Thorpeness Coastal Erosion Appraisal

Final Report

December 2014

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Issue and revision record

Revision	Date	Originator	Checker	Approver	Description
A	27/11/2014	J Williams	S Hampshire	P Phipps	Draft
B	09/12/2014	J Williams	S Hampshire	P Phipps	Final

Information Class: Standard

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Executive Summary

Focusing on the coastline and coastal processes at Thorpeness, Suffolk, this report has two main objectives: (a) to review and add to the present understanding of recent coastal erosion at Thorpeness; and (b) to use the evidence base from existing professional studies and the local experience and knowledge from coastal experts and Thorpeness residents. The report then examines if it may be possible to predict how coastal evolution is likely to proceed in the short (annual), medium (decadal) and long-term (centennial) time-scales with due consideration given to historical trends, limits to prediction and uncertainty.

The report first provides a brief review of the contemporary coastal erosion problems at Thorpeness and the coastal protection schemes implemented to offset erosion since the 1970s. Processes that drive coastal evolution at Thorpeness, including tides and extreme water levels, tidal currents and waves, are then reviewed and the historical and contemporary behaviour of the coastal environment that has relevance to the present-day and future physiographic conditions at Thorpeness is examined. A further section reviews the historical and contemporary behaviour of the present-day coastal environment including the behaviour and coastal influences of sea-bed sediments and bedforms and the local shoreline behaviour. Consideration is then given to whether or not the prediction of future coastal evolution is possible with available evidence and data before presenting conclusions and recommendations for further investigations.

The key outcomes from the study include:

- Identification of the most important geological and geomorphological controls and the physical processes and events that characterise the present day and historical behaviour of the coastline at Thorpeness;
- An improved understanding to the coastal erosion cycles at Thorpeness that occur at approximately 30 year intervals and the identification of new information believed to be required to advance understanding further;
- Recognition that the Coralline Crag outcrop north of Thorpeness has an important role in a number of coastal processes including the location and dynamic behaviour of the Ness, the sediment exchanges between the offshore Sizewell-Dunwich Bank and the sediment transfer mechanisms delivering sediments to the Thorpeness frontage;

- Identification of the important role of the offshore features that apparently grow and decay to the south of the Ness and their influence on the spatial and temporal distribution of incident wave energy; and
- Recognition that although the coastal erosion 'hotspot' at Thorpeness is localised, it is related to processes operating at much longer time-scales over a much larger area, and understanding the future behaviour of the beach at Thorpeness will require further work encompassing data analysis and numerical modelling that draws on all available information.

At the present time localised severe beach erosion has a potential to destroy residential property in the short-term and thus the underlying coastal erosion problem to be managed at Thorpeness remains the same as that set out in the 2010 Project Appraisal Report (PAR). The challenge now is manage the present problems and develop a sustainable management strategy that balances management of a naturally evolving shoreline with the aspirations of the community. It is believed that this cannot be achieved without following the recommendations for additional work set out in this report.

1 Introduction

Thorpeness is located at the southern end of the Greater Sizewell Bay on the mid-Suffolk coast approximately 4km north of Aldeburgh and 16km south of Southwold (Figure 1.1). The Greater Sizewell Bay is located in Coastal Sediment Cell 3, between the Wash and the Thames Estuary. Cell 3 is divided into a number of sub-cells, and Thorpeness lies within sub-cell 3-C, between Lowestoft and the Port of Felixstowe (Suffolk Shoreline Management Plan, SMP2, 2010). The northern part of the frontage is backed by cliffs comprising weakly cemented Pleistocene rocks and sediments. The elevation and slope angle of the cliffs decrease southwards. The beach sediments mostly comprise sand with a superficial covering of gravel which includes a number of ridge features associated with tidal forcing and storms. Immediately to the north of Thorpeness an accumulation of coarser sediment (a Ness feature) is located on an outcrop of more resistant geology.

Figure 1.1: Location of Thorpeness.

Thorpeness is included within Lowestoft to Languard Point SMP2 (Royal Haskoning, 2010b,c) and is considered within Policy Development Zone 5 and Policy Unit: ALB 14.1 and MIN 13.3. A change in the present shoreline management policy is due for final sign off by the Environment Agency. No Active Intervention formally identified for the frontage will be replaced by:

- 1st epoch until 2025: Managed Realignment[1] with the current alignment maintained at existing defences;
- 2nd epoch 2025 – 2055: Managed Realignment with review of maintaining the current alignment at existing defences and
- 3rd epoch 2055 – 2105: Managed Realignment.

1 For a comprehensive explanation of managed realignment readers are recommended to consult: Esteves, L. S., 2014. Managed Realignment: A Viable Long-Term Coastal Management Strategy? Springer Briefs in Environmental Science, DOI 10.1007/978-94-017-9029-1_7, Springer, Netherlands.

There are two potential consequences of this shift in policy: (a) significant further investment will be required to deliver the policy objectives; or (b) a policy that includes intervention to manage erosion risk will be found not to be viable on the grounds of sustainability and/or affordability. However, consideration of policy consequences and actions are beyond the scope of the review of physical processes provided in this report and are not considered further.

Thorpeness is widely recognised as being prone to slow coastal erosion and historically, the frontage has experienced erosion rates of between 0.1 to 0.4m/year (Royal Haskoning, 2010b,c; Halcrow, 1995). Monitoring and historical data considered in SMP2 predicts erosion of the frontage between 10m to 25m over the next 100 years (Royal Haskoning, 2009). However, coastal erosion has been episodic with periods of intense erosion, notably in the decades 1910-1920, 1940-1950, 1970-1980, and 2010-present, followed by long quiescent periods. In all cases erosion has threatened properties located close to the frontage. While the risk of severe erosion episodes permanently altering the long-term coastal evolution trend is thought to be low, frequent significant erosion events during the period 2010 to 2014 may be an early warning of a change in the long-term behaviour of the shoreline. Equally, they may simply be repeat of similar erosion cycles recorded in the 1940s and 1970s, albeit possibly with greater intensity than previously.

In response to severe erosion in the mid-1970s a gabion defence structure extending alongshore approximately 200m to protect a series of properties on the cliff top was completed around 1980. This has subsequently been subjected to erosion during another active coastal erosion phase between 2010 and the present and additional defences have been constructed which themselves are now threated by ongoing severe erosion. Specifically, the beach levels have decreased significantly during storm events exposing the toe of the structures and outflanking has occurred either side of the gabions at the adjacent stretch of unprotected cliffs. This has resulted in cliff line retreat of over 12m to the north and along a 120m section of cliff to the south of structure. Prior to the recent emergency repair works undertaken by Suffolk Coastal District Council (SCDC), ongoing erosion threatened some 17 properties.

2 Purpose of this Report

Focusing on the coastline at Thorpeness, Suffolk, this report has two main objectives:

- To review and add to the understanding of recent coastal erosion at Thorpeness; and
- To use the evidence base from existing professional studies and the local experience and knowledge from Thorpeness residents.

Since the local behaviour of a coastline is frequently controlled by processes occurring at large spatial and temporal scales, Thorpeness cannot be considered in isolation from the wider coastal environment of Suffolk. Furthermore in order to understand the history of shoreline change at Thorpeness it is necessary to have an appreciation of the marine and meteorological forces and other factors that cause change. This will also help to understand the risks and uncertainties associated with forecasting future shoreline change.

In order to develop, and provide evidence to support an improved conceptual understanding of future coastal evolution along the Thorpeness frontage and the adjacent coastlines, this review has accessed a wide range of reports and other relevant material. The literature on the hydrodynamics and morphodynamics of the Suffolk coast is extensive, and a good understanding of the main drivers of broad-scale coastal change have been established. However, this report deliberately focusses on those aspects of the physical environment that are less well understood and have a direct bearing on local coastal processes and erosion problems at Thorpeness. This information has been used to inform an assessment of the potential future coastal evolution at Thorpeness and will in turn provide the understanding required to develop options to help alleviate the present erosion problems in a proposed Phase 2 of the study.

The report comprises 7 sections:

- **Section 3: Thorpeness Coastal Erosion Review**: presents a brief review of the contemporary coastal erosion problems at Thorpeness and the coastal protection measures implemented to offset erosion since the 1970s. It presents also the concerns and views of local stakeholders to recent changes in Environment Agency (EA) Management Policy.
- **Section 4: Coastal Processes:** reviews the coastal processes that drive coastal evolution at Thorpeness including tides and extreme water levels, tidal currents and waves.
- **Section 5: Coastal Environment:** examines the historical and contemporary behaviour of the present-day coastal environment and includes the behaviour and coastal influences of sea-bed sediments and bedforms and the local shoreline behaviour.
- **Section 6: Coastal Morphodynamics:** presents a conceptual understanding of the processes that have given rise to the three major cycles of erosion recorded at Thorpeness since 1900.
- **Section 7: Future Coastal Evolution:** reviews briefly the key evidence presented in the proceeding sections and considers to extent to which prediction of future coastal evolution is possible.
- **Section 8: Conclusions**: presents a summary of the key findings from the study.
- **Section 9: Recommendations**: identify key elements required to advance the present incomplete understanding of coastal processes at Thorpeness.

3 Thorpeness Coastal Erosion Review

Before looking at the range of physical processes that influence the behaviour of the coastline at Thorpeness it is first useful to briefly review the past and recent sequence of natural events and to describe the coastal management actions undertaken in response to the coastal erosion that has resulted. These are summarised in Appendix A.

3.1 Historical erosion record

Although some anecdotal evidence is available prior to 1900, the first credible record of coastal erosion documents a storm in October 1911 that resulted in cliff recession of around 10m over a shoreline length of approximately 200m (Figure 3.1).

Figure 3.1: Coastal erosion and property damage due to the October 1911 storm: (a) a typical sea front property undermined by erosion; and (b) the Coast Guard station.

(a) (b)

Source: Thorpeness Coastal Futures Group

Although high tides during 1942 are said to have resulted in sediment loss at the Ness and damage to the sand dunes, no significant impacts at Thorpeness are recorded. It is noted that during the period 1930 to 1950, shingle built up along the frontage to create a substantial berm and the beach was judged to be in a healthy state (Figure 3.2). It is believed that the well-developed berm feature saved Thorpeness from the worse effects of the 'Great Storm' in 1953 (personal communication).

Figure 3.2: A typical aerial view of the relatively stable coastline at Thorpeness between 1936 and 1975.

Source: Thorpeness Coastal Futures Group

In late 1974 and the summer of 1975 two periods of severe weather occurred resulting in erosion of 2/3 of the foreshore to a depth of around 2m along the whole frontage. This was followed on 18 November 1975 by a severe N-NW gale (estimated to be Force 8-9). The previous beach erosion made the frontage much more susceptible to erosion and the beach was lowered by a further 2m allowing waves to reach and undermine the cliff base (Figure 4). The eroded material was transported and deposited several hundred meters southwards. The beach was reported as being left in a very flat condition.

Figure 3.3: View of severe coastal erosion at North End after the storm on 18 November, 1975.

Source: Thorpeness Coastal Futures Group

In response to the erosion in 1975, the Thorpeness Estate and Suffolk County funded defences comprising a gabion slope (*c*. 40^{o}) covered with shingle and extending around 250m south from *Red House*. The scheme was completed around 1980, and although the beach remained relatively flat, there was evidence of some beach recovery with the construction of a shingle berm along the frontage. Beach recovery continued through the 1980s to establish profiles similar to the pre-1970s. These were judged at that time to provide adequate coastal protection.

Major erosion during prolonged storms in April and May 2010 lowered the beach in a manner similar to that recorded in the early 1970s and a severe storm on 19 June 2010 removed beach sediments and exposed the gabion revetment slope below North End Avenue after almost 30 years of burial beneath the beach sediments (Figure 3.4 and Figure 3.5).

Figure 3.4: Various views of exposed gabions and cliff outflanking in 2010.

Source: http://www.stacey.peak-media.co.uk/Thorpeness

Figure 3.5: Beach set-back in front of coastal protection at Thorpeness (looking north). The white dashed line indicates approximately the location of the natural shoreline before the recent erosion cycle.

Source: Mike Page, 2011

In addition to the beach erosion (Figure 3.5), outflanking has occurred at each end of the gabions. Soft cliff erosion was most significant at the northern end of the frontage. It is believed that this serious erosion event was preceded by around 12 months of beach erosion which left the frontage in a weakened condition. It is argued by Royal Haskoning (2010a) that the eroded sediment moved northwards towards the Ness. The evidence to support this is provided in Figure 3.6 which shows aerial photographs of the southern end of the Ness in 2009 and in late 2010. Although not considered, it is equally plausible that this material came from the north as the northwards widening of the deposit might indicate (Figure 3.6b). Unfortunately no analysis of sediment grading was undertaken which would help establish the provenance of this deposit.

Figure 3.6: Aerial photographs of the southern end of the Ness: (a) 2009; and (b) 2010 showing an accretion trend attributable to storm events in April/May 2010

Source: Royal Haskoning, (2010a)

In response to the erosion in 2010, a *c*. £700,000 SMP compliant emergency protection scheme comprising repairs to the gabions and the emplacement of sand/shingle filled Geobags finished with a covering of shingle from the Ness was completed in two phases over the winters of 2010/11 (*Phase 1*) and 2011/12 (*Phase 2*), (Figure 3.7). This was jointly funded by SCDC, the EA and North End Avenue residents.

Figure 3.7: *Phase 2*: (a) during construction looking south; (b) during construction looking north; and (c) damage to *Phase 1* Geobags bags following the 'St Jude's Day' storm on 14 October, 2013.

These most recent coastal defence works were designed under the premise that they would act as an erosion backstop that would only be exposed infrequently to high erosion pressure for short periods. This has unfortunately proven not to be the case and beach erosion and damage to the scheme occurred during early 2013 and again in October the same year. While some beach recovery took place during summer of 2013 further major erosion occurred during December 5th - 6th 2013 (Figure 3.8). At this time a surge elevation of 1.3m and 2.0m was measured at Harwich and Lowestoft, respectively. This was especially significant with regards to coastal erosion since the surge was coincident with high spring tides so that water levels at Harwich and Lowestoft reached around 3.5m ODN and 3.3m ODN, respectively (National Tidal and Sea Level Facility). To place this in context, the Highest Astronomical Tide (HAT) at Sizewell, just to the north of Thorpeness is only 1.62m (BEEMS, 2013). Interpolating the water levels associated with this event between Harwich and Lowestoft, suggests that the return period for the water level at Thorpeness was approximately 1:250 years.

Figure 3.8: Coastal erosion in 2013: (a) exposed Geobags; (b) beach access point at *Jonnygate*; and (c) beach lowering and shoreline erosion.

Despite the magnitude of this event, and low beach levels at the time, erosion was not as great as that observed in the spring of 2013. However, there was significant damage to the lower layers of gabion baskets just above the existing Geobags and evidence that wave run-up had reached the vegetated crest at the top of the gabion baskets.

Inspections have shown that although being of a lower abrasion resistance, and suffering extensive minor puncturing since installation, the *Phase 1* Geobags have fared better than those used in *Phase 2* for reasons unknown at present. However, *Phase 1* Geobags were covered by beach material after installation and remained buried until exposure in autumn of 2013. They were again partly covered by beach material in November 2013 and fully covered in May 2014 (Figure 3.9b). Their location on the beach profile places the *Phase 1* Geobags in a less aggressive environment and their design profile may have contributed further to their resilience when compared with the *Phase 2* frontage which may now need to be strengthened to meet PAR objectives (SCDC, 2010).

Based on the available historical evidence summarised above Royal Haskoning (2010b,c) has suggested the site is subject to an erosion cycle with a period and duration of approximately 30 year and 10 years, respectively. However, the mechanisms behind such a cycle have not been explained, nor has fully convincing evidence and/or data been advanced to support this assertion.

3.2 The situation in autumn 2014

The damage to the frontage in 2013 has been ‘repaired’ subsequently by replacing the eroded beach sediments with material from the beach to the south. It is believed that this material originated from the erosion of the beach in front of North End Avenue and thus the 2013 erosion event has many things in common with the events in 1970s. In addition, local residents immediately south of the gabion slope have instigated their own coastal protection works (Figure 3.10a). This follows a recent history of privately funded *ad hoc* coastal protection works in Thorpeness (e.g. Figure 3.10b).

Figure 3.9: Beach frontage below North End Avenue: (a) on 12/10/2013 showing storm erosion; and (b) on 31/10/2014 following beach recharge and profiling works.

(a) (b)

Figure 3.10: Privately-funded defence works: (a) immediately south of the gabion slope (October 2014); and (b) further south off Church Road (construction around 2004).

(a) (b)

It is believed on the basis of historical records and on the likelihood of further storms in the near future that may be coincident with high tidal conditions, that the present ‘stable’ beach morphology may only be temporary and a concern that the defence life of *Phase 1* and *Phase 2* defences will be much shorter than expected remains, as does the treat to properties from further coastal erosion. It is believed that future extreme weather events and/or beach erosion may again expose and damage the *Phase 1* and *Phase 2*

Geobags and potentially result in further settling of the gabion slope and recession of the cliffs they currently protect.

At the time of writing this report the scheme remains vulnerable to further erosion in the autumn/winter of 2014/2015. For this reason the main local stakeholder group, the Thorpeness Coastal Futures Group[2] , has expressed three primary concerns about the present day local coastal erosion problem:

- At the northern frontage residents have invested in defence works and are seeking reassurance that the defences will be maintained and continue to deliver the objectives described in the 2010 PAR;
- In the central frontage there is a concern that the defences to the north have disrupted sediment supply and could potentially increase erosion; and
- Residents and businesses have a perception that the erosion problem is reflected in investment confidence and blight.

In response to the erosion and damage to the *Phase 1* and *Phase 2* defences, and to the EA policy changes, options now need to be explored to make the defences more resilient and able to deliver the objectives outlined in the PAR that underpinned the 2011/12 works. Preliminary work[3] on the issue has generated a number of potentially viable works options with whole-life costs and has included preliminary consultation with key stakeholders. This aspect of the work may be considered further in a subsequent study. For now the primary concern of the present study is to better understand the causes of the erosion problem and to evaluate whether it is possible, using available data, to predict with confidence how the local coastline is likely to behave in the future.

2 http://thorpenesscfg.wordpress.com/

3 J. T. Mackley and their linked consultant Royal Haskoning DHV (RHDHV) working with local Engineer Andrew Hawes (AH)

4 Coastal Processes

Tidal levels within the North Sea basin are generated by the tidal wave moving in from the Atlantic. It enters the North Sea both from the north of Scotland and through the English Channel. The tidal wave, in effect, travels along the Suffolk coast in a southerly direction. The Thorpeness shoreline is exposed to a microtidal range (mean spring tidal range = 1.92m, BEEMS, 2013, Table 4.1) so that wave energy is focused onto a relatively narrow band of the beach. Consequently, the beaches at Thorpeness are more vulnerable to erosion during storms than beaches in macrotidal and megatidal ranges where wave energy is distributed over a larger beach area as the tide rises and falls during a given storm.

Table 4.1: Water Levels at Sizewell

Reference	Level (m AOD), HR (2010)	Level (m AOD), BEEMS (2013)
HAT	1.68	1.62
MHWS	1.22	1.20
MHW	-	1.04
MHWN	0.83	0.87
MSL	0.16	0.12
MLWN	-0.42	-0.62
MLW	-	-0.88
MLWS	-1.01	-1.10
LAT	-1.61	-1.69

Source: HR Wallingford, 2010; BEEMS, 2013

At Thorpeness the tidal system is ebb dominant, with flood and ebb tides running in a southerly and northerly direction, respectively. As already noted the beaches are very sensitive to variation in water level, particularly when a surge is superimposed on the tidal wave as a consequence of:

- Persistent northerly winds blowing over the North Sea which act to 'pile up' water levels in the southern North Sea;
- The abrupt switch between a strong southerly to a strong northerly wind potentially releasing a series of surge waves into the southern North Sea; and
- Storm surges entering the North Sea round the north of Scotland and progressing down the North Sea.

The return periods for extreme water levels (a combination of surge and tide) for locations to the north (Sizewell) and south (Aldeburgh) of Thorpeness are shown in Table 4.1.

Table 4.2: Extreme water levels (m ODN). Thorpeness is located at Ch. 40 - 41, between the two locations shown below.

		Return period (years)								
Site	**Ch.**	**1:1**	**1:5**	**1:10**	**1:25**	**1:50**	**1:100**	**1:250**	**1:500**	**1:1000**
Sizewell	**39**	2.05	2.41	2.57	2.78	2.93	3.09	3.29	3.45	3.61
Alde	**45**	2.05	2.41	2.57	2.78	2.93	3.08	3.29	3.45	3.60

Source: EA, 2007; Royal Haskoning, 2009

BEEMS (2012) also present estimates of the 1:10,000 year extreme water level for Sizewell (Table 4.3). This table includes estimates for present day sea level and for two future climate change scenarios based on different CO_2 emission. Although extrapolation of available data to obtain these estimates, and the assumptions made by the climate models for various emission scenarios, make these extreme water level estimates unreliable, they nevertheless provide an indication of extreme water levels that could conceivably occur at Thorpeness. While BEEMS (2012) has used UKCP09[4], in IPCC AR5[5] there has been a radical change in the definition of emissions scenarios. These are no longer based on the Special Report on Emissions Scenarios (SRES) but on Representative Concentration Pathways (RCP) that include changes in the specific characteristics of the scenarios and the ways in which they are defined. Although these changes may affect predicted future extreme water levels at Thorpeness (depending on the local down-scaling model used), an assessment of impacts is beyond the scope of the present report and may require addressing in subsequent studies.

Table 4.3: 1:10,000 year extreme still water level at Sizewell (m ODN) for present day and UKCP09 SRES: (a) A1F1 high emissions; and (b) H++ scenario (1.9m SLR)

Present day	A1F1	H++	Method
3.61	4.40	5.51	Joint probability analysis (JPA)
5.05	5.84	6.95	Generalised Pareto Distribution
4.26	-	-	Dixon & Tawn (1997)

Source: BEEMS, 2012

Most recently, estimates of 1:10,000 year extreme still water levels at Sizewell have been revised in BEEMS, (2014). Selected results from this work are shown in Table 4.4 which also includes data from McMillan *et al*. (2011) and HR Wallingford (2010) for comparison. The new H++ high estimate (with 1.9m of sea level rise, SLR) is 7.63m ODN, some 6.43m above the present mean high water spring (MHWS) tidal elevation. While these estimates of potential extreme tidal elevations are extremely unlikely, lower elevations have a greater probability of occurrence and should be considered in any future evaluation of coastal defence design options for Thorpeness.

Table 4.4: Revised 1:10,000 year still water level at Sizewell (m ODN), obtained using different methods, for a range of climate change and sea level scenarios. (Note: Levels are based on the Lowestoft sea level records for the period 1964-2014. High tide levels at Sizewell are assumed to be 15cm higher than at Lowestoft).

