beach profiles are consistent with previous macro-scale studies; to determine whether there is evidence of spatially or temporally coherent trends or cycles of beach evolution. The analysis is entirely data-driven and the analysis methods are general and transferable to other sites where extensive observations are available.

2. Study site

2.1. Geographic description

The Suffolk Coast is aligned approximately North-South and runs from Corton, just north of Lowestoft, to Landguard Point, near Felixstowe, with a total length of approximately 80 km, (see Fig. 2a, b), and is considered to be one of the more salubrious coastal areas in England. It contains historic coastal towns, coastal harbours and ports, natural coastline and several sites of international scientific interest. The main urban centres in the Suffolk area are Lowestoft and Felixstowe which have been protected against coastal erosion for many years by a wide variety of defences including sea walls, revetments, breakwaters, groynes as well as soft engineering options including beach recharge. The main industrial sites on the coast are the ports of Lowestoft and Felixstowe and the Sizewell nuclear power station complex. The county of Suffolk has a long record of coastal change; gradual erosion of the cliffs has been extensively documented and numerous villages have been lost to the sea over the centuries (EA, 2011a).

The sediments found on the Suffolk shoreline have come from very different sources and are of varied types (Royal Haskoning, 2009). The composition of the beaches along this coastline ranges from gravel, mixed sand-gravel and sand. The main sources of sediment are via littoral drift and the significant sections of the Suffolk shoreline comprising soft cliffs whose erosion provides an intermittent but continuing supply of sediment to the beaches (Brooks and Spencer, 2010), and the rate of cliff erosion is linked to the beach levels at the toe of the cliffs (Lee, 2008). Towards the southern part of the Suffolk Coast, a well-sorted fine to medium sand is predominant (Chillesford Sand of the Norwich Crag) while coarse grain shelly sand is found to the north of this area. Deposits of Baventian clay can be found on the Norwich Crag, north of Easton Woods and in Covehithe cliffs, (Profile S015). Coarser sand and gravel deposits were found in Westleton Beds (Hey, 1967; West, 1980). The sedimentary nature of the coastline means that it is highly erodible and susceptible to the effects of sediment transport driven by energetic waves and tides in the North Sea.

The configuration of the offshore bathymetry in the area of Suffolk is dominated by channels and sandbanks. Robinson (1966) remarked that the shape and alignment of these are a response to the residual tidal current in the area. Specifically, around Benacre, the movement of the ness northward can be explained by the ebb residual towards the coast feeding sediment to the area north of the ness which, itself, creates the ebb residual characteristics. It was argued by Zimmerman (1981) that concave shoreline features such as nesses would act to create a dipole of eddies in the tidal residual flow thereby creating a net offshore flow in front of the ness. Robinson (1980) suggested that the interaction of waves and tidal currents is a primary driver of sediment transport in the nearshore area which can lead to beach accretion and/or erosion. Due to their influence on tidal currents and wave propagation it was argued that the offshore sandbanks play an important role in the maintenance and development of the nesses; and that coarser sediments are moved onshore by the effect of waves and the finer ones offshore by the effect of tidal currents. HR Wallingford (2002) concluded from their "Southern North Sea Sediment Transport Study" that the offshore banks fed Benacre Ness and the amount of sediments supplied depended on the strength of the link with the bank system directly offshore of Benacre Ness.

2.2. Tides

The tidal regime in the area is predominantly meso-tidal, with tidal ranges in the north just falling into the micro-tidal category. Lowestoft has a spring tidal range of 1.9 m. The tidal range increases southward along the coastline to Felixstowe Pier which has a spring tidal range of 3.30 m (Royal Haskoning, 2009).

Tides in the North Sea are produced by the tidal wave propagating north from the southern Atlantic Ocean (Howarth, 1989). This tidal wave enters the North Sea around the north of Scotland and through the English Channel and it is modified by the configuration of the North Sea basin; generating a resultant tidal progression that circulates anticlockwise around an amphidromic point located approximately halfway between Lowestoft and the Dutch coast (Otto et al., 1990; Huthnance, 1991). As a consequence, the tidal wave moves down the Suffolk coast in a southerly direction, amplifying gradually as it progresses southwards; giving a tidal range of 1.9 m for a spring tide at Lowestoft, increasing towards the south at Thorpeness with a range of 2.4 m (UKHO, 2015). Tidal current residuals are produced by the non-linearity of the tidal current, usually due to significant variations in the sea bed depth and presence of coastlines (Robinson, 1981), and are considered to be indicative of potential long term tidal sediment transport trends. Further, Prandle (1997) argued that the tidal current, through the residual currents, affects vertical mixing, sedimentation, biology and thermal balance on the large scale. Early computational studies, such as the one by Nihoul and Ronday (1975), illustrated that the residual currents in the southern North Sea had a complex structure which was influenced by the shoreline geometry, sandbanks and other irregular seabed features. The subsequent improvement in modelling techniques and computational power has meant that much more detailed calculations are now possible.

Fig. 2 shows the tidal residual currents for the Suffolk area, computed with a depth-averaged model, (Horrillo-Caraballo, 2005). Simulations were carried out for a period corresponding to several spring-neap cycles and were validated against field measurements. The formation of eddies at headlands is clear although dipole patterns, as described by Zimmerman (1981), are not evident due to the asymmetries in the seabed. Offshore trends are evident at Orford Ness, Thorpeness, Walberswick and to a lesser extent Benacre.

2.3. Waves, sediment transport and morphodynamics

The wave climate in the southern North Sea is characterised by waves of low to moderate energy. According to Schans et al. (2001), significant wave heights near to the coast are usually less than 1 m and the predominant wave period about 4 s. Fig. 3 shows a wave rose constructed from 20 years of hindcast output from the UK Meteorological Office wave hindcast model for a point in front of the Suffolk coast, (52°16′9.48″N, 1°51′56.88″E), showing the bimodality of the wave directions and the NNE/S predominance in the Suffolk area. Given the highly oblique bimodal wave climate, it may be expected that longshore sediment transport is a significant driver of beach evolution along this coast. Nearshore wave characteristics along the Suffolk coast are significantly affected by the offshore sandbank system. The preferential attenuation of waves by individual banks can generate localised drift reversals, (Coughlan et al., 2007; Burningham and French, 2014). Furthermore, the natural interannual atmospheric variations in wind, and therefore waves, can be strong enough to create regional-scale drift reversals (Wang and Reeve, 2010).

An early study into the potential longshore sediment transport rates along the East Anglian coast by Vincent (1979) found considerable annual variability. The continuity of longshore transport is punctuated by several estuarine systems and nesses (Burningham and French, 2016). Details of these processes at the Blyth, Alde/Ore and Deben inlets have been presented by Burningham and French (2006, 2007). Beyond Felixstowe the sediment transport is interrupted by the deep channel between Harwich and Felixstowe. From Sizewell south to Felixstowe the littoral drift is predominantly southward. Royal Haskoning (2009) found the highest annual transport rates, 141,000m^3, around Orford Ness and Bawdsey. The large sediment transport rates result in unusual shingle features such as Orford Ness, which at approximately 16 km long, is one of the largest shingle spits in Europe. Elsewhere along the Suffolk coast the picture is less clear. In a small area north of Benacre Ness, longshore transport has found to be in the northward direction. The exact location where the transport direction changes from the north to south is not well-defined but is often taken to be around Benacre Ness. Benacre Ness is a large mobile sand and shingle beach extending over several kilometres along the shore, which is gradually migrating towards the north, at a rate of around 6 km over the last 200 years; a rate of nearly 30 m per year. This movement is against what is perceived to be a predominant net southerly drift, (May and Hansom, 2003; EA, 2010). Fig. 4 shows potential longshore sediment transport pathways determined qualitatively from wave conditions hindcast from wind records by Vincent (1979) and using a combination of computational models and data analysis by HR Wallingford (2002).

The sediment supply for Orford Ness has come from the eroding coastline to its north, which has diminished considerably by the turn of the millennium (HR Wallingford, 2002). EA (2007b) noted that the area of East Lane Bawdsey (Profile S063 in Fig. 2), is the central point of sediment transfer between Orford Ness, Shingle Street (Profiles

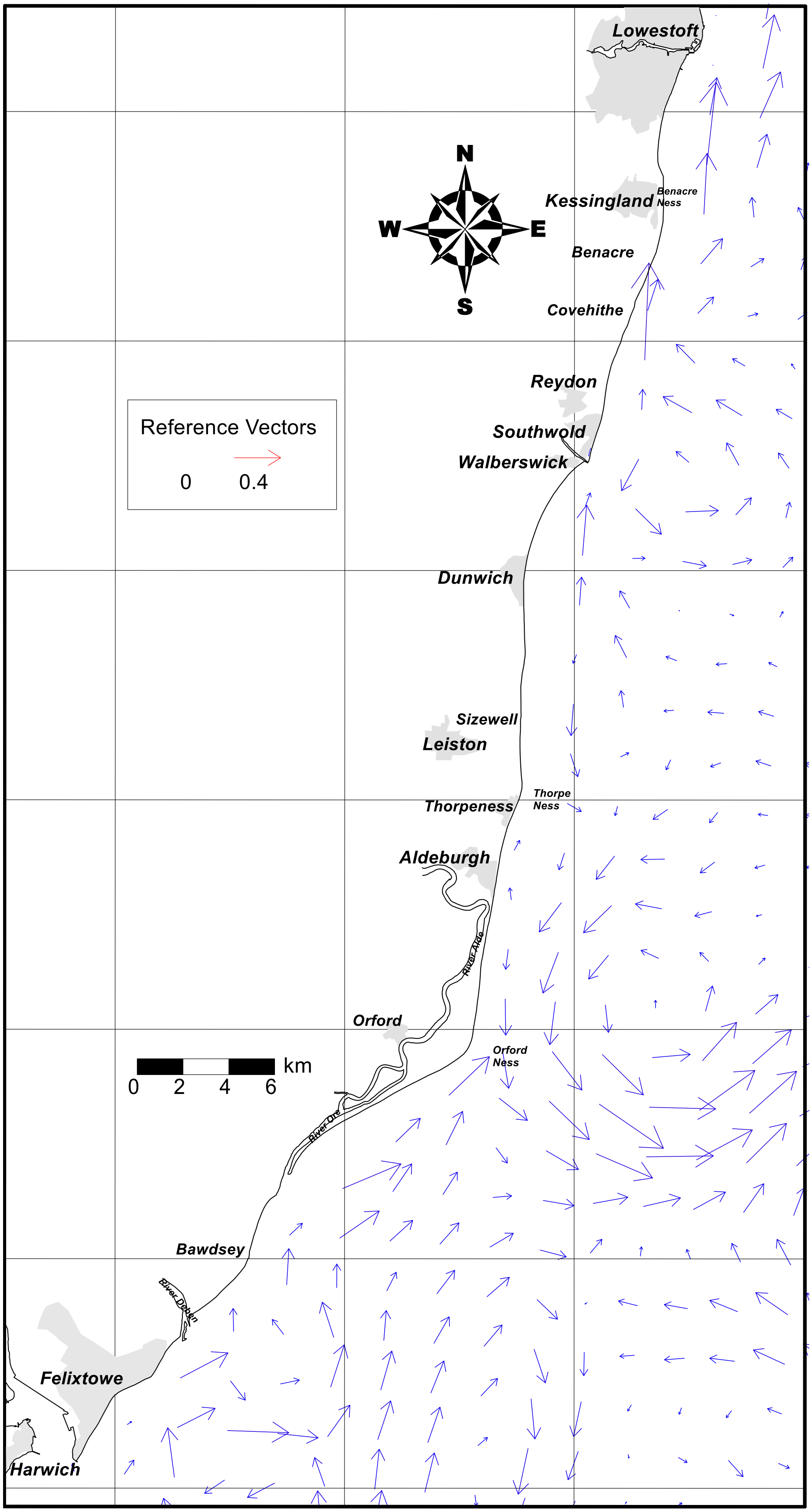


Fig. 2. Computed residual tidal currents, (m/s), around Suffolk.
(Adapted from Horrillo-Caraballo, 2005).

