Appendix F
Shoreline Interactions & Responses

APPENDIX F - CONTENTS

F1 INTRODUCTION

This appendix reports on a number of activities carried out in the course of the SMP development to assess the interaction of SMP policy and coastal processes. It builds on the baseline description of the coastal processes described in appendix C.

The appendix contains the assessment of coastal defences (Task 2.1b), the development of baseline scenarios (Task 2.2), the assessment of flood risk (Task 2.5) and finally the assessment of the shoreline response to the options selected for appraisal (Task 3.2). The appendix also reports on the additional tasks carried out in order to provide sufficient data to enable preferred policies to be selected following the policy appraisal process. These are reported on in detail in section F6 of this appendix, and their specific role in the policy development process is highlighted in appendix E (section E5).

It is important to note that this appendix contains a full record of the assessments undertaken and decisions made along the route to concluding draft and final SMP policies for The Wash. All of this information has been used within the decision making process, but it may not have necessarily been taken forward and reported on within the main SMP document or non-technical summary. In some instances insights have changed in the course of the SMP process, so it is possible that the text in the appendices seems to contradict the content of the main SMP document or non-technical summary. In such cases, this is highlighted in the introduction to the appendix section. The main SMP document and the non-technical summary contain the agreed SMP policies.

F2 ASSESSMENT OF COASTAL DEFENCES

F2.1 Introduction

The aim of Task 2.1 as a whole is to review coastal behaviour and dynamics. The appreciation of these processes underpins the sound development of the SMP. This includes assessment of the natural features as well as considering the existing defences. The results from this task are used to develop the baseline scenarios, identify risks, and test the response and implications of different management policy packages over three separate timescales (present day to 2025, 2025 to 2055 and 2055 to 2105).

Task 2.1 is divided into two explicit tasks, and this note deals with the second part of this task, referred to as 2.1b. This task consists of the assessment, in broad terms, of every coastal defence within the boundaries of the SMP study area. It has been split down further into two stages:

- Theoretical approach based on condition, according to the SMP guidance;
- Validation by asset managers.

This text incorporates the validation from the Asset Managers, which has also led to updated NFCDD information and changes to residual life estimates derived from improved methods as used for the Environment Agency's System Asset Management Plans.

F2.2 Residual Life Based on Condition Grade

F2.2.1 Method

SMP Guidance

The SMP guidance provides residual life numbers based on the existing defence condition grades for a number of defence types (table F2.2.1). This information has been derived from previous NADNAC (National Appraisal of Defence Needs and Costs) deterioration profiles.

Table F2.2.1 Estimate of deterioration for assessment of residual life (from SMP guidance)

Defence Description		Estimate of Residual Life (years)				
		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Seawall (concrete/masonry)	Fastest	25	15	10	5	0
	Slowest	35	25	15	7	0
Revetment (concrete/rock)	Fastest	25	15	10	5	7
	Slowest	35	25	15	7	0
Timber Groyne/ timber structures	Fastest	15	10	8	2	0
	Slowest	25	20	12	7	0
Gabion	Fastest	10	6	4	1	0
	Slowest	25	10	7	3	0

Additional Method for Grassed Embankments

The SMP guidance does not, however, contain residual life estimates for grassed earth embankments, which constitute a high proportion of the flood defences around the Wash. As a result we have developed a residual life profile for this asset type. In discussion with the Environment Agency and Defra we have decided to use the latest knowledge on asset deterioration, which were improved in 2007 from the NADNAC information for use in the Environment Agency's Strategic Asset Management Plans (SAMP), adapting this so that it is in the same format as the SMP guidance.

Defence class number 45 (type 2) from NADNAC, described as a wide earth embankment with turf revetment, most closely matches the grassed earth embankments characteristic of the Wash area. The SAMP (2007) deterioration profile for this defence type is shown in table F2.2.2. This information differs from the SMP guidance in that the SAMP numbers indicate the number of years to reach a condition from new, whereas the SMP numbers indicate the number of years from a condition to failure.

Table F2.2.2 SAMP deterioration profile for a wide earth embankment with turf revetment

Number	Type		Time (years) to Reach Condition from New				
			Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
45	Type 2, W, FP, Turf	Best estimate	0	13	20	28	33
		Fastest	0	10	15	22	25
		Slowest	0	15	25	35	40

Following consultation with EA Policy and with Defra, it was decided to simply convert the deterioration profiles from SAMP (2007) directly to residual life profiles. Grade 5 is assumed to signify failure; the difference in years between a certain grade and Grade 5 is assumed to be the residual life of a defence of that grade. This approach is comparable to the one used to establish the residual life profiles in the SMP guidance. Technically this assumes that the assigned condition is always at the 'top' of the condition, but this is acceptable given the uncertainties in the scientific background of the deterioration rates. Table F2.2.3 defines the final residual life assessments adopted to use for the grassed earth embankments (sea banks) of the Wash.

There are a number of earth embankments within the Wash study area that have additional toe protection in the form of revetment or berm units. Following discussion with the Asset Managers it has been concluded that this type of defence should be treated as a simple earth embankment as this is the weakest element of the defence despite any additional hard elements that it may have.

Table F2.2.3 Estimate of deterioration for assessment of residual life adopted for grassed earth embankments (sea banks)

Defence Description		Estimate of Residual Life (years)				
		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Sea bank	Fastest	25	15	10	3	0
	Slowest	40	25	15	5	0

Note that the guidance also does not contain residual life numbers for 'natural defences' such as shingle banks. These occur along the eastern shore of the Wash. Following discussion with the Environment Agency it has been decided that the shingle ridges will be treated as natural defences, despite their regular maintenance, and therefore their condition and resulting residual life can be determined simply by the assessment of coastal processes.

Further Assumptions

There were a number of other assumptions that were made in relation to the defence type. In some cases the descriptions of the individual defences are not clear and therefore we have had to make certain assumptions to assign a defence to a specific SMP category. The assumptions are listed in table F2.2.4.

Table F2.2.4 Assumptions regarding SMP defence types

Specific NFCDD Description	Assumed SMP Category
Gabion Groyne constructed from gabion baskets	Gabion
Gabion Groyne	Gabion
Sea bank with berm	Sea bank
Sea bank with grass berm	Sea bank
Retaining wall and embankment	Sea bank
Concrete defence/promenade	Seawall
Sea bank with seaward berm and stone toe revetment	Sea bank
Floodbank with stone toe revetment	Sea bank
Sea bank with gabion toe	Sea bank
Set back bank with stone toe and gabion basket revetment	Sea bank
Sea bank with wetland berm	Sea bank
Floodbank with gabion toe and stone berm	Sea bank
Floodbank with berm	Sea bank
Pre-cast concrete Groyne	Revetment (concrete/rock)

F2.2.2 Data availability

Data relating to specific elements of each defence was provided by the defences' asset managers from the National Flood and Coastal Defence Database (NFCDD). This database includes a description of each defence and an Overall Condition Grade that was assigned to the defence during the last inspection. In some cases an Overall Condition is not available, and therefore we have used the Manual Override Condition from NFCDD instead. This override grade was assigned by the asset manager to certain defences based upon the condition of the asset elements and their weightings.

It is also necessary to mention that the received NFCDD data does contain an estimate of residual life, but as specified in the SMP guidance these have not been used for the defence assessment, and instead the residual life for each defence has been derived using the method discussed in section 2.1. As part of the validation by the asset managers, they have assessed the appropriateness of the calculated residual life profiles.

The NFCDD database also contained a number of defences that were outside the boundaries of the study area that was provisionally agreed at 29 May's Client Steering Group meeting, and so were removed from the final output. There were also a number of secondary and tertiary defences that were included within the NFCDD database; however these were removed following discussions with the EA when it was decided that only managed defences (which in most cases are the frontline defences) should be considered throughout this assessment.

There are a number of defences protecting Hunstanton that are managed by the Borough Council of King's Lynn and West Norfolk, and therefore details were not available within the received NFCDD data. Information for these defences was therefore derived from the Hunstanton Sea Defence Condition Survey (St La Haye Limited 2005).

F2.2.3 Results

Referencing of the defences
A unique 'SMP2 Reference' has also been assigned to all relevant frontline defences within the SMP study boundary. Defences were numbered in numerical order starting at the right hand bank of the River Steeping, south of Gibraltar Point.

Assessment for 'No active intervention'
The results of Task 2.1b are shown in table F2.2.7. This table provides an overall summary of the defences present within the study area and includes an individual defence's location, description and maintainer. Up to this column all information comes directly from NFCDD. The table also summarises the assumptions used for the condition assessment, the Defence Category (see section 2.2), and the fastest and slowest estimates of residual life under the No active intervention (NAI) policy. The Defence Category column relates to the With Present Management scenario, see section 2.3.2.

The residual life for each defence has also been used to define the epoch during which the defence is likely to fail. The three epochs are defined under the SMP guidance for Task 2.2:

- Epoch 1 - Present day to 2025;
- Epoch 2 - 2025 to 2055;
- Epoch 3 - 2055 to 2105.

This is not necessarily an essential part of Task 2.1b, but it will provide vital information for the completion of Task 2.2 (Baseline scenarios).

Table F2.2.7 also demonstrates that there are a number of defences that have the potential to fail within epoch 1, but may not fail until epoch 2. This provides uncertainty to the assessment of defence failure and will need to be taken into account in subsequent tasks.

The condition grades for each defence are presented diagrammatically in figure F2.2.1, and the estimate of the residual life for each defence is presented in figure F2.2.2. Figure F2.2.3 illustrates an expected failure plan for the three previously defined epochs.

Assessment for 'With Present Management'

In order to prepare the defence assessment output for the 'With Present Management (WPM)' scenario to be analysed as part of Task 2.2, it was necessary to define the functions of the defence 'practice' rather than simply the specifics of the structure itself. As a result an extra column has been inserted into the output table in table F2.2.7 (labelled 'Defence Category') in order to determine how the present management and practices in the study area affect shoreline processes and behaviour. Defences have been categorised using the guidance from table D2 in appendix D of the SMP Guidance. A summary of the categories and the assumptions for each are included in table F2.2.5.

Table F2.2.5 Assumptions for the 'With Present Management baseline' assessment

Defence Type Category	Example Structure	Brief Assumptions
Linear Stoppers	Seawall, Grassed embankments	Minimise breach, structural integrity remains and wall is rebuilt at a similar standard of effectiveness
Linear Reducers	Maintained shingle barrier	Continues to reduce erosion, although level of effectiveness may change and therefore rate of erosion may change
Cross-shore interrupters	Groyne, breakwaters	Continues to interrupt drift but not necessarily the same amount
Changers	Recharge/recycling	Continues to recharge with same amount, sediment type and timing

Note that we have assumed that maintained grassed embankments will act as linear stoppers, just like seawalls.

F2.2.4 Discussion

In terms of condition grade (figure F2.2.1) there is a mixed array in the Wash study area. Condition grades generally range from 1 to 4, with only one defence exhibiting grade 5 and only a small number labelled as 4. The defence that exhibits grade 5 is Groyne number 15A (DEF_1_117) in front of Hunstanton and it is assumed that this defence has failed and is no longer maintained. The defences with a condition grade of 4 are limited to secondary and tertiary defences only, so they have not been included in the final assessment. In summary the majority of the defences have a condition grade of either 2 or 3.

Figure F2.2.2, the assessment of residual life for a scenario of No active intervention, indicates that the frontline defences between Gibraltar Point and the outfall of The Haven have residual lives of between 3 and 25 years. Figure F2.2.2 also indicates that the defences between the outfall of The Haven to Ongar Hill have the highest residual lives within the study area.

This defence failure is further clarified by figure F2.2.3 which groups the residual life estimates into the three epochs previously discussed in this section. This figure again emphasises the relative vulnerability of the stretch of coast between Gibraltar Point and the outfall of The Haven, and in the vicinity of the River Great Ouse outfall to Snettisham Scalp, where the majority of the defences are estimated to fail within the next 18 years under a policy of NAI.

F2.3 Additional Defence Information

Due to the nature of many of the defences around the Wash, there is a need to consider how the defences are managed in addition to the description and condition of each defence. This is particularly important when considering the managed natural features, such as the shingle banks. The following sections will discuss the management practices for the defences between Hunstanton and Heacham, and Freiston Shore.

F2.3.1 Hunstanton-Heacham Defences

Detailed information on the defences between Hunstanton and Heacham, notably the management regime for the natural shingle ridge, is provided in section F6.3.2 (page 316).

F2.3.2 Hunstanton Cliffs

The cliffs at Hunstanton consist of composite weak rock cliffs and extend between 1 and 3 kilometres north from the northern end of the Hunstanton promenade. They are 18 metres high at the highest point around the lighthouse and coastguard station. They provide a significant safety concern to both the public and cliff-top amenities as there is the potential for large volumes of material to be released during individual failure events.

The regional geological structure and cliff geomorphology provides the preparatory conditions for failure and forcing conditions are present in the form of coastal wave and tide conditions. These are augmented by subaerial processes and together this can lead to powerful failure triggers on susceptible cliff lengths.

However as discussed by Drake and Phipps (2007), the accurate prediction of cliff recession and long-term geomorphological change is problematic.

There is no obvious evidence of toe protection at the cliffs, and therefore a number of properties situated near the edge of the cliff will have to be abandoned in the short term if present management practices continue.

F2.3.3 Freiston Shore Managed realignment

As part of the Wash Banks Strategy (1997) a scheme of Managed realignment was instigated at Freiston Shore. The most recent reclamation at Freiston Shore was located too far seaward, and therefore there was not enough intertidal area for the saltmarsh to recover sufficiently or dissipate wave energy effectively. Therefore erosion of the sea bank had been occurring during high wave energy events in winter storms. The Wash Banks Strategy identified that the most viable option was to retreat the sea defences back to the old bank.

The 78 hectare realignment site was studied intensively, and this included numerical modelling. The embankment was then breached in August 2002. There were three main stages necessary in order to prepare the site for the breach event:

- Strengthening of the old bank.
- Creating artificial creeks and connecting them with creeks on the saltmarsh.
- Breaching the embankment at three locations at 50m established widths.

Table F2.2.7 Defence Assessment Results

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs)[2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_001	053BDWSHL0101C02	TF5533258111	Alongside Steeping Haven opp Gibraltar Point	Sea defence (man-made)	Sea bank with grass berm	347.30	Environment Agency	50	11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_002	053BDWSHL0101C03	TF5536057847	Steeping Haven to 1.2km South	Sea defence (man-made)	Sea bank	1201.90	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_003	053BDWSHL0101C04	TF5425557505	1.2km South of Steeping Haven to cross bank at IDB PS	Sea defence (man-made)	Sea bank	1811.90	Environment Agency		>20	4		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_004	053BDWSHL0101C05	TF5293056265	Cross bank at IDB PS	Sea defence (man-made)	Sea bank with berms	443.80	Environment Agency		>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_005	053BDWSHL0303C02	TF5290556234	Sea Lane Wainfleet	Sea defence (man-made)	Private Sea Bank	448.30	Private		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_006	053BDWSHL0303C01	TF5041853599	Between Sea Lane (RAF Wainfleet) and Sea Lane Wainfleet.	Sea defence (man-made)	Jubilee Sea Bank (private defence)	3620.10	Private		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_007	053BDWSHL0601C02	TF4967953019	Sea Lane, immediately south of	Sea defence (man-made)	Jubilee Sea Bank (private defence)	1019.80	Private		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_008	053BDWSHL0601C01	TF4702250855	Horseshoe Point to just south of Sea Lane	Sea defence (man-made)	Jubilee Sea Bank (private defence)	3769.80	Private		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_008a 1	053BDWSHL0101C06	TF5261956582	Cross bank at IDB PS to pullover 170m South	Sea defence (man-made)	Raised earth embankment	177.30	Environment Agency		11-20	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1

[1] Estimate under NAI policy
[2] Estimate under NAI policy
[3] Epoch 1 (present day to 2025), Epoch 2 (2025 to 2055), Epoch 3 (2055 to 2105)

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs)[2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_008a	053BDWSHL0401C02	TF5249456456	176m South of IDB PS to 2.3 km North of RAF Wainfleet Tower	Sea defence (man-made)	Raised earth embankment	1216.70	Environment Agency		11 - 20	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_008b	053BDWSHL0401C03	TF5163255594	2.3km North of RAF Wainfleet tower to tower	Sea defence (man-made)	Raised earth embankment	2421.40	Environment Agency		6 - 10	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_008c	053BDWSHL0701C01	TF5000453908	RAF Wainfleet Tower to 151m South	Sea defence (man-made)	Raised earth embankment	151.00	Environment Agency		11 - 20	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_008d	053BDWSHL0701C02	TF4995653765	151 to 400m South of RAF Wainfleet Tower	Sea defence (man-made)	Raised earth embankment with 3m long trench sheeters	374.70	Environment Agency		6 - 10	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_008e	053BDWSHL0701C03	TF4973853468	400 to 570m south of RAF Wainfleet Tower	Sea defence (man-made)	Raised earth bank	40.90	Environment Agency		11 - 20	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_008f	053BDWSHL0701C04	TF4971153437	570m South of RAF Wainfleet to 1.56km North of Horseshoe PS	Sea defence (man-made)	Raised earth bank	2354.70	Environment Agency		11 - 20	4***		Sea bank	4	3	2010	5	2012	Linear Stopper	1
DEF_1_008g	053BDWSHL0701C05	TF4798751835	1.6km North of Horseshoe PS	Sea defence (man-made)	Raised earth embankment with trench sheeters to control badger activity	36.30	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_008h	053BDWSHL0701C06	TF4796451806	0.2 to 1.6km North of Horseshoe PS	Sea defence (man-made)	Raised earth bank	1342.50	Environment Agency		> 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_009	053BDWSHL0701C07	TF4702250855	Horseshoe PS to 200m North	Sea defence (man-made)	Sea bank	202.20	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_010	053BDWSHL0901C01	TF4684050926	Horseshoe PS to Toft Marsh	Sea defence (man-made)	Sea bank	1232.60	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs)[2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_011	053BDWSHL1001C01	TF4596850126	Toft Marsh	Sea defence (man-made)	Sea bank	486.10	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_012	053BDWSHL1001C02	TF4581349686	Toft Marsh	Sea defence (man-made)	Sea bank	547.90	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_013	053BDWSHL1001C03	TF4547849334	North of Sailors Home	Sea defence (man-made)	Sea bank	916.60	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_014	053BDWSHL1001C04	TF4485448897	Sailors Home to Leverton PS	Sea defence (man-made)	Sea bank	2186.60	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_015	053BDWSHL1301C01	TF4346547285	South of Leverton PS	Sea defence (man-made)	Sea bank	312.80	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_016	053BDWSHL1301C02	TF4365547036	South of Leverton PS	Sea defence (man-made)	Sea bank with berm on seaward side	170.40	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_017	053BDWSHL1301C03	TF4354746903	South of Leverton PS	Sea defence (man-made)	Sea bank with seaward berm and stone toe revetment	131.60	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_018	053BDWSHL1301C04	TF4346446801	North of Butterwick	Sea defence (man-made)	Sea bank with berm	2116.30	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_019	053BDWSHL1301C05	TF4239945137	Immediately North of Butterwick PS	Sea defence (man-made)	Sea bank with stone toe revetment, berm and gabion mattress batter protection	953.10	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_020	053BDWSHL1301C06	TF4180044446	Immediately South of Butterwick PS	Sea defence (man-made)	Sea bank with berm and stone toe revetment	1204.10	Environment Agency		11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs) [2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_021	053BDWSHL1301C07	TF4113043443	Cross bank at North of Freiston Shore nature reserve	Sea defence (man-made)	Sea bank with berm	374.60	Environment Agency		>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_022	053BDWSHL1701C01	TF4079943619	Cross bank at North of Freiston Shore nature reserve to New bank	Sea defence (man-made)	Sea bank	1148.50	Environment Agency		>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_023	053BDWSHL1701C02	TF4017342708	Freiston Shore (New cross bank)	Sea defence (man-made)	Sea bank	544.30	Environment Agency		6 - 10	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_024	053BDWSHL1701C03	TF4028542185	Freiston Shore Nature reserve to Haven Bank	Sea defence (man-made)	Sea bank	3239.80	Environment Agency		>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_026	053BDWSHL1901C02	TF3953539276	Sea bank to 75m d/s of field dyke	Sea defence (man-made)	Sea bank with stone toe revetment	300.00	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_027	053BDWSHL1901C03	TF3925639165	75m d/s of field dyke to 900m u/s of Cut End Road	Sea defence (man-made)	Sea bank with stone and gabion revetments	2119.30	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_028	053BDWSHL1901C04	TF3720439423	Immediately d/s of Hobhole PS	Sea defence (man-made)	Set back bank with stone toe and gabion basket revetment	814.90	Environment Agency		6 - 10	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_029	053BDWSHL1901C05	TF3662739921	Hobhole PS frontage	Sea defence (man-made)	Floodwall	44.90	Internal Drainage Board		11 - 20	2		Seawall	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_030	053BDWSHL1901C06	TF3658839900	U/S side of Hobhole outlet channel	Sea defence (man-made)	Seabank with gabion toe	29.30	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_031	053BDWSHL1901C07	TF3657839872	Hobhole PS to Jolly Sailor garden	Sea defence (man-made)	Sea bank with stone toe revetment	185.70	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs)[2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_032	0531430010101C07	TF3601439956	Frampton Marsh PS to Slippery Gowt	Sea defence (man-made)	Floodbank with stone toe revetment	619.10	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_033	053BDWSHL2001C03	TF3676639190	Between training bank and Wyberton PS	Sea defence (man-made)	Sea bank with wetland berm	1295.70	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_035	053BDWSHL2001C01	TF3676639190	Frampton Marsh	Sea defence (man-made)	Sea bank	1904.70	Environment Agency		6 - 10	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_036	055BD52000101C51	TF3429834985	Frampton Marsh to Earl Marsh Pumping Station	Sea defence (man-made)	Grassed earth embankment	4438.90	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_037	055BD52000101C52	TF3429834985	Pumping station near hundred acre farm (TF3434734950) to Earl Marsh pumping station (TF3427334211)	Sea defence (man-made)	Grassed earth embankment	527.30	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_038	055BD52000102C51	TF3432034190	Earl Marsh to New marsh, Fosdyke	Sea defence (man-made)	Grassed earth embankment	1942.80	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_039	055BD52000102C52	TF3287732878	New Marsh to concrete slipway, Fosdyke	Sea defence (man-made)	Grassed earth embankment	769.80	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_040	055BD52000102C53	TF3223632449	Fosdyke	Sea defence (man-made)	Earth embankment	205.80	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_041	055BD52000102C54	TF3206632338	Along warehouse frontage, Fosdyke	Sea defence (man-made)	Sea bank	25.80	Environment Agency	200	6 - 10	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_042	055BD52000102C55	TF3204132327	Warehouse to industrial store, Fosdyke	Sea defence (man-made)	Grassed earth embankment	83.90	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2

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DEF_1_043	055BD52000102C56	TF3196232337	Behind industrial store, Fosdyke	Sea defence (man-made)	Retaining wall and embankment	122.00	Environment Agency	200	6 - 10	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_044	055BD52000201C51	TF3190532189	Fosdyke Bridge to ditch at (TF3270532534)	Sea defence (man-made)	Masonry wall	15.10	Environment Agency	200	>20	2		Seawall	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_045	055BD52000201C52	TF3192632198	Drainage ditch to southwest corner of nature reserve.	Sea defence (man-made)	Grassed earth embankment	21.90	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_046	055BD52000201C53	TF3195332208	Nature reserve - SW corner to NE corner	Sea defence (man-made)	Sea defence wall	29.30	Environment Agency	200	>20	2		Seawall	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_047	055BD52000201C54	TF3195332208	Middle Marsh road track to Grass ramp at sluice	Sea defence (man-made)	Grassed earth embankment	51.00	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_048	055BD52000202C51	TF3468234015	Sluice at (TF3464734023) to split in embankment at (TF3816735601)	Sea defence (man-made)	Grassed earth embankment	4052.70	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_049	055BD52000202C52	TF3825235565	Grass ramp at (TF3875235416) to joining of two embankments at (TF3815135608)	Sea defence (man-made)	Grassed earth embankment	515.20	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_050	055BD52000202C53	TF387453541	Embankment joint (TF3962035064) to embankment split (TF3875235416)	Sea defence (man-made)	Grassed earth embankment	942.70	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_051	055BD52000202C54	TF3962135057	Alongside parallel embankment	Sea defence (man-made)	Grassed earth embankment	242.80	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2

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DEF_1_052	055BD52000202C55	TF3984634966	Join in embankments at (TF3985334970) to Lawyers Sluice (TF4083134540)	Sea defence (man-made)	Grassed earth embankment	991.70	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_053	055BD52000301C51	TF4082834538	Lawyers Sluice to Fleet Haven outfall	Sea defence (man-made)	Grassed earth embankment	578.00	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_054	055BD52000302C51	TF4388932890	Fleet Haven outfall to Dawsmere pumping station	Sea defence (man-made)	Grassed earth embankment	162.10	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_055	055BD52000401C51	TF4617830912	Dawsmere pumping station to end of asphalt track at (TF4670630268)	Sea defence (man-made)	Grassed earth embankment	967.90	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_056	055BD52000401C52	TF4672830258	End of asphalt track at (TF4670630268) to White house farm	Sea defence (man-made)	Grassed earth embankment	341.90	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_057	055BD52000402C51	TF4810028525	White House farm to ramp on bank at (TF4834127942)	Sea defence (man-made)	Grassed earth embankment	1775.30	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_058	055BD52000402C52	TF4893627002	Ramp on bank at (TF4834127942) to Lutton Leam outfall	Sea defence (man-made)	Grassed earth embankment	545.50	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_059	055BD52000402C53	TF4920026524	Lutton Leam outfall to West lighthouse	Sea defence (man-made)	Grassed earth embankment	213.20	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_060	055BD52000501C51	TF4931425728	North of east lighthouse	Sea defence (man-made)	Grassed earth embankment	553.50	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2

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DEF_1_061	055BD52000501C52	TF4941726272	East of Nene outfall	Sea defence (man-made)	Grassed earth embankment	217.50	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_062	055BD52000502C51	TF5346425922	(TF5346725921) to (TF5632126468)	Sea defence (man-made)	Grassed earth embankment	2978.90	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_063	052BDWSHG0601C01	TF5679426231	LFDC Boundary to Pumping Station	Sea defence (man-made)	Earth embankment	565.20	Private			2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_064	052BDWSHG0601L02	TF5679426231	Pumping Station to Sluice	Sea defence (man-made)	Earth embankment	924.50	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_065	052BDWSHG0601L03	TF5743925588		Sea defence (man-made)	Earth embankment	3204.10	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_066	052BDWSHG0601L04	TF5969423761		Sea defence (man-made)	Earth embankment	183.50	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_067	052BDWSHG0601L05	TF5984323654		Sea defence (man-made)	Earth embankment	168.30	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_068	052BDWSHG0701L02	TF6026723681		Sea defence (man-made)	Earth embankment	1980.00	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_069	052BDWSHG0701L03	TF6009725561		Sea defence (man-made)	Earth embankment	537.60	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_070	052BDWSHG0701L04	TF6040325938		Sea defence (man-made)	Earth embankment	543.20	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_071	052BDWSHG0701L05	TF6075426257		Sea defence (man-made)	Earth embankment	127.20	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1

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DEF_1_072	052BDWSHG0701L06	TF6080326372		Sea defence (man-made)	Earth embankment	701.00	Environment Agency	200		3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_073	052BDWSHG0701L07	TF6112626995		Sea defence (man-made)	Earth embankment	3584.10	Environment Agency		>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_074	052BDWSHG0701L08	TF6368529332		Sea defence (man-made)	Earth embankment	1272.20	Environment Agency	200	>20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_075	052BDWSHG0701L09	TF6472730067		Sea defence (man-made)	Earth embankment	974.40	Environment Agency	200	>20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_076	052BDWSHG0801L10	TF6532830224		Sea defence (man-made)	Earth embankment	37.70	Environment Agency	200	>20	3	3	Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_077	052BDWSHG0801L02	TF6529330238	From stile gate at Wolferton Pumping Station to change of direction.	Sea defence (man-made)	Earth embankment	222.30	Environment Agency	200	11 - 20	3	3	Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_078	052BDWSHG0801L06	TF6509130333	South of the RSPB reserve	Sea defence (man-made)	East Sea Bank - Shingle Ridge	288.90	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_079	052BDWSHG0801L07	TF6489830542	Adjacent to RSPB Reserve	Sea defence (man-made)	East Sea Banks - Shingle Ridge	866.60	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_080	052BDWSHG0801L08	TF6482831385	adjacent to Snettisham RSPB Reserve	Sea defence (man-made)	East Sea Bank - Shingle Ridge	605.90	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_081	052BDWSHG0802L04	TF6479531988	Snettisham South Beach	Sea defence (man-made)	East Seabank - Snettisham Hard Defences	565.10	Environment Agency	200	>20	1		Sea bank	1	25	2032	40	2047	Linear Stopper	2

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DEF_1_082	052BDWSHG0802L03	TF6476532552	Snettisham Scalp	Sea defence (man-made)	East Seabank - Shingle Ridge	530.30	Environment Agency	200	>20	3		Shingle ridge	3	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_083	052BDWSHG0802L05	TF6465133065	Snettisham Beach	Sea defence (man-made)	East Sea bank - Shingle Ridge	438.50	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_084	052BDWSHG0802L06	TF6471733497		Sea defence (man-made)	Shingle Ridge	9.60	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_085	052CANNGO1401C02	TF6471733503	Snettisham Coastal park	Coastal protection (man-made)	Shingle Ridge	1146.40	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_086	052CANNGO1401C03	TF6513034557	Heacham Dam	Coastal protection (man-made)	Shingle Ridge with Wave Wall	393.40	Environment Agency	200	>20	1		Shingle ridge	1	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_087	052CANNGO1401C04	TF6529834910	Snettisham Coastal Park	Coastal protection (man-made)	Shingle Ridge	88.10		200		2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_088	052CANNGO1401C06	TF6534034987	Snettisham Coastal Park	Coastal protection (man-made)	Shingle Ridge	1374.90	Environment Agency	200		2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_089	052CANNGO1301C01	TF6595336217	Jubilee Ramp to Heacham South Beach end of huts	Coastal protection (man-made)	Shingle Ridge Defence with marram grass on part of crest and FO. Properties on FO in places change FO slope	722.90	Environment Agency		>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence
DEF_1_090	052CANNGO1301C03	TF6636737473	Heacham North Beach Ramp	Coastal protection (man-made)	Jubilee Boat Ramp - concrete ramp over defence. Rock armour either side	12.80	Environment Agency	200	>20	1		Seawall	1	25	2032	35	2042	Linear Stopper	2
DEF_1_091	052CANNGO1301C02	TF6618436898	Heacham South Beach to Heacham N north (Jubilee Road)	Coastal protection (man-made)	East Shingle Ridge with marram grass on part of crest FO	623.90	Environment Agency	200	>20	2		Shingle ridge	2	Natural Defence	Natural Defence	Natural Defence	Natural Defence	Linear Reducer/ Changer	Natural Defence

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DEF_1_092	052CANNGO1201C01	TF6636537486	Heacham North Beach	Coastal protection (man-made)	Concrete Defence	469.90	Environment Agency	200	>20	1		Seawall	1	25	2032	35	2042	Linear Stopper	2
DEF_1_093	052CANNGO1201C02	TF6637037935	Heacham North Beach	Coastal protection (man-made)	Concrete Defence/ Promenade	1573.40	Environment Agency	200	>20	1		Seawall	1	25	2032	35	2042	Linear Stopper	2
DEF_1_094	052CANNGO1202C01	TF6666039463	Hunstanton South Beach	Coastal protection (man-made)	Concrete Defence / Promenade	540.40	Environment Agency	200	>20	2		Seawall	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_095	052CANNGO1203C01	TF6675339995	Hunstanton South Beach	Coastal protection (man-made)	Hunstanton South Beach Concrete Defence / Promenade	293.70	Environment Agency	200	>20	2		Seawall	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_096	052BDWSHG0801L03	TF6509130333	From the change of direction nr to Wolferton Pmpg stn to the start of the RSPB pits.	Sea defence (man-made)	Earth embankment	275.80	Environment Agency	200		2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_097	052BDWSHG0801L04	TF6509230609	From the start of the RSPB pits to the start of concrete revetment on the FI	Sea defence (man-made)	Earth embankment	537.30	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_098	052BDWSHG0801L05	TF6500231126	Stretch of defence adjacent to RSPB pits with conc. revt on FI	Sea defence (man-made)	Earth embankment	871.90	Environment Agency	200	11 - 20	3		Sea bank	3	10	2017	15	2022	Linear Stopper	1
DEF_1_099	052BDWSHG0802C08	TF6490931988	RSPB Crossbank to End Of Revetment.	Sea defence (man-made)	Earth embankment	332.40	Environment Agency		6 - 10	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_100	052BDWSHG0802L01	TF6492032310	From end of the conc. revt. on FI to the road crossing	Sea defence (man-made)	Earth embankment	1111.40	Environment Agency	200		3		Sea bank	3	10	2017	15	2022	Linear Stopper	1

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DEF_1_101	052BDWSHG0802L02	TF6517233380	Road crossing inland earth embankments east.	Sea defence (man-made)	Earth embankment	16.70	Environment Agency	-999	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_102	052CANNGO1401L01	TF6517033396		Sea defence (man-made)	Earth embankment	3258.10	Environment Agency	200	11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_103	052CANNGO1301C04	TF6631636166	STW Outfall To South Beach Road	Sea defence (man-made)	Earth Embankment	761.20	Environment Agency			2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_104	052CANNGO1301C05	TF6638136881	South Beach Road	Sea defence (man-made)	Seabank with road over. Minor embankment on north side, changing to road as crest then embankment on south side	153.60	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_105	052CANNGO1301C06	TF6651936949	Geacham North Jubilee Road to Heacham South (South Beach Road)	Sea defence (man-made)	Road over bank at North end	535.90	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_106	052CANNGO1201C03	TF6667037458	Heacham to Hunstanton Jubilee Road to end of caravan park, Hunstanton	Sea defence (man-made)	Sea Bank	2000.10	Environment Agency		6 - 10	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_107	052CANNGO1201C04	TF6668739432	Join of first and second line defences	Sea defence (man-made)	Earth embankment	40.60	Environment Agency		11 - 20	2		Sea bank	2	15	2022	25	2032	Linear Stopper	1/2
DEF_1_108*	-	TF6690040300	Hunstanton South Beach to Leisure Centre	Sea defence (man-made)	Concrete curved wave wall and recurve wave wall on promenade	320.10	Borough Council of King's Lynn & West Norfolk			1		Sea wall	1	25	2032	35	2042	Linear Stopper	2

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DEF_1_109*	-	TF6710040600	Beach access/slip in front of Leisure Centre	Sea defence (man-made)	Plain concrete wall with recurve wave wall on promenade	6.30	Borough Council of King's Lynn & West Norfolk			4		Sea wall	4	5	2012	7	2014	Linear Stopper	1
DEF_1_110*	-	TF6710040600	Beach access/slip to TF6715040750	Sea defence (man-made)	Blockwork curve wall and recurve wave wall on promenade	259.00	Borough Council of King's Lynn & West Norfolk			4		Sea wall	4	5	2012	7	2014	Linear Stopper	1
DEF_1_111*	-	TF6715040750	TF6715040750 to TF6717040800	Sea defence (man-made)	Plain battered concrete wall and recurve wave wall on promenade	33.00	Borough Council of King's Lynn & West Norfolk			3		Sea wall	3	10	2017	15	2022	Linear Stopper	1
DEF_1_112*	-	TF6717040800	TF6717040800 to northern extent of sea walls	Sea defence (man-made)	Plain battered concrete wall with recurve profile	550.00	Borough Council of King's Lynn & West Norfolk			3		Sea wall	3	10	2017	15	2022	Linear Stopper	1
DEF_1_113*	-	566768.3E 340044.6N	Groyne no. 19***	Sea defence (man-made)	Permeable timber zig-zag Groyne	89.80	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_114*	-	566809.5E 340124.9N	Groyne no. 18**	Sea defence (man-made)	Permeable timber zig-zag Groyne	90.30	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_115*	-	566850.4E 340203.9N	Groyne no. 17**	Sea defence (man-made)	Permeable timber zig-zag Groyne	89.60	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_116*	-	566894.2E 340282.0N	Groyne no. 16**	Sea defence (man-made)	Permeable timber zig-zag groyne	93.90	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_117*	-	566909.0E 340325.0N	Groyne no. 15A**	Sea defence (man-made)	Permeable timber stakes	41.60	Borough Council of King's Lynn & West Norfolk			5		Timber Groyne	5	0	2007	0	2007	Cross shore interrupte r	1
DEF_1_118*	-	566930.9E 340365.9N	Groyne no. 15**	Sea defence (man-made)	Permeable timber zig-zag Groyne	87.60	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_119*	-	566978.7E 340441.7N	Groyne no. 14**	Sea defence (man-made)	Permeable timber zig-zag Groyne	94.60	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs)[2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_120*	-	567000.0E 340483.0N	Groyne no. 13A**	Sea defence (man-made)	Permeable timber zig-zag Groyne	31.30	Borough Council of King's Lynn & West Norfolk			3		Timber Groyne	3	8	2015	12	2019	Cross shore interrupte r	1
DEF_1_121*	-	567020.4E 340521.7N	Groyne no. 13**	Sea defence (man-made)	Permeable timber zig-zag Groyne	95.40	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_122*	-	567051.3E 340603.7N	Groyne no. 12**	Sea defence (man-made)	Permeable timber zig-zag Groyne	90.50	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_123*	-	567078.7E 340689.3N	Groyne no. 11**	Sea defence (man-made)	Permeable timber zig-zag Groyne	89.70	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_124*	-	567104.9E 340774.8N	Groyne no. 10**	Sea defence (man-made)	Permeable timber zig-zag Groyne	89.20	Borough Council of King's Lynn & West Norfolk			2		Timber Groyne	2	10	2017	20	2027	Cross shore interrupte r	1/2
DEF_1_125*	-	567126.6E 340859.7N	Groyne no. 9**	Sea defence (man-made)	Pre-cast concrete Groyne	56.10	Borough Council of King's Lynn & West Norfolk			2		Revetme nt (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupte r	1/2
DEF_1_126*		567139.7E 340907.9N	Groyne no. 8**	Sea defence (man-made)	Pre-cast concrete Groyne	55.60	Borough Council of King's Lynn & West Norfolk			2		Revetme nt (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupte r	1/2
DEF_1_127*		567152.9E 340973.6N	Groyne no. 7**	Sea defence (man-made)	Pre-cast concrete Groyne	55.20	Borough Council of King's Lynn & West Norfolk			2		Revetme nt (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupte r	1/2
DEF_1_128*		567156.0E 341030.9N	Groyne no. 6**	Sea defence (man-made)	Pre-cast concrete Groyne	58.00	Borough Council of King's Lynn & West Norfolk			2		Revetme nt (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupte r	1/2
DEF_1_129*		567165.4E 567113.5N	Groyne no. 5**	Sea defence (man-made)	Pre-cast concrete Groyne	52.70	Borough Council of King's Lynn & West Norfolk			2		Revetme nt (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupte r	1/2
DEF_1_130*		567175.6E 341146.4N	Groyne no. 4**	Sea defence (man-made)	Pre-cast concrete Groyne	43.80	Borough Council of King's Lynn & West Norfolk			2		Revetme nt (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupte r	1/2

SMP2 Reference	NFCDD Reference	Grid Reference	Location	Defence Type	Description	Length (m)	Maintainer	Design Standard	NFCDD Residual Life	Overall Condition	Manual Override Condition	Category for condition assessment	Condition used for assessment	Residual Life (yrs)[1] - Fastest	Year of Failure - Fastest	Residual Life (yrs)[2] - Slowest	Year of Failure - Slowest	Defence Category	Defence Failure (Epoch)[3]
DEF_1_131*		567188.0E 341197.4N	Groyne no. 3**	Sea defence (man-made)	Pre-cast concrete Groyne	37.70	Borough Council of King's Lynn & West Norfolk			2		Revetment (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupter	1/2
DEF_1_132*		567203.4E 341251.4N	Groyne no. 2**	Sea defence (man-made)	Pre-cast concrete Groyne	37.30	Borough Council of King's Lynn & West Norfolk			2		Revetment (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupter	1/2
DEF_1_133*		567218.4E 341296.9N	Groyne no. 1**	Sea defence (man-made)	Pre-cast concrete Groyne	38.60	Borough Council of King's Lynn & West Norfolk			2		Revetment (concrete/ rock)	2	15	2022	25	2032	Cross shore interrupter	1/2

* Information taken from St La Haye Ltd's Hunstanton Sea Defence Condition Survey Report (2005).

** Groyne numbering from northern extent of sea wall at Hunstanton to southern extent of Local Authority's defence.

*** Condition grades from information provided by Asset Managers.

Figure F2.2.1 Defence Condition Grade from NFCDD Data

Figure F2.2.2 Residual Life under No active intervention Policy

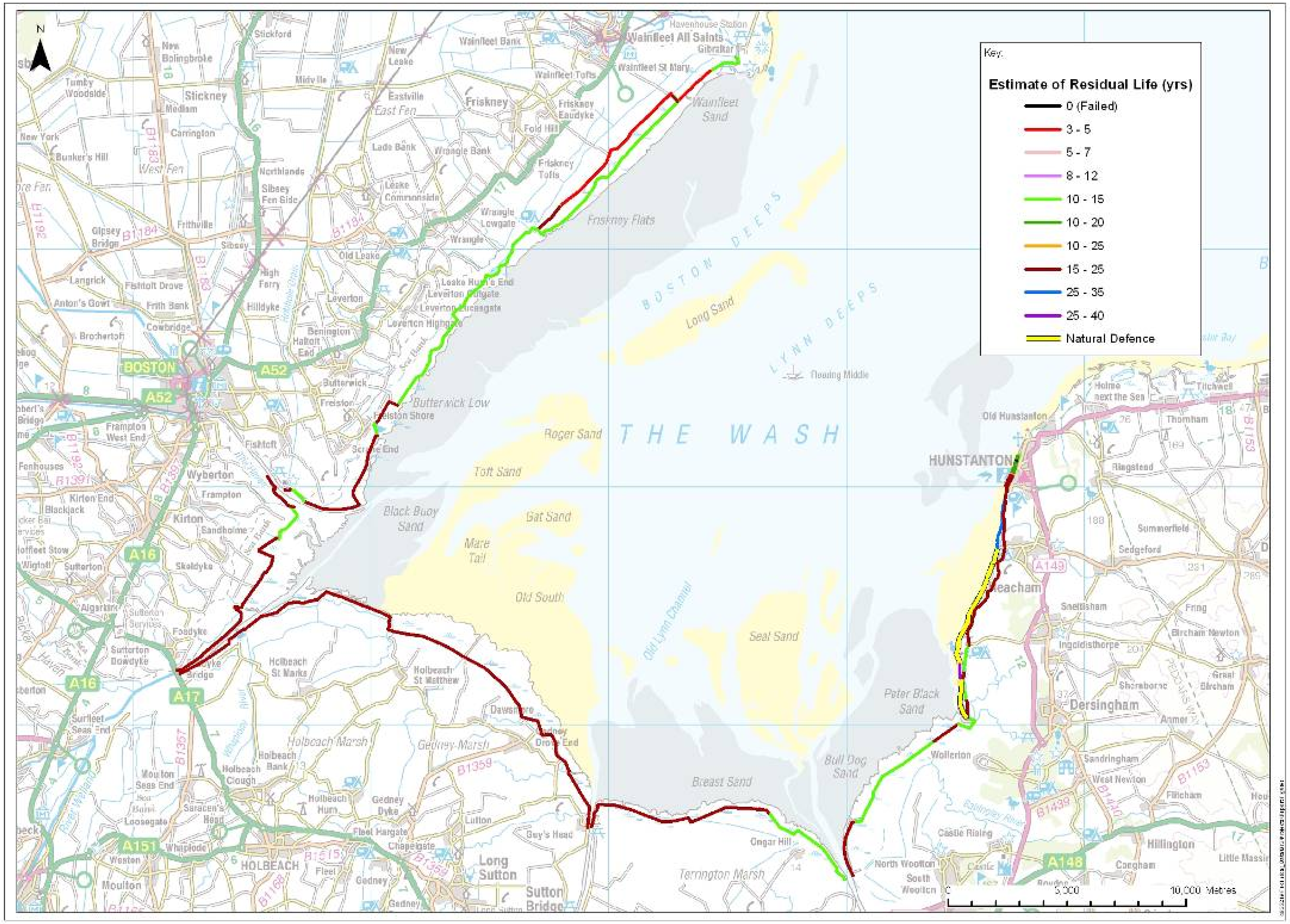
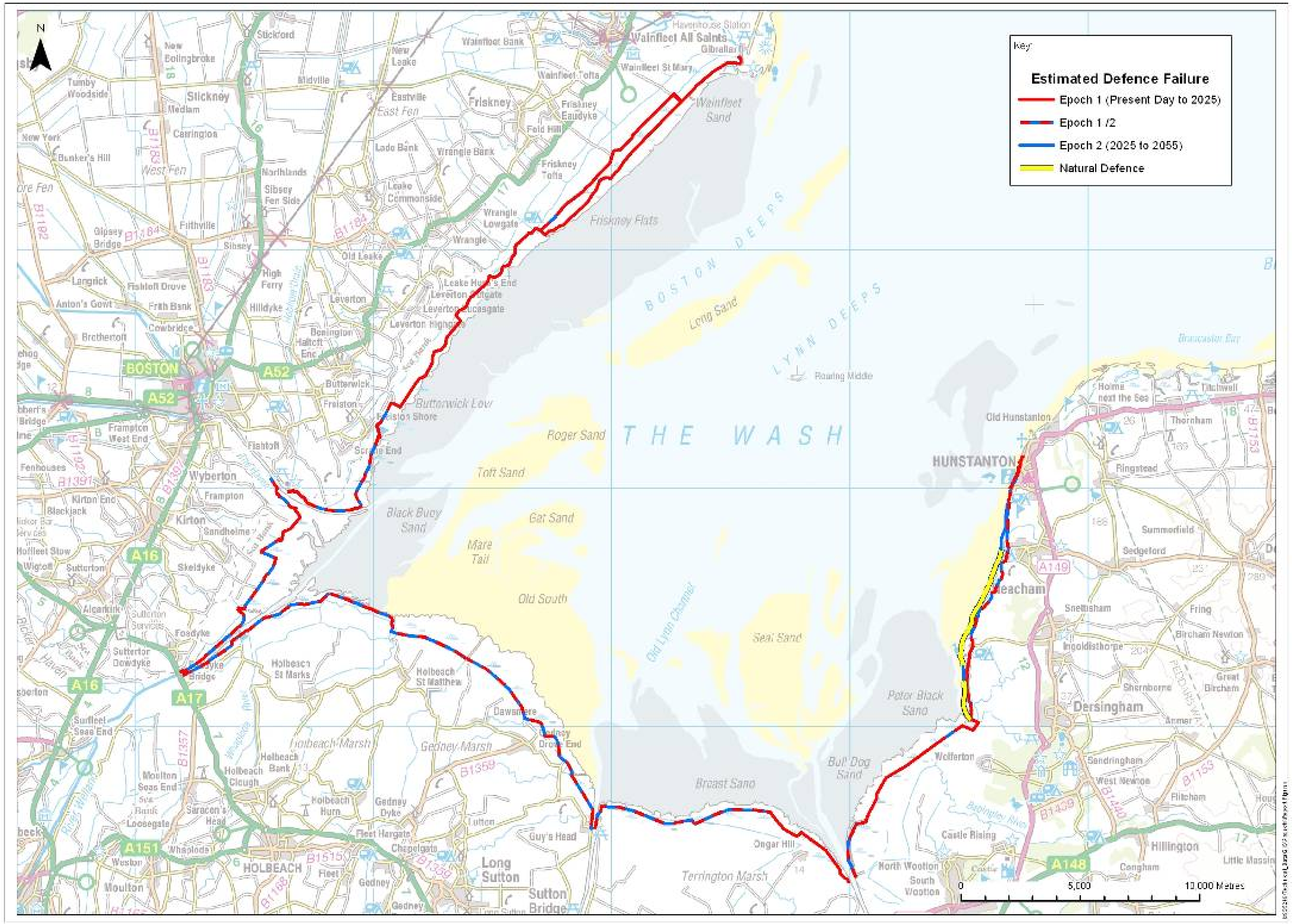


Figure F2.2.3 Estimated Defence Failure



F3 DEVELOP BASELINE SCENARIOS

F3.1 Introduction

F3.1.1 Aim

The aim of Task 2.2 as a whole is to provide an appreciation of how the shoreline is behaving and the influence that coastal management has upon this behaviour. This will provide the basis upon which flood and coastal risks are determined. This analysis will then be used to develop and appraise policy scenarios.

Task 2.2 is divided into three explicit tasks:

- A description of the baseline response assessments for the 'No active intervention (NAI)' scenario. This assumes that defences are no longer maintained and will fail over time.
- A description of the baseline response assessment for a 'With Present Management (WPM)' scenario. This assumes that all defences are maintained to provide a similar level of protection to that provided at present.
- Production of mapping to illustrate predicted shoreline change.

Both the NAI and WPM scenarios will discuss coastal evolution within 3 epochs: Present day to 2025; 2025 to 2055; and 2055 to 2105.

In order to break this task down into manageable sections of work, the Wash coastline has been sub-divided into five frontages. These were chosen using the natural geomorphological breaks in the coastline and have been used in previous SMP tasks (namely 2.1a). The five frontages are described below and are shown in figure F3.1.1.

- Frontage A (Wainfleet and Friskney) – Right hand bank of River Steeping (Gibraltar Point) to The Horseshoes (Wrangle Lowgate).
- Frontage B (Leverton, Butterwick and Freiston) – The Horseshoes (Wrangle Lowgate) to left hand bank of The Haven.
- Frontage C (Frampton, Holbeach and Gedney) – Right hand bank of The Haven to the left hand bank of the River Nene.
- Frontage D (Terrington, Wootton and Wolferton) – Right hand bank of the River Nene to the left hand bank of the River Ingol outfall.
- Frontage E (Heacham, Hunstanton and Old Hunstanton) – Right hand bank of the River Ingol outfall to northern extent of the cliffs at Old Hunstanton.

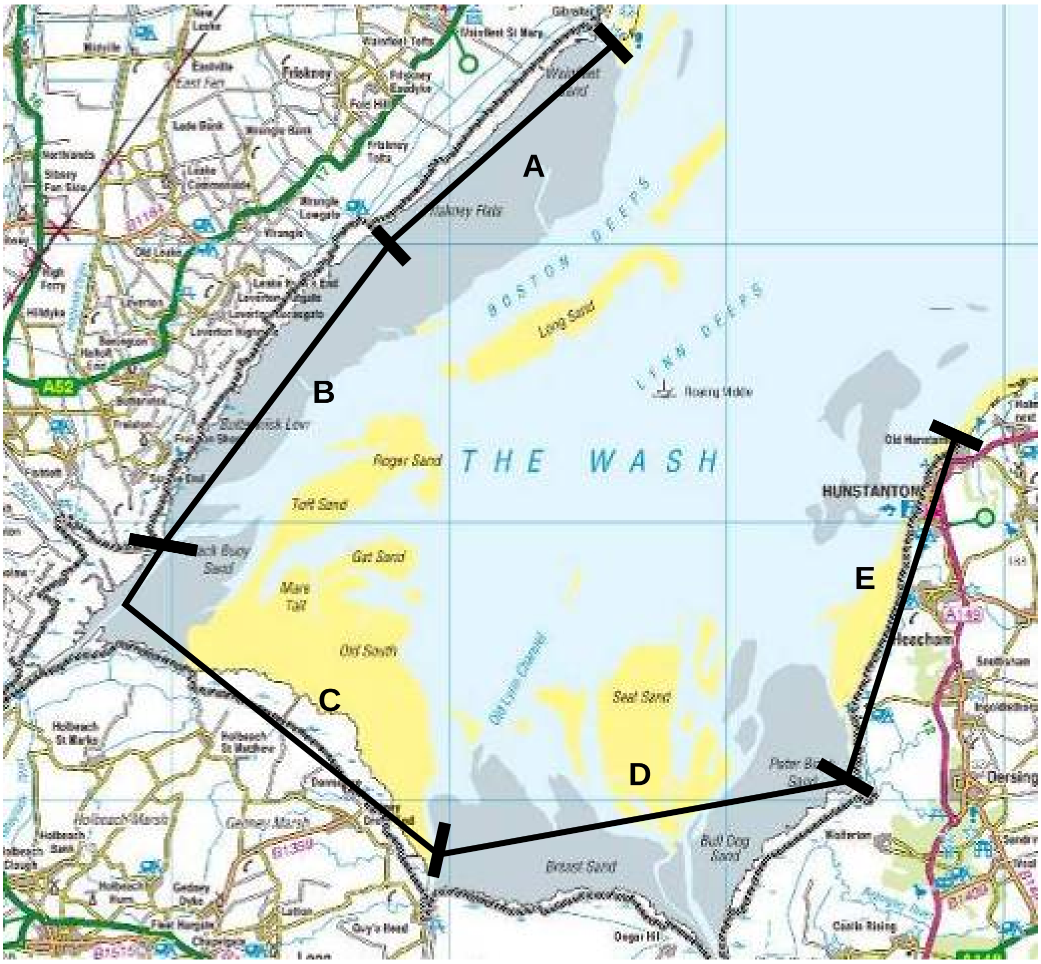
It is important to note that this text was produced in an early stage of the SMP, and that the insights into the future development of salt marsh and mud flat have developed since then. section F6.2.1 describes the latest insights. In summary: on the medium and long term there is an envelope of possible developments, ranging from continuation of the current growth (‘accretional future’) to a reversal leading to loss of salt marsh and mud flat (‘erosional future’); it is also possible that the current extent and ratio of salt marsh and mudflat will broadly remain. The analysis in this section is largely based on an erosional future in epoch 2 and 3. The changing insights have informed policy development from the baseline scenarios described in this section; see section 5.2 in appendix E.

F3.1.2 Layout

This section of the appendix is split into nine main sections. The first five discuss each frontage individually. These sections summarise the main aspects of each frontage, including key geomorphological components and physical processes, as well as a summary of the method used to establish the baseline scenarios and the outcome of the assessment for each scenario for the three epochs. The final sections of this report provide a broad summary of the Wash area as a whole and the main conclusions drawn from the assessment, as well as the main assumptions and references used within the analysis itself.

This report is accompanied by a summary of the conclusions in the required SMP format.

Figure F3.1.1 Frontages used for Task 2.2 Development of Baseline Scenarios



F3.1.3 Sea Level Rise

For the purpose of the assessment of baseline scenarios, the rate of sea level rise will need to be taken into account. The following summarises the current guidance relating to sea level rise.

Defra's sea level rise guidance for the East of England, East Midlands, London, and south-east England (south of Flamborough Head) is summarised in table F3.1.1 (FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts October 2006). All values are rounded to the nearest 0.5mmyr^{-1}.