		2100			
	2008	**Medium emissions, 95% estimate (0.65m SLR)**	**High emissions, 95% estimate (0.8m SLR)**	**H++ low 95% estimate (0.93m SLR)**	**H++ high 95% estimate (1.9m SLR)**
McMillan *et al.* (2011)	4.21 ± 0.60	4.86 ± 0.60	5.01 ± 0.60	5.14 ± 0.60	6.11 ± 0.60
HR (2010)	4.84 ± 0.57	5.49 ± 0.57	5.64 ± 0.57	5.77 ± 0.57	6.74 ± 0.57

[4] http://www.metoffice.gov.uk/services/climate-services/uk/ukcp

[5] http://www.ipcc.ch/report/ar5/

			2100		
BEEMS (2014) (Additive approach)	5.73	6.38	6.53	6.66	7.63

4.1 Nearshore currents

In the vicinity of Thorpeness nearshore tidal currents affecting the beach and nearshore sediments are generated by a combination of astronomically forced tidal motions, wave action (including wave set-up, wave-generated offshore-directed sub-surface currents and wave-generated longshore currents), and storm-associated currents. While there are no known measurements of local tidal currents, they are believed to possess properties similar to those measured by Lees & Heathershaw (1981), Lees (1983) and most recently during a series of BEEMS studies around the Sizewell area.

As has been noted above, the flood and ebb tides flow southward and northward, respectively, approximately parallel to the coast and there are local spatial variations in tidal flow speed and directions near the coast due to the effects of local bathymetry and shoreline morphology. Although the tidal currents are rectilinear, with an ellipticity of *c*. 5%, there is also a marked asymmetry in tidal current velocities over a tidal cycle, with peak spring tide flood currents (southward) around 20% stronger than ebb currents (northward) so that offshore, the maximum flood tidal flow speeds reach 1.7m/s on spring tides and 0.9m/s on neaps and maximum ebb tidal flow speeds reach and 1.4m/s on spring tides and 0.8m/s on neaps.

Lees (1983) cites evidence to support the view that the Thorpeness headland and the Ness generates a lee eddy to the south of the Ness during flood tides and to the north of the Ness during ebb tides. As a consequence of the anticlockwise flow during ebb tides, the nearshore tidal flow north of the Ness flows south for a longer period than it flows north and thus enhances the potential to transport sediments alongshore from the north by wave action onto the Ness. The nearshore consequences to the tidal flow caused by a clockwise eddy circulation to the south of the Ness generated during flood tides is unknown. However, it is likely that it may weaken or even reverse the southerly directed flow for part of the flood tidal cycle.

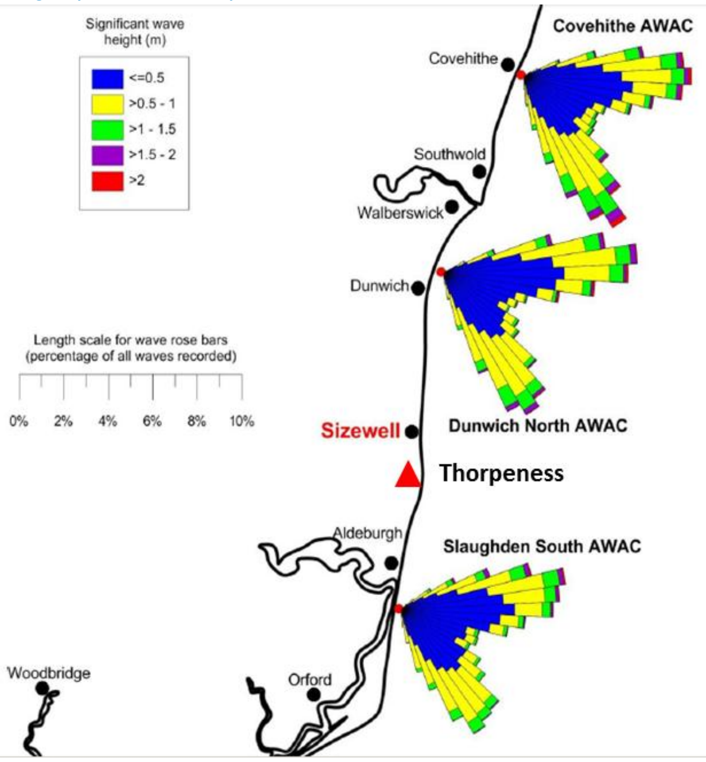
It is believed that the complex interplay between tidal flows offshore and the eddy features generated by the Thorpeness headland plays a part in the maintenance of the Ness and the beach morphodynamics along the Thorpeness frontage. However, there is presently insufficient data or numerical modelling results available to fully appreciate the significance of these processes with regards to shoreline behaviour and future evolution of the Thorpeness frontage.

4.2 Waves

Although waves have been the focus of considerable effort reported in a range of BEEMS studies summarised in BEEMS (2012), there are no long-term (>10 years) wave observations for the Suffolk coast or adjoining offshore areas. Thus in studies to define the wave climate, reliance has been made on wave hindcast data (e.g. Halcrow, 2001a,b).

In general available data show that Suffolk has a moderate wave climate with offshore waves from the northeast and southeast sectors being dominant. Less frequent waves from the north-northeast sector tend to be larger (Figure 4.1). The largest waves recorded by a Waverider buoy deployed offshore from the Sizewell-Dunwich Bank complex (SDBC) in 18m of water from 11 February 2008 to 24 February 2011 had a mean direction, θ, of 155° (the direction of travel), a significant wave height, *Hm0*, of 4.71m and peak period, *Tp*, of 9.1s (wave power, *Pw*, 1.54 x 105J/m/s), BEEMS (2012). The Halcrow (2001a) wave hindcast study estimated a maximum 1 in 100 year offshore *Hm0* value of 7.8m for waves from the N – NNE sector.

Figure 4.1: Wave rose figures showing measured[6] *Hm0* and θ during the three year period between October 2006 to September 2009. Bar lengths represent the percentage of waves recorded from each direction (5.625° intervals) and height (0.5m intervals).



Source: BEEMS, 2012

Owing to the longer fetch, waves generated by a given wind speed from the northeast are larger than those from the southeast for the same wind speed. The observational and hindcast wave data show no direct correlation between wind speed/direction and waves indicating that swell waves may play a role in defining the wave climate during some periods (BEEMS, 2012). Importantly, in a given year, the

[6] AWAC, see http://www.nortek-as.com/en/products/wave-systems/awac

differences between wave energy levels from each sector can mean that sediment transport under extreme waves differs in direction from that under more frequent moderate waves.

While overall the inshore wave climate of the Suffolk coast is well-correlated with the offshore conditions for wave directions between north and east, the net wave energy acting on different sections of the coast appears to change along the coast. A summary of *Hm0* values for inshore waves at stated return periods is shown in Table 4.5. A number of authors have attributed the shape of the Suffolk coast to the variation in wave energy along it (e.g. Pethick, 1999; Royal Haskoning, 2009). Such variability can contributes to changes in the direction of net longshore sediment transport over daily to annual time-scales.

There is strong wave refraction and attenuation (by bottom friction and breaking related to water depth, wave period, wave steepness and wave height) over the Sizewell-Dunwich Bank Complex, SDBC, (*cf*. Coughlan *et al.,* 2007; and Section 3). Dissipation processes regulate the maximum size of inshore waves and as a consequence the bank affords a degree of protection to the coast from large waves (*cf*. Tucker *et al*., 1983). For example, at Sizewell, modelling has shown that waves characterised by *Hm0* > 2.8 to 4.3m will break over the bank and reduce *Hm0* by around 1.5m. This is supported by measurements reported by BEEMS (2012) which show the wave heights landward of the bank are reduced by up to 1.3m and appear to be capped at around 2.5 to 3.0m.

Table 4.5: Return periods of nearshore wave heights at specified water levels

Wave height return period (years)	*Hm0* (m)	Water Level return period (years)	Water level (m AOD)
1	2.19	1	3.64
1	2.25	1	3.64
5	2.31	5	4.00
5	2.43	5	4.00
5	2.44	5	4.00
10	2.50	10	4.16
10	2.52	10	4.16
10	2.53	10	4.16
20	2.60	20	4.31
20	2.61	20	4.31
20	2.62	20	4.36
50	2.72	50	4.51
50	2.73	50	4.51
100	2.73	50	4.51

Source: Royal Haskoning, 2009

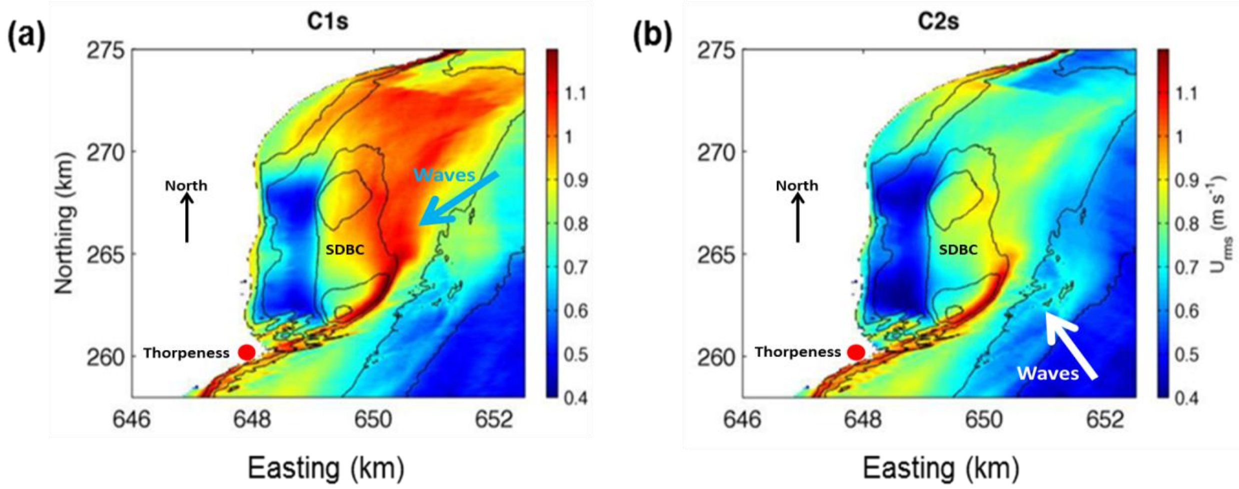
The relationship between bank elevation and the height of waves inshore of the bank is important from a beach morphodynamic perspective. Any lowering of the bank in the future will result in higher waves inshore and a redistribution of wave energy along the shoreline. Conversely, increases in bank elevation, regionally or locally, will increase the coastal protection. While this effect is largely confined to the shoreline north of Thorpeness, its effects may be felt further south and may be manifested as changes to sediment transport towards the Ness. A further consequence of wave attenuation by breaking concerns storm surge conditions which increase the water depth over the SDBC and allow a greater transmission of wave energy towards the shoreline. The morphology and behaviour of the SDBC is considered further in Section 5.

Results from SWAN wave modelling using up-to-date bathymetry are presented in BEEMS (2012). The results are from two wave scenarios that define storm wave conditions during MHWS conditions (i.e. +1.2m ODN) and with an additional surge component of 2.1m (i.e. +3.3m ODN), Table 4.6, are used for illustrative purposes.

Table 4.6: Results from the SWAN wave model, (‡, Figure 4.2a; † and ‡ , Figure 4.2b).

Scenario	*Hm0* (m)	*Tp* (s)	θ (°)	DSPR (°)	MSL (m ODN)
C1†	3.8	11	62 (NE)	16	+1.2
C2†	4.7	9	152 (SE)	16	+1.2
C1s‡	3.8	11	62 (NE)	16	+3.3
C2s‡	4.7	9	152 (SE)	16	+3.3

Figure 4.2: Wave orbital velocity near the sea bed during surge conditions in Greater Sizewell Bay. Colour shading indicates the magnitude of the orbital motions and contours plot the bed elevations 0, -2.5, -4, -10 and -15m ODN. (a) C1s = NE waves, 3.8m at 11s; (b) C2s = SE waves, 4.7m at 9s.

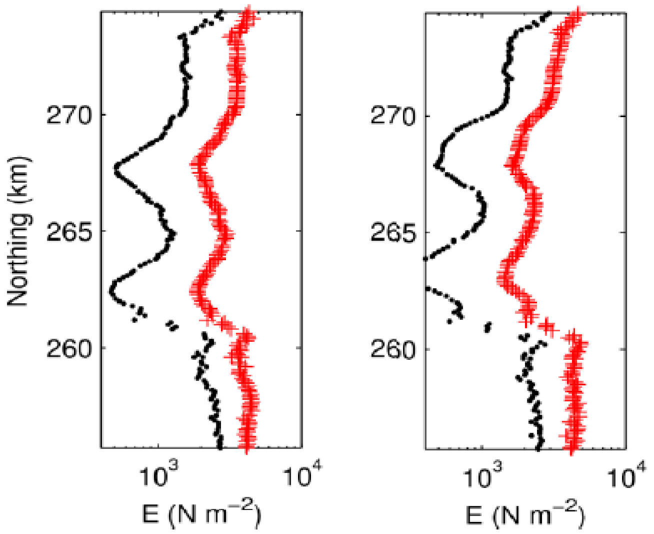


Source: BEEMS, 2012

Figure 4.2 show the bottom wave orbital velocity, *Uw*, distribution predicted by the SWAN wave model in the vicinity of Thorpeness for: (a) NE; and (b) SE waves. Since wave-induced near-bed flows impose a shear stress on the sea bed, *Uw* values are related to sediment mobility. However, the wave motion alone results in very little net sediment transport. Rather, it provides the force necessary to re-suspend bed sediments which can then be transported by any superimposed tidal current. It is striking in Figure 4.2 that irrespective of wave direction, the model results show that Thorpeness is located in a zone of high *Uw* values (> 1m/s) that extends around the offshore contour (-4m ODN) of the southern part of the SDBC and south westwards from the southern end of the bank system to the Thorpeness frontage. The model results show also complex interactions with the Coralline Crag ridges that extend north east from Thorpeness (see Section 5 and Figure 5.2). Calculations show that the *Uw* values predicted by the model around the Thorpeness region are sufficient to mobilise the sandy sediments that dominate the region (*cf*. Soulsby, 1997).

The SWAN model outputs are also presented in Figure 4.3 which shows the north-south distribution of wave energy along the -2.5m ODN contour for MHWS plus surge (+3.3m ODN, red crosses) and MHWS (+1.2m ODN, black crosses) conditions for NE and SE wave scenarios (Table 4.6). There is a clear peak in wave energy at Thorpeness (Northing 261) which extends south and out of the model domain. The wave energy level is approximately the same as those predicted near Walberswick/Southwold at the northern limit of the model domain. The implications of these model results for the Thorpeness frontage are considered further in Section 6.

Figure 4.4: SWAN model output showing wave energy distribution along the -2.5m ODN depth contour (red crosses) for the scenario (a) C1s and (b) C2s. Also shown are results for the same wave conditions for a still water depth value = MHWS (i.e. scenarios C1 and C2, +1.2m ODN, black crosses)



Source: BEEMS, 2012

The breaking wave height along the frontage at the Mean High Water Spring water level has been determined using the method from the US Army Corps of Engineers Shore Protection Manual (1984).

Table 4.7 shows the breaking wave height and the wave crest level at approximately the lowest beach level (-1.0m AOD) for a number of typical wave periods.

Table 4.7: Calculated theoretical breaking wave height associated with MHWS still water level

Wave Period (s)	Breaking Wave Height (m)	Wave Crest Level (m AOD)
10.6	1.36	1.66
8.0	1.33	1.64
6.0	1.28	1.59

For a 1:50 year wave height and 1:50 year water level the maximum wave run up is estimated to be 5.83m AOD for a beach slope of 1:3.5 at the toe of the present defence structure.

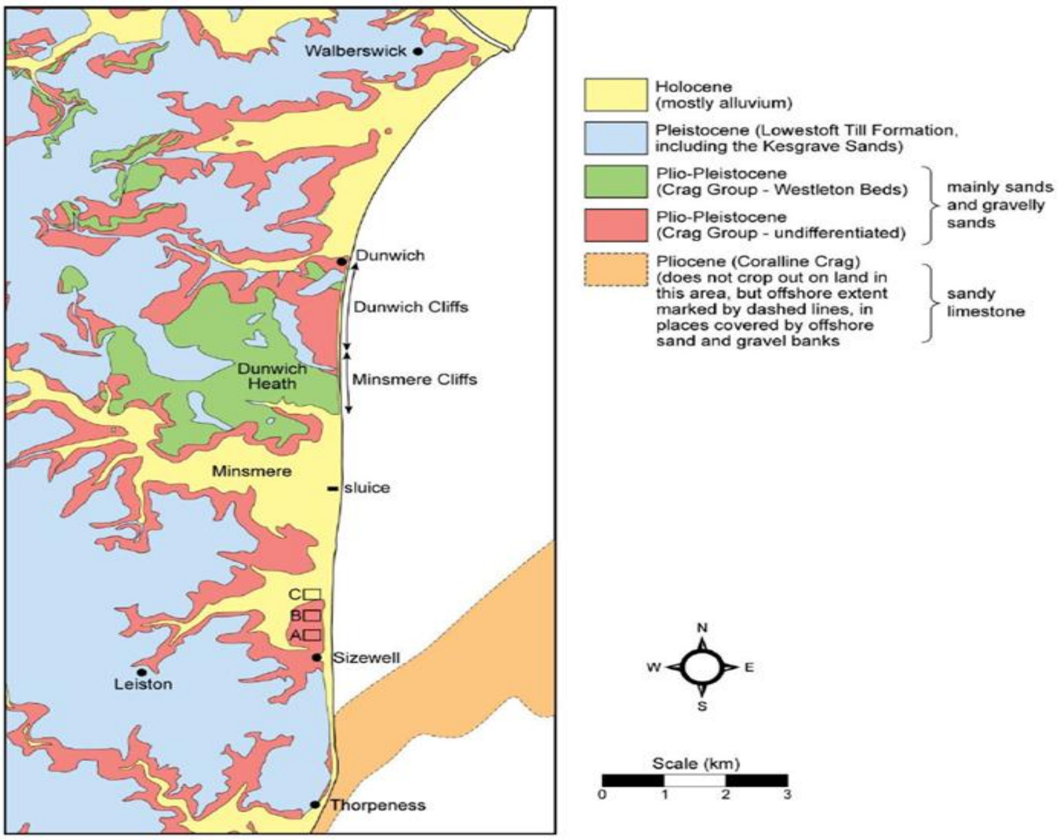
5 The Coastal Environment

5.1 Geology

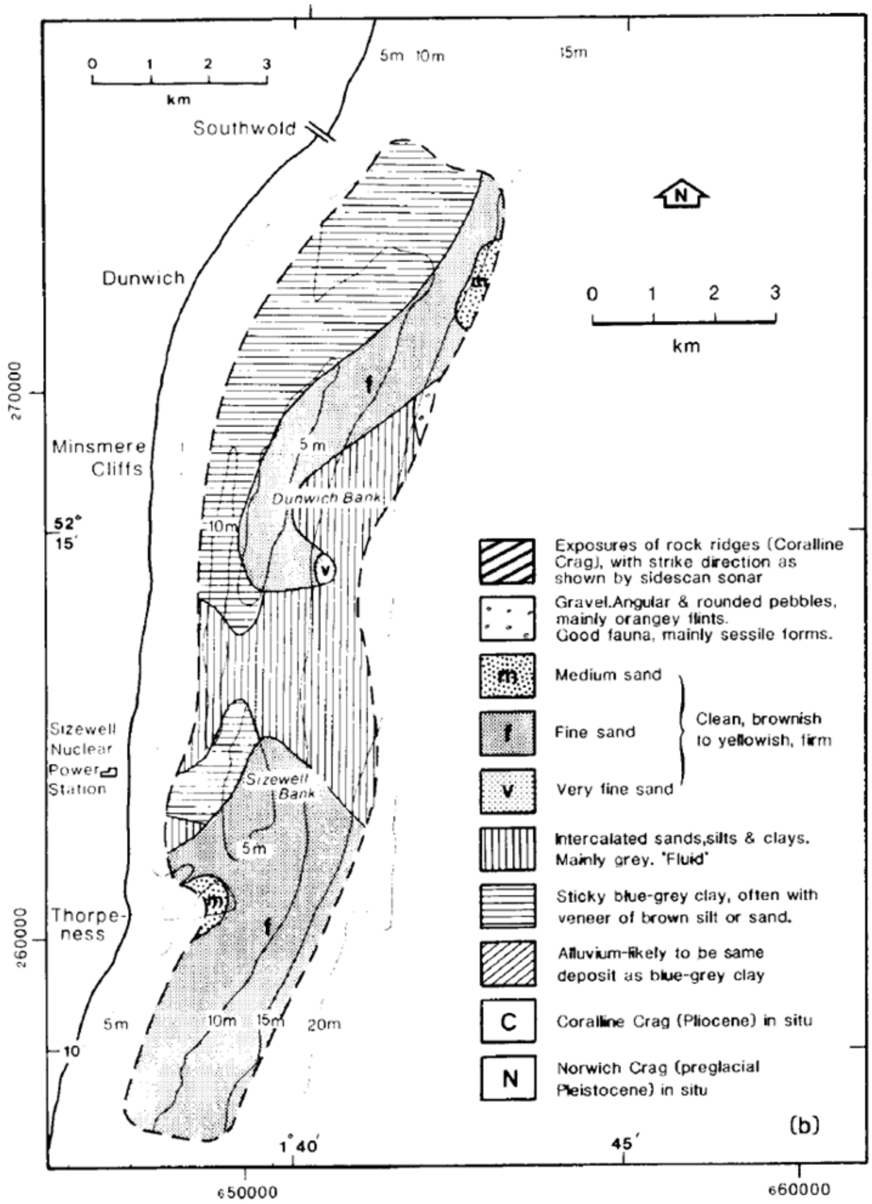
The regional geology provides a context for understanding patterns of change to the East Anglian coastline (Figure 5.1). Here we only consider the most recent marine transgression from the last glacial maximum when sea level was approximately 120m lower than in the present day. During the period 8000-6000 BP the sea level rose rapidly and established an overall morphology and bathymetry similar to the present day (Lees, 1980; Eisma *et al*., 1981; Shennan *et al*., 2000). From 4000 BP to present sea level rise has occurred at a rate of 1-1.5mm/year. There is evidence of accelerating relative sea-level rise in recent years with an average rate of 2.59 mm/yr (1956–2009) and 4.65 mm/yr (1993-2009) (BEEMS TR139). For the past 50 years, a rate of 2.57 mm/yr has been measured at the Lowestoft tide gauge (Woodworth *et al*. 2009). The general effect of sea-level rise is to push the soft shoreline landwards, except where coastal processes favour sediment accumulation. . To the north of Thorpeness the low cliffs comprise largely of unconsolidated Crag Group sediments (Zalasiewicz *et al*. 1988). Near Thorpeness the Crag is covered by 2-4m of glacial till (the Lowestoft Till Formation).

Figure 5.1: (a) Simplified geological map of the land between Walberswick and Thorpeness (Source: BEEMS, 2012); and (b) offshore sediment distribution (Lees, 1983).