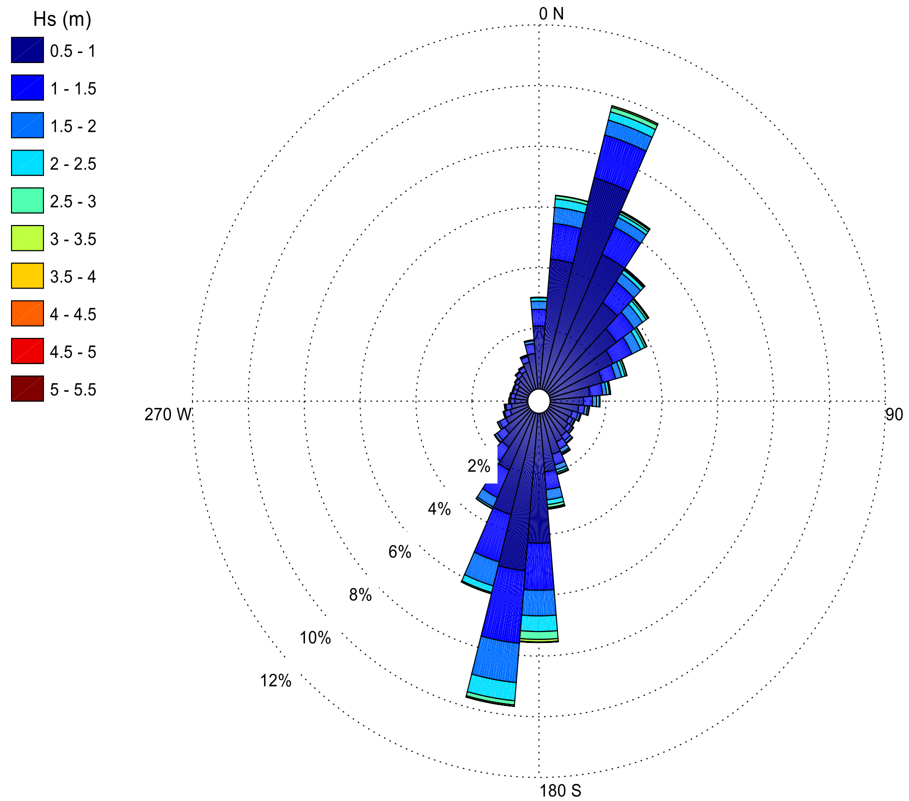


Fig. 3. Wave rose for a location offshore of Dunwich at 22 m water depth.
(Adapted from Horrillo-Caraballo et al., 2017).

S059 and S060), and the Knolls (Profiles S066 and S067). Alongshore transport is affected by this hard point and its impact is exacerbated when the adjacent beaches are in an eroded state. East Lane acts as an anchor point for retaining sediment coming from the north. Orford Ness acts as a major sediment source in the area and the Knolls acts as a sediment sink and also as an anchor point. These areas were identified as being of extreme importance for the sustainability of this stretch of coastline by Royal Haskoning (2002). In a subsequent study Royal Haskoning (2010) postulated that the area close to Thorpeness experiences an erosive phase approximately once every 30 years, but generally the coastline remains stable. An analysis of aerial photographs by EA (2011b) demonstrated that an erosion event occurred before 2005 which exposed the gabions and eroded the beach to the north leaving the base of the nearby cliffs unprotected against the action of the sea. The gabions were exposed again during storms in 2010.

Lees (1980) and Lee (2008) both argued that the coastal morphology and storm action determined the magnitude of the sediment transport in the Dunwich area, while Sears et al. (2009) contended that the soft material in the Dunwich cliffs was a major source of beach material that was released to the shoreline through the combination of surface erosion, land sliding and seepage erosion.

The numerous tidal inlets and nearshore sandbanks along the coast the patterns of sediment transport with a rich complexity. Unpicking the contributions of tides and waves is made harder due to the directional bimodality of the wave climate which means the net littoral drift is the relatively small difference between much larger values of northward and southward longshore drift.

A broad pattern that emerges is that any long-term geomorphological trends evident in historical datasets may be punctuated by the intermittent effects of individual storms. This reinforces the importance of accessing records that span many seasons, from which any exceptional beach response to individual storms can be viewed within the context of longer term, larger scale changes.

2.4. Human intervention

The complexity of the Suffolk coastal system is a major challenge for local authorities responsible for managing the shoreline and development planning in the coastal zone. Reacting to the variations in beach levels local councils have performed several interventions (soft engineering works) on the coast, such as beach nourishment, sediment redistribution and recycling practices (Pontee, 2005; Pontee and Parsons, 2012). For example, in response to repeated storm events, the shingle ridge between Dunwich and Walberswick is regularly re-profiled, using bulldozers, so as to protect the area of grazing marsh in the landward area of the ridge. Similarly, the beach and barrier system at Easton Broad has been re-profiled in order to protect the lagoon and the freshwater habitats behind the barrier. The large demand for sediment and the elevated price of nourishment material have led to the nourishment works being suspended. The management policy has been altered to 'do nothing' and the area has been left to react naturally to sea-level changes and coastal processes. Nevertheless, some recycling of sediments continues at Slaughden where the Orford Ness barrier is particularly vulnerable to breaching. This nourishment scheme has used sediment from the nearby beach at Sudbourne since 2002. Sediment has also been added to beaches further north where a long-term erosional trend is evident (EA, 2007a).

Coastal structures have been used in Suffolk to defend the coast from erosion; the two main urban areas in this part of the country have been protected against coastal erosion for many years, with the extension of the seawall and groynes. In October 2008 a scheme was completed south of Felixstowe consisting of T-shaped rock groynes and beach recharge (EA, 2011a). The Central Felixstowe scheme involved the construction of 18 groynes, a rock revetment, concrete works to the promenade and a beach recharge in order to safeguard approximately 1500 homes in the town. This scheme was finished in June 2012. Coastal

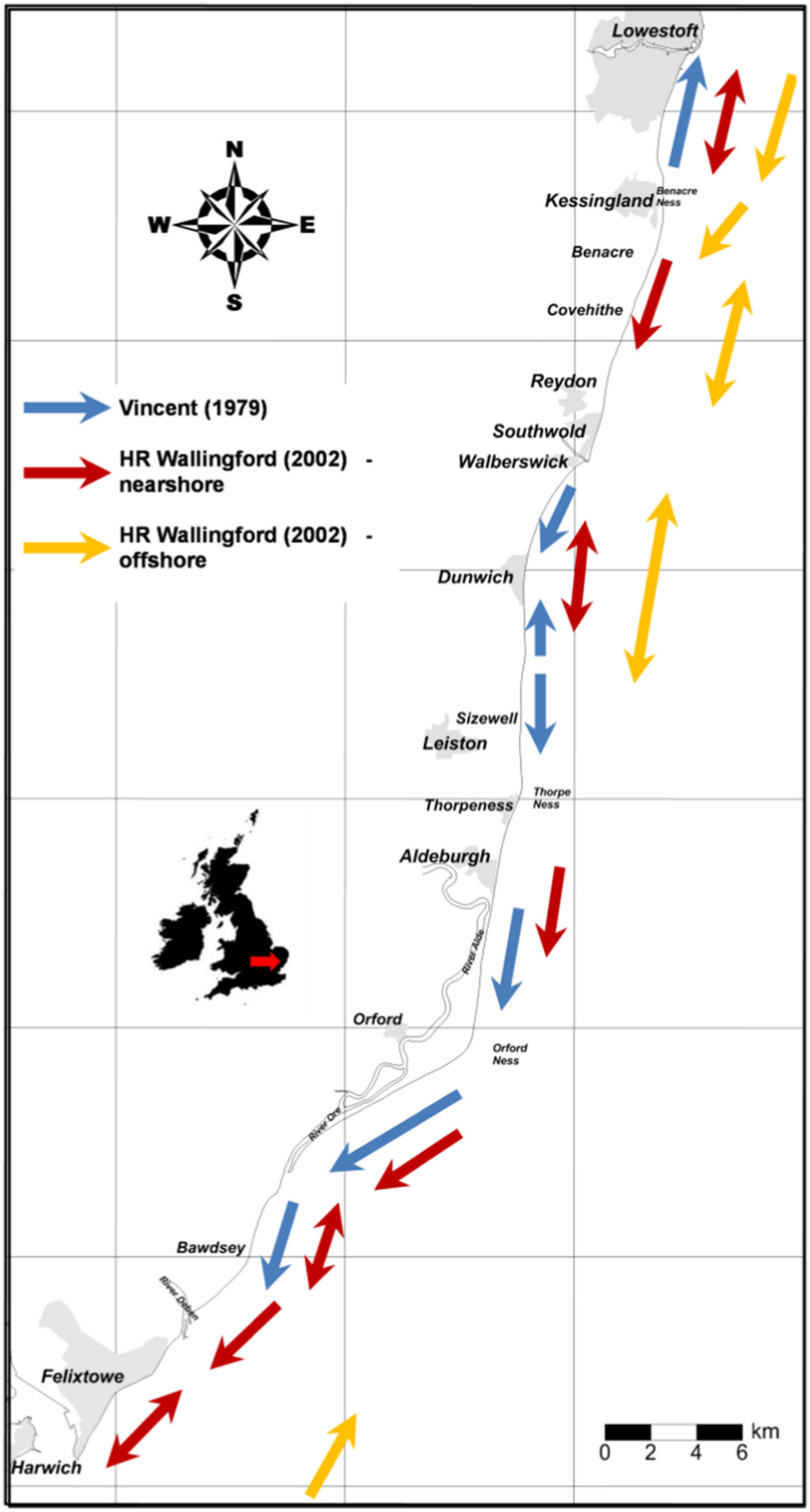


Fig. 4. Potential littoral transport as estimated by Vincent (1979) and schematic sediment transport pathways, HR Wallingford (2002).

defences have also been updated in small towns and villages (such as Southwold and Aldeburgh) in the Suffolk area, which have a long standing tradition for coastal defences. For example, at Southwold, during 2006 new rock groynes were built, beach recharge implemented and other structures were updated (VolkerStevin, 2018).

In summary, the picture that emerges is of a shoreline comprising varied sedimentary rock types and multiple beach forms. Cliff recession provides local intermittent sediment supply and estuaries bring new alluvial deposits onto the beach where they are reworked by waves and tides. The complexity of the sedimentary system and dynamics of the beach makes understanding the meso-scale morphodynamics of the Suffolk coast both difficult and challenging.

3. Survey data

The UK Environment Agency has been undertaking approximately biannual surveys of beach profiles along the Suffolk coast since the middle of 1991 to support shoreline management planning through long-term beach monitoring (SCDC and WDC, 2018). The records cover the period between August 1991 and July 2013; profiles are measured twice per year usually in winter and summer (averaging 44 surveys per profile). Changes in bed elevation have been measured along 74 fixed cross-shore profiles spaced approximately 1 km apart along the shore labelled from S001 in the north to S074 in the south as shown in Fig. 5. Beach profiles have been measured using conventional surveying techniques (e.g. triangulation, traversing, chain survey, etc.). More recently, surveys have been undertaken using electronic monitoring equipment (e.g. total station, Real Time Kinematic Global Positioning System - RTK GPS). Lee et al. (2013) demonstrated that the total station method can achieve an accuracy of the order of 2 mm over a distance of approximately 1 km. The expected accuracy of the RTK GPS system is approximately 30 mm in the vertical and horizontal, when a minimum of two receivers are used, one acting as a base station and the other as a mobile station, the former providing corrections and the latter dedicated to data collection (PCO, 2018). Profiles have been chosen in order to ensure that they are representative of the frontage area where the measurement is taken (Cooper et al., 2000), and are measured at fixed intervals along the beach in autumn and spring. The profiles extend along the inter-tidal zone and cover the backshore, the foreshore and sometimes the nearshore. For this analysis, only beach profile surveys that extended from the dune region to a water depth of the MLWL (Mean Low Water Level) were included.