Table 1.1 Sea Level Rise Guidance (Defra 2006)

TIME PERIOD	NET SEA LEVEL RISE ($mmyr^{-1}$)	TOTAL SEA LEVEL RISE (mm)
1990 – 2025	4.0	140
2025 – 2055	8.5	255
2055 – 2085	12.0	360
2085 – 2115	15.0	450

It is important to note that further analysis of shoreline response was carried out following on from these results. This particularly concerns the intertidal development of PDZ1, identifying that the developments in epoch 2 and 3 are very uncertain and could range from an erosional to an accretional future; this is discussed in more detail in section F6.2. The analysis in this section is based on the ‘erosional future scenario’ as described there.

F3.2 Frontage A – Wainfleet and Friskney

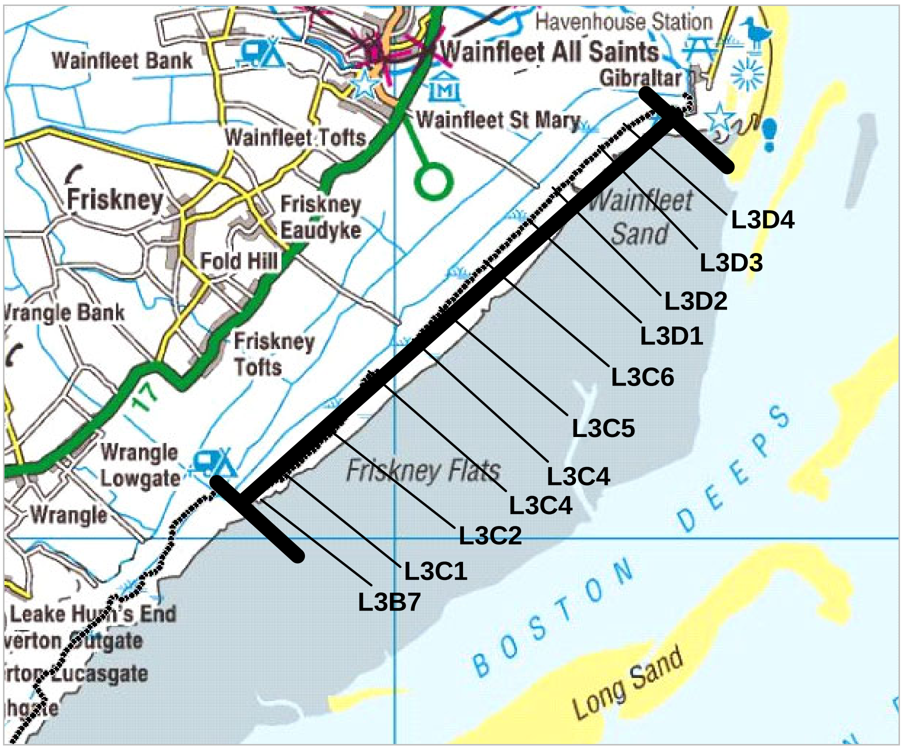
F3.2.1 Introduction

This frontage contains the large village of Wainfleet All Saints and the smaller village of Friskney further landward. All of the mud and sand flats, known locally as Friskney Flats and Wainfleet Sand, are used as a bombing range by the MoD.

The frontage is characterised by extensive backshore coastal lowland of reclaimed intertidal flats that are now protected from large-scale flooding by a series of grassed earth embankments. Wide intertidal flats extend up to 6 kilometres seaward from the shoreline and areas of saltmarsh exist in the upper intertidal (backshore) zone.

Figure F3.2.1 outlines the location of this frontage and also shows the location of the profiles used by the Anglian Coastal Monitoring Programme (EA SMG 2007).

Figure F3.2.1 Frontage A Anglian Coastal Monitoring Programme profiles



F3.2.2 Key Geomorphological Components

The key geomorphological components that are contained within this frontage and that affect the morphological development of the frontage are as follows:

- Gibraltar Point is a soft mini 'headland' and forms the northern limit to this frontage and also acts to constrain the mouth of the Wash as a whole. Due to its relatively small size compared with the Wash, it can be classified as a secondary control and provides a degree of shelter against wave attack to this frontage. The sandbanks, lying just offshore to the east, are closely linked to the development of the spit system and therefore act to enhance this sheltering effect.
- Long Sand, the sand bank that lies parallel with this frontage, is generally exposed at low water. It has a significant effect on wave energy reaching the marginal tidal flats and will therefore act to shelter the coastline from wave attack.
- This offshore bank also has an effect on the erosion and accretion of materials along the frontage. It provides shelter to a significant length of intertidal area. As a result if the bank was to accrete and therefore increase in size, the shelter along the frontage would increase and this would then promote increased accretion. If the bank was subject to erosion and therefore decreased in size, there would be decreased shelter along the frontage and erosion is likely to occur. The exact orientation and shape of the sand bank will also cause localised areas of accretion and erosion in the same way.
- The deep water channel, Boston Deeps, that also runs parallel with the coastline, will control the position of the low water mark along this frontage, and therefore whether there is a trend of erosion or accretion of the lower mudflat.
- The wide intertidal flats effectively dissipate the incoming wave and tidal energy, and therefore limit the amount that reaches the upper profile. As a result a wider intertidal area, such as noted in this frontage, will decrease erosion or probability of flooding caused by the incoming energy.
- Continued land claim has, however, maintained the saltmarshes in an immature state. As a result the marsh height has remained relatively low and has not been colonised by the usual salt-tolerant plant species. It has not been able to follow the normal succession from mudflat, to pioneer saltmarsh, to established saltmarsh. This immature saltmarsh absorbs less energy than an established saltmarsh and causes higher energy to impact on the system and therefore puts increased pressure on the defences.
- The earlier reclaimed areas behind the defences are topographically lower due to compaction, oxidation, wind deflation and the longer history of deposition in the more recently reclaimed areas. Some of the earlier reclaims are now up to 4m below mean high water springs.

Table F3.2.1 summarises each feature in terms of the control it exerts on the Wash system as a whole, its influences and interactions in terms of the other components of the system, and its status with respect to the geomorphological system.

Table 3.2.1 Frontage A Key Geomorphological Components Summary

FEATURE	CONTROL EXERTED	INFLUENCES & INTERACTIONS	STATUS
Gibraltar Point	Stores sand transported from the Lincolnshire coast (situated to the north) Is a 'soft' fixing of the northern mouth of the Wash Provides some degree of shelter from wave attack Influences wave propagation – waves defract around the point causing localised shelter in the lee of the system	Spit growth is limited by sediment supply and the extent of deep water provided by Boston Deeps	Secondary, transient control
Boston Deeps	Is a route for the flow of tidal energy within the Wash Its position determines the position of the low water mark on the foreshore and therefore the width of the intertidal area	It interacts with the outfall of the Rivers Witham and Welland and provides a pre-defined flow path during the ebb tide Its depth and width are determined by the strength of the tidal currents	Primary, persistent control under WPM
Long Sand	Is a store of sediment transported from the Lincolnshire coast to the north and from the intertidal area Provides some degree of shelter from wave attack and therefore influences the position of low water on the foreshore	Its height and width are determined by large-scale tidal circulation patterns and the extent of sediment supply	Secondary, transient control

FEATURE	CONTROL EXERTED	INFLUENCES & INTERACTIONS	STATUS
	Influences tidal circulation and generally encourages flow around the bank.		
Wide intertidal area	Is effective in dissipating wave and tidal energy before it reaches the backshore area and defence line Is a store of sediment transported in suspension.	The width is determined by the position of low water mark, which is mainly controlled by Boston Deeps, and to some extent the position of Long Sand. Receives some shelter from Gibraltar Point	Primary, transient control

F3.2.3 Patterns of Change

Historic Change

The area in the vicinity of Wainfleet Sand has experienced enhanced sediment accumulation due to the sheltering effect of the accreting spit at Gibraltar Point and its associated offshore banks. As a result the long-term natural trend along this frontage is one of accretion and seaward advance of the coastline. This has been illustrated by a general seaward movement of the low water mark between 1828 and 1995. Alternatively this apparent seaward movement of the low water mark may also be due to the landward migration of sand banks to join the shore.

Between Wainfleet and Friskney a horizontal accretion rate of 42 myr^{-1} was calculated in front of a 1996 embankment, 10-25 myr^{-1} seaward of a 1973 structure and 14-27 myr^{-1} in front of a 1976/77 land claim.

The University of Newcastle (1998a) compared the width of the intertidal zone with the movement of the saltmarsh/mudflat boundary between 1971/74 and 1982/85 from Gibraltar Point to the River Witham. This study noted that the rate of advance of the saltmarsh/mudflat boundary decreased from the north to the south, until approximately 9 km north of the River Witham outfall it reversed from advance to retreat. This retreat around the outfall of the River Witham suggested a continually decreasing tidal width, which provided less energy dissipation and therefore put increased pressure on the defences.

Recent (1991 – 2006) change

Between 1994 and 2000 Pethick (2002) found that the majority of the salt marsh advanced at an average rate of 5.6 myr^{-1}.

In terms of horizontal change, between 1991 and 2006 the saltmarsh/mudflat boundary has accreted (moved seaward) by an average of 100 m. This horizontal change is also reflected in the fact that the total area of saltmarsh increased by just over 140 hectares between 1992 and 2006 (Environment Agency 2003b).

In general, both the saltmarsh (upper and lower) and the mudflats (upper and lower) experienced vertical accretion between 1994 and 2006. An average vertical accretion rate was calculated from all the average rates for each profile along this frontage. On the saltmarsh rates were calculated at 0.007 myr^{-1} and averages on the mudflat were 0.002 myr^{-1}.

A typical profile (L3D2) is shown in figure F3.2.2, taken from the Anglian Coastal Monitoring Programme Coastal Trends Analysis report (EA SMG 2007). The saltmarsh/mudflat boundary can be clearly seen at approximately chainage 350 m and the strong yearly accretion trend is evident. The saltmarsh/mudflat boundary has moved approximately 100m between 1994 and 2006. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

Figure F3.2.2 Typical frontage A Saltmarsh and Mudflat Development: Profile L3D2

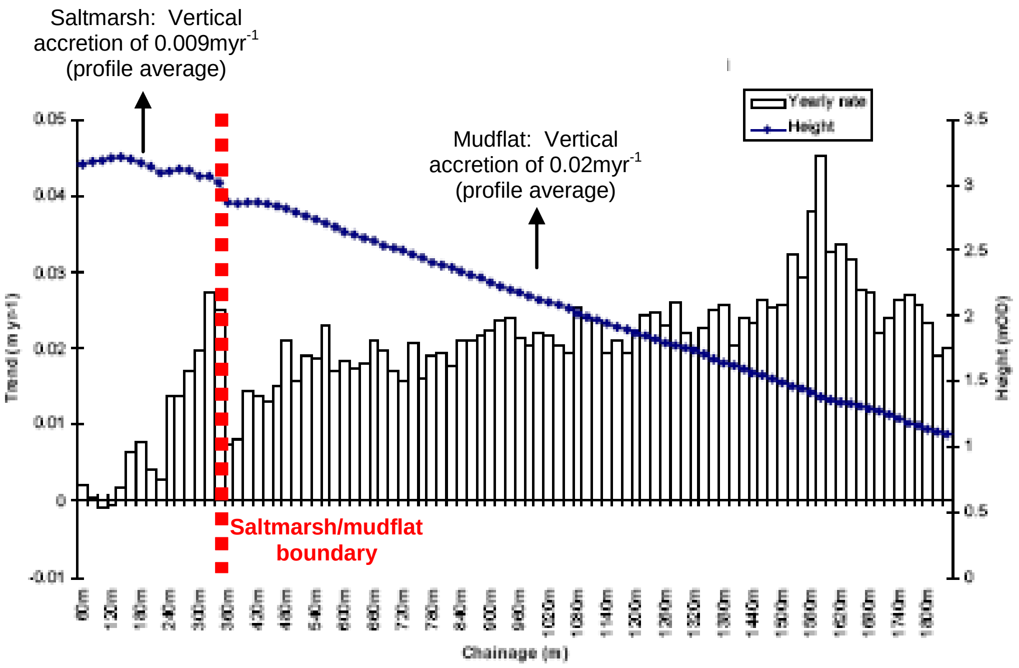
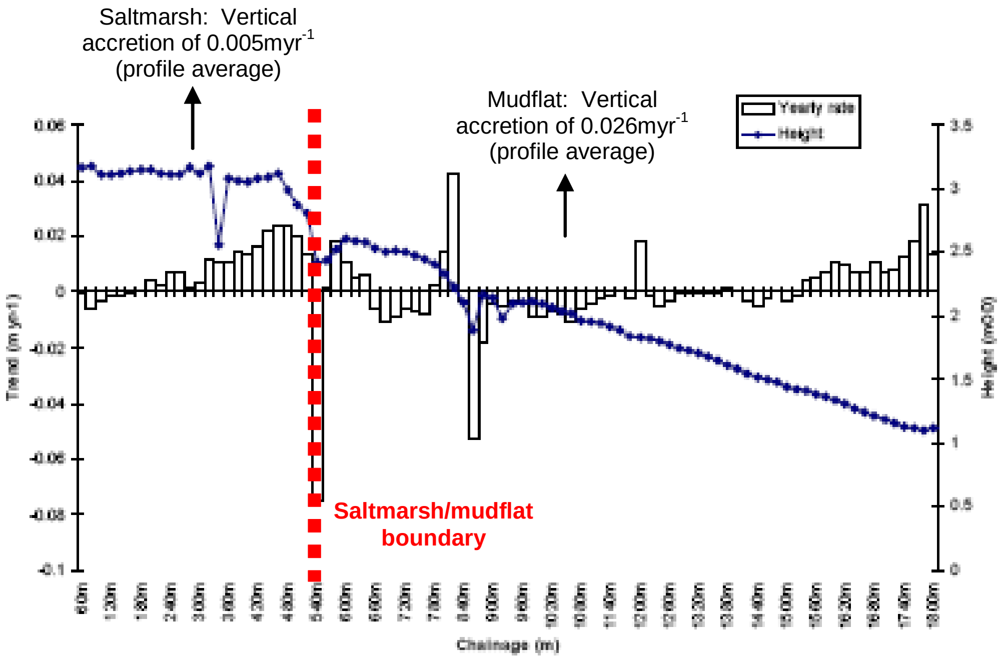


Figure F3.2.3 L3C6 Saltmarsh and Mudflat Development



There are, however, two localised profiles that exhibit different trends. Profile L3C6 has exhibited a trend of erosion of the upper mudflat, but stability of the saltmarsh/mudflat boundary and of the upper and lower saltmarsh. This profile is shown in figure F3.2.3, again taken from the Coastal Trends Analysis report (EA SMG 2007). The saltmarsh/mudflat boundary can be clearly seen at approximately chainage 550 m. There was no movement of the saltmarsh/mudflat boundary between 1994 and 2006. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

However, according to the Coastal Trends Analysis Report (EA SMG 2007) this profile crosses a network of drainage channels which explains the localised vertical erosion along the upper mudflat.

The other profile of interest is profile L3D4 as shown in figure F3.2.4 (EA SMG 2007). This profile has been subject to erosion of the upper and lower mudflat, landward movement (erosion) of the saltmarsh/mudflat boundary, but stability of the saltmarsh. However as is evident from aerial photographs (figure F3.2.5) the bottom of this profile crosses the River Steeping as it meanders across the saltmarsh and mudflat to the sea. There will therefore be significant erosion around the channel as the river meanders and changes its course. This explains the trend for erosion along the upper and lower mudflat.

Figure F3.2.4 L3D4 Saltmarsh and Mudflat Development

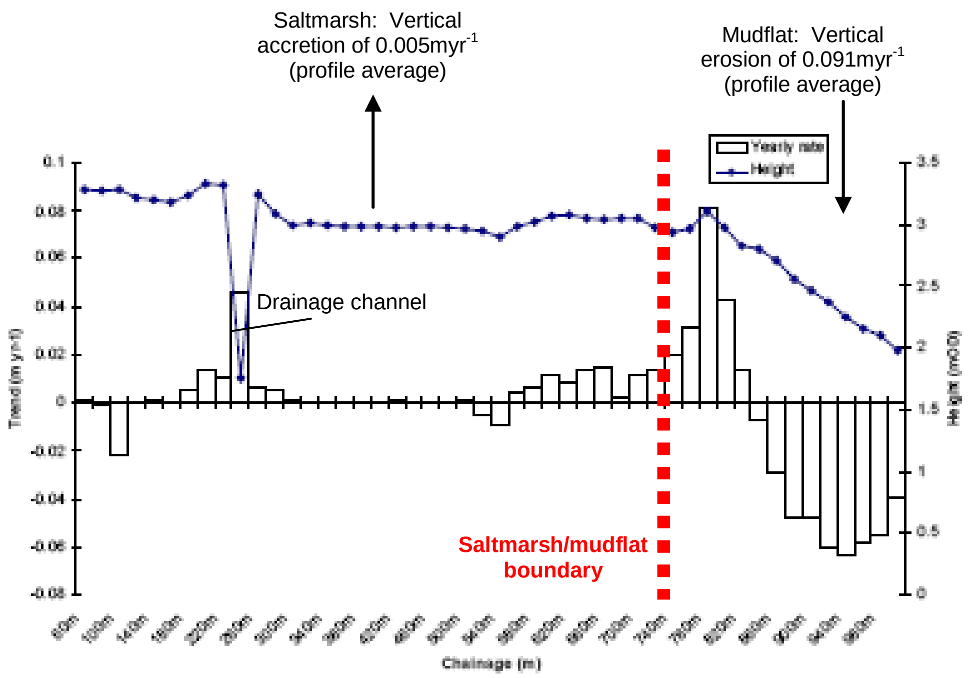
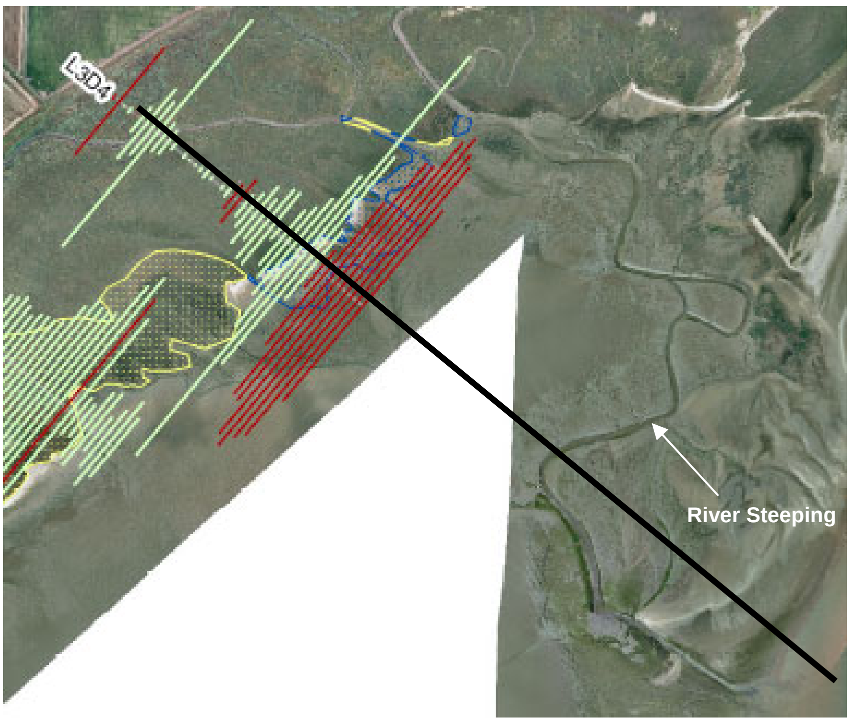


Figure F3.2.5 L3D4 and River Steeping Outfall Locations



F3.2.4 Tidal Currents

Tidal currents can be relatively strong in the Wash, especially in the main channels during spring tides, due to its large tidal range. Average current velocities are between 0.8-1.0 ms^{-1} (HR Wallingford 1972).

F3.2.5 Current Residuals

Net water transport throughout the water column off the coast of this frontage is directed towards the north in the order of approximately 54,000 m^3/m/tide (Posford Duvivier 1996). The overall direction of movement along this frontage is directly to the north-east parallel with the coast (Posford Duvivier 1996).

F3.2.6 Sediment

The main sources of sediment found on this frontage are as follows:
- The Holderness coast (situated to the north).
- The Humber estuary (also situated to the north).
- The Lincolnshire coast (also situated to the north).
- The North Norfolk coast to the east.
- The North Sea as a whole.
- The Sea floor within the mouth of the Wash.

The main sinks of the sediment on this frontage are:
- Long Sand (offshore bank).
- Intertidal area.
- Offshore banks associated with the Gibraltar Point spit system.

In terms of sediment transport, over the mudflats sediment is mostly transported in suspension. Sediment is deposited when the velocity of the tide is low (< 0.12 cms^{-1}). Sand and gravel may be deposited under higher flows and exist where there is a greater disturbance due to wave action.

The primary sediment transport mechanism along this frontage will be suspended sediment transport, due to the dominance of sands and silts in the water column. This is in contrast to the eastern shore of the Wash where both bedload and suspended sediment transport occur due to the existence of larger sediment sizes.

F3.2.7 Processes

Tides

Tidal levels (from Admiralty Tide Tables) at Tab's Head (mouth of The Haven) are shown in table F3.2.2:

Table 3.2.2 Tidal levels at Tab's Head (mODN)

MHWS	MHWN	MLWN	MLWS
3.30	1.90	-1.30	-3.00
Tidal range (springs): 6.30m			
Tidal range (neaps): 3.20m			

As a result the mean high water (MHW) has been calculated at **2.60 mODN**, and mean low water (MLW) at **-2.15 mODN**. The mean tidal range is therefore 4.75 m.

Extreme Water Levels

Table 3.2.3 shows the Extreme Water Level (EWL) analysis for Burgh Sluice, situated at the northern extent of the frontage (Mott MacDonald 2006) in mODN:

Table 3.2.3 EWLs for Burgh Sluice (Mott MacDonald 2006)

RETURN PERIOD							
1:1	**1:10**	**1:25**	**1:50**	**1:100**	**1:200**	**1:500**	**1:1000**
4.26	4.45	4.63	4.76	4.90	5.03	5.21	5.34

Waves

The following wave information has been taken from the University of Newcastle's (2001) report into Wave Attenuation over inter-tidal surfaces.

- Mean wave height (H_s) = 0.61 m
- Mean wave period (T_z) = 3.30 s
- Waves are predominantly from an offshore direction, approaching The Wash from the north to north-east sector.

The average wave height and energy attenuation recorded along each Wash transect as part of the study is shown in table F3.2.4.

Table F3.2.4 Results of University of Newcastle's (2001) Wave Attenuation study

TRANSECT	DOMINANT SURFACE TYPE	AVERAGE ATTENUATION OF INCIDENT WAVE HEIGHT	AVERAGE ATTENUATION OF INCIDENT WAVE ENERGY
Wrangle Flats	Mudflat	16%	10%
	Saltmarsh	91%	97%
Butterwick Low	Mudflat	23%	36%
	Saltmarsh	64%	72%
Breast Sand	Mudflat	36%	56%
	Saltmarsh	78%	91%

F3.2.8 Existing Management

This frontage is characterised by raised grassed earth embankments (sea banks). In many places the frontline earth embankment is backed by a secondary, and sometimes tertiary, line of defence also in the form of a earth embankment. These were constructed at earlier phases in the reclamation history. The sequence of successive defences shows progressive increases in crest level. Maintenance of the earlier structures ceased once new front line defences were constructed.

The majority of the frontline defences are expected to fail within the next 10 to 25 years (epoch 1), under a policy of No active intervention. This is with the exception of a short section of frontline defence that defends the Friskney Flats area. This section of defence has a much lower condition grade (grade 4) and therefore is predicted to fail within 3 to 5 years. In terms of maintenance, the earth embankments are monitored and kept in condition by the Environment Agency, with the exception of a short stretch of frontline defence in the Friskney Flats region that is privately owned by the Jubilee Bank Consortium.

F3.2.9 Analysis of Intertidal Development

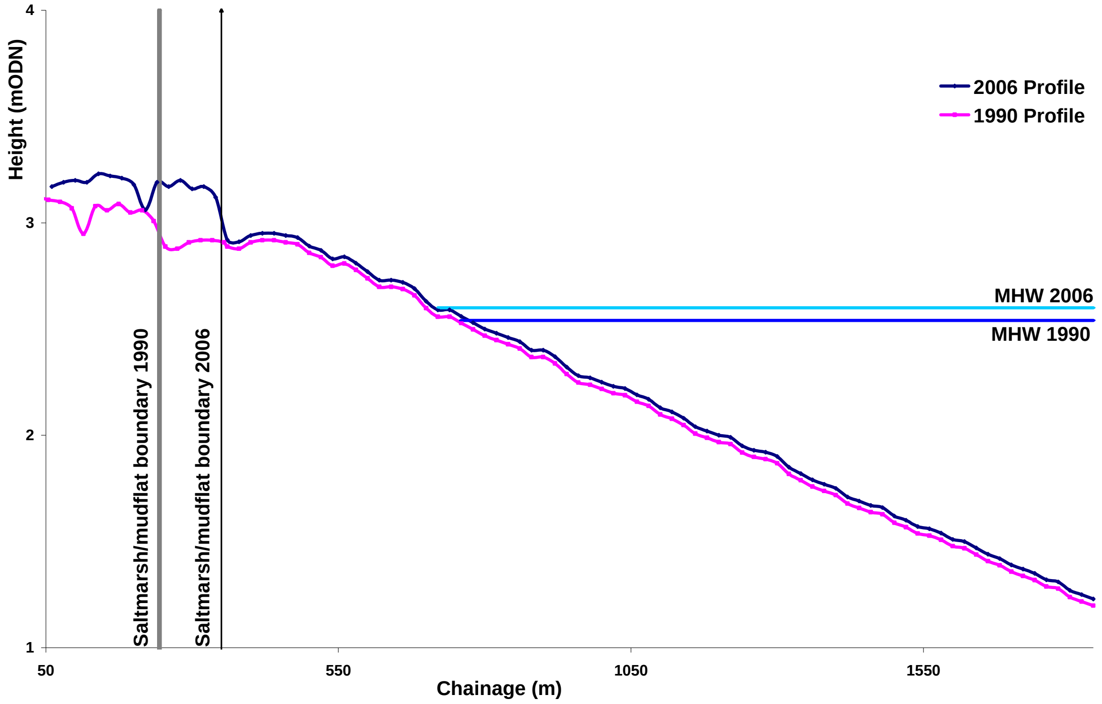
The following summarises the general trend of intertidal and foreshore development, as assumed from information provided through the Coastal Trends Analysis Report (EA SMG 2007):

- Saltmarsh vertical accretion rates = **7 mmyr^{-1}**.
- Mudflat vertical accretion rates = **2 mmyr^{-1}**.
- Horizontal accretion (movement of saltmarsh/mudflat boundary) = **6.6 myr^{-1}**.

- Defra's (2006) sea level rise prediction between 1991 and 2006 (period of monitoring) = approximately **4.0 mmyr^{-1}**.

From this data, the assumed saltmarsh and mudflat development between 1990 and 2006 can be shown diagrammatically, as shown in figure F3.2.6:

Figure F3.2.6 Assumed Saltmarsh and Mudflat Development 1990 – 2006



The key stages of intertidal development are as follows:

- The entire profile is built up with fresh accumulations of sediment during tidal inundation, either directly by water flowing across the mudflat, or by creeks filling up and then overtopping onto the surrounding saltmarsh.
- At a critical point in this upward growth the upper mudflat becomes exposed for long enough each day to allow species (tolerant to submergence and salinity) to colonize. The first species to colonise are usually benthic microalgae, especially epipelic diatoms.
- This then raises the elevation further, eventually enabling colonisation by saltmarsh species such as *Salicornia* (grasswort). At this point the upper mudflat has made the transition to lower saltmarsh.
- This produces the seaward shift of the saltmarsh/mudflat boundary.
- However as the mudflat profile does not shift seaward, sea level rise causes the position of MHW and MLW to move landward.
- This effectively causes a squeeze of the intertidal area.

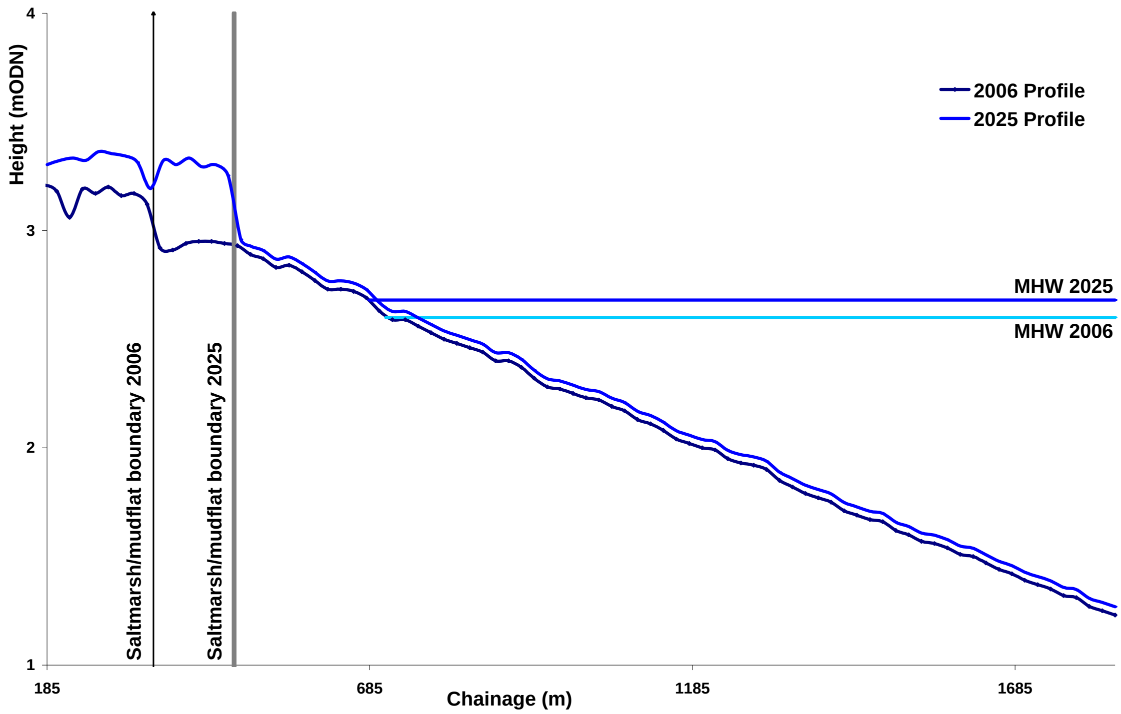
F3.2.10 Impacts: With Present Management

Epoch 1 (present day to 2025)

Defra (2006) predicts that sea level rise between 2006 and 2025 will be around 4.0mmyr^{-1} therefore MHW in 2025 will be approximately **2.68 mODN**.

Over this epoch, coastal response will be much the same as recently. The rate of saltmarsh sedimentation (7 mmyr^{-1}) will exceed the rate of sea level rise (4mmyr^{-1}) therefore there will be continued vertical accretion across the saltmarsh. The rate of sedimentation (2 mmyr^{-1}) across the mudflats will not, however, exceed the rate of sea level rise (4 mmyr^{-1}) therefore there will be continued vertical accretion across the mudflat, but further landward movement of the mean high and low water marks. The saltmarsh/mudflat boundary will continue to move seaward by 6.6 myr^{-1}. Figure 3.2.7 below represents typical profile change in epoch 1.

Figure 3.2.7 Typical Profile Change in epoch 1



The processes that are likely to occur will be much the same as the present day (see section 2.9).

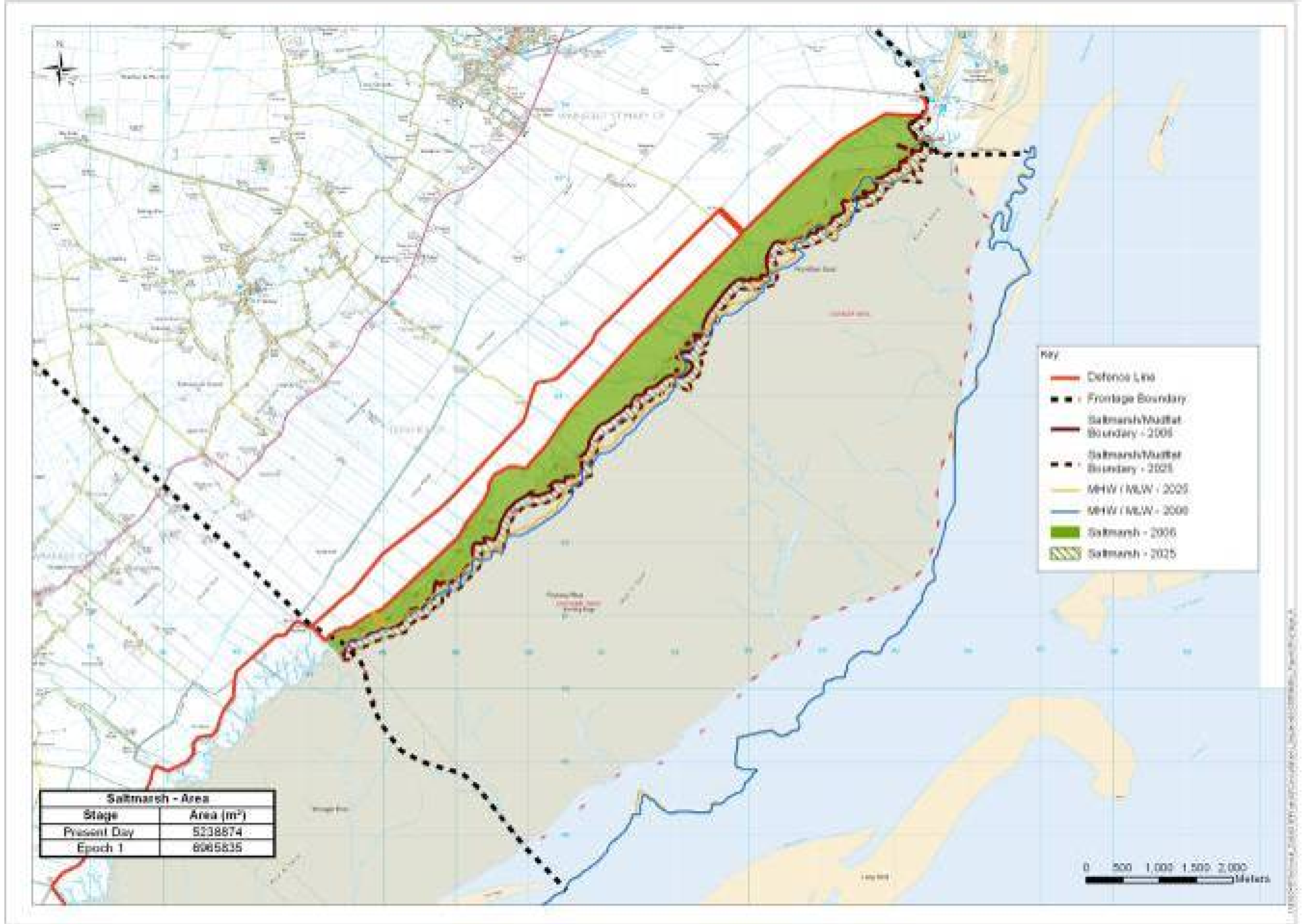
This is the typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross marsh drainage channels.

In terms of the backshore, it is likely to continue to grow, with accretion of the established saltmarsh and movement seaward of the saltmarsh/mudflat boundary.

The predicted continued accretion in this frontage will promote continued accretion in frontages B and C, as sediment will be transported from this frontage to the adjacent ones.

The predicted shoreline evolution for epoch 1 under a scenario of WPM is shown in figure 3.2.8.

Figure F3.2.8 frontage A Predicted Shoreline Evolution epoch 1 WPM



Epoch 2 (2025 to 2055)

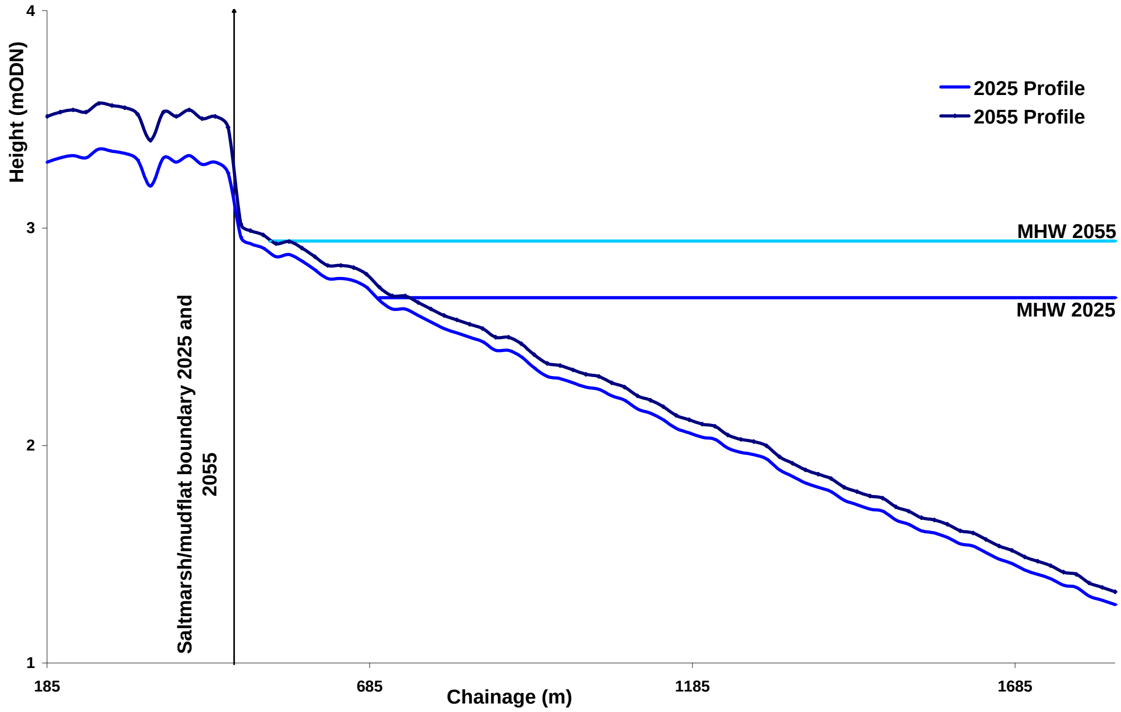
Defra (2006) predicts that sea level rise between 2025 and 2055 will be around 8.5mmyr^{-1}**,** therefore MHW in 2055 will be approximately **2.94mODN**.

Over this epoch there will be some changes in coastal responses as a result of sea level rise. Across the saltmarsh the rate of sedimentation (7mmyr^{-1}) does not exceed the rate of sea level rise (8.5mmyr^{-1}) but there is likely to be continued vertical accretion as the saltmarsh is not inundated on every tide (as can be seen by the position of MHW). Across the mudflat the rate of sedimentation (2mmyr^{-1}) does not exceed the rate of sea level rise (8.5mmyr^{-1}) but there is likely to be continued accretion, but further landward movement of the mean high and low water marks, both at greater rates than seen in the previous epoch. The significantly increased water depth across the mudflat will result in larger waves and therefore increased pressure on the saltmarsh/mudflat boundary.

Due to the fact that the rate of sedimentation is similar to the rate of sea level rise, the saltmarsh/mudflat boundary should be able to hold its position, therefore in this epoch there is not likely to be any landward movement (erosion) of the saltmarsh/mudflat boundary.

Figure F3.2.9 represents typical profile change in epoch 2.

Figure F3.2.9 Typical Profile Change in epoch 2



This situation is likely to cause a steepening of the saltmarsh/mudflat boundary, causing it to become unstable and liable to slumping and collapse.

Instability of the saltmarsh/mudflat boundary will be more apparent during individual storm events.

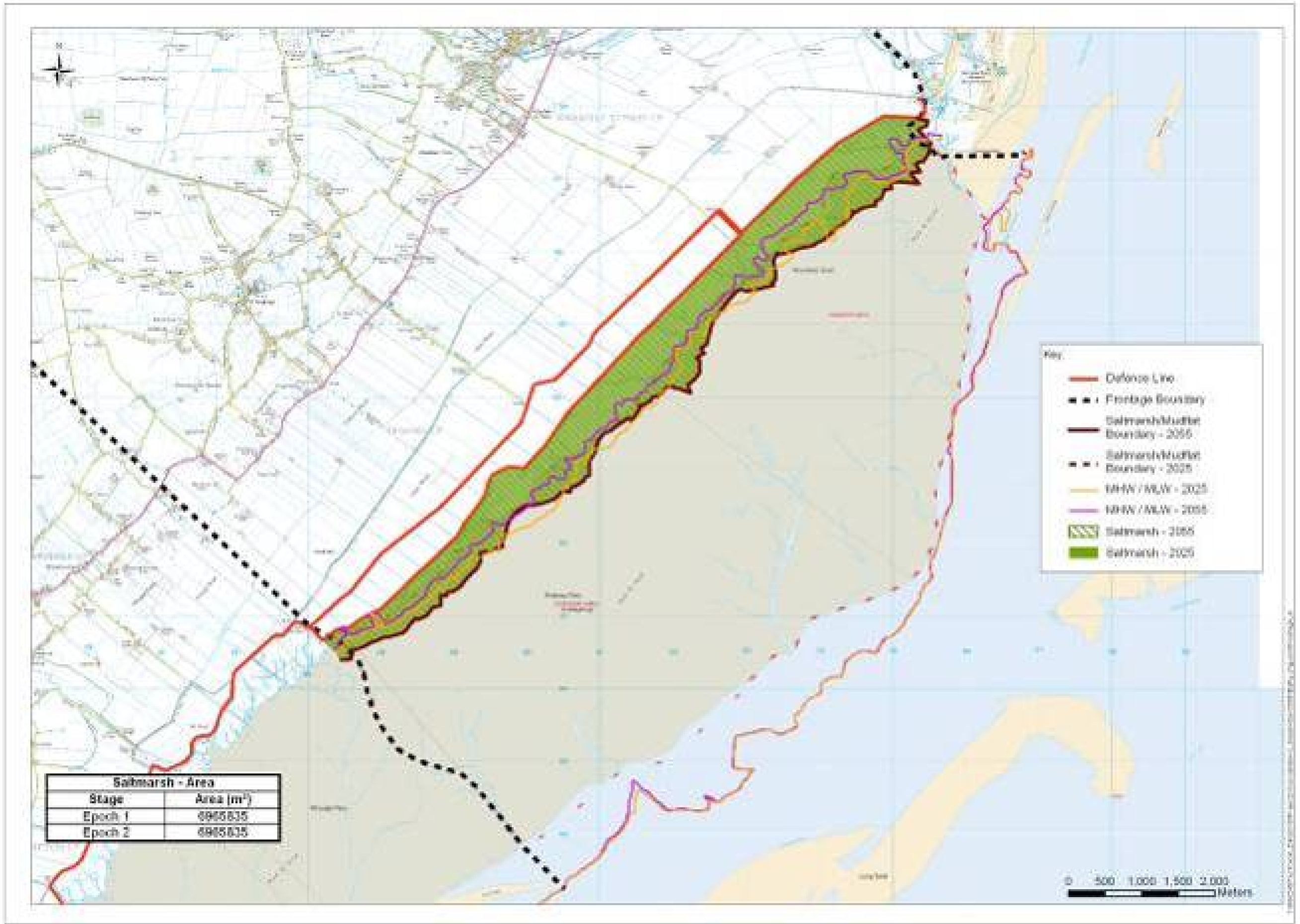
Again, this is the typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross marsh drainage channels

The area of the backshore is likely to remain the same and there will be increased pressure upon it due to the movement of the mean high water mark landward up the profile.

The continued accretion in this frontage will promote continued accretion in frontages B and C, as sediment will be transported from this frontage to the adjacent ones.

The predicted shoreline evolution for epoch 2 under a scenario of WPM is shown in figure F3 2.10.

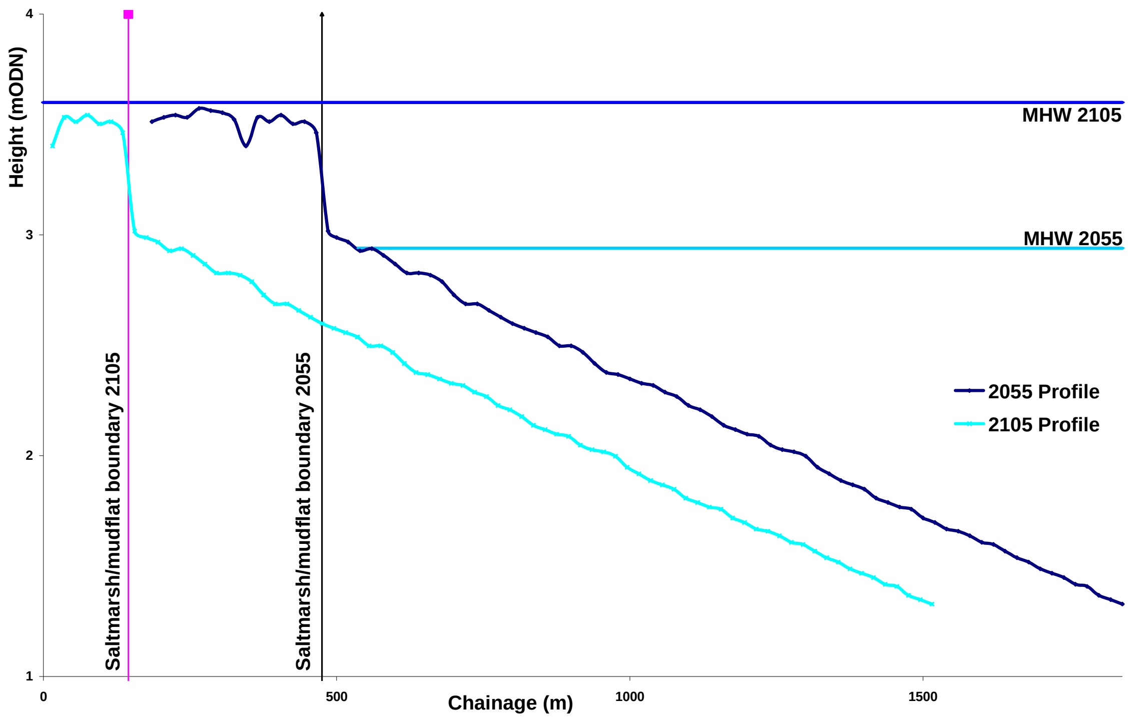
Figure F3.2.10 frontage A Predicted Shoreline Evolution epoch 2 WPM



Epoch 3 (2055 to 2105)

Defra (2006) predict that sea level rise between 2055 and 2085 will be around 12.0 $mmyr^{-1}$ between 2055 and 2085, and around 15.0 $mmyr^{-1}$ between 2085 and 2105. As a result MHW in 2105 will be approximately **3.60 mODN**.

Figure F3.2.11 Typical Profile Change in epoch 3



Over this epoch the rate of sedimentation will be significantly outpaced by the rate of sea level rise. Across the saltmarsh, the rate of sedimentation (7.0 $mmyr^{-1}$) does not exceed the rate of sea level rise (between 12.0 and 15.0 $mmyr^{-1}$). The same will occur across the mudflat, where the rate of sedimentation across the mudflat (2.0 $mmyr^{-1}$) is significantly less than the rate of sea level rise (as stated above). As a result there is likely to be a reduced rate of vertical accretion on both the mudflat and saltmarsh due to the increased depth of water. This will enable larger waves to form over the intertidal area, leading to increased wave attack and therefore the tendency for erosion rather than accretion.

Consequently there will be a further landward movement of the mean high and low water marks, both at greater rates than seen in the previous epoch. Figure F3.2.11 represents typical profile change assuming no vertical accretion rates on the saltmarsh and mudflats (therefore the same profile as 2055) and landward movement of the saltmarsh/mudflat boundary as in the previous epoch (rate of 6.6 myr^{-1} assumed).

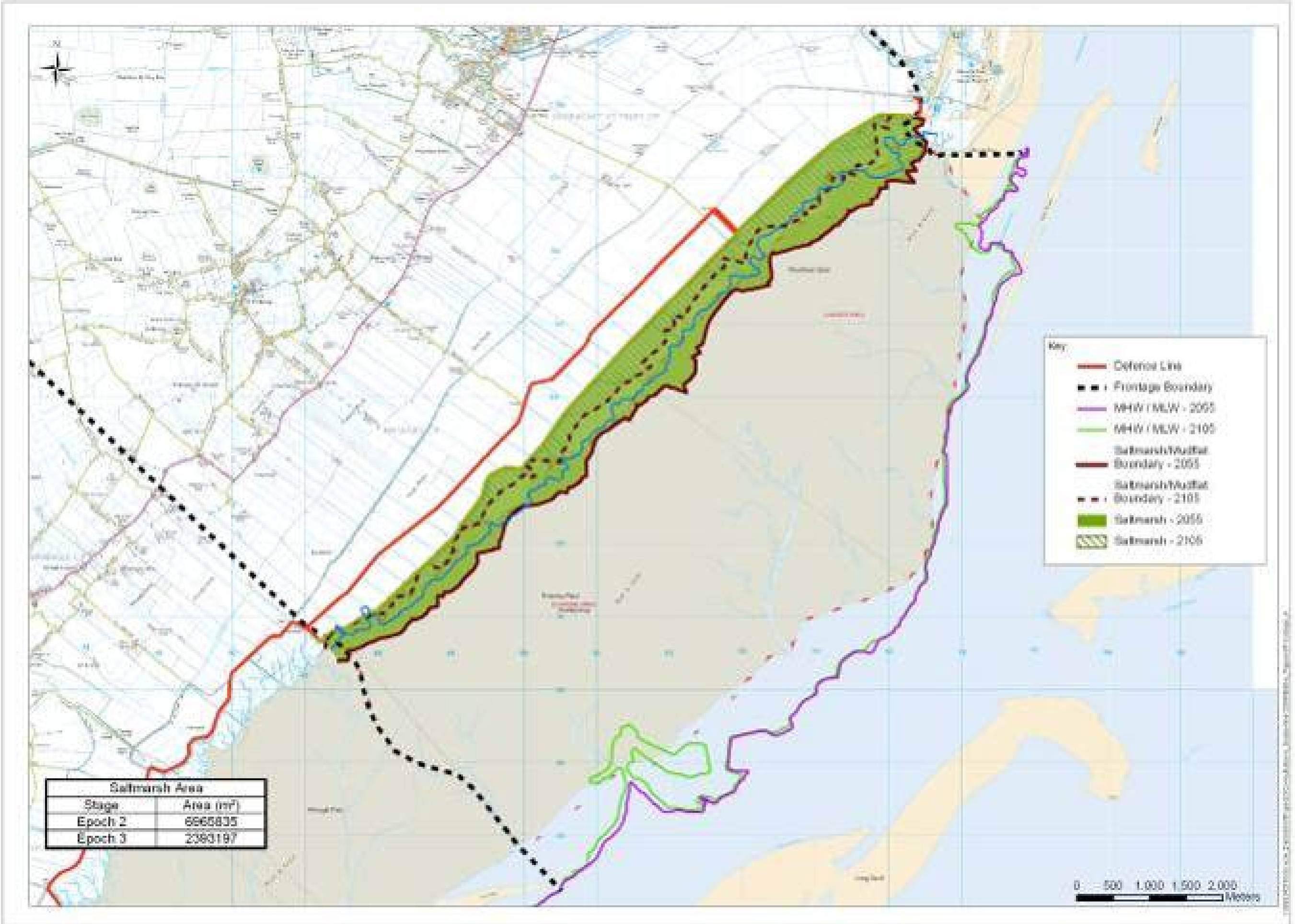
It is evident from figure F3.2.11 that by 2105 the saltmarsh will be inundated at mean high water, assuming no further vertical accretion occurs. It has been suggested that sea level rise may bring about increased vertical accretion on the saltmarsh, but as the saltmarsh/mudflat boundary is moving landward there will be a general decrease in the total saltmarsh area. Figure F3.2.11 also represents a generalised intertidal profile, and in reality it is likely that the whole profile will shift and become less steep.

Figure F3.2.11 also clearly highlights the extent of coastal squeeze that is likely to have occurred by 2105 as the saltmarsh is compressed between its eroding seaward edge and the fixed earth embankments.

The onset of widespread erosion in this frontage will act to initiate and aid erosion in frontage B, and possibly bring about a trend of erosion in frontage C.

The predicted shoreline evolution for epoch 3 under a scenario of WPM is shown in figure F3.2.12.

Figure F3.2.12 frontage A Predicted Shoreline Evolution epoch 3 WPM



F3.2.11 Impacts: No active intervention

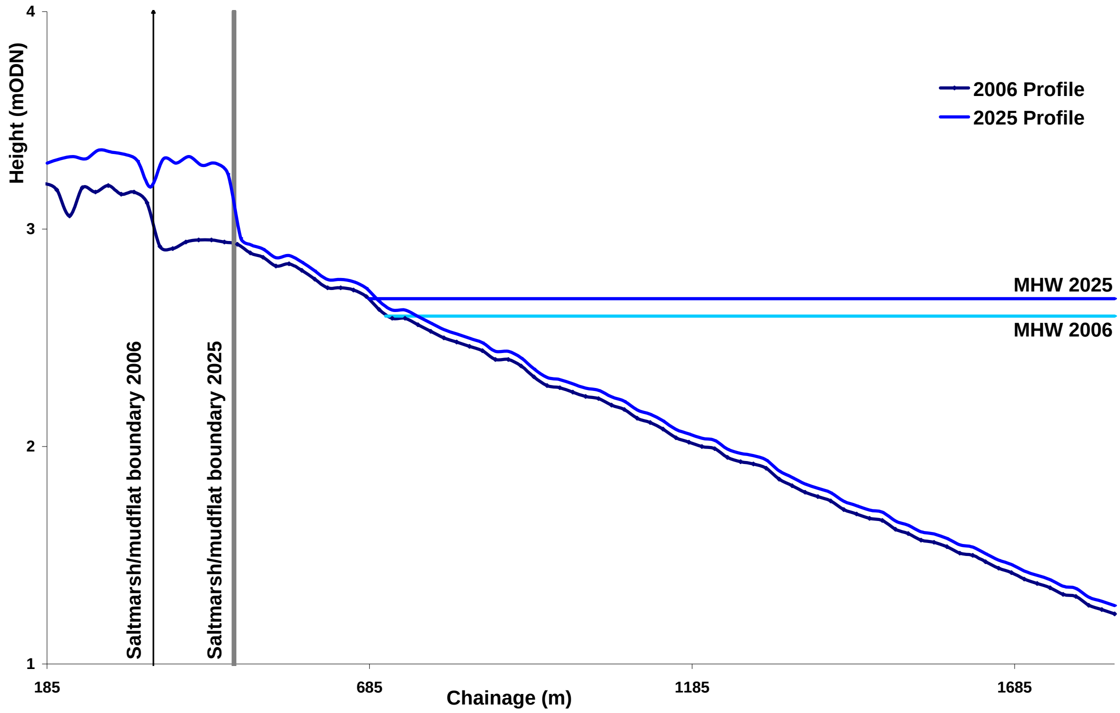
Epoch 1 (present day to 2025)

Defra (2006) sea level rise between 2006 and 2025 is predicted to be around 4.0 $mmyr^{-1}$ therefore MHW in 2025 will be approximately **2.68 mODN**.