(a)



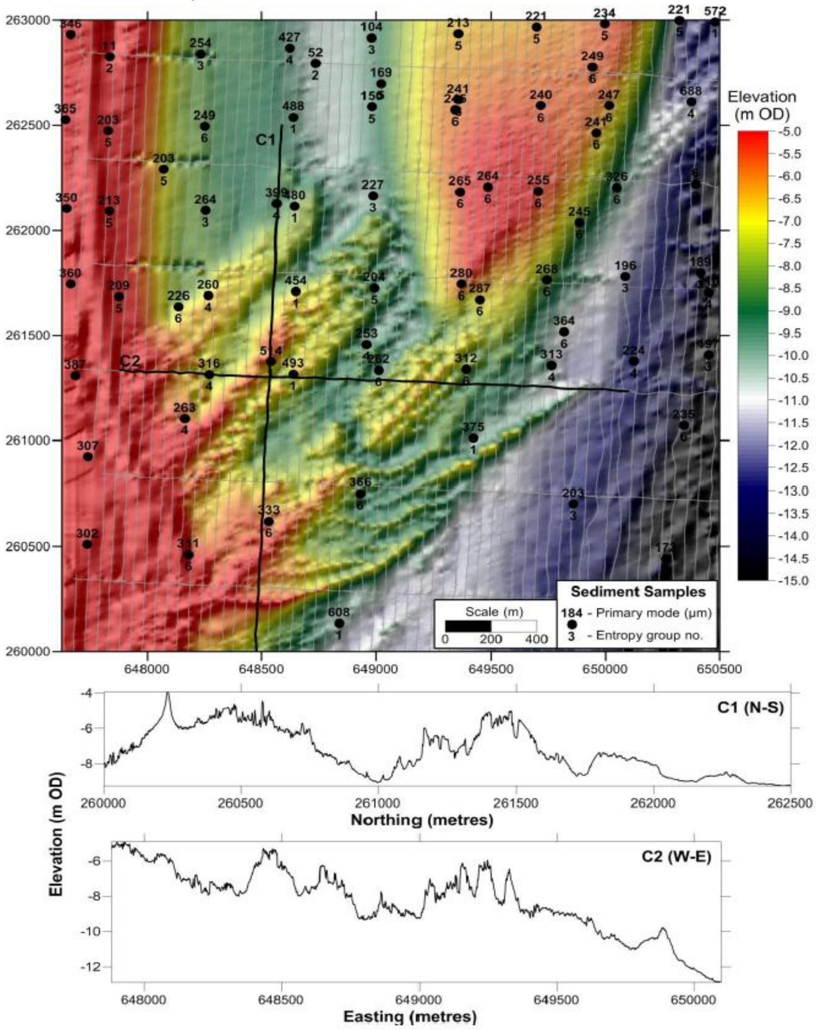
(b)


0 1 2 3
km
5m 10m
15m
Southwold
Dunwich
Minsmere
Cliffs
270000
52°
15'
Dunwich Bank
5 m
10m
f
m
v
Sizewell
Nuclear
Power
Station
Sizewell
Bank
5m
f
m
Thorpe-
ness
260000
5m
10m
15m
20m
10
1°40'
45'
650000
660000
N
0 1 2 3
km
Exposures of rock ridges (Coralline Crag), with strike direction as shown by sidescan sonar
Gravel.Angular & rounded pebbles, mainly orangey flints. Good fauna, mainly sessile forms.
Medium sand
Fine sand
Very fine sand
Clean, brownish to yellowish, firm
Intercalated sands,silts & clays. Mainly grey. 'Fluid'
Sticky blue-grey clay, often with veneer of brown silt or sand.
Alluvium-likely to be same deposit as blue-grey clay
C
Coralline Crag (Pliocene) in situ
N
Norwich Crag (preglacial Pleistocene) in situ
(b)

The geological feature of greatest significance to Thorpeness is the ridge of Coralline Crag composed of cemented iron-stained Pliocene shelly sand (*cf*. Bamber, 1995) that extends north-eastwards from Thorpeness beneath the modern beach sediments (Figure 5.1 and Figure 5.2). Its greater resistance to erosion compared with the other deposits, and its concurrence with the bathymetry, is confirmed by seismic evidence (HRW *et al*., 2002). It has been suggested that the position of the Ness to the north of Thorpeness is comparatively fixed by this geological unit which also serves to anchor the SDBC. The Coralline Crag ridge under Thorpeness is also recognised as being important in protecting the Sizewell coast (EDF, 2002[7]). A slight 'headland' at Thorpeness occurs because these relatively more resistant rocks occur at the base of the cliff, and they extend out to form the offshore sea bed (Bamber, 1995).

7 http://sizewell.edfenergyconsultation.info/wpcontent/uploads/SzC-Stage-1-Environmental-Report.pdf

Figure 5.2: Bathymetry of the southern end of the trough showing ridges of Coralline Crag extending north eastwards from Thorpeness under the southern end of the SDBC. The black circles indicate the location where sea bed sediment samples have been obtained.



Source: BEEMS, 2012

5.2 Sea Bed Sediments

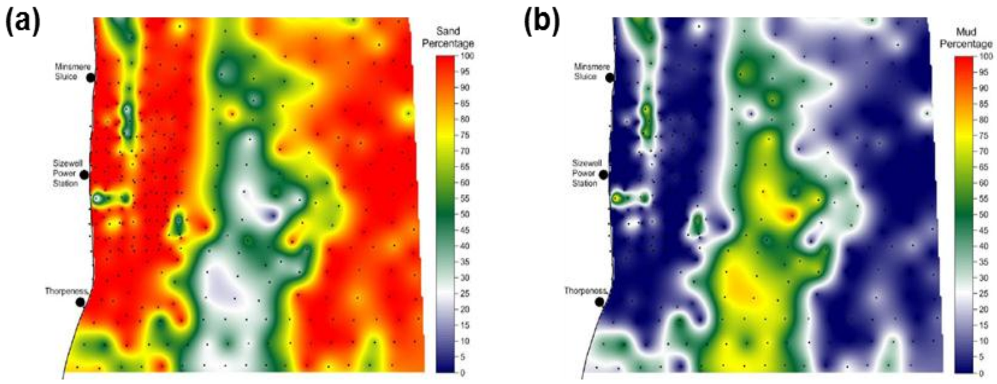
Surficial sea bed sediment maps for the southern North Sea have been produced by Cameron *et al*. (1992) and the British Geological Survey (BGS, 1996). Offshore the seabed is composed of clayey, silty, fine sands[8] of the Westkapelle Ground Formation overlying the shelly, medium to coarse grained, sands[9] of the

8 Westkapelle Ground Formation

9 Red Crag

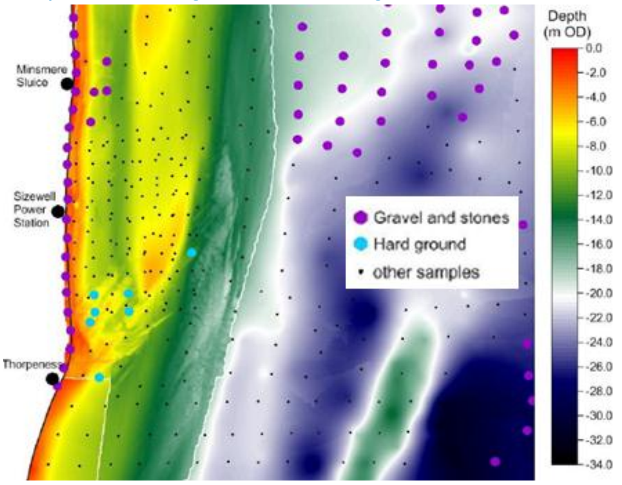
Red Crag. The offshore distribution and type of sea bed sediment is reported in BEES (2012) and is summarised in Figure 5.3 and Figure 5.4.

Figure 5.3: Offshore sediment distribution showing: (a) percentage of sand; and (b) percentage of mud in the Thorpeness vicinity.



Source: BEEMS, 2012

Figure 5.4: Distribution of samples described in the field by the surveyor as containing gravel and stones (purple dots), or as 'hard ground' containing little or no unconsolidated sediment (blue dots) superimposed on the bathymetry.



Source: BEEMS, 2012

Key findings from a wide range of studies of sediments and bedforms relevant to the Thorpeness area reported by BEEMS (2012) include:

- The shoreline morphology, grain size distribution and sand colour evidence suggest that sand may move offshore from Thorpeness towards the southern end of Sizewell Bank. This supports previous observations reported by McCave (1978) and Carr (1981);
- Bedform orientation and cross-sectional evidence reveals a southward movement of sand along much of the seaward flank of the SDBC. There is also some evidence of a localised northward movement of sand along the south-eastern (shoreward) side of Sizewell Bank;

- At the southern end of the trough between Thorpeness and the southern end of the SDBC four well-defined ridges (height typically 2.5m) extend in a north easterly direction away from the Ness. These ridges are composed of Coralline Crag and are relatively resistant to erosion (Figure 5.2). The ridges extend beneath the southern end of Sizewell Bank and crop out on its eastern side. There is therefore no continuous ‘deep’ water channel between Thorpeness and the southern end of Sizewell Bank. BEEMS (2012) suggest that this local geology and bathymetry offers resistance to water flow and thus may present a barrier to bed-load sediment transport; and
- In the deeper water (c. 18m) southeast of Thorpeness the horns of large submarine barchanoid dunes indicate long-term net transport to the south or southeast thus conforming the general understanding of the southerly sediment transport pathways.

5.3 Sediment Transport

The offshore zone seaward of Thorpeness as far as approximately 2^{o} E, has a great number of sea bed mobility indicators including sand streaks and ribbons, megaripples and sandwaves. Where there is any indication of asymmetry, the movement is more frequently, towards the south, towards the Thames Estuary (Stride, 1982). Further offshore sediment movement is indicated by bedforms as being more frequently towards the north (Stride, 1982; Royal Haskoning, 2009).

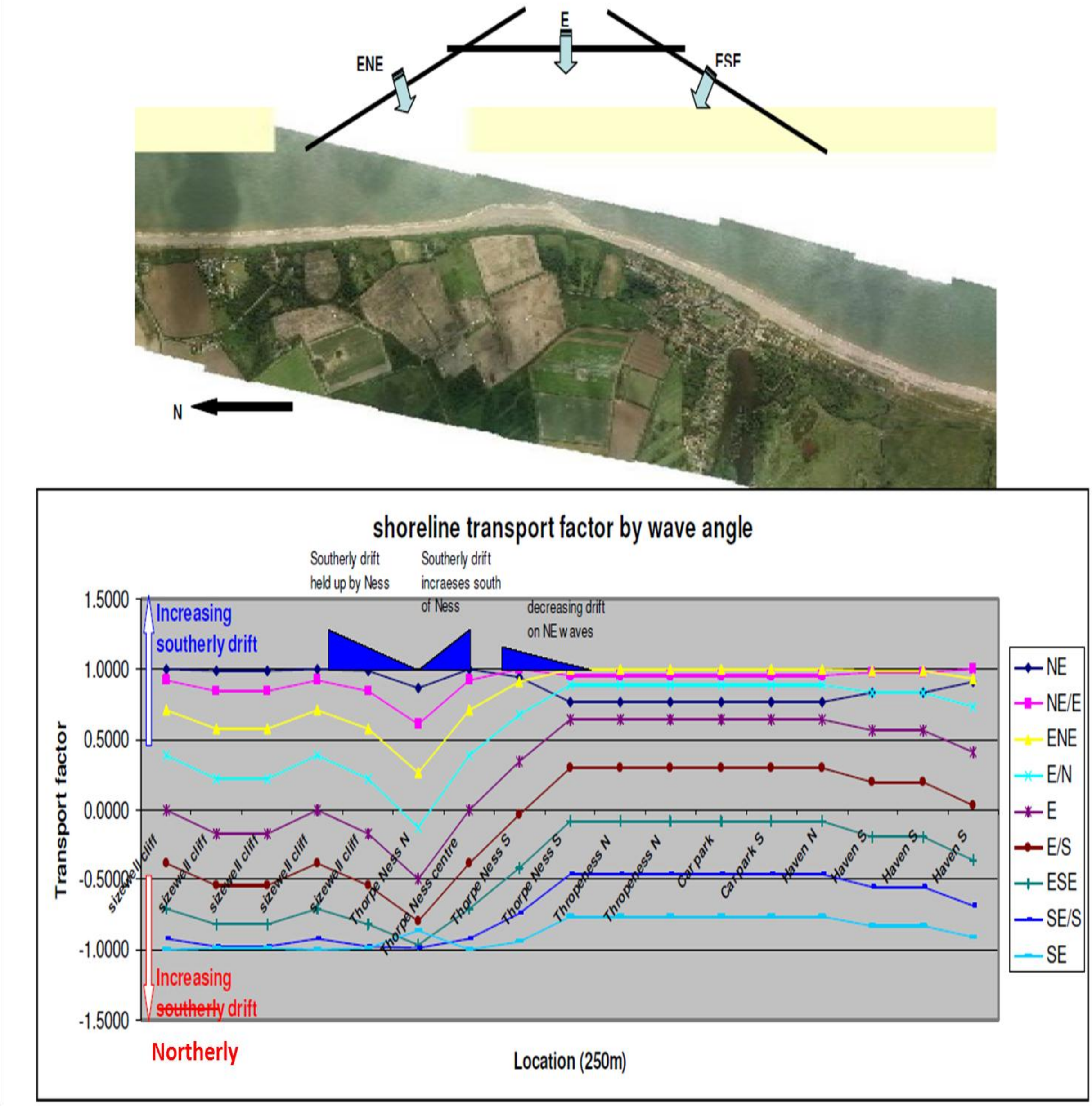
Although the geomorphological expression of sediment transport is a western movement of the SDBC and the coastline, evidence from grain size and sedimentary bedforms shows clearly a net southward transport of finer and medium sands in the long-term (likely years to decades and greater). It is expected also that gravel may also move south (BEEMS, 2012). In addition there is anecdotal evidence in the Thorpeness area of periods of northerly directed gravel transport driven by waves from southerly directions. BEEMS (2012) note that fluctuations in the supply of sediment from the north may contribute to the long-term future behaviour of the coast at Thorpeness.

In the wider area interaction between cliff erosion, alongshore sediment supply and transport, the movement of nearshore sand banks, tidal flows, waves and storm surges control the coastal landscape between Southwold and Thorpeness. The net southerly drift of sediment towards Thorpeness along the Sizewell frontage is maintained by complex sediment transport processes, which begin with the input of around 40,000m^3/year of sediment from cliff erosion at Dunwich to the north. Several longshore sediment models have been developed for the Suffolk coast. The studies that include the Thorpeness area are:

- A beach plan shape model by Halcrow (2001a,b) from Southwold to Thorpeness. All calculated transport rates were directed to the south and were relatively low (11,000m^3/year at Minsmere and 3,500m^3/year at Sizewell). The result at Thorpeness indicated wave-driven southerly longshore transport rate of only 300m^3/year. This reflects the shape of the embayment between Minsmere and Thorpeness and the corresponding changes in incident wave angles; and
- Vincent (1979) and Onyett and Simmonds (1983) report wave-driven southerly directed longshore transport rates of 200,000m^3/year and 55,000m^3/year to the north and south of Thorpeness, respectively.

The coastline between Sizewell and Thorpeness is sensitive to changes in wave energy and sediment supply and is frequently affected by storm surges which can result in significant beach, dune and cliff erosion and result in quite large fluctuations in beach position (BEEMS, 2012). A further investigation of alongshore sediment transport focussed specifically on Thorpeness and considering only relative differences in transport rates is reported by Royal Haskoning (2010), Figure 5.5. The analysis considers different in-shore wave directions applied uniformly along the coast, in comparison with the shoreline orientation. Unfortunately, the figure was incorrectly labelled in the original document causing some initial confusion. While being an oversimplification of alongshore transport due to no account being taken of wave climate, the analysis nevertheless illustrates the importance of shoreline orientation to incident waves and demonstrates that a more detailed analysis that takes account of actual wave conditions using a more robust approach might prove to be informative with regards to better understanding the local sediment movement for different wave conditions.

Figure 5.5: Sediment transport assessment.

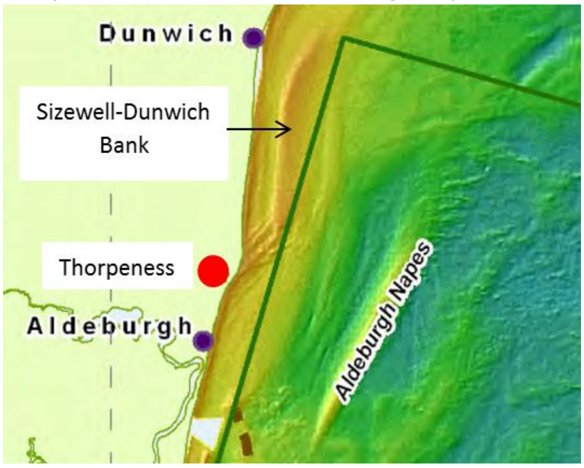


Source: Royal Haskoning, 2010a

5.4 Sea Bed Features

Offshore the SDBC is the most significant feature affecting coastal processes at Thorpeness. The bank is approximately 11km long and 1km wide with a 1:60 slope on the western flank and a 1:200 slope on the eastern flank (Figure 5.6). SDBC is connected to the headland at Thorpeness by a series of erosion resistant Coralline Crag ridges. Between the SDBC and the shore is a 6-8km long shore-parallel bathymetric low. The channel between the Ness and the SDBC is between 6 to 8m deep. Another less well-defined bank orientated at around 30°N called Aldeburgh Napes is located approximately 10km offshore from Aldeburgh (Figure 5.6).

Figure 5.6: Offshore bathymetry based on Seazone Solutions Limited data gridded at 75m showing the location of Thorpeness, the SDBC and Aldeburgh Napes.

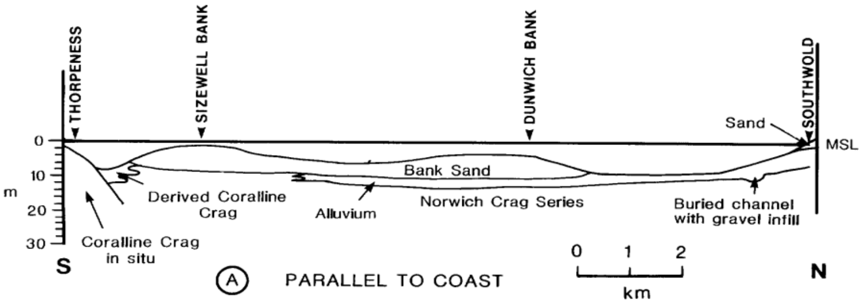


Source: Emu, 2009

Without recourse to a modelling study, the influence of Aldeburgh Napes on the local coastal processes at Thorpeness is presently unclear. However, it is anticipated that the bank will afford some degree of wave shelter for certain wave directions and may act to focus waves on certain stretches of the coast for other wave directions. Further, if the bank is subject to cycles of erosion and accretion, its impact on the shoreline is also likely to change. With available information it is not possible to be more precise about the role of the bank in the morphodynamic behaviour of the Thorpeness shoreline. It is believed that comparisons between the EA bathymetric survey data from 2014, with surveys from earlier periods may shed some light on this issue.

A schematic cross-section through the major sediment units parallel to coast from Thorpeness to Southwold is shown in Figure 5.7. The more resistant in situ Coralline Crag outcrop beneath Thorpeness is shown at the southern end of the section together with derived Coralline Crag material deposited a little further north.

Figure 5.7: Schematic diagram of the major sediment units parallel to coast from Thorpeness to Southwold.



Source: Lees, 1983

It is useful to review briefly the past morphological behaviour of the SDBC as this provides understanding of contemporary behaviour and guidance on how the system may behave in the future.

Hydrographic chart analyses by Carr (1979) for the period 1824 to 1965 show that:

- Sizewell Bank extended northwards at a rate of around 50m/year to join Dunwich Bank around 1921-1922 to create the SDBC;
- During the period 1867 to 1965 the individual and composite elements of the present SDBC migrated landwards at a rate of around 11m/year, reducing the width of the area between the beach and the bank by around 35% (0.9km); and
- The volume of sediment lost between Southwold and Thorpeness during the period 1867 to 1965 is approximately equal to the gain of sediment by the banks. However, Carr (1979) remarks that it is not tenable to argue for a simple exchange of material between the beaches and the banks.

The work of Carr (1979) is supported by more recent analysis of SDBC behaviour by BEEMS (2012) who report that there has been a progressive landward movement of the SDBC over the last 150 years. This has been driven by:

a) erosion of the eastern flank by tide and wind-driven currents which drive the southward movement of sediments; and

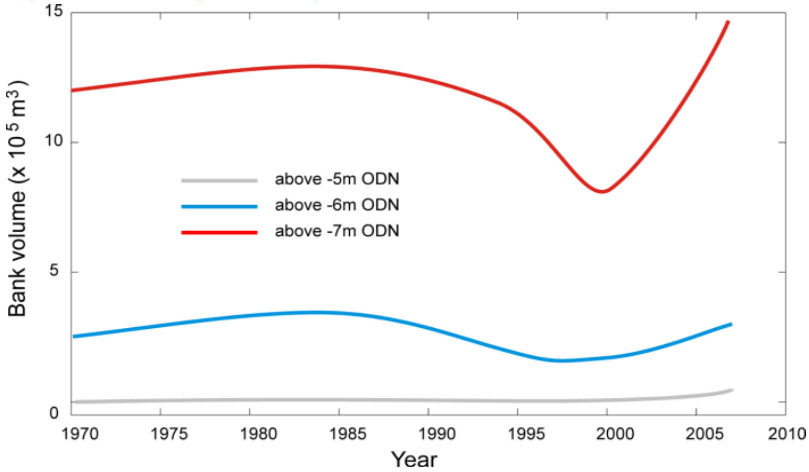
(b) wave-induced transport across the crest of the banks in a predominant NE to SW direction, especially during storms which are most frequent and severe from a north easterly direction.

BEEMS (2012) conclude that there is no significant modern-day alongshore exchange of sediment from the area south of Thorpeness northwards into Greater Sizewell Bay. Spatial trends in particle size modes and bedform asymmetry indicate net sediment transport from north to south in the area east of Sizewell Bank and in the trough. Morphological evidence also suggests north to south longshore drifting around Thorpeness.

Studies (e.g. BEEMS, 2012) have shown that the southern end of the SDBC has remained anchored to the seabed at the Thorpeness headland outcrops of Coralline Crag (Figure 5.2). While the position and height of the SDBC has varied over time, a slow anti-clockwise rotation about this ‘fixed’ southern point, and cycles of erosion and accretion, has resulted in progressive shoreward migration of the SDBC. In their summary report of numerous studies, BEEMS (2012) conclude that the westerly rotation is driven by wave action which transports sediment from the crest into the adjacent trough to the west, most significantly during north-easterly storms.

The BEEMS (2012) summary report confirms the earlier work of Carr and shows that the SDBC continues to migrate shoreward. Interestingly, while the slow shoreward migration of the SDBC has continued uninterrupted since observations were first made in 1824, contemporary data shows that the volume of the bank varies through time. For example, Figure 5.8 shows the changes in the volume of SDBC between 1970 and 2007 measured below the -5, -6 and -7m contours (derived from BEEMS, 2012). These data show: (a) a slight increase in bank volume from 1970 to 1985; (b) a decrease in bank volume between 1985 and 2000; and (c) a sharp increase in bank volume from 2000 to 2007. While on first inspection these data might appear to suggest losses or gains of sediment to the bank system, there is little evidence of change to the swale areas or the shoreline and thus the apparent gains in volume probably reflect lowering and lateral spreading of the bank. Conversely, volume losses probably reflect elevation increases and narrowing of the bank system. Access to the original data would help to understand this behaviour better.

Figure 5.8: Temporal changes in the volume of the SDBC from 1970 to 2007.