A subgroup of measured profiles used in this study is shown in Fig. 6, which illustrates the range of behaviours typical of those observed along this stretch of shoreline. Measurements extend seaward to approximately the mean low water spring level (MLWS) which is not as far as the depth of closure; estimated as 6.3 m determined from the formula of Hallermeier (1981). Following the interpolation technique described by Li et al. (2005), the measured profiles were interpolated to a regular spacing of 0.5 m resolution. All elevations for the profiles are referenced to ODN (Ordnance Datum Newlyn).

The beach transects illustrate the complex behaviour of the profiles and shoreline around Suffolk coastal area and the ten profiles shown in Fig. 6 illustrate the range of beach behaviours encountered within the records.

4. Methodology

To gain insights into the shoreline evolution and quantify the longer term trends in the study area, the analysis methodology comprises three components:

1. Calculation of beach positions and volumes over time;
2. Classification of beach trends over the observation period; and
3. An investigation of the intra-survey shoreline movements.

The first is aimed at quantifying the movement of the shoreline over time and related changes in volume of beach material in the measured profile to uncover any long term trends in overall sediment availability. Beach volumes (volume per unit distance along the shoreline) were calculated from the 0 m chainage down to the mean low water level. The method used for calculating the volumes was the trapezoidal numerical integration function available in MATLAB. The second component maps a spatial picture of the meso-scale trends in beach movement. Further a classification system used in practice to capture both movements in the shoreline and changes in beach slope is presented. The latter is discussed in more detail below. The final component resolves the meso-scale trends into approximately bi-annual variations which provide an insight into the range of timescales at which the shoreline is evolving.

The classification scheme suggested by Townend and McLaren (1988) was implemented for this stretch of coast. The classification scheme, designed for assessing changes over the periods of decades, is called the 'Foreshore Change Classification System' in which changes in the slope of the beach between the MHWS and MLWS are classified into 13 possible categories. The Foreshore Change Parameter, (FCP), takes on positive/negative values if the beach profile moves seaward/landward respectively. Numerical values are assigned according to the type of change in beach slope. The numerical value of the FCP provides no indication of the rate of beach change, simply its sense (sign) and type (value).

Fig. 7 shows the FCP classification scheme; which is colour coded so that the colours purple to pale blue represent advancing profiles, the green colours represent no movement and the yellow to red colours represent retreating profiles. The sense and type of movement is determined from the changes in the position of the MHWS and MLWS line. This is illustrated in Fig. 8 which shows how the FCP is determined.

The measurements made by the Environment Agency have been collected using accepted techniques as described in Section 3. We have excluded Profiles S001 and S009 from the analysis as there were uncertainties about the quality of the recorded measurements for these locations; Profile S063 has also been excluded due to large gaps in the survey records.

5. Results and discussion

Results are discussed in a 'dimensional' order; that is first positional changes, then beach volume changes, (in m^3/m-run), and finally the coastal trends classification which relies on position and gradient changes.

5.1. Positional changes

The survey data is first analysed to present the mean variation of the shoreline positions of each profile over a period of 22 years (from Aug 1991 to July 2013) as described in Section 3, as well as the variance of the shoreline changes over this period. The shoreline change presents the shoreline movement (either retreat or advance) against a reference year, when the measurement of all profiles are available, which in this case is the survey taken in August 1992. Burningham and French (2016) note the highly varied nature of the Suffolk coastline dynamics and this variability is evident from the subset of profiles in Fig. 6 and more fully in Fig. 9, which shows changes of the shoreline for each of the profiles against the measurement from August 1992. As may be seen from Fig. 9, there are a few profiles accreting to a much greater degree than others (such as S003, S004, S046 and S060). The largest accretional changes occur at Profile S060 over the period between 2000 and 2006 with the shoreline moving approximately 80 m seaward. The tendency then stays stable and becomes marginally erosional from 2008 to the end of 2012. These changes have occurred as a result of the movement of sediment from the mouth of river Ore through this profile during the years of accretion (Carr, 1986). In contrast, the area near Profile S013 has experienced some of the largest erosion along this coast since 1993; the shoreline receding by approximately 110 m. Profile S008 shows a severe erosion trend from 1991 to 2005 followed

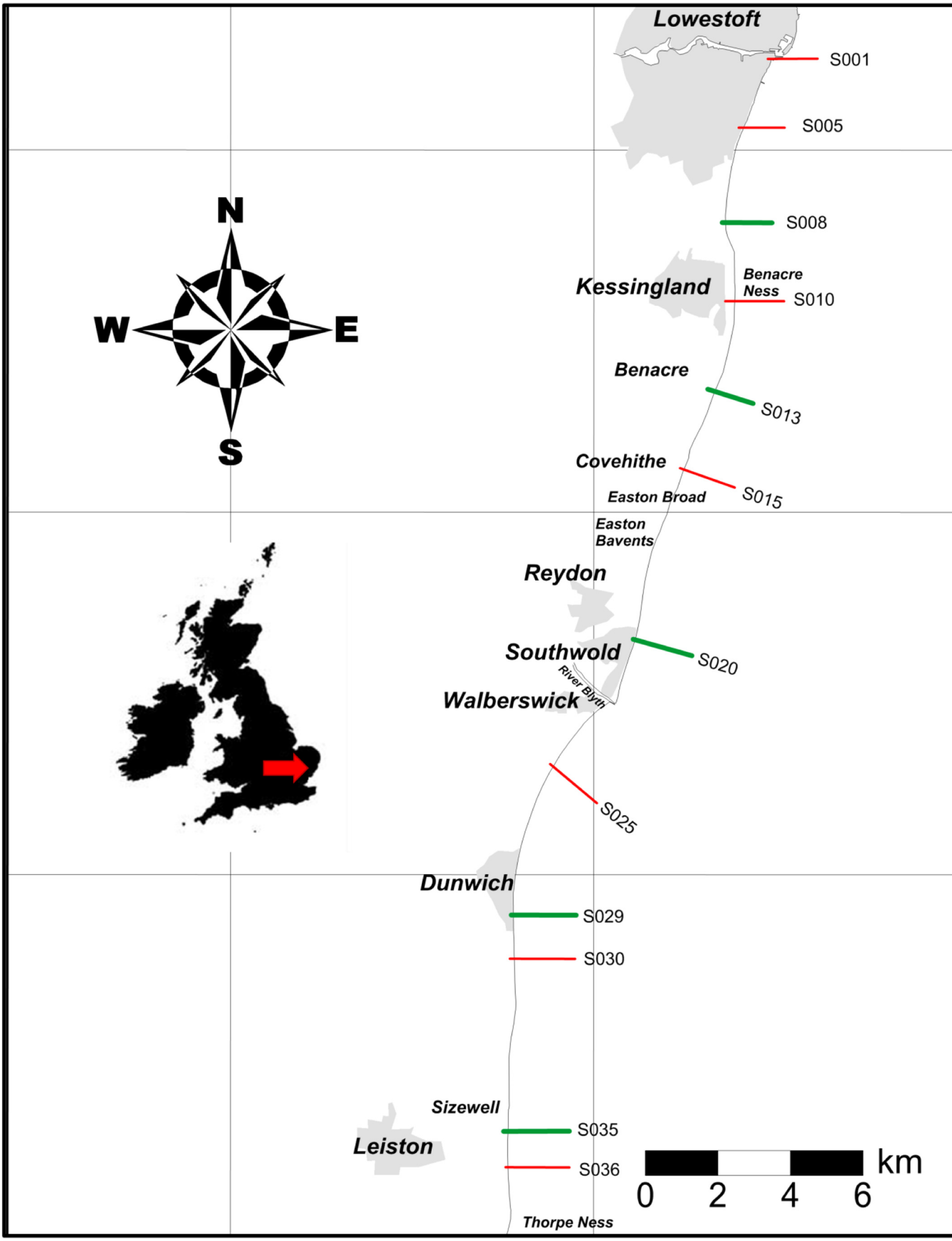


Fig. 5. a. Suffolk frontage profile locations (north). In green, profiles included in the study. b. Suffolk frontage profile locations (south). In green, profiles included in the study.

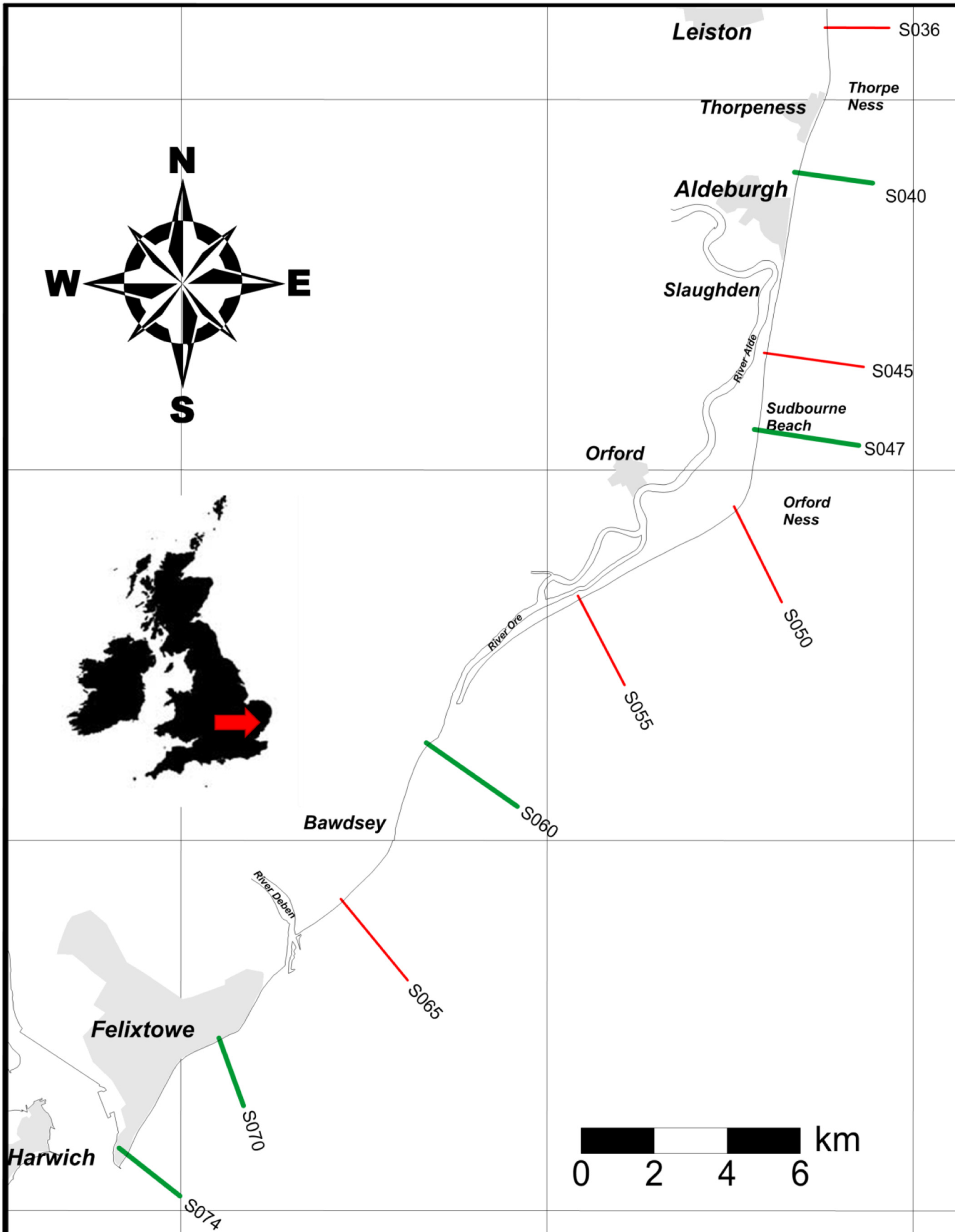


Fig. 5 (*continued*).