Coastal response will be much the same as seen in the WPM scenario up to the beginning of epoch 2 when the majority of the defences are assumed to have failed.

Up to the end of epoch 1 the rate of saltmarsh sedimentation (7 $mmyr^{-1}$) will exceed the rate of sea level rise (4 $mmyr^{-1}$) therefore there will be continued vertical accretion across the saltmarsh. The rate of sedimentation (2 $mmyr^{-1}$) will not, however, exceed the rate of sea level rise (4 $mmyr^{-1}$) therefore there will be continued vertical accretion, but further landward movement of the mean high and low water marks. The saltmarsh/mudflat boundary will continue to move seaward by 6.6 myr^{-1}. Figure F3.2.13 represents typical profile change up to the end of epoch 1.

Figure F3.2.13 Typical Profile Change in epoch 1



After 2017, assuming defence failure, the MHW mark does not reach the old defence line and as a result there will not initially be flooding of the former reclaimed area, however inundation of the former reclaimed areas is likely to occur during storm events and spring tides.

As a result the backshore will continue to grow between present day and 2025, with accretion of the established saltmarsh and movement seaward of the saltmarsh/mudflat boundary. After epoch 1, the backshore area will remain the same and will be subject to localised areas of erosion during storm events.

Initially the continued accretion in this frontage will promote continued accretion in frontages B and C, as sediment will be transported from this frontage to the adjacent ones.

Figure F3.2.14 illustrates the position of the high and low water marks for epoch 1 under a scenario of NAI.

Epoch 2 (2025 to 2055)

Defra (2006) predict that sea level rise between 2025 and 2055 will be around 8.5 mmyr^{-1}**,** therefore MHW in 2055 will be approximately **2.94 mODN**.

The MHW does not extend up to the old defence line, however there is likely to be more frequent inundation of the former reclaimed areas during storm events.

As a result the backshore will be subject to localised areas of erosion during storm events. This process will also be reflected in the development of frontage B.

Figure F3.2.14 illustrates the position of the high and low water marks for epoch 2 under a scenario of NAI.

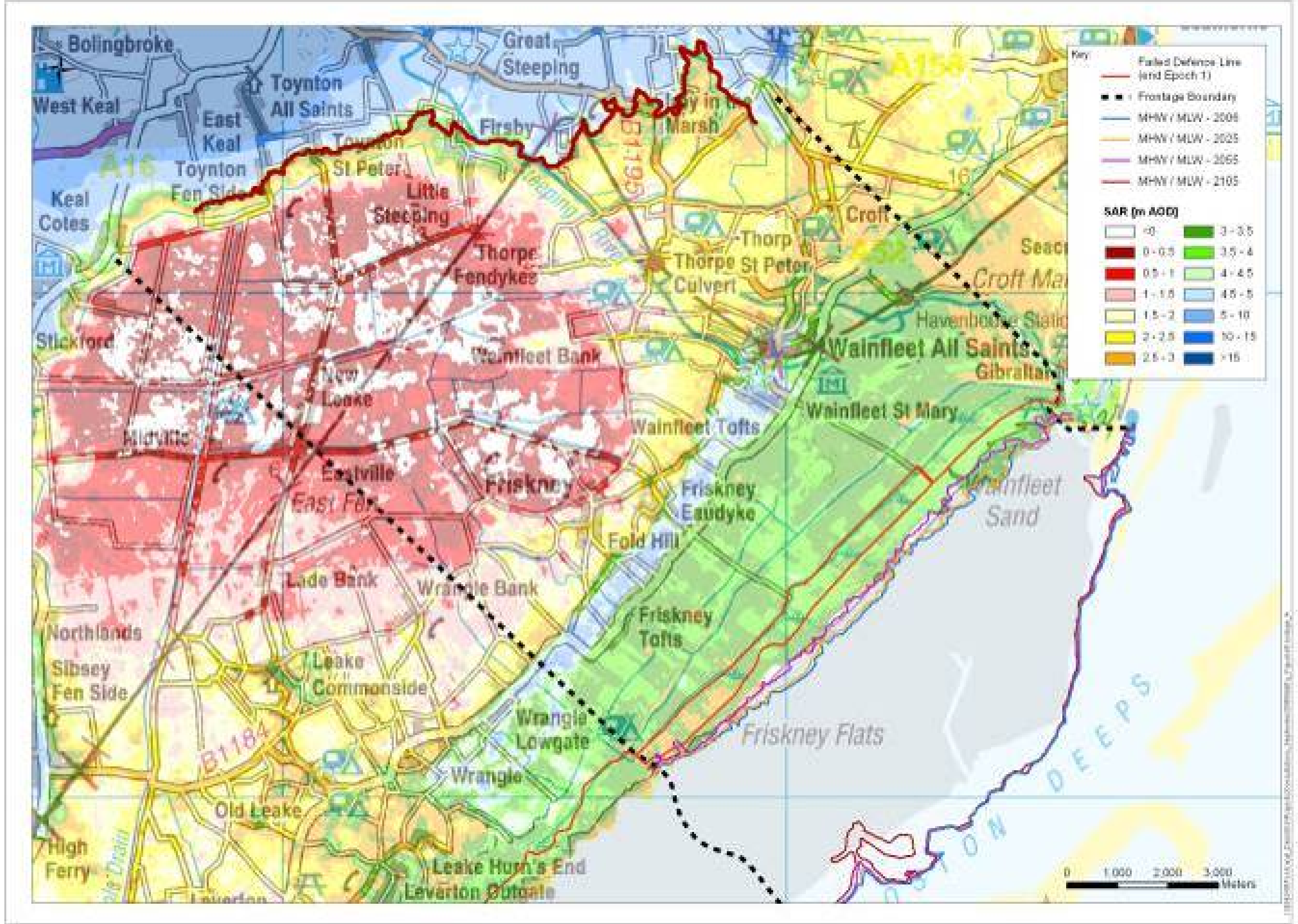
Epoch 3 (2055 to 2105)

Defra (2006) predict that sea level rise between 2055 and 2085 will be around 12.0 mmyr^{-1} between 2055 and 2085, and around 15.0 mmyr^{-1} between 2085 and 2105. As a result MHW in 2105 will be approximately **3.60 mODN**.

During this epoch there will be increased inundation of the former land reclaim areas, not only during storm events, but also during high tides. It is likely that the backshore areas will begin to see the initial stages of saltmarsh development. This will generally occur landward of the mean sea level. This development will also occur simultaneously in frontage B.

Figure F3.2.14 illustrates the position of the high and low water marks for epoch 3 under a scenario of NAI. This figure clearly illustrates the landward extent of mean high water during this epoch.

Figure F3.2.14 frontage A Predicted Shoreline Evolution All epochs NAI



F3.3 Frontage B – Leverton, Butterwick and Freiston

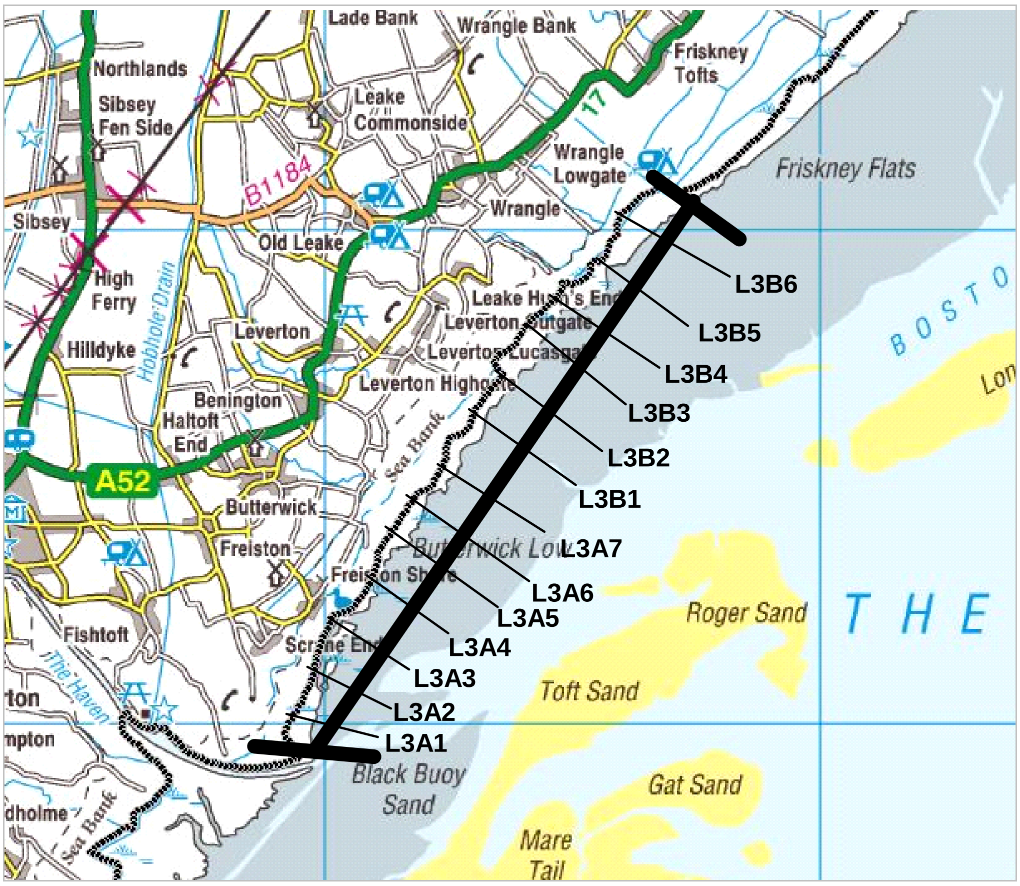
F3.3.1 Introduction

This frontage contains a number of small villages, including Benington, Leverton, Butterwick and Freiston, as well as the small hamlet of Freiston Shore. There is a nationally important RSPB reserve at Freiston Shore that has been developed on the Managed realignment site. The open prison of North Sea Camp is located at the southern end of the frontage.

The frontage is similar to that of frontage A – there is extensive coastal lowland of reclaimed intertidal flats that is now protected by large-scale flooding by a series of grassed earth embankments. The intertidal flat width decreases from the north of the cell to the south, ranging from approximately 4 kilometres in the north to less than 1 kilometre in the south. The frontage's southern limit is the left hand bank of The Haven, and therefore this will have an influence upon the sediment dynamics and currents.

Figure F3.3.1 outlines the location of this frontage and also shows the location of the profiles used by the Anglian Coastal Monitoring Programme (EA SMG 2007).

Figure F3.3.1 Anglian Coastal Monitoring Programme profiles



F3.3.2 Key Geomorphological Components

The key morphological components that are contained within this cell and that affect the morphological development of the cell are listed below:

- Toft Sand, Roger Sand, Bar Sand and the southern limit of Long Sand, are all sandbanks within the Wash embayment which will have an influence on this frontage. They lie parallel with the coastline and are generally exposed at low water. They have a significant effect on wave energy reaching the marginal tidal flats. They will therefore act to provide shelter to the coastline from wave attack.
- These offshore banks also have an effect on the erosion and accretion of materials along the frontage.
- The deep water channel, Boston Deep, that also runs parallel with the coastline, will control the position of low water mark along this frontage. The effect of Boston Deeps combined with the position of the sea defences along this frontage, causes the intertidal width to decrease from the north to the south of this frontage.
- To the north of the frontage, where the intertidal flats are wide, the incoming wave and tidal energy is effectively dissipated. This limits

the amount of energy that reaches the upper profile before it is able to cause erosion or flooding.

- The outfall of The Haven joins with the outfall of the Welland at Clay Hole and then links with Boston Deeps. This combined outfall of two major rivers and the deep water channel has a significant control on the position of the mean low water mark to the south of the frontage.
- Continued land reclaim has however maintained the saltmarshes in an immature state.
- The earlier reclaimed areas behind the defences are topographically lower due to compaction, oxidation, wind deflation and the longer history of deposition in the more recently reclaimed areas. Some of the earlier reclaims are now up to 4m below mean high water springs.

Table F3.3.1 summarises each feature in terms of the control it exerts on the Wash system as a whole, its influences and interactions in terms of the other components of the system, and its status with respect to the geomorphological system.

Table F3.3.1 Key Geomorphological Components Summary

FEATURE	MAJOR CONTROLS	INFLUENCES	STATUS
Boston Deeps	Is a route for the flow of tidal energy within the Wash. Its position determines the position of the low water mark on the foreshore and therefore the width of the intertidal area.	It interacts with the outfall of the Rivers Witham and Welland and provides a pre-defined flow path during the ebb tide Its depth and width are determined by the strength of the tidal currents.	Primary, persistent control under WPM
Offshore banks (Long Sand, Toft Sand, Roger Sand and Bar Sand)	Are stores of sediment transported from the Lincolnshire coast to the north and from the intertidal area Provide some degree of shelter from wave attack and therefore influence the position of low water mark on the foreshore Influence tidal circulation and	Their height and width are determined by large-scale tidal circulation patterns and the extent of sediment supply	Secondary transient control

FEATURE	MAJOR CONTROLS	INFLUENCES	STATUS
	generally encourage flow around the individual banks		
Wide intertidal area	Is effective in dissipating wave and tidal energy before it reaches the backshore area and defence line Is a store of sediment transported in suspension.	The width is determined by the position of low water mark, which is mainly controlled by Boston Deeps, and to some extent Long Sand.	Primary, transient control
Combined outfall of The Haven and River Witham (trained)	Link up with the Boston Deeps to provide an uninterrupted flow of water along the western side of the Wash. Provides some degree of limitation to the westward growth of Toft Sand and Roger Sand.	Its existence is controlled by the continued flow of water out of The Haven and River Welland. The strength and direction of the outfall is primarily controlled by the existence of the training walls	Secondary, persistent control under WPM

F3.3.3 Patterns of Change

Historic Change

Hill (1988) has calculated that the saltmarshes at Freiston Low and Butterwick Low in front of the 1952 and 1979/80 embankments have retreated by between 2 and 3 myr^{-1} and 15 myr^{-1} respectively. In addition Inglis and Kestner (1958) and Kestner (1962) calculated a mean seaward advance of approximately 8 myr^{-1} between 1828 and 1952 in the same area.

From the northern boundary of this frontage to the Pumping Station between Leverton Outgate and Leverton Lucasgate, the saltmarsh/mudflat boundary moved seaward in a northward direction between 1971/74 and 1982/85 (University of Newcastle 1998a). South of this Pumping Station the trend is reversed and the salt marsh/mudflat boundary retreated at an annual rate of 1.4myr^{-1} (University of Newcastle 1998a).

From the beginning of the frontage in the north to Butterwick the mean high water spring mark has generally advanced (rates of between 0 and 13 myr^{-1}), whereas south of Freiston Shore there has been a general trend of retreat (rates of between 0 and 8 myr^{-1}).

Mean sea level has generally retreated between 0 and 56 myr^{-1}, however to the south of Butterwick, the position of mean sea level has been reasonably static (and shows signs of both advance and retreat) until the River Witham outfall where a higher rate of retreat is apparent (approximately 8 myr^{-1}).

Recent (1991 – 2006) change

Pethick (2002) calculated saltmarsh accretion rates of 88 $mmyr^{-1}$ at Butterwick Low (to the south of the frontage) but rates of 9 $mmyr^{-1}$ at Wrangle Flats (to the north).

In terms of horizontal change, between 1991 and 2006 the saltmarsh/mudflat boundary has accreted (moved seaward) by an average of approximately 73m. This horizontal change is also reflected in the fact that the total area of saltmarsh increased by just over 40 hectares between 1992 and 2006 (Environment Agency 2003b).

In general, both the saltmarsh (upper and lower) and the mudflats (upper and lower) also experienced vertical accretion between 1994 and 2006. An average vertical accretion rate was calculated from all the average rates for each profile along this frontage. On the saltmarsh rates were calculated at 0.007 myr^{-1} and averages on the mudflat were 0.006 myr^{-1}.

A typical profile (L3B5) is shown in figure F3.3.2 taken from the Anglian Coastal Monitoring Programme Coastal Trends Analysis (EA SMG 2007). The saltmarsh/mudflat boundary can be clearly seen at approximately chainage 400 m and the yearly accretion trend is evident. This profile is slightly unusual as the saltmarsh/mudflat boundary did not move between 1994 and 2006. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

Figure F3.3.2 Typical frontage A Saltmarsh and Mudflat Development: Profile L3B5

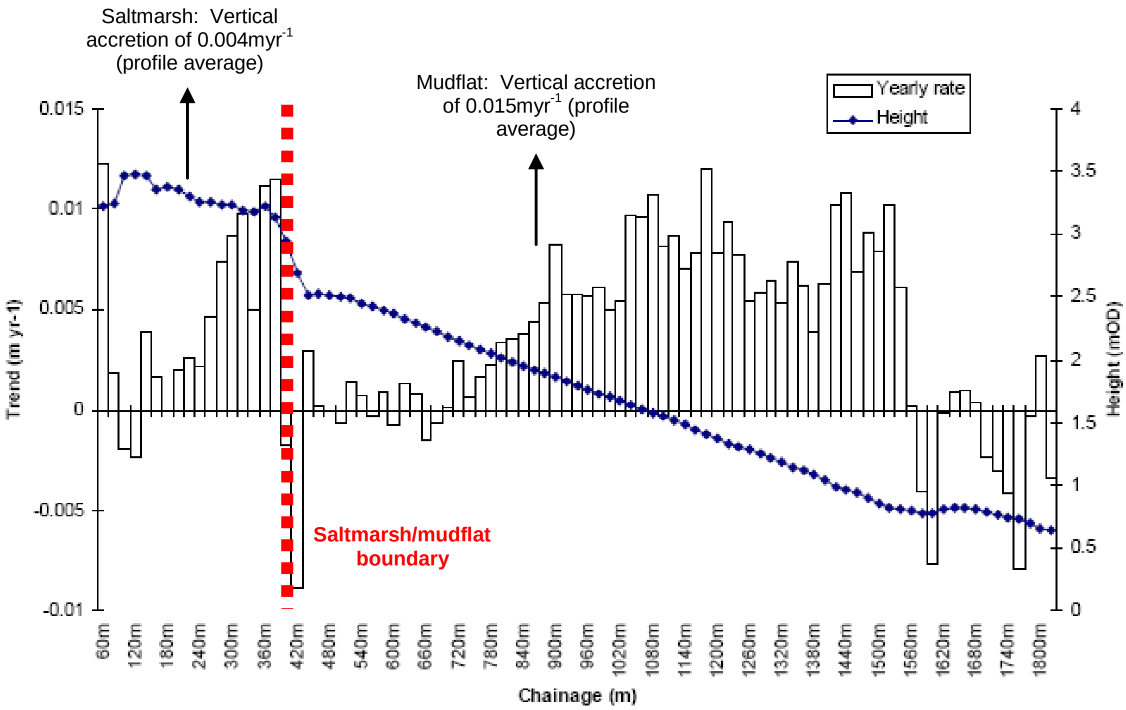
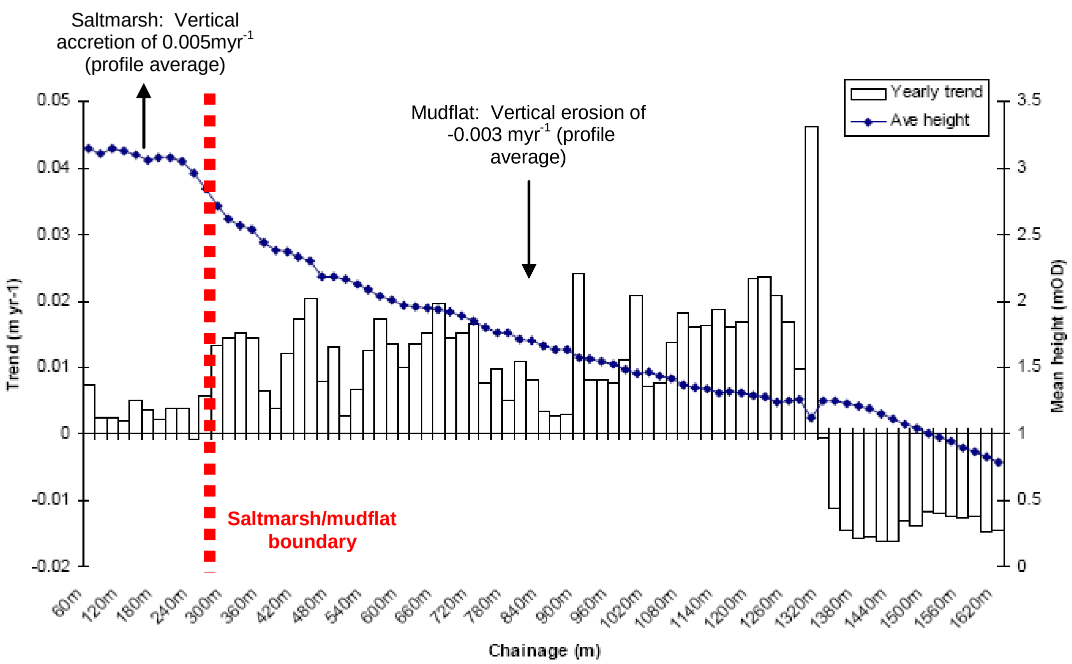


Figure F3.3.3 L3A6 Saltmarsh and Mudflat Development



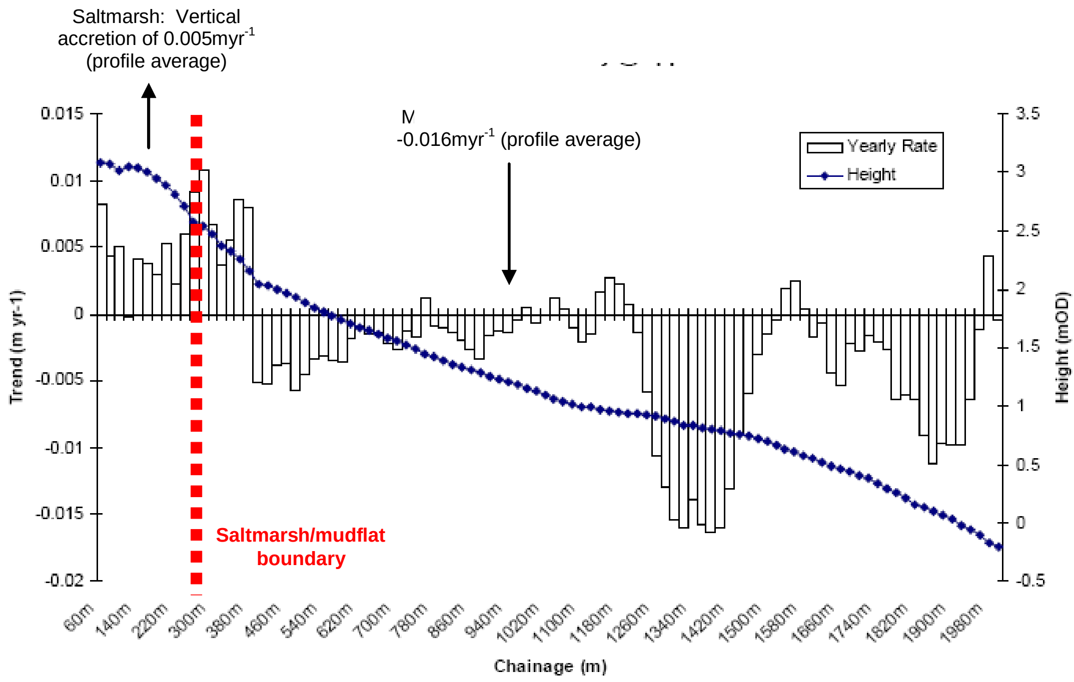
As with frontage A, there are a number of profiles that exhibit different trends. Profile L3A6 has exhibited a trend of erosion of the lower mudflat, but accretion of the upper and lower saltmarsh. The saltmarsh/mudflat boundary has also moved seaward (accretion). This profile is shown in figure F3.3.3, again taken from the Anglian Coastal Monitoring Programme Coastal Trends Analysis (EA SMG 2007). The saltmarsh/mudflat boundary can be seen at approximately chainage 300 m. This boundary moved 60m seaward between 1994 and 2006. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

However, according to the Coastal Trends Analysis Report (EA SMG 2007) this profile crosses a drainage channel which explains the localised vertical erosion along the lower mudflat.

Another profile of interest is profile L3A7 as shown in figure F3.3.4 (EA SMG 2007). This profile has also exhibited a trend of erosion of the upper and lower mudflat, but accretion of the upper and lower saltmarsh. The saltmarsh/mudflat boundary has also moved seaward (accretion) by 80 metres.

There are no drainage channels present at the end of this profile, but it lies between two large channels which are likely to influence erosion/accretion patterns.

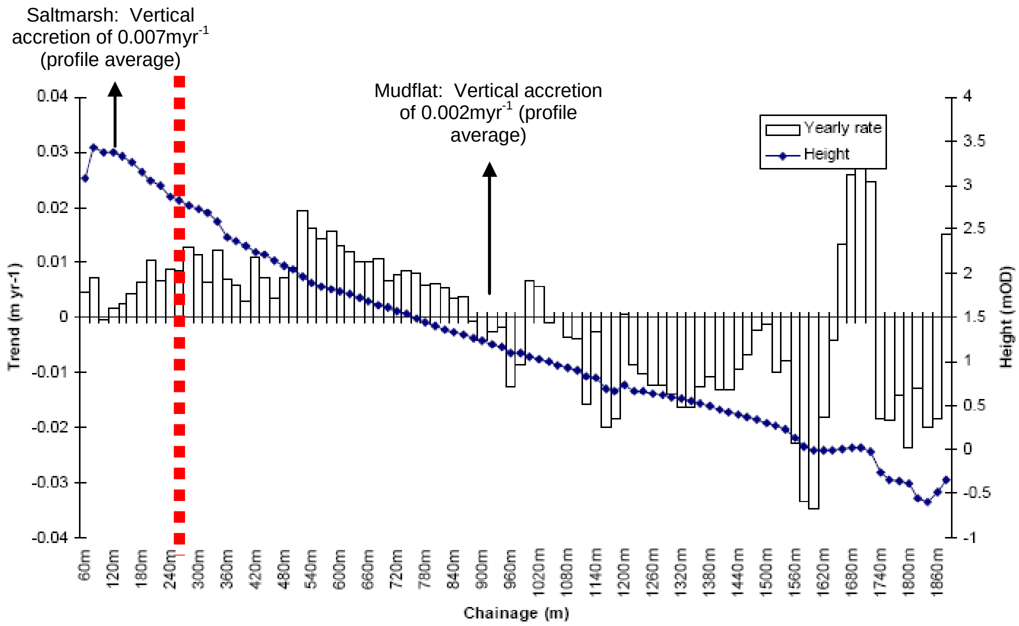
Figure F3.3.4 L3A7 Saltmarsh and Mudflat Development



Profile L3B2, shown in figure F3.3.5, shows accretion throughout the whole profile, with the exception of the lower mudflat which experienced erosion. The saltmarsh/mudflat boundary also remained static during the period.

The erosion of the lower mudflat along this profile does however appear to be due to the shifting drainage channel that crosses the bottom of the profile.

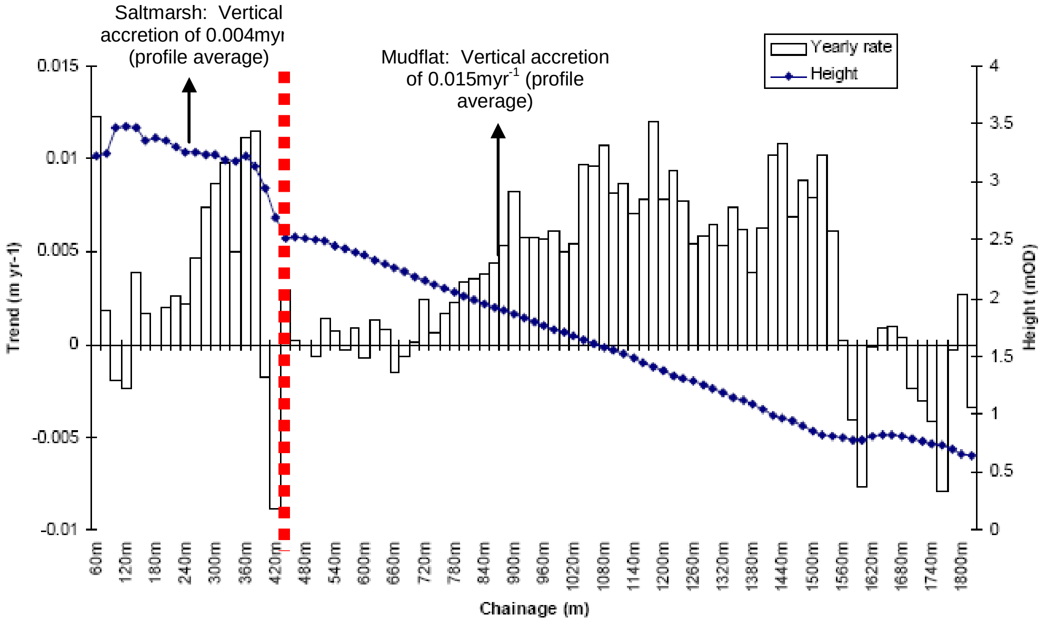
Figure F3.3.5 L3B2 Saltmarsh and Mudflat Development



Profile L3B5, shown in figure F3.3.6, has exhibited variability over the upper saltmarsh and accretion at the lower saltmarsh. The boundary remained static over the 1991 to 2006 period. The upper mudflat has been subject to variable accretion and erosion, whereas the lower mudflat has seen a strong trend of accretion. This profile is also interesting as it exhibits a clear vertical height shift at the saltmarsh/mudflat boundary.

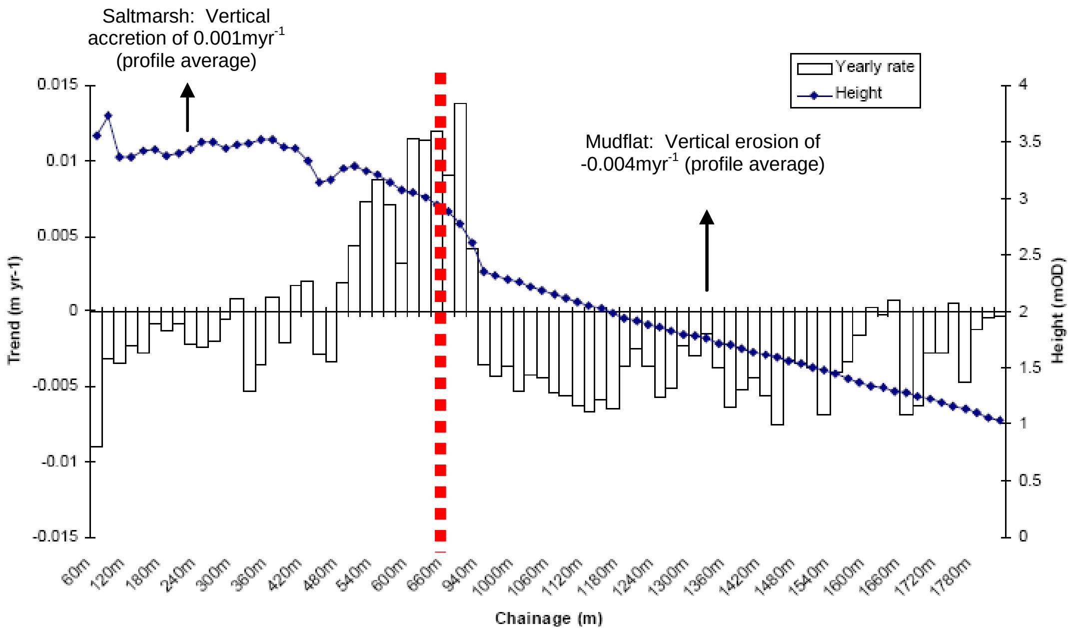
The trends noted at this profile are likely to be due to the drainage channel that cuts across the profile along the lower mudflat.

Figure F3.3.6 L3B5 Saltmarsh and Mudflat Development



The final profile that exhibits a trend that is different to the general trend of accretion is Profile L3B6, shown below. This shows erosion of the upper and lower mudflat, accretion of the lower saltmarsh and around the saltmarsh/mudflat boundary, and erosion of the upper saltmarsh. The saltmarsh/mudflat boundary saw no change between 1992 and 2006. These trends are likely to be greatly affected by the series of drainage channels that cut across the profile along the lower mudflat.

Figure F3.3.7 L3B6 Saltmarsh and Mudflat Development



In summary, the horizontal accretion rates along this frontage are significantly lower than those recorded in both frontages A and C.

F3.3.4 Tidal Currents

Tidal currents can be relatively strong in the Wash, especially in the main channels during spring tides, due to its large tidal range. Average current velocities are between 0.8 and 1.0 ms^{-1} (HR Wallingford 1972).

F3.3.5 Current Residuals

Net water transport throughout the water column off the coast of this frontage is directed towards the south-west in the order of between 30,000 and 45,000m^3/m/tide (Posford Duvivier Wash SMP1). The overall direction of movement along this frontage is directly to the north-east parallel with the coast (Posford Duvivier Wash SMP1).

F3.3.6 Sediment

The main sources of sediment found on this frontage are as follows:

- The Holderness coast (situated to the north).
- The Humber estuary (also situated to the north).
- The North Norfolk coast to the east.
- The North Sea as a whole.
- The sea floor within the mouth of the Wash.

- The combined outfalls of The Haven and River Welland (southern extent of the cell). This provides input of a small quantity of sediment, mostly fine-grained sediment.
- Limited erosion from the mudflats in frontage A.

The main sinks of sediment on this frontage are:

- Toft Sand, Roger Sand and Long Sand (offshore banks).
- Intertidal area.

In terms of sediment transport, over the mudflats sediment is mostly transported in suspension. Sediment is deposited when the velocity of the tide is low (< -0.12 cms^{-1}). Sand and gravel may be deposited under higher flows and exist where there is a greater disturbance due to wave action.

The primary sediment transport mechanism along this frontage will be suspended sediment transport, due to the dominance of sands and silts in the water column. This is in contrast to the eastern shore of the Wash where both bedload and suspended sediment transport occur due to the existence of larger sizes.

F3.3.7 Processes

Tides
Tidal levels along this frontage are the same as for frontage A (see section 2.7.1).

Extreme Water Levels
Table F3.3.2 shows the EWL analysis for the River Witham (Hobhole), situated at the southern extent of the frontage (Mott MacDonald 2006) in mODN:

Table F3.3.2 EWLs for River Witham (Hobhole) (Mott MacDonald 2006)

RETURN PERIOD							
1:1	**1:10**	**1:25**	**1:50**	**1:100**	**1:200**	**1:500**	**1:1000**
4.82	5.30	5.49	5.64	5.78	5.93	6.12	6.27

Waves
Information regarding waves along this frontage is the same as for frontage A and can therefore be found in section 2.7.3.

F3.3.8 Existing Management

As with frontage A, the majority of the defences in this frontage are earth embankments, although there are a few earth embankments with added toe protection, such as stone toe revetments and gabion mattress batter protection. This frontage is also characterised by both secondary and tertiary lines of defence in addition to the maintained frontline earth embankment. These are grassed earth embankments but do not have any additional toe protection. Maintenance of the earlier structures ceased after new front line defences were constructed.

The majority of the frontline defences towards the northern reaches of the frontage are expected to fail within the next 10 to 25 years, under a policy of No active intervention, and will therefore fail sometime during epoch 1. The defences around the Freiston Shore area and along the left hand bank of the River Witham are, however, in a better condition and are predicted to fail in epoch 2.

Management of the outfall of The Haven is also an issue for this frontage. The Haven does not take a natural course into the mudflats of the Wash, but is instead trained to a point where it joins the River Welland at Tabs Head. In fact the whole of the lower course of this river, up to Boston town centre, is man-made and has been artificially straightened and widened to allow commercial and pleasure craft to navigate safely into Boston docks. The river outfall is managed by training walls along both the right and left hand banks. In terms of navigation along the River, the Port of Boston undertakes regular dredging to maintain the shipping channels.

In terms of maintenance, the earth embankments are managed and maintained by the Environment Agency.

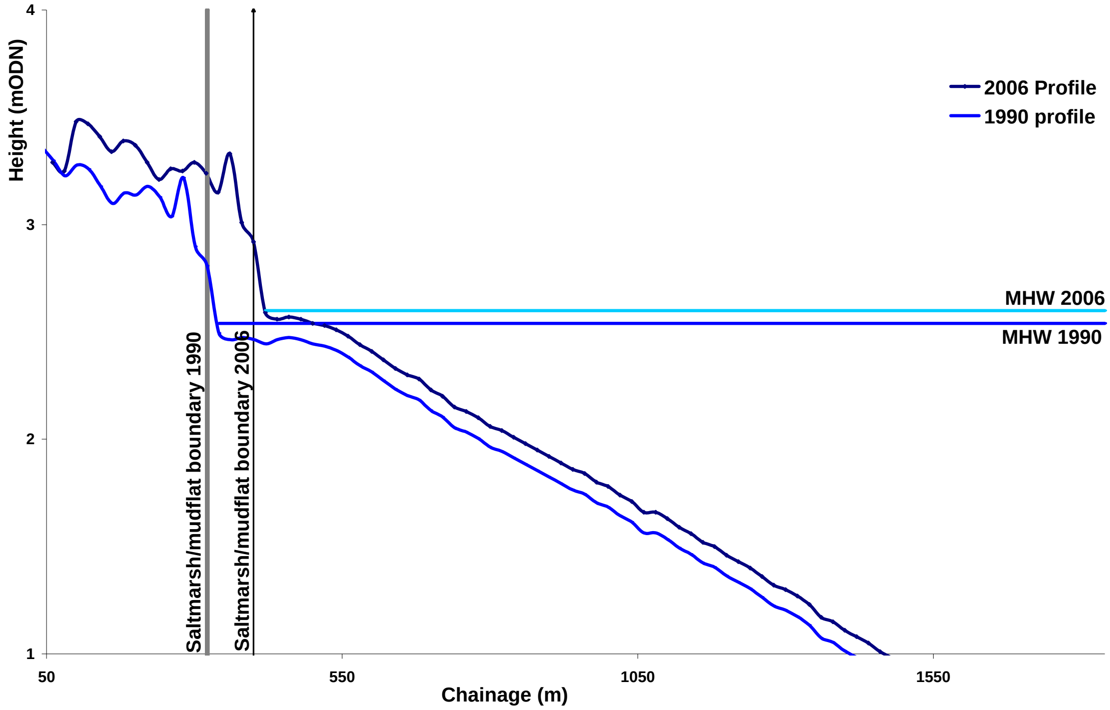
F3.3.9 Analysis of Intertidal Development

The following summarises the general trend of intertidal and foreshore development, as assumed from information provided through the Coastal Trends Analysis Report (EA SMG 2007):

- Saltmarsh vertical accretion rates = **7 mmyr^{-1}**
- Mudflat vertical accretion rates = **6 mmyr^{-1}**
- Horizontal accretion (movement of saltmarsh/mudflat boundary) = **4.9 myr^{-1}**
- Defra's (2006) sea level rise prediction between 1991 and 2006 (period of monitoring) = approximately **4.0 mmyr^{-1}**

From this data, the assumed saltmarsh and mudflat development between 1990 and 2006 can be shown diagrammatically, as shown in figure F3.3.8. This is based on profile L3B5.

Figure F3.3.8 Assumed Saltmarsh and Mudflat Development 1990 – 2006



The key stages of intertidal development along this frontage are as follows:

- The whole profile is built up with fresh accumulations of sediment during tidal inundation, either directly by water flowing across the mudflat, or by creeks filling up and then overtopping onto the surrounding saltmarsh.
- At a critical point in this upward growth the upper mudflat becomes exposed for long enough each day to allow species (tolerant to submergence and salinity) to colonize. The first species to colonise are usually benthic microalage, especially epipelic diatoms.
- This then raises the elevation further, eventually enabling colonisation by saltmarsh species such as *Salicornia* (grasswort). At this point the upper mudflat has made the transition to lower saltmarsh.
- This produces the seaward shift of the saltmarsh/mudflat boundary.
- Generally as the mudflat profile does not shift seaward, sea level rise causes the position of MHW and MLW to move landward.
- This effectively causes a squeeze of the intertidal area.
- However with the above profile the position of MHW actually extends up to the saltmarsh/mudflat boundary.
- This is probably due to the fact that this particular profile did not exhibit a seaward movement of the boundary or mudflat accretion to the extent of 6 $mmyr^{-1}$. As a result a landward movement of the MHW mark would have been seen.
- This frontage does not exhibit definite trends to the same extent as frontage A did, mainly due to the lower levels of the saltmarsh.

Therefore it needs to be remembered that rates of vertical and horizontal erosion and accretion are averages for the entire frontage, and mask individual profile changes.

F3.3.10 Impacts: With Present Management

Epoch 1 (present day to 2025)

Defra (2006) predict that sea level rise between 2006 and 2025 will be around 4.0 $mmyr^{-1}$ therefore MHW in 2025 will be approximately **2.68 mODN.**

Over this epoch, coastal response will be much the same as seen between 1990 and 2006. The rate of sedimentation across both the saltmarsh and mudflat (7$mmyr^{-1}$ and 6$mmyr^{-1}$ respectively) exceeds the rate of sea level rise (4$mmyr^{-1}$) therefore there will be continued vertical accretion across both the saltmarsh and mudflat. As a result there will be a seaward movement of the mean high and low water marks. The saltmarsh/mudflat boundary will continue to move seaward by 4.9 myr^{-1}. Figure F3.3.9 below represents typical profile change in epoch 1.

The processes that are likely to occur will be much the same as the present day (see section 2.9).

This is a typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross marsh drainage channels.

In terms of the backshore, it is likely to continue to grow, with accretion of the established saltmarsh and movement seaward of the saltmarsh/mudflat boundary.

The predicted continued accretion in this frontage will promote continued accretion in frontages A and C, as sediment will be transported from this frontage to the adjacent ones.

The predicted shoreline evolution for epoch 1 under a scenario of WPM is shown in figure F3.3.10.

Figure F3.3.9 Typical Profile Change in epoch 1

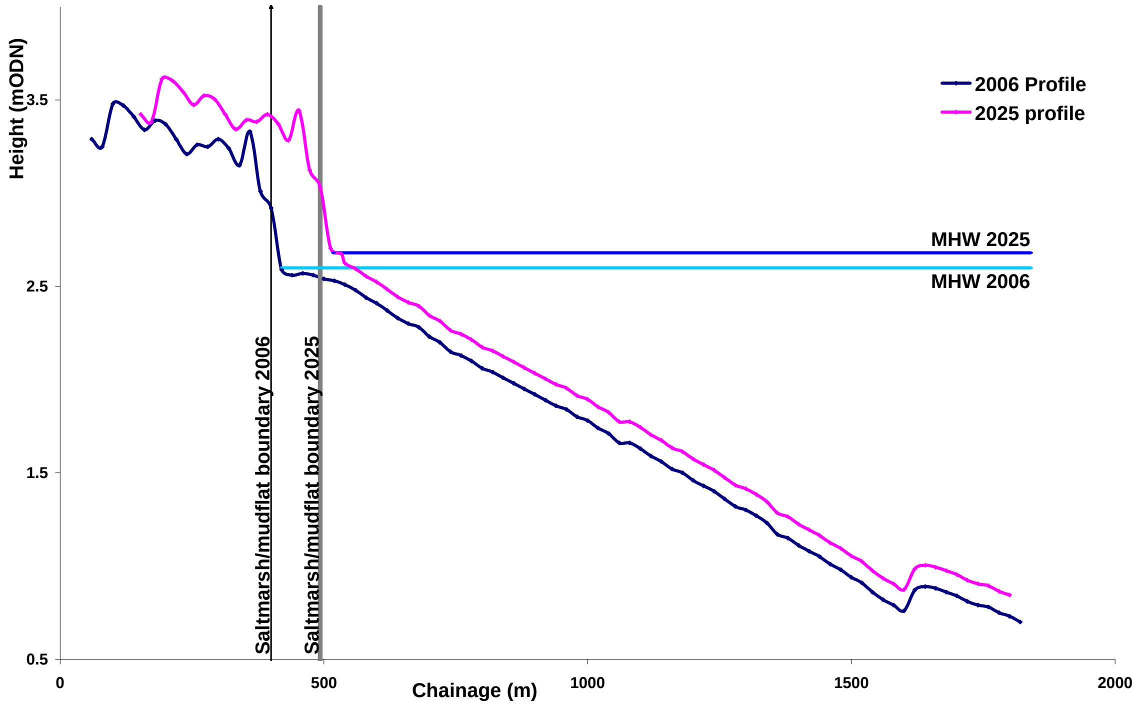
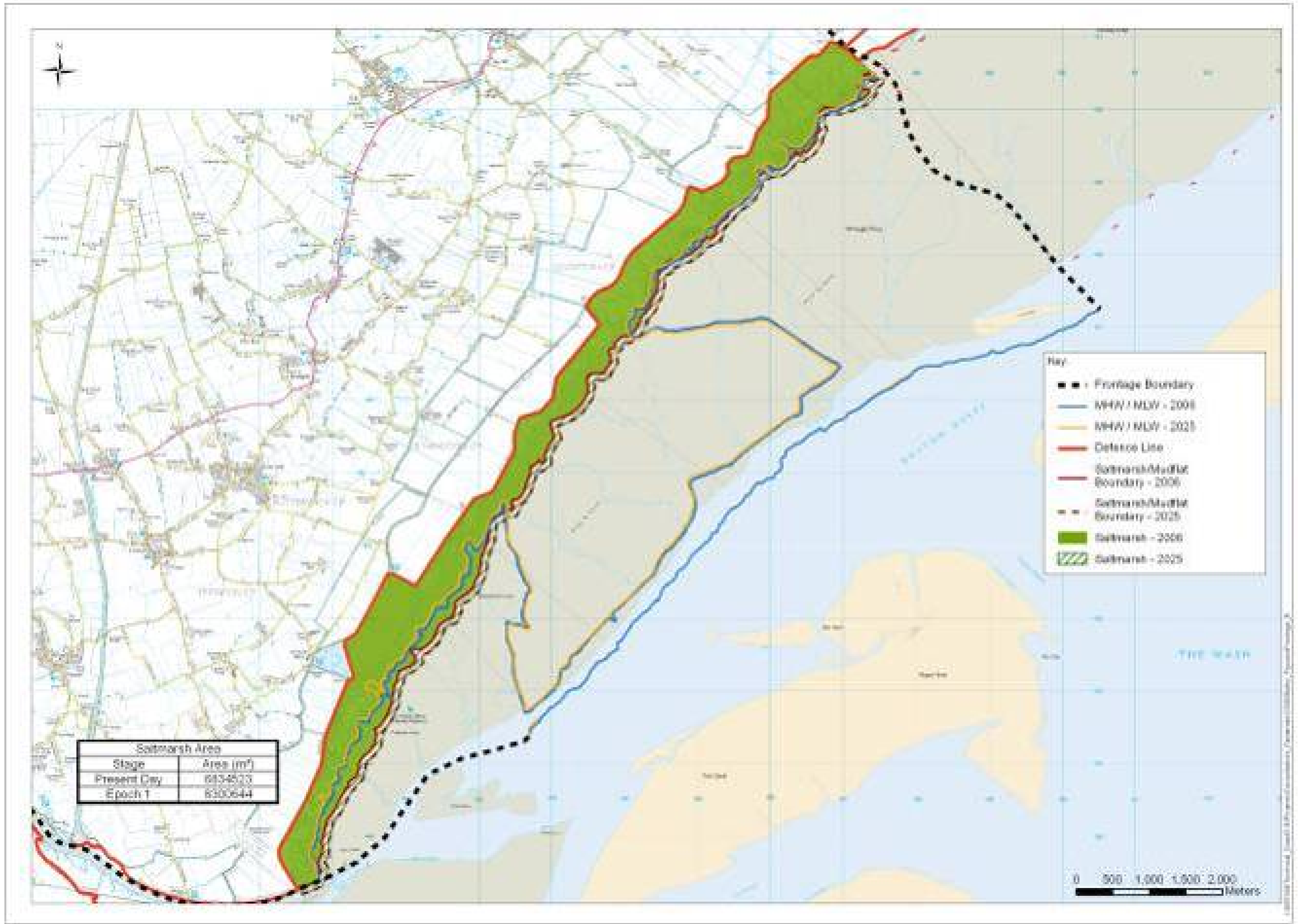


Figure F3.3.10 frontage B Predicted Shoreline Evolution epoch 1 WPM



Epoch 2 (2025 to 2055)
Defra (2006) predict that sea level rise between 2025 and 2055 will be around 8.5 $mmyr^{-1}$ therefore MHW in 2055 will be approximately **2.94 mODN.**

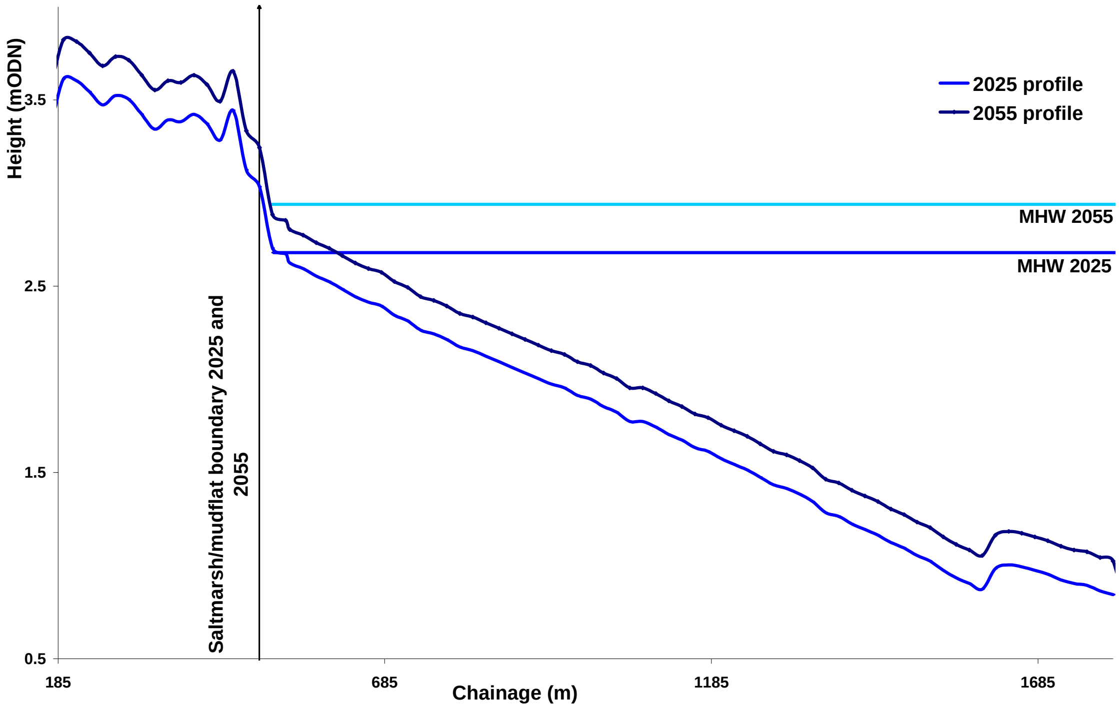
Over this epoch there will be some changes in coastal responses as a result of sea level rise. Across the saltmarsh the rate of sedimentation (7 $mmyr^{-1}$) will not exceed the rate of sea level rise (8.5 $mmyr^{-1}$) and therefore there will be continued vertical accretion as the saltmarsh is not inundated on every tide (as can be seen by the position of MHW). Across the mudflat the rate of sedimentation (6 $mmyr^{-1}$) does not exceed rate of sea level rise (8.5 $mmyr^{-1}$) but there is likely to be continued accretion. The significantly increased water depth across the mudflat will result in larger waves and therefore increased pressure on the saltmarsh/mudflat boundary.

Due to the fact that the rate of sedimentation is similar to the rate of sea level rise, the saltmarsh/mudflat boundary should be able to hold its position, therefore in this epoch there is not likely to be any landward movement (erosion) of the saltmarsh/mudflat boundary.

The position of mean high and low water along the profile is likely to remain the same due to the lack of movement of the saltmarsh/mudflat boundary.

The typical profile change in epoch 2 is represented in figure F3.3.11.

Figure F3.3.11 Typical Profile Change in epoch 2



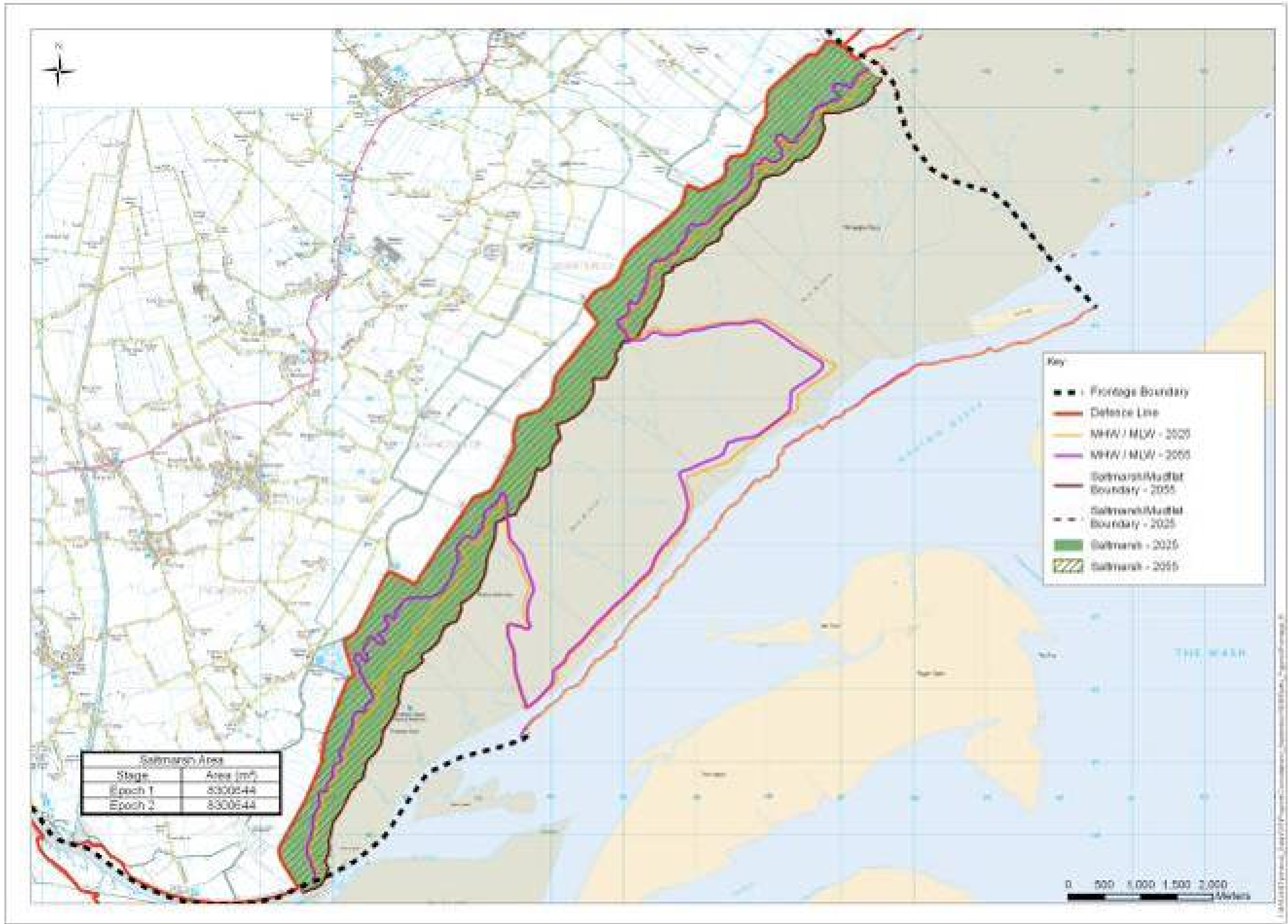
Again, this is the typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross drainage channels.