Source: Modified from BEEMS, 2012

While arguments about bank growth and spreading have credibility, it is equally noteworthy that studies of the evolution of the SDBC (e.g. Carr, 1981; Lees, 1982; Pontee *et al.,* 2004; Pye & Blott, 2006) have identified that relatively large volumes of sediment supplied to the coastal zone north of the SDBC from cliff erosion during periods of higher wave energy, delivers sediment initially onto the Sizewell beaches and then possibly to the SDBC from Thorpeness. This supports the much earlier suggestion by McCave (1978) that sediment is transferred from Thorpeness to the SDBC. It has been further suggested that this process in turn raises the height of the bank thereby providing more protection to the adjacent coastline from waves. This reduction in wave energy reduces the sediment supply to the bank and thus bank volume (and height) will decline over time, exposing the shoreline to increased wave energy levels which again act to increase the sediment supply to the bank if the mechanisms to move sediment offshore and northwards from Thorpeness continue to be effective. The cyclical change in the morphology of the SDBC indicated in Figure 5.8 supports this view. At a larger regional scale, quasi-periodic cycles of offshore bank growth and decay have been linked with rapid episodic erosion events along the Suffolk coast resulting in the removal and/or redistribution of beach material further down the beach profile or offshore.

It has been speculated that some proportion of the sand component of the transported sediment arriving at the northern margin of Thorpe Ness is transported offshore and onto the SDBC leaving the gravel component as a lag deposit to form the core of the Ness. Royal Haskoning (2009) report that the net southerly longshore sediment transport past Thorpe Ness is low. This is likely to act therefore as a significant constraint on sediment movement to the south and severely restrict the ability of natural processes to replenish sediment lost from beaches during storm conditions if an offshore supply is absent.

5.5 Thorpe Ness

While sea level rise has generally resulted in erosion of the soft coastal geology of Suffolk, sediment accretion has occurred at some locations where coastal processes act to favour accumulation. One such area, locally called Thorpe Ness, is situated approximately 1km north of Thorpeness village. The Ness it is an accumulation of sand and coarse sediments in the form of a wide arcuate beach. Pye (2001) defines the Ness as an embayment beach ridge plain consisting of a series of relict storm beach ridges and an active shoreface system, which has built out seawards to form the present landform. The long-term stability of this feature in the backshore area is demonstrated by areas of well-established vegetated shingle. Seawards of this stable area is an area of more mobile shingle with transitory berm features. Similar coastal features are found at other locations and are one of the defining characteristic of Suffolk’s coastline.

The origin and maintenance of the Ness is related to the relationship between the dominant wave direction, longshore transport and the coastal orientation. At Thorpeness a coastal projection is associated with the Coralline Crag outcrop (*cf*. Birkbeck College & Babtie, 2000) and by presenting a less acute angle between the shoreline and the approaching waves, and thus reducing longshore transport potential significantly, this feature encourages the accretion of wave-driven material on the north-face of the outcrop. Conversely, the south side of the ‘Ness’ there is either little net sediment gains or losses owing to efficient interception of longshore transport up-drift and the possible transport of some percentage of the net southerly drift off shore to the SDBC.

In most cases, over an extended period of time, nesses tend to moves *en mass* in a northwards direction as material is deposited on and lost from the northern and southern margins, respectively. For example Benacre Ness has move approximately 6km in 200 years (May & Hanson, (2003). However, there has been no discernable movement of Thorpe Ness and it has been suggested that its position astride the Coralline Crag outcrop has stabilised the Ness and restricted its natural tendency to move northwards. However, the mechanisms to achieve this have not yet been fully explained.

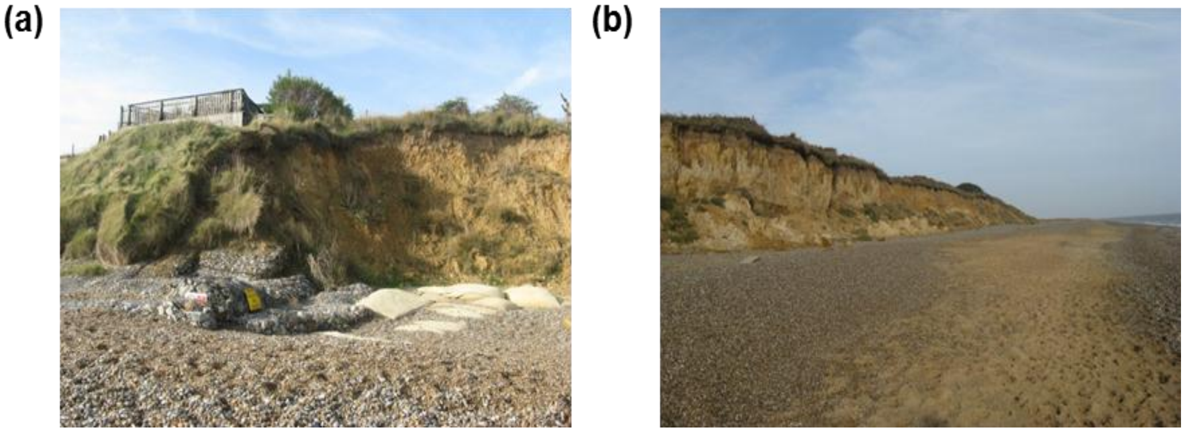
In considering the establishment and maintenance of the Ness Robinson (1980) asserts that a sediment bridge exists between the SDBC and the coast at Thorpeness, and that the onshore transfer of sediment from the SDBC has helped to maintain the Ness feature and given it a stability of position which is not apparent for other similar Nesses along the East Anglian coast. This view is diametrically opposed to that from McCave (1978) who advanced a hypothesis suggesting a transfer of sediments from the SDBC to the shore at Thorpeness. Further evidence to support the view of McCave that sediment is transferred from Thorpeness to the SDBC is provided by Carr (1981) who examined sediment grain size trends. The issue of sediment transfer magnitude and direction between the shoreline and the southern end of the SDBC remain unresolved. However, irrespective of the transfer direction, any transfer of sediment between the Ness and the SDBC is likely to be greatly affected by the tidal flows between the two features and to have a significant impact on sediment delivery to the Thorpeness frontage.

5.6 Cliff Erosion

BEEMS (2012) present data on cliff recession and the volumes of sediment supplied to the coast from cliff erosion at Thorpeness between 1883 and 2010. These values were obtained using data from Environment Agency monitoring profiles, Ordnance Survey six-inch County Series maps (surveyed 1883, 1903, 1926, 1951 and 1970) and Environment Agency beach profile data (surveyed summer 1991 and July 2010). For EA profile numbers SO37 (S1B8) (Thorpe Ness north) and SO38 (S1A1) (Thorpeness, Beacon Hill Lane) recession rates and sediment release from 1883 to 2010 are reported as being zero (BEEMS, 2012). However, recent beach lowering has exposed some section of the Thorpeness cliffs to wave attack and some erosion has occurred.

It is clear, however, that cliff erosion to the north of the last property on North End Avenue is ongoing and significant. Figure 5.9 shows: (a) shoreline set-back of around 10m immediately to the north of the most northerly gabions; and (b) actively eroding cliffs with recent falls and slumps evident. While being present at this location, it is understood that the Coralline Crag dips to the north here and thus shoreline resistance to erosion is likely to be less than further to the south. Further, the gabion defences built in 1975 add further to coastal resilience and to edge effects shown in Figure 5.9a, thereby possibly accelerating erosion to the north for some undefined distance.

Figure 5.9: (a) shoreline set-back of around 10m immediately to the north of the most northerly gabions; and (b) looking north from the location in photograph a towards actively eroding cliffs with recent falls and slumps evident.



Source: Report Author, 31 November, 2014.

5.7 Thorpeness Beach

A wide beach, typically with a trough-shaped profile, backed by in the north by soft cliffs with a height around 4m AOD composed of a mixture of sand and gravel-size sediments (MSG) derived from glacial till, has been present historically at most locations along the Thorpeness frontage. The shingle beach has a number of ridged features and an active shoreface system. All available evidence indicates that there is a net southerly drift of sediment and a potential for net offshore transport of fines under erosive conditions.

It is important to note that the majority of the beach is composed of sand which is buried beneath a coarser surface layer of well-rounded shingle[10]. The characteristics of the surface layer is the product of complex sorting processes that preferentially select different grain sizes from the beach 'core' depending on the forcing conditions (waves). As a result the surface layer is highly unstable with lateral changes occurring within a few metres and temporal changes occurring over periods as short a single tidal cycles (Powell, 1990). It is noted here that the major efforts to understand beach dynamics have focussed on sandy beaches and despite their widespread occurrence only limited attention given to gravel beaches and even less to beaches composed of mixed sand and gravel. Empirical approaches and numerical models of MSG beaches are therefore poorly developed and results are therefore unreliable. For this reason the prediction of their response to storms, or their subsequent recovery time is not possible at this time and reliance must be given instead to observations where they exist.

10 Rounding of this nature implies that the sediments have been subjected to abrasion for a considerable period. Owing to the size of the individual particles tidal currents would be insufficient to produce such well-developed rounding and thus wave action is considered to be the primary mechanism.

6 Coastal Morphodynamics

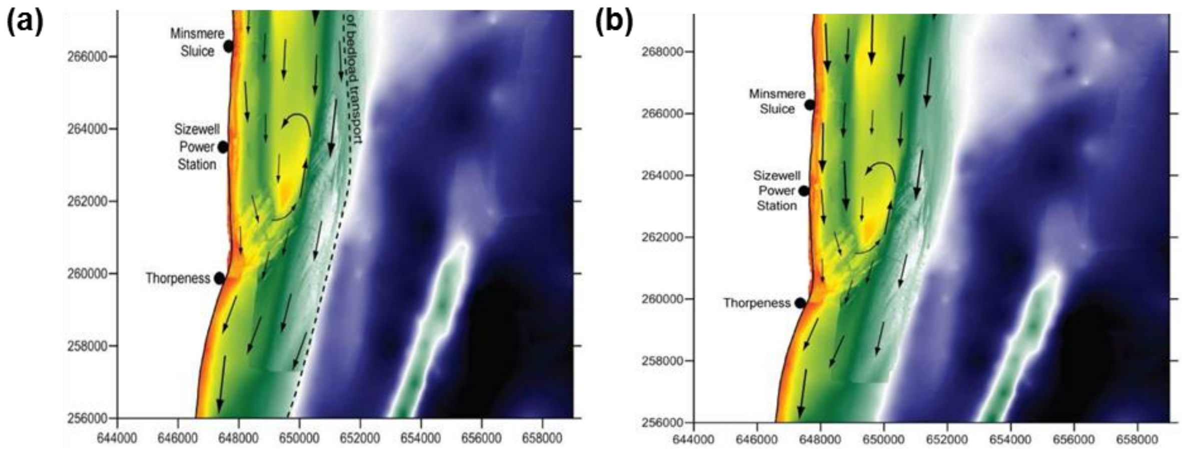
In this section evidence presented in Sections 3 – 5 is used to develop a conceptual understanding of the processes that have given rise to the three major cycles of erosion recorded at Thorpeness since 1900. This information will be used in turn to comment on possible future coastal evolution in the short (annual) to medium-term (decadal).

6.1 Sediment transport around the Ness

Since the net alongshore sediment transport from Sizewell Bay is directed to the south, there must be mechanisms that facilitate sediment to move around the Ness and thereby maintain the beaches at Thorpeness. Recent data analysis based on interpretations of survey data and grain size trends has identified sediment pathways associated with the Ness and the SDBC (BEEMS, 2011). This is demonstrated schematically in Figure 6.1 for: (a) bedload; and (b) suspended load. Irrespective of the transport mode, Figure 6.1 indicates that some proportion of the net southerly sediment drift is drawn offshore north of the Ness and enters a recirculation region around the Sizewell Bank (possibly associated with the flow eddy previously discussed). The remaining sediment continue its journey southwards being first deflected offshore by the Ness and Thorpeness headland and then drawn in closer to the coast. Appealing as this simple picture is, it omits some important details relevant to the local conditions at Thorpeness and must therefore be considered only as a guide to likely pathways suggested in previous studies.

Reinforcing previous conjecture Pethick & Leggett (1993) suggested that the Ness is the main point at which sediment moving south is taken offshore into the SDBC. However, according to Halcrow (1998), the high percentage of flint shingle at Thorpe Ness implies a seaward source, as the cliffs nearby cannot provide the required volume of this type of sediment. This suggestion is disputed in Future Coast (2002) where it is argued that shingle-sized sediment is not presently sourced from offshore because, even under storm conditions, the currents are not strong enough to mobilise this size of sediment. Therefore uncertainties remain as to the interrelation between the Ness and the SDBC and with the southern transfer of sediment to Thorpeness.

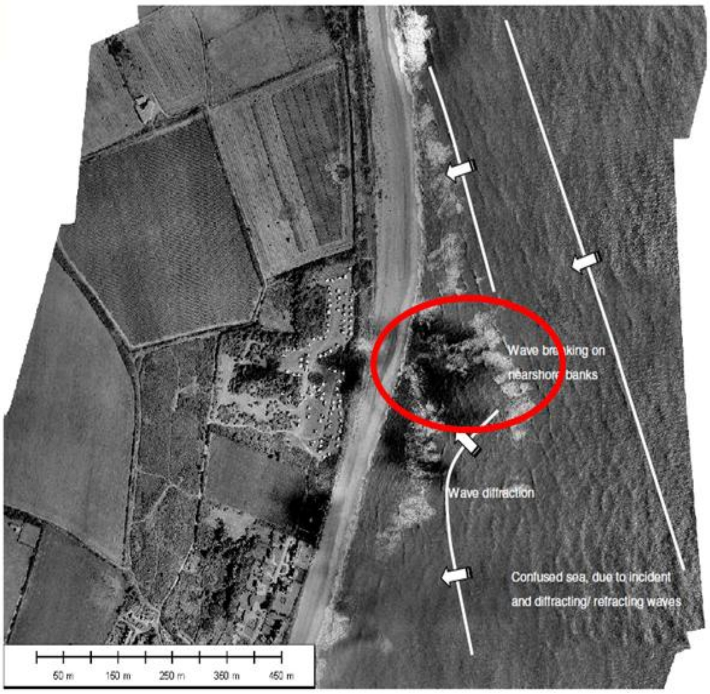
Figure 6.1: Interpretation of net sediment transport pathways for: (a) medium and coarse sand-sized sediment travelling as bedload; and (b) fine sand-sized sediment travelling in suspension.



Source: BEEMS, 2011

Of particular significance to beach protection at Thorpeness is an observation by Carr (1979) that at times a small bank-like feature(s) extends south of the SDBC. The author suggests that the change in coastal orientation associated with the Coralline Crag outcrop ridges (Figure 5.2) acts as a platform upon which this nearshore bank can grow south from the Ness in the manner of a banner bank (e.g. Dyer & Huntley, 1999). However, the growth, persistence and decay of this feature has not been documented with sufficient spatial and temporal resolution to elucidate its behaviour and the potential impacts it may have on the Thorpeness frontage. However, it is interesting to note that in a preliminary study of the frontage prior to the construction works in 2011, a nearshore feature was identified by the wave breaking patterns shown by an aerial photograph of Thorpeness taken in 1994 (Figure 6.2). This annotated photograph shows clearly well-defined patterns of wave refraction and diffraction associated with an offshore bar-like feature that acts to focus the NW waves onto the frontage approximately coincident with North End Avenue.

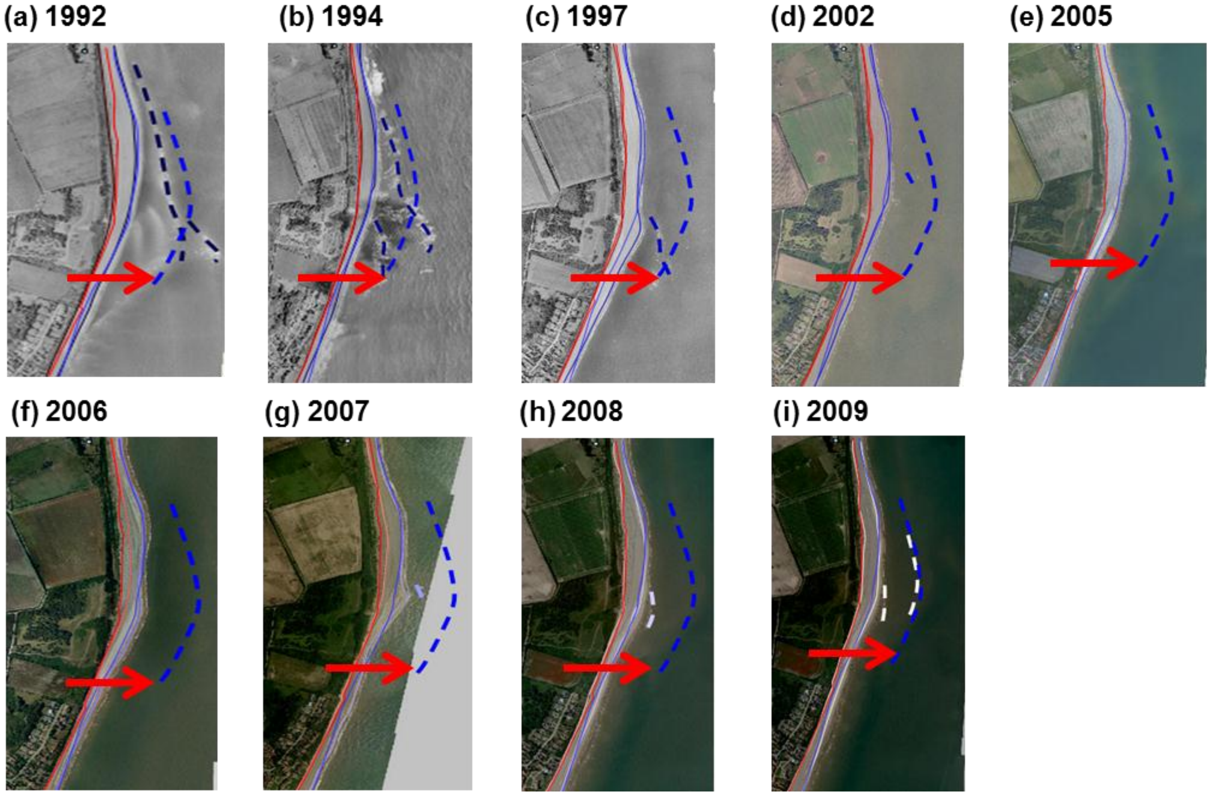
Figure 6.2: Inshore wave responses to seabed features offshore from Thorpeness in 1994.



Source: Royal Haskoning, 2010a

This idea is further supported by the sequence of annotated aerial photographs in Figure 6.3 spanning the years 1992 to 2008 showing the changes in the location of wave breaking offshore. These images indicate that dynamic features are present just offshore with a potential to modify significantly the wave energy distribution arriving at the Thorpeness shoreline. Following this to a logical conclusion it can be speculated that the position and extent of these features strongly influence the way in which the coast behaves (Royal Haskoning, 2010a). What remains unclear, however, is the mechanism that triggers the growth of these features, their morphology and whether or not other features are present further offshore that remain hidden owing to the moderate waves pertaining during the fair weather conditions of the overflights. It is noted that the alongshore migration of oblique bar-like features has been observed in numerous coastal studies (*cf*. Garnier *et al.*, 2006). It has been suggested that some aspects of their morphodynamics are linked to the alongshore migration of a sediment pulse from previous storm events. Irrespective of the mechanisms it is clear that bar-like features are present at times offshore from the Thorpeness frontage and that their morphology will probably influence the adjacent beach behaviour.

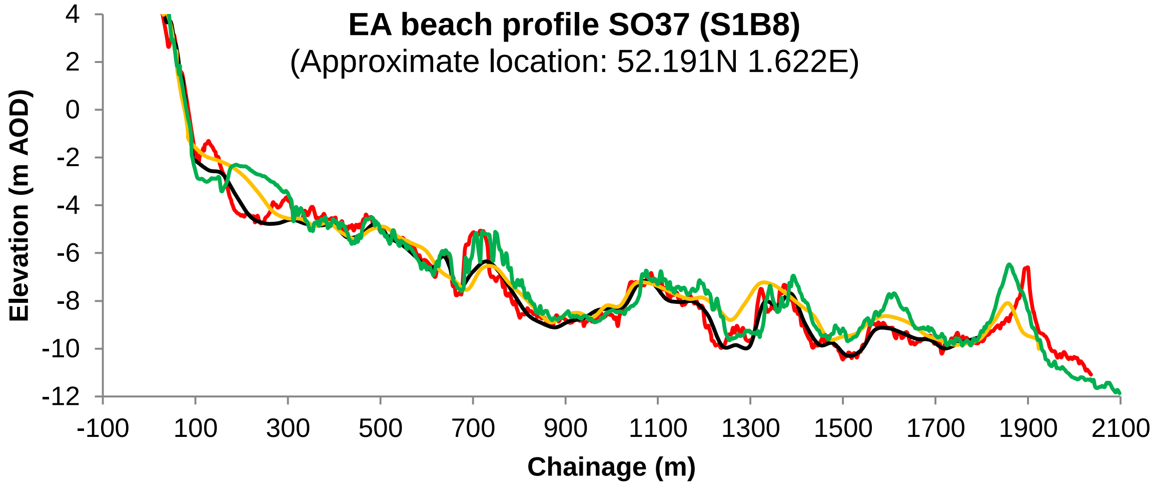
Figure 6.3: Variation between 1992 and 2009 in wave breaking positions indicating the presence of an ephemeral shallow crested ridge extending south from the Ness. The red arrows indicate the approximate southern extent of the features as indicated by breaking waves.



Source: Royal Haskoning, 2010

While the physical features of the ridges are undefined, and their presence is only indicated by wave breaking patterns, nevertheless, the effect of such a ridge would be to refract and diffract waves from an easterly or north easterly direction and possibly create areas of wave focus leading to local differential erosion at the shoreline. Further, a key feature of the near-shore bar behaviour indicated by Figure 6.3 is a progressive retreat to the north and migration offshore between 1992 and 2009. This change in morphology would progressively increase the exposure of the Thorpeness frontage to waves and contribute to the beach lowering known to precede severe erosion events (e.g. 2010). Severe erosion that has occurred at various positions along the Thorpeness frontage in the past supports this view as do comments by Royal Haskoning (2010a) who state that in 2010, as a result of the offshore conditions, the nearshore ridge developed in such a manner as to focus erosion along the northern section of the village.

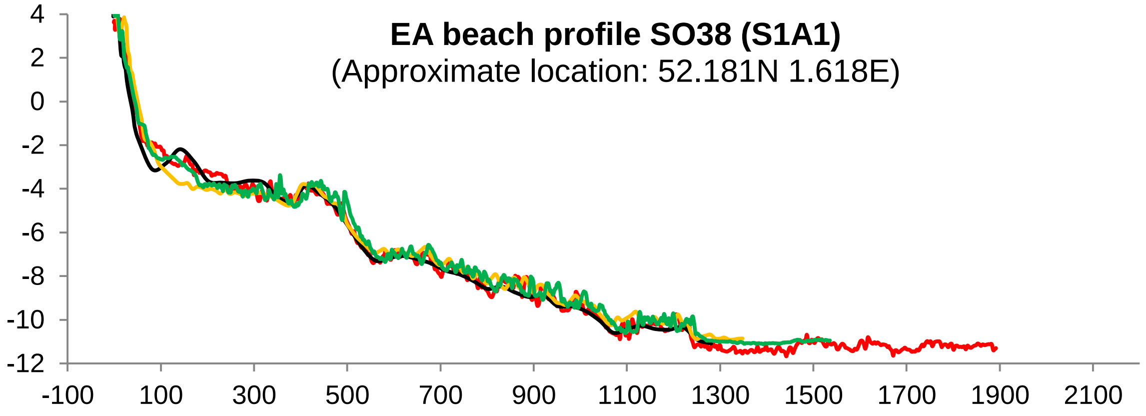
Figure 6.4: Measured EA beach profile SO37 (S1B8) north of Thorpeness for August 1992 (red line), August 1997 (black line), July 2003 (orange line) and August 2007 (green line).