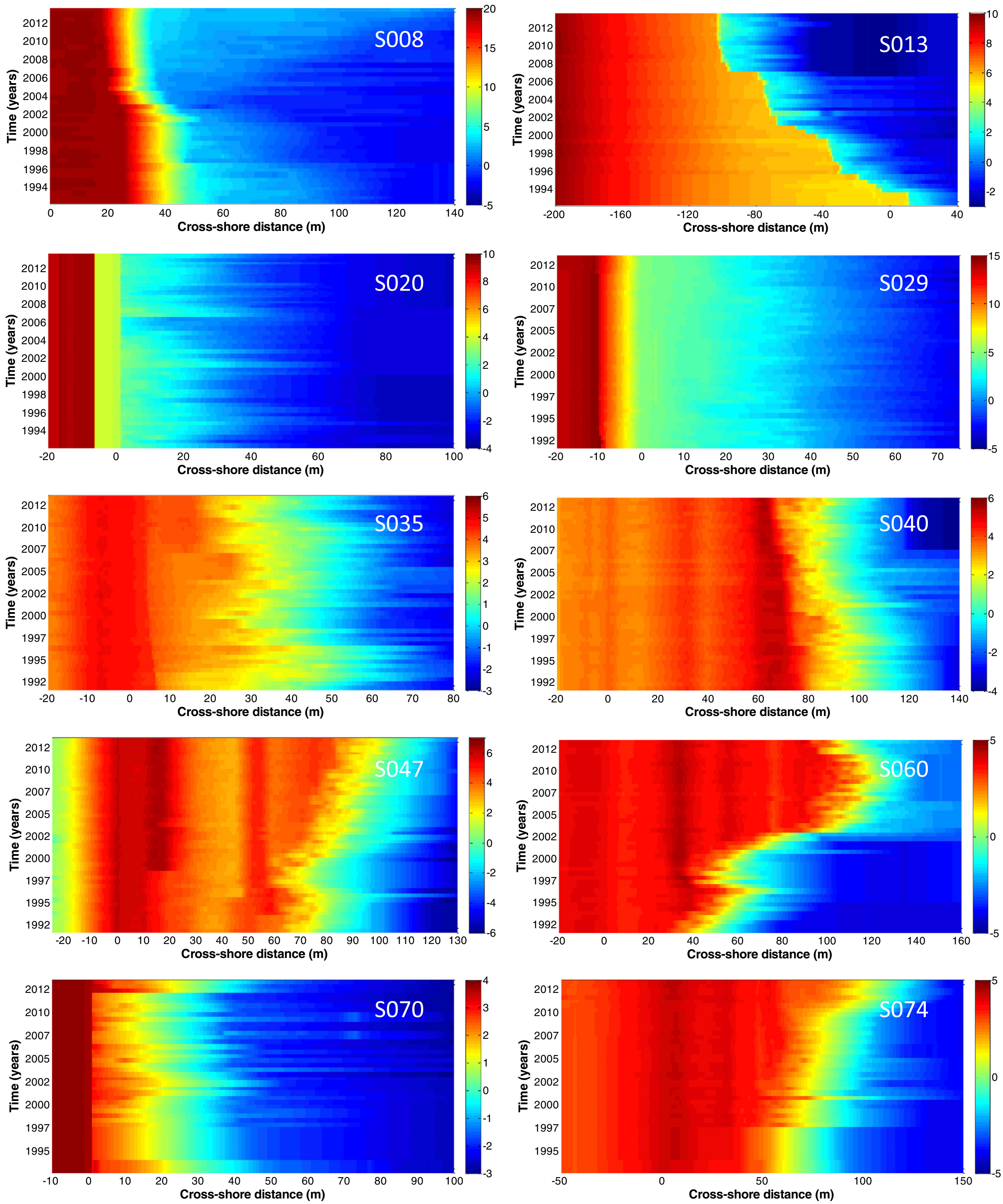
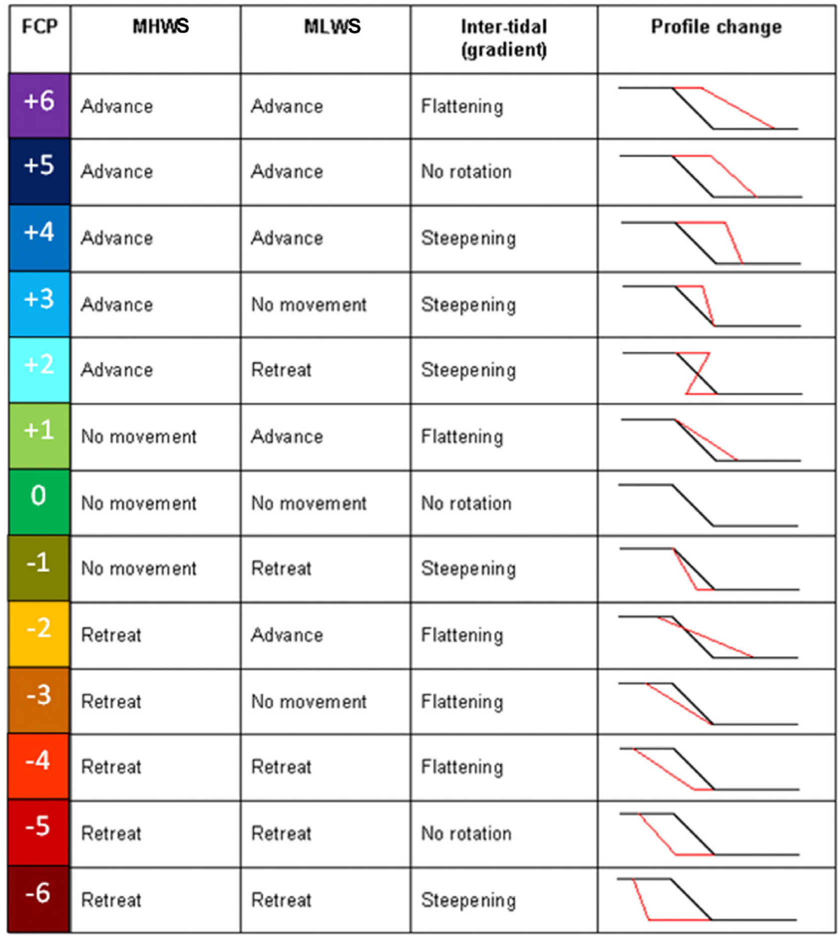


Fig. 6. Time stack of measured beach elevations for selected profiles. Note that axis and contour scales vary from profile to profile.

then by a period of strong accretion until summer 2013. The accretion of the beach in this profile is mostly due to the northerly migration of Benacre Ness increasing the size of the beach face (EA, 2011a). The area to the south of Benacre Ness, where Profile S013 is located, presents a typical beach profile backed by an eroding cliff. The recession of the cliff face is approximately 120 m over the survey period, i.e. average rate of ~6 m/yr, and is the fastest erosional trend along the Suffolk (EA, 2011a). The recent accretion at S008 and sustained erosion at



FCP	MHWS	MLWS	Inter-tidal (gradient)	Profile change
+6	Advance	Advance	Flattening	
+5	Advance	Advance	No rotation	
+4	Advance	Advance	Steepening	
+3	Advance	No movement	Steepening	
+2	Advance	Retreat	Steepening	
+1	No movement	Advance	Flattening	
0	No movement	No movement	No rotation	
-1	No movement	Retreat	Steepening	
-2	Retreat	Advance	Flattening	
-3	Retreat	No movement	Flattening	
-4	Retreat	Retreat	Flattening	
-5	Retreat	Retreat	No rotation	
-6	Retreat	Retreat	Steepening	

Fig. 7. Foreshore change classification system (adapted from EA, 2011a). Schematic profile changes are shown in red. The zones above high water and below low water are shown as flat in the 'profile change' column as information from these zones is not used in the classification.

S013 has coincided with the northward movement of Benacre Ness and may be interpreted as the consequence of the Ness continuing to move further north along the coast.

Profile S020, shows a high variability of beach levels with no significant trend, showing a 'dynamically stable' profile which exhibits large fluctuations (~±100%) about a mean of ~50 m^2/m. Erosional episodes

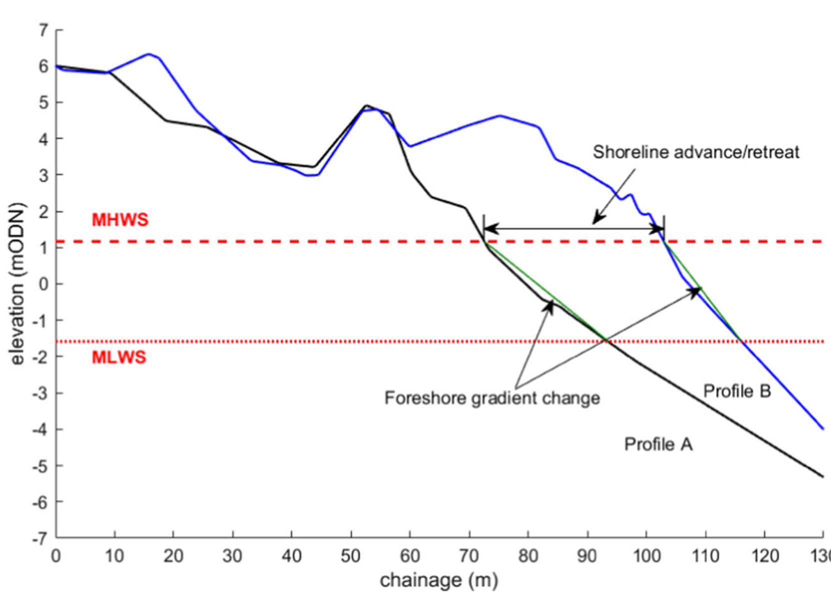


Fig. 8. Sketch of a beach profile showing shoreline advance/retreat between Profile A and Profile B.

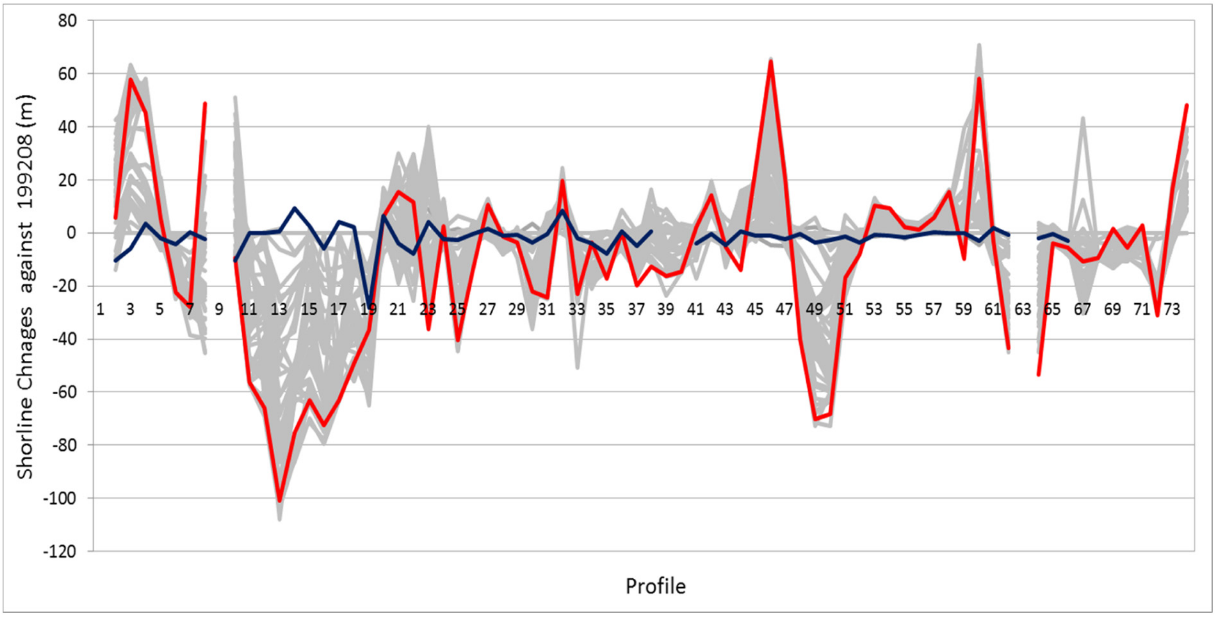


Fig. 9. Shoreline changes against the survey measurement of August 1992. First shoreline change data (corresponding to August 1991) in blue and last shoreline change data (July 2013) in red; the rest in grey.

at Profile S020 have a moderate positive correlation with the winter seasonal storm waves determined from hindcast wave data from the UK Meteorological Office wave for a location near Profile S020. Profile S029 exhibits a similar behaviour but with much smaller fluctuations of ±15% about the mean. The most noticeable changes in bed elevations are in the middle and lower sections of the beach. The envelope of beach levels across the profile is very consistent and has a range of about 1 m. The difference in the magnitude of beach level variations is attributed to the presence of Dunwich/Sizewell bank near S029 which provides some shelter to the shore from incident waves.