The area of the backshore is likely to remain the same but it will be subject to increased pressure due to the increase in mean sea level.

The continued accretion in this frontage will promote continued accretion in frontages A and C, as sediment will be transported from this frontage to the adjacent ones.

The predicted shoreline evolution for epoch 2 under a scenario of WPM is shown in figure F3.3.12.

Figure F3.3.12 frontage B Predicted Shoreline Evolution epoch 2 WPM



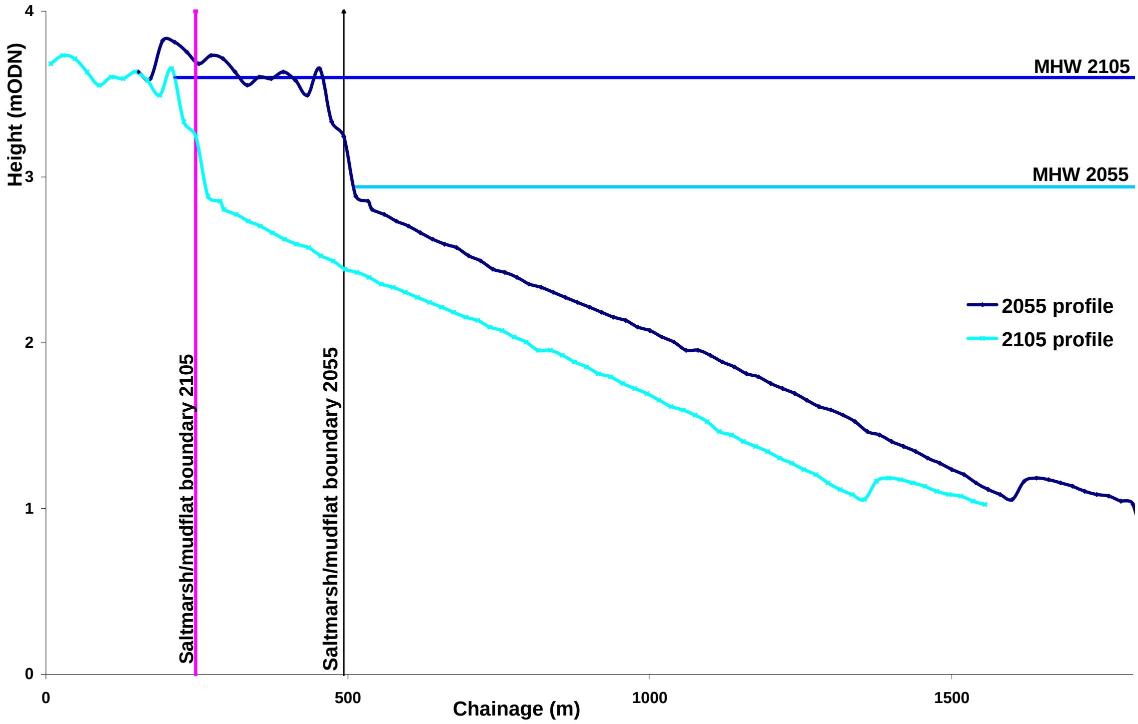
Epoch 3 (2055 to 2105)

Defra (2006) predict that sea level rise between 2055 and 2085 will be around 12.0 mmyr^{-1}, and around 15.0 mmyr^{-1} between 2085 and 2105. As a result MHW in 2105 will be approximately **3.60 mODN.**

Over this epoch the rate of sedimentation will be significantly outpaced by the rate of sea level rise. Across the saltmarsh, the rate of sedimentation (7.0 mmyr^{-1}) does not exceed the rate of sea level rise (between 12.0 and 15.0 mmyr^{-1}). The same will occur across the mudflat, where the rate of sedimentation (6.0 mmyr^{-1}) is also significantly lower than the rate of sea level rise (as stated above). As a result there is likely to be a reduced rate of vertical accretion on both the mudflat and saltmarsh due to the increased depth of water which will cause larger waves to form over the intertidal area, leading to increased wave attack and therefore the tendency for erosion rather than accretion.

Consequently there will be landward movement of the mean high and low water marks. Figure F3.3.13 represents typical profile change assuming no vertical accretion rates on the saltmarsh and mudflats (therefore the same profile as 2055) and landward movement of the saltmarsh/mudflat boundary as in the previous epoch (rate of 4.9 myr^{-1} assumed).

Figure F3.3.13 Typical Profile Change in epoch 3



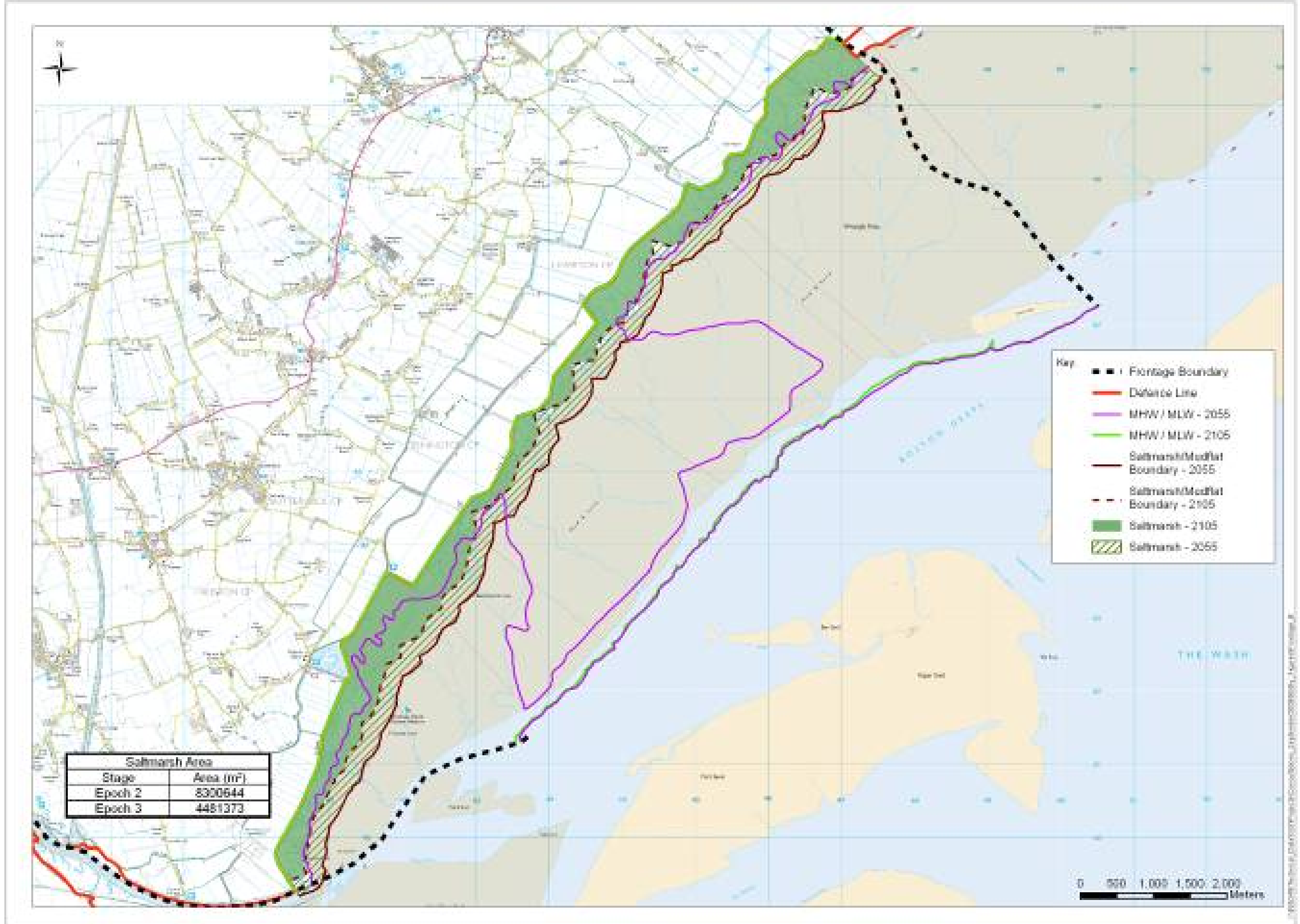
It is evident from figure F3.3.13 that by 2105 the saltmarsh will be inundated at mean high water if no further vertical accretion occurs. It has been suggested that sea level rise may bring about increased vertical accretion on the saltmarsh, but as the saltmarsh/mudflat boundary is moving landward there will be a general decrease in total saltmarsh area. Figure F3.3.13 also represents a generalised intertidal profile, and in reality it is likely that the whole profile will shift and become less steep.

Figure F3.3.13 also clearly highlights the extent of coastal squeeze that is likely to have occurred by 2105 as the saltmarsh is compressed between the eroding seaward edge and the fixed earth embankments.

The onset of widespread erosion in this frontage will act to initiate and aid erosion in frontage A, and possibly bring about a trend of erosion in frontage C.

The predicted shoreline evolution for epoch 3 under a scenario of WPM is shown in figure F3.3.14.

Figure F3.3.14 Frontage B Predicted Shoreline Evolution epoch 3 WPM



F3.3.11 Impacts: No active intervention

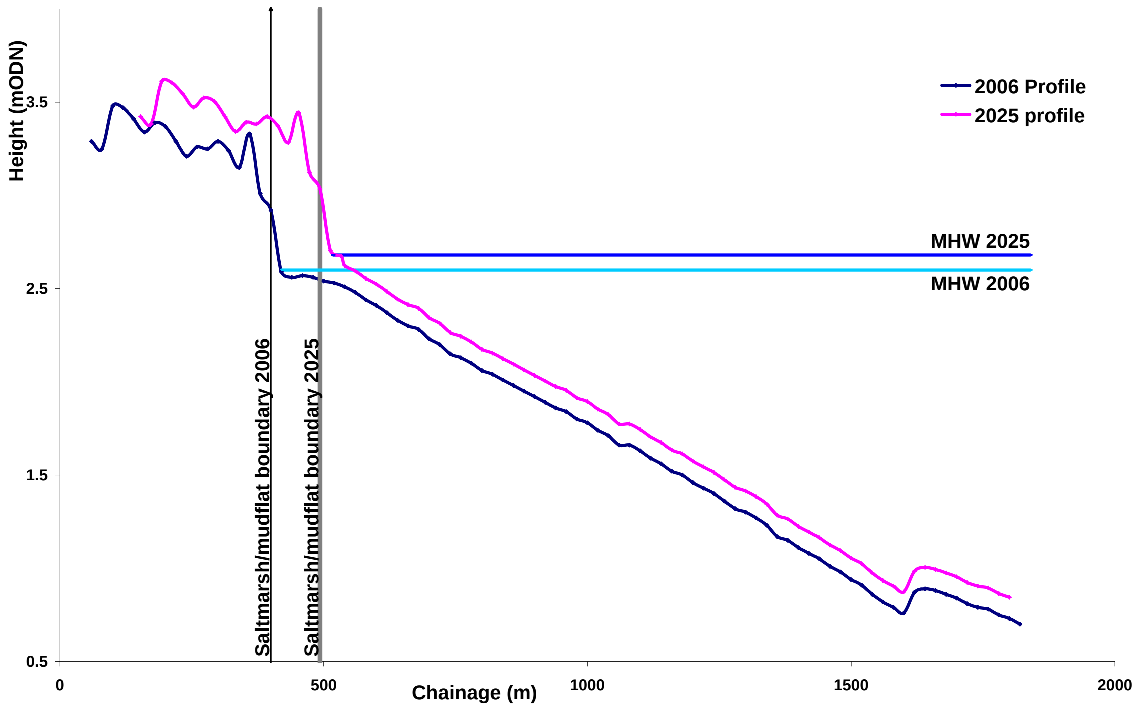
Epoch 1 (present day to 2025)

Defra (2006) predict that sea level rise between 2006 and 2025 will be around 4.0 mmyr^{-1} therefore MHW in 2025 will be approximately **2.68 mODN.**

Coastal response will be much the same as seen in the WPM scenario up to the end of epoch 1 when the majority of the defences are assumed to have failed.

Up to the end of epoch 1 the rate of sedimentation across both the saltmarsh and mudflat (7 mmyr^{-1} and 6 mmyr^{-1} respectively) exceeds the rate of sea level rise (4 mmyr^{-1}) therefore there will be continued vertical accretion across both the saltmarsh and mudflat. As a result there will be a seaward movement of the mean high and low water marks. The saltmarsh/mudflat boundary will continue to move seaward by 4.9 myr^{-1}. Figure F3.3.15 below represents typical profile change in epoch 1.

Figure F3.3.15 Typical Profile Change in epoch 1



After epoch 1, assuming defence failure, the MHW mark does not reach the old defence line and as a result there will not initially be flooding of the former reclaimed area, however inundation of the former reclaimed areas is likely to occur during storm events.

As a result the backshore will continue to grow between present day and the end of epoch 1, with accretion of the established saltmarsh and movement seaward of the saltmarsh/mudflat boundary. After epoch 1, the backshore area will remain the same and will be subject to localised areas of erosion during storm events.

Initially the continued accretion in this frontage will promote continued accretion in frontage A and C, as sediment will be transported from this frontage to the adjacent ones.

Figure F3.3.16 illustrates the position of the high and low water marks for epoch 1 under a scenario of NAI.

Epoch 2 (2025 to 2055)
Defra (2006) predict that sea level rise between 2025 and 2055 will be around 8.5 $mmyr^{-1}$ therefore MHW in 2055 will be approximately **2.94 mODN.**

The MHW mark does not extend up to the old defence line, however there is likely to be more frequent inundation of the former reclaimed areas during storm events. This is with the exception of the defences along the left hand bank of the River Witham and along the Freiston Shore frontage which have the potential to remain until 2032.

As a result the backshore will be subject to localised areas of erosion during storm events. This process will also be reflected in the development of frontage B.

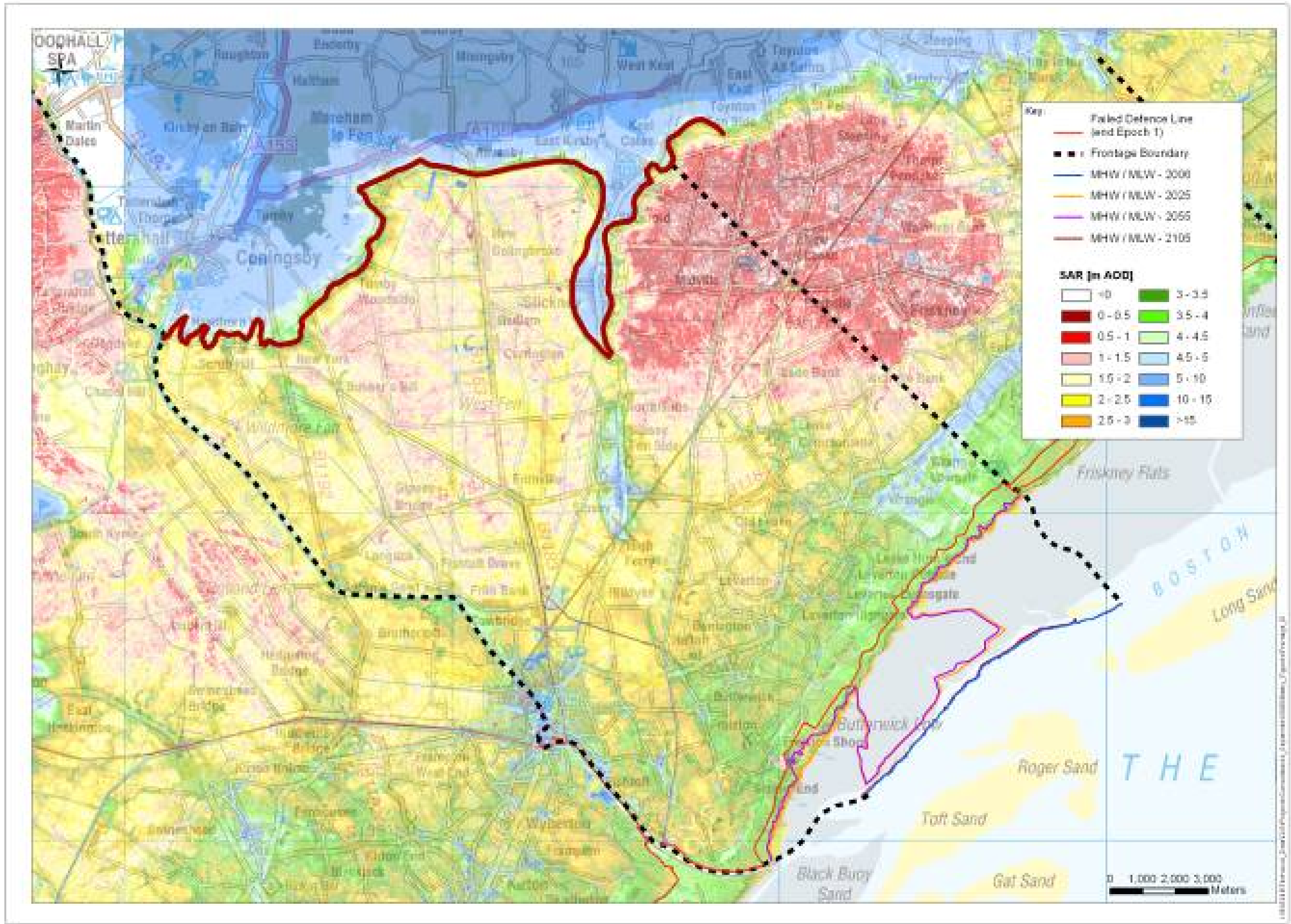
Figure F3.3.16 illustrates the position of the high and low water marks for epoch 2 under a scenario of NAI.

Epoch 3 (2055 to 2105)
Defra (2006) predict that sea level rise between 2055 and 2085 will be around 12.0 $mmyr^{-1}$, and 15.0 $mmyr^{-1}$ between 2085 and 2105. As a result MHW in 2105 will be approximately **3.60 mODN.**

During this epoch there will be increased inundation of the former land reclaim areas, not only during storm events, but also during high tides. It is likely that the backshore areas will begin to see the initial stages of saltmarsh development. This will generally occur landward of the mean sea level. This development will also occur simultaneously in frontage A.

Figure F3.3.16 illustrates the position of the high and low water marks for epoch 3 under a scenario of NAI. This figure clearly illustrates the landward extent of mean high water during this epoch.

Figure F3.3.16 Frontage B Predicted Shoreline Evolution All epochs NAI



F3.4 Frontage C – Frampton, Holbeach and Gedney

F3.4.1 Introduction

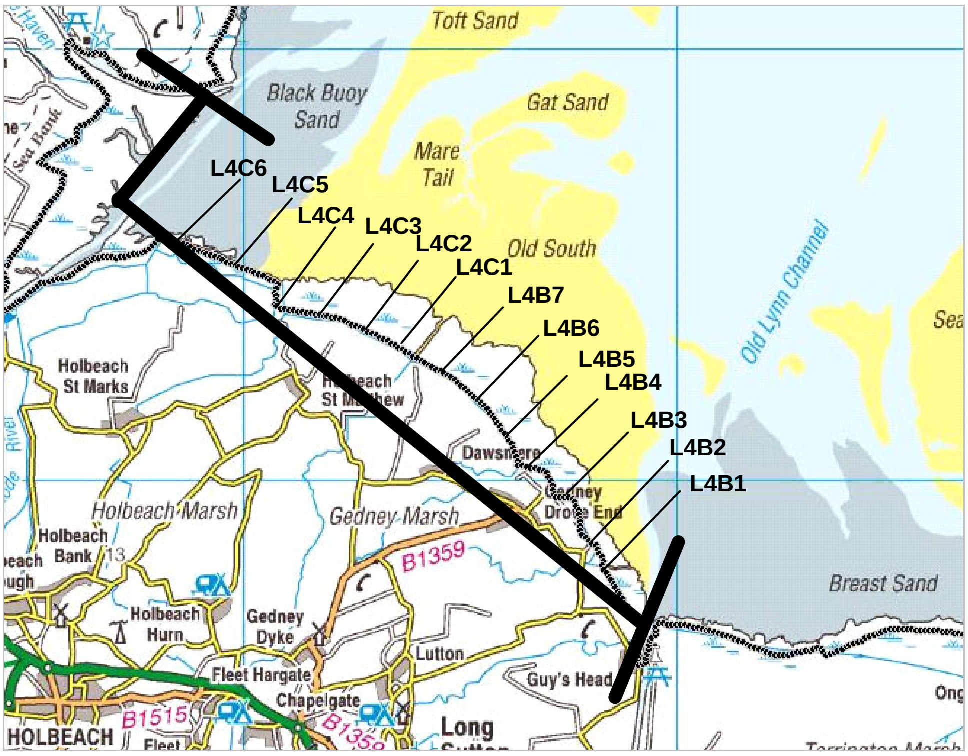
This frontage contains the small town of Kirton, as well as the villages of Frampton, Holbeach St Marks, Holbeach St Matthew and Gedney Drove End. This frontage is characterised by a long history of sediment accretion, as the majority of sediment entering the Wash embayment is preferentially deposited along this frontage. There is extensive coastal lowland of reclaimed intertidal flats which is wider than frontages A and B at most locations. Accretion is particularly apparent around the combined outfall of the Witham and Welland.

This frontage is bounded by the River Witham at its western limit and the River Nene at its eastern limit. It is also influenced by the River Welland which outfalls into the Wash approximately 5 kilometres to the south-west of the River Witham outfall.

As with frontage A, a large area of the intertidal flats is used as a bombing range by the MoD.

Figure F3.4.1 outlines the location of this frontage and also shows the location of the profiles used by the Anglian coastal Monitoring Programme (EA SMG 2007).

Figure F3.4.1 Anglian Coastal Monitoring Programme profiles



F3.4.2 Key Geomorphological Components

The key geomorphological components that are contained within this frontage and that affect the morphological development of the cell are listed below:

- Black Buoy Sand, Toft Sand, Roger Sand, Mare Tail and Gat Sand are all sandbanks within the Wash embayment which will have an influence on this frontage. Unlike sandbanks that affect other frontages, such as Long Sand, these sandbanks are all connected to the intertidal area of this frontage. This reflects the sediment accretion patterns in the embayment as a whole.
- These sandbanks, although they are attached to the intertidal area, will still act to have a significant effect on wave energy reaching the foreshore. They will also have an effect on the erosion and accretion of materials along the frontage.
- The deep water channel, known as the Lynn Deeps, situated in the middle of the Wash embayment, will control the position of the low water mark along this frontage. It is also responsible for feeding incoming sediment preferentially into frontage C.
- The trained outfall of The Haven joins with the trained outfall of the Welland at Clay Hole and then links with Boston Deeps. This combined outfall of two major rivers has a significant control on the position of the mean low water mark at the western limit of the frontage. These two trained outfalls also trap sediment which explains the large width of mature saltmarsh (greater than 1.5 kilometres in most locations).
- At the eastern limit the Nene outfalls into the Wash at Crabs Hole. To the west of the Nene outfall there is a large width (approximately 0.5 kilometres) of mature saltmarsh, but to the east there is only a very limited width of saltmarsh with mainly mudflat. This demonstrates that the trained outfalls of the Nene and Welland act to trap sediment between them.

Table F3.4.1 summarises each feature in terms of the control it exerts on the Wash system as a whole, its influences and interactions in terms of the other components of the system, and its status with respect to the geomorphological system.

Table F3.4.1 Key Geomorphological Components Summary

FEATURE	MAJOR CONTROLS	INFLUENCES	STATUS
Offshore banks (Black Buoy Sand, Toft Sand, Roger Sand, Mare Tail and Gat Sand)	Are stores of sediment transported from the Lincolnshire coast to the north and from the intertidal area Provide some degree of shelter from wave attack and therefore influences the position of low water on the foreshore Influence tidal circulation and generally encourage flow around the banks	Their height and width are determined by large-scale tidal circulation patterns and the extent of sediment supply	Secondary, transient control
Wide intertidal area	Is effective in dissipating wave and tidal energy before it reaches the backshore area and defence line Is a store of sediment transported in suspension	The width is determined by the position of low water mark, which is mainly controlled by Lynn Deeps and the strength of incoming wave energy	Primary, transient control
Trained combined outfall of The Haven and River Witham	Link up with the Boston Deeps to provide an uninterrupted flow of water along the western side of the Wash. Provides some degree of limitation to the westward growth of Toft Sand and Roger Sand.	Its existence is controlled by the continued flow of water out of The Haven and River Welland. The strength and direction of the outfall is primarily controlled by the existence of the training walls	Secondary, persistent control under WPM
Trained outfall of River Nene	Link up with the Lynn Deeps to provide an uninterrupted flow of water through the middle of the Wash.	Its existence is controlled by the continued flow of water out of the River Nene.	Secondary, persistent control under WPM

FEATURE	MAJOR CONTROLS	INFLUENCES	STATUS
	Provides some degree of limitation to the eastward growth of Gat Sand and Old South	The strength and direction of the outfall is primarily controlled by the existence of the training walls	
Lynn Deeps	Is a route for the flow of tidal energy within the Wash Its position determines the position of the low water mark on the foreshore and therefore the width of the intertidal area.	It interacts with the outfall of the Rivers Witham and Welland and provides a pre-defined flow path during the ebb tide Its depth and width are determined by the strength of the tidal currents	Primary, persistent control under WPM

F3.4.3 Patterns of Change

Historic Change
Between 1971/74 and 1982/85, the total saltmarsh area between the River Witham and River Welland was characterised by a net accretion of 18 hectares, and in the same time period the saltmarsh between the River Welland and River Nene accreted by 269 hectares. There has also been a constant seaward movement of the low water mark between the River Welland and River Nene, reinforcing the long-term accretion noted throughout this frontage.

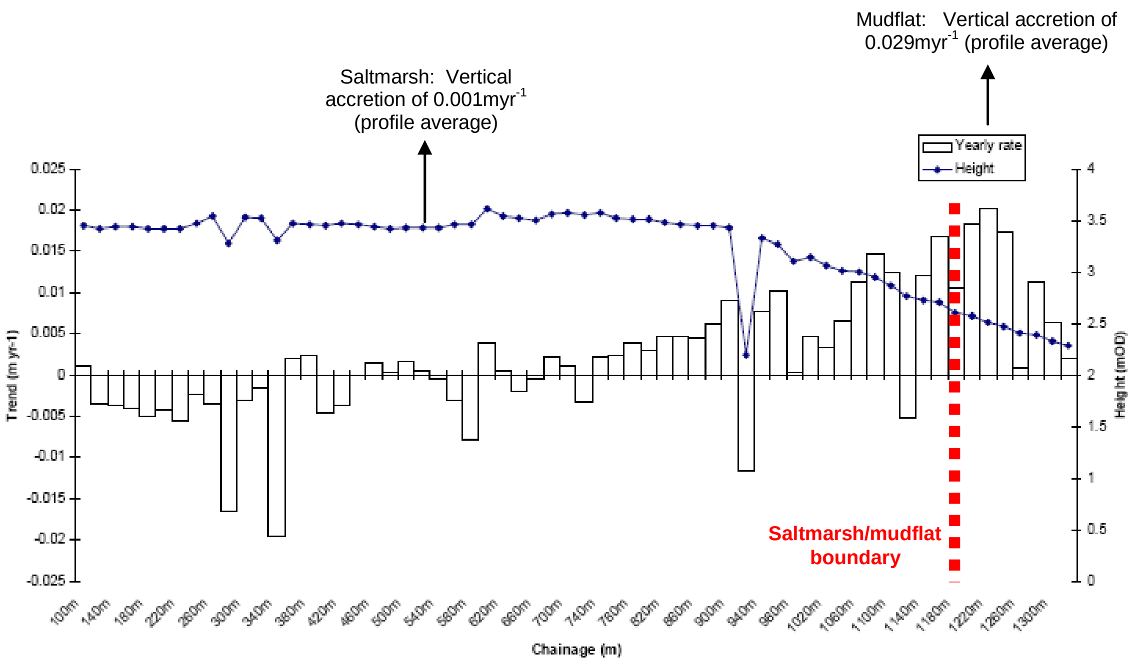
Recent (1991 – 2006) change
Environment Agency monitoring for this frontage has shown a general trend of both vertical and horizontal accretion. In terms of horizontal change, between 1991 and 2006 the saltmarsh/mudflat boundary accreted (moved seaward) by an average of 106 m. This horizontal change is also reflected in the fact that the total area of saltmarsh increased by just under 300 hectares between 1992 and 2006.

The general trend over this frontage between 1994 and 2006 was variability across the upper saltmarsh, accretion along the lower saltmarsh, and strong accretion along the upper mudflat. An average vertical accretion rate of was calculated from all the average rates for each profile along this frontage for both the saltmarsh and mudflat. On the saltmarsh rates were calculated at 0.004 myr^{-1} (accretion) and averages on the mudflat were -0.002 myr^{-1} (erosion).

Unfortunately, due to the large extent of the mudflats along this frontage, monitoring was unable to extend any significant distance over the mudflat profile and therefore there is limited data for the upper mudflat, and no data for the lower mudflat. Having studied the profiles along this frontage, it is also apparent that vertical erosion tends to occur across the lower mudflat, whereas vertical accretion has been recorded across the upper mudflat close to the saltmarsh/mudflat boundary. As a result the calculated trend of vertical erosion (-0.002 myr^{-1}) cannot be used as an average for the entire mudflat along this frontage.

A typical profile (L4C2) is shown in figure F3.4.2 taken from the Anglian Coastal Monitoring Programme Coastal Trends Analysis (EA SMG 2007). The saltmarsh/mudflat boundary can be clearly seen at approximately 1200 m chainage. The variability along the upper saltmarsh and accretion along the lower saltmarsh is evident, as is the strong accretion trend along the upper mudflat and lower saltmarsh. This emphasises the fact that the saltmarsh is accreting in a seaward direction, and therefore total saltmarsh area is also accreting. The series of "dips" in the profile are drainage channels. The saltmarsh/mudflat boundary has moved 200m between 1994 and 2006. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

Figure F3.4.2 Typical frontage C Saltmarsh and Mudflat Development: Profile L4C2



In contrast to frontages A and B, there do not appear to be any localised profiles that exhibit widely differing trends. Localised variability across individual profiles can usually be explained by drainage channels crossing the profile.

F3.4.4 Tidal Currents

Tidal currents can be relatively strong in the Wash, especially in the main channels during spring tides, due to its large tidal range. Average current velocities are between 0.8 and 1.0 ms^{-1} (HR Wallingford 1972).

F3.4.5 Current Residuals

Net water transport throughout the water column off the coast of this frontage is complicated, with 50,000 m^3/m/tide being directed towards the south-west (directly onto the frontage) and 30,000 m^3/m/tide and 21,000m^3/m/tide being directed towards the east south-east and south-east respectively (Posford Duvivier Wash SMP1). The overall direction of movement along this frontage is directly to the south south-west onto the frontage.

F3.4.6 Sediment

The main sources of sediment found on this frontage are as follows:
- The Holderness coast (situated to the north).
- The Humber estuary (also situated to the north).
- Erosion from frontages A and B.
- The North Norfolk coast to the east.
- The North Sea as a whole.
- The sea floor within the mouth of the Wash.
- The River Witham, Welland and Nene outfalls. These provide input of a small quantity of mostly fine-grained sediment.
- Limited erosion of the mud/sand flats within this frontage.

The main sinks of sediment on this frontage are:
- Offshore banks (Roger Sand, Toft Sand and to some extent Long Sand).
- Intertidal area.

In terms of sediment transport, over the mudflats sediment is mostly transported in suspension. Sediment is deposited when the velocity of the tide is low (< 0.12 cms^{-1}). Sand and gravel may be deposited under higher flows and exist where there is greater disturbance due to wave action.

The primary sediment transport mechanism along this frontage will be suspended sediment transport, due to the dominance of sands and silts in the water column. This is in contrast to the eastern shore of the Wash where both bedload and suspended sediment transport occur due to the existence of larger sediment sizes.

F3.4.7 Processes

Tides
Tidal levels (from Admiralty Tide Tables) at the Port of Sutton Bridge are shown in table 4.2:

Table F3.4.2 Tidal levels at Port of Sutton Bridge (mODN)

MHWS	MHWN	MLWN	MLWS
3.80	2.00	-1.20	-2.00
Tidal range (springs): 5.80			
Tidal range (neaps): 3.20			

As a result the mean high water (MHW) has been calculated at **2.90 mODN**, and mean low water (MLW) at **-1.60 mODN**. The mean tidal range is therefore 4.50 m.

However the levels recorded at the mouth of The Haven (as used for frontages A and B) will be used in later analysis as they will give a more accurate prediction of levels along the entire frontage, and not simply at a point approximately 5 km inland at the Port of Sutton Bridge. The MHW for the mouth of The Haven is **2.60 mODN** and MLW is **-2.15 mODN**. As a result the mean tidal range can be calculated at 4.75 m.

Extreme Water Levels
Table F3.4.3 shows the EWL analysis for the River Welland (at Lawyers), situated near the western extent of the frontage, and at the mouth of the River Nene (at West Lighthouse) situated near the eastern extent of the frontage (Mott MacDonald 2006) in mODN:

Table F3.4.3 EWLs for River Welland (Lawyers) and River Nene (West Lighthouse)

LOCATION	RETURN PERIOD							
	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
River Welland (Lawyers)	4.84	5.32	5.51	5.66	5.80	5.95	6.14	6.29
River Nene (West Lighthouse)	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35

Waves
Information regarding waves along this frontage is the same as for frontage A and can therefore be found in section 2.7.3.

F3.4.8 Existing Management

The defence types are generally sea banks (grassed earth embankments), as with other frontages, but they are in a better condition, with residual life estimates of between 15 and 25 years, which suggests that they will not fail until the end of epoch 1 or beginning of epoch 2 (under a policy of NAI). All of the defences within this frontage are maintained by the Environment Agency. At some locations there is a secondary defence line, but maintenance of these earlier structures ceased once new front line defences were constructed.

As with frontage B, this frontage encompasses the outfall of three rivers into the Wash embayment: the trained outfall of The Haven (as discussed in section 3.8); trained outfall of the River Welland and the outfall of the River Nene. The River Welland outfalls into the Wash at Tabs Head through training walls that form the Welland Cut. Here it merges with The Haven and the training walls cease to allow both rivers to find a natural course to the deeper channels of the Wash. The River Nene outfalls into the Wash beyond Twin Lighthouses and is trained up to this point. This estuary is very active and experiences regular re-grading of its profile.

F3.4.9 Analysis of Intertidal Development

The following summarises the general trend of intertidal and foreshore development, as discussed in section 4.3.2:

- Saltmarsh vertical accretion rate = **4.0 mmyr^{-1}**.
- Mudflat vertical erosion rate = **-2 mmyr^{-1}**.
- Horizontal accretion (movement of the saltmarsh/mudflat boundary) = **7.1 myr^{-1}**.
- Defra's (2006) sea level rise prediction between 1991 and 2006 (period of monitoring) = approximately **4.0 mmyr^{-1}**.

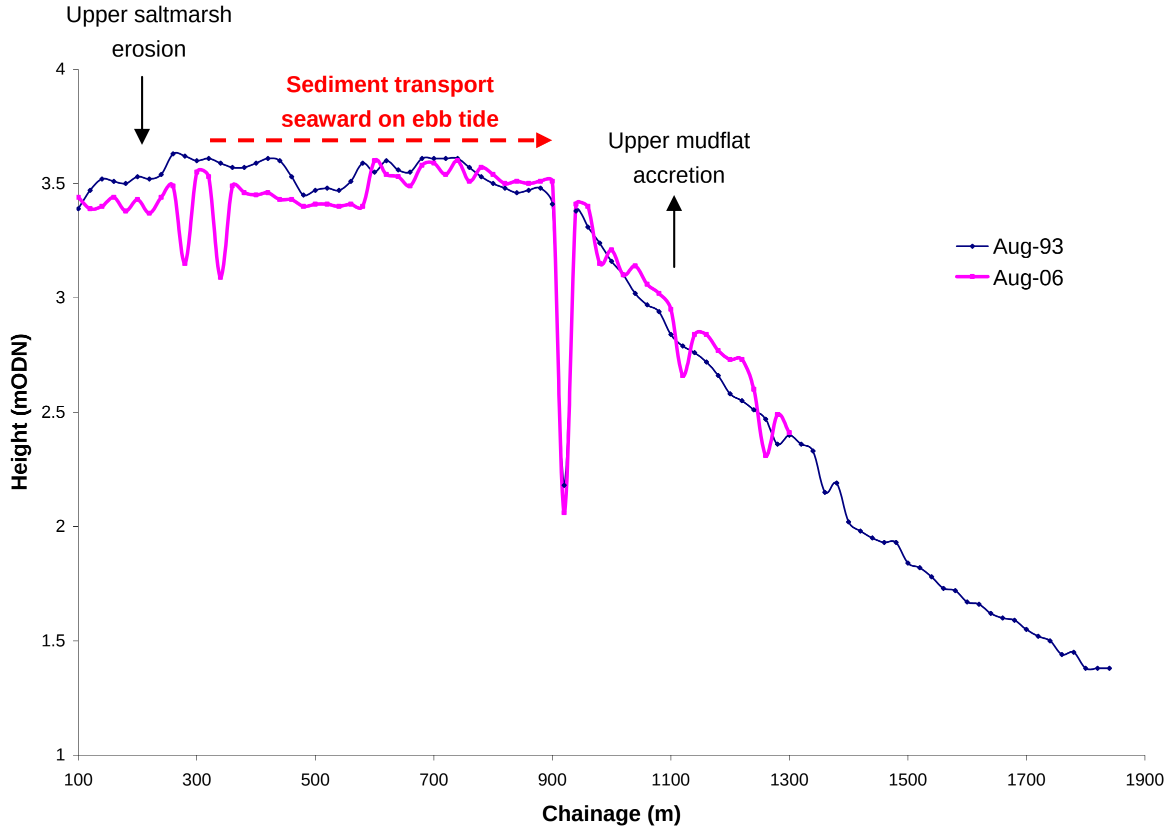
The mechanisms of saltmarsh growth for this frontage are not as straightforward as for frontages A and B as the saltmarsh is more developed and the saltmarsh/mudflat profile is not as steep as A and B. The rates discussed above also mask erosion or accretion trends across the individual sections of the profile, for example erosion along the upper saltmarsh and accretion at the upper mudflat. Therefore it is useful in this situation to identify these mechanisms before assuming that past intertidal development will continue.

Figure F3.4.3 shows the actual measured profile for L4C2 using Environment Agency monitoring data from August 1993 and August 2006 (EA SMG 2007).

The key stages of intertidal development are as follows:

- On the ebb tide water drains across the upper saltmarsh, effectively pulling sediment across the saltmarsh in a seaward direction. This causes erosion of the saltmarsh surface.
- Sediment eroded from the upper saltmarsh is moved to the lower saltmarsh/upper mudflat, causing accretion of the lower saltmarsh in the vicinity of the saltmarsh/mudflat boundary.
- At a critical point in this upward growth the upper mudflat becomes exposed for long enough each day to allow species (tolerant to submergence and salinity) to colonize. The first species to colonise are usually benthic microalgae, especially epipelic diatoms.
- This then raises the elevation further, eventually enabling colonization by saltmarsh species such as *Salicornia* (grasswort). At this point the upper mudflat has made the transition to lower saltmarsh.
- This process produces a seaward movement of the saltmarsh/mudflat boundary and causes the total area of saltmarsh to increase.

Figure F3.4.3 Actual Profile L4C2 Development 1993-2006



As a result of the analysis of intertidal development it is apparent that the rates stated at the beginning of this section (section 4.9), as identified from EA monitoring profiles, cannot be applied directly to predictions of future evolution. In summary, recent intertidal development can be summarised by assuming zero vertical accretion/erosion across the saltmarsh and mudflat, and then to simply apply the rate of horizontal movement of the saltmarsh/mudflat boundary to reflect overall saltmarsh accretion. Table F3.4.4 summarises these assumptions.

Table F3.4.4 Summary of Assumptions for Recent Intertidal Development for frontage C

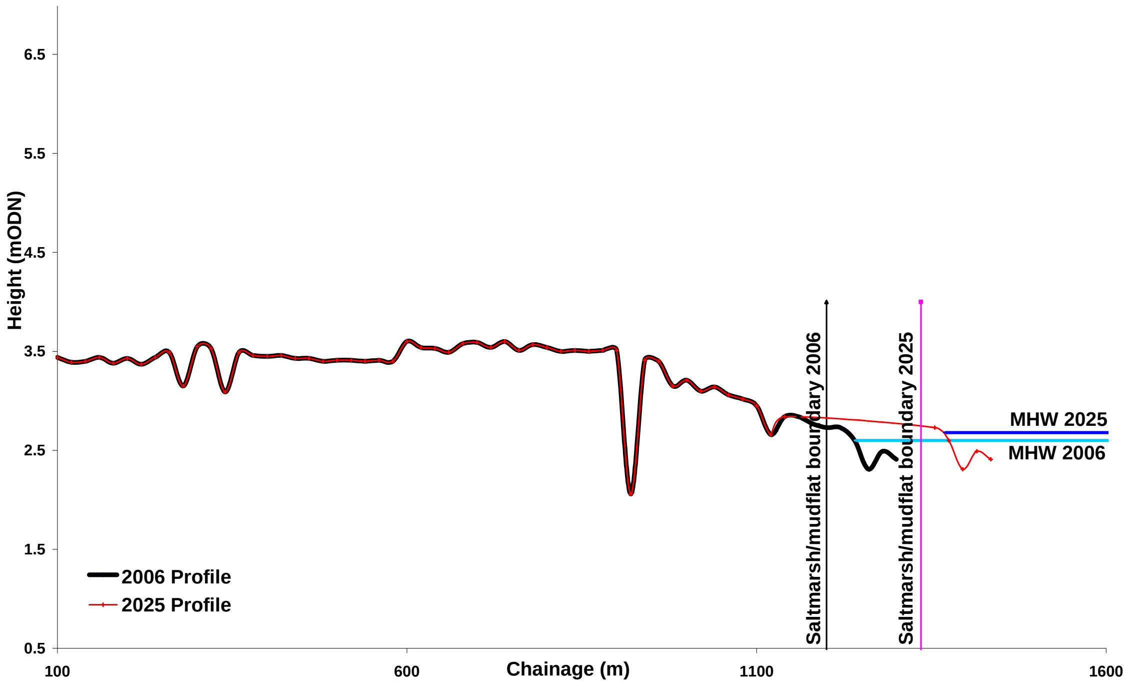
LOCATION ALONG PROFILE	RATE (myr^{-1})
Saltmarsh (vertical)	0.0
Mudflat (vertical)	0.0
Saltmarsh/mudflat profile (horizontal)	7.1

F3.4.10 Impacts: With Present Management

Epoch 1 (present day to 2025)
Defra (2006) predicts that sea level rise between 2006 and 2025 will be around 4.0 $mmyr^{-1}$ therefore MHW in 2025 will be approximately **2.68 mODN**.

Over this epoch, coastal response will be much the same as seen since 1990. Saltmarsh will continue to advance in a seaward direction at a rate of 7.1 myr^{-1}, leading to a general increase in saltmarsh area. Figure F3.4.4 represents typical profile change in epoch 1. This is a generalised profile and it is likely that there will be localised erosion of the upper saltmarsh and localised accretion of the upper mudflat to reflect the process of intertidal development discussed in section 4.9. The newly formed saltmarsh is also likely to rise in elevation over the epoch as opposed to remaining at a constant level as illustrated by figure F3.4.4 This figure is important as it suggests that coastal squeeze is not occurring to the same extent as on frontages A and B. This is mainly due to the fact that along frontage C (and D) there has not been the degree of reclamation as along frontages A and B, where land claim has encroached relatively further onto the former mudflat. Therefore the saltmarsh/mudflat system in frontage C appears to exist under a more natural state.

Figure F3.4.4 Typical Profile Change in epoch 1



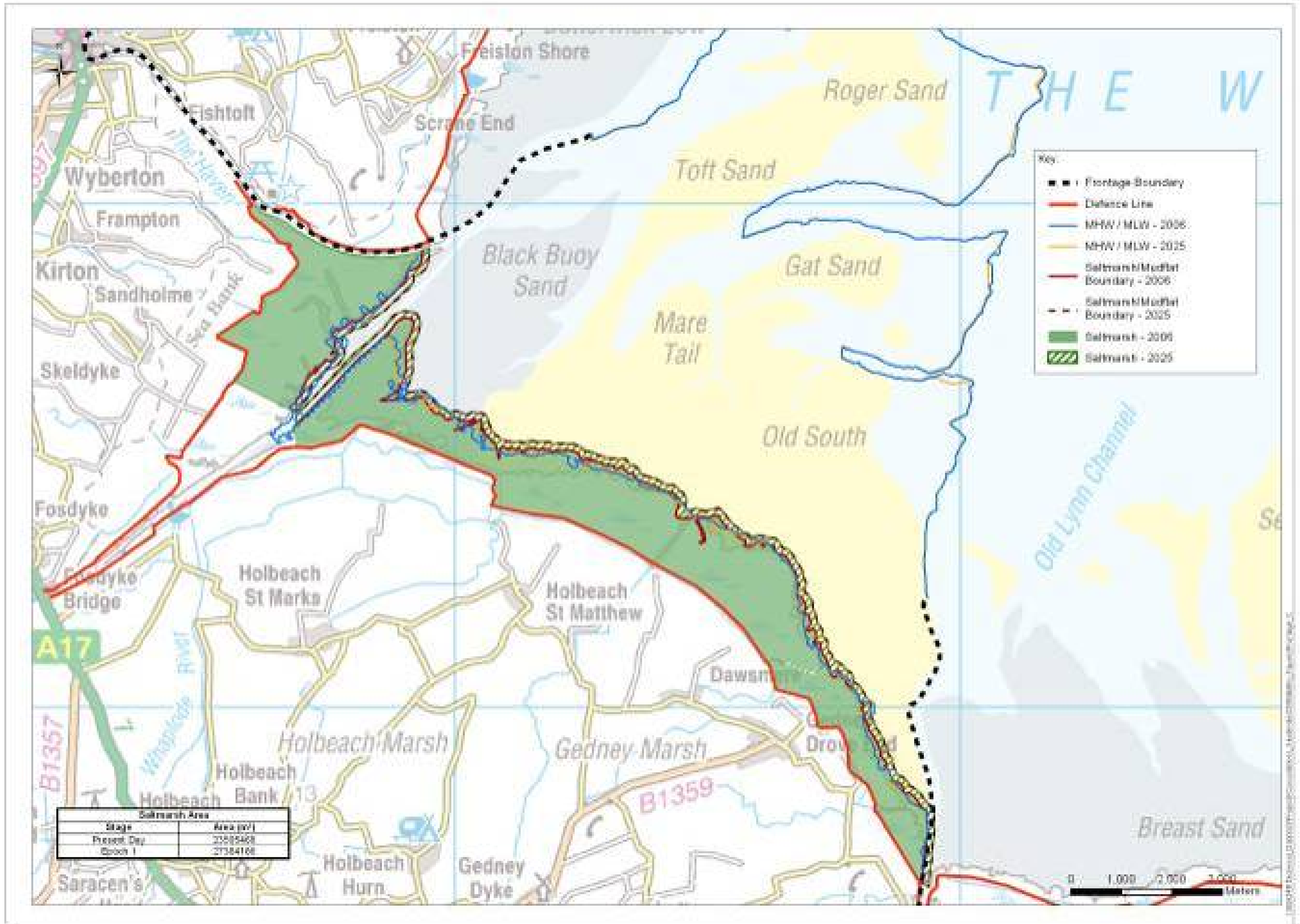
This is the typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross marsh drainage channels, or in the vicinity of the two river outfalls (Welland and Nene).

It terms of the backshore, it is likely to continue to grow, with accretion at the seaward edge of the established saltmarsh and movement seaward of the saltmarsh/mudflat boundary.

The predicted continued accretion in this frontage will promote continued accretion in frontage D, as sediment is likely to be exchanged across the entire frontage between the River Welland and Snettisham Scalp (frontages C and D).

The predicted shoreline evolution for epoch 1 under a scenario of WPM is shown in figure F3.4.5.

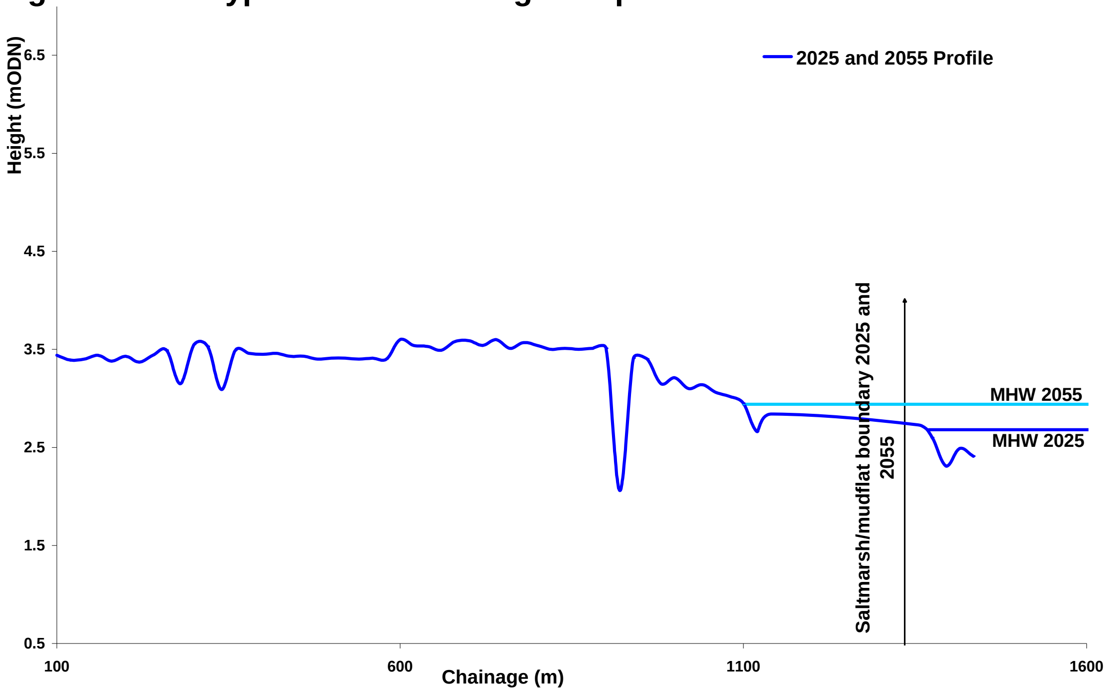
Figure F3.4.5 Frontage C Predicted Shoreline Evolution epoch 1 WPM



Epoch 2 (2025 to 2055)
Defra (2006) predicts that sea level rise between 2025 and 2055 will be around 8.5 $mmyr^{-1}$ therefore MHW in 2055 will be approximately **2.68 mODN.**

Over this epoch there will be some changes in coastal response as a result of sea level rise. Across both the saltmarsh and mudflat there will continue to be zero vertical accretion/erosion. Due to the rise in sea level, and therefore the new position of MHW across the profile, the saltmarsh is unlikely to be able to advance any significant distance in a seaward direction. Figure F3.4.6 shows a typical profile along this frontage in epoch 2. This figure clearly demonstrates that coastal squeeze is likely to occur as the low water mark moves up the profile towards the earth embankments.

Figure F3.4.6 Typical Profile Change in epoch 2



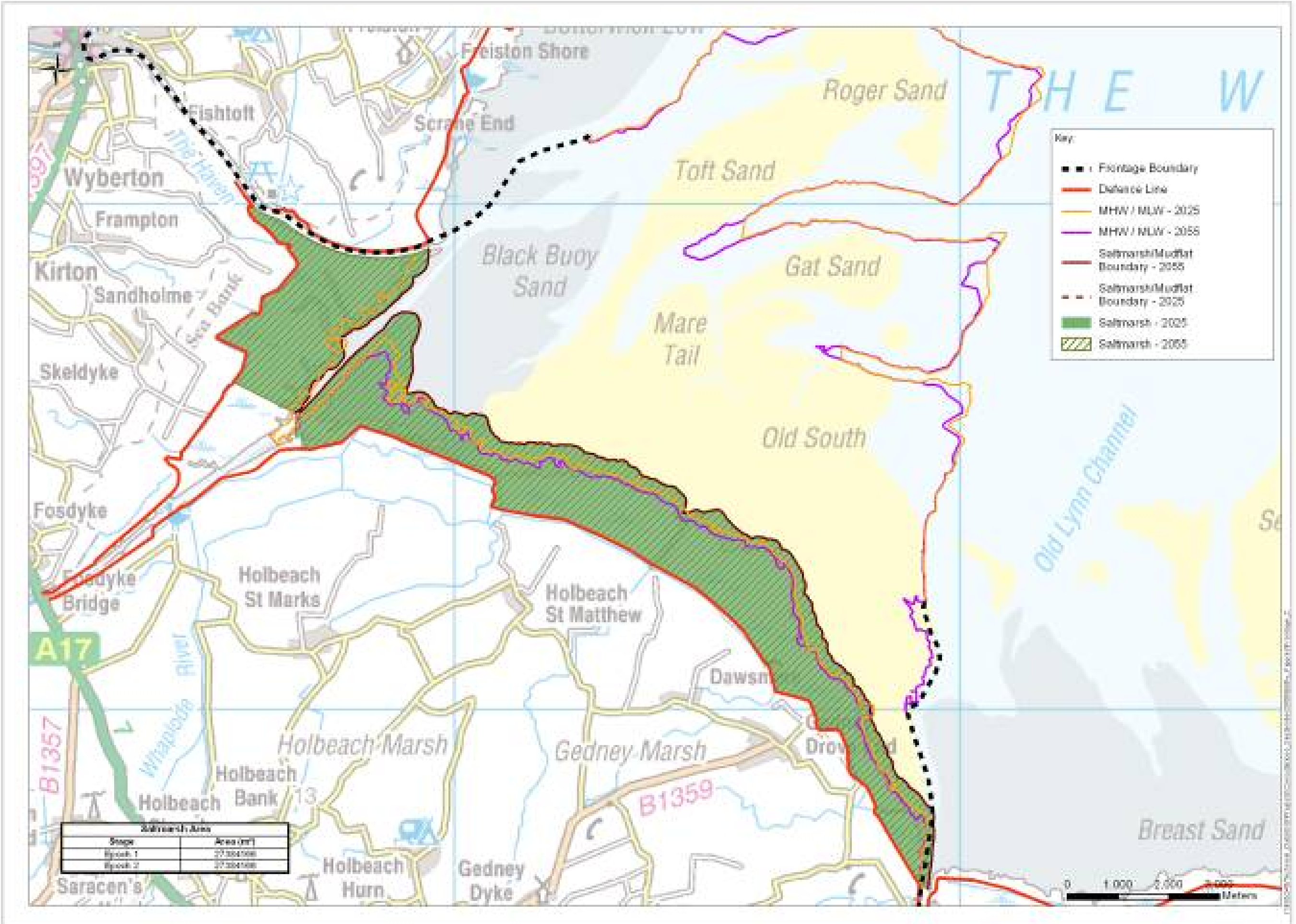
Again this is the typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross marsh drainage channels or in the vicinity of the two river outfalls (Welland and Nene).