Source: Environment Agency via SCDC

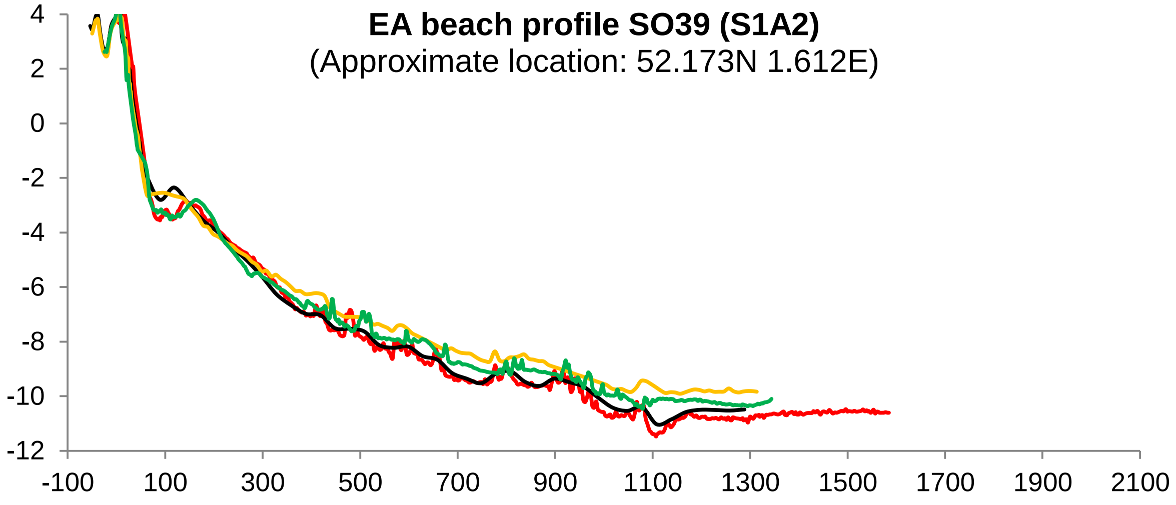
Further evidence demonstrating that features exist offshore that may promote sediment accumulation, and development of features that may extend southwards at times is shown by the beach profiles measured by the EA at location SO37 between 1997 and 2008 (Figure 6.4). It is thought that the apparent differences between these profiles reflects the different spatial resolution of each survey and other errors rather than any movement of the features per se. Ridge-like features, with heights of the order of 2m are clearly evident and would act in a manner to promote sedimentation and possibly to the development of a banner bank and would affect the inshore wave climate in the manner eluded to above. It is noted that these features are absent from the beach profiles measured at location SO38 adjacent to the property called *Jonnygate* off Admirals Walk (Figure 6.5). Even further to the south profile SO39 shows offshore accretion of up to 2m during the period 1997 to 2003 followed by erosion between 2003 to 2007 (Figure 6.6) and the ridges evident in profiles SO37 are again absent.

Figure 6.5: Measured EA beach profile SO38 (S1A1) north of Thorpeness for August 1992 (red line), August 1997 (black line), July 2003 (orange line) and August 2007 (green line).



Source: Environment Agency via SCDC

Figure 6.6: Measured EA beach profile SO39 (S1A2) north of Thorpeness for August 1992 (red line), August 1997 (black line), July 2003 (orange line) and August 2007 (green line).



Source: Environment Agency via SCDC

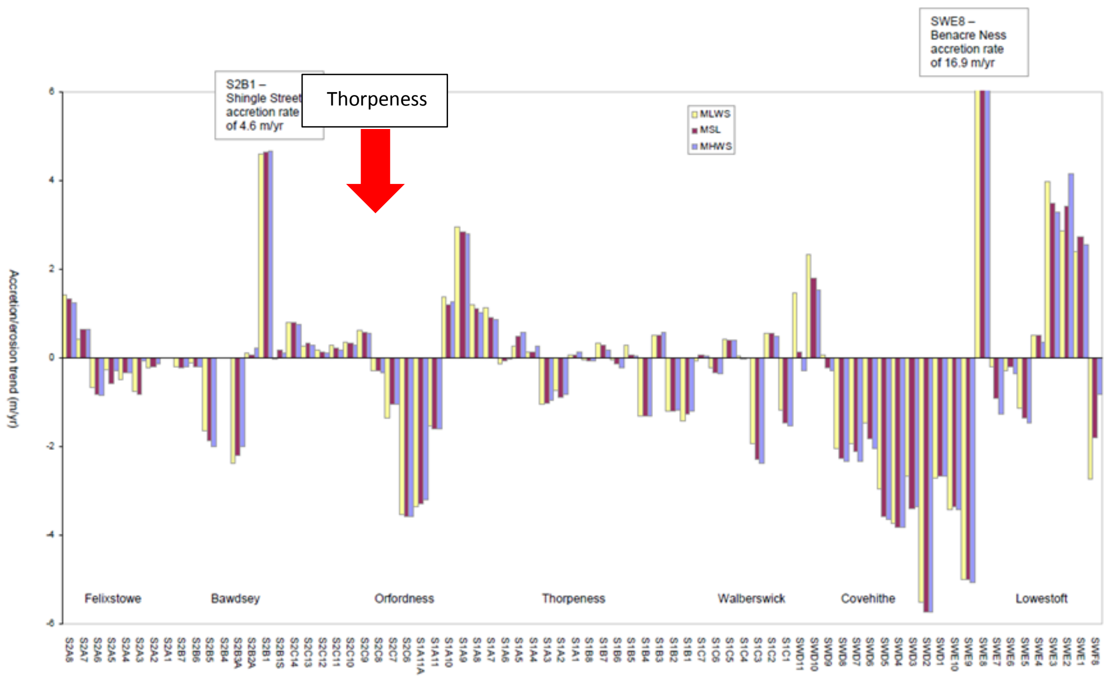
6.2 Onshore sediment transport at Thorpeness

Of relevance to post-storm beach recovery at Thorpeness are the earlier observations reported by Blackley (1979) of the shoreward migration of bars driven by wave action following a storm. The work is based on observation between March 1978 and May 1979 when the beach at Thorpeness was believed to be in a recovery stage after the erosion that led to the need for the gabions around 1975. In spite of regular beach profile monitoring, the onshore migration of bars has not been commented upon subsequently. If it exists, such a process could provide a cross-shore mechanism that could potentially provide sediment for some beach recovery during calmer conditions in addition to alongshore supply. However, the degree to which changes of the nearshore bathymetry persist after erosion events remains uncertain.

6.3 Shoreline behaviour at Thorpeness

A broad-scale analysis of historical trends in shoreline position between Felixstowe and Lowestoft is shown in Figure 6.7, (EA, 2011). This figure shows in general terms that the coast at Thorpeness is characterised by accretion to the north and erosion to the south. However, the amount of erosion and accretion at Thorpeness is significantly less than that measured at other locations along the coast of Suffolk (e.g. Orfordness and Covehithe). At the present time evidence of accretion on the Ness is provided by two well-defined berm features: (a) a mid-shore berm running south from the centre of the Ness to the toe of the cliff just north of the major scour area adjacent to the northern limit of the defences; and (b) a foreshore berm, also running south along the Ness to just north of the scour area.

Figure 6.7: Erosion/accretion trends along the Suffolk coast.



Source: Environment Agency, 2011b

In order to better understand local beach behaviour, and provide information for coastal managers, beach profiles at Thorpeness have been regularly monitored since 1992. The cross-shore evolution for the Thorpeness area has been analysed using the monitoring survey profiles from the Anglian Region Coastal

Monitoring Programme (3 profiles since 1991) and the profiles from the Shoreline Management Group (19 profiles since 2009). These data are presented and described in the Coastal Morphology Report for Thorpeness (*Phases 1* and *2*, EA, 2011a; 2013). The location of these beach profiles is shown in Figure 6.8 and their most landward coordinates are given in Table 6.1. It is noted that the naming convention of the profiles changed during the period considered here and additional profiles were added to the survey between SO37 and SO39 (Figure 6.8) in 2009 order to monitor the behaviour of Thorpeness beach in greater detail.

Figure 6.8: Location of EA beach profiles.

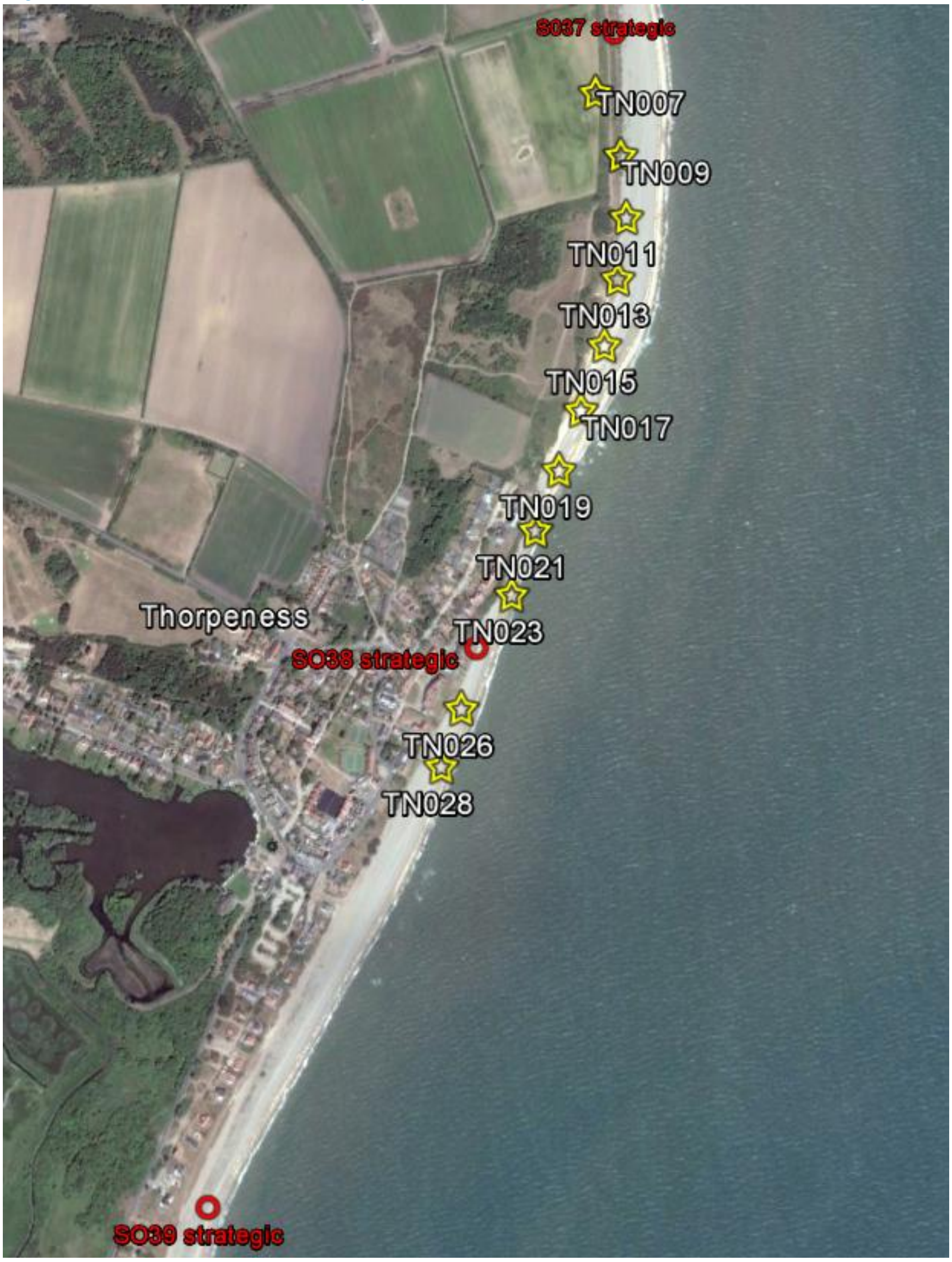


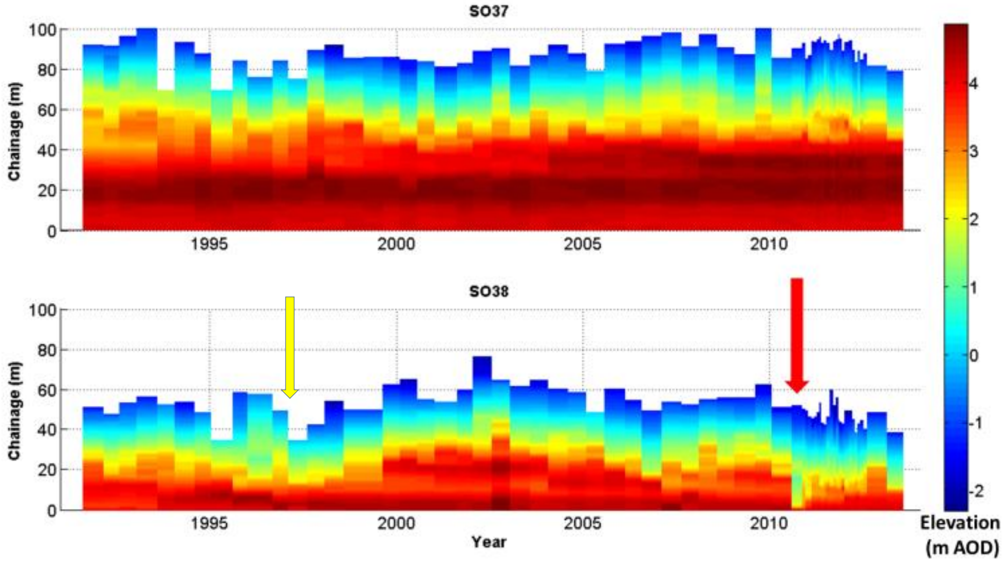
Table 6.1: Coordinates of EA beach profiles.

Old profile name	New profile name	OS National Grid Easting	OS National Grid Northing	Latitude	New profile name
S1B8	SO37	647656.799	260948.912	52.19111762	1.622022012
S1A1	SO38	647485.313	259916.891	52.18193477	1.618765716
S1A2	SO39	647107.111	259006.807	52.17393840	1.612582904
S1B8_A	TN007	647631.220	260845.609	52.19020222	1.621573169
S1B8_B	TN009	647678.340	260742.306	52.18925420	1.622185652
S1B8_C	TN011	647692.913	260639.003	52.18832078	1.622322978
S1B8_D	TN013	647684.245	260535.700	52.18739779	1.622121028
S1B8_E	TN015	647667.823	260423.986	52.18640282	1.621799757
S1B8_F	TN017	647634.853	260314.954	52.18543932	1.621238901
S1B8_G	TN019	647604.517	260213.998	52.18454711	1.620722411
S1B8_H	TN021	647571.277	260113.555	52.18366079	1.620163928
S1B8_I	TN023	647538.176	260006.605	52.18271603	1.619602751
N/A	TN026	647466.680	259818.402	52.18105943	1.618421935
N/A	TN028	647439.690	259723.507	52.18022008	1.617958812

The temporal behaviour of the beach profiles at the locations shown in Figure 6.8 and elsewhere has already been investigated and reported, albeit rather superficially (e.g. EA, 2011a; 2013). In this report these data are re-examined in order to investigate the impact of the recent storm events and to place them in a broader historical context. The study aims also to determine if further analysis of beach profile data might prove to be helpful in future studies targeted at providing a better understanding of the coastal processes at Thorpeness.

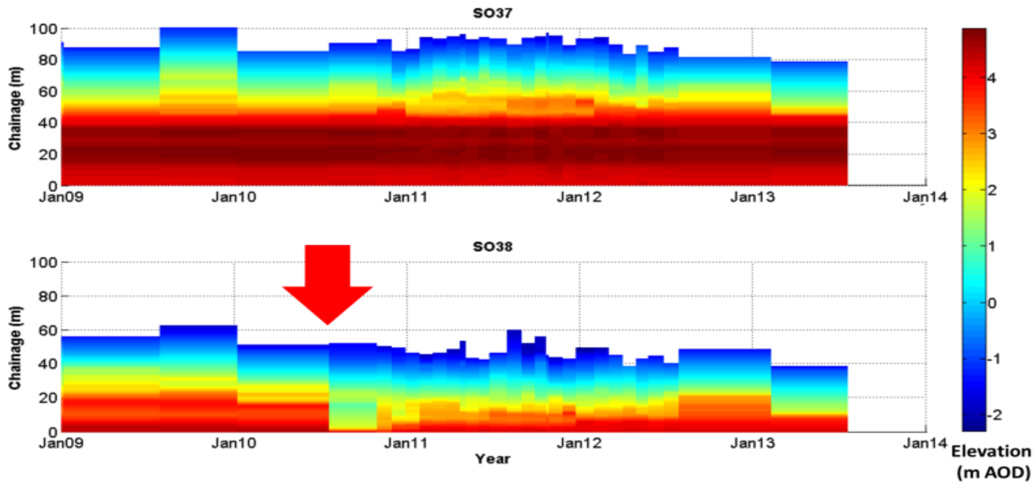
The longest measured beach profile records made available to this study are from locations SO37-SO39 (Figure 6.8) and span approximately 22 years from August 1991 to December 2013. Data from profiles SO37 (on the southern shoreline of the Ness) and SO38 (approximately coincident with Jonnygate) are shown in Figure 6.9. Being much further south profile SO39 has not been examined here. The data presented in Figure 6.9 extends seaward from zero chainage to around -1m AOD and have been 'time-stacked' to show temporal changes in profile elevation. While the majority of SO37 is largely time-invariant, a second berm feature is shown to develop from around 2004 at approximately chainage 30m. All indications are that this part of the shoreline is stable with only some superficial accretion along limited sections of the profile. Profile SO38, however, exhibits quite different behaviour showing: (a) erosion from around 1994 to 1997 (b) accretion from around 1997 to 2003; (c) erosion between 2003 and 2007; and (d) accretion up to around 2009. After that date, there is evidence of erosion (supported anecdotally) followed by the erosion events of 2010 (indicated by the red arrow). The beach shows some evidence of recovery up to around 2013, when further significant erosion occurs. Data have not been made available for the period beyond 2013.

Figure 6.9: Time-stacked EA beach profiles from 6 August 1991 to 18 November 2013 from locations: (a) SO37, north of Thorpeness; and (b) SO38, approximately coincident with *Jonnygate (*Figure 6.8).



The erosion event(s) at SO38 in 2010 are unprecedented in the 22 year record presented here. The periods leading up to the storm and afterwards are shown in greater detail in Figure 6.10 for both profiles SO37 and SO38. In this figure, the higher frequency of beach profile measurement in response to the recent erosion events is shown.

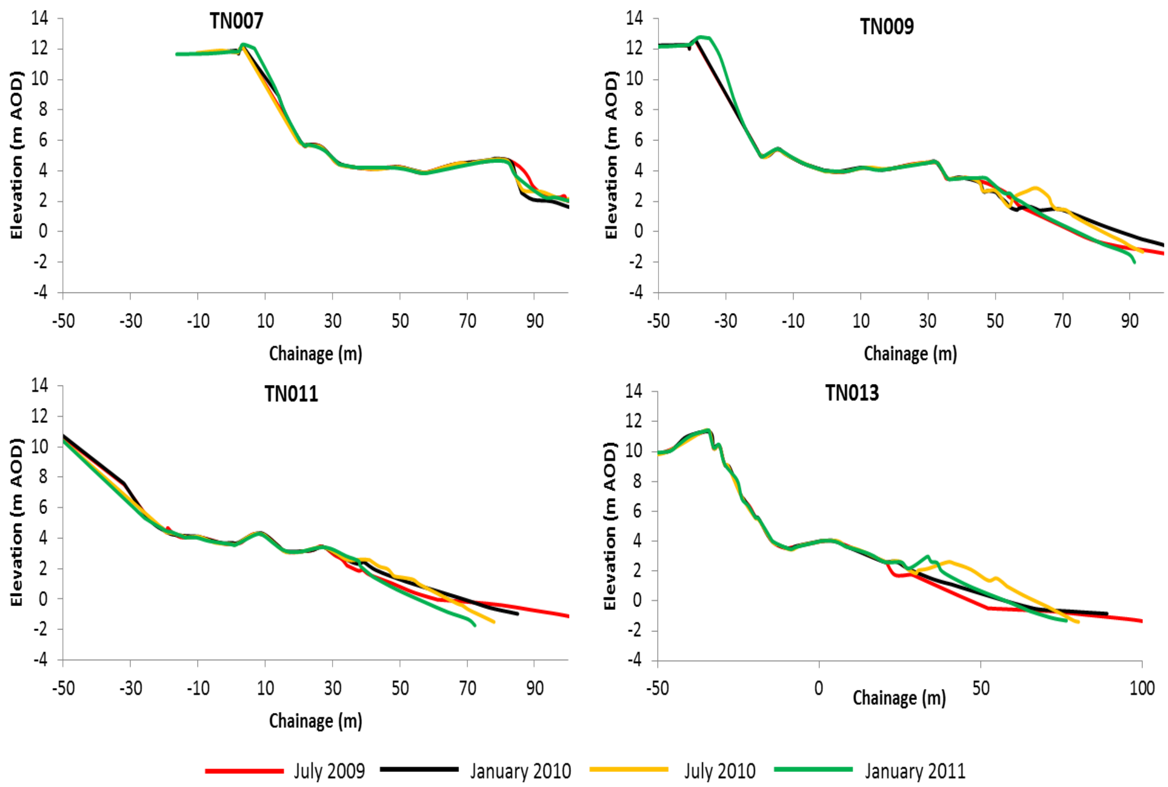
Figure 6.10: Detail from time-stacked EA beach profiles from January 1991 to July 2013 from locations: (a) SO37, north of Thorpeness; and (b) SO38, approximately coincident with *Jonnygate* (Figure 6.8).



Beach profiles measured at locations TN007 to TN021 (Figure 6.8) in July 2009, January 2010, July 2010 and January 2011 provide an opportunity to look at the 2010 erosion events in more detail at different locations along the Thorpeness frontage. This period is selected as it spans the time of severe beach erosion and is examined to determine the alongshore extent of the storm impact. For clarity, the beach behaviour at the 11 profiles locations are illustrated in Figure 6.11 (TN007-TN013), Figure 6.12 (TN015-TN021) and Figure 6.13 (TN023-TN028). Further profiles from later dates reflect beach management actions and thus have less value for investigating the natural responses of the beach to storms and associated beach recovery periods.