Profile S035 shows an accretional trend during 1991 to summer 1996; from winter 1996 to summer 2000 there is an erosional trend; then an accretion is observed between winter 2001 and winter 2003 with a stable trend from summer 2003 to winter 2009, after which there is erosion with a partial recovery during 2012. For this profile a marginally erosional trend is observed in Fig. 9. Profile S040 displays a persistent erosional trend of ~1 m/year throughout the period with occasional small spikes of accretion in 2000/2001, 2005 and 2012/2013. Profile S047 exhibits a behaviour that is totally dissimilar to the other profiles. The backshore beach ridge area of the profile is fairly stable; it also shows an accretional trend of ~1.4 m/year, interrupted during the winter season 1995/1996.

Profile S060 shows a substantial depositional trend during the period of 1991 to 2013, the accretion rate is approximately ~3.6 m/yr. This profile is in the area called Shingle Street near to the mouth of River Ore, and which can feed sediments to profile S060 in particular, although the nearby profiles, S059 and S061, are eroding or retreating (see Table A1 - Appendix). EA (2011a) note that there is movement of sediment southwards from the Orford Ness tip bypassing the mouth of the River Ore. This sediment movement can supply sediment to the small ness at Shingle Street or connect with the sand bars that can be seen around the area at low water level. This profile shows the second highest deposition trend along the Suffolk coast, moving seawards almost 80 m since 1991. In general terms, Profile S070 presents no overall movement at all during the comparison period. It also displays a seasonal behaviour of erosion during winter and accretion in summer, with negligible net trend. Profile S070 shows no movement at MHWS and at MLW and no rotation. Profile S074 has an accretional trend (~2.3 m/year), in common with Profiles S047 and S060.

The variations in shoreline position over time along the whole of the Suffolk coast are summarised in Fig. 10. A set of shoreline position changes at each profile are computed by measuring, for each survey, the change relative to the position in the August 1991 survey. The mean, maximum and minimum change are extracted from the set of changes for each profile. Fig. 10 shows the location of the profiles along the Suffolk coast (left panel) and the average change of the shoreline for each profile represented by the red bars together with error bars represented by the maximum and minimum values of the shoreline changes (right panel), apart from Profiles S001, S009 and S063 which have been excluded from the analysis.

More than half of the profiles (57%) show an erosional/retreating trend over the 22-year period. It is clear from Fig. 10 that the most noticeable tendency of erosion was observed along the cliffs located between Profiles S011 and S019; south of Kessingland and north of Southwold. Burningham and French (2016) surmise that in this region there is little or no supply of sediment from the North due to the sediment being held in Benacre Ness. As sediment moves south there is an imbalance in sediment demand that cannot be satisfied by material made available by the erosion of the soft cliffs in the area. The same happens in the areas north and south of Orford Ness (Profiles S048 – S052) but to a lesser extent.

Apart from the areas noted above, where cliff erosion and beach erosion are a concern, the shoreline is relatively stable; between profiles S020 and S046 (south of Southwold and the area north of Orford Ness); between profiles S051 and S059 (south of Orford Ness and south of Hollesley) and between profiles S065 and S071 (north of the mouth of the Deben Estuary and the area of Old Felixstowe).

5.2. Volumetric changes

The volumetric analysis is performed by integrating each beach profile from the foreshore to the most seaward point. Fig. 11 shows the time history of the volume of material in each profile per unit width of beach for the ten profiles shown in Fig. 6.

Where the shoreline position has remained stable over time but there is a deficit of sediment supply the phenomenon of 'beach steepening' is present. As noted by Lee (2008), the movement of the high water and low water marks is not necessarily the same. If, say, the high water mark remains fairly constant but the low water mark is receding then the slope of the beach will increase as sediment is being removed

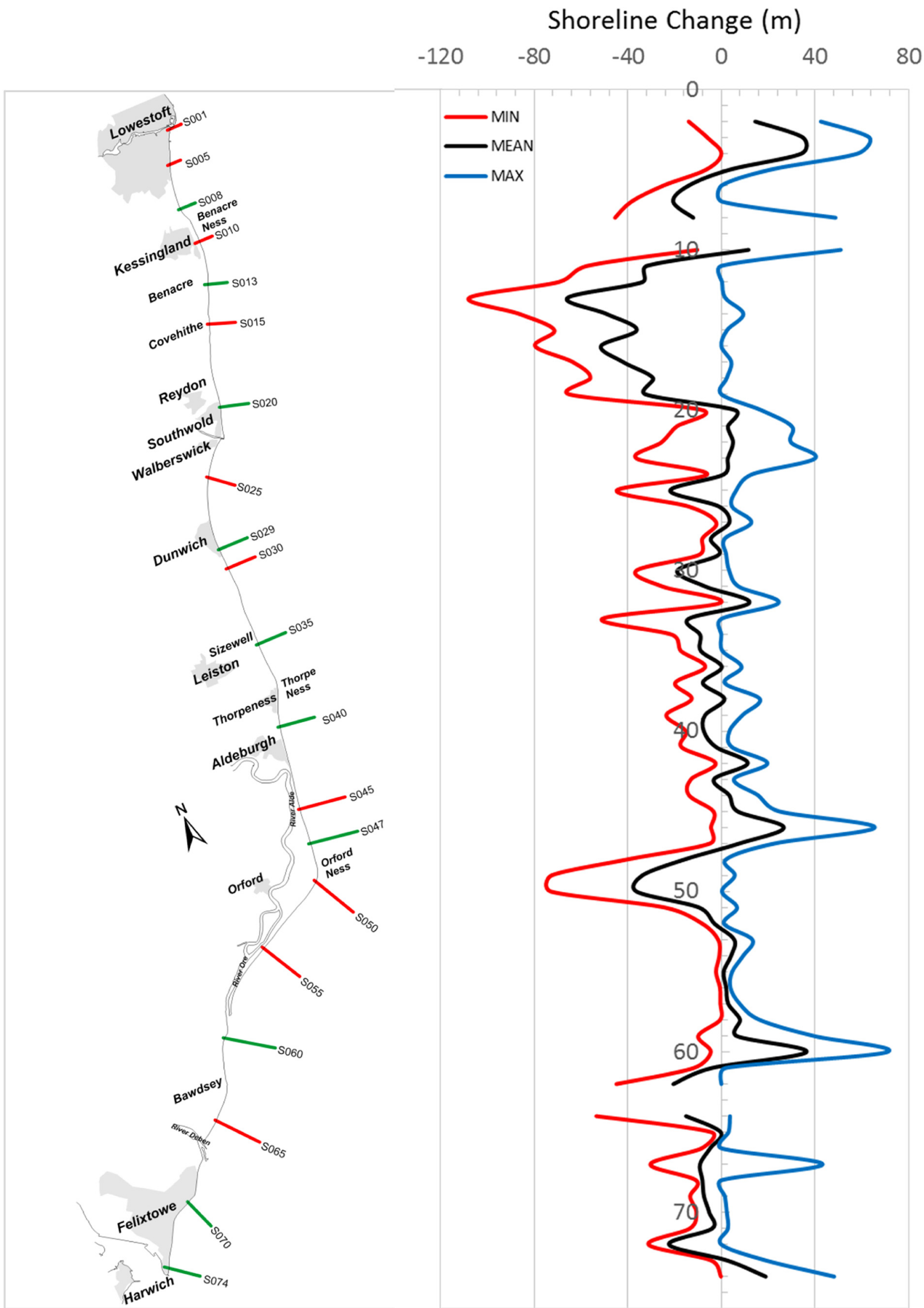


Fig. 10. Profile locations (left panel) and mean, maximum and minimum shoreline changes against the shoreline from August 1992 over 22 years for each profile along the Suffolk coast (right panel).

from the profile. To check whether there is evidence for this on the Suffolk coast the 'volumes' of the profiles have been calculated and are displayed in Fig. 11 as a function on time. A steepening beach will show a fairly stable shoreline position with a reducing volume. As may be seen from Fig. 11, the trends in beach volume vary along the Suffolk shoreline. Most are fairly stable or slightly accreting, while S013, just to the south of Benacre Ness, shows a marked decrease over time which corresponds to beach retreat rather than steepening. In fact, of the ten profiles in Fig. 11, only two have exhibited steepening over the survey period, S020 and S040.

In summary, beaches along the Suffolk coast show highly varied morphodynamic behaviour. Generally speaking, while the northern part of the coastline is erosive the southern part shows some long-term accretional trends, as might be expected from the predominant southward longshore transport. However, high energy storms have led to episodic erosional events. The long-term morphodynamic behaviour is also affected by a number of rivers discharging into this coastline, which contribute sediment to and reshape the littoral transport regime. Nevertheless, the volume of sediment in the beaches is stable when viewed at a decadal scale, and even erosive beaches such as at S008 have accumulated sediment since 2005.

5.3. Foreshore classification

Using the Foreshore Change Parameter (FCP) described earlier, the entire shoreline along the Suffolk coast can be classified. The results of the foreshore classification of the 74 beach profiles are listed in Table A1 (see Appendix).

In Table A1 (see Appendix), it is clear that the FCP values vary significantly with location although there are some patterns. Where there are cliffs backing beaches there is a general erosional tendency and short-term retreats can be heavy, as can be seen from profiles S013-S019. The response of shingle beaches seems to depend on the plan shape of the coastline. Where the plan view of the shoreline is convex, shingle beaches are found to be erosive, as is the case for Profiles S038 – S040 and S048-S052, but where the plan view of the shoreline is concave, they are accretive as seen with Profiles S053-S058.

The majority of profiles backed by hard defences, such as a seawall or revetment, are stable or accreting. There are a few exceptions (e.g. Profiles S071, S072) which are defended and are eroding. The majority of the profiles backed by cliffs are eroding, seemingly as sediment supply from neighbouring areas is being hindered. For example, the eroding beaches at Profiles S013 – S019 receive little or no supply of sediments from the north as these are being accumulated by Benacre Ness. A similar situation pertains to the areas north and south of Orford Ness, between profiles S048 and S052. Overall, 57% of the 71 profiles display an erosional trend over the period of the study, with the remainder being stable or accretive.

Fig. 12 shows the results of Table A1 in map form, ascribing the FCP of each profile to strips centred about the profiles. The trends suggest: northward movement of Benacre Ness (accretion to the north and erosion to the south); flattening of Orford Ness with erosion at its head and accretion along both flanks; accretion at the entrance to Harwich due to net southward longshore drift against the harbour breakwater. In Fig. 12, the green arrows represent the sediment transport pathways inferred from the coastal trends and the grey arrows represent the potential littoral transport from Vincent (1979).

The statistics of the general coastal trends are summarised in Table 1, excluding Profiles S01, S009 and S063. Tables 2 and 3 present the same data but cross-tabulating coastal trends with foreshore gradient and coastal trends and defences respectively. According to EA (2011a), beaches at only 28% of the 74 profiles have hard defences (e.g. seawalls, timber groynes, revetments, etc.), so that the remaining 72% are responding naturally to the prevailing tides and waves. The areas that have been protected are those fronting centres of population, (such as Lowestoft, Southwold and Felixstowe). The beaches at these locations are mostly backed by concrete seawalls with timber groynes, altering the way they respond in comparison with natural beaches.