The area of the backshore is likely to remain the same and there will be increased pressure upon it due to the movement of the mean high water mark landward up the profile.

The processes occurring along this frontage are likely to be mirrored in frontage D.

The predicted shoreline evolution for epoch 2 under a scenario of WPM is shown in figure F3.4.7.

Figure F3.4.7 Frontage C Predicted Shoreline Evolution epoch 2 WPM



Epoch 3 (2055 to 2105)
Defra (2006) predicts that sea level rise between 2055 and 2085 will be around 12.0 $mmyr^{-1}$ and 15.0 $mmyr^{-1}$ between 2085 and 2105. As a result MHW in 2105 will be approximately **3.60 mODN**.

Over this epoch the growth and stability of the saltmarsh noted in previous epochs is likely to cease, as the position of MHW completely inundates the profile. However there is not likely to be a significant amount of erosion across the saltmarsh, as sediment will be deposited during the flood tide and eroded during the ebb tide. Instead there is likely to be erosion of the saltmarsh horizontally at the saltmarsh/mudflat boundary, reducing the total area of saltmarsh present. Figure F3.4.8 illustrates the typical profile change assuming no vertical erosion across the saltmarsh and mudflat, but assuming an erosion rate of 7.1 myr^{-1} at the saltmarsh/mudflat boundary.

Figure F3.4.8 Typical Profile Change in epoch 3

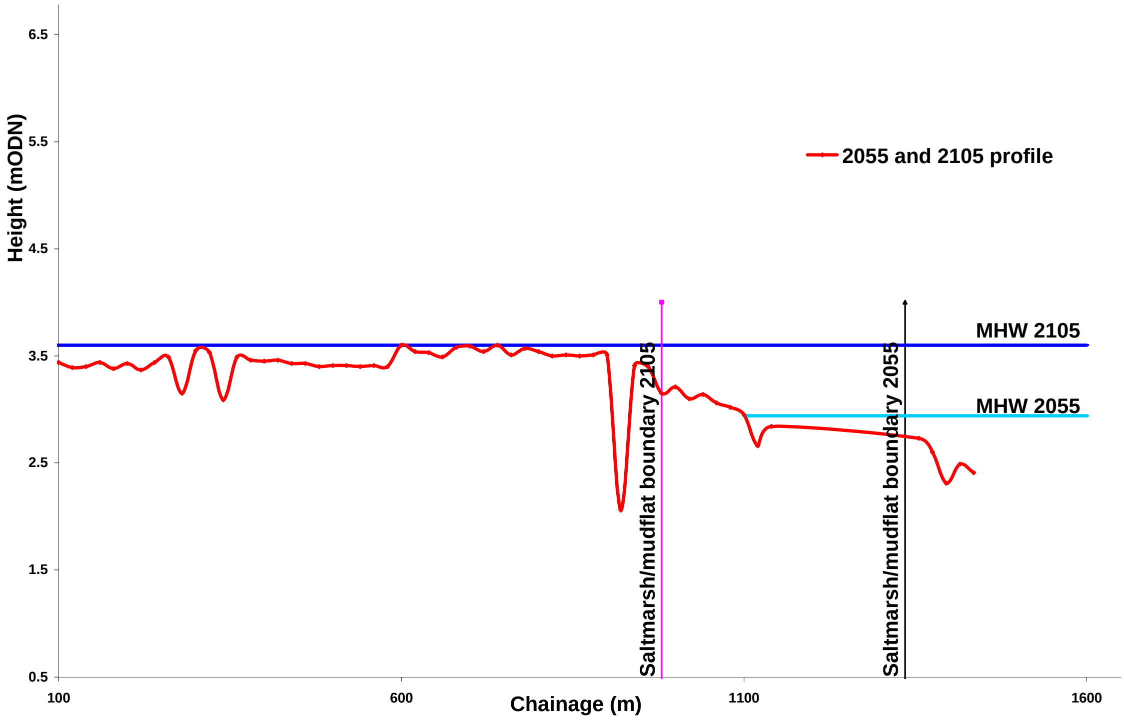


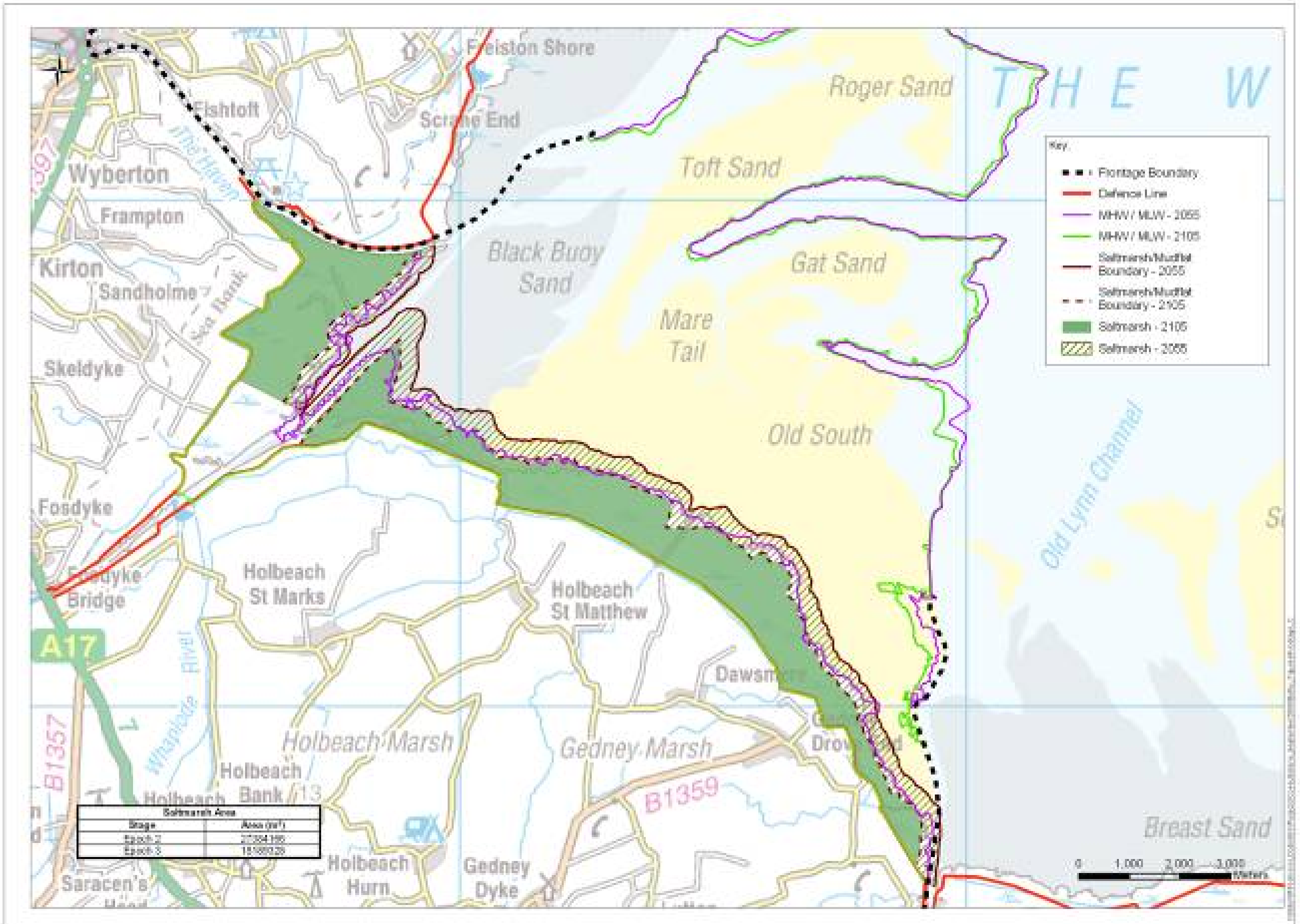
Figure F3.4.8 clearly shows that although after 2055 (beginning of epoch 3) there will be a change in a trend of accretion, to a trend of erosion, the total area of saltmarsh is still significantly large, with the total saltmarsh width extending to greater than 800 m. This is in comparison to a width of between approximately 150 and 250 m predicted across frontages A and B by the end of epoch 3. As a result there will be relatively less pressure on the defences, and therefore less likelihood of overtopping and flooding of the low-lying land.

The onset of erosion in this frontage will act to aid erosion in frontage D, although there is the potential for this to be mitigated by increased erosion in frontages A and B which could provide an increased supply of sediment to frontages C and D.

It is important to note that the profile illustrated in figure F3.4.8 is based upon the assumed profile for the end of epoch 2. In reality it is likely that the profile itself will take on a more natural slope, but the boundary between the saltmarsh and mudflat is likely to steepen and become more pronounced as a result of erosion at its seaward edge. Due to the small depth of water across the saltmarsh itself, there may also be the onset of vertical accretion across the saltmarsh, potentially causing a steepening of the saltmarsh/mudflat boundary.

The predicted shoreline evolution for epoch 3 under a scenario of WPM is shown in figure F3.4.9.

Figure F3.4.9 Frontage C Predicted Shoreline Evolution epoch 3 WPM



F3.4.11 Impacts: No active intervention

Epoch 1 (present day to 2025)

Defra (2006) predicts that sea level rise between 2006 and 2025 will be around 4.0 $mmyr^{-1}$ therefore MHW in 2025 will be approximately **2.68 mODN**.

Coastal response will be much the same as seen in the WPM scenario up to the end of epoch 1 as all of the defences along this frontage are not expected to fail until the end of epoch 1 or beginning of epoch 2.

As a result figure F3.4.4 is applicable, illustrating continued saltmarsh horizontal growth in a seaward direction at a rate of 7.1 myr^{-1}. The text in section 4.10.1 discusses the development of the intertidal zone during epoch 1 (WPM) in more detail, and the same can be applied to epoch 1 for a scenario of NAI.

Figure F3.4.10 illustrates the position of the mean high and mean low water marks for epoch 1 under a scenario of NAI.

Epoch 2 (2025 to 2055)

Defra (2006) predicts that sea level rise between 2025 and 2055 will be around 8.5 $mmyr^{-1}$ therefore MHW in 2055 will be approximately **2.94 mODN**.

Around the beginning of this epoch, under NAI, it is assumed that the defences along this frontage will have deteriorated to a condition of 5 (failure imminent) and therefore it can be assumed that the defences will have totally failed. However in this scenario the assumed 2055 MHW position will not extend a significant distance landward along the profile and will certainly not reach the former defence line. As a result there will still be a significant width of saltmarsh (between 300 and 1500m) that will act as a buffer zone on high tides. As a result there is only likely to be flooding of the backshore areas on the highest tides of the year, or during high tides combined with adverse weather conditions (storm surge and strong winds).

The position of mean high and mean low water marks at the end of this epoch (2055) is shown in figure F3.4.10.

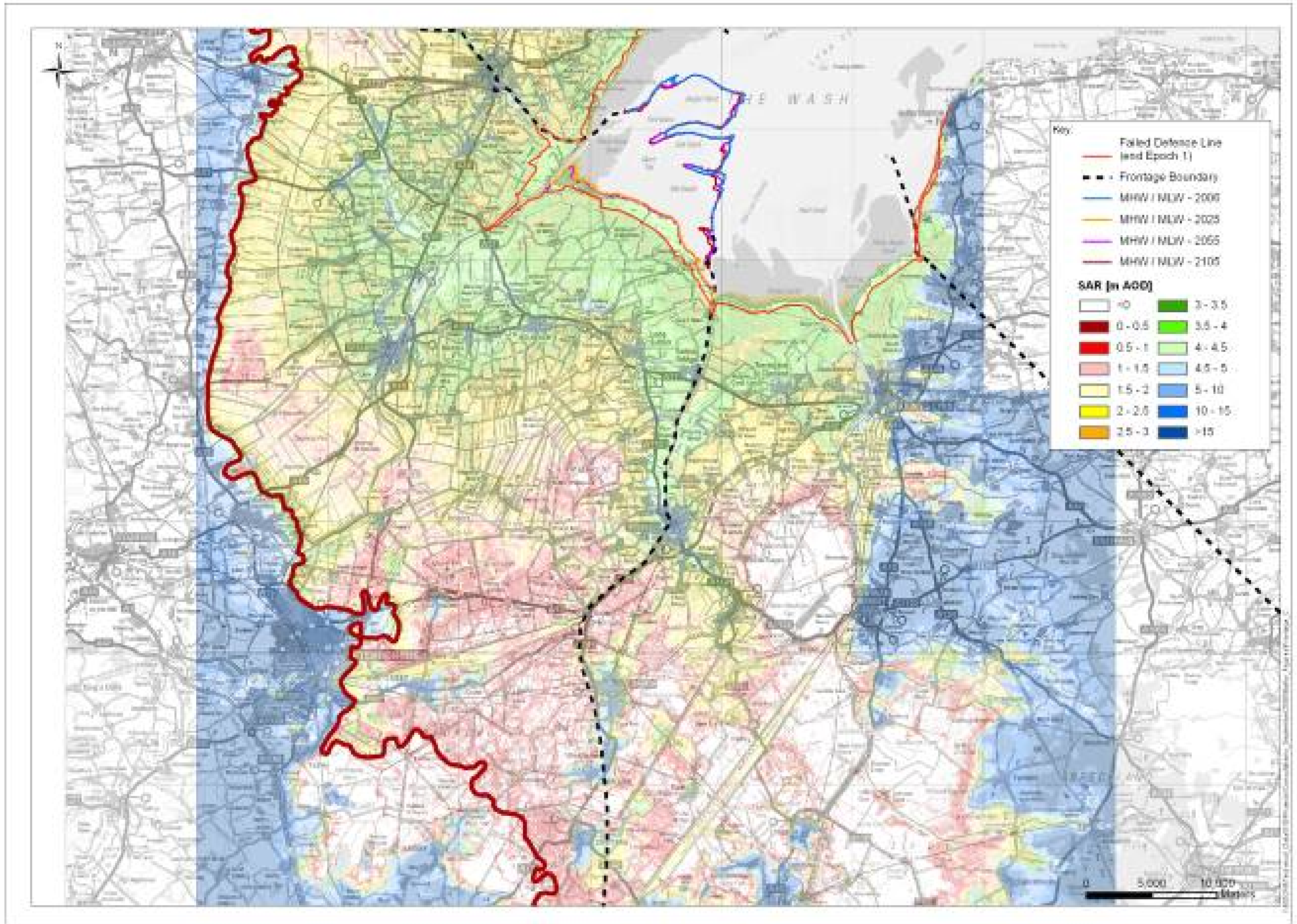
Epoch 3 (2055 to 2105)

Defra (2006) predict that sea level rise between 2055 and 2085 will be around 12.0 $mmyr^{-1}$ and 15.0 $mmyr^{-1}$ between 2055 and 2085. As a result MHW in 2105 will be approximately **3.60 mODN**.

During this epoch the position of MHW will move landward up the profile but by the end of epoch 2 it is not expected to reach the failed defence line. As a result there will only be inundation of the backshore area on higher than average tides. However by the end of epoch 3, the MHW mark will have moved a significant distance inland, causing saltmarsh to become established in the backshore areas.

The position of mean high and mean low water marks at the end of this epoch (2105) is shown in figure F3.4.10.

Figure F3.4.11 Frontage C Predicted Shoreline Evolution All epochs NAI



F3.5 Frontage D – Terrington, Wootton and Wolferton

F3.5.1 Introduction

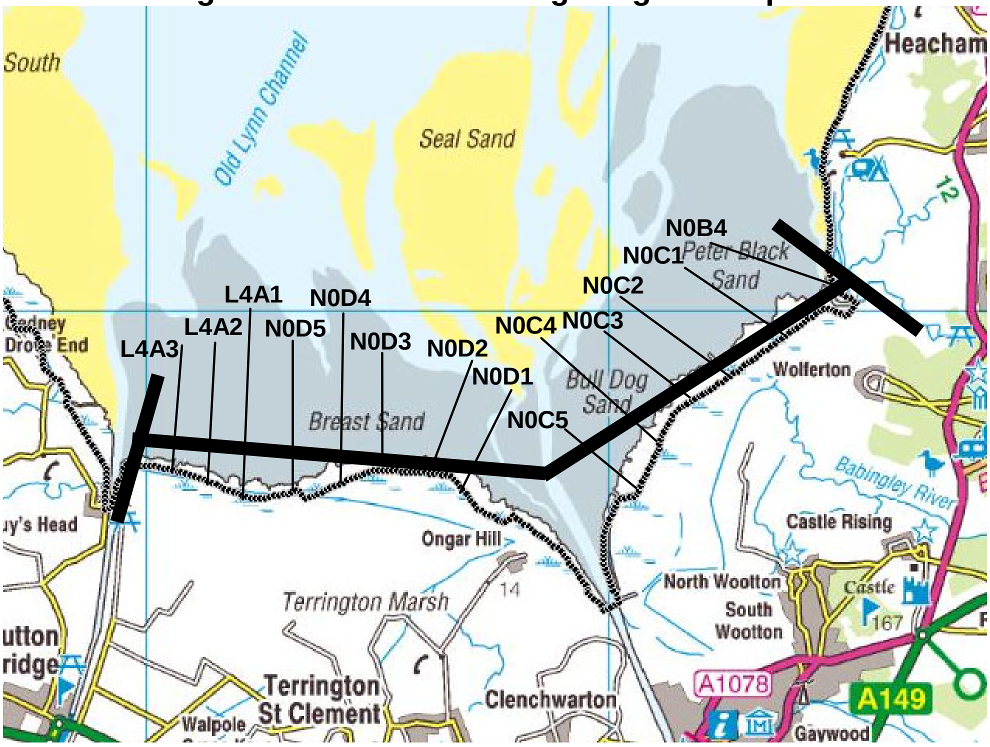
This frontage contains the large town of King's Lynn and smaller town of Terrington St Clement, as well as a number of smaller villages such as Castle Rising, North and South Wootton, Clenchwarton and Walpole Cross Keys.

The frontage is characterised by extensive backshore coastal lowland of reclaimed intertidal flats that is now protected from large-scale flooding by a series of grassed earth embankments. Wide intertidal flats extend up to 4 kilometres seaward from the shoreline and areas of salt marsh exist in the upper intertidal zone.

The frontage is bounded by the River Nene at its western limit and the outfall of Wolferton Creek at its eastern limit. The River Great Ouse also outfalls towards the middle of the frontage. This outfall produces a complex pattern of sedimentation at the mouth of the river and this dictates the shape of Seal Sand. Seal Sand is known as a bird's foot delta and is characterised by a series of ever-changing channels, determined by the outfall of the River Great Ouse.

Figure F3.5.1 outlines the location of this frontage and also shows the location of the profile used by the Anglian Coastal Monitoring Programme profiles.

Figure F3.5.1 Anglian Coastal Monitoring Programme profiles



F3.5.2 Key Geomorphological Components

The key geomorphological components that are contained within this frontage and that affect the morphological development of the frontage are listed below:

- Seal Sand, the sand bank that forms the bird's foot delta of the River Great Ouse, is generally exposed at low water. It has a significant effect on wave energy reaching the marginal tidal flats. It will therefore act to shelter the coastline from wave attack.
- This sand bank also has an effect on the erosion and accretion of materials along the frontage. By providing shelter to a significant length of intertidal area it means that if it were to accrete and therefore increased in size, it would increase the shelter along the frontage and promote increased accretion. If the bank was subject to erosion and therefore decreased in size, there would be decreased shelter along the frontage and erosion is likely to occur. The exact orientation and shape of the sand bank will also cause localised areas of accretion and erosion in the same way.
- The deep water channel, known as the Lynn Deeps, situated in the middle of the Wash embayment, will control the position of the low water mark along this frontage.
- The wide intertidal flats effectively dissipate the incoming wave and tidal energy, and therefore limit the amount that reaches the upper profile. As a result a wider intertidal area, such as noted in this frontage, will

decrease erosion or the probability of flooding caused by the incoming wave energy.

- The trained outfalls of the Rivers Nene and Great Ouse form a series of deltaic deposits and transient flow channels. Sedimentation around the outfall of the River Great Ouse forms a bird's foot delta.

Table F3.5.1 summarises each feature in terms of the control it exerts on the Wash system as a whole, its influences and interactions in terms of the other components of the system, and its status with respect to the geomorphological system.

Table F3.5.1 Key Geomorphological Components Summary

FEATURE	MAJOR CONTROLS	INFLUENCES	STATUS
Offshore bank (Seal Sand)	Is a store of sediment transported out of the River Great Ouse as well as from the intertidal area Provides some degree of shelter from wave attack and therefore influences the position of low water on the foreshore Influences tidal circulation	Its height and width are determined by large-scale tidal circulation patterns and the extent of sediment supply	Secondary, transient control
Wide intertidal area	Is effective in dissipating wave and tidal energy before it reaches the backshore area and defence line Is a store of sediment transported in suspension	Its width is determined by the position of the low water mark, which is mainly controlled by Lynn Deeps and the strength of incoming wave energy	Primary, transient control
Trained outfall of Rivers Nene and Great Ouse	Link up with the Lynn Deeps to provide an uninterrupted flow of water along the middle and eastern sides of the Wash Provide some degree of limitation to the westward growth of Breast Sand and eastern extent of Peter Black Sand	Its existence is controlled by the continued flow of water out of the Rivers Nene and Great Ouse The strength and direction of the outfall is primarily controlled by the existence of the training walls	Secondary, persistent control under WPM

FEATURE	MAJOR CONTROLS	INFLUENCES	STATUS
Lynn Deeps	Is a route for the flow of tidal energy within the Wash Its position determines the position of the low water mark on the foreshore and therefore the width of the intertidal area.	It interacts with the outfall of the Rivers Witham and Welland and provides a pre-defined flow path during the ebb tide Its depth and width are determined by the strength of the tidal currents	Primary, persistent control under WPM

F3.5.3 Patterns of Change

Historic Change

In the 19th century, the extension of the River Nene outfall altered tidal and current patterns such that the rate of horizontal extension of the Wingland saltmarsh (to the west of the frontage) was as high as 50myr^{-1} (Kestner 1962).

In general, between 1828 and 1995, there was a general pattern of seaward movement of the low water mark. Towards the end of this period the pattern became more complicated, with landward movement occurring between the River Nene and Bulldog Sand. Posford Duvivier (1997a) also commented that the apparent seaward movement of the low water mark may be due to the landward migration of sand banks to join the shore.

Towards the seaward edge of the saltmarsh along the entire frontage, vertical accretion rates of greater than 25 mmyr^{-1} have been measured, with lower rates being found on the higher older saltmarshes (Hill 1988).

The University of Newcastle compared rates of saltmarsh change between 1971/4 and 1982/5 between the Nene and the Ouse, as well as between the Ouse and Hunstanton. Results showed a net change of -2.28 km^2 (erosion) between the Nene and the Ouse, but +0.44 km^2 (accretion) between the Ouse and Hunstanton (end of frontage E).

In particular horizontal saltmarsh accretion rates of between 5 and 11 myr^{-1} were recorded at Terrington and Wingland Marshes (to the west of the frontage) where the last land-claims took place in 1955 and 1974 respectively. Coles (1978) then recorded a 100 to 150 m seaward advance (accretion) of the mudflats two years after completion of the 1974 embankment at Wingland Marshes. Between Wolferton and Wootton a 2 to12 myr^{-1} seaward extension (horizontal accretion) of the saltmarsh occurred in front of 1960/67 embankments.

In summary historic change has been characterised by variable trends in advance or retreat, mainly caused by adjustments to changes in the tidal prism and plan form morphology caused by reclamation, flood defence practices and the construction of river outfall training walls.

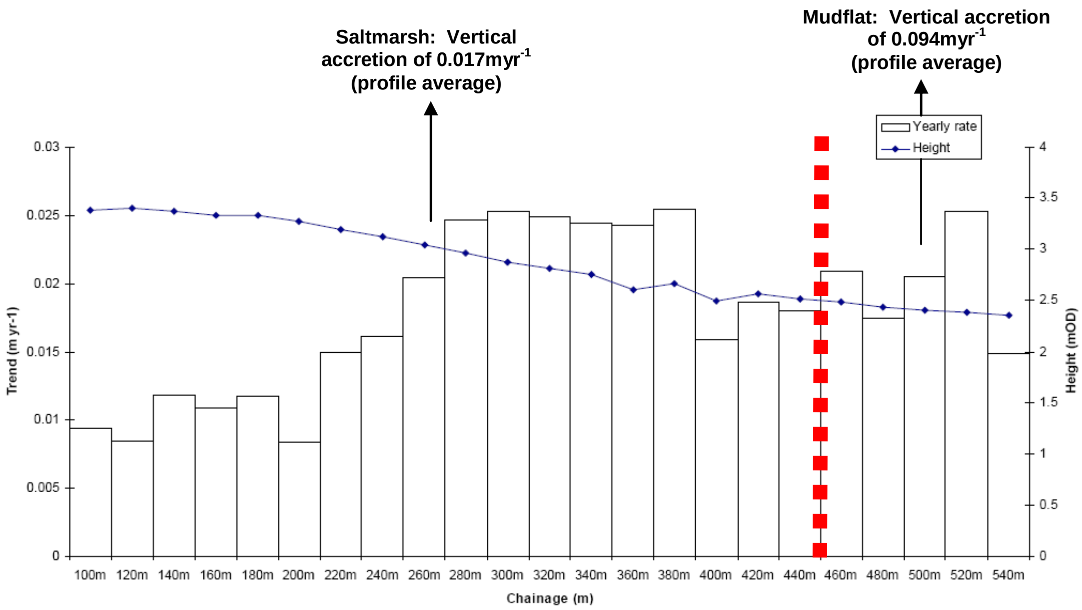
Recent (1991 – 2006) change

Pethick (2002) calculated saltmarsh vertical accretion rates of 20 $mmyr^{-1}$ at Breast Sand and observed a general seaward advance of the saltmarsh/mudflat boundary at a rate of 3 myr^{-1} between 1994 and 2000. Pethick also noted a seaward advance of the boundary of 16 myr^{-1} to the eastern end (ie. adjacent to the River Great Ouse outfall) and a landward retreat of between 1 and 2 myr^{-1} to the western end (ie. adjacent to the River Nene outfall). This reflects the abilities of the river outfalls to either promote increased erosion or accretion as the river channel changes course.

Environment Agency monitoring has shown that, throughout the entire frontage between 1991 and 2006, in terms of horizontal change, the saltmarsh/mudflat boundary has accreted (moved seaward) by an average of 133 m. This horizontal change is also reflected in the fact that the total saltmarsh increased by 445 hectares between 1992 and 2006. Vertical accretion across both the saltmarsh (upper and lower) and the mudflat (upper as no data was available for lower) was also apparent at all profiles along this frontage between 1994 and 2006. Vertical accretion rates were higher on the lower saltmarsh than the upper saltmarsh due to new saltmarsh formation taking place at the saltmarsh/mudflat boundary. An average vertical accretion rate was calculated from all the average rates for each profile along this frontage. On the saltmarsh rates were calculated at 0.017 myr^{-1} and averages on the mudflat were 0.063 myr^{-1}.

A typical profile (N0D3) is shown in figure F3.5.2 taken from the Anglian Coastal Monitoring Programme Coastal Trends Analysis (EA SMG 2007). The saltmarsh/mudflat boundary at this profile lies at approximately chainage 450 m and the figure clearly shows the strong trend of accretion throughout the majority of the profile. The saltmarsh/mudflat boundary has moved approximately 150 m in a seaward direction between 1994 and 2006. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

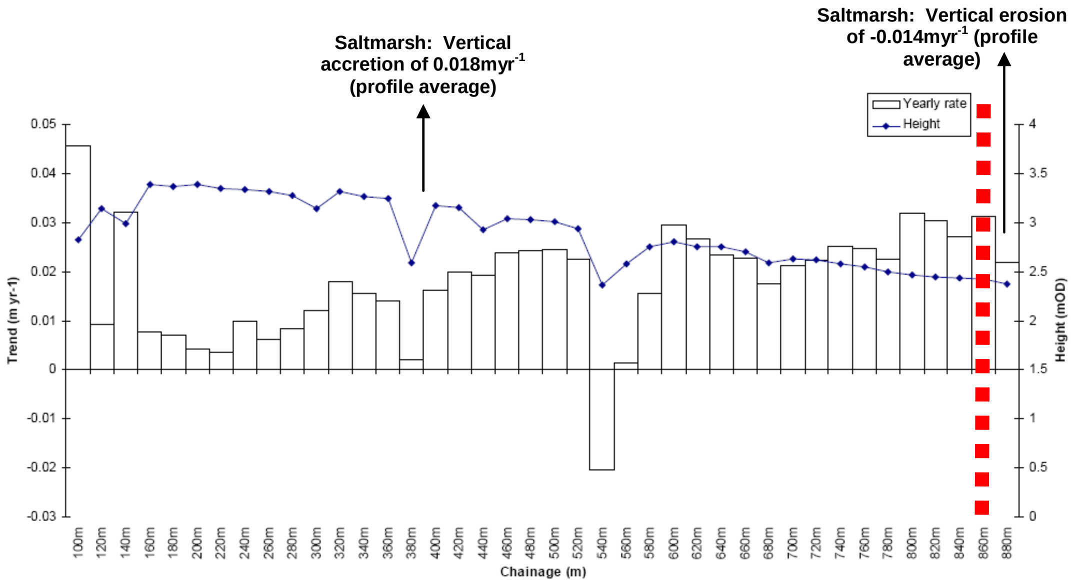
Figure F3.5.2 Typical frontage D Saltmarsh and Mudflat (upper) Development: Profile N0D3



There is only one profile along this frontage that exhibits different trends to those described above. Profile L4A1 has exhibited a trend of vertical accretion across the whole profile, but erosion (landward movement) of the saltmarsh/mudflat boundary. This profile is shown in figure F3.5.3, again taken from the Anglian Coastal Monitoring Programme Coastal Trends Analysis (EA SMG 2007). The saltmarsh/mudflat boundary along this profile lies at approximately chainage 860 m. The saltmarsh and mudflat vertical accretion rates shown are for this profile only.

However, according to the Coastal Trends Analysis Report (EA SMG 2007) this profile crosses a network of drainage channels which may explain the localised vertical erosion around the saltmarsh/mudflat boundary. This is the only profile along the entire length of frontage D that exhibits a trend of horizontal erosion, and as a result this horizontal erosion is believed to be a localised trend only.

Figure F3.5.3 L4A1 Saltmarsh and Mudflat Development



F3.5.4 Tidal Currents

Tidal currents can be relatively strong in the Wash, especially in the main channels during spring tides, due to its large tidal range. Average current velocities are between 0.8 and 1.0 ms^{-1} (HR Wallingford 1972).

Expected tidal currents in the Old Lynn Channel (to the west of the frontage) shown in table F3.5.2 (from Admiralty chart):

Table F3.5.2 Expected Tidal Currents in the Old Lynn Channel

Time period	Tidal current speed (ms^{-1})
Peak flood, spring tide	1.20
Peak ebb, spring tide	1.02
Peak flood, neap tide	0.56
Peak ebb, neap tide	0.51

F3.5.5 Current Residuals

Net water transport throughout the water column off the coast of this frontage is reasonably complex. The overall movement is directly to the south south-west onto the frontage.

F3.5.6 Sediment

The main sources of sediment found on this frontage are as follows:

- The Holderness coast (situated to the north).
- The Humber estuary (situated to the north).
- The North Norfolk coast to the east.
- The North Sea as a whole.
- The sea floor within the mouth of the Wash.
- Rivers Nene and Great Ouse.

The main sinks of sediment on this frontage are:

- Seal Sand (offshore bank).
- Intertidal area.

In terms of sediment transport, over the mudflats sediment is mostly transported in suspension. Sediment is deposited when the velocity of the tide is low (< 0.12 cms^{-1}). Sand and gravel may be deposited under higher flows and exist where there is greater disturbance due to wave action.

The primary sediment transport mechanism along this frontage will be suspended sediment transport due to the dominance of sands and silts in the water column. This is in contrast to the eastern shore of the Wash where both bedload and suspended sediment transport occur due to the existence of larger sediment sizes.

F3.5.7 Processes

Tides

Tidal levels (from Admiralty Tide Tables) at the Port of Sutton Bridge and King's Lynn are shown in table F3.5.3:

Table F3.5.3 Tidal Levels at Port of Sutton Bridge and King's Lynn (mODN)

Location	MHWS	MHWN	MLWN	MLWS
King's Lynn	3.77	1.97	-1.23	-2.03
	Tidal range (springs): 5.80m			
	Tidal range (neaps): 3.20m			
Port of Sutton Bridge	3.80	2.00	-1.20	-2.00
	Tidal range (springs): 5.80m			
	Tidal range (neaps): 3.20m			

The values for King's Lynn will be used in the later analysis as this should give a more accurate prediction of tide levels across the whole frontage. As a result the mean high water (MHW) has been calculated at **2.86 mODN** and mean low water (MLW at **-1.63 mODN**). The mean tidal range is therefore 4.50 m.

Extreme Water Levels
Table F3.5.4 shows the EWL analysis for the River Nene at West Lighthouse (Mott MacDonald 2006), situated to the western extent of the frontage, at King's Lynn (Mott MacDonald 2006), situated to the middle of the frontage, and at the mouth of the River Great Ouse (Royal Haskoning 2007), also situated to the middle of the frontage, all in mODN.

Table F3.5.4 EWLs for River Nene and River Great Ouse (Mott MacDonald 2006 and Royal Haskoning 2007)

Location	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1,000
River Nene (West Lighthouse)	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35
Mouth of Great Ouse	4.93	5.43	5.63	5.78	5.93	6.08	6.28	6.43
Mouth of River Nene	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35

Waves
Information regarding waves along this frontage is the same as for frontage A and can therefore be found in section 2.7.3.

F3.5.8 Existing Management

The whole of frontage D is defended by grassed earth embankments, maintained by the Environment Agency, which have residual lives of between 10 and 25 years. As a result, under a policy of NAI, the defences are not expected to fail until the latter part of epoch 1 or beginning of epoch 2. There are a number of secondary defences behind the primary defence line, but maintenance of these earlier structures ceased after new front line defences were constructed. As a result they will not be considered for this Task.

Frontage D encompasses the outfalls of two rivers: The Nene and the Great Ouse. The management of the Nene outfall has been discussed within section 4.8 and will therefore not be re-discussed here. The River Great Ouse outfalls into the Wash through the trained channel of the Lynn Cut. This trained channel extends for approximately 3 km into the Wash sandbanks to West Stones Beacon. At this point it is free to discharge into any of the varying outer channels.

F3.5.9 Analysis of Intertidal Development

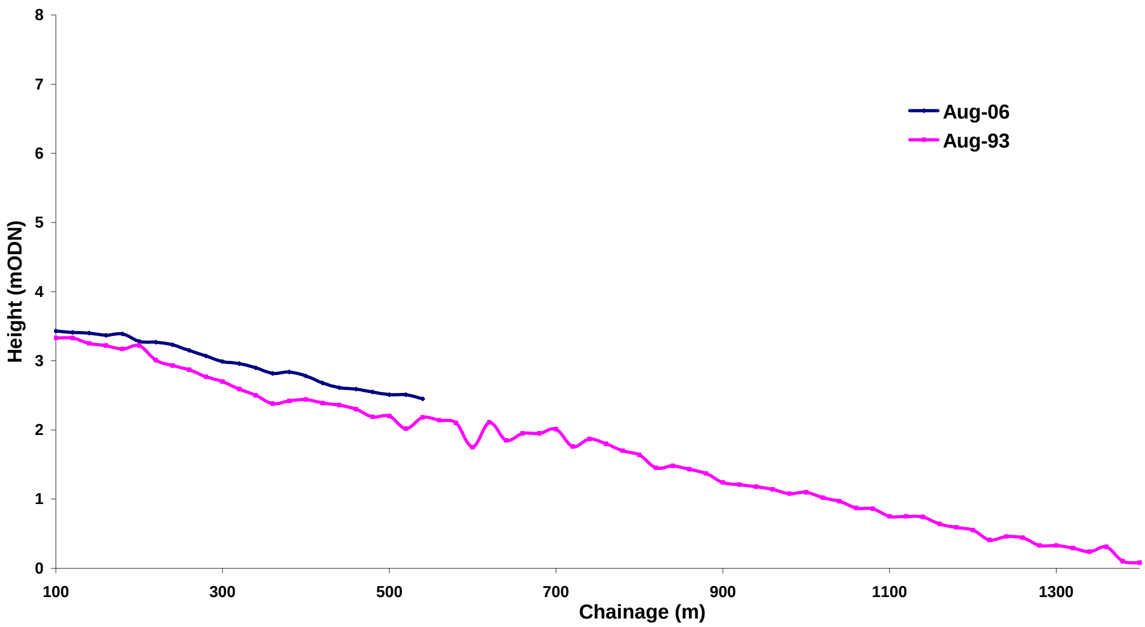
The following summarises the general trend of intertidal and foreshore development, as assumed from information provided through the Coastal Trends Analysis Report (EA SMG 2007):

- Saltmarsh vertical accretion rates = **17 mmyr^{-1}**.
- Mudflat vertical accretion rates = **63 mmyr^{-1}.**
- Horizontal accretion movement of the saltmarsh/mudflat boundary) = **8.9 myr^{-1}**.
- Defra's (2006) sea level rise prediction between 1991 and 2006 (period of monitoring) = approximately **4.0 mmyr^{-1}.**

As with frontage C, the mechanisms of saltmarsh growth for this frontage are not as straightforward as for frontages A and B as the saltmarsh is more developed and the intertidal profile is not as steep. The rates stated above also act to mask higher areas of accretion at the lower saltmarsh and upper mudflat. Therefore it is useful to identify these mechanisms before assuming that past intertidal development will continue.

Figure F3.5.4 shows the actual measured profile for N0D3 using Environment Agency monitoring data from August 1993 and August 2006 (EA SMG 2007). This figure is also useful as it shows the lack of current measured data for the middle and lower mudflats.

Figure F3.5.4 Actual Profile N0D3 Development 1993-2006



The key stages of intertidal development are as follows:

- Saltmarsh and upper mudflat is built up with fresh accumulations of sediment during tidal inundation, either directly by water flowing across the mudflat, or by creeks filling up and then overtopping onto the surrounding saltmarsh.

- This generally occurs at the lower saltmarsh, in the vicinity of the saltmarsh/mudflat boundary, where inundation occurs regularly, but may also occur on the upper saltmarsh on high spring tides.
- At a critical point in this upward growth the upper mudflat becomes exposed for long enough each day to allow species (tolerant to submergence and salinity) to colonize. The first species to colonise are usually benthic microalgae, especially epipelic diatoms.
- This then raises the elevation further, eventually enabling colonization by saltmarsh species such as *Salicornia* (grasswort). At this point the upper mudflat has made the transition to lower saltmarsh.
- This produces the seaward shift of the saltmarsh/mudflat boundary.
- However as sediment accumulation on both the saltmarsh and mudflat outpaced sea level rise significantly there was a movement of the low water mark in a seaward direction.
- Therefore during this period it appears that the intertidal area did not undergo a significant “squeeze” as seen with frontage A and B.

As a result of the analysis of intertidal development it is apparent that the rates stated at the beginning of this section can be applied directly to predictions of future evolution. However it will be necessary to assume lower rates across the upper saltmarsh profile than across the lower saltmarsh profile.

F3.5.10 Impacts: With Present Management

Epoch 1 (present day to 2025)
Defra (2006) predicts that sea level rise between 2006 and 2025 will be around 4.0 $mmyr^{-1}$ therefore in 2025 will be approximately **2.94 mODN**.

Over this epoch, coastal response will be much the same as seen since 1990. Saltmarsh will continue to advance in a seaward direction at a rate of 8.9 myr^{-1}, leading to a general increase in saltmarsh area. The middle and lower saltmarsh is likely to continue accreting by 17 $mmyr^{-1}$. Unfortunately it is not possible to predict the development of the mudflat as there is a lack of data for this section of profile. Figure F3.5.5 represents typical profile change in epoch 1. This figure assumes that there will be zero accretion rates across the upper saltmarsh, although in reality there is still likely to be some limited accretion when the saltmarsh is completely inundated during high spring tides.

Figure F3.5.5 Typical Profile Change in epoch 1

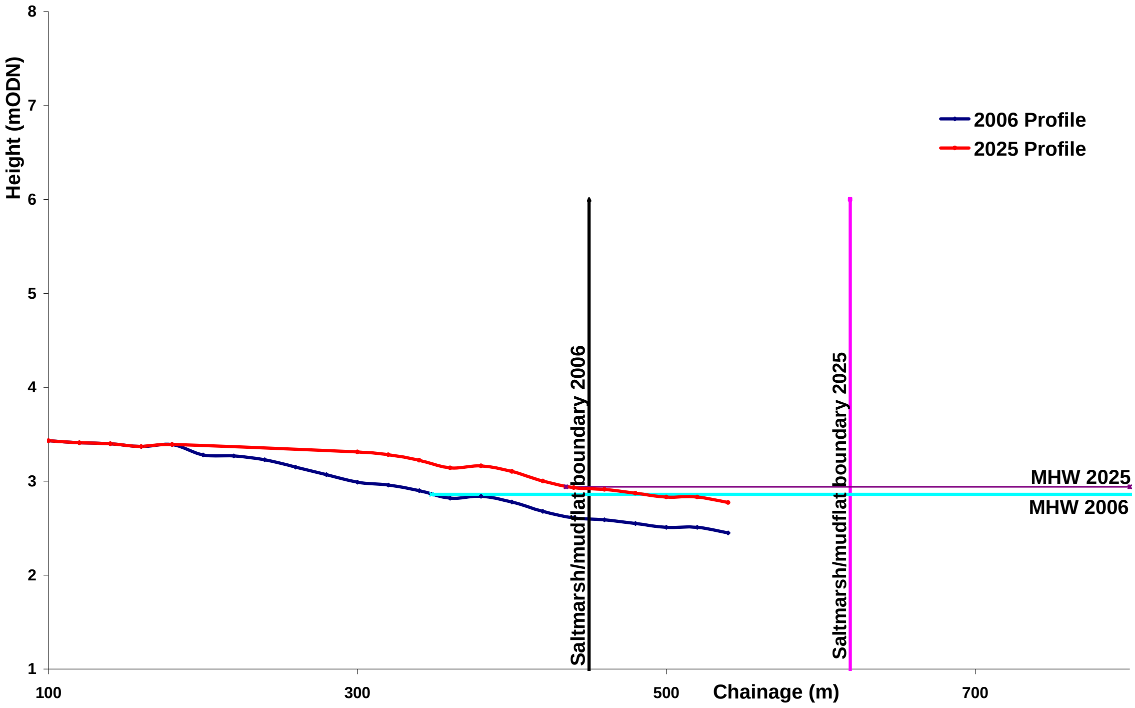


Figure F3.5.5 is also important as it suggests that coastal squeeze is not occurring to the same extent as on frontages A and B. This is mainly due to the fact that along frontage D (and C) there has not been the degree of reclamation as along frontages A and B, where land claim has encroached too far onto the former mudflat. Therefore the saltmarsh/mudflat system exists under a more natural state and follows a more natural profile.

This is a typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross drainage channels, or in the vicinity of the two river outfalls (Nene and Great Ouse).

In terms of backshore, it is likely to continue to grow, with accretion at the seaward edge of the established saltmarsh and movement seaward of the saltmarsh/mudflat boundary.

The predicted continued accretion in this frontage will promote continued accretion in frontage C, as sediment is likely to be exchanged across the entire frontage between the Welland and Snettisham Scalp (frontages C and D).

The predicted shoreline evolution for epoch 1 under a scenario of WPM is shown in figure F3.5.6.

Figure F3.5.6 Frontage D Predicted Shoreline Evolution epoch 1 WPM

epoch 2 (2025 to 2055)

Defra (2006) predicts that sea level rise between 2025 and 2055 will be around 8.5 $mmyr^{-1}$ therefore MHW in 2055 will be approximately **3.20 mODN.**

Over this epoch there will be some changes in coastal response as a result of sea level rise (figure F3.5.7). Due to the position of predicted mean high water by the end of this epoch (2055) it is likely that the saltmarsh/mudflat boundary will remain in the same place as in epoch 1, but there is still likely to be vertical accretion across the saltmarsh due to the fact that it will be subject to infrequent inundation on higher than average tides. Figure F3.5.7 also suggests that sea level rise may not bring about the extent of coastal squeeze as noted along the western side of the Wash (frontages A and B) and to some extent in frontage C.

Again this is a typical situation and it is important to note that there will be localised areas of either horizontal accretion or erosion occurring at profiles which cross marsh drainage channels or in the vicinity of the two river outfalls (Nene and Great Ouse).

The area of the backshore is likely to remain the same and there will be increased pressure upon it due the rise in sea level and the inundation of the saltmarsh during high spring tides, and possibly high tides combined with surge and adverse weather conditions.

The predicted shoreline evolution for epoch 2 under a process of WPM is shown in figure F3.5.8.

Figure F3.5.7 Typical Profile Change in epoch 2

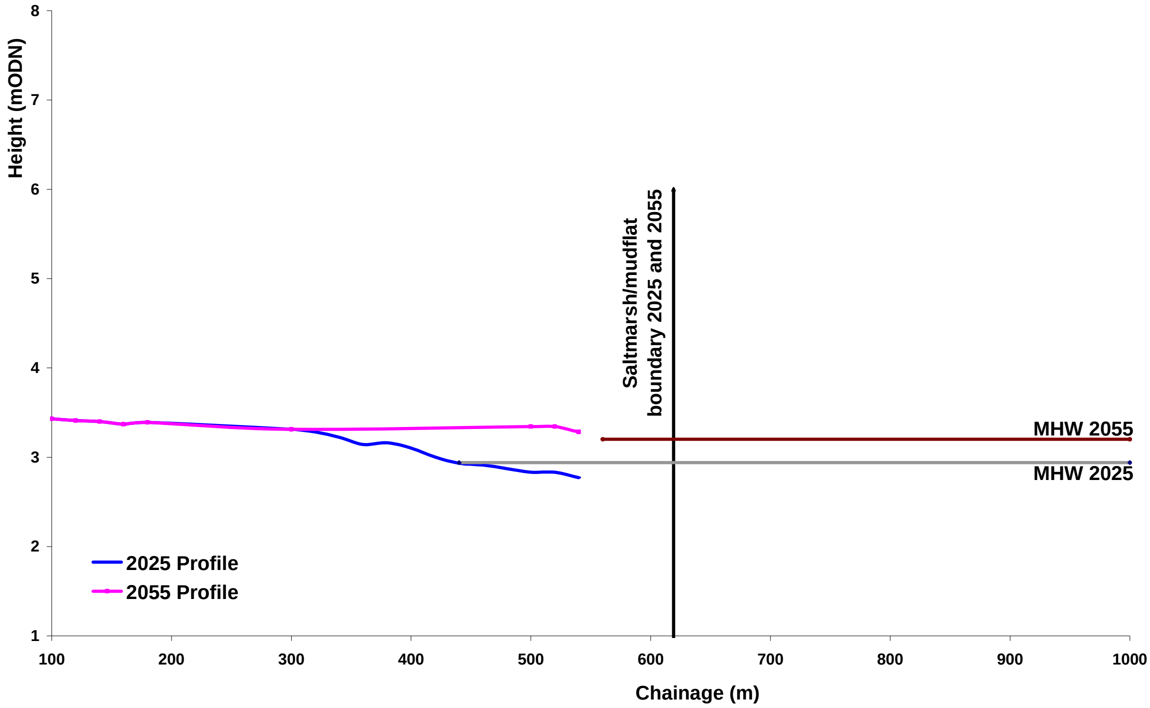
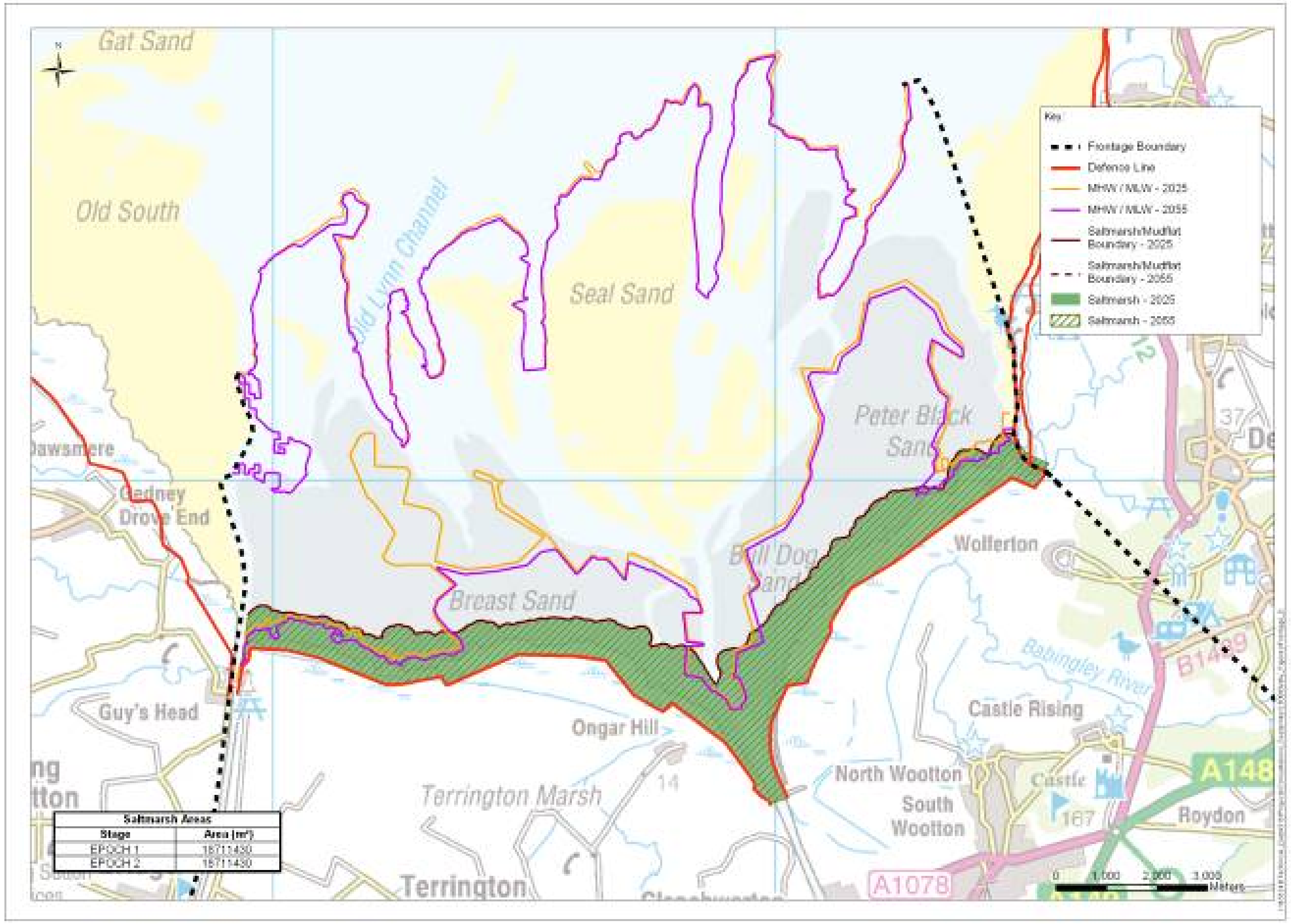


Figure F3.5.8 Frontage D Predicted Shoreline Evolution epoch 2 WPM



Epoch 3 (2055 to 2105)

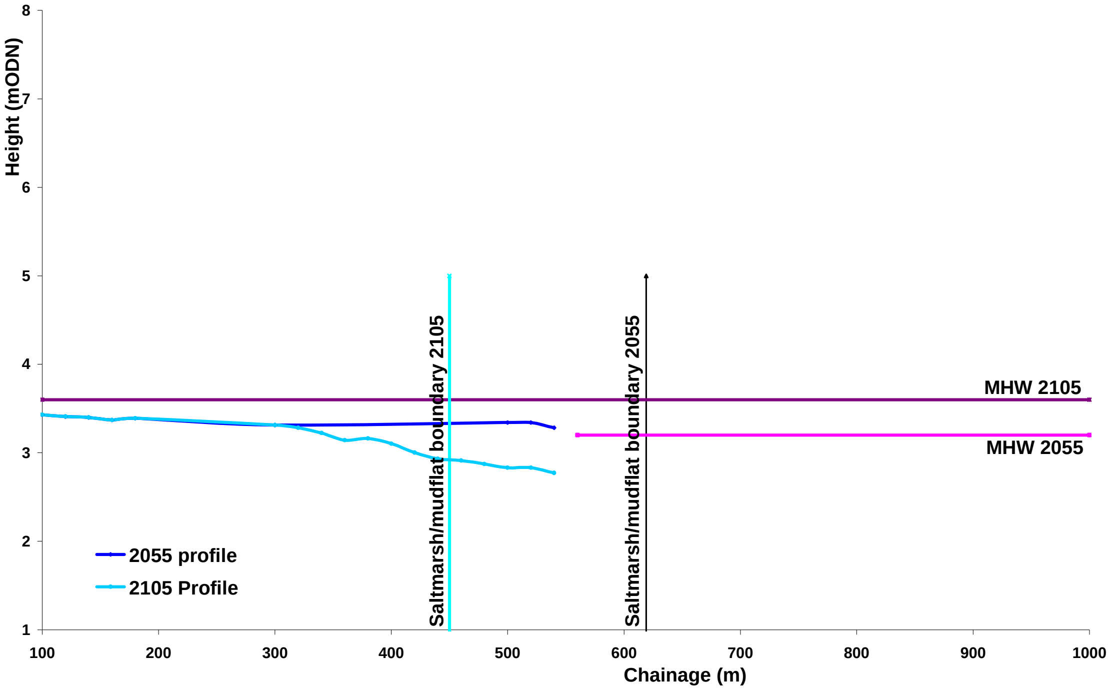
Defra (2006) predicts that sea level rise between 2055 and 2085 will be around 12.0 $mmyr^{-1}$ and 15.0 $mmyr^{-1}$ between 2085 and 2105. As a result MHW in 2105 will be approximately **3.86 mODN**.