As expected, profiles in Figure 6.11 (TN007-TN013) show some seasonal variability. While it is noted that some accretion occurs on the lower part of TN013 in July 2010 which is subsequently removed, there is little evidence of systematic changes in the profiles or of a significant change in the profiles before or after the storm events of 2010.

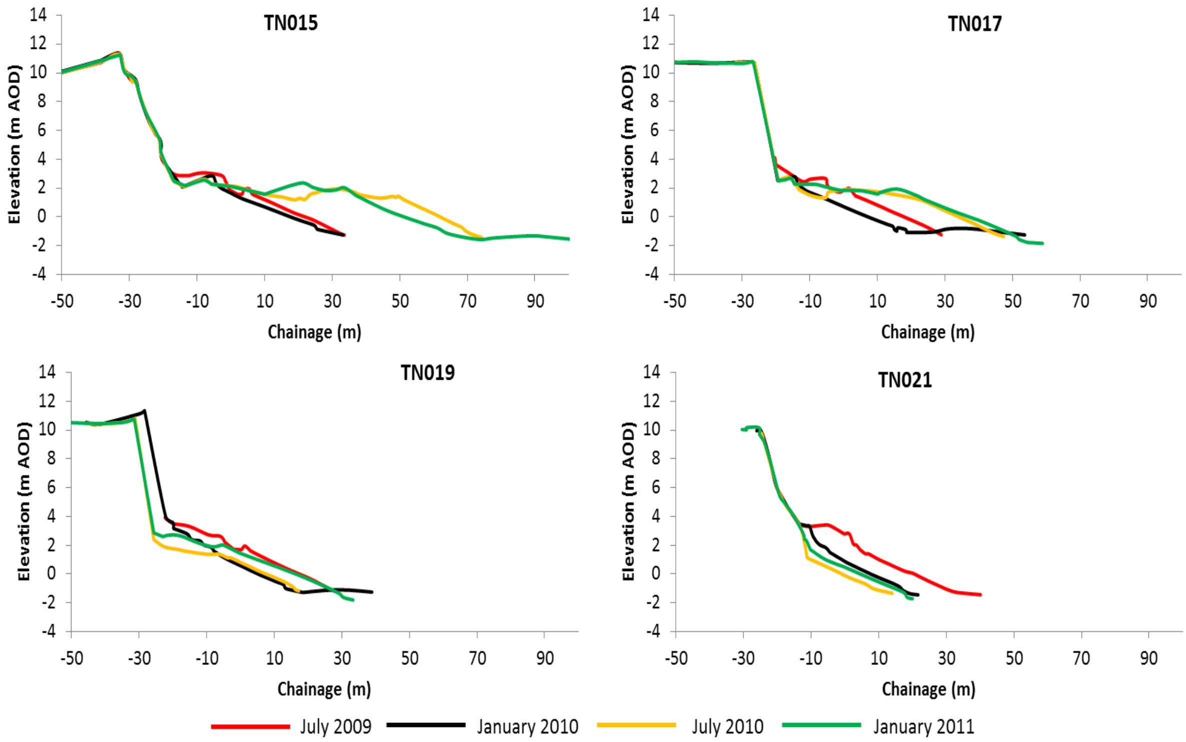
Figure 6.11: Selected EA beach profiles at locations TN007-TN013 (see Figure 6.8) in July 2009, January 2010, July 2010 and January 2011.



However, the impacts of the 2010 storms are clearly evident in Figure 6.12 (TM015-TM017). Considering TM015 and TM017 first, these profiles shows a loss in beach volume between July 2009 and January

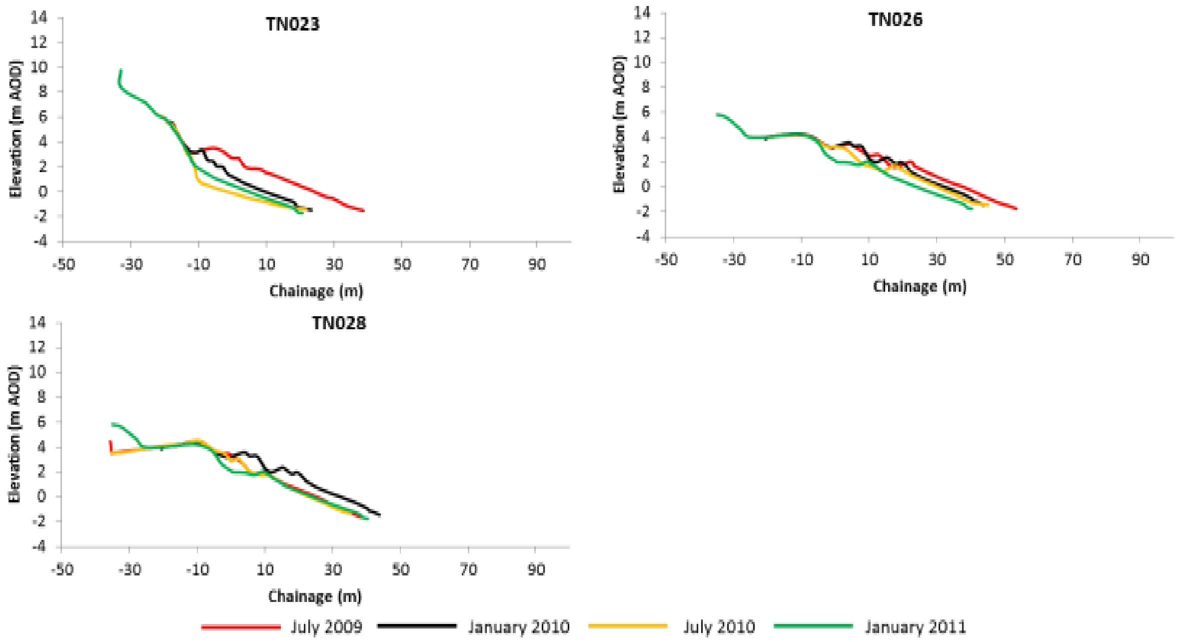
2010. However, accretion is significant between January 2010 and July 2010, with the bulk of this deposition understood to occur after the June 2010 storm event (Royal Haskoning, 2010a). Thereafter the profiles remain stable up to January 2011. Interestingly profile TM019, located just to the north of the main erosion areas associated with the 2010 events (Figure 6.12), and to the south of the area of significant post-storm accretion (TM015 and TM017) has the least temporal variance. The first real evidence of the 2010 storm impacts is seen in profile TM021 where beach lowering during the period July 2009 to January 2010 was followed further erosion in the period between January 2010 and July 2010. There is some evidence of minor beach recovery in the period up to January 2011.

Figure 6.12: Selected EA beach profiles at locations TN015-TN021 (see Figure 6.8) in July 2009, January 2010, July 2010 and January 2011.



Profile TM023 in Figure 6.13 shows erosion occurring for the entire period with significant beach lowering of the order of 2m preceding the 2010 storm events. Similarly TM026 shows erosion occurring from July 2009 to January 2011. However, the amount of erosion is around half that at TM023. TM028 shows accretion between July 2009 and January 2010 followed by minor erosion up to January 2011.

Figure 6.13: Selected EA beach profiles at locations TN023-TN028 (see Figure 6.8) in July 2009, January 2010, July 2010 and January 2011.



Looking collectively at the EA beach profiles, Figure 6.14 shows a time-stack of all EA beach profiles at locations TN019-TN029 (see Figure 6.8) measured between July 2009 and November 2013 (11 beach profiles at each location). In order to provide a different view of the temporal behaviour of the five beach profiles these data are also shown as 3D plots in Figure 6.15. The black arrows in both these figures indicate the approximate time of occurrence and the impacts of the 2010 storm and show that effects can be seen at all of the locations. In all cases there is a striking reduction in beach level of around 2m around the time of the storms. In all cases, these events were preceded by a period of beach lowering in 2009.

Figure 6.14: Time-stack of all EA beach profiles at locations TN019-TN029 (see Figure 6.8) measured between July 2009 and November 2013.

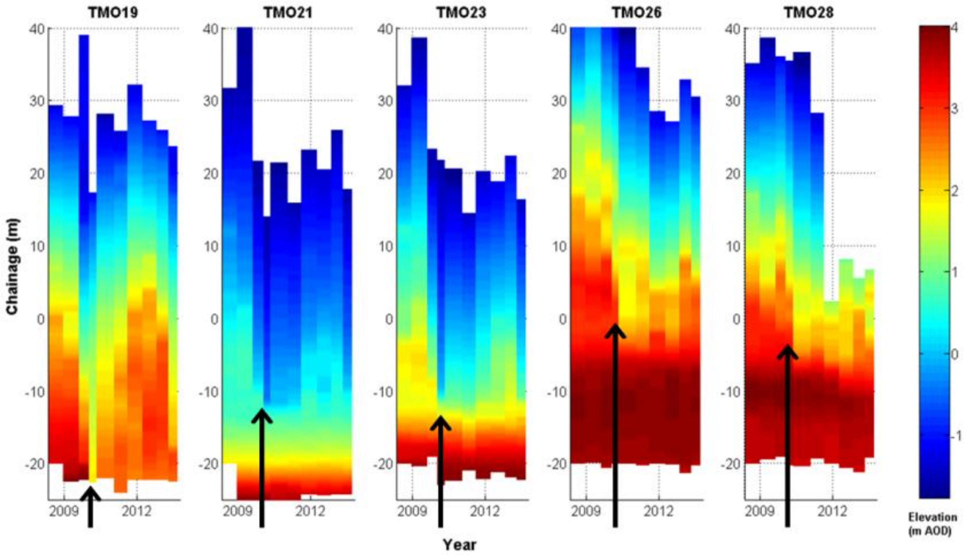
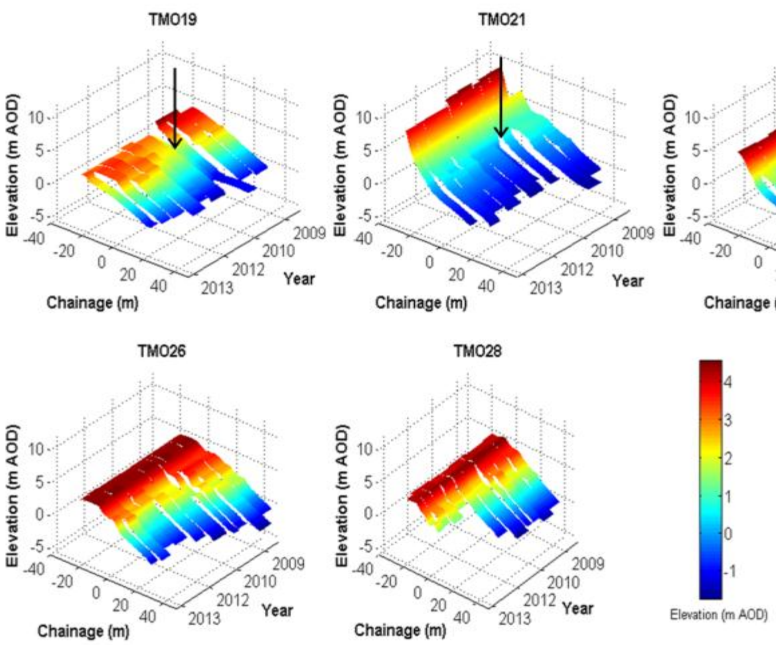


Figure 6.15: 3D Time-stack of all EA beach profiles at locations TN019-TN029 (see Figure 6.8) measured between July 2009 and November 2013.



The behaviour of the beach profiles reported above show a coherent response to the 2010 storm events. While it is believed more can be learned from careful analysis of these data, this lies outside the scope of the present study. Further investigations are therefore recommended.

6.4 The erosion hotspot: North End Avenue

In considering why the storm impacts are so concentrated along a relatively short part of the Thorpeness frontage beneath North End Avenue there are a range of possible contributory factors to consider. Based upon simple energy considerations, a primary factor concerns the distribution of wave energy along this frontage. Put simply, the severe erosion beneath North End Avenue probably reflects in part a ‘focus’ of wave energy significantly greater that that along other parts of the frontage. Although the mechanism by which this focus arises remain unclear at present, it is most probably related to the offshore sea bed morphology which acts in such a way as to refract and diffract incident waves creating a zone of high incident wav energy along a narrow coastal corridor. Secondly, as a consequence of beach lowering and recession in the months preceding the 2010 storms, waves were able to reach the base of the defences during the storm events owing to the combination of a storm surge and spring tide which elevated mean water levels well above the normal spring tide level. During such high-water conditions some portion of the wave energy will be reflected offshore by the defence structures and interact with the incident wave field in a process called *interference*. Constructive wave interference occurs when the crest and/or trough of one wave passes through, or is superimposed upon, the crest and/or trough of another wave. The effect of constructive interference is to increase locally the amplitude (height) of the waves which in turn increases the near-bed currents and turbulence the waves generate. Together these enhancements can act to entrain more bed sediment and to hold them in suspension for a longer period. If the suspension of sediment is then acted upon by even a weak net current directed alongshore, beach sediments will be transported away in greater quantities than would occur without wave reflection. This process results in further lowering of the beach will in turn allow larger waves to reach the shoreline and increase sediment losses still further unless other processes act to restore beach levels.

While lowering of the beach in the time preceding the 2010 storm events contributed to the severity of the erosion between January and July 2010, the erosion was not exceptional and more severe erosion occurred around 1997 (profile SO38, Figure 6.9). However, in this case, the beach recovered and was not impacted by a storm. Further examination of the tidal/surge/metocean conditions pertaining during this period may help to explain why erosion of the severity of that in 2010 did not occur in the late 1990s.

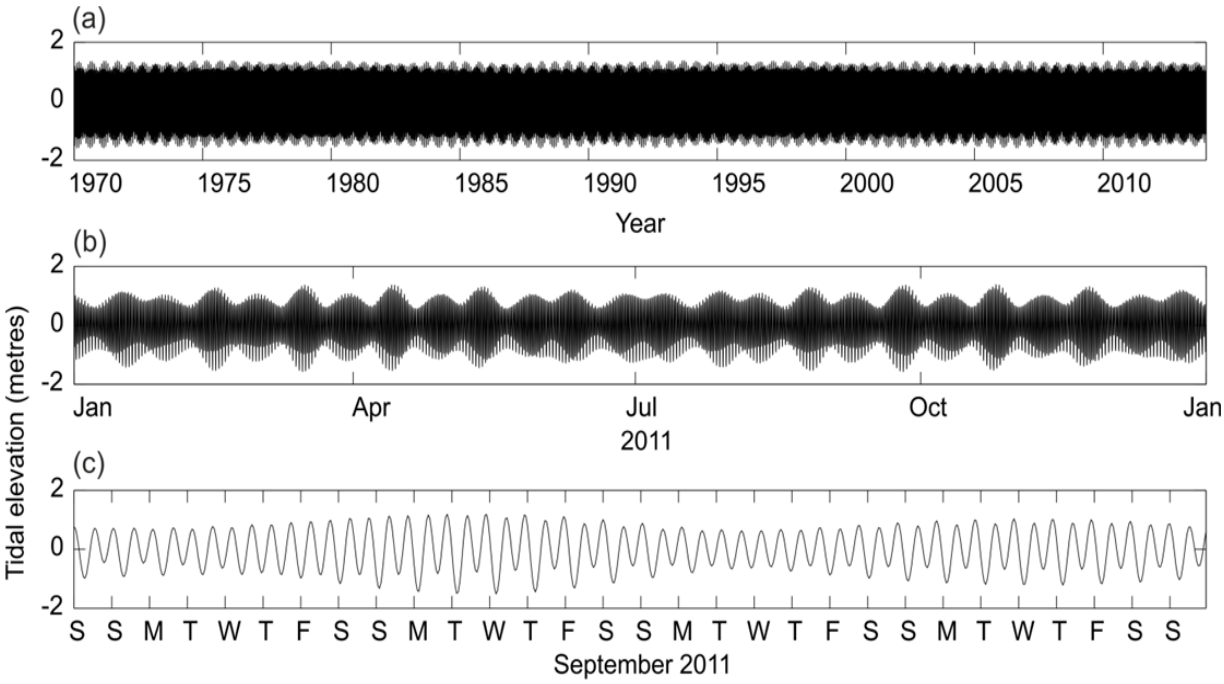
6.5 Other possible factor contributing to erosion at Thorpeness

The cycles of erosion and accretion associated with complex southerly directed net sediment transport from Sizewell Bay, the SDBC and the Ness cannot be fully explained with the information presently available. This study therefore examined two potential mechanisms associated with long-term tidal modulations and global atmospheric processes that have been shown in other studies of to explain at least some of the variance in coastal behaviour. These are, respectively, the nodal tidal cycle and the changes in the North Atlantic atmospheric pressure distribution expressed in a parameter termed the North Atlantic Oscillation (NAO) index.

6.6 Ocean forcing by the 18.6 years nodal tidal cycle

Using the tidal constituents for Thorpeness, the astronomical tide was calculated for the period 1970 to 2014 using MIKE[11] software. Figure 6.16a shows the full 44 year time-series with tides for 2011 and September 2011 shown in Figure 6.16b and Figure 6.16c, respectively to illustrate the tidal characteristics at Thorpeness more clearly. The motivation for looking at such a long tidal record stems from a curiosity about possible links between tidal modulation at long time-scales and cycles of erosion described above. Analysis of the tidal record in Figure 6.16a is shown in Figure 6.17 and Figure 6.18. In Figure 6.17a the mean annual tidal elevation (black dashed line), mean monthly tidal elevation (blue line) and average monthly maximum tidal elevation (red line, offset = -60cm for inter-comparison purposes) are shown. Below that Figure 6.17b shows the peak annual HW elevation (dark blue dashed line) and peak monthly HW elevation (light blue line) and Figure 6.17c shows the peak annual LW elevation (dark grey dashed line) and peak monthly LW elevation (light grey line). The 18.6 year nodal cycle is clearly evident in Figure 6.17a. The amplitude of the tidal modulation at this period is shown more clearly in Figure 6.18 which shown (a) the mean annual HW elevation (back circles) and monthly mean HW elevation; and (b) mean annual LW elevation (back circles) and monthly mean LW elevation. Of significance this figure shows peaks in the mean tidal elevation occurring around 1977, 1995 and 2014. Around these dates Figure 6.18 shows that the mean tidal elevation is around 6cm higher than at tidal minima around 1970, 1988 and 2007.

Figure 6.16: (a) Predicted tidal time-series 1970-2014; (b) tidal time-series for 2011; and (c) tidal time-series for September 2011.



11 http://www.mikebydhi.com/

Figure 6.17: (a) Mean annual tidal elevation (black dashed line), mean monthly tidal elevation (blue line) and average monthly maximum tidal elevation (red line, offset = -60cm for inter-comparison purposes); (b) peak annual HW elevation (dark blue dashed line) and peak monthly HW elevation (light blue line); (c) peak annual LW elevation (dark grey dashed line) and peak monthly LW elevation (light grey line).

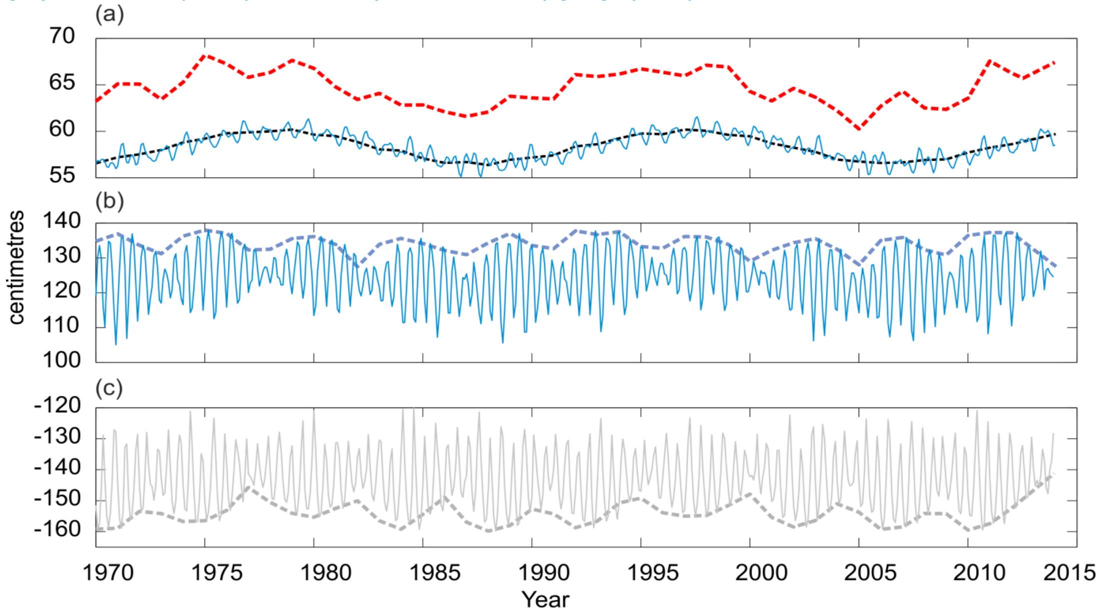
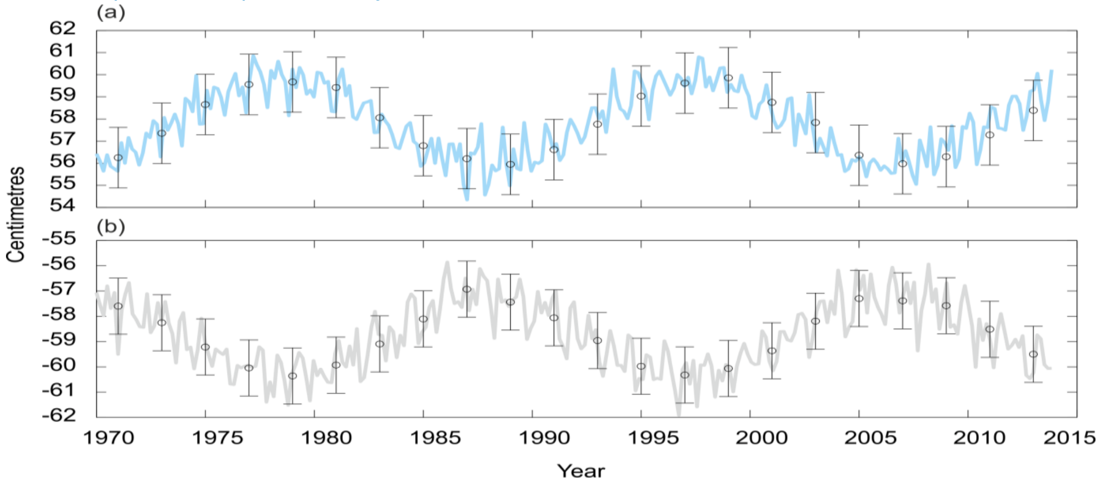


Figure 6.18: (a) Mean annual HW elevation (back circles) and monthly mean HW elevation; and (b) mean annual LW elevation (back circles) and monthly mean LW elevation. Error bar show ± 1 standard deviation.