Tables 1–3 show that the foreshore gradient of the profiles in the Suffolk coast is 'flattening' in ~52% of the area; nearly a third of the profiles, (31%), are 'steepening' and around 17% of the profiles have no rotation of

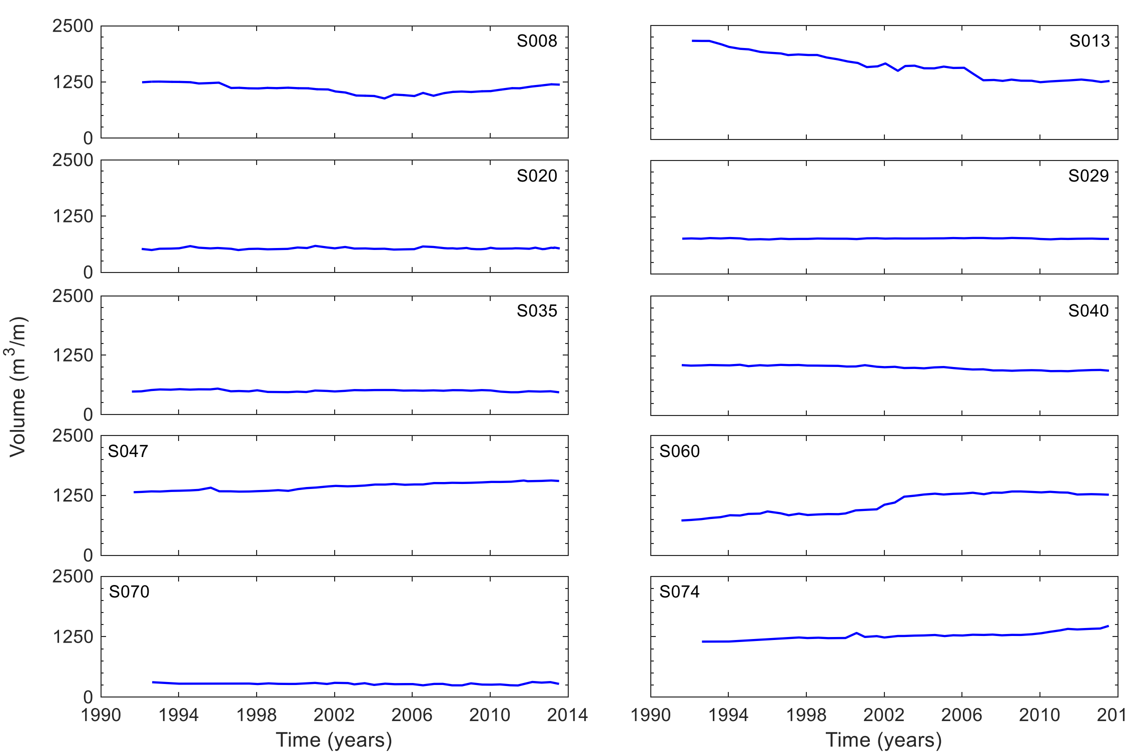


Fig. 11. Profile volume for selected profiles as a function of time.

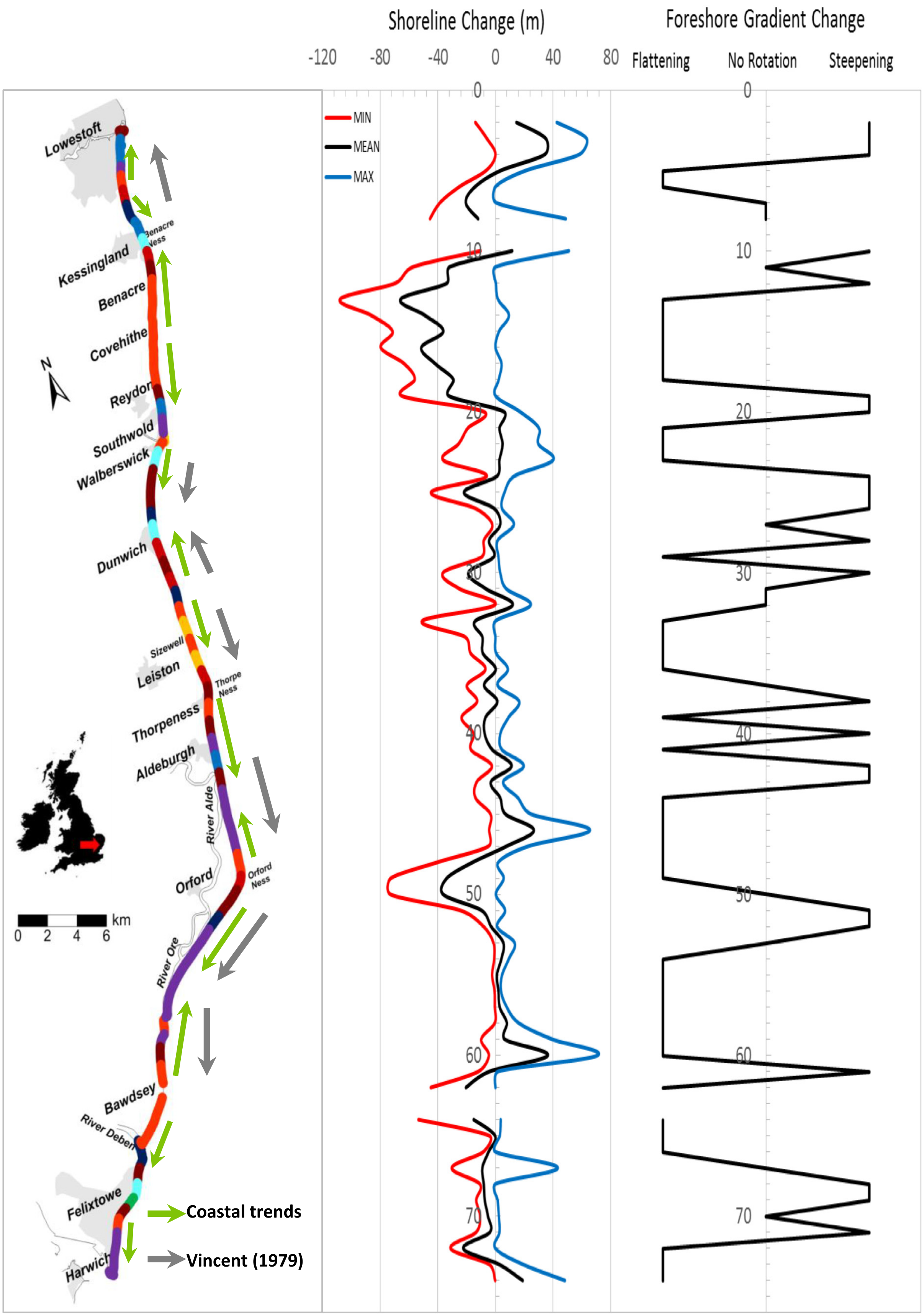


Fig. 12. Foreshore change classification system for each profile (left panel - For the colour reference see Fig. 7). Average shoreline changes against the shoreline from August 1992 over 22 years for each profile (middle panel) and foreshore gradient changes (right panel).

Table 1
Results of foreshore gradients and mean trends in the Suffolk coast.

Category	Profile change	Number of profiles	Percentage by category (%)
Foreshore gradient	Flattening	37	52.1
	No rotation	12	16.9
	Steepening	22	31.0
	No trend	0	0.0
Coastal trend	Shoreline retreat	41	57.7
	No movement	1	1.4
	Shoreline advance	29	40.8
	No trend	0	0
Defences	Beach backed by cliff/sea walls, etc	36	50.7
	Beach with no defences	35	49.3
Beach backed by	Sea walls/groynes (eroding)	5	7.0
	Sea walls/groynes (accreting)	12	16.9
	Sea walls/groynes (no change)	1	1.4
	Cliffs (eroding)	15	21.1
	Cliffs (accreting)	2	2.8
	Dunes(eroding)	6	8.5
	Dunes(accreting)	2	2.8
	Shingle (eroding)	14	19.7
	Shingle (accreting)	14	19.7

the foreshore slope. On the basis of these results it is difficult to support the contention that the presence of hard defences causes beach steepening or 'coastal squeeze', (Taylor et al., 2004; Doody, 2004); one third of the 18 beaches backed by hard structures have flattened over the period. There are certainly eroding beaches backed by seawalls, but there are rather more accreting beaches backed by hard defences and so the evidence for 'coastal squeeze' is mixed. It should be recalled that these are meso-scale trends and will not necessarily correspond to the beach response during individual storm events. Indeed, Pontee et al. (2002) describe how changes in the slope of a beach during a storm can depend upon the presence of seawalls at the back of the beach, as well as the prevailing sediment availability, water depth and antecedent state of the beach.

5.4. Correlation between positional and volumetric changes

Plotting the relative positional and volumetric changes with respect to the initial survey provides a map of how a particular beach evolves over time. Each dot on the plot corresponds to a survey; by 'joining the dots' the line traces out a trajectory describing the beach evolution in time. The first dot is at the origin. A trace going from the origin downward and to the left corresponds to a beach that is retreating and losing volume. A steepening beach with a stable shoreline will be characterised by a close to zero shoreline position change (x-axis value) and a negative volume change. The slope of the graphs in Fig. 13 may be interpreted as the rate of change of beach volume with shoreline position. As such, a positive gradient is to be expected. A negative gradient would correspond to either steepening with shoreline advance and lower beach erosion or flattening with shoreline erosion and lower beach building, equivalent to FCP $= \pm 2$. If the gradient remains constant throughout the period then this indicates a translational movement of the profile, (FCP $= \pm 5$), with volume and shoreline position closely correlated as evident for profiles S008 and S047. A range of distinct behaviours is evident in Fig. 13, which plots the trajectories for four of the ten beach profiles used earlier. For profile S008, there has been shoreline retreat and beach volume loss from 1992 until 2004, and since then, the beach has begun to recover with an

Table 2
Cross-tabulation table for foreshore gradient and coastal trends.

	Coastal trend		
Foreshore gradient	Shoreline retreat	No movement	Shoreline advance
Flattening	22	–	15
No rotation	6	1	5
Steepening	13	–	9

Table 3
Cross-tabulation table for foreshore gradient and coastal trends.

	Defences		
Coastal trends	Beach backed by cliff	Beach backed by sea walls, groynes	No defences
Shoreline retreat	15	7	19
No movement	0	1	0
Shoreline advance	2	12	15

increase in its volume, as well as the shoreline advancing. For Profile S013, the beach has experienced simultaneous volume loss and shoreline retreat. At Profile S047 the beach is accretive with a general trend of advancing shoreline. Both shoreline and volumetric changes at S035 are relatively small over the period, illustrating overall retreat superimposed with some episodic erosion/recovery cycles. An animated sequence of beach profiles and trajectory for profile S008 may be found in the additional materials.

5.5. Inter-survey shoreline trends

Fig. 14 shows the temporal variation of the shoreline changes for selected profiles in this study (Fig. 5a, b) profiles against the reference survey in Aug 1992, together with a time history of hindcast wave heights at a point offshore of Dunwich. There is considerable variability in both the rate and direction of shoreline movement at most of the profiles. Many of the profiles show both accretion and erosion during the period of surveys. While there is some evidence of a seasonal fluctuation this is not consistently present. There are a few very large changes (notably profiles S020, S060, S013) which are associated with beach recharge in the case of profile S020; but in all cases these are nullified by the time of the following measurement, indicating a short-lived fluctuation in shoreline position. The shoreline changes for Profiles S013, S020 and S035 are found to be the largest, as also shown in Fig. 10. The maximum erosion, more than 100 m within the 22 year study period, occurred at profile S013, which is due mainly to the accumulation of sediments at Benacre Ness (to the north of profile S013). The variations in the erosion at this profile tend to reduce in amplitude after 2007.

A recharge of the beach around profile S020 was made in the summer of 2006 in order to increase the beach width and after the construction of the new groynes, (EA, 2010). Since then the beach has receded at a steady rate until the summer of 2009.