Over this epoch, the growth and stability of the saltmarsh noted in previous epochs is likely to cease, as the position of MHW completely inundates the profile. However there is not likely to be a significant amount of erosion across the saltmarsh, as sediment will be deposited during the flood tide and eroded during the ebb tide. Instead there is likely to be erosion of the saltmarsh horizontally at the saltmarsh/mudflat boundary, reducing the total saltmarsh present. Figure F3.5.9 illustrates the typical profile change assuming no vertical erosion across the saltmarsh and mudflat, but assuming an erosion rate back to the position of the boundary in 2006 (ie deduced horizontal erosion rate of 3.38 myr^{-1}).

As with frontage C, although this epoch is likely to see a change from a trend of erosion to a trend of accretion, the total area of saltmarsh is still significantly large, with the total saltmarsh width still extending to greater than 400 m. This is in comparison to a width of between approximately 150 and 250 m predicted across frontages A and B by the end of epoch 3. As a result there will be relatively less pressure on the defences, and therefore less likelihood of overtopping and flooding of the land behind the defences.

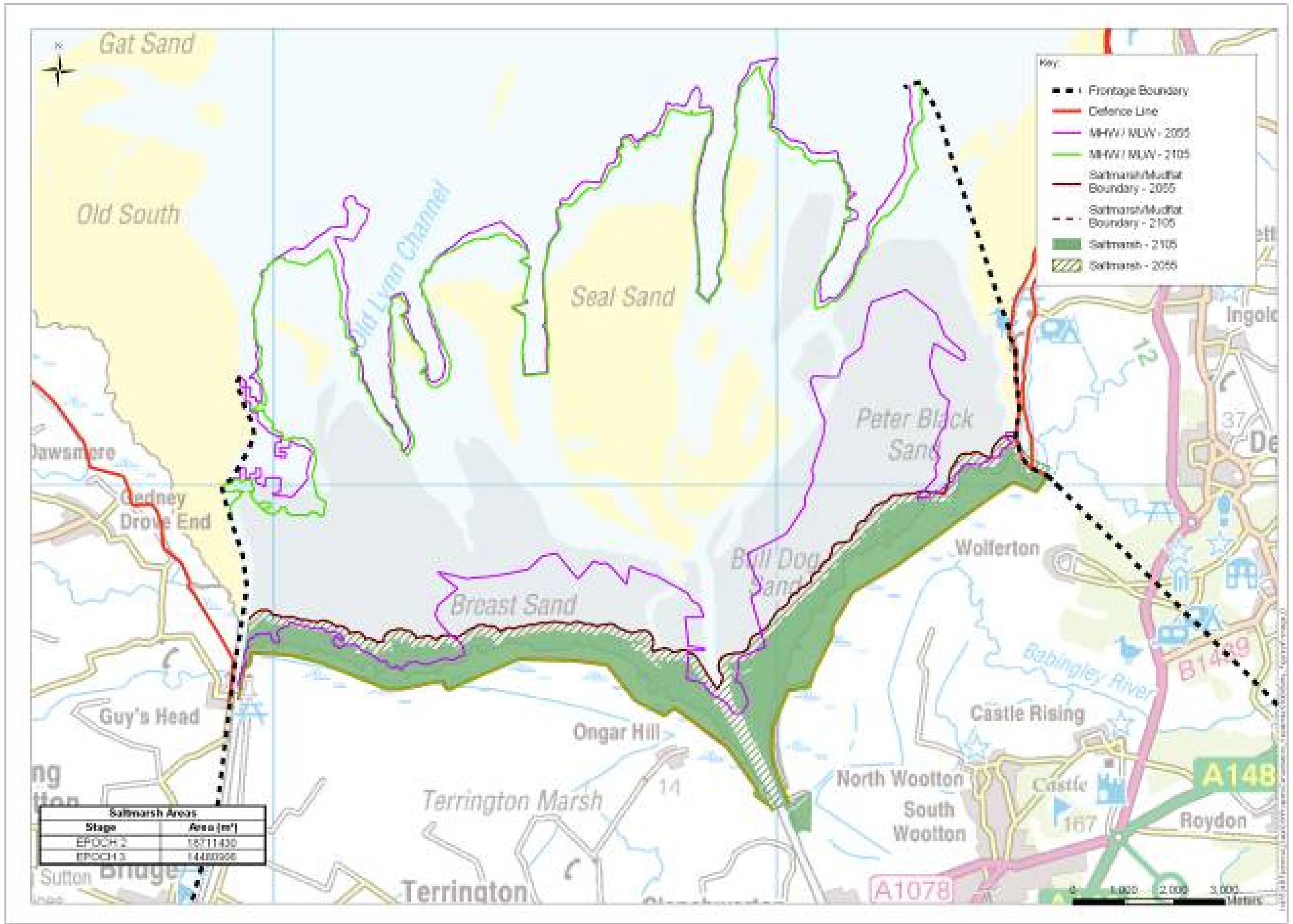
The onset of erosion in this frontage will act to aid erosion in frontage C. It is also important to note that during epoch 3 it is predicted that the saltmarsh/mudflat boundary will erode to approximately chainage 450 m, whereas across frontage C it is only predicted to erode to approximately chainage 900 m. As a result this difference in predicted boundary position between the two frontages may either cause a sheltering effect to this frontage, or cause increased levels of erosion along frontage C.

Figure F3.5.9 Typical Profile Change in epoch 3



The predicted shoreline evolution for epoch 3 under a scenario of WPM is shown in figure F3.5.10.

Figure F3.5.10 Frontage D Predicted Shoreline Evolution epoch 3 WPM



F3.5.11 Impacts: No active intervention

Epoch 1 (present day to 2025)
Defra (2006) predicts that sea level rise between 2006 and 2025 will be around 4.0 $mmyr^{-1}$ therefore MHW in 2025 will be approximately **2.86 mODN**.

Coastal response will be much the same as seen in the WPM scenario up to the end of epoch 1 as all of the defences along this frontage are not expected to fail until the end of epoch 1 or beginning of epoch 2.

As a result figure F3.5.5 is applicable, illustrating continued saltmarsh horizontal growth in a seaward direction at a rate of 8.9 myr^{-1}. The text in section 5.10.1 discusses the development of the intertidal zone during epoch 1 (WPM) in more detail, and the same can be applied to epoch 1 for a scenario of NAI.

Figure F3.5.11 illustrates the position of mean high and mean low water marks for epoch 1 under a scenario of NAI.

Epoch 2 (2025 to 2055)
Defra (2006) predicts that sea level rise between 2025 and 2055 will be around 8.5 $mmyr^{-1}$ therefore MHW in 2055 will be approximately **3.20 mODN.**

Around the beginning of this epoch, under NAI, it is assumed that the defences along this frontage will have deteriorated to a condition of 5 (imminent failure) and therefore it can be assumed that the defences will have totally failed. However in this scenario the assumed 2055 MHW position will not extend a significant distance landward along the profile and will certainly not reach the former defence line. As a result there will still be a significant width of saltmarsh (between 300 and 800 m) that will act as a buffer zone on high tides.

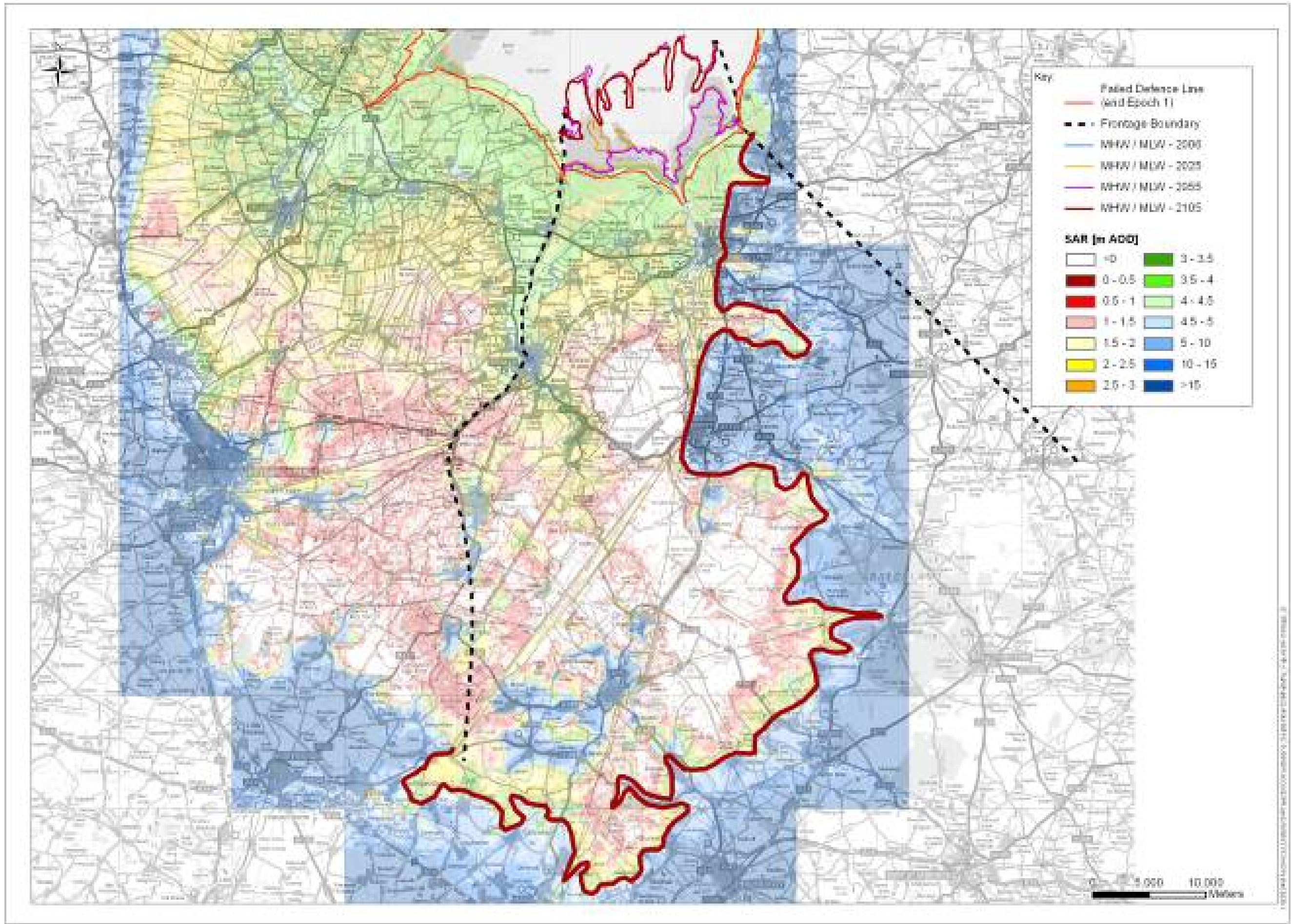
The position of mean high and mean low water marks at the end of the epoch 2 (2055) is shown in figure F3.5.11.

Epoch 3 (2055 to 2105)
Defra (2006) predicts that sea level rise between 2055 and 2085 will be around 12.0 $mmyr^{-1}$ and 15.0 $mmyr^{-1}$ between 2085 and 2105. As a result MHW in 2105 will be approximately **3.86 mODN.**

As with frontage C under a scenario of NAI the position of the MHW and MLW marks is not likely to reach up to the position of the failed defence line by the end of epoch 2 and as a result there will only be localised flooding of the backshore area on the highest tides of the year or during storms. However by the end of epoch 3 (2105) there will be flooding of the backshore and this will subsequently turn into saltmarsh.

The position of mean high and mean low water marks at the end of epoch 3 (2105) is shown in figure F3.5.11.

Figure F3.5.11 Frontage D Predicted Shoreline Evolution All epochs NAI



F3.6 Frontage E – Heacham, Hunstanton and Old Hunstanton

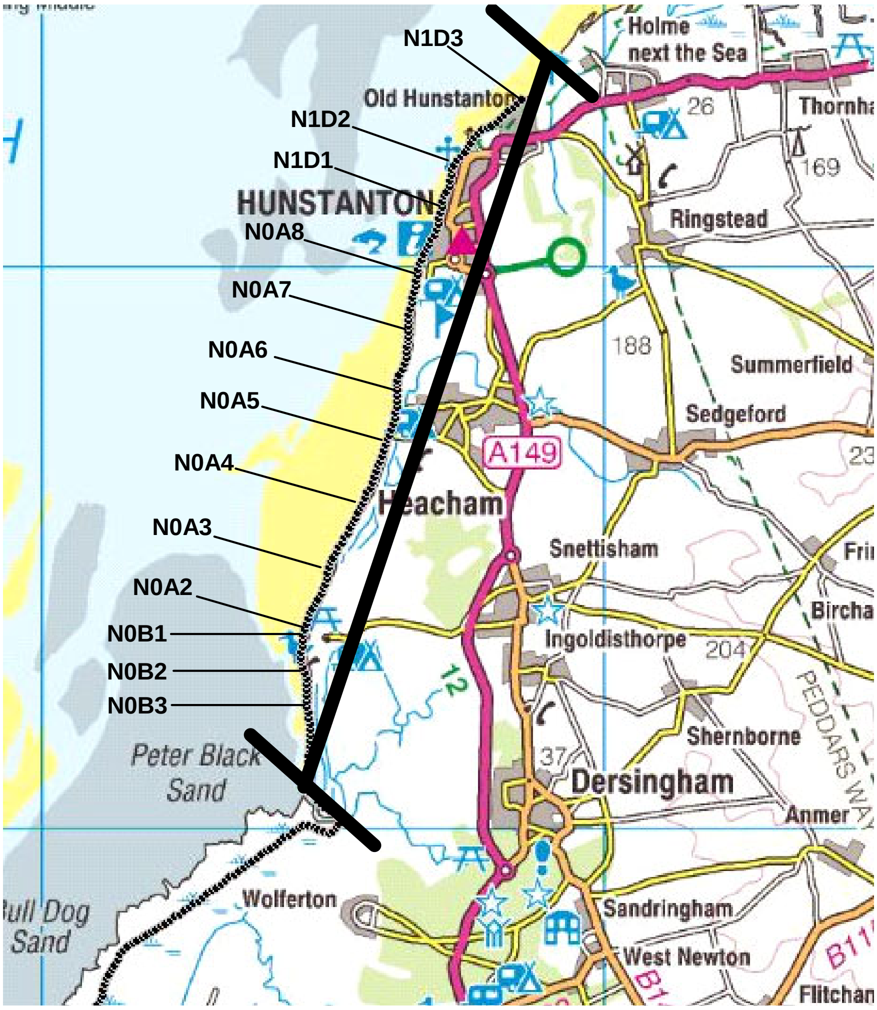
F3.6.1 Introduction

A beach ridge, up to 6 metres high, extends 11 km from near the start of this frontage to the more elevated ground at Hunstanton and encloses a low-lying area between it and rising ground. The lowland has a variable width of up to 2.5 km. A broad intertidal flat extends over 3 km seaward of the ridge. The coastal orientation changes at Snettisham Scalp where a large mussel bed lies on the intertidal flat.

The frontage at Old Hunstanton contains sea cliffs between 10 and 20 m in height. They expose Cretaceous ferruginous sandstones, know locally as Carstone, in the lower part, overlain by the Red Chalk and preceding the White Lower Chalk. A foreshore platform of jointed sandstone fronts the cliffs. Former low cliffs at the southern end of the frontage are now landscaped and defended by sea walls. An offshore bank (Sunk Sand) extends over 4 km from the coast with a large dry area at low water.

Figure F3.6.1 outlines the location of this frontage and also shows the location of the profiles used by the Anglian Coastal Monitoring Programme (EA SMG 2007).

Figure F3.6.1 Anglian Coastal Monitoring Programme profiles



F3.6.2 Key Geomorphological Components

The key geomorphological components that are contained within this frontage and that affect the morphological development of this frontage are listed below:

- The cliffs at Old Hunstanton (sandstone and chalk at the northern undefended end and glacial deposits at the southern end) form the northern limit of this frontage and act to constrain the mouth of the Wash as a whole. Due to its relatively small size compared with the Wash, and its history of erosion, it can be classified as a secondary control. The specific geology of the cliffs is the most influential factor in controlling the prevalent cliff failure mechanism and therefore the rate of erosion.
- The erosion of the cliffs at Old Hunstanton releases some quantities of generally fine material to the fronting beach, and therefore onto the frontage as a whole.

- The main deep water channel, Lynn Deeps, that runs parallel with the coastline, will control the position of the low water mark along this frontage, and therefore whether there is a trend of erosion or accretion of the lower mud/sand flats.
- The offshore sandbanks, namely Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand have an effect on the erosion and accretion of materials along the frontage. They provide some degree of shelter to a small amount of intertidal area, particularly to the north of this frontage.
- Towards the middle and southern sections of the frontage there is a relatively wide intertidal flat which effectively dissipates the incoming wave and tidal energy, and therefore limits the amount that reaches the upper profile. As a result a wider intertidal area, such as noted in this frontage, will decrease erosion or the probability of flooding caused by the incoming energy.
- Snettisham Scalp, a mussel bed at the transition between the sand and shingle beaches to the north and the muddy foreshore to the south, accentuates the sheltering effect of the inter-tidal area.
- The beach ridge between Wolferton Creek (Heacham) and Hunstanton encloses an area of low-lying ground between it and rising ground.

Table F3.6.1 summarises each feature in terms of the control it exerts on the Wash system as a whole, its influences and interactions in terms of the other components of the system, and its status with respect to the geomorphological system.

Table F3.6.1 Key Geomorphological Components Summary

FEATURE	CONTROL EXERTED	INFLUENCES & INTERACTIONS	STATUS
Old Hunstanton cliffs (and associated wave cut platform)	Is a ‘soft’ fixing of the eastern mouth of the Wash Provides some quantities of generally fine material to the fronting beach and the frontage as a whole	Erosion rates are controlled by the specific geology of the cliffs as well as the strength of the dominant wind and wave conditions	Secondary, transient control
Lynn Deeps	Is a route for the flow of tidal energy within the Wash	It interacts with the outfall of the Rivers Witham and Welland and provides a pre-	Primary, persistent control under WPM

FEATURE	CONTROL EXERTED	INFLUENCES & INTERACTIONS	STATUS
	Its position determines the position of the low water mark on the foreshore and therefore the width of the intertidal area	defined flow path during the ebb tide Its depth and width are determined by the strength of the tidal currents	
Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand	Are stores of sediment transported from the Lincolnshire coast to the north and from the intertidal area Provide some degree of shelter from wave attack and therefore influences the position of low water on the foreshore	Their height and width is determined by large-scale tidal circulation patterns and the extent of sediment supply	Secondary, transient control
Wide intertidal area (middle and southern sections)	Is effective in dissipating wave and tidal energy before it reaches the backshore area and defence line Is a store of sediment transported in suspension	The width is determined by the position of low water mark, which is mainly controlled by the Lynn Deeps, and to some extent Long Sand To the south of the frontage, the intertidal area receives enhanced protection from the mussel bed at Snettisham Scalp	Primary, transient control

F3.6.3 Patterns of Change

Historic Change

The northern section of the cliffs at Old Hunstanton (undefended) has been receding at a low rate due to undercutting of the chalk and small toppling falls. The southern section (glacial deposits) receded at a medium rate before the construction of the seawall in 1928. After construction of the sea wall, there was local placement of toe protection to the southern end of the cliffs which interrupted the natural cycle of recession at Hunstanton. Between 1981 and 1995 rates of 0.1 myr^{-1} were measured at the northern cliff section, and 0.2 myr^{-1} at the southern end. Maximum rates of 0.3 myr^{-1} have been measured (Phipps 1999). In total, since 1885 the cliffs have retreated by up to 30 metres in a series of failures of varying size and nature.

Historically the shingle ridge (extending between Snettisham to just south of Hunstanton) has moved landwards and in places has now come up against rising ground as for instance at Heacham.

The intertidal area has shown a tendency to alternate between advance and retreat since 1828, but since 1890 it has shown a significant trend of narrowing. An accretion zone has been historically noted between just south of Hunstanton to just north of Heacham. The coastline between just north of Heacham (including Heacham) to just north of Snettisham Scalp, there has been overall erosion, leading to an erosion zone. The area between Snettisham Scalp and Wolferton Creek has however seen overall accretion, leading to a zone of accretion.

As a result there has been a general trend of accretion along the frontage: between the River Great Ouse and Hunstanton between 1971/74 and 1982/85 there has been a net change of +0.44 km^2 (Hill 1988). This general trend of accretion was reflected in the seaward movement of the low water mark between 1828 and 1995. The zone of erosion around Heacham however experienced a landward retreat of the low water mark.

Recent (1991 – 2006) change

Assessment of beach volumes suggests a progressively increasing volume since 1992, which indicates a positive influence from recycling activity. Environment Agency monitoring between 1991 and 2000 indicated that between just north of Dersingham to Hunstanton there was a general retreat of the mean high water spring mark, at rates ranging between 0 and 6 myr^{-1}.

This masks the retreat of the mean high water spring mark at Snettisham, as well as lower advances at Hunstanton. The comparative movements at Snettisham may be due, in part, to regular beach recharge activities.

The lower sand flats between Shepherd's Point and Heacham also show a trend of horizontal erosion, whereas the sand/shingle ridge on the upper beach at these locations shows a trend of stability. These profiles have been heavily modified through sediment reprofiling, recycling and nourishment.

Sunk Sand, off Hunstanton, has increased significantly in size in the south-west and south-east directions while Thief Sand, Sunk Sand and Ferrier

Sand all suffered erosion (about 1.5 km) off their northern ends (Hydraulics Research Station 1975a).

The Hunstanton-Heacham Beach Management Manual defined three zones of accretion and one zone of erosion between just south of Hunstanton to the end of the frontage. However analysis of the vertical movement of both the sand/shingle ridge and the sand/mudflat by the EA SMG (2007) suggests differing zones from the ones outlined in the Beach Management Manual. The EA SMG (2007) analysed the sand/shingle ridge by obtaining the position of the beach at specific heights, for example at MHWS, for each profile. From this a trend of movement of the upper beach could be obtained. The vertical accretion of the sand/mudflat was analysed in a similar manner to the saltmarsh analysis undertaken along the southern and western shores. The average vertical accretion/erosion rates are shown in table F3.6.2 for each profile in frontage E, and are also illustrated in figure F3.6.2.

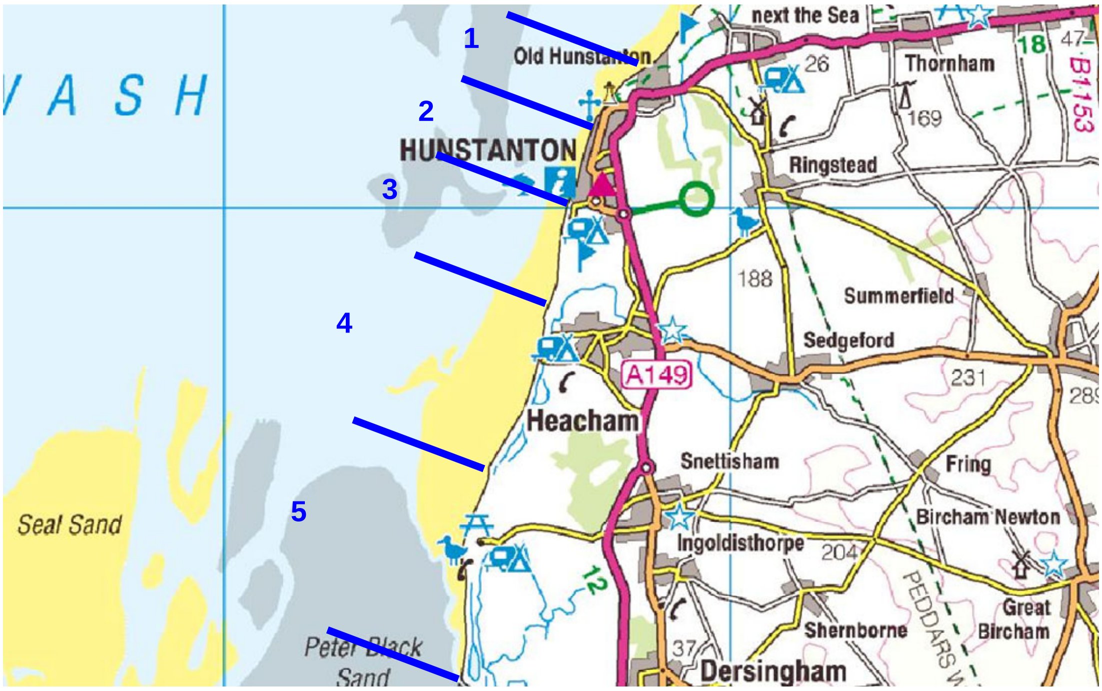
Table F3.6.2 Average Vertical Accretion/Erosion Rates for frontage E

PROFILE	SHINGLE RIDGE (myr^{-1})	SAND/MUDFLAT (myr^{-1})	PREVIOUS ZONES*	NEW ZONES**
N0B3	0.015	0.023	Accretion	Zone 5 - Accretion
N0B2	**-0.019**	0.021		
N0B1	0.010	0.006		
N0A2	0.008	0.012		
N0A3	**-0.019**	0.008		
N0A4	0.000	**-0.004**	Erosion	Zone 4 - Erosion
N0A5	N/A	**-0.003**		
N0A6	**-0.059**	0.027		Zone 3 - Accretion
N0A7	**-0.014**	0.011	Accretion	
N0A8	**-0.008**	**-0.032**		Zone 2 - Erosion
N1D1	**-0.008**	**-0.001**	Hunstanton	
N1D2	**-0.011**	**-0.005**	Hunstanton cliffs	Zone 1 - Erosion

*taken from Hunstanton-Heacham Beach Management Manual draft (Jacobs 2007).

** derived from data shown above (EA SMG 2007).

Figure F3.6.2 frontage E Identified Erosion/Accretion Zones



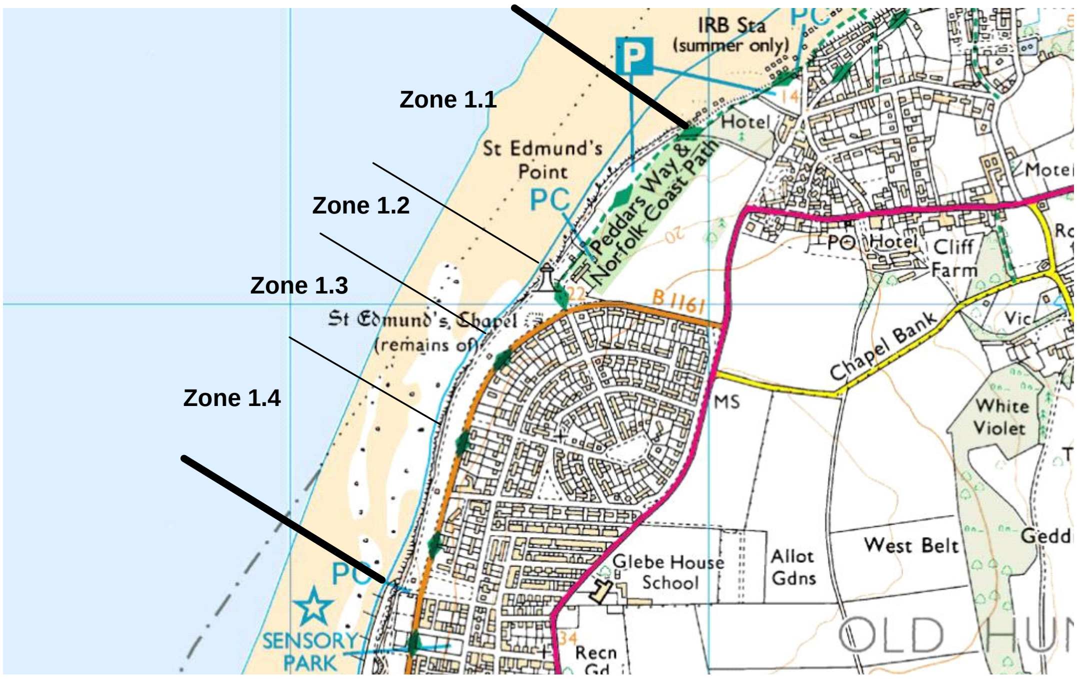
The horizontal erosion/accretion rates, and therefore landward or seaward movement of the shingle ridge, has also been analysed by the SMG (2007). The results are shown in table F3.6.3. However these rates will not be used when predicting the future evolution of the shoreline under a scenario of With Present Management as it can be assumed that the shingle ridge will be regularly re-profiled and renourished in order to mitigate any movement of the ridge.

Table F3.6.3 Shingle Ridge Movement (averages)

ZONE	PROFILE	SHINGLE RIDGE MOVEMENT (myr^{-1})	ZONE AVERAGE SHINGLE RIDGE MOVEMENT (myr^{-1})
5	N0B3	0.3	-0.16
	N0B2	-0.6	
	N0B1	0	
	N0A2	0	
	N0A3	-0.5	
4	N0A4		Stable
	N0A5		
3	N0A6	-1.6	-1.05
	N0A7	-0.5	
2	N0A8		-1.50
	N1D1	-1.5	
1	N1D2	N/A - cliffs	N/A - cliffs

There has been considerable monitoring and condition surveys undertaken in order to monitor the rates of regression of the Hunstanton cliffs and attempt to analyse the methods of failure over the short-, medium- and long-term time scales. Drake and Phipps (2007) collated existing monitoring information and were able to divide the section of cliffs into three distinct sections, characterised by differing rates of erosion. Previously, Mott MacDonald undertook a review of cliff regression at Hunstanton and collated long term regression rates between 1885 and 2004. For this assessment the average rates stated by Mott MacDonald (2005) have been used and as a result Zone 1 has been sub-divided into four sub-zones: 1.1, 1.2, 1.3 and 1.4 to reflect differences in long-term erosion rates. Figure F3.6.3 illustrates the boundary of the four zones.

Figure F3.6.3 Four Sub-Zones of Zone 1, frontage E



Cliff retreat usually occurs in a series of failures of varying size and nature. The main geomorphological processes acting on these cliffs consist of longshore drift, erosion by wave attack, rock slope instability and soil slope degradation. At the base of the cliffs a Carstone wave cut platform has become apparent as a result of continuing erosion processes. It is likely that sea level rise and continued platform lowering will lead to increased rates of erosion.

Table F3.6.4 summarises the long-term (1885-2004) recession rates that are applicable to the four sub-zones (Mott MacDonald 2005). It is important to note that cliff regression has been described as cyclical and therefore regression events usually occur during a series of ‘peaks’, separated by intervening periods of little activity. Therefore the rates shown in table F3.6.4 are averages over the long-term and mask short-term changes.

Table F3.6.4 Long-term Cliff Recession Rates

SUB-ZONE	MOTT MACDONALD (2005) STATION NUMBERS	TYPICAL LONG-TERM RATE (myr^{-1})
1.1	0 (A) to 14	0.07
1.2	15 to 22	0.10
1.3	23 to 29	0.22
1.4	30 to 39	0.16

Table F3.6.5 summarises both the vertical and horizontal erosion/accretion rates for frontage E.

Table F3.6.5 Frontage E Summary of Vertical and Horizontal Erosion/Accretion Rates

ZONE	SUB-ZONE	MIDDLE/LOWER PROFILE (SAND/MUDFLAT) VERTICAL RATE ($mmyr^{-1}$)	UPPER PROFILE (BEACH) VERTICAL RATE ($mmyr^{-1}$)	CLIFF HORIZONTAL RATE (myr^{-1})
1	1.1	N/A	N/A	-0.07
	1.2	N/A	N/A	-0.10
	1.3	N/A	N/A	-0.22
	1.4	N/A	N/A	-0.16
2		-17.00	-8.00	N/A
3		+19.00	-37.00	N/A
4		-4.00	0.00	N/A
5		+14.00	-1.00	N/A

F3.6.4 Tidal Currents

Tidal currents can be relatively strong in the Wash, especially in the main channels during spring tides, due to its large tidal range. Average current velocities are between 0.8 and 1.0 ms^{-1} (HR Wallingford 1972). Offshore at Hunstanton the tidal currents generally run north/south on the ebb and flood.

F3.6.5 Current Residuals

Net water transport throughout the water column off the coast of this frontage is directed towards the north to north-west in the order of between 10 and 14,000 m^3/m/tide (Posford Duvivier 1996). The overall direction of movement along this frontage is directly to the north west parallel with the coast (Posford Duvivier 1996).

F3.6.6 Sediment

The main sediment sources of sediment found on this frontage are as follows:

- It is thought that erosion of the Hunstanton cliffs provide a contribution to maintaining beach levels along this frontage. This is particularly apparent during individual cliff failure events.
- The Holderness coast (situated to the north).
- The Humber estuary (also situated to the north).
- The North Norfolk coast to the east.
- The southern North Sea.
- The sea floor within the mouth of the Wash.
- Erosion of small areas of intertidal area within the frontage, for example between Heacham and Snettisham Scalp.

The main sinks of the sediment on this frontage are:

- Offshore banks - Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand.
- Intertidal area.

In terms of sediment transport, over the mudflats sediment is mostly transported in suspension. Sediment is deposited when the velocity of the tide is low (<0.12 cms^{-1}). Sand and gravel may be deposited under higher flows and exist where there is a greater disturbance due to wave action.

In contrast to the northern and western shores, where suspended sediment transport dominates, the eastern shore is characterised by a mixture of both bedload and suspended sediment transport due to the existence of larger sediment sizes.

Littoral drift, driven by waves predominantly from the north-north-east sector (000 – 030°), is from north to south which causes north to south transport of foreshore clastic materials predominantly derived from cliff failure and cliff erosion events. As a result there is deposition of sediment at Snettisham Scalp. In addition a smaller amount of suspended sediment may be exported to the north Norfolk coast along the eastern margin of the Wash.

F3.6.7 Processes

Tides

Tidal levels (from Admiralty Tide Tables) at Hunstanton are shown in table F3.6.6.

Table F3.6.6 Tidal levels at Hunstanton (mODN)

MHWS	MHWN	MLWN	MLWS
3.65	1.85	-1.25	-2.85
Tidal range (springs): 6.50m			
Tidal range (neaps): 3.10m			

As a result the mean high water mark (MHW) has been calculated at **2.75 mODN**, and mean low water (MLW) at **-2.05 mODN**. The mean tidal range is therefore 4.80m.

Extreme Water Levels
Table F3.6.7 shows the Extreme Water Level (EWL) analysis for Hunstanton, Heacham and Snettisham (Royal Haskoning 2007) in mODN.

Table F3.6.7 EWLs for Hunstanton, Heacham and Snettisham (Royal Haskoning 2007)

LOCATION	RETURN PERIOD							
	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
Hunstanton	4.73	5.24	5.45	5.60	5.76	5.91	6.11	6.27
Heacham	4.81	5.31	5.52	5.67	5.82	5.97	6.18	6.33
Snettisham Scalp	4.86	5.36	5.56	5.71	5.86	6.02	6.22	6.37

Waves
Information regarding waves along this frontage is the same as for frontage A and can therefore be found in section 2.7.3.

F3.6.8 Existing Management

The management practices along this frontage are very different to the other four frontages. This is due to the fact that the coastal geomorphology on the eastern side of the Wash embayment is markedly different to that of the western and southern shores.

Until the 1930s and 40s the natural beach ridge provided flood defence. After the 1940s a grassed earth embankment was constructed 100-300m landward of the beach ridge along the southern part of the frontage between Snettisham and Heacham. The frontline defence between the southern extent of this frontage and Heacham is generally a maintained natural sand/shingle ridge. There is occasional earth embankment or wave return wall toe protection, such as at Heacham Dam, where the shingle ridge is armoured with concrete blockwork. The grassed earth embankment is also classed as a frontline defence and therefore a large section of this frontage effectively has two lines of defence. This grassed earth embankment is expected to fail within the next 10 to 25 years, under a policy of No active intervention (NAI), and will therefore fail towards the end of epoch 1 or beginning of epoch 2.

The defences failed catastrophically in 1953 resulting in large loss of life. The defences breached again in 1978. As a result the management practices between Hunstanton and Heacham have been well documented and there is a wealth of monitoring information (environmental monitoring and beach surveys) available to justify current practice and support future options. Due to the direction of sediment transport along this section of coastline it is possible to undertake annual recycling of material from the Shingle spit located to the south of Snettisham to the areas of erosion located just south of Hunstanton adjacent to the boat ramp. Currently an annual programme of recycling is undertaken, with 10,374 m^3 of sand being taken from the spit and placed on the eroding beaches to the north in 2006 alone. Beach maintenance works are also carried out in response to ‘cliffing’. These management practices act to reduce the degree of overwashing of the ridge and prevent its landward migration in response to sea level rise. The volume of shingle recycled between 1993 and 2006 is shown in table F3.6.8 (Environment Agency 2007).

Table F3.6.8 Volume of Shingle Recycled 1993 to 2006

YEAR	VOLUME SHINGLE RECYCLED(m^3)
1993	58,000
1994	33,700
1995	31,600
1996	7,000
1997	6,600
1998	9,620
1999	8,992
2000	8,016
2001	5,988
2002	3,570
2003	3,396
2004	18,465
2005	5,442
2006	10,374

This table clearly shows that after 1995 a decreased volume of sediment was moved from Snettisham Scalp. This was mainly to preserve the shingle ridge for environmental benefits. Between 1996 and 2006 the volume of material on the Scalp has remained constant. Average volumes recycled are now around 8,000 m^3.

Various other management activities have also been undertaken in recent years, including replacement of the eroded revetment at Heacham, raising the existing wave wall at Hunstanton, and beach nourishment works at Heacham and Snettisham.

A recent Project Appraisal Report has concluded that it will be economically viable to continue the existing management practices along the Heacham-Hunstanton frontage (between Hunstanton South Beach and Snettisham) until 2012, at which point the practices will be reviewed once again.

To the north of this frontage, the composite weak rock cliffs at Old Hunstanton (SMP boundary) provide natural coastal defence for a number of properties located around the Old Hunstanton area. The northern section of cliffs is undefended, while the southern section is landscaped and has been protected by a seawall built in 1928. The seawall was damaged in the 1953 storm surge. The Groyne field in front of Hunstanton was constructed to reduce the rate of southward littoral drift. At Hunstanton South Beach and Heacham North Beach there is also concrete stepwork revetment, promenade and wave wall protection.

In terms of maintenance, the Environment Agency is responsible for the shingle ridge between Hunstanton South Beach and Snettisham. The Borough Council of King's Lynn and West Norfolk manages Hunstanton North Beach. To the south, mud flats on the approaches to the tidal River Great Ouse have defences under responsibility of the Environment Agency.

F3.6.9 Impacts: With Present Management

Epoch 1 (present day to 2025)
Defra sea level rise between 2006 and 2025 is around **4.0 mmyr^{-1}** therefore MHW in 2025 will be approximately **2.83 mODN**.

Coastal Response and Local Impacts
In epoch 1, changes in shoreline exposure due to the effects of sea level rise and sandbank evolution would be slight. Assuming continued management of the shingle ridge will also mean that rates of vertical and horizontal movement along the ridge itself will remain the same as noted between 1994 and 2006 (EA SMG 2007). The following comments are relevant for the individual zones along this frontage in epoch 1.

Zone 1
The trend of narrowing of the intertidal zone and lowering of the beach platform is likely to continue, leading to beach steepening. The long-term cliff erosion rates stated in table F3.6.4 have had a factor applied to them in order to include a provision for increased rates due to predicted sea level rise. Leatherman's (1990) historical projection model has been used to 'scale-up' these long-term cliff recession rates. The following equation, based on Leatherman's (1990) work has been used.

$$\text{Future recession rate} = \frac{\text{historical recession rate}}{\text{historical sea level rise}} \times \text{future sea level rise}$$

Equation 1

Table F3.6.9 shows calculations for Zone 1 cliff recession rates in order to take account of sea level rise, using the above equation. The historical sea level rise has been taken from POL Report 112 'Spatial Analyses for the UK Coast' (Dixon and Tawn 1997) and the predicted sea level rise rate has been taken from table F3.1.1 (Defra 2006).

Table F3.6.9 Calculated Future Cliff Recession Rates

ZONE	HISTORICAL RECESSION RATE (myr^{-1})	HISTORICAL SEA LEVEL RISE (myr^{-1})	FUTURE PREDICTED SEA LEVEL RISE (myr^{-1})	FUTURE RECESSION RATE EPOCH 1 (myr^{-1})
1.1	0.07	0.0022	0.004	0.13
1.2	0.10	0.0022	0.004	0.18
1.3	0.22	0.0022	0.004	0.40
1.4	0.16	0.0022	0.004	0.29

Towards the southern end of the cliffs (sub-zones 1.3 and 1.4), where the mean high water mark is closest to the toe of the cliffs, regression rates may increase by more than predicted. Zone 1.3 is likely to remain the focus of wave aggression.

If management of the toe of the cliffs was to be carried out, such as artificial toe protection, this may reduce the annual sediment supply to the beach ridge to the south, creating the potential for increased erosion rates along Zones 2, 3, 4 and 5.

<u>Zone 2</u>

Given the rate of sea level rise in epoch 1 (4 $mmyr^{-1}$) it is likely that the rate of vertical erosion of the middle to lower beach (sand/mudflat) measured between 1994 and 2006 (table F3.6.5) is likely to remain constant. This vertical erosion rate refers to the beach seaward of the Groyne, and is therefore beyond the influence of the sheltering effect of the Groyne. The upper beach (sand/shingle ridge) is also likely to continue to eroding at 8 $mmyr^{-1}$, as measured between 1994 and 2006.

The Groyne and sea wall will continue to provide significant protection against flooding, however the continued vertical erosion across the whole beach profile will mean that the toe of the seawall may begin to be exposed and therefore increased maintenance may need to be undertaken in order to maintain the standard of protection currently provided by the defences.

Zone 3
This sub-zone is likely to see continued accretion along the middle to lower beach at similar rates to those noted between 1994 and 2006 and continued erosion of the upper profile. It is not however possible to assign specific accretion or erosion rates to this sub-zone as management practices mean that it has been highly modified, and will continue to be so. However it is possible to suggest that over this epoch there will be the increased need for maintenance in order to maintain the current standard of protection provided by the shingle ridge.

Zone 4
The adverse orientation of this zone means that the shoreline is exposed to north-westerly storms and therefore is likely to continue to retreat significantly. As a result the trend of erosion along the mid to lower beach will continue, and continued beach nourishment, recycling and re-profiling operations will be required to attempt to counteract this lowering. However this management process could lead to the creation of an over-steepened ridge profile that will have an increased potential for failure.

As with zone 3, it is not possible to assign specific accretion or erosion rates to this stretch of coastline due to its highly modified nature. However it is expected that there will be an increased need for management operations along this zone during epoch 1.

Zone 5
Due to the fact that this zone has approximately the same orientation as zone 3, and has also displayed similar accretion/erosion trends since 1994, it is likely that its future evolution will also be similar. However it is also important to note that there are likely to be some localised areas of either horizontal accretion or erosion occurring at profiles which cross creeks, such as at N0B3 and N0B2 which are both intercepted by Wolferton Creek.

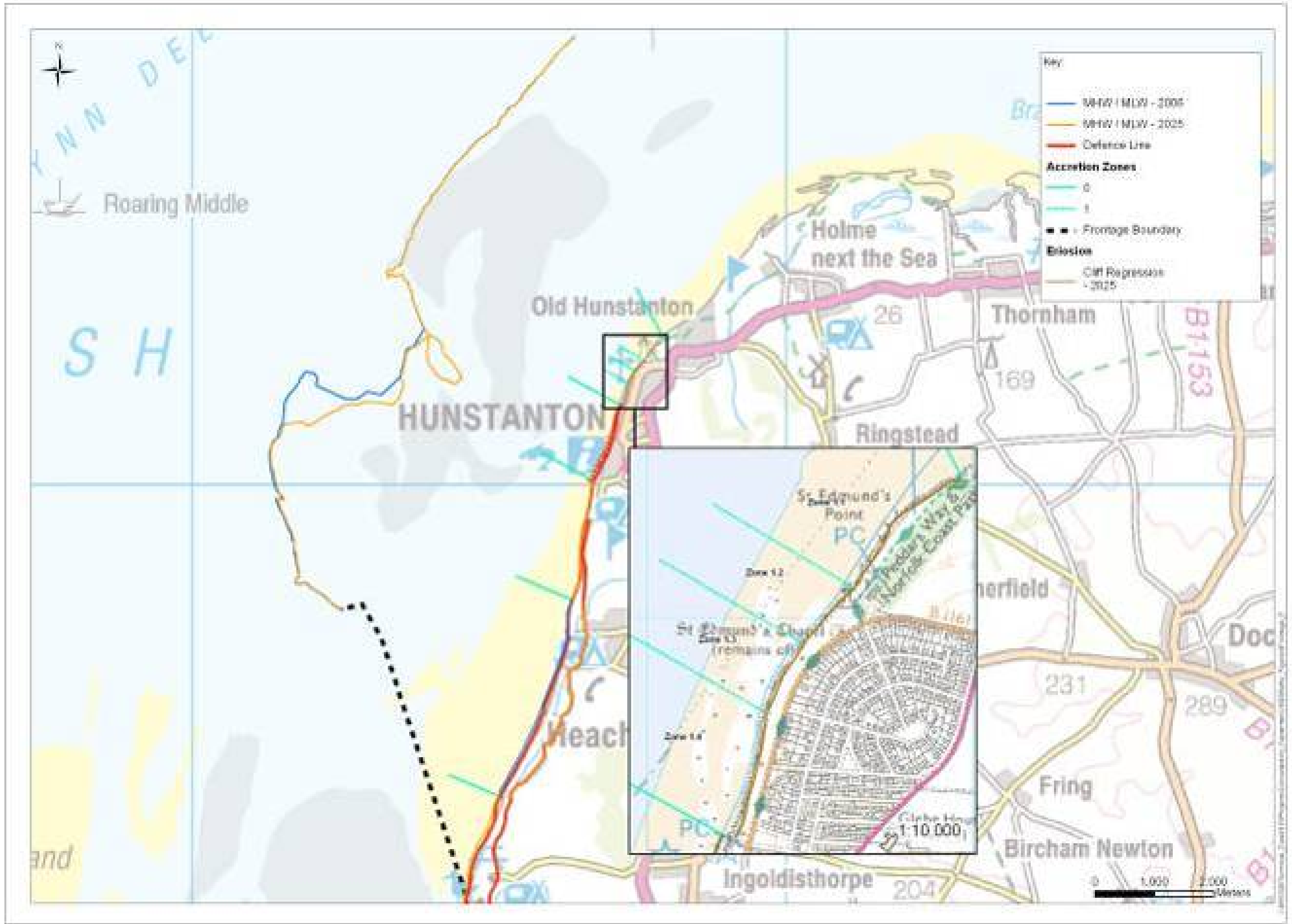
Table F3.6.10 summarises predicted rates for Zones 1 to 5 under a scenario of WPM during epoch 1.

Table F3.6.10 Frontage E shoreline evolution in epoch 1

Zone	Sub-Zone	Sand/mudflat vertical rate ($mmyr^{-1}$)	Beach vertical rate ($mmyr^{-1}$)	Cliff horizontal rate (myr^{-1})
1	1.1	N/A	N/A	-0.13
	1.2	N/A	N/A	-0.18
	1.3	N/A	N/A	-0.40
	1.4	N/A	N/A	-0.29
2		-17.00	-8.00	N/A

The predicted shoreline evolution for epoch 1 under a scenario of WPM is shown in figure F3.6.4.

Figure F3.6.4 Frontage E Predicted Shoreline Evolution epoch 1 WPM



Epoch 2 (2025 to 2055)
Defra sea level rise between 2006 and 2025 will be around **8.5 $mmyr^{-1}$** therefore MHW in 2055 will be approximately **3.08 mODN**.

Coastal Response and Local Impacts
By the end of epoch 2, the movement of the sandbanks offshore of this frontage would more significantly affect the shoreline in terms of sediment transport, erosion and accretion. This movement would lead to improved wave conditions which would have the greatest impact immediately to the south of Hunstanton South Beach (zone 3). The area in front of Heacham (zone 4) is likely to experience increased rates of erosion due to the sediment divide effect, and its intensification as a result of sea level rise. The following comments are relevant for the individual zones along this frontage in epoch 2.

Zone 1
The same factor (Equation 1) has been applied to the long-term cliff erosion rates stated in table F3.6.4 for epoch 2. Table F3.6.11 shows the results of these calculations for epoch 2.

Table F3.6.11 Calculated Future Cliff Recession Rates

ZONE	HISTORICAL RECESSION RATE (myr^{-1})	HISTORICAL SEA LEVEL RISE (myr^{-1})	FUTURE PREDICTED SEA LEVEL RISE (myr^{-1})	FUTURE RECESSION RATE EPOCH 2 (myr^{-1})
1.1	0.07	0.0022	0.0085	0.27
1.2	0.10	0.0022	0.0085	0.39
1.3	0.22	0.0022	0.0085	0.85
1.4	0.16	0.0022	0.0085	0.62

It is possible that, to the northern end of the cliffs (zone 1.1), sea level rise within this epoch, combined with continued lowering of the beach platform, may reactivate toe erosion leading to higher regression rates than stated in table F3.6.11. Zone 1.3 may also see higher regression rates than stated in table F3.6.11 as it will remain the focus of wave aggression.

Within this epoch there is an increased likelihood that management of the toe of the cliffs would be carried out in order to protect a number of the cliff top amenities. However this may reduce the annual sediment supply to the beach ridge to the south, creating the potential for increased erosion rates along zones 2, 3, 4 and 5.

Zone 2
Vertical erosion rates across the whole beach profile are likely to remain the same as any impacts caused by sea level rise increase during this epoch (8.5 $mmyr^{-1}$) is likely to be balanced by an increased supply of material from

increased erosion of the cliffs to the north of the frontage. As a result the rates stated in table F3.6.5 as measured between 1994 and 2006 can also be applied to epoch 2.

As with epoch 1, the Groyne and sea wall will continue to provide significant protection against flooding, however the continued vertical erosion of the beach will mean that the toe of the seawall may begin to be exposed and therefore increased maintenance may need to be undertaken in order to maintain the standard of protection currently provided by the defences.

Zone 3

Due to improvements in the wave conditions approaching this zone brought about by movement of the offshore sandbanks, there are likely to be increased accretion rates across the middle to lower beach profile (sand/mudflats). Erosion of the upper profile (beach) is also likely to reduce given more natural material would be available to be transported up the profile from the lower beach to the upper beach. It is again not possible to assign specific accretion or erosion rates to this sub-zone as management practices mean that it has been highly modified, and will continue to be so. However it is possible to suggest that over this epoch the need for maintenance in order to maintain the current standard of protection provided by the shingle ridge may be reduced given the change in wave conditions.

Zone 4

The movement of the offshore banks during this epoch will act to intensify the sediment divide effect, leading to increased erosion rates along the mid to lower profile. This will lead to the creation of an over-steepened ridge profile that will have an increased potential for failure. The continued management of this zone (reprofiling and renourishment) is likely to lead to the creation of a further over-steepened ridge profile that will have an increased potential for failure.

As with zone 3, it is not possible to assign specific accretion or erosion rates to this stretch of coastline due to its highly modified nature. However it is expected that there will be an increased need for management operations along this zone during epoch 1.

Zone 5

Due to the fact that this zone has approximately the same orientation as zone 3, and has also displayed similar accretion/erosion trends since 1994, it is likely that its future evolution will also be similar. However it is also important to note that there are likely to be some localised areas of either horizontal accretion or erosion occurring at profiles which cross creeks, such as at N0B3 and N0B2 which are both intercepted by Wolferton Creek.

Table F3.6.12 summarises predicted rates for Zones 1 to 5 under a scenario of WPM during epoch 2.

Table F3.6.12 Frontage E shoreline evolution in epoch 2

Zone	Sub-Zone	Sand/mudflat vertical rate (mmyr^{-1})	Beach vertical rate (mmyr^{-1})	Cliff horizontal rate (myr^{-1})
1	1.1	N/A	N/A	-0.27
	1.2	N/A	N/A	-0.39
	1.3	N/A	N/A	-0.85
	1.4	N/A	N/A	-0.62
2		-17.00	-8.00	N/A

The predicted shoreline evolution for epoch 2 under a scenario of WPM is shown in figure F3.6.5.

Figure F3.6.5 Frontage E Predicted Shoreline Evolution epoch 2 WPM

Epoch 3 (2055 to 2105)

Defra sea level rise between 2055 and 2085 is predicted to be around **12.0 mmyr^{-1}** and **15.0 mmyr^{-1}** between 2085 and 2105, therefore MHW in 2105 will be approximately **3.74 mODN**.

<u>Coastal Response and Local Impacts</u>

By the end of epoch 3, sea level rise will have outpaced sediment accretion and unless new sandbanks develop, the exposure of the frontage will increase. This will generally lead to a reduction in accretion rates and an increase in erosion rates, with greater water depths, and therefore larger waves, putting increased pressure on the existing defences. Under a scenario of with present management, there would be an increased need for maintenance of the existing structures in order to maintain the required standard of protection. The following comments are relevant for the individual zones along this frontage in epoch 3.

<u>Zone 1</u>

The same factor (Equation 1) has been applied to the long-term cliff erosion rates stated in table F3.6.4 for epoch 3. Table F3.6.13 shows the results of these calculations for epoch 2.

Table F3.6.13 Calculated Future Cliff Recession Rates

Zone	Historical Recession Rate (Myr^{-1})	Historical Sea Level Rise (Myr^{-1})	Future Predicted Sea Level Rise (Myr^{-1})	Future Recession Rate 2055-2085 (Myr^{-1})	Future Recession Rate 2085-2105 (Myr^{-1})
1.1	0.07	0.0022	0.015	0.38	0.48
1.2	0.10	0.0022	0.015	0.55	0.68
1.3	0.22	0.0022	0.015	1.20	1.50
1.4	0.16	0.0022	0.015	0.87	1.09

Within this epoch there is an increased likelihood that management of the toe of the cliffs would be carried out in order to protect a number of the cliff top amenities. However this may reduce the annual sediment supply to the beach ridge to the south, creating the potential for increased erosion rates along zones 2, 3, 4 and 5.

<u>Zone 2</u>

Vertical erosion rates across the entire beach profile are likely to increase due to the increased exposure to wave attack expected in this epoch, coupled with the significant sea level rise increase (to between 12 and 15 mmyr^{-1}). It has been assumed that the vertical erosion rates stated in table F3.6.5 will double, however it is difficult to be certain about the effect that sea level rise will have on the erosion rates. Vertical erosion may occur to such an extent that underlying glacial deposits become exposed across the beach profile. If this was to occur, there would be the need for a specific nourishment programme in front of Hunstanton.