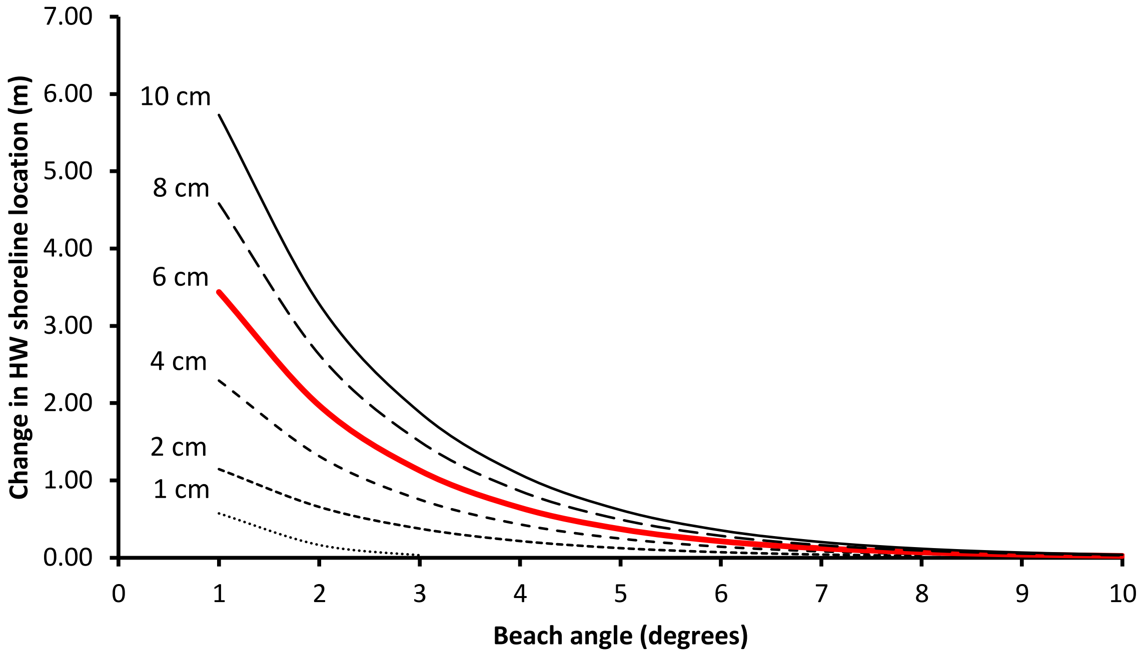
While there are potentially some temporal correlations between the tidal maxima shown in Figure 6.18 and the erosion cycles at Thorpeness, there is no direct cause effect relationship since tidal maxima have also occurred during times when the beach at Thorpeness is believed to have been in a healthy state (e.g. 1987). This is discussed further below.

However, there are two possible consequences of the apparently small cyclical change in tidal range to consider. The first of these is illustrated in Table 6.2. This tabulates the theoretical shoreline recession in response to changes in the mean high water elevation during the nodal tidal cycle for a range of beach slopes in the Thorpeness region. Figures in red correspond most closely to the conditions at the eroding beach frontage and indicate a shoreline recession of around 0.5m. These data are presented graphically in Figure 6.19 which shows the changes in the high water location of the shoreline as a function of beach angle for a range of mean high water elevation changes occurring during the nodal tidal cycle. The curve in red is most closely associated with the conditions at the eroding beach frontage at Thorpeness.

Table 6.2: Theoretical shoreline recession in response to changes in the mean high water elevation during the nodal tidal cycle for a range of beach slopes in the Thorpeness region. Figures in red correspond most closely to the conditions at the eroding beach frontage and indicate a recession of around 0.5m.

		Change in mean HW level (cm)					
Beach angle θ_b (degrees)	**tan (θ_b)**	**1**	**2**	**4**	**6**	**8**	**10**
1	0.017	0.57	1.15	2.29	3.44	4.58	5.73
2	0.035	0.16	0.66	1.31	1.97	2.63	3.28
3	0.052	0.03	0.38	0.75	1.13	1.5	1.88
4	0.07		0.22	**0.43**	**0.65**	0.86	1.08
5	0.087		0.12	**0.25**	**0.37**	0.49	0.62
6	0.105		0.07	**0.14**	**0.21**	0.28	0.35
7	0.123		0.04	0.08	0.12	0.16	0.2
8	0.141		0.02	0.05	0.07	0.09	0.12
9	0.158			0.03	0.04	0.05	0.07
10	0.176			0.02	0.02	0.03	0.04

Figure 6.19: Changes in the high water location of the shoreline as a function of beach angle for a range of mean high water elevation changes occurring during the nodal tidal cycle. The curve in red is most closely associated with the conditions at the eroding beach frontage.



In 'normal' conditions, the shingle beach at Thorpeness is characterised by relatively high angles of repose (typically around 5 degrees). Therefore a modest increase in mean sea level of around 5cm will have little impact (Figure 6.19). However, it is known that prior to the major beach erosion events in the 1970s, and the most recent events in 2010-13, beach lowering had occurred, resulting is a reduction in beach slope. It can be seen in Figure 6.19 that this would promote much greater shoreline recession.

A second and more subtle consequence of the nodal tidal cycle concerns the tidal currents. During nodal tidal maxima, tidal currents will be slightly stronger than during nodal tidal mimima and thus may impact on the mobilisation and transport of sediments. Specifically, the effect of small changes in tidal flow speeds is amplified since bedload transport is related to the square of the current speed and suspended transport to current speed to the power three or four. Thus, in simple terms for bedload, an increase in peak tidal flow from say 1.5m/s to 1.6m/s potentially gives rise to 20% more sediment transport. For suspended sediment transport the increase is potentially around 50%.

A further consequence of a slight increase in the flow speed concerns the threshold of sediment motion (i.e. the flow speed required to entrain, or set in motion, sediments at rest on the bed). It is widely acknowledged that since the marine transgression, the present North Sea bed sediments have been subject to tidal and wave forcing which has acted to move sediments from areas of high energy to areas of lower energy. As a result it is likely that the majority of sediments are now located in areas where they are move only during peak tidal flows or during storm conditions. Any minor increase in tidal flow speed associated with the nodal cycle could therefore cross a threshold and mobilise sediments that would otherwise remain static.

It is not suggested here that these nodal tide effects are the cause of beach erosion cycles at Thorpeness. They are merely flagged here as possible contributory factors that could potentially result in shoreline recession, making the coast more vulnerable to wave attack, and elevate tidal flow speeds above threshold, and result in more sediment transport that could either contribute the formation of offshore features or to their removal. Further investigation of these effects is considered to be helpful for advancing understanding of the coastal processes at Thorpeness.

6.7 North Atlantic Oscillation (NAO) Index

Previous reports have suggested a link between increased storminess in the North Atlantic during recent years with a period of time during which the annual North Atlantic Oscillation (NAO) index has been strongly positive (Hurrell, 1995; Hurrell & Deser, 2009). Further, Lozano *et al*. (2004) have demonstrated that the winter (months: DJFM) NAO index (hereafter termed NAOw) shows a quasi-decadal variability which agrees well with the changes in number of winter storms in the period 1965 to 1995. In broad terms a positive NAOw values are typically associated with stronger-than-average westerlies over the middle latitudes, more intense weather systems over the North Atlantic and wetter/milder weather over western Europe.

Figure 6.20 shows the annual and NAOw indices from 1970 to 2014. It might be expected therefore that if weather 'patterns' were in any way related to the cycles of erosion at Thorpeness, it would be expected that NAO and/or NAOw index values would be positive during the 1970s and for 2010-present. However, what Figure 6.20 shows is that the NAO was weakly positive in the early 70's and 80's, strongly positive for 5 years or so around 1990 and followed by weak positive peak around 1998 and 2003.

However, in a study of the Sefton coast, NW England, Esteves *et al.* (2011) noted that increased erosion occurred at times of decreasing NAOw values and reduced erosion at times of increasing NAOw values. Erosion tends to be more pronounced when decreasing NAOw values lead to a strong negative NAO phase. Interestingly for Thorpeness this occurred most strongly around 2010. There is also a similar event around 1997 which coincides with an erosive phase along beach profile S038 (Figure 6.9b). There is also evidence (not illustrated) of a similar albeit smaller NAOw minimum just prior to 1970. These results do not fully explain the erosion cycle observed at Thorpeness. However, they do illustrate a further possible mechanism that may contribute to the cycle. Unfortunately, it is not possible to predict future NAO values at present and thus this has limited use for prediction of future erosion cycles. Also of interest Esteves *et al.* (2011) also observed that for an approximately equivalent storm beach and dune erosion was more serve during the summer months than during the winter.

Figure 6.20: Annual and winter (DJFM) NAO indices from 1970 to 2014 (Source: Hurrell, James & National Center for Atmospheric Research Staff (Eds). Last modified 05 Sep 2014. "The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based)." Retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based).

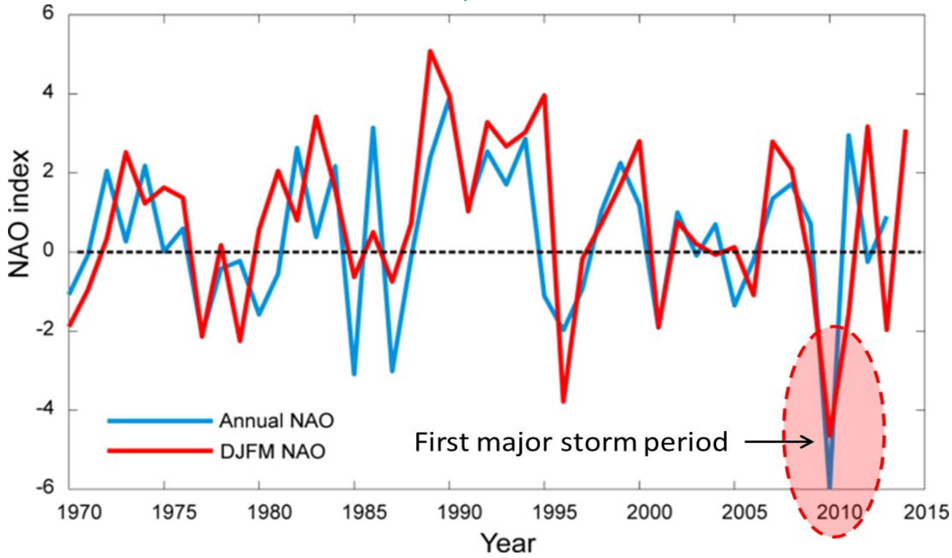
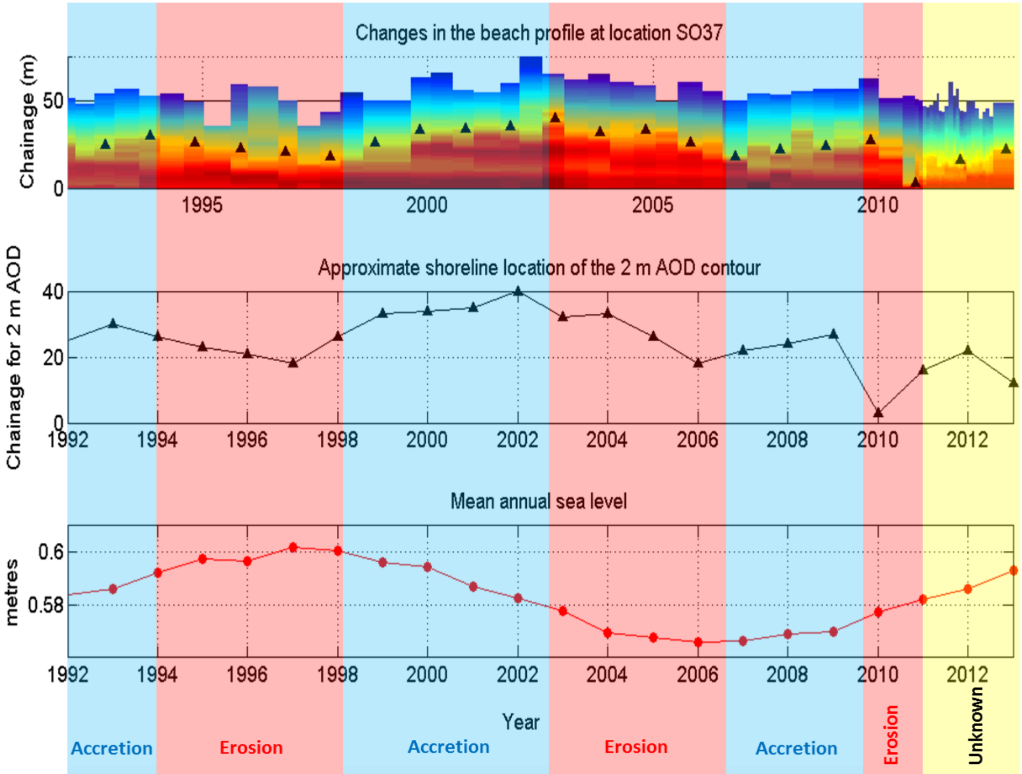


Figure 6.21: (a) Time-stacked EA beach profiles at location SO38 (from Figure 6.8); (b) mean annual HW and LW elevations (from Figure 6.18); and (c) the winter (DJFM) NAO index (from Figure 6.20) spanning the period 1991 to 2013. The red and blue shading overlaying this figure indicates periods of net erosion and accretion at SO37, respectively. The yellow shading is used to denote a period of beach management interventions.



The combined plot in Figure 6.21 shows time-stacked EA beach profiles at location SO38 (from Figure 6.09), mean annual HW and LW elevations (from Figure 6.17) and the winter (DJFM) NAO index (from Figure 6.20) spanning the period 1991 to 2013. The red and blue shading overlaying this figure indicates periods of net erosion and accretion at SO37, respectively. While no clear direct relationships between shoreline behaviour, nodal tidal cycle and NAOw is evident in this figure, it is believed that further investigation is merited using additional shoreline behaviour data gathered over a longer period. For example it is possible that peaks in the nodal cycle may provide the trigger to initiate beach erosion if the beach is already in a vulnerable state for some other reason.

7 Future Coastal Evolution

In many respects the first-order causes of the erosion at Thorpeness can be explained using the broad-scale understanding of the regional coastal processes discussed above and some well-understood coastal geomorphology principals. It is widely acknowledged that sediment is transported from north to south along the shoreline between Southwold and Aldeburgh. While there is debate about the amount of sediment moved, it is clear that some is retained at the Ness to the north of Thorpeness and that exchanges occur with the SDBC. These processes are controlled to some degree by the nature of the local geology. The changes in coastal orientation at this location attributable to geology and sediment accretion decreases the angle of incidence between the beach and incidence angle of the dominant NE waves thereby reducing the alongshore sediment transport. In simple terms, the sediment being transported from the north collects along the northern shoreline of the Ness thereby reducing the amount of sediment reaching the southern side. As a result the shoreline to the south is effectively starved of sediments and any processes that act to mobilise and transport the beach sediments to the south of the Ness will result in beach erosion if the supply is less than the loss. While it can be argued that this explanation is an over-simplification of the complex coastal processes at Thorpeness, it is considered to describe the effects which acting over a centennial time-scale will ultimately define the evolution of the coastline at this location.

Historically, coastal erosion and shoreline retreat have affected much of the Suffolk coastline post marine transgression. Without intervention, erosion will proceed at the present ‘hotspots’ for the foreseeable future and continue to have substantial impact on the integrity of the coastline at Thorpeness. It is also very likely that without active and substantial coastal management to moderate coastal processes, the rate of erosion will accelerate in response to sea level rise and possibly changes to storm magnitude, duration, grouping and frequency. However, there is also a high level of uncertainty regarding the predictions of future ‘storminess’, which is currently assumed to be associated with a warmer climate[12]. Without knowledge of the changes likely to occur in the forcing terms, predictions of future coastal behaviour are subject to great uncertainty.

At a local scale the SDBC has the potential to change over time-scales shorter than a few decades. A reduction in the size of this feature north of Thorpeness may increase the magnitude of extreme events on the shoreline and increase the risk of erosion. Conversely, if the SDBC continues to migrate in a shoreward direction, the future welding of the bank to the shoreline could occur resulting in an extensive shoreline advance that would increase coastal protection to the north of Thorpeness with unknown consequence to the shoreline to the south. However, sediment exchange mechanisms between the bank complex to the north of Thorpeness and the beaches of the Ness and those further south are not understood well enough to determine how this process might operate, and at what rate. Speculation about how the system might respond to climate change is therefore not very informative or helpful.

In addition to the possible changes to the offshore banks and other sea bed features, the sensitivity of the coastline to potential future changes in sea level, sediment flux (marine and fluvial) and storm surge events is critical for understanding the future consequences for Thorpeness. While the sensitivity to these factors can be inferred from an investigation of historical events, extrapolation of past trends to predict future coastal evolution must make a range of assumptions that contribute to uncertainty. Further, the accuracy

12 Somewhat counter intuitively, historical records indicate that stormy periods in the past (e.g. 13th and late 17th century) were associated with cooler periods, rather than warmer periods.

and reliability of methods used to determine previous sea levels is highly variable with errors in estimation almost spanning the entire change in mean sea level over the last 2000 years (e.g. BEEMS, 2012, *Fig. 14*).

While it is considered that a clearer understanding of how the Thorpeness coastline will evolve this century will result from the recommended work outlined in Section 9, predictions of coastal evolution will remain subject to uncertainty. The aim of further work must be to define this uncertainty with greater confidence so that resilient strategies can be developed able to cope with worse case scenarios.

8 Conclusions

This report has placed the Thorpeness coastline within a regional context and has identified important geological and geomorphological controls and a number of physical processes and events that characterise the present day and historical behaviour of the Thorpeness coastline. Specifically with regards to coastal erosion the study has identified that:

- The shoreline is subjected to periods of erosion lasting several years. Historically these have occurred at approximately 30 year intervals during the decades 1910-1920, 1940-1950, 1970-1980 and 2010 to present;
- During each erosion phase, erosion has been focussed on a relatively short section of the coastline (*c*. 500m in 2010 to present). However, the location of the erosion 'hotspot' has tended to shift around so that during 1970-1980 and 2010 to present, erosion is focussed on the frontage below North End Avenue. Previously, the erosion around 1910 was further south (toward Benthills);
- There is a local perception that the frequency of erosion events has changed through time evidenced in 2013-14 by three significant weather events that have placed high erosion pressure on the northern Thorpeness frontage and caused major damage to defences built between 2010 and 2012. However, the number and strength of winter storms during 2013-14 was exceptional and their occurrence does not necessarily imply any longer-term underlying trends in weather severity. It is noted that other areas of the UK coastline also suffered unprecedented erosion during the same period.
- SWAN wave modelling previously reported has shown that Thorpeness is located in a zone of relatively high wave energy that extends around the seaward flank of the SDBC and impacts on the coastline to the south of the Ness. The model results show also complex interactions with the Coralline Crag ridges that extend seawards to the north east from Thorpeness. There can be little doubt that the bed features indicated by wave breaking south of the Ness will have a significant effect on the waves arriving at the coast, perhaps acting at times to focus wave energy at specific short section of the Thorpeness frontage while at other time being configured in such a way as to spread the energy more widely. An improved understanding of the relationship between these features, waves and beach morphodynamics is therefore required as this is likely to play a significant role in determining the dynamic behaviour of the Thorpeness beach. It is suggested that the behaviour of these features, and their links to the wider coastal morphology, may be related to the erosion cycles experienced at Thorpeness.

Regarding coastal erosion periodicity at Thorpeness, it might be expected, taking account of historical trends, that the present erosion phase at Thorpeness may be followed at some time in the future by a quiescent period lasting of the order 30 years and characterised by relative shoreline stability. This might then be followed by another period of severe erosion from around 2045. If historical trends then remain the same, the coast will return to its erosive condition with further erosion for 5 to 10 years beyond 2045. However, great caution must be exercised when attempting to extrapolate past coastal behaviour into the future, especially when this information is used to inform coastal management strategies. It is stressed that at present there is no risk-free means of predicting when the present erosional trend will end and no certainty that the most recent erosion phase since 2010 is related to the apparently cyclical coastal erosion processes observed in the relatively recent past. Given the present incomplete understanding the coastal processes great caution must be exercised therefore if coastal management strategies are to be based on the belief that past historical phases of erosion and stability will continue into the future.

The SMP intent for the management of this frontage identifies a need for transition from a (community perceived) policy of long-term Hold-The-Line to one of (Managed) Realignment. Prior to 2010, short term, soft defence measures have been viewed as being suitable to resist generally low levels of coastal erosion with occasional high pressure ‘spikes’. Recently, however, the three significant weather events impacting on the northern frontage of Thorpeness have caused major damage to defences built between 2010-2012. It is clear that the damage to, and further deterioration of, the present defence indicates that the existing defences will not maintain the standard of protection required over the next 30 years. This issue has raised awareness in the community of continuing erosion risk and the need for a higher standard of protection to be provided. While it might be argued that the erosion might have been foreseen, it is equally valid to argue that many of the more vulnerable properties on North End Avenue may have been lost in 2013 if works had not been undertaken in 2011 / 2012.

A key objective of any proposed works must remain to be the provision of a sustainable and effective defence to properties over the next 30 to 50 years in a manner that does not interfere with the continued supply of sediment through the area and which addresses the recurrence of periods of severe local erosion. At the present time it remains problematic to reduce the coastal erosion problem at Thorpeness to a ‘simple’ cause-effect relationship. In this respect the primary constraint is a lack of data with which to investigate the offshore near-field and far-field sediment transport pathways over time-scales commensurate with the historical erosion sequences.

It is therefore considered to be premature to advocate a particular strategy for managing the coastal erosion problems currently experienced at Thorpeness. Any future decisions must be based on a sound understanding of the local coastal processes. However it is considered that the present understanding of local coastal processes is not yet well-enough established to inform coastal defence designs and implementation of further defences without better appreciating how the coastline is likely to evolve in the future is likely to result in an unsatisfactory outcome for all stakeholders.

The underlying coastal erosion problem to be managed at Thorpeness remains the same as that set out in the 2010 PAR. That is that localised severe beach erosion has potential to destroy residential property in the short-term and that an approach to manage that pressure is required in order to create time for adaptation to the significant change in approaches to coastal management advocated by the EA. The challenge now is to better understand the coastal processes through the steps outlined in the recommendations from this work, and to balance management of a naturally evolving shoreline with the aspirations of the community.

9 Recommendations

The work documented in this report aims to contribute to the development of a sustainable, cost-effective, longer-term coastal management strategy providing the best outcomes for local residents, visitors and the environment. However, at the present time and stage in the investigations of coastal dynamics at Thorpeness it is considered that the understanding of local coastal processes is not yet well-enough established to inform coastal defence designs. The recommendations set out here define key elements in a possible second phase of work to advance the present incomplete understanding of coastal processes at Thorpeness.