Fig. 15 shows the shoreline changes for the same profiles as those in Fig. 14. In this case the shoreline rates are calculated for each survey with respect to the reference survey carried out in August 1992; the first full survey at all profiles. This is termed the 'cumulative' change and when considered as a function of the averaging period provides an insight into the importance of different scales of evolution.

It is evident from Fig. 15 that the erosion rates computed over short time scales, say up to about 5 years (1998), are quite volatile and may even change sign. Once the averaging period gets above about 10 years (2002), the computed shoreline change rates become much more stable (as a function of averaging period). Some appear to asymptote towards constant values while others approach, to a first approximation, a linear dependence. In all cases, once the averaging period exceeds 5 years the sign of the mean rate of change remains the same. The only exception to this is Profile S008 which is located immediately to the north of Benacre Ness, and most likely influenced by the northward movement of Benacre Ness during the measurement period. Towards the beginning of the period the Ness was sufficiently far south not to influence the Profile and so it exhibited an erosive tendency similar to the nearby profiles. As the Ness moved towards Profile S008 this erosive tendency was replaced by an accretive one. This evolution is clearly on at least a decadal scale. The rate of change of profile S013 reaches a minimum of approximately −15 m/yr around 1994 and then increases to around −5 m/yr at the end of winter 2012/2013.

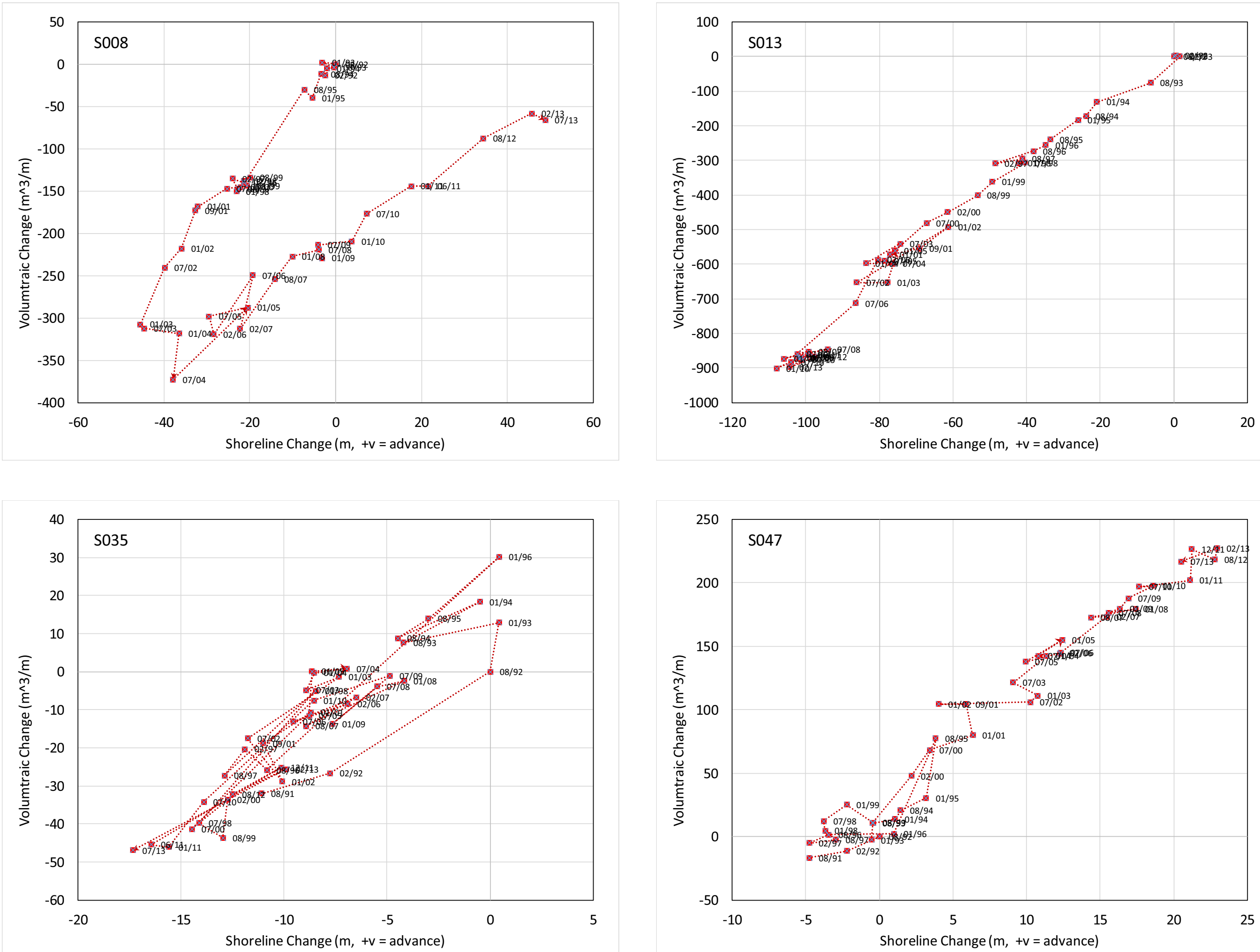


Fig. 13. Correlation between positional and volumetric changes at selected locations, where data points are joined by a line in chronological order.

Another more intriguing interpretation of Fig. 15 is as follows. Consider a shoreline that exhibits a change of position, $x(t)$, that follows a polynomial trend in time, say $x(t) = \alpha t^n$ where α is a constant. Integrating this function over the interval t ε [0, T] and dividing by the length of the period to find a mean yields $\langle x(t)\rangle = \alpha T^n/(n \;\; 1)$. That is, a shoreline that is stable or moving at a steady rate, apart from small variations, will exhibit this stable or linear change rate as the averaging period increases. At shorter averaging periods Fig. 15 shows some quite rapid fluctuations in the computed rates of change; many of the plots having an oscillatory nature which becomes damped as the averaging period increases. This may be understood by considering the case where the change in shoreline position follows a cosinusoidal variation in time: $x(t) = \alpha\, cos(\Omega t)$ where, as before, α is a constant and Ω is the period of oscillation. Integrating this function and dividing by the length of the period to find a mean yields $\langle x(t)\rangle = \alpha sinc(\Omega t)$ where $sinc(x)$ is the '*sinc*' function, which has the features of a damped oscillation and is closely related to the spherical Bessel function of the first kind, (Bracewell, 1999). The plots in Fig. 15 show that the oscillations in the computed mean are removed once the averaging period is above about 5 years. This suggests that the fluctuations in the rate of shoreline position typically have time scales several times smaller than this. If the movements in shoreline position had a spectrum of periods of variation, then the computed mean would also oscillate until the averaging period became several times larger than the largest scale of fluctuation. That the oscillations in the mean rate become negligible once the averaging period exceeds about 5 years indicates that the spectrum of fluctuations in the shoreline position has little or no content above a period of 5 years. This suggests that rather than there being a continuous range of scales of variation there is a window, from about 5 years to some value of the order of a decade or more, over which the spectrum of variations has very low energy. The reduction in variability over time-scales beyond approximately five years in the time averaged shoreline movements is indicative of a gap in the spectrum of shoreline variability between approximately 5 years and some yet to be determined upper limit is unexpected. A signature due to ENSO or NAO as found by Magar et al. (2012) and Barnard et al. (2015) in their analyses of ocean-facing beaches, might have been anticipated. Its absence here, especially as Castelle et al. (2018) found variations of this nature in wave activity in the Northeast Atlantic, can be attributed to the combination of the more sheltered situation of the Southern North Sea and the high level of beach management along this coast. Beyond this period, it is difficult to divine longer term variations from this dataset, although Burningham and French (2017) have shown that these may be significant along this coast. One important exception to this observation is the shoreline movements associated with the gradual longshore movement of ness features.

This finding has implications for both model developers and coastal managers. It provides an explanation of why the use of simple linear extrapolation of long-term retreat rates has so far provided a reasonable guide for shoreline management purposes. There are some important caveats. There is evidence that features such as Benacre Ness have not always moved at either a constant rate or in the same direction (May and Hansom, 2003). A better understanding of the processes driving the evolution of such features is clearly required for accurate prediction. Further, conclusions drawn from a *meso*-scale spatial analysis cannot be

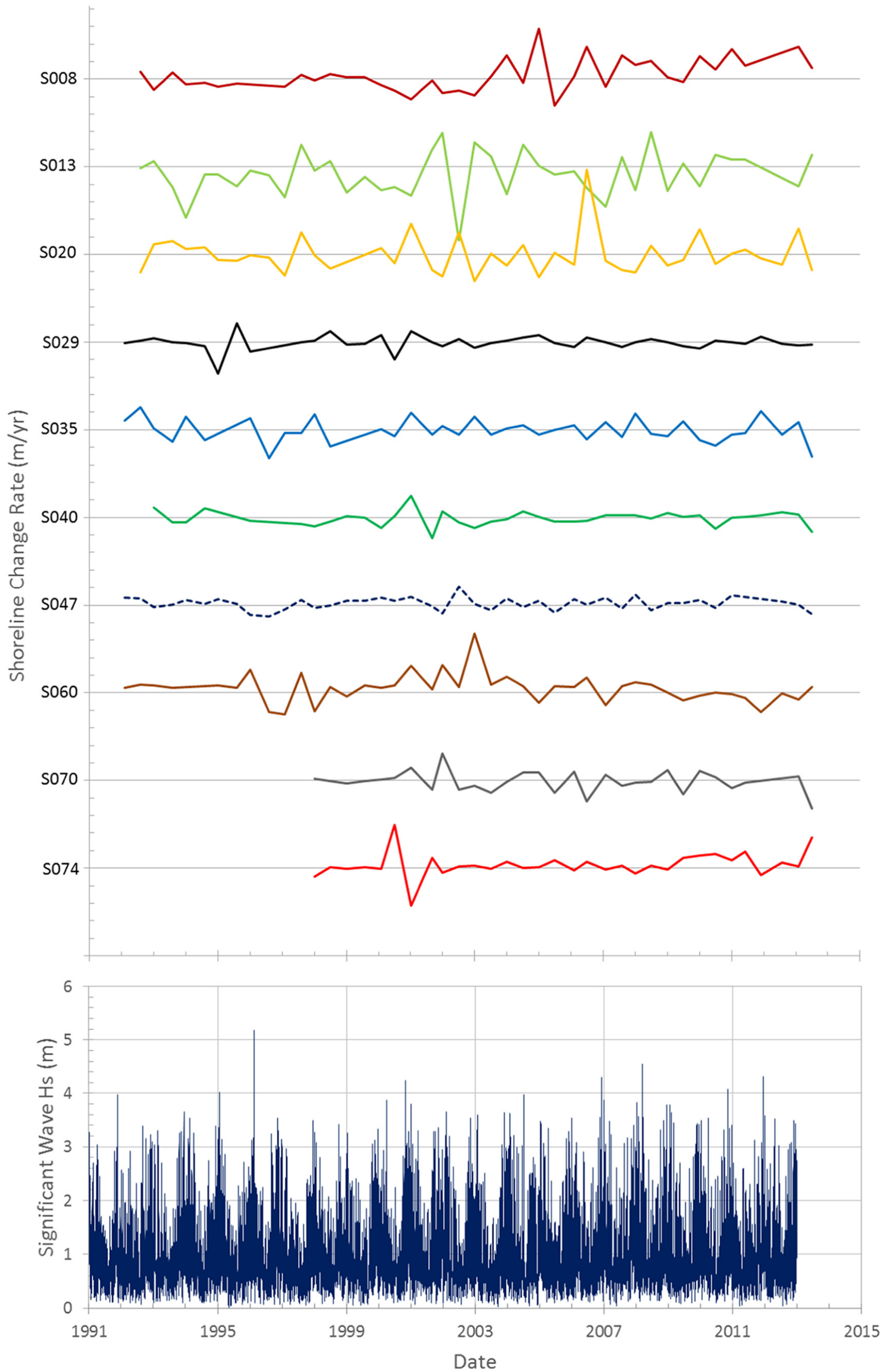


Fig. 14. Short-term shoreline change rates for selected profiles. Shoreline change rates are calculated between two consecutive surveys, usually every half a year. Significant wave height for a location offshore of Dunwich at 22 m water depth.