The Groyne and sea wall will continue to provide significant protection against flooding, however they would be subject to increased pressure as beach levels fall.

Zone 3

Despite seeing improvements in the wave conditions approaching this zone in epoch 2, it is likely that the increase in vertical accretion rates across the lower to middle profile and the decrease in accretion rates across the upper profile will not continue. This is mainly due to the predicted increase in rate of sea level rise (between 12 and 15 $mmyr^{-1}$).

It is again not possible to assign specific accretion or erosion rates to this sub-zone as management practices mean that it has been highly modified in the past, and will continue to be so. However it is possible to suggest that over this epoch the need for maintenance in order to maintain the current standard of protection provided by the shingle ridge may be reduced given the change wave conditions.

Zone 4

The general increased exposure along this frontage will lead to increased erosion rates across the mid to lower profile. It is uncertain how the system will react to this level of increased exposure; however it can be assumed that there will be an increased need for management activities in order for the shingle ridge to maintain the required standard of protection.

As with zone 3, it is not possible to assign specific accretion or erosion rates to this stretch of coastline due to its highly modified nature. However it is expected that there will be an increased need for management operations along this zone during epoch 1.

Zone 5

Due to the fact that this zone has approximately the same orientation as zone 3, and has also displayed similar accretion/erosion trends since 1994, it is likely that its future evolution will also be similar. However it is also important to note that there are likely to be some localised areas of either horizontal accretion or erosion occurring at profiles which cross creeks, such as at N0B3 and N0B2 which are both intercepted by Wolferton Creek.

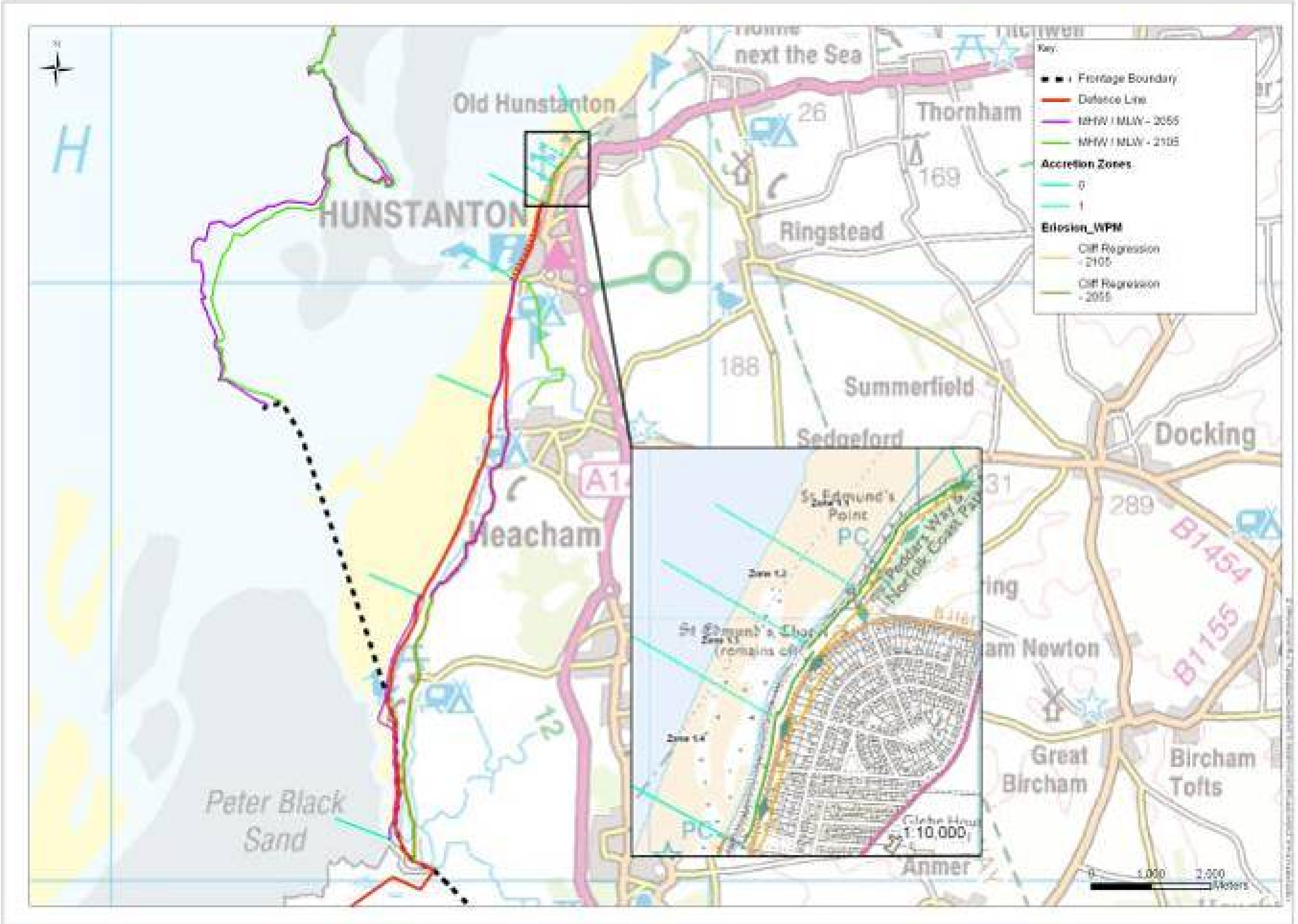
Table F3.6.14 summarises predicted rates for Zones 1 to 5 under a scenario of WPM during epoch 3.

Table F3.6.14 Frontage E shoreline evolution in epoch 3

Zone	Sub-Zone	Sand/mudflat vertical rate ($mmyr^{-1}$)	Beach vertical rate ($mmyr^{-1}$)	Cliff horizontal rate (myr-1)
1	1.1	N/A	N/A	-0.42
	1.2	N/A	N/A	-0.60
	1.3	N/A	N/A	-1.32
	1.4	N/A	N/A	-0.96
2		-34.00	-16.00	N/A

The predicted shoreline evolution for epoch 3 under a scenario of WPM is shown in figure F3.6.6.

Figure F3.6.6 Frontage E Predicted Shoreline Evolution epoch 3 WPM



F3.6.10 Impacts: No active intervention

The majority of the information used to determine shoreline evolution under a scenario of NAI was taken from the “Do Nothing” scenario described in the Strategy/Project Appraisal Report undertaken for the Hunstanton to Heacham frontage by Posford Duvivier (2001).

Epoch 1 (present day to 2025)

Zone 1
The cliffs would continue to recede at rates similar to those described in the epoch 1 WPM section. The slower recession rate of the northern chalk and sandstone cliffs will enhance the sheltering effect for the less resistant slow southern cliffs over time.

Zone 2
The majority of the hard defences in front of Hunstanton are expected to fail towards the end of epoch 1, or beginning of epoch 2. As a result, during epoch 1, shoreline development is likely to be the same as discussed under the WPM scenario for epoch 1 (section 6.9.1).

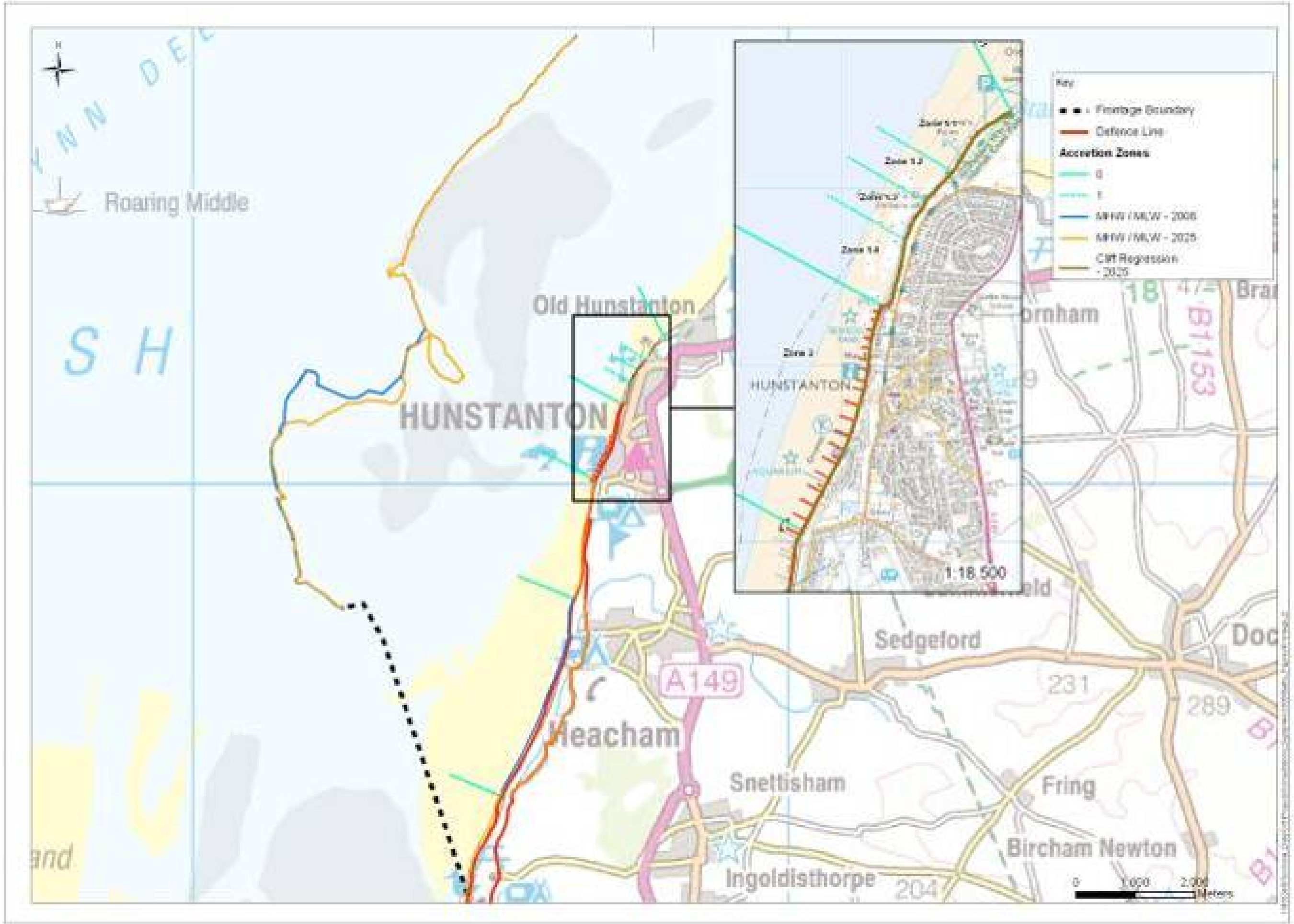
Zone 3
The hard defences in zone 3 are not predicted to fail until epoch 2 and therefore shoreline development is likely to be the same as discussed under the WPM scenario for epoch 1 (section 6.9.1).

Zone 4
The shingle ridge along the majority of zone 4 is more susceptible to breach and therefore failure and is predicted to fail within 5 years once a scenario of NAI has been implemented. In this situation there would be flooding of the area between the shingle ridge and the earth embankment. The secondary earth embankment is predicted to fail towards the end of epoch 1 or beginning of epoch 2 and therefore would continue to provide protection to the backshore during epoch 1.

Zone 5
The shingle ridge along the majority of zone 5 is the most susceptible to breach, and therefore failure, and is predicted to fail within 2 years once a scenario of NAI has been implemented. In this situation there would be flooding of the area between the shingle ridge and the earth embankment. The secondary earth embankment is predicted to fail within epoch 1 therefore by the end of epoch 1 there is likely to be flooding of the backshore areas.

Figure F3.6.7 summarises the predicted positions of mean high and mean low water along this frontage under a scenario of NAI at the end of epoch 1.

Figure F3.6.7 Frontage E Predicted Shoreline Evolution epoch 1 NAI



Epoch 2 (2025 to 2055)

Zone 1

The cliffs would continue to recede at rates similar to those described under the epoch 2 WPM (section 6.9.2). The slower recession rate of the northern chalk and sandstone cliffs will enhance the sheltering effect for the less resistant slow southern cliffs over time.

Zone 2

By the beginning of epoch 2 it is likely that the majority of the hard defences will have failed. The sea wall would fail by excessive overtopping, causing washout and inundation, or by undermining of the toe of the defence causing instability. Once the defence has failed it is predicted that the coast will erode at a similar rate to the undefended cliffs to the north. Initially the rate is likely to be higher as the coastline retreats to a more natural state. After this initial high rate, regression will be in line with cliff regression rates. In order to map shoreline changes for zone 2 it has been assumed that regression will commence at the start of epoch 2 at a rate of 0.53 myr^{-1} (an average of the cliff erosion rates stated in table F3.6.12). In reality it is expected that rates will exceed this and therefore it is a conservative value. As a result by the end of epoch 2 an approximate 16 metre width of Hunstanton's frontage will have been eroded.

Zone 3

The hard defences in zone 3 are not predicted to fail until the end of epoch 2 and therefore shoreline development is likely to be the same as discussed under the WPM scenario for epoch 2 (section 6.9.2).

Zone 4

By the end of epoch 2 the secondary earth embankment is predicted to have failed and as a result there will be widespread flooding of the backshore area, inundating the village of Heacham.

Zone 5

There will be continued flooding during this epoch, but it is likely that the shingle ridge may build up again, at a more natural and lower elevation, and begin a natural trend of roll-back. Zone 5 is a natural zone of accretion of coarse material, as the general sediment transport is from north to south along the entirety of frontage E.

Figure F3.6.8 summarises the predicted positions of mean high and mean low water along this frontage under a scenario of NAI at the end of epoch 2.

Figure F3.6.8 Frontage E Predicted Shoreline Evolution epoch 2 NAI

Epoch 3 (2025 to 2055)

Zone 1
The cliffs would continue to recede at rates similar to those described under the epoch 3 WPM (section 6.9.3). It is likely that the slower recession rate of the northern chalk and sandstone cliffs will enhance the sheltering effect for the less resistant slow southern cliffs over time.

Zone 2
During this epoch there will be continued erosion of the Hunstanton frontage at a rate similar to those stated under the WPM scenario for epoch 3 (section 6.9.3). As a result, by the end of epoch 3, a further 41 metre section of Hunstanton's frontage will have been eroded (assuming an average rate of 0.75 and 0.94 myr^{-1}).

Zone 3
By the beginning of epoch 3 it is likely that the hard defences protecting the southern stretches of Hunstanton will have failed. Under this scenario it is not known how the shoreline will react. Before the hard defences were constructed it is likely that there would have been a natural shingle ridge system protecting the backshore area along this zone, similar to that seen in zones 4 and 5. As a result, following failure of the defence there is likely to be a significant change in beach formation processes and the shingle ridge is likely to be re-built, particularly during storm events characterised by north-westerly waves. Following reformation of the ridge, it is likely to begin a natural process of roll back. However in general this zone will be subject to widespread inundation back to higher ground, even after the potential reformation of the shingle ridge.

Zone 4
Throughout epoch 3 there will be continued widespread flooding of the backshore area. This will be accompanied by the potential reformation of the shingle ridge at a more natural elevation and profile. Once formed, the shingle ridge is likely to be subject to natural roll back in a landward direction.

Zone 5
There will be continued flooding during this epoch accompanied by roll-back of the shingle ridge.

Figure F3.6.9 summarises the predicted positions of mean high and mean low water along this frontage under a scenario of NAI at the end of epoch 3.

Figure F3.6.9 Frontage E Predicted Shoreline Evolution epoch 3 NAI

F3.7 Conclusions

F3.7.1 With Present Management

Throughout the frontages that are characterised by saltmarsh it is expected that initially there is likely to be continued saltmarsh growth under a scenario of With Present Management. This growth will continue throughout epoch 1, and also into epoch 2 for frontages C and D. However towards the end of epoch 2 it is likely that increased pressure brought about by sea level rise will cause erosion of the saltmarsh at its seaward edge. The defences will remain intact due to the nature of this scenario, but it is likely that there will be increased overtopping and erosion of the defences, and therefore an increased need for management. This situation is only predicted towards the end of epoch 2.

F3.7.2 No active intervention

As a result of the Wash embayment having been split into a number of frontages it has not been possible to create an overview of the effects of a scenario of NAI on the backshore. Figure F3.7.1 highlights the extent of predicted MHW at the end of epoch 3 under a scenario of NAI. Throughout epoch 1 and 2, it is predicted that there will only be minor inundation of the backshore area. This flooding is likely to occur on high spring tides, or during severe storm events. However by the end of epoch 3 the position of MHW is likely to extend a significant distance along the backshore, causing widespread flooding during normal tidal events.

F3.8 Baseline Scenario Statement Tables

The following tables (table F3.1 and table F3.2) present the overall conclusions of the Baseline Scenarios assessment in the required SMP format.

F3.9 Assumptions and general notes

The following assumptions have been applied during the assessment of shoreline evolution for the Wash frontages:

- The predicted year that a defence is expected to fail in is assumed to signify total defence failure. Therefore it has been assumed that once a defence has “failed”, it will have no residual effect as a defence.
- Once the primary defence has failed, the secondary and tertiary lines of defence will also no longer function as sea defences. This is because they are currently not maintained.
- All accretion/erosion rates quoted are an average for the entire frontage length (unless stated) and mask localised trends of erosion and accretion.

- All rates and predictions of future morphological development in the With Present Management scenario assume that WPM will continue in the adjoining SMP areas (particularly SMP 2a, 2b and 2c) as well as the adjoining SMP2d frontages (B and C).

The following notes summarise sources of individual erosion/accretion rates as well as a number of points that need to be considered when reading the main text:

- Vertical accretion rates have been taken from the Shoreline Management Group's Coastal Trends Analysis report (2007) and are an average of those experienced throughout the entire frontage between 1994 and 2006. These vertical changes were derived from annual topographic beach surveys.
- Horizontal accretion rates have been taken from the Shoreline Management Group's Coastal Trends Analysis report (2007) and are an average of those experienced throughout the entire frontage between 1992 and 2006. These horizontal changes were derived from analysis of a series of aerial photographs.
- Although increased storminess is predicted in the future as an effect of climate change, a quantitative assessment of these effects has not been included in any of the scenarios above. Currently there are no long-term data sets available to identify specific trends in the occurrence of storms. However it should be noted that the coastline development discussed in each scenario may actually occur earlier than predicted if the frequency and strength of storms increases. In addition increased storminess could also cause increased erosion rates along both the Holderness and Lincolnshire coasts. There is uncertainty as to whether this release of sediment would reach the Wash embayment, or whether it would be transferred offshore into offshore sediment stores (sand banks) or into the wider sediment transport system of the North Sea.
- The Defra rates of sea level rise quoted are conservative and therefore the scenarios represent the worst case scenario.
- The "backshore" zone, as discussed in the future scenarios section, is defined as the zone that lies above the normal high water mark and which interacts with the foreshore. The backshore zone makes up the first of three zones along the coastal cross-section. The second is the "foreshore" and the third is the "shoreface".

Table F3.1 Baseline Scenario Statement Tables – No active intervention

	Predicted Change For Years 0 – 20 (2025)	Years 20 – 50 (2055)	Years 50 – 100 (2105)
PDZ1a – **Wainfleet and Friskney**	• Defences remain.	• Defences will have failed by the beginning of this epoch.	• No defences remain.
	• Continued vertical accretion across the salt marsh and mud flat. • Landward movement of the mean high and mean low water marks. • Movement seaward of the salt marsh/mud flat boundary. • Expect a general increase in established salt marsh. • Towards the end of the epoch flooding will occur only on the highest tides of the year, or during high tides combined with adverse weather conditions.	• No further increase in salt marsh area. • More frequent inundation of the former reclaimed area, particularly during storm events. • Backshore will be subject to localised areas of erosion during storm events.	• Overall decrease in salt marsh area. • Increased inundation of the former reclaimed areas, during the majority of high tides. • Towards the end of the epoch, the backshore will begin to see the initial stages of salt marsh development (landward of the mean sea level).
PDZ1b – **Leverton, Butterwick and Freiston**	• Defences remain.	• Majority of the defences will have failed by the beginning of this epoch.	• No defences remain.
	• Continued vertical accretion across the salt marsh and mud flat. • Seaward movement of the mean high and mean low water marks. • Movement seaward of the salt marsh/mud flat boundary. • Towards the end of the epoch, when the defences have failed, flooding will occur only on the highest tides of the year, or during high tides combined with adverse weather conditions.	• No further increase in salt marsh area. • More frequent inundation of the former reclaimed area, particularly during storm events. • Backshore will be subject to localised areas of erosion during storm events.	• Overall decrease in salt marsh area. • Increased inundation of the former reclaimed areas, during the majority of high tides. • Towards the end of the epoch, the backshore will begin to see the initial stages of salt marsh development (landward of the mean sea level).

	Predicted Change For Years 0 – 20 (2025)	Years 20 – 50 (2055)	Years 50 – 100 (2105)
PDZ1c – **Frampton, Holbeach and Gedney**	• Defences remain.	• Majority of the defences will have failed by the beginning of this epoch.	• No defences remain.
	• Continued seaward movement of salt marsh/mud flat boundary. • Relatively less coastal squeeze in comparison to frontages A and B due to less historic reclamation. • General stability of the natural salt marsh. • Towards the end of the epoch, when some of the defences have failed, flooding of the backshore areas will only occur on the highest tides of the year, or during high tides combined with adverse weather conditions.	• No further increase in salt marsh area. • Large width of salt marsh will continue to act as a buffer zone on high tides. • Landward movement of the high and low water marks. • Flooding of the new backshore area (former reclaimed land) will only occur during the highest tides of the year, or during high tides combined with adverse weather conditions.	• Overall decrease in salt marsh area. • Continued landward movement of the high and low water marks. • Salt marsh development will be initiated in the new backshore area as a result of more frequent flooding.
PDZ1d - **Terrington, Wootton and Wolferton**	• Defences remain.	• Majority of the defences will have failed by the beginning of this epoch.	• No defences remain.
	• Continued seaward movement of the salt marsh/mud flat boundary. • Relatively less coastal squeeze in comparison to frontages A and B due to less historic reclamation. • General stability of the natural salt marsh, as with frontage C. • Towards the end of the epoch, when some of the defences have failed, flooding of the backshore areas will only occur on the highest tides of the year, or during high tides combined with adverse weather conditions.	• No further increase in salt marsh area. • Large width of salt marsh will continue to act as a buffer zone on high tides. • Landward movement of the high and low water marks. • Flooding of the new backshore area (former reclaimed land) will only occur during the highest tides of the year, or during high tides combined with adverse weather conditions.	• Overall decrease in salt marsh area. • Continued landward movement of the high and low water marks. • Salt marsh development will be initiated in the new backshore area as a result of more frequent flooding.

	Predicted Change For Years 0 – 20 (2025)	Years 20 – 50 (2055)	Years 50 – 100 (2105)
PDZ2, PDZ3 and PDZ4 – **Heacham, Hunstanton and Old Hunstanton**	• Failure of the shingle ridge in towards the southern extent of the frontage. • Failure of southern end of the secondary bank behind the shingle ridge.	• Majority of defences in front of Hunstanton will have failed towards the beginning of epoch 2. • Defences towards south of Hunstanton will fail later, towards the end of epoch 2. • Secondary bank behind the failed shingle ridge will also have failed.	• No defences remain.
	• Continued cliff recession and beach steepening in front of the cliffs. • In front of Hunstanton there will be continued erosion of the whole beach profile. • The shoreline between Hunstanton and the northern extent of Heacham, and between Snettisham Scalp and the southern extent of the frontage, there will be continued accretion along the middle to lower beach, but erosion of the upper profile. • In front of Heacham, southwards towards Snettisham Scalp, there will be significant retreat of the shingle ridge. • Flooding of the backshore area behind the failed shingle ridge, but secondary bank will continue to provide protection into epoch 2 in some places (towards the southern end).	• Continued cliff recession and beach steepening in front of the cliffs. • Erosion will be initiated along the undefended shoreline in front of Hunstanton. Initially the erosion rates will be high, but will then begin to mirror those seen along the Hunstanton cliffs to the north as they settle down to a more natural state/position. • The shoreline between Hunstanton and the northern extent of Heacham, and between Snettisham Scalp and the southern extent of the frontage will be the same as under a WPM as defences will remain. There will be increased accretion rates along the middle to lower beach, but erosion of the upper profile. • Behind the failed shingle ridge, the secondary bank will also have failed, leading to widespread flooding of the backshore area.	• Continued cliff recession and erosion in front of Hunstanton. • Along the remainder of the frontage, there will be continued flooding of the backshore area. • There is the potential for the shingle ridge to be re-built at a more natural elevation and profile. Once formed, this shingle ridge would re-commence a natural trend of rollback.

Table F3.2 Baseline Scenario Statement Tables – With Present Management

	Predicted Change For		
	Years 0 – 20 (2025)	**Years 20 – 50 (2055)**	**Years 50 – 100 (2105)**
PDZ1a – **Wainfleet and Friskney**	• Defences remain.	• Defences remain.	• Defences remain. • Need for higher, strengthened earth embankments.
	• Continued vertical accretion across the salt marsh and mud flat. • Landward movement of the mean high and mean low water marks. • Movement seaward of the salt marsh/mud flat boundary. • General increase in established salt marsh.	• Continued vertical accretion across the salt marsh and mud flat. • Landward movement of the mean high and mean low water marks, at higher rates than seen in epoch 1. • Increased pressure on the salt marsh/mud flat boundary, but it should be able to hold its position. • Steepening of the salt marsh/mud flat profile, causing it to become unstable, particularly during storm events.	• Tendency for erosion. • Rate of sedimentation significantly outpaced by rate of sea level rise. • Reduced rate of vertical accretion on both the salt marsh and mud flat. • Further landward movement of the mean high and mean low water marks. • Landward movement of the salt marsh/mud flat boundary. • Coastal squeeze • Large loss of salt marsh area.
PDZ1b – **Leverton, Butterwick and Freiston**	• Defences remain.	• Defences remain.	• Defences remain. • Need for higher, strengthened earth embankments.
	• Continued vertical accretion across the salt marsh and mud flat. • Seaward movement of the mean high and mean low water marks. • Movement seaward of the salt marsh/mud flat boundary. • General increase in established salt marsh	• Continued vertical accretion across the salt marsh and mud flat. • Increased pressure on the salt marsh/mud flat boundary, but it should be able to hold its position. • Position of mean high and mean low water marks will remain the same.	• Rate of sedimentation significantly outpaced by rate of sea level rise. • Reduced rate of vertical accretion on both the salt marsh and mud flat. • Landward movement of the mean high and mean low water marks. • Landward movement of the salt marsh/mud flat boundary. • Coastal squeeze evident in large loss of salt marsh area.

	Predicted Change For		
	Years 0 – 20 (2025)	**Years 20 – 50 (2055)**	**Years 50 – 100 (2105)**
PDZ1c – **Frampton, Holbeach and Gedney**	• Defences remain.	• Defences remain.	• Defences remain. • Salt marsh area will still be relatively large, therefore there may not be the need to strengthen and raise the existing defences.
	• Continued seaward movement of salt marsh/mud flat boundary, producing a general increase in total salt marsh area. • Relatively less coastal squeeze in comparison to frontages A and B due to less historic reclamation. • General stability of the natural salt marsh, as with frontage D.	• Landward movement of the high and low water marks causing an overall reduction in salt marsh area (coastal squeeze). • General stability of the natural salt marsh.	• Salt marsh becomes increasingly unstable. • High tide level will completely inundate the profile. • Landward movement of the salt marsh/mud flat boundary producing a general decrease in total salt marsh area. • Despite these changes, the total area of salt marsh will remain relatively large (in comparison with frontages A and B). • This will lead to relatively less chance of overtopping and flooding of the low-lying land. • The onset of erosion in this frontage will act to aid erosion in frontage D.

	Predicted Change For		
	Years 0 – 20 (2025)	**Years 20 – 50 (2055)**	**Years 50 – 100 (2105)**
PDZ1d - **Terrington, Wootton and Wolferton**	• Defences remain.	• Defences remain.	• Defences remain. • Salt marsh will area will still be relatively large, therefore there may not be the need to strengthen and raise the existing defences.
	• Continued seaward movement of the salt marsh/mud flat boundary, producing a general increase in total salt marsh area. • No coastal squeeze due to relatively less reclamation compared to frontages A and B. • General stability of the natural salt marsh, as with frontage C.	• Position of salt marsh/mud flat boundary will remain constant, but there will be vertical accretion across the salt marsh due to regular inundation during higher than average tides. • Relatively less loss of salt marsh (coastal squeeze) compared with frontages A, B and C. • General stability of the natural salt marsh.	• Salt marsh becomes increasingly unstable. • High tide level will completely inundate the profile. • Landward movement of the salt marsh/mud flat boundary producing a general decrease in total salt marsh area. • Despite these changes, the total area of salt marsh will remain relatively large (in comparison with frontages A and B). • The onset of erosion in this frontage will act to aid erosion in frontage C.

	Predicted Change For		
	Years 0 – 20 (2025)	**Years 20 – 50 (2055)**	**Years 50 – 100 (2105)**
PDZ2, PDZ3 and PDZ4 – **Heacham, Hunstanton and Old Hunstanton**	• Defences remain. • Sea walls in front of Hunstanton will require increased maintenance as the toe becomes exposed. • The shingle ridge along the entire frontage will need to be maintained (reprofiled/nourished) in order to maintain the current standard of protection.	• Defences remain. • Toe protection/management of the cliffs would be necessary. • Sea walls in front of Hunstanton will require increased maintenance as the toe becomes exposed. • The shingle ridge along the entire frontage will need increasing maintenance (reprofiling/nourishment) in order to maintain the current standard of protection.	• Defences remain. • Toe protection/management of the cliffs would be necessary. • Sea walls in front of Hunstanton will require increased maintenance as the toe becomes exposed due to falling beach levels. • The beach in front of Hunstanton may require renourishment. • The shingle ridge along the entire frontage will need increasing maintenance (reprofiling/nourishment) in order to maintain the current standard of protection.
	• Continued cliff recession and beach steepening in front of the cliffs. • In front of Hunstanton there will be continued erosion of the whole beach profile • The shoreline between Hunstanton and the northern extent of Heacham, and between Snettisham Scalp and the southern extent of the frontage, there will be continued accretion along the middle to lower beach, but erosion of the upper profile. • In front of Heacham, southwards towards Snettisham Scalp, there will be significant retreat of the shingle ridge.	• Movements of the sandbanks offshore would begin to significantly affect the frontage, particularly in the area to the south of Hunstanton South Beach, which would see an improvement in wave conditions, but also in front of Heacham, where the sediment divide effect would be increased. • Continued cliff recession and beach steepening in front of the cliffs. • In front of Hunstanton there will be continued erosion of the whole beach profile. • The shoreline between Hunstanton and the northern extent of	• General exposure of the frontage will increase. • Continued cliff recession and beach steepening in front of the cliffs. • In front of Hunstanton there will be increased erosion of the entire beach profile, potentially exposing the underlying glacial deposits. • The shoreline between Hunstanton and the northern extent of Heacham, and between Snettisham Scalp and the southern extent of the frontage, there will be decreased accretion rates (potentially turning to erosion) along the middle to lower beach, and increased erosion of the upper profile. • In front of Heacham, southwards

	Predicted Change For		
	Years 0 – 20 (2025)	Years 20 – 50 (2055)	Years 50 – 100 (2105)
		Heacham, and between Snettisham Scalp and the southern extent of the frontage, there will be increased accretion rates along the middle to lower beach, but erosion of the upper profile. • In front of Heacham, southwards towards Snettisham Scalp, there will be increased erosion of the mid to lower profile, creating an oversteepened ridge profile that will have an increased potential for failure.	towards Snettisham Scalp, there will be further increased erosion of the mid to lower profile, creating a further oversteepened ridge profile. Into this epoch, the potential for ridge failure will be significant.

F4 FLOOD RISK

F4.1 Introduction

Annex G1 of the SMP Guidance (Defra 2006) provides support on classifying the risks according to the *likelihood* of the feature being lost or damaged, and the scale of the *impact*. It presents the following Risk Matrix for each feature under each of the three epochs.

IMPACT				
	High	Medium High Risk	High Risk	Very High Risk
	Medium	Low Risk	Medium Risk	High Risk
	Low	Negligible Risk	Low Risk	Medium Risk
		Low	Medium	High
			LIKELIHOOD	

The *likelihood* of the feature being damaged or lost is dependent upon flood risk and or coastal erosion. SMP Guidance (Defra 2006) states that,

> *'For the purpose of the SMP it can be assumed that, should flood defences be breached, the whole flood plain can be defined to be "at risk". The flood risk areas should be based on the information produced by the Environment Agency e.g. the Flood Map'*
>
> (p.43, section 2.5, paragraph 4)

Note that this section of appendix F deals specifically with flood risk. Coastal erosion along the Hunstanton frontage is dealt with separately under the No active intervention Scenario which is part of the Baseline Scenarios task. This information is provided in detail in section F3.6.

F4.2 The Wash

Due to the large expanse of low-lying land in the Wash SMP study area, it would not be applicable to follow the SMP Guidance and develop a list of features and the likelihood of that feature being lost due to food risk.

It is, however, useful to highlight the maximum possible flood extent, based on a level of 6.5mODN which relates to the expected 0.1% (1 in 1000) flooding probability level in 2100 in a No active intervention scenario. This plot is provided in figure F4.1. This is simply the 6.50mODN water level extrapolated across the digital terrain model (ignoring coastal and fluvial defences) and therefore only defines the potential at risk areas.

The Environment Agency flood maps also assume that there are no defences, but they do take into account the influence of the tide (for example how far the water could potentially travel during one tidal cycle). The Environment Agency flood maps indicate the extent of river flooding with a

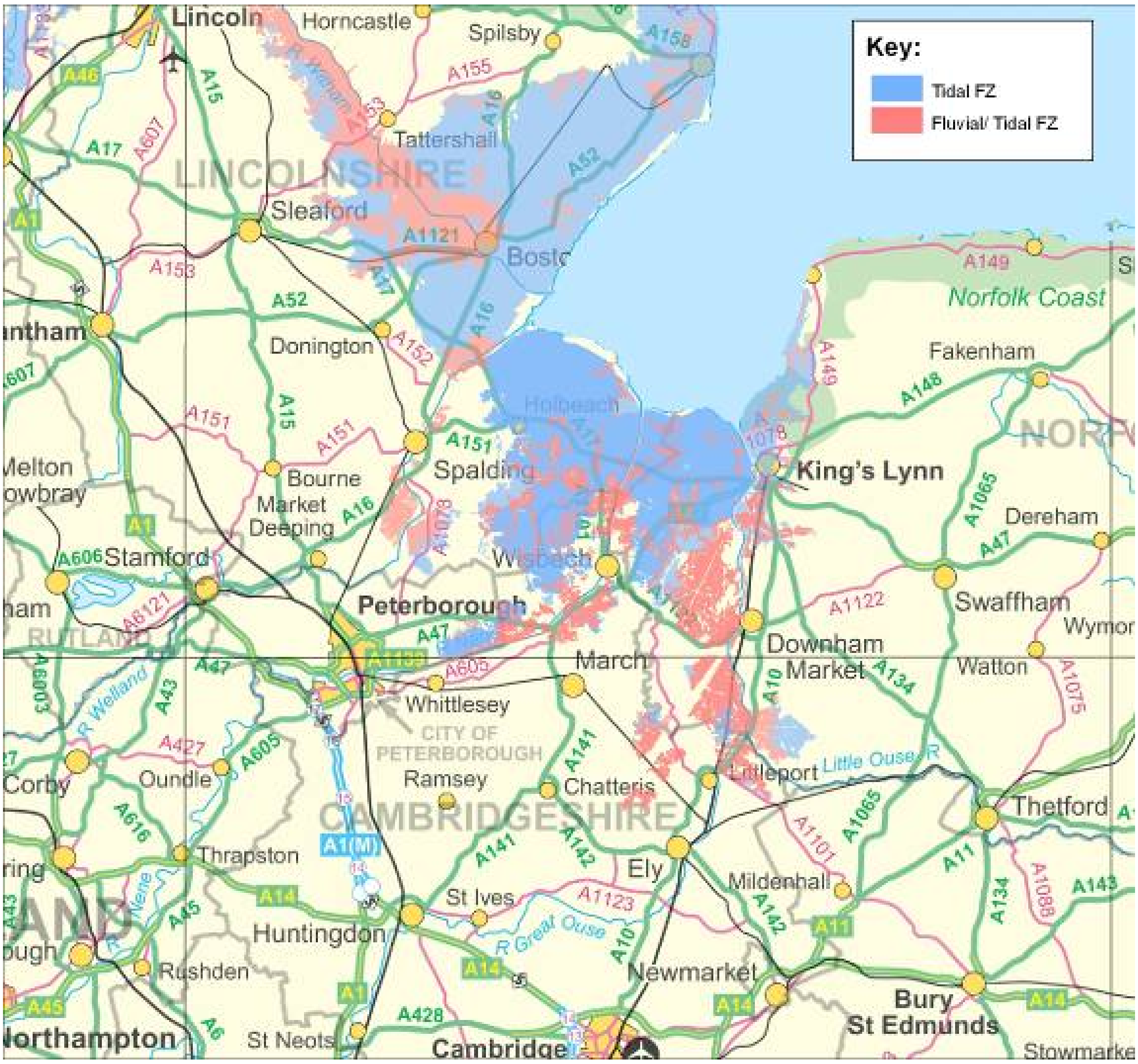
1% (1 in 100) chance of happening in any year and the extent of flooding from the sea with a 0.5% (1 in 200) chance of happening each year. The flood zones also indicate the extent of an extreme flood from rivers or the sea with a 0.1% (1 in 1000) chance of happening in any year. The Environment Agency's flood map for the Wash SMP area is provided in figure F4.2.

The two figures (figure F4.1 and figure F4.2) are simple overviews of the flood risk for the Wash SMP2 area. They do, however, highlight the importance of the defences and the scale of loss associated with a No active intervention policy along the frontage.

More detail regarding flood risk and the impact of flooding is available within the more strategic reports produced for the Wash area, such as the Strategic Flood Risk Assessments (SFRAs) and Areas Benefiting from Defences (ABDs) work. SFRA reports are available from the relevant Local Authority.

Figure F4.1 Flood Risk

Figure F4.2 Environment Agency Flood Map (what level of event?)



F5 ASSESS SHORELINE RESPONSE

F5.1 Introduction

F5.1.1 Aim

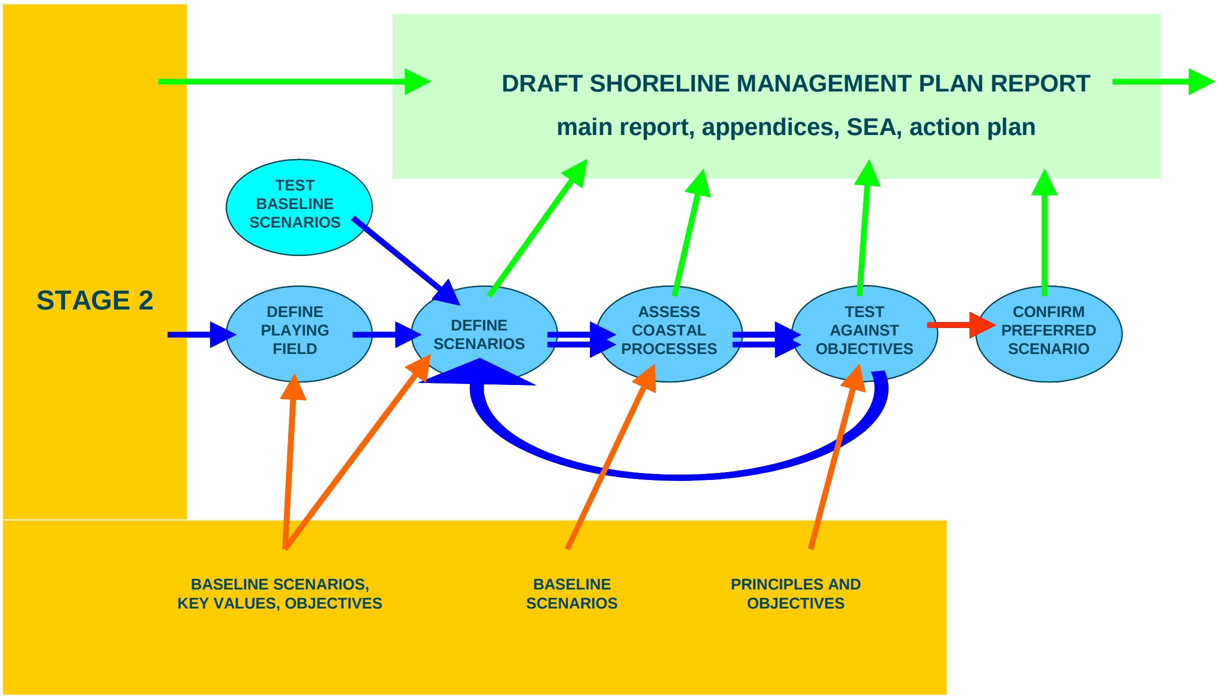
The overall aim of this Task (Task 3.2 as defined by the SMP Guidance) is to carry out an assessment of the shoreline interactions and responses to the Policy Packages. This formed an essential input into the appraisal itself.

Figure F5.1 provides an overview of where this Task sits within the policy development and appraisal process. It is important to note that an iterative process of fine-tuning with respect to the Policy Packages was undertaken. With each ‘cycle’ of fine-tuning, the assessment of shoreline response was also updated and presented at the relevant CSG or EMF meeting. This section will only report on the ‘second-cycle’ of fine-tuning and therefore accompanies the Policy Appraisal Results as presented in section E5.2 of appendix E.

It is important to note that further analysis of shoreline response was carried out following on from these results. This particularly concerns the intertidal development of PDZ1, identifying that the developments in Epoch 2 and 3 are very uncertain and could range from an erosional to an accretional future; this is discussed in more detail in section F6.2. The analysis in this section is based on the ‘Erosional future scenario’ as described there.

In addition, further work was carried out on PDZ2, assessing the links between the shingle ridge, Snettisham Scalp and the saline lagoons; this is discussed in more detail in section F6.3

Figure F5.1 The Wash SMP2 Policy Development and Appraisal Process



> It is important to note that this text was produced in an early stage of the SMP, and that the insights into the future development of salt marsh and mud flat have developed since then. Section F6.2.1 describes the latest insights. In summary: on the medium and long term there is an envelope of possible developments, ranging from continuation of the current growth ('accretional future') to a reversal leading to loss of salt marsh and mud flat ('erosional future'); it is also possible that the current extent and ratio of salt marsh and mudflat will broadly remain. The analysis in this section is largely based on an erosional future in epoch 2 and 3. These changing insights have informed policy development from the tentative policies described in this section; see section 5.2 in appendix E.
>
> It is also important to note that the policy packages discussed in this section are the tentative policy packages which have formed the basis for later discussions that have led to the draft and final Plan and policies as described in the main SMP document. This process is described in section E5 of appendix E.

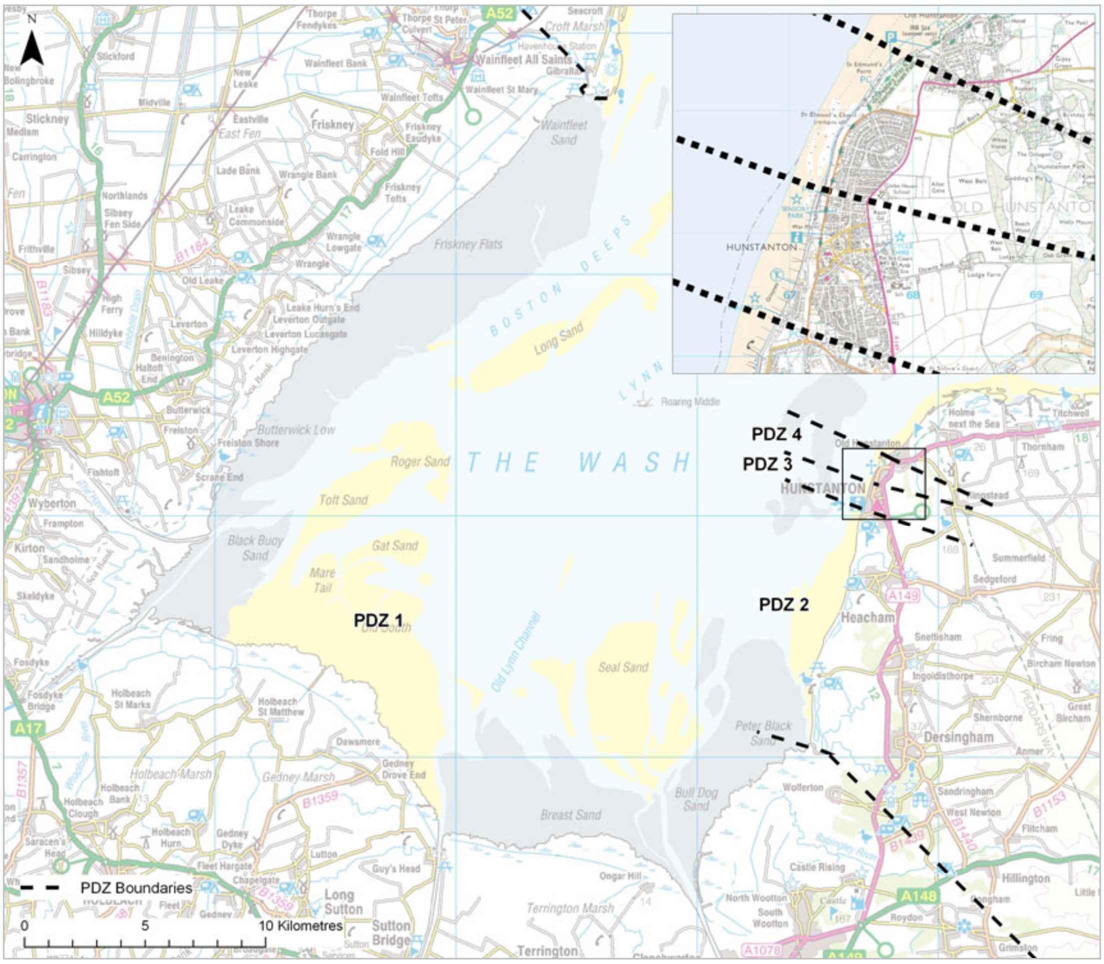
F5.1.2 Approach

The starting point of this task consists of the Policy Packages (PPs) and associated defence alignments. This is discussed in detail in appendix E.

For each PP, this assessment discusses the coastal evolution over the three epochs. The assessment uses the Policy Development Zones (PDZs) for which the PPs were developed. However, in order to assess the coastal processes at an appropriate scale, PDZ1 has been subdivided into three sub-PDZs (PDZ1.1, PDZ1.2 and PDZ1.3). The PDZs and sub-PDZs are as follows, and are shown diagrammatically in figure F5.2.

- PDZ1 – Gibraltar Point to Wolferton Creek;
    - PDZ1.1 – Gibraltar Point to left hand bank of River Witham,
    - PDZ1.2 – right hand bank of River Witham to left hand bank of River Nene.
    - PDZ1.3 – right hand bank of River Nene to left hand bank of Wolferton Creek.
- PDZ2 – Wolferton Creek to south Hunstanton (up to start of coast protection rather than flood defences);
- PDZ3 – Hunstanton Town;
- PDZ4 – Hunstanton Cliffs.

Figure F5.2 Policy Development Zones



F5.2 Overall Shoreline Response and General Assumptions

F5.2.1 Background

The Wash is a large embayment with its shape being influenced by the four main river outfalls and tidal streams. The geomorphology is dominated by a series of sand banks, low water channels, deepwater tidal channels and large inter-tidal expanses. The tidal channels are generally located parallel to the main axis of tidal flow and separate the flood/ebb dominant sediment transport pathways. These deepwater channels are incised into the underlying geology and reflect the old fluvial channels pre-reclamation.

The tidal range and sediment behaviour has a greater influence on the development of the Wash than the fluvial flow of the rivers. The main sedimentary processes involve sediment being transport into the centre of the embayment on the flood tide as suspended sediment, and then being transport out of the embayment along the outer flanks on the ebb tide. The sedimentary pattern is also influenced, to an extent, by high river flows and wave activity. During times of high freshwater flow from the rivers, there will be enhancement of the ebb current relative to the flood current. This leads to the increased potential for sediment export. Wave action also has the potential to cause localised areas of erosion and therefore increased sediment mobilisation.

The historic trend of land claim across the SMP area has reduced the influence of its tributary rivers which reduced the tidal prism, causing a loss of tidal energy within the embayment. This has led to a trend of saltmarsh accretion, which has been recorded in recent shoreline monitoring profiles.

F5.2.2 Overall Coastal Response

Before dealing with each PDZ/sub-PDZ individually it is beneficial to discuss the wider shoreline response of the whole SMP2 area. The majority of the PPs (apart from Hold the line) for each PDZ/sub-PDZ involve realignment, with the extent of realignment distinguishing between each individual PP.

As a result, it is useful to assess the shoreline response of the Wash SMP2 area assuming realignment (at an undefined scale). Sections 2 to 7 will then assess the specific shoreline response for an individual PDZ/sub-PDZ based upon the specific PP (ie. specific extent of realignment).

Realignment will increase the tidal prism (but to varying extents) and therefore has the potential to decrease the Wash's effectiveness as a sediment sink, although due to the fact that the reclaimed areas are generally at a lower elevation than the current saltmarsh, there is potential for accretion in these areas (as water may pond) and therefore saltmarsh development.

Realignment will also affect the deepwater tidal channels, inter-tidal expanses and sand banks, although it is thought that their position will be affected, but not their geomorphological functionality.

Although the above discussion suggests that there are likely to be some large-scale changes as a result of realignment, these changes are isolated to localised foreshore impacts, and are unlikely to have larger-scale longshore impacts. Each PDZ is also generally constrained by a river outfall. This generally acts to isolate each PDZ and therefore there is a lack of longshore interaction between PDZs. As a result, sections 2 to 7 will focus on cross-shore interactions within a specific PDZ only. This is applicable to all PDZs, except for the PDZ3 and PDZ4, where there is the potential for longshore interaction, and as a result this is discussed within the relevant section.

F5.2.3 Saltmarsh Development in Managed realignment Sites

The degree to which saltmarsh development will occur on a Managed realignment site is dependant on the soil conditions present in the site itself. Therefore, if the soil is resistant to erosion by waves and tidal currents, sediment accretion will occur at a similar rate (at least) to that of sea level rise. This will lead to the colonisation of plants which can withstand saline conditions, allowing further accretion, and leading to the development of saltmarsh.

The most successful Managed realignment schemes have been noted where the elevation of the site is within the elevation at which saltmarsh can grow. Success is also greatly dependant on whether the site is adjacent to an existing saltmarsh area which can act as a seed bank for flora and as a migration site for fauna. The size of the breach, presence of a relict/artificial creek network, and degree to which the site is sheltered from waves are also key factors which dictate whether a Managed realignment site will be a success.

In order to ensure continuity, and simplification, across this assessment, it has been assumed that following realignment, the former backshore area will develop into saltmarsh within the length of epoch 1 (i.e. 20 years). For example if an area is realigned in epoch 2, it has been assumed that saltmarsh development will occur by the end of epoch 2.

Although this is a simplified approach, it is not unsubstantiated. In August 2002, as part of the Wash Banks Flood Defence Scheme, the primary earth embankment protecting a 66 hectare site at Freiston Shore was breached in three places creating a large area of new intertidal habitat. Following the realignment, extensive monitoring has been undertaken to assess the success of the scheme. This has included a 4 year environmental monitoring programme between 2002 and 2006 which focused on accretion/erosion rates, vegetation colonisation, establishment and succession, invertebrate colonisation and fish utilisation (Brown et al 2007), a further 5th year of accretion and vegetation surveys in 2007 (Brown 2008) and a PhD thesis that investigated the impacts of the realignment on the intertidal sediment dynamics (Symonds 2006). As a result of this extensive monitoring, the following conclusions can be drawn from the Managed realignment scheme at Freiston Shore:

- The scheme was a success.
- The newly created intertidal area was colonised by halophytic vegetation (vegetation that is adapted to surviving in saline environments) some 12 months after the breach. It has been noted that, by September 2005, 70% of the realignment area was covered by saltmarsh vegetation. The site's biodiversity is now close to matching the surrounding marsh land.
- The site can be described as accretional. Accretion has occurred at rates similar to those of the adjacent saltmarsh at the equivalent elevation range. Mean annual accretion rates have been noted of between 6 and 10 $mmyr^{-1}$.
- The site now experiences low wave activity, reducing the loading on the new frontline defence.
- The realignment scheme has not caused any adverse effects on the old established saltmarsh.
- Initial high rates of erosion were noted in the creeks outside of the realignment site, but this regained its natural equilibrium within 5 years following the breach.

The morphology and overall coastal processes of the Freiston Shore site is comparable to the stretch of coast between Gibraltar Point and River Witham, and to some extent to the coast between the River Witham and Wolferton Creek (although here the saltmarsh is more developed and is experiencing less erosion). As a result it is logical to assume that the saltmarsh development discussed above is likely to occur on the varying extents of realignment proposed by each of the agreed Policy Packages.

It is important to note here that, as with the Freiston Shore example, identifying and excavating old creek lines within the realigned site is extremely important in allowing saltmarsh development. Also, due to the fact that the potential realignment areas in this SMP are often lower in surface elevation and therefore lower in tidal frame, than the adjacent marshes, they may be vulnerable to scour and erosion, with strong flood and ebb currents created following bank breach. This process has been noted at the Medway Estuary. As a result, it is essential that comprehensive research is undertaken in order to fully understand the hydrological, sedimentological and ecological aspects of a potential realignment site, and the effects of realignment on the site and surrounding intertidal area.

These are all something that will need to be considered as part of any strategies or schemes that follow this SMP.

F5.2.4 Control of Rivers and River Outfalls

It has also been assumed in this assessment that the rivers and river outfalls will be controlled as they are today (so With Present Management). This management consists of maintenance of training walls and dredging to maintain the required navigable depth along the rivers. If this management is not continued, there is the potential for the following (Posford Duvivier 1995):

- Accretion at/near the tidal limit sluice which will impede the flood discharge through the sluice, and therefore decrease the upstream flood defence standard;
- Siltation at the land drainage outfalls, which will impede discharge and therefore decrease the land drainage standards. This will have a negative effect on the high grade agricultural land, and could lead to declassification of the land to a lower grade.
- Mud build-up at the side of the tidal channel around the high water mark, which will lead to an over steepened bank and increased potential for random slip failure of the banks. This is likely to endanger the tidal flood defences.
- Reduced navigational depths along the rivers, which will jeopardise the functioning of the main ports of the Wash area.

F5.2.5 Increased Rainfall and Storminess

Climate change impacts have been included in the assessment per PDZ/sub-PDZ in terms of using the current prediction of sea level rise, although the potential for increased rainfall and storminess has not.