- A detailed gap analysis is now required to identify data omissions that prevent the further advancement of understanding. Specifically this should focus on: nearshore and offshore bathymetry and topography (historical and contemporary); sediment transport pathways and magnitude; and local hydrodynamics and waves. In addition, there is very little information about the physical characteristics of the beach and offshore sediments and about the thickness of sediment cover and the nature of the underlying geology. Together these data will inform modelling studies (see below) and help to improve the present conceptual understanding of coastal processes.
- The geology beneath Thorpeness is believed to have importance beyond its role as a hard point on the coast and an anchor point for the Ness and the SDBC. The depth of the Coralline Crag beneath the beach sediments may be an important contributory factor in determining local beach mobility thought its influence on beach drainage. The hard, relatively impermeable layer it provides beneath the beach will prevent efficient drainage and the potentially high pore water pressures this can create will result in greater erosion susceptibility. These aspects of the beach properties require further study.
- The complex interactions between the tidal flow eddy features generated by the Thorpeness headland plays a part in the maintenance of the Ness and the beach morphodynamics along the Thorpeness frontage. Measurements and/or numerical modelling results are required in order to fully appreciate the significance of these processes with regards to shoreline behaviour and future evolution of the Thorpeness frontage.
- While the evidence for the source of the modern-day sediment for the SDBC presented in BEEMS (2012) is inconclusive, potential pathways from Thorpeness cannot be discounted. Numerical modelling is recommended therefore to explore these potential pathways and to quantify their role in the future maintenance of the bank system and the related shoreline response in the vicinity of Thorpeness. A calibrated and validated model would then provide a credible tool to investigate future shoreline evolution in response to changes in mean sea level and/or wave climate. Numerical modelling of hydrodynamics, waves and sediments should be used to investigate alongshore and cross-shore sediment transport during storm and quiescent periods. The modelling must be founded on existing data (and the data recommended above) and draw on past models of the area as far as practicable. The models MIKE21/LITPACK and XBeach (for storm impacts) are recommended. However, it is noted that since the future occurrence frequency and magnitude of storm events is unknown, numerical modelling results cannot be extrapolated far into the future to predict coastal evolution with a level of certainty required to develop effective and sustainable coastal defence solutions. At best, the models can be used to examine coastal responses to a number of short-term scenarios and assessments of longer-term coastal evolution must rely on expert judgments based on a sound conceptual model evolved through the steps identified here.
- It is considered that a study of the role played by shoreline orientation to incident waves in controlling alongshore sediment transport and associated aspects of coastal evolution which takes account of the wave climate will improve present understanding of local coastal processes.

- Both numerical modelling studies and the development of an improved model for conceptualising the future evolution of the coastline would profit from appropriate field observations. For this purpose the deployment of an X-Band radar system similar to that currently in use to monitor the SDBC from Sizewell would provide the following information at high spatial and temporal resolution over an area extending at least 2km from the deployment site: (a) bathymetry (derived using a wave celerity inversion algorithm); (b) wave parameters; and (c) surface current speed. In addition to providing data currently missing for the area, the system would also provide a simple and effective means of monitoring coastal changes in the offshore area that are thought to play a significant role in the periodic coastal erosion events experienced along the Thorpeness frontage. The system would provide therefore an early warning of coastal changes that may potentially trigger erosion and thus be a very useful coastal management tool.
- Full use has not yet been made of the beach profile measurements from locations SO37-SO39 and TN007-TN026 (and possibly elsewhere). The initial exploratory analysis present here indicates that further understanding of beach behaviour can be extracted from the information contained in the profile data. However, the temporal behaviour of the profiles alone is not sufficient to advance understanding. Additional data pertaining to wave conditions (measurements or hindcast) are also required. A further potential problem with using profile data to infer coastal morphodynamics concerns the time interval between successive profile measurements. In some cases this may be too long to capture important responses to hydrodynamic forcing and lead to undesirable aliasing. The present increase in beach monitoring frequency is therefore welcome and if possible be extended to further profile locations to the north and south of the frontage presently monitored.
- It is believed that the complex interplay between tidal flows offshore and the eddy features generated by the Thorpeness headland plays a part in the maintenance of the Ness and the beach morphodynamics along the Thorpeness frontage. However, there is presently insufficient data or numerical modelling results available to fully appreciate the significance of these processes with regards to shoreline behaviour and future evolution of the Thorpeness frontage. X-Band radar data would be particularly helpful in this respect.
- Given the present state of knowledge about the coastal processes at Thorpeness summarised in this report it is advised that the emplacement of any additional structures would be premature and could potentially result in unforeseen consequences to other parts of the frontage. While numerical modelling may provide an indication of the short-term impacts of structures, longer-term (>1year) impacts will be much less reliable. Nevertheless, the modelling would provide a mean of comparing the relative impacts of different defence options and thereby guide local coastal management actions.

10 References

Bamber, R. N., 1995. Thorpeness: structure, topography and benthic communities. Consultancy report prepared for Nuclear Electric Plc.

BEEMS, 2011. Sea-bed sediment characteristics, bedforms and sediment transport pathways in the Sizewell area. BEEMS Technical Report TR107, 144pp.

BEEMS, 2012. Physical Science relating to possible Present and Future Coastal Geo-Hazards at the Sizewell New Nuclear Build Site. BEEMS Technical Report TR105, 190pp.

BEEMS, 2013. Estimation of extreme sea levels at Sizewell, Suffolk, Report TR252, 51 pp.

BEEMS, 2014. Update on Estimation of extreme sea levels at Sizewell, Report TR322, 45 pp.

BGS, 1996. Saxmundham England and Wales Sheet 191, Solid and Drift Geology, 1: 50,000. British Geological Survey, Keyworth, Nottingham.

Birkbeck College/University College, 1999. Analysis of Coastal Change: Monitoring and Modelling of Erosion and Sedimentation along the Suffolk Coast. Shoreline Monitoring Preliminary Report by the London Joint Research School of Geological and Geophysical Sciences. Environment Agency. 47pp.

Birkbeck College & Babtie, 2000. Spits and Nesses. Basic processes and effects on long-term coastal morphodynamics. Final Report.

Blackley, M. W. L., 1979. Beach changes between Aldeburgh and Southwold, March 1978 to May, 1979. Sizewell and Dunwich Banks field study Topic Report 3. Institute of Oceanographic Sciences Report 90, 30pp, unpublished manuscript.

Brooks, S.M. 2010. Coastal change in historic times – linking offshore bathymetry changes and cliff recession in Suffolk. The Crown Estate, 92 pages. ISBN: 978-1-906410-21-6

Brooks, S. M. & Spencer, T., 2010. Temporal and spatial variations in recession rates and sediment release from soft rock cliffs, Suffolk coast, UK. *Geomorphology*, 124(1), 26-41.

Cameron T. D. J., Crosby, A., Balson, P.S., Jeffrey, D.H., Lott, G.K., Bulat, J. & Harrison, D.J., 1992. United Kingdom Offshore Regional Report: The geology of the southern North Sea. British Geological Survey. HMSO, London, 152 pp.

Carr, A. P., 1979. Sizewell-Dunwich banks field study topic report: 2. Long-term changes in the coastline and offshore banks. IOS Report 89, 30pp.

Carr, A. P., 1979. Long-term changes in the coastline and offshore banks. Sizewell and Dunwich Banks field study Topic Report 3. Institute of Oceanographic Sciences Report 89, 25pp, unpublished manuscript.

Carr, A. P., 1981. Evidence for the sediment circulation along the coast of East Anglia. Marine *Geology*, 40(3), M9-M22.

Coughlan, C., Vincent, C.E., Dolphin, T.J., & Rees, J.M. 2007. Effects of Tidal Stage on the Wave Climate Inshore of a Sandbank. *Journal of Coastal Research*, SI 50, 751–756.

Dixon, M.J. & Tawn, J.A., 1997. Estimates of Extreme Sea Conditions. Final Report. Spatial Analyses for the UK Coast. Proudman Oceanographic Laboratory, Bidston Observatory, Internal Document No. 112, 217pp.

Dyer, K. R., & Huntley, D. A., 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*, 19(10), 1285-1330.

Eisma. D., 1981. Supply and deposition of suspended matter in the North Sea, In S-D. Nio, R. T. E, Schüttenhelm, C. E, Van Weering T. J. (Eds.). Holocene Marine Sedimentation in the North Sea Basin. (pp. 415-428). International Association of Sedimentologists, Special Publication.

Emu Ltd & University of Southampton, 2009. Outer Thames Estuary Regional Environmental Characterisation. Marine Aggregate Levy Sustainability Fund (MALSF), 09/J/1/06/1305/0870, 146pp.

Environment Agency, 2007. Suffolk Coastal Trends Analysis, Shoreline Management Group, EA, 46pp.

Environment Agency, 2011a. Coastal Morphology Report Thorpeness (Phase 1), RP024/S/2011, 44pp.

Environment Agency, 2011b. Coastal Trends Report Suffolk (Lowestoft to Languard Point, Felixstowe). RP022/S/2011.

Environment Agency, 2013. Coastal Morphology Report Thorpeness (Phase 2), RP030/S/2013, 31pp.

Esteves, L. S., Williams, J. J. & Brown, J. M., 2011. Looking for evidence of climate change impacts in the eastern Irish Sea. *Natural Hazards and Earth System Science*, 11 (6), 1641-1656.

Future Coast, 2002. Draft Shoreline Behaviour Statement: Blyth Estuary to Thorpe Ness. January, 2002 version.

Garnier, R., Calvete, D., Falqués, A., & Caballeria, M., 2006. Generation and nonlinear evolution of shore-oblique/transverse sand bars. *Journal of Fluid Mechanics*, 567, 327.

Gratiot, N., Anthony, E. J., Gardel, A., Gaucherel, C., Proisy, C., & Wells, J. T., 2008. Significant contribution of the 18.6 year tidal cycle to regional coastal changes. *Nature Geoscience*, 1(3), 169-172.

Halcrow, 2001. Lowestoft to Thorpeness Coastal Process and Strategy Study, Environment Agency.

Halcrow Group Ltd. 2001a. Lowestoft to Thorpeness Coastal Processes and Strategy Study. Volume 1, Coastal Processes. September 2001. Halcrow Maritime, Swindon.

Halcrow Group Ltd. 2001b. Lowestoft to Thorpeness Coastal Process and Strategy Study. Volume 2: Coastal Processes. Technical report to Waveney District Council, EA Anglian Region and Suffolk Coastal District Council.

HR Wallingford, 2010. Sizewell Power Station Extreme Sea Level Studies. Joint Probability of Waves and Sea Levels and Structure Response. Technical Note 01. Report to EDF Energy, HR Wallingford, Wallingford.

Hurrell, J. W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science,* 269, 676-679.

Hurrell, J. W., & Deser, C., 2009. North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems*, 78(1), 28-41.

Lees, B.J., 1980. Introduction and Geological Background. Sizewell - Dunwich Banks. Field Study Topic Report 1. Institute of Oceanographic Sciences Report No. 88, 24pp plus figures.

Lees, B. J., 1982. Quaternary sedimentation in the Sizewell-Dunwich banks area, Suffolk. Bulletin of the Geological Society of Norfolk, 32, 1-35.

Lees, B. J., 1983. Sizewell-Dunwich Banks field study topic report: 7. Final report. A study of nearshore sediment transport processes. IOS Report 146, 49pp.

Lees, B. J., 1983. The relationship of sediment transport rates and paths to sandbanks in a tidally dominated area off the coast of East Anglia, UK. *Sedimentology*, 30(4), 461-483.

Lees, B. J., & Heathershaw, A. D., 1981. Sizewell-Dunwich banks field study topic report: 5. Offshore sediment movement and its relation to observed tidal current and wave data. IOS Report 123, 119pp.

Lozano, I., Devoy, R. J. N., May, W. & Andersen, U., 2004. Storminess and vulnerability along the Atlantic coastlines of Europe: analysis of storm records and of a greenhouse gases induced climate scenario. *Marine Geology*, 210, 205-22.

McCave, I. N., 1978. Grain size trends and transport along beaches: Examples from Eastern England. Marine Geology, 28, M43-M51.

McMillan, A., Batstone, C., Worth, D., Tawn, J., Horsburgh, K. & Lawless, M., 2011. *Coastal Flood Boundary Conditions for UK Mainland and Islands*. Project SC060064/TR2: Design Sea Levels. Environment Agency, Bristol, 133pp.

May V. J. & Hansom J. D., 2003. Coastal geomorphology of Great Britain. Geological Conservation Review Series 28. Joint Nature Conservation Committee, Peterborough.

McLean, R. F., & Kirk, R. M., 1969. Relationships between grain size, size-sorting, and foreshore slope on mixed sand-shingle beaches. *New Zealand Journal of Geology and Geophysics*, 12(1), 138-155.

Pethick, J., & Leggett, D., 1993. The morphology of the Anglian Coast. In *Coastlines of the southern North Sea*, ASCE 52-54.

Pethick, J., 1999. Sizewell Foreshore Changes 1996-1999. *Report to Sizewell Shoreline Management Group*. Coastal Geomorphology Partnership, Department Of Marine Sciences and Coastal Management, University Of Newcastle, 10 pp.

Pontee, N. I., 2005. Management Implications of Coastal Change in Suffolk, UK. Maritime Engineering, 158, Issue MA2, pp 69 – 83.

Pontee, N. I., Pye, K., & Blott, S. J., 2004. Morphodynamic behaviour and sedimentary variation of mixed sand and gravel beaches, Suffolk, UK. *Journal of Coastal Research*, 256-276.

Powell, K. A., 1990. Predicting short-term profile response for shingle beaches. Report SR219, HR Wallingford, UK.

Pye, K., 2001. The nature and geomorphology of coastal shingle. In Packham, J. R., Randall, R.E., Barnes, R. S. K. and Neal, A. (eds) *Ecology and Geomorphology of Coastal Shingle*. Westbury Publishing, 2-22.

Pye, K. & Blott, S. J., 2006. *Minsmere Sea Defences Coastal Processes Assessment - Further Report*. Prepared for the Royal Society for the Protection of Birds (East Anglia Office). Kenneth Pye Associates Ltd., External Investigation Report ER601, 15 pp.

Pye, K., & Blott, S. J., 2006. Coastal processes and morphological change in the Dunwich-Sizewell area, Suffolk, UK. *Journal of Coastal Research*, 453-473.

Pye, K. & Blott, S. J., 2010. *Beach Erosion at North End, Thorpeness, Suffolk*. Kenneth Pye Associates Ltd., External Investigation Report EX1220, October 2010.

Pye, K. & Blott, S. J., 2011. *Sea Bed Sediment Characteristics, Bedforms and Sediment Transport Pathways in the Sizewell Area*. Report prepared for BEEMS and EDF Energy. Kenneth Pye Associates Ltd. External Investigation Report EX1212, March 2011. British Energy Estuarine and Marine Studies (BEEMS) Technical Report TR107, April 2011, EDF Energy, London.

Pye, K. & Blott S. J., 2013. *Estimation of Extreme Sea Levels at Sizewell*. Report prepared for BEEMS and EDF Energy. Kenneth Pye Associates Ltd. External Investigation Report EX1345, January 2013. British Energy Estuarine and Marine Studies (BEEMS) Technical Report TR252, November 2013, EDF Energy, London.

Pye, K. & Blott S. J., 2014. *Estimation of Extreme Sea Levels at Sizewell: Addendum Report*. Report prepared for BEEMS and EDF Energy. Kenneth Pye Associates Ltd. External Investigation Report EX1723, June 2014. British Energy Estuarine and Marine Studies (BEEMS) Technical Report TR252 Addendum, EDF Energy, London.

Pye, K., Blott, S. J. & Dolphin, T., 2014. *Shoreline Variability and Accretion/Erosion Trends in Sizewell Bay*. Report prepared for BEEMS and EDF Energy. Kenneth Pye Associates Ltd. External Investigation Report EX1364, October 2012. British Energy Estuarine and Marine Studies (BEEMS) Technical Report TR223, Edition 2, February 2014, EDF Energy, London.

Reis, A. H. & Gama, C., 2010. Sand size versus beachface slope—An explanation based on the Constructal Law. *Geomorphology*, 114(3), 276-283.

Robinson, A. H. W., 1980. Erosion and accretion along part of the Suffolk coast of East Anglia, England. *Marine Geology*, 37(1), 133-146.

Royal Haskoning, 2009. Suffolk SMP2 Sub-cell 3c. Review of Coastal Processes and Geomorphology, Suffolk SMP2 3c, 124pp.

Royal Haskoning, 2010a. Thorpeness Erosion Response Works. Stage 1 Report for Suffolk Coastal District Council, 9W2244/R/303906/PBor, 84pp.

Royal Haskoning, 2010b. Suffolk SMP2 Sub-cell 3c, Policy Development Zone 5 – Thorpeness to Orford Ness, V. 9, 48pp.

Royal Haskoning, 2010c. Suffolk SMP2 Sub-cell 3c, Policy Development Zone 4 – Dunwich Cliffs to Thorpeness, V. 9, 48pp.

Royal Haskoning, 2011. Coastal Trends Report Suffolk (Lowestoft to Languard Point, Felixstowe), RP022/S/2011, 46pp.

Shennan, I., Lambeck, K., Flather, R., Horton, B., McArthur, J., Innes, J., Lloyd, J., Rutherford, M. & Wingfield, R., 2000. Modelling western North Sea palaeogeographies and tidal changes during the Holocene. In Shennan, I., Andrews, J. (eds.) *Holocene Land - Ocean Interaction and Environmental Change Round the North Sea*. Geological Society, London, Special Publications 166, 299-319.

Shore protection manual, 1984. 4th Edition, 2 Vol, U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, DC.

Soulsby, R. L., 1997. *Dynamics of Marine Sands*. Thomas Telford Ltd.

Stride, A.H. (Ed.), 1982. *Offshore tidal sand*. Chapman and Hall, London, New York.

Suffolk Coastal District Council (SCDC), 2015. Project Appraisal Report (PAR): Thorpeness Erosion Response Works, 69pp.

Taylor, J. A., Murdoch, A. P. & Pontee, N. I., 2004. A Macroscale Analysis of Coastal Steepening Around the Coast of England and Wales, The Geographical Journal, 170(3), 179 – 188.

HR Wallingford, BEEMS, U. E. A., Haskoning, & D'Olier, B., 2002. Southern North Sea Sediment Transport Study, Phase 2. HR Wallingford Report, EX, 4526.

Tucker, M. J., Carr, A. P. & Pitt, E. G., 1983. The effect of an offshore bank in attenuating waves. *Coastal Engineering*, 7, 133-144.

Waveney District Council, 1998. Benacre Ness to Thorpeness Strategy/Process Study Project Appraisal Report. Community Services Department

Woodworth, P. L., Teferle, F. N., Bingley, R. M., Shennan, I. & Williams, S.D.P., 2009. Trends in UK mean sea level revisited. *Geophysical Journal International*, 176, 19-30.

Zalasiewicz, J., Mathers, S. J., Hughes, M. J., Gibbard, P. L., Peglar, S. M., Harland, R., Nicholson, R. A., Boulton, G. S., Cambridge P. & Wealthall, G. P., 1988. Stratigraphy and palaeoenvironments of the Red Crag and Norwich Crag Formations between Aldeburgh and Sizewell, Suffolk, England. *Philosophical Transactions of the Royal Society B* 322, 221-272.

11 Glossary

AOD	Above ordnance datum
BEEMS	British Energy Estuarine and Marine Studies
BP	Before present
Ch	Chainage
DSPR	Directional spreading (waves)
EA	Environment Agency
HAT	Highest astronomical tide
IPCC	Intergovernmental Panel on Climate Change
JPA	Joint probability analysis
LAT	Lowest astronomical tide
PAR	Project Appraisal Report
MHWS	Mean high water spring
MHW	Mean high water
MHWN	Mean high water neap
MLWN	Mean low water neap
MLW	Mean low water
MLWS	Mean low water spring
MSL	Mean sea level
NAO	Annual North Atlantic Oscillation index
NAOw	Winter North Atlantic Oscillation index
ODN	Ordnance Datum Newlyn
RCP	Representative Concentration Pathways
SCDC	Suffolk Coastal District Council
SDBC	Sizewell-Dunwich Bank complex
SLR	Sea level rise
SMP2	Second Shoreline Management Plan
SRES	Special Report on Emissions Scenarios
UKCP09	UK Climate Projections 2009

Notation

D50	Median grain size (mm)
Hm0	Significant wave height (m)
Pw	Wave power (J/m/s)
Tp	Peak wave period (s)
Uw	Bottom wave orbital velocity (m/s)
θ	Mean wave direction (degrees N)
θ_b	Mean beach angle

Appendices

Appendix A. Chronology of events and reference material in the study area

Table A.1: Chronology of events and reference material in the study area

Date	Event
1975	Placement of gabion baskets to protect the cliff below North End Avenue
1991	Profile monitoring starts. Three profiles available from the Anglian Region Coastal Monitoring Programme
2009	Addition of surveyed profiles by the Shoreline Management Group's. Profile placed closer together.
January 2009	SUFFOLK SMP2 Sub-cell 3c. Appendix C. Draft Report
January 2010	SPM2 Publication of Policy Development of Zone 4 and 5
2010	Marine Estate Research Report
Early 2010	Erosion of significant volume of sediment from the gabions area and erosion of the unprotected cliff pace just to the north of this
October 2010 – December 2010	Emergency beach protection works: Sand/shingle Geobags placed immediately south of the existing gabions
February 2011	Shingle recharge from the Ness completed.
June 2011	*Phase 1* works completed
July 2011	Survey *Phase 1*
August to November 2011	*Phase 2* works: Strengthening of the gabions with Geobags
September 2011	*Phase 2* monitoring begins
Spring 2013	Major erosion damage to *Phase 2* works
Summer 2013	Some beach recovery observed
Autumn/Winter 2013	Major erosion damage to *Phase 2* works

Appendix B. Name, amplitude and phase of tidal constituents at Thorpeness (Source MIKE by DHI)

Table B.1: Name, amplitude and phase of tidal constituents at Thorpeness (Source MIKE by DHI).

No.	Name	Amp.	Phase	No.	Name	Amp.	Phase
1	Z0	0	0	36	H1	0.0004	212.99
2	SA	0	17.62	37	M2	0.8757	311.62
3	SSA	0	193	38	H2	0.0004	204.94
4	MSM	0	319.3	39	MKS2	0.0002	29.74
5	MM	0	38.97	40	LDA2	0	325.46
6	MSF	0	352.2	41	L2	0	328.62
7	MF	0	188.55	42	T2	0.0001	92.35
8	ALP1	0	7.76	43	S2	0.2187	14.39
9	2Q1	0	316.88	44	R2	0.0002	268.55
10	SIG1	0	60.2	45	K2	0.0708	345.46
11	Q1	0.0448	129.94	46	MSN2	0	242.34
12	RHO1	0	188.3	47	ETA2	0	54.75
13	O1	0.1361	183.07	48	MO3	0	311.52
14	TAU1	0.0001	273.33	49	M3	0	77.56
15	BET1	0	33.66	50	SO3	0	208.02
16	NO1	0.0001	191.25	51	MK3	0	226.97
17	CHI1	0	272.62	52	SK3	0	268.03
18	PI1	0.0001	236.41	53	MN4	0	168.36
19	P1	0.036	318.27	54	M4	0	334.27
20	S1	0.0002	277.31	55	SN4	0	292.81
21	K1	0.1345	323.39	56	MS4	0	294.33
22	PSI1	0.0002	80.48	57	MK4	0	40.84
23	PHI1	0.0001	287.04	58	S4	0	41.32
24	THE1	0	30.28	59	SK4	0	270.77
25	J1	0	288.59	60	2MK5	0	352.02
26	SO1	0	227.89	61	2SK5	0	356.32
27	OO1	0	40.03	62	2MN6	0	266.95
28	UPS1	0	335.55	63	M6	0	213.02
29	OQ2	0	306.92	64	2MS6	0	338.52
30	EPS2	0	353.46	65	2MK6	0	176.82
31	2N2	0	291.72	66	2SM6	0	156.32
32	MU2	0	76.93	67	MSK6	0	34.79
33	N2	0.1382	288.11	68	3MK7	0	156.54
34	NU2	0	136.25	69	M8	0	26.46
35	Z0	0	0				