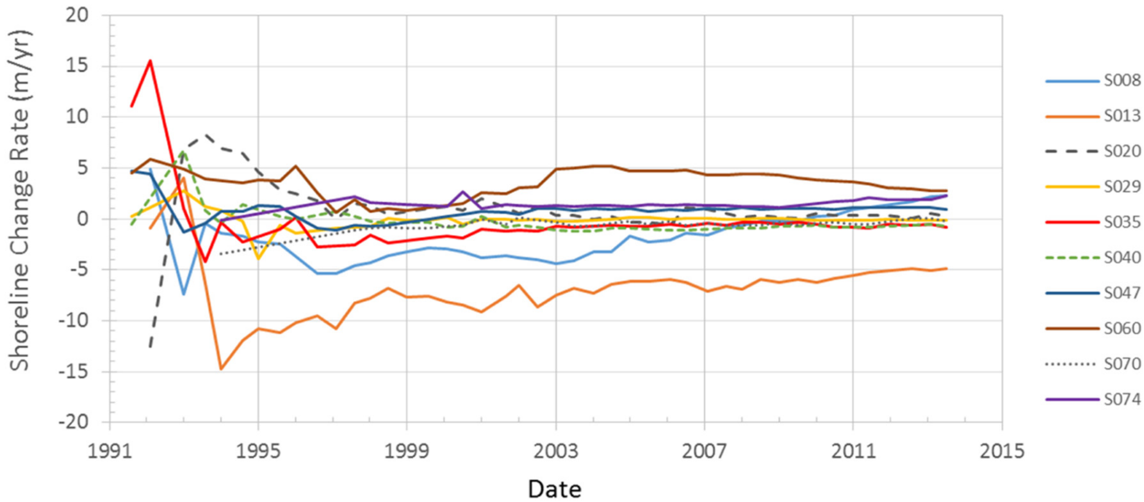


Fig. 15. "Cumulative" annual rate of shoreline changes for the selected profiles, against the shoreline position in August 1992.

expected to apply without modification to specific sites such as the vicinity of groynes or tidal inlets, where again our knowledge of the processes is not complete and further research is necessary.

6. Conclusions

In the present work we have undertaken a detailed assessment of a unique set of beach profile surveys covering the period 1991 to 2013 in order to investigate the meso-scale evolution of beaches along the Suffolk coast. Based on the result of the analyses the following conclusions can be drawn:

- Over the period of the observations the majority of monitored beaches in Suffolk have flattened. This is in contrast with the macro-scale studies of Taylor et al. (2004) and Burningham and French (2017) who found that approximately 61% of the coast of England and Wales and approximately 89% of the Suffolk beaches have shown a steepening trend since the beginning of the 20th century, respectively. We conclude that the majority of the Suffolk beaches are not exhibiting the phenomenon of coastal squeeze at meso scales;
- Over the period of the observations the majority of beaches backed by hard defences have accreted and a small majority of undefended beaches have retreated, from which may be deduced that there is little evidence of a causal link between hard defences and beach erosion over the period;
- The absence of any coherent meso-scale spatial pattern of coastal squeeze (manifested by persistent erosion or beach steepening) is notable in the context of the observation of Pontee (2011) who highlighted the influence of meso-scale changes in morphological processes as potential drivers of coastal squeeze. We conclude that while larger scale processes, such as sea-level rise, may be driving the long-term coastal response this is moderated by meso-scale variations arising from fluctuations in wave conditions and anthropogenic interventions, leading to ephemeral reversals of the larger scale trends;
- Coherent spatial patterns of behaviour emerge at the synoptic scale and include: the eroding soft cliffs between Benacre and Easton Bavents; erosion around the head of Orford Ness and accretion along both its flanks; the regions of accretion and erosion to the north and south of Benacre Ness, respectively; and the accretion in the area immediately updrift of Harwich Harbour breakwater. We surmise that the drivers of beach evolution on this scale do not, or cannot, operate at *meso* scales due to the combination of underlying geological variations, the number of tidal inlets that interfere with littoral transport and the anthropogenic interventions employed to manage the beaches;
- The analysis of temporal fluctuations in shoreline position shows evidence of some recurrent behaviours, but these are confined to periods below several years. This matches the observations relating to spatial scales of variation and we infer that that the beach morphodynamics on this coast are operating predominantly at synoptic scales, albeit combined with long-term trends arising from rising sea level, which has important implications for modelling meso-scale beach morphology on this coast. Assuming that the short-term fluctuations average out over time, this would provide an explanation of why the simple linear extrapolation of long-term retreat rates has so far provided a reasonable if imperfect guide for shoreline management purposes (DEFRA, 2002);
- Under the current coastal management regime, the volume of beach material appears to be fairly consistent and generally favourable from a beach management perspective, although the distribution of material across any particular profile can vary considerably between consecutive surveys to give the impression of rapid shoreline advance or retreat. We conclude that the overall sense is a coastline that exhibits a 'dynamic persistence' at the decadal scale, by which is meant the combination of beach management practices, geological constraints and tidal inlets restricts the scales of coastal response yielding a sense of stability at decadal scales. Located within are well-defined areas that are evolving progressively over the period, such as the eroding soft rock cliffs between Kessingland and Reydon, and the notable features of Benacre Ness, Thorpe Ness and Orford Ness where the coastal processes are driving meso-scale dynamics which appear in the beach profile measurements as trends of retreat and advance.

The measurements used for this study have been gathered using traditional techniques and are restricted to beach elevations gathered along discrete transects taken at specific instants. As such they exhibit some drawbacks in comparison to more recent data-gathering exercises that make use of continuous and areal monitoring techniques that are now available. Indeed, the rapidity of data capture and processing that is now achievable means that observations can be used in conjunction with computational models through data assimilation techniques (Scott and Mason, 2007), although care needs to be adopted in choosing an appropriate model and to ensure that data assimilation does not simply become a technique that compensates for failures of the model. The value of the dataset here is in its duration and areal distribution as well as its consistency of measurement variables and measuring technique. The latter two items are of particular importance when the duration of recording extends beyond the lifetime of instrument types. These considerations are adduced to conclude that long-term monitoring of coastal change at regional scales continues to have scientific and engineering value for understanding the interplay of processes at different scales. Furthermore, from a pragmatic point of view, the use of traditional methods provides a consistent, affordable and credible means to collect observations within the context of shoreline management planning and the level of resources often made available for this.

Here, a comprehensive analysis of an outstanding set of beach profile measurements has been presented. While it is recognised that such a resource is not available at many sites, and that the cost and effort required to create an extensive and quality-controlled dataset is significant, it provides a scarce exemplar of the value of long-term monitoring and the wider benefits to coastal science, engineering and management. The simple conceptual model of small fluctuations superimposed on long-term trends has limitations. Firstly, temporal variations at the upper end of the meso scale could appear as quasi-linear trends in a data set covering only 22 years, thereby being conflated with secular trends. Secondly, the spatial pattern of erosion and accretion associated with mobile features such as Benacre Ness will move and require more than a pointwise linear extrapolation to capture properly. Further, there is evidence of recurring morphological configurations at some tidal inlets along this coast (Burningham and French, 2006). A better understanding of the processes driving the evolution of such features, and the impact upon their immediate meso-scale littoral neighbourhood will be required for improved prediction.

Data access

The beach survey data has been provided under licence by the Environment Agency for the purposes of the iCOASST project, and ownership rights rest with the EA. Information derived from this data is available from the authors.

Acknowledgements

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Appendix A

Table A1
Classification of beach profiles according to Foreshore Change Parameter (FCP) (after Townend and McLaren, 1988) and type of defence. Profiles S001, S009 and S063 have been omitted from the analysis – see text for further details.

Profile	Defence	FCP	Profile	Defence	FCP	Profile	Defence	FCP
S001	seawall and groyne	-	S026	shingle bank no longer managed	-6	S051	shingle	-6
S002	seawall and groyne	+4	S027	shingle bank no longer managed	+5	S052	shingle	-6
S003	seawall and groyne	+4	S028	cliffs	+2	S053	shingle	+5
S004	seawall and groyne	+4	S029	cliffs	-5	S054	shingle	+6
S005	seawall and groyne	+6	S030	cliffs	-6	S055	shingle	+6
S006	Cliffs	-4	S031	sand/shingle bank	-5	S056	shingle	+6
S007	Cliffs	-5	S032	dunes	+5	S057	shingle	+6
S008	Cliffs	+5	S033	dunes	-4	S058	shingle	+6
S009	sea wall	-	S034	dunes backed by Sizewell bank	-2	S059	shingle bank	-4
S010*	sea wall	+2	S035	dunes backed by Sizewell bank	-4	S060	shingle bank	+6
S011	dunes	-5	S036	cliffs	-2	S061	shingle backed by embankment	-6
S012	dunes/shingle barrier	-6	S037	cliffs	-5	S062	shingle backed by embankment	-4
S013	cliffs	-4	S038	shingle beach	-6	S063	rock hard point	-
S014	cliffs	-4	S039	shingle beach	-4	S064	cliffs	-4
S015	cliffs	-4	S040	Shingle ridge	-6	S065	cliffs	-4
S016	cliffs	-4	S041*	seawall and groyne	+6	S066*	revetments and old timber groynes	-4
S017	cliffs	-4	S042*	sea wall	+4	S067*	shingle backed by	+5

Table A1 (*continued*)

							sea wall	
S018	cliffs	-4	S043*	seawall and groyne	-6	S068*	seawall and groyne	-6
S019	cliffs	-6	S044	shingle bank	+6	S069*	seawall and groyne	+2
S020	seawall and groyne	+4	S045	shingle bank	+6	S070*	seawall and groyne	0
S021	seawall and groyne	+6	S046	shingle	+6	S071*	seawall and groyne	-6
S022	dunes	- 2	S047	shingle	+6	S072*	sea wall & T-shaped rock groyne	-4
S023	dunes	-4	S048	shingle	-4	S073*	sea wall & T-shaped rock groyne	+6
S024	shingle bank managed	+2	S049	shingle	-4	S074	dunes and shingle	+6
S025	shingle bank managed	-6	S050	shingle	-5			

Note: * profiles protected by hard defences. The other profiles are natural which includes cliffs, dunes, shingle beaches and areas of 'beach management' where beaches, generally fronting low-lying land, have undergone some intervention in the form of mechanical sediment redistribution occurring at some stage during the monitoring period.

Profile S008 (see Fig. 5a) is located in the area of Kessingland and a seawall in front of the profile offers protection to part of the town behind, and its shoreline has been relatively stable, apart from sudden erosion around 2003. Profile S013 is located north of Benacre Broad and Covehithe, in which the intertidal beach is backed by an eroding cliff. Profile S020 is located by the town of Southwold and is backed by a seawall and is near a groyne and Profile S029, located south of Dunwich, is backed by a historically eroded cliff that is considered to be stable, (Royal Haskoning, 2009). Profile S035, located at Sizewell, comprises a dune system that is backed by the Sizewell Bank and Profile S040 is located north of Aldeburgh, (see Fig. 5b), and contains a shingle ridge. Both profiles have been largely stable with a slight advancing trend. Profile S047 is located on Sudbourne beach, which extends north from Orford Ness, a barrier system comprising distinct beach ridges separating the River Ore from the sea. Profile S060 is located in Shingle Street, north of Bawdsey which also comprises a ridge system that provides protection. For both Profiles S047 and S060, the shoreline is generally accretive over the study period. Profile S070 is located in the town of Felixstowe, south of the pier. This part of the coast is protected by rock groynes and concrete sea wall, where the shoreline has been clearly stable. Profile S074 is located at Landguard Point, close to Felixstowe; this profile is backed by an old concrete wall and timber groyne, showing an advancing shoreline.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2019.04.033.

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