Increased rainfall has the potential to cause higher freshwater flow out of the rivers and into the Wash embayment. This would enhance the ebb currents relative to the flood currents, leading to an increased potential for sediment transport out of the SMP2 area and therefore a trend of erosion of the inter-tidal area.

Increased wave activity (resulting from increased storminess) may also mobilise an increased volume of sediment from the sea bed, and therefore again an increased potential for sediment transport out of the SMP2 area. The increased wave activity may also cause changes to localised sections of the Wash frontage, again leading to increased sediment mobilisation and allowing larger waves to reach the defences, leading to the need for increased maintenance of the defences and higher defences in some areas.

F5.2.6 Creation of High Grade Agricultural Land on Reclaimed Saltmarsh

A number of the PPs incorporate some form of reclamation of the current saltmarsh to create high grade agricultural land. It is therefore important to consider the whether it is feasible to reclaim saltmarsh for use as Grade 1 or

Grade 2 agricultural land. This section will look at the factors that determine the agricultural grade of the land and the various numerical/descriptive limits of these factors.

The main physical factors that determine the grade of agricultural land are as follows:

- Climate – temperature and rainfall;
- Site – gradient, micro-relief and flood risk;
- Soil – texture, structure, depth, stoniness and chemical limitations.

Due to the fact that the potential areas for Advance the line are generally adjacent to current Grade 1 and Grade 2 land, it can be assumed that climate will in fact remain constant and therefore is not a factor that needs to be investigated. Therefore suitability of the saltmarsh for creation of Grade 1 or 2 agricultural land can be assessed based on Site and Soil.

Site

The main factors in terms of Site are the gradient of the land, the presence of micro-relief, and the flood risk.

For Grade 1 and 2 agricultural land, the gradient of the site should be a maximum of 7°. Calculations have been undertaken using SAR data and it is predicted that the gradients of the potential sites are much lower than 7° (is in fact in the region of 1°).

Micro-relief deals with any complex changes in slope angle and direction over short distances, or the presence of boulders or rock outcrops. It is predicted that the existing saltmarsh will not have any complex changes of slope angle/direction. This is assuming that the creeks are infilled and the land is levelled.

As the land will be reclaimed for agricultural use, it is assumed that flood risk will be very rare and short lived (both in summer and in winter) and this will therefore meet the specifications for Grade 1 land.

Soil

The main factors in terms of Soil are the texture and structure, the depth, the stoniness, and the chemical limitations.

In terms of soil depth, for Grade 1 there is a 60cm soil depth limit for Grade 1 soil, and considering the volume of sediment accretion across the saltmarsh this should not be a problem.

For stoniness, table F5.1 needs to be applied.

Table F5.1 Stoniness for Grade 1 and Grade 2 Agricultural Land

	Limiting % (vol) of hard stones in top 25cm of soil	
	Stones >2cm*	**Stones >6cm***
Grade 1	5	5
Grade 2	10	5

*Stones retained on a 2cm or 6cm square mesh sieve, as appropriate.

As the saltmarsh sediment is generally deposited fine sediment, it is thought that the land has the potential to be Grade 1.

The texture and structure factors are more difficult to assess as they deal with the specifics on the saltmarsh. However although these factors are the most difficult to assess, they will probably be the most important (limiting) factor in determining whether saltmarsh can be turned to Grade 1 or 2 land. Soils with a high proportion of silt or fine sand (which is likely to include saltmarsh) are inherently weakly structured and are prone to surface capping and slaking, especially if the topsoils have a low organic matter content. This is also closely linked to the chemical limitations of a saline soil. Sodium rich clay and silty soils developed in marine alluvium are potentially unstable if the land is drained. Progressive leaching of salt from the soil profile has the potential to lead to deflocculation of the clay particles and may lead to structural collapse (slaking) and drain failure through siltation. Measures can be taken to avoid or ameliorate these conditions, but such measures may prove unsuccessful.

Conclusions

The above discussion indicates that the current saltmarsh in the Wash SMP2 area has the potential to be turned into Grade 1 land as it meets the majority of the limiting factors. There is a large uncertainty surrounding the salinity of the soil and the effect that this salinity has on the structure of the soil. There are methods available to improve the saline condition if possible, although again there is an uncertainty regarding whether such methods would be successful.

Looking at the difference in the areas of Grade 1 and Grade 2 land in the Wash SMP2 area, it is apparent that the current Grade 1 land is located at an elevation of greater than 2.0 to 2.5 mODN. The Grade 2 land is lower than approximately 2.0mODN. The potential reclamation areas have historically experienced vertical accretion and are therefore currently at a location higher than 2.0mODN, and should therefore be suitable for Grade 1 land.

There are also important lessons to be learnt from historic reclamations. It is generally accepted that reclamations undertaken for the purpose of agriculture require between 1 and 3 years of intensive drainage to make the land suitable. Sandy soils generally take the least amount of time to be made suitable, whereas for clay soils the length of time is verging on 3 years.

This assessment of shoreline response under the PPs will therefore assume that the saltmarsh areas identified for potential reclamation will be suitable for agricultural purposes. The related time-scales between reclamation and agricultural use are also seen to be negligible in terms of the timeframe of the SMP.

F5.3 Gibraltar Point to River Witham (PDZ1.1)

F5.3.1 Introduction

For this sub-PDZ, there are four Policy Packages that were taken forward to appraisal:

- Maximum landward realignment: Landward Managed realignment to the maximum extent per epoch as defined in the Playing Field, including land use adaptation as required;
- 'Habitat-led' realignment: Setting a target size for the increase of intertidal habitat per epoch and find the most appropriate locations to achieve this;
- Hold the line: keep the existing alignment for all locations and for all three epochs;
- Local rebalancing: rationalise the alignment of the defence (if needed) to optimise the value for agriculture, habitats and other interests.

The northern area of this sub-PDZ primarily consists of the village of Wainfleet All Saints and the smaller village of Friskney further inland. The mud and sand flats, locally known as Friskney Flats and Wainfleet Sand, are used by the MoD as a bombing range. Towards the south of the sub-PDZ, there are numerous small villages such as Leverton and Freiston. Freiston Shore RSPB reserve has been developed on an area of Managed realignment.

There is an extensive intertidal area that constitutes the coastal lowland protected by a series of grassed earth embankments. These intertidal flats extend from 1 to 4 kilometres in the south, to 6 kilometres in the north, in a seaward direction. Much of the backshore zone is saltmarsh.

Figure F5.3 outlines the location and boundaries of the sub-PDZ.

Further details of the baseline characteristics of the sub-PDZ are summarised in table F5.2. These are given in more detail in the Baseline Scenarios report (see section F3).

Figure F5.3 PDZ1.1 Boundaries

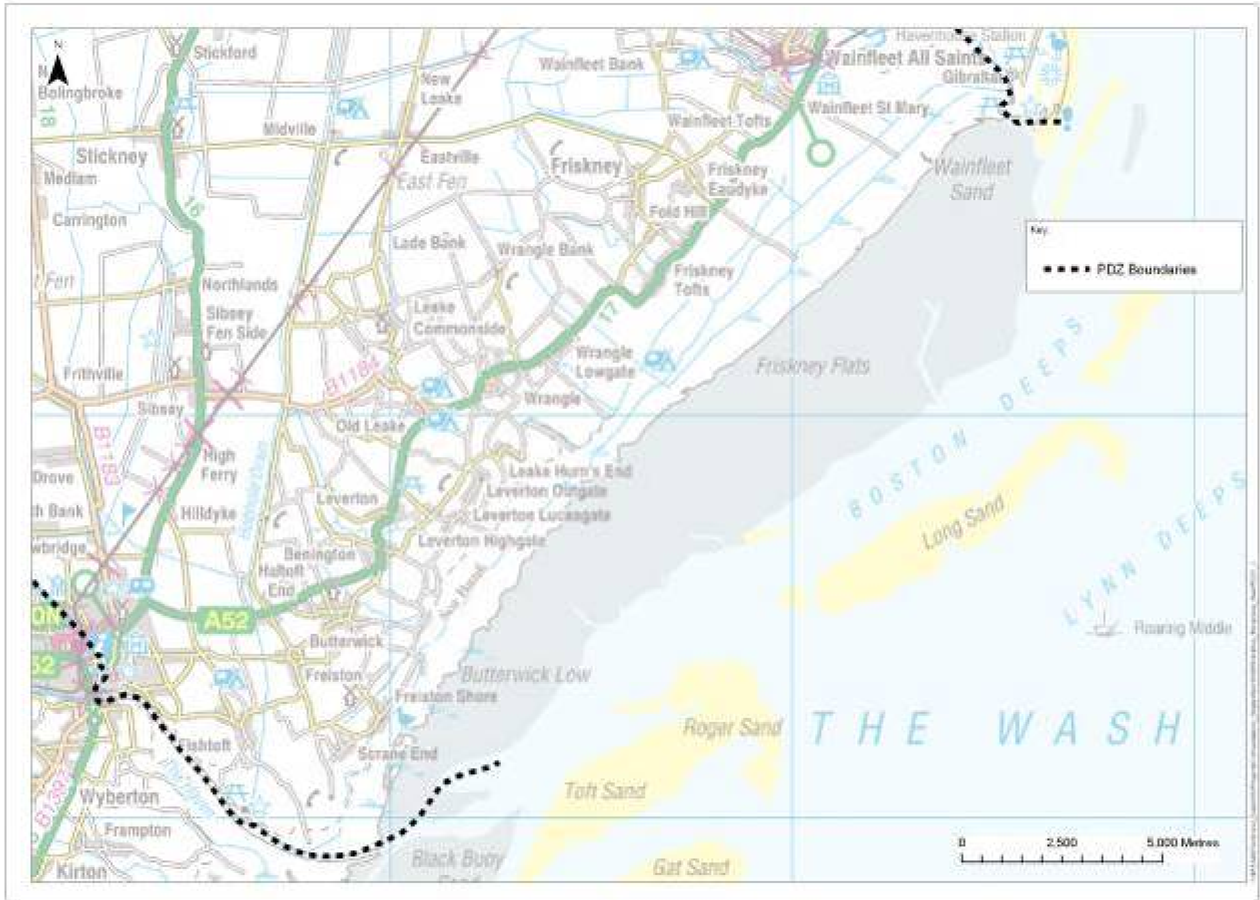


Table F5.2 PDZ1.1 Baseline Information

Geomorphological Components	*Gibraltar Point* – a soft mini headland that constrains the mouth of the Wash. *Long Sand, Toft Sand, Roger Sand and Bar Sand* – sand banks exposed at low water reducing wave energy, providing shelter to the intertidal area. Change in the shape of the bank could result in either accretion or erosion of localised areas. *Boston Deeps* – a parallel deep water channel that controls the low water mark along the sub-PDZ and subsequent mudflat erosion and accretion trends. *Clay Hole* – the outfall of both The Haven and The Welland that links to Boston Deeps. *Intertidal flats* – effective incoming wave and tidal energy dissipater. *Saltmarshes* – immature due to the continued land claim resulting in low level marsh height and little plant colonisation.
Historic Change	Wainfleet Sand has sediment accumulation due to Gibraltar Point providing shelter. The low water mark has moved seaward from 1828 to 1995. This is supported by an increased horizontal accretion rate with a decreased rate of advance of the saltmarsh/mudflat boundary from north to south. The saltmarshes at Freiston Low and Butterwick Low have retreated by 2-3myr^{-1} and 153myr^{-1} respectively (Hill, 1988). At Leverton Outgate, the saltmarsh/mudflat boundary has moved seaward whereas south of the Pumping Station this boundary has retreated. North of Butterwick, the MHWS mark has advanced, but it has retreated south of Freiston Shore.
Recent Change (1991-2006)	As a general rule, the whole sub-PDZ has seen an increase in saltmarsh both horizontally and vertically. There are local profiles that exhibit different trends. These areas of local erosion appear to be in areas of drainage channel networks and river profiles that explain the vertical erosion rates recorded.
Tidal Currents	Tidal currents can be relatively strong in the Wash due to its large tidal range. Average current velocities are between 0.8 and 1.0ms^{-1} (HR Wallingford, 1972).
Current Residuals	The current residuals of this sub-PDZ are divided. In the north the water column is directed north at approximately 54,000m^3/m/tide. In the southern half of the sub-PDZ it is directed to the south-west with 30,000 to 45,000m^3/m/tide. The overall direction of movement along the sub-PDZ is parallel to the coast in a north-easterly direction.
Sediment	Sources: Holderness Coast, Humber Estuary, North Norfolk coast, North Sea, the Wash mouth floor, The Haven and River Welland outfalls. Sinks: Long Sand, Toft Sand, Roger Sand, Long Sand, intertidal area and offshore banks associated with Gibraltar Point. Transport of sediment is primarily suspended with sediment deposited during low tidal velocities.

Processes	Tidal levels at Tab's Head (mCD): MHWS 3.30, MHWN 1.90, MLWN -1.30, MHWS -3.00. Extreme water levels vary from 4.26m for 1:1yr return period at Burgh Sluice to 6.27m for 1:1000 yr return period at River Witham (Mott Macdonald, 2006). Waves: mean wave height (Hs) 0.61m, mean wave period (Tz) 3.30s, waves are predominantly from an offshore direction approaching from the north to north-east.	
Existing Management	The majority of the defences are earth embankments, some supported by toe protection. There are often secondary and tertiary defences in addition to the sea bank. Most of the defences are expected to fail within the next 10 to 25 years under No active intervention, with the defences landward of Friskney Flats predicted to fail within 5 years, whereas those at Freiston Shore are only expected to fail within the next 50 years. The earth embankments are monitored and maintained by the Environment Agency with the Friskney Flats area owned by the Jubilee Bank Consortium.	
Intertidal Development	Northern section	Southern section
	Saltmarsh vertical accretion rates = 7mmyr^{-1}.. Mudflat vertical accretion rates = 2mmyr^{-1}. Horizontal accretion = 6.6myr^{-1}. Defra sea level rise prediction based on 1991 to 2006 = approx. 4.0mmyr^{-1}	Saltmarsh vertical accretion rates = 7mmyr^{-1}. Mudflat vertical accretion rates = 6mmyr^{-1}. Horizontal accretion = 4.9myr^{-1}. Defra sea level rise prediction based on 1991 to 2006 = approx. 4.0mmyr^{-1}

F5.3.2 Future Developments Independent of Policy Packages

The policy packages in this zone have both localised and longshore impacts on coastal processes, but this occurs against the background of the ongoing development of the intertidal area which is driven by expected sea level rise and overall processes in the Wash. These background developments for each epoch are described here, based on the Baseline Scenarios analysis; the subsequent sections focus on the specific developments per policy package.

The rate of sea level rise for epoch 1 at $4mmyr^{-1}$ predicted by Defra is slower than the rate of saltmarsh sedimentation at $7mmyr^{-1}$. This will result in the continued vertical accretion across the saltmarsh. With a lower mudflat accretion rate than sea level rise at $2mmyr^{-1}$, the mudflats will continue with growth but the mean high and low water marks will move landward. Overall the saltmarsh/mudflat boundary will continue to move seaward at $6.6myr^{-1}$. The mean high and low water marks will continue to move landward due to sea level rise. Local profiles will exhibit areas of horizontal accretion or erosion where they intersect drainage channels.

In epoch 2, the rate of sea level rise would be greater at $8.5mmyr^{-1}$, which is greater than both the predicted rate of saltmarsh and mudflat accretion. Despite this trend, it is expected that the vertical accretion across the saltmarsh would continue during epoch 2 as there would not be significant inundation of the saltmarsh on every high tide (i.e. there would be sufficient inundation and velocities across the saltmarsh to promote sedimentation, but not enough to cause erosion). The mean high and low water marks will continue to move landward as the rate of sea level rise increases. The saltmarsh/mudflat boundary is likely to remain stable.

In epoch 3, the faster rate of sea level rise (between 12.0 and $15.0mmyr^{-1}$) will restrict the accretion of the saltmarsh and mudflats and erosion of the saltmarsh/mudflat boundary is likely to begin, causing a landward movement of the boundary.

Note that the uncertainty of the predicted developments (both background development and related to the policy packages) increases from epoch 1 to epoch 3.

F5.3.3 Impacts: Maximum landward realignment

<u>Epoch 1 (present day to 2025)</u>

The analysis is based on the assumption that the new formal defence lines will be brought up to standard first, after which the existing frontline defences will be breached in various locations. The agreed Playing field defines the location of the new formal defence lines (i.e. the Maximum landward realignment extent). The area of saltmarsh will increase following breaching of the existing frontline banks during the first epoch, leading to a change in the area of saltmarsh in subsequent epochs.

Epoch 1 will therefore be dominated by vertical and horizontal accretion of both the saltmarsh and mudflats, and realignment will create an increased intertidal area, which is likely to have developed into saltmarsh by the end of the epoch.

The associated movement under Maximum landward realignment for epoch 1 is illustrated in figure F5.4.

Epoch 2 (2025 to 2055)

Epoch 2 allows a much greater area of Managed realignment to occur. In some places, the agreed playing field allows the coastline to be realigned by up to 3km inland of its present position.

The associated movement under Maximum landward realignment for epoch 2 is illustrated infigure F5.5.

Epoch 3 (2055 to 2105)

There will be no further realignment in epoch 3; therefore this epoch will be characterised by further development of the saltmarsh within the realigned areas. This will further reduce wave energy for the realigned defences, although this trend will start to be counteracted by the background development of coastal squeeze in this epoch. Note that there is uncertainty regarding how quickly the young saltmarsh in the formerly defended areas will develop, and this will greatly affect its potential to effectively dissipate wave energy.

The associated movement under Maximum landward realignment for epoch 3 is illustrated in figure F5.6.

F5.3.4 Impacts: 'Habitat-led' realignment

Epoch 1 (present day to 2025)

The 'Habitat-led' realignment for this sub-PDZ moves the current defences landward at the south of the sub-PDZ around Freiston Shore. This small area of realignment will begin the development into saltmarsh. However, overall this package will be much the same as with Hold the line as the landward realignment of the defences is not particularly great. As a result accretion (both vertical and horizontal) will be dominant in epoch 1.

This movement is illustrated in figure F5.7.

Epoch 2 (2025 to 2055)

In this epoch, the 'habitat–led' PP will require realignment back to the secondary defence line along a number of sections of the sub-PDZ. This will cause an increase of saltmarsh area in the newly realigned sections. Overall the saltmarsh area will increase due to the realignment, and there will be continued vertical accretion.

This movement is illustrated in figure F5.8.

Epoch 3 (2055 to 2105)
Erosion will be the prominent process on this sub-PDZ during this epoch. Although the wider foreshore, created as a result of alignments in epoch 3, will lead to an increase in wave dissipation, the small scale of the realignment means that defences would need to be able to withstand increased overtopping and greater wave energy pressure. The realignment at the north of the sub-PDZ in the lee of Gibraltar Point will allow saltmarsh to develop in this area.

This movement is illustrated in figure F5.9.

F5.3.5 Impacts: Hold the line

Epoch 1 (present day to 2025)
This Policy package leads to an unchanged defence alignment, so the coastal processes are as described in section F5.3.2. Sea level rise and possible increased storminess may increase loading on the defences, but this is to some extent counteracted by the accretion of the intertidal area causing increased wave dissipation.

The movement associated with the Hold the line policy is illustrated in figure F55.10.

Epoch 2 (2025 to 2055)
The defence alignment remains unchanged, so the coastal processes are as described in section F5.3.2. Sea level rise and possible increased storminess will increase loading on the defences; the dissipative effect of the foreshore will still increase, but at a slower rate.

The movement associated with the Hold the line policy is illustrated in figure F5.11.

Epoch 3 (2055 to 2105)
The defence alignment remains unchanged, so the coastal processes are as described in section F5.3.2. The process of coastal squeeze in this epoch could significantly increase hydraulic pressure on the defences.

The movement associated with the Hold the line policy is illustrated in figure F5.12.

F5.3.6 Impacts: Local rebalancing

Epoch 1 (present day to 2025)

The local rebalancing for this sub-PDZ moves the current defences landward to the secondary line of defence in a number of locations. Saltmarsh will gradually develop in those areas of realignment. As a result the shoreline response will be similar to that described in section F5.3.5, but with a small increase in natural defence which will act to reduce the loading on the defences at the realignment locations.

This movement for local rebalancing is illustrated in figure F5.13.

Epoch 2 (2025 to 2055)

In this epoch, the defence alignment does not change. Shoreline response will generally be similar to that described in section F5.3.5, although the increased intertidal areas will continue to develop and will act to dissipate wave energy.

This movement for local rebalancing is illustrated in figure F5.14.

Epoch 3 (2055 to 2105)

Again, this epoch sees no further changes in defence alignment. The foreshore width will start to decrease, but a significant width will remain throughout the frontage as a result of the realignment from earlier epochs.

This movement for local rebalancing is illustrated in figure F5.15.

Figure F5.4 PDZ1.1 Maximum landward realignment epoch 1

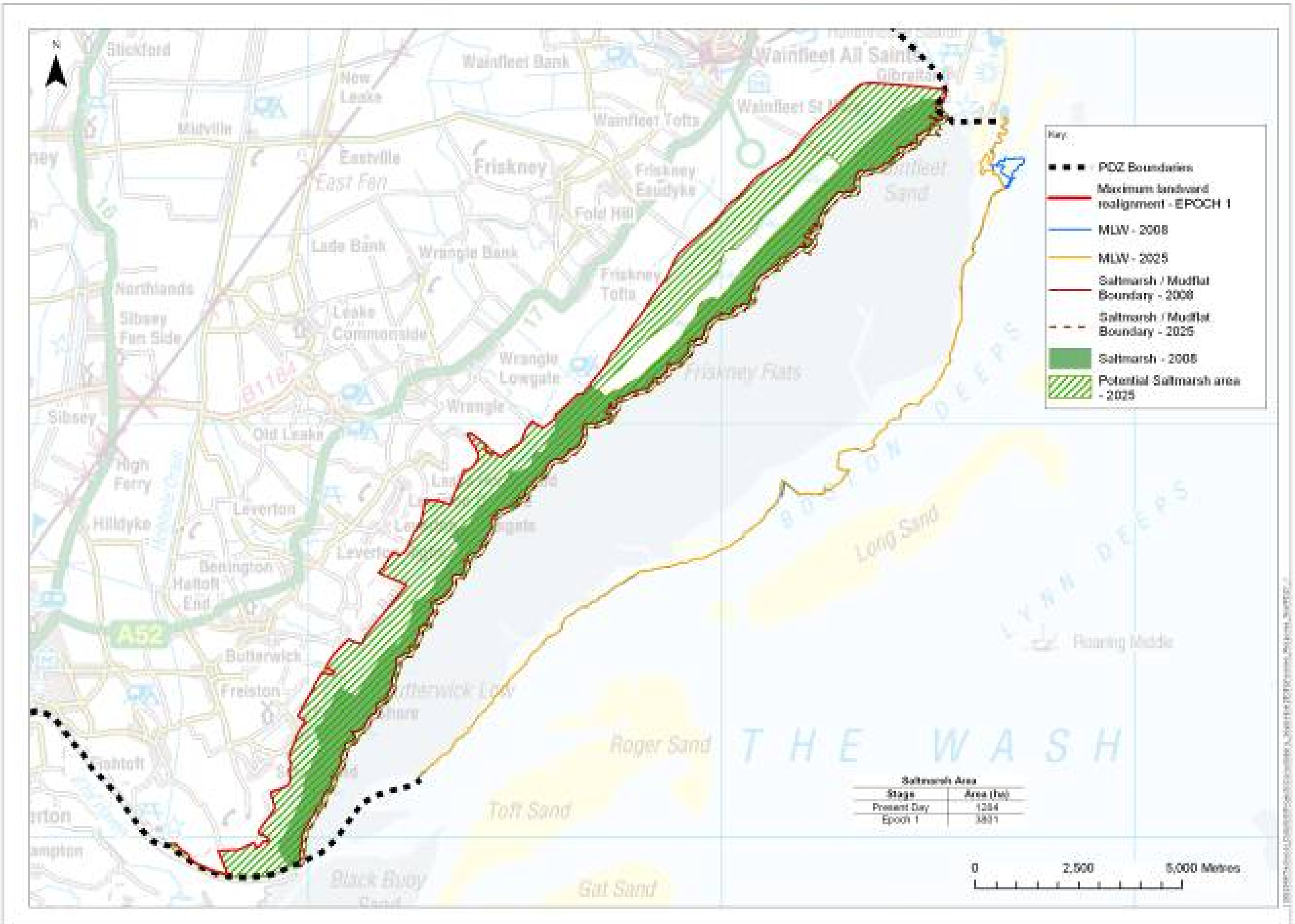


Figure F5.5 PDZ1.1 Maximum landward realignment epoch 2

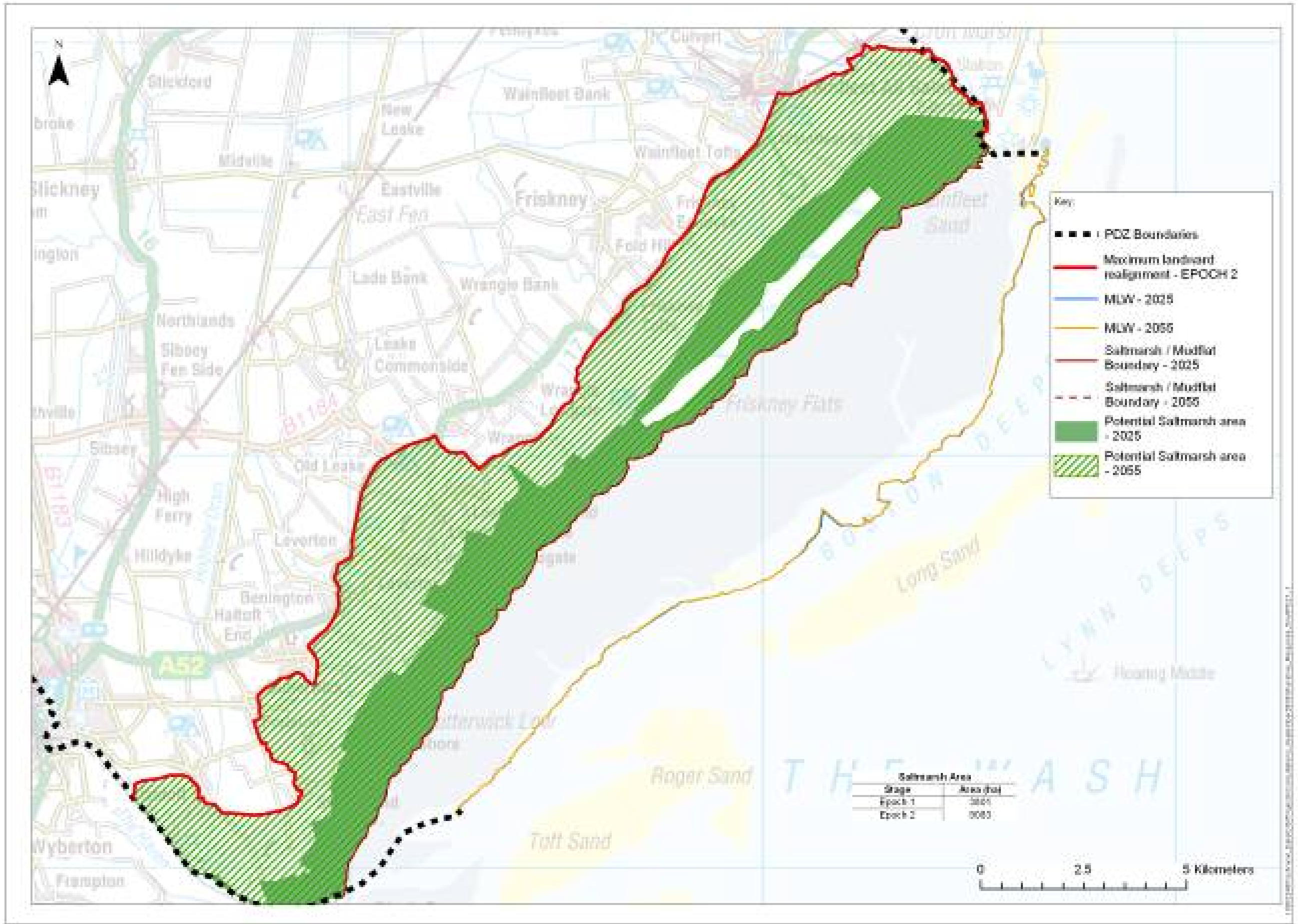


Figure F5.6 PDZ1.1 Maximum landward realignment epoch 3

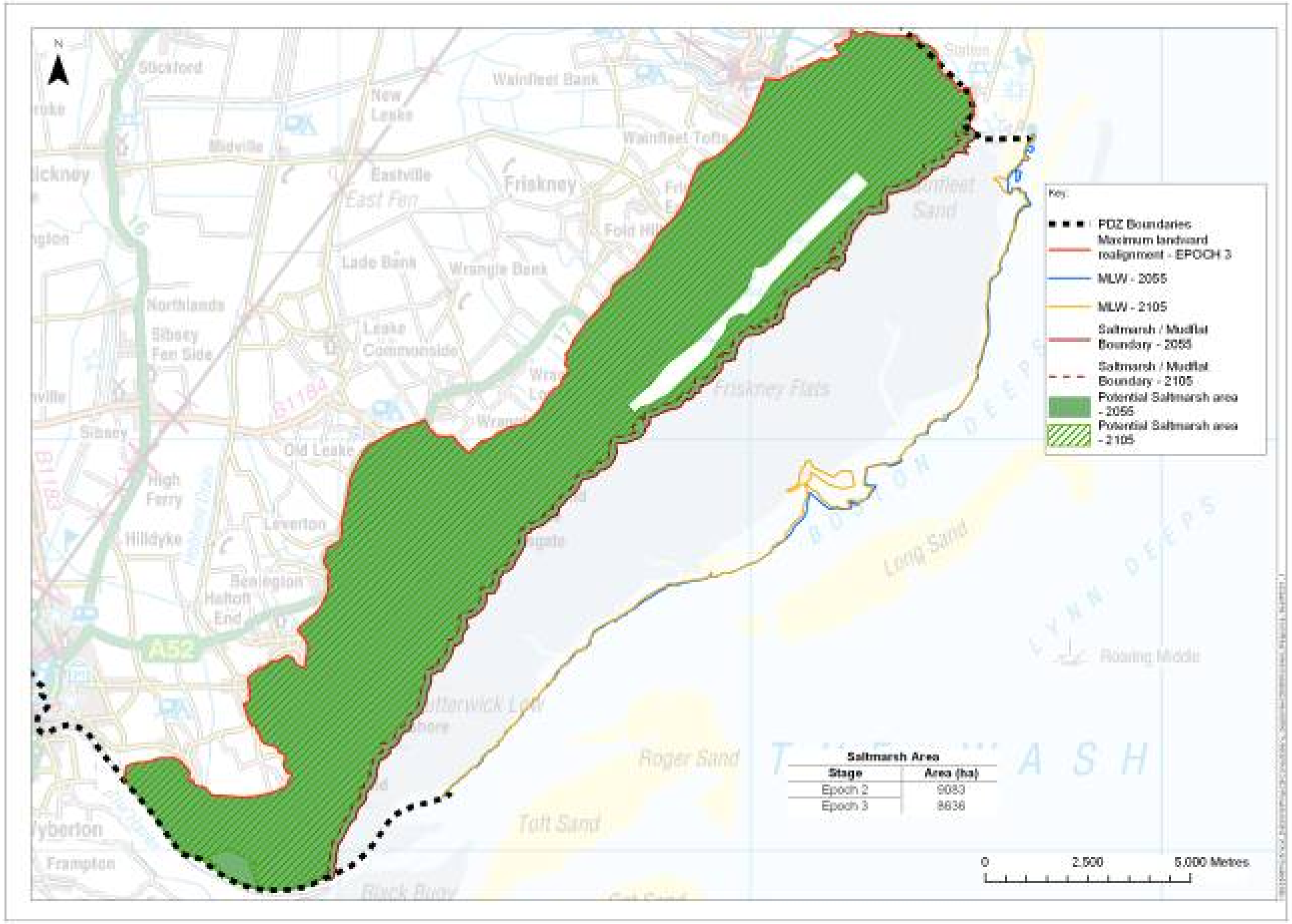


Figure F5.7 PDZ1.1 'Habitat-led' realignment epoch 1

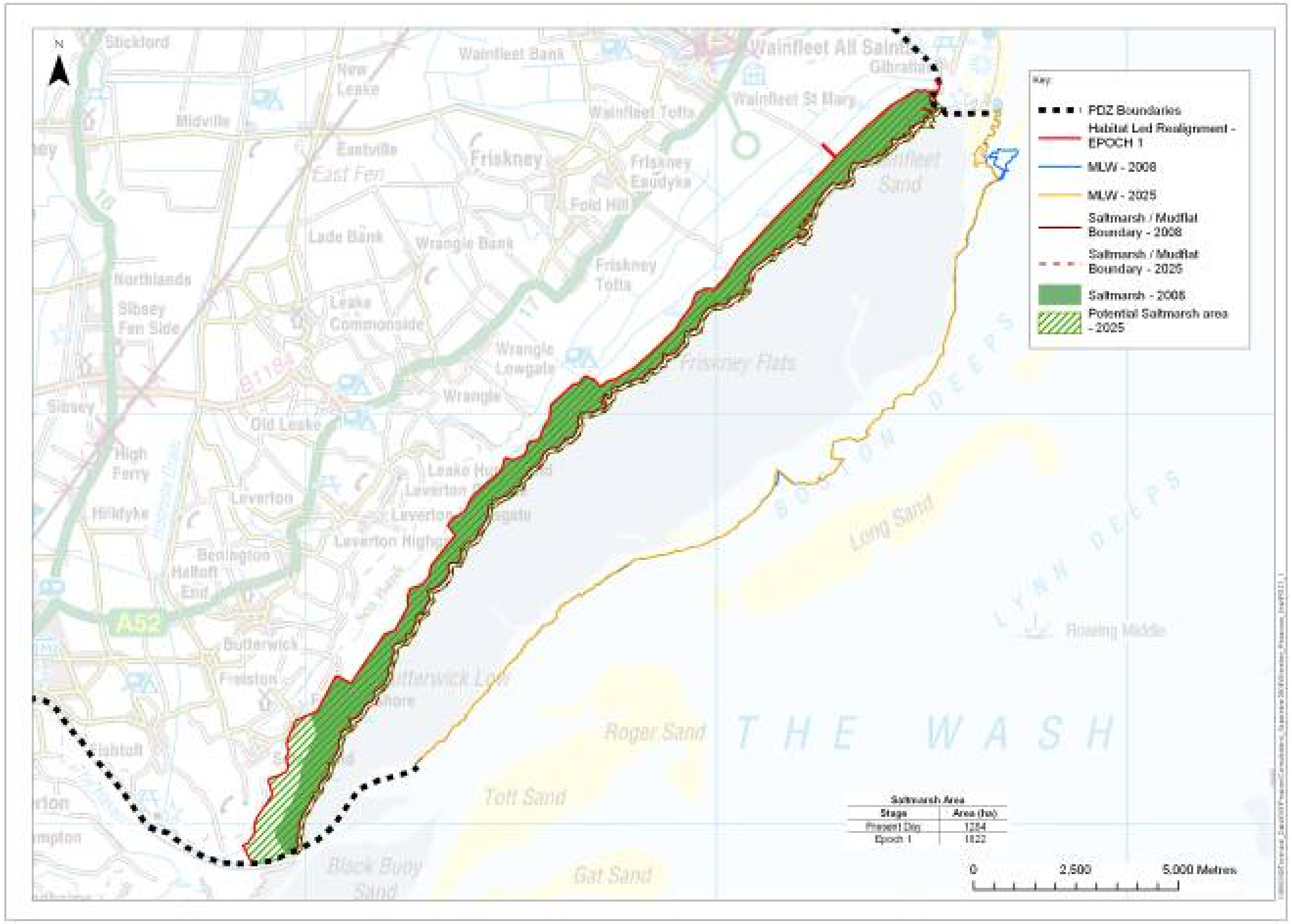


Figure F5.8 PDZ1.1 'Habitat-led' realignment epoch 2

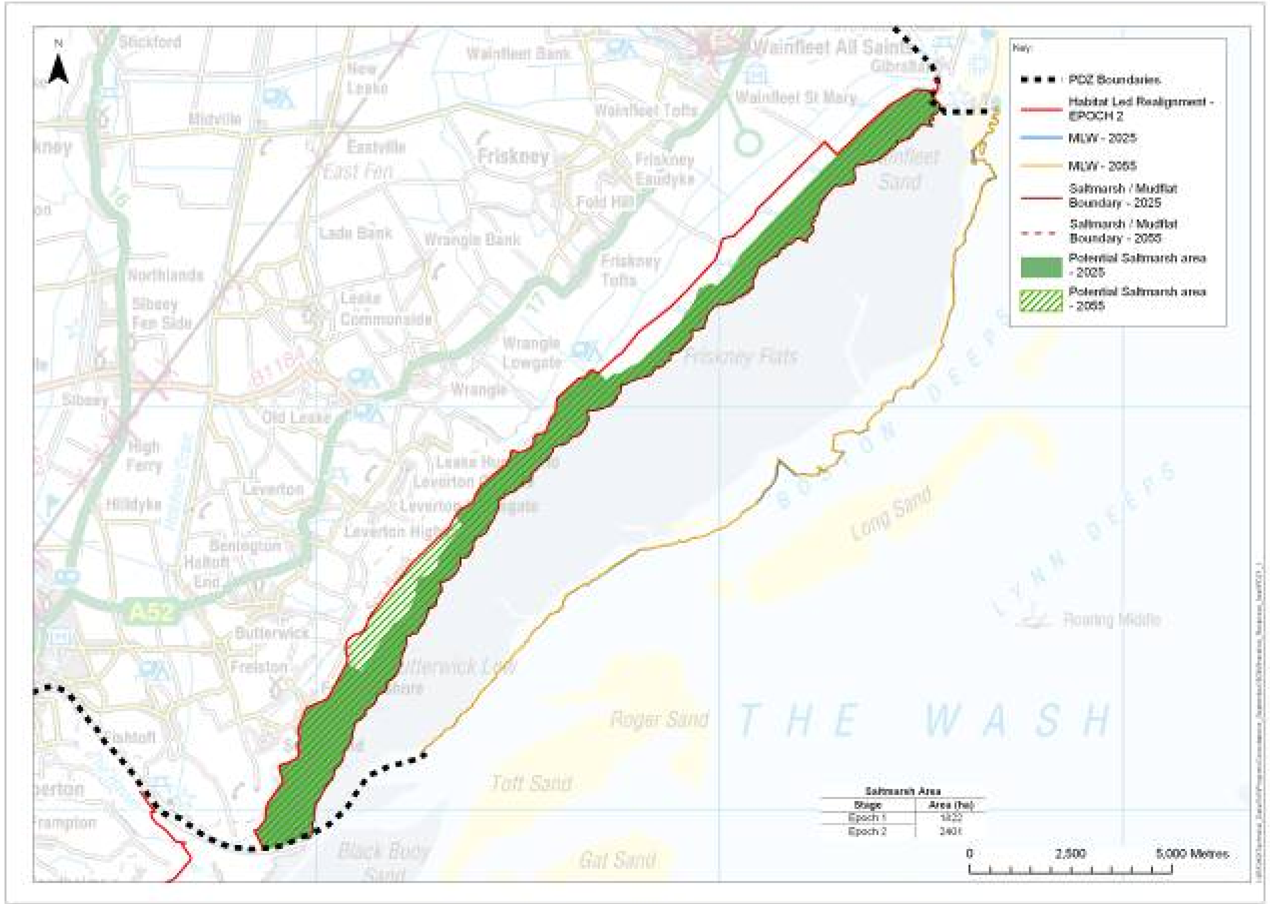


Figure F5.9 PDZ1.1 'Habitat-led' realignment epoch 3

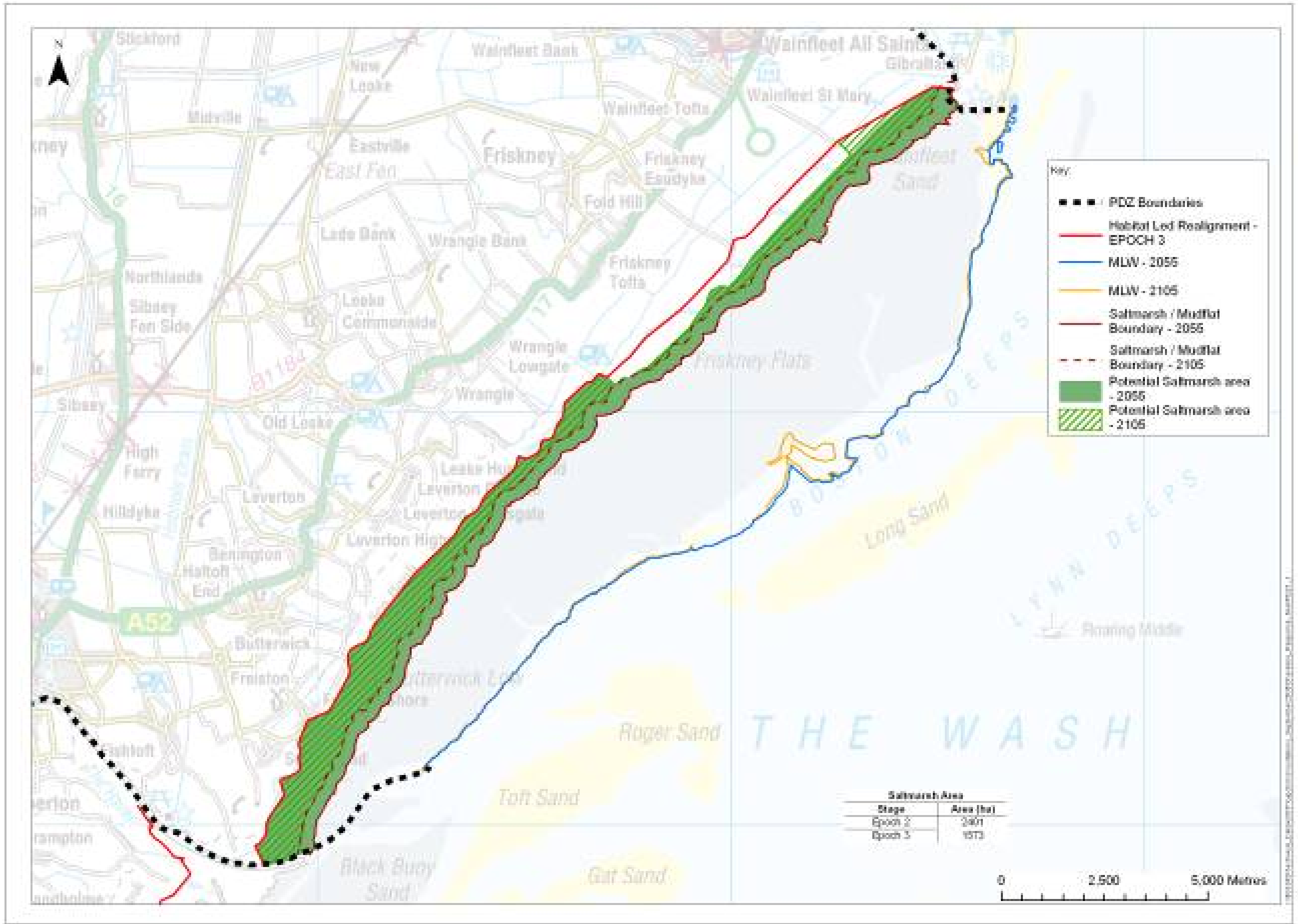


Figure F5.10 PDZ1.1 Hold the line epoch 1

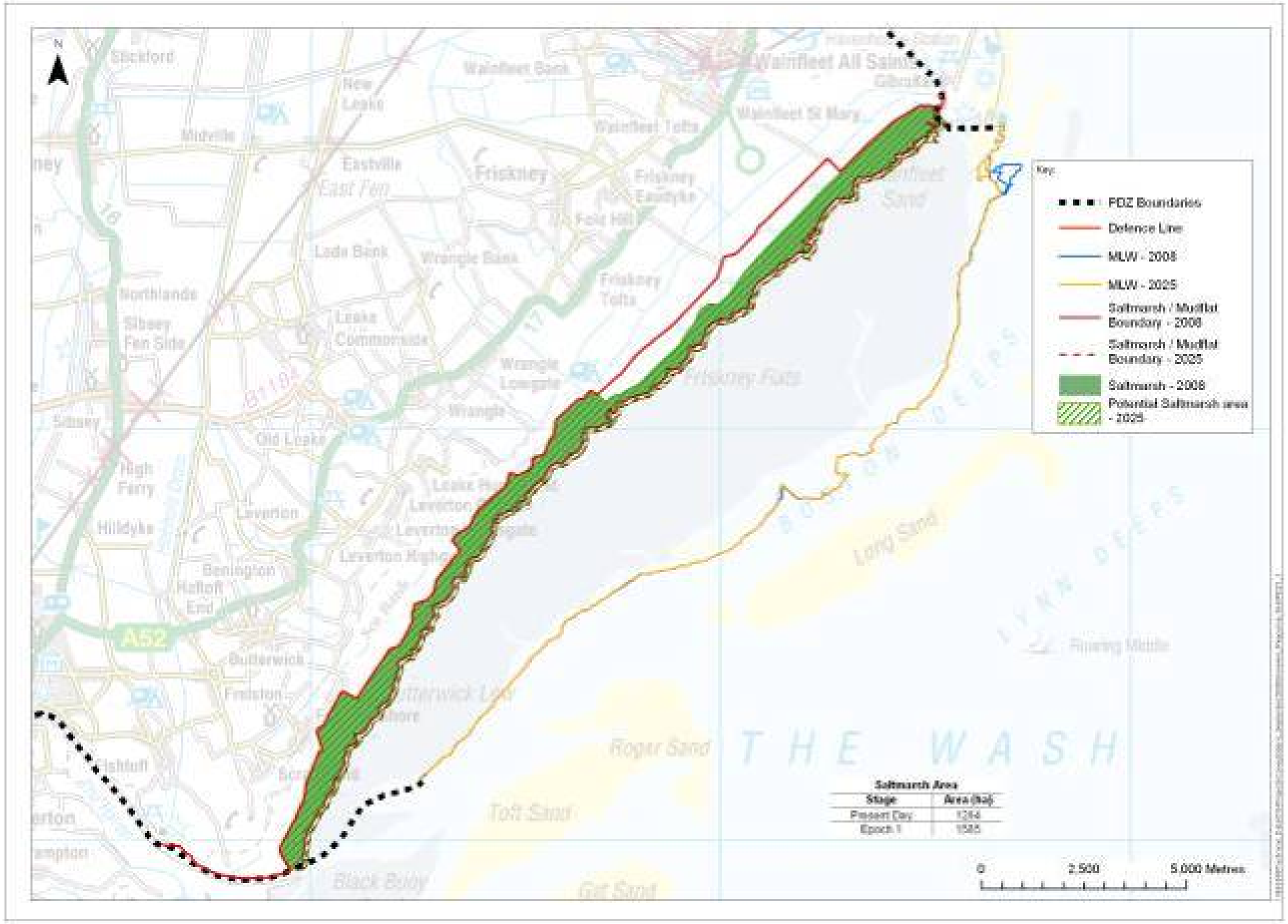


Figure F5.11 PDZ1.1 Hold the line epoch 2

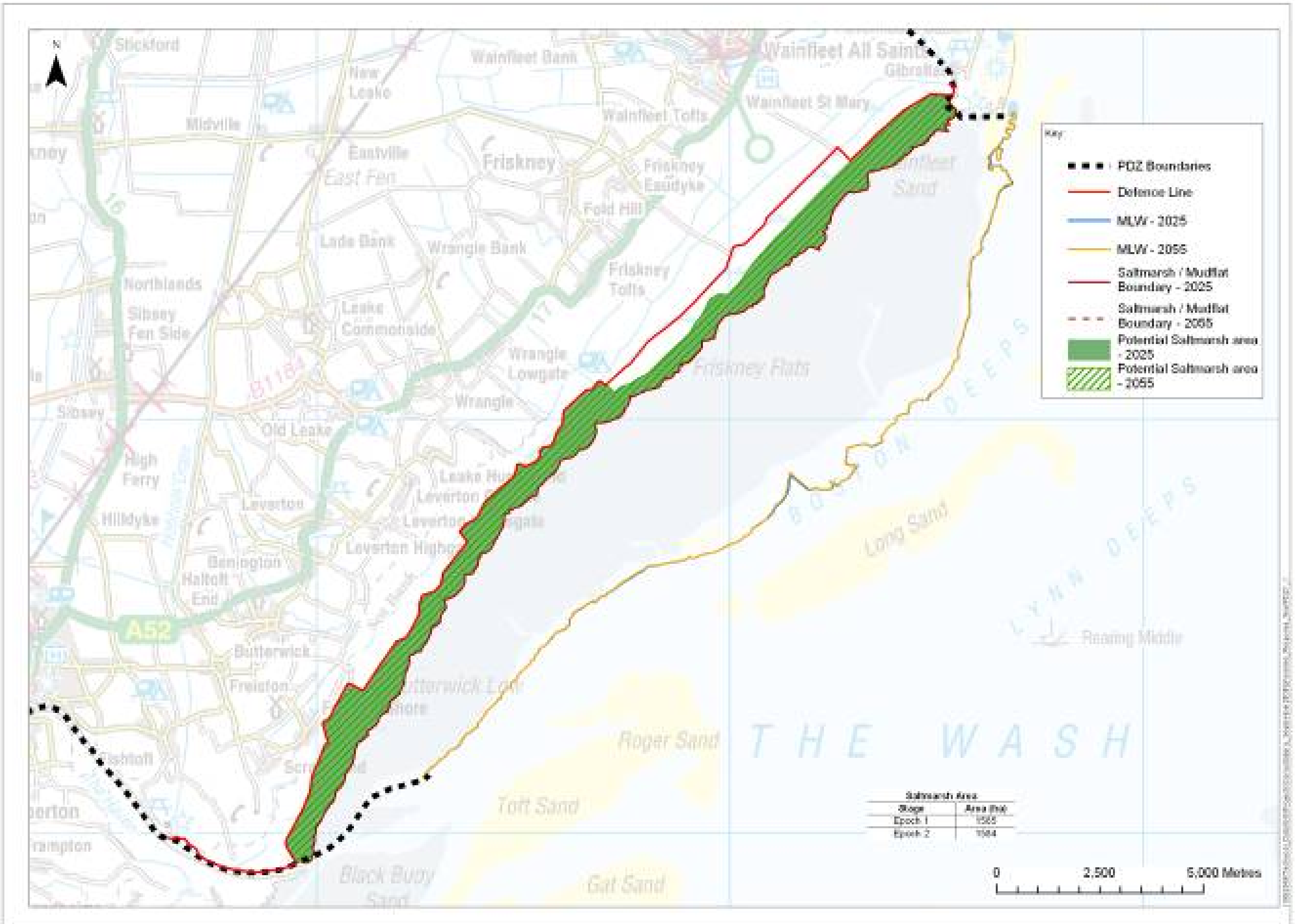


Figure F5.12 PDZ1.1 Hold the line epoch 3

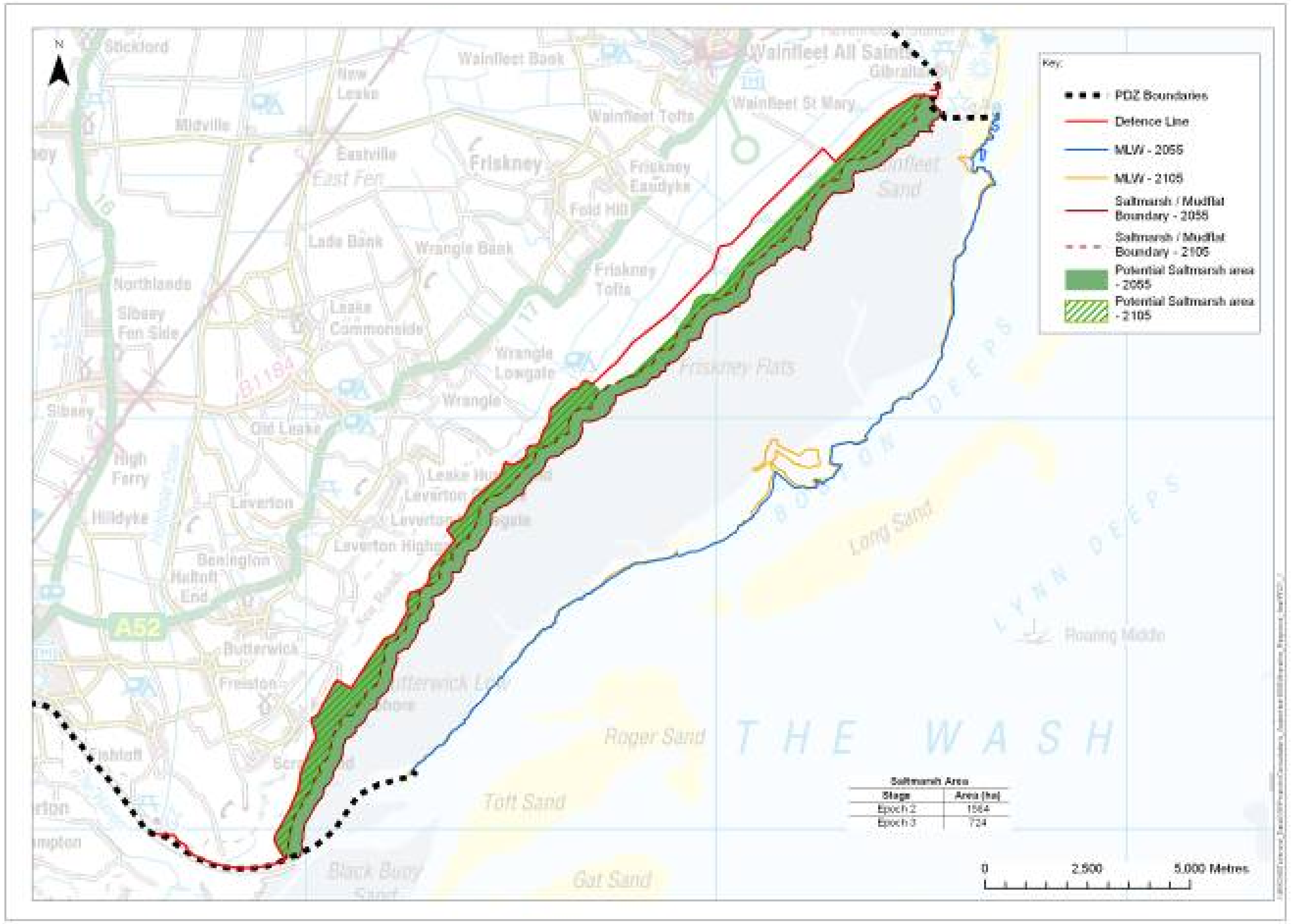


Figure F5.13 PDZ1.1 Local rebalancing epoch 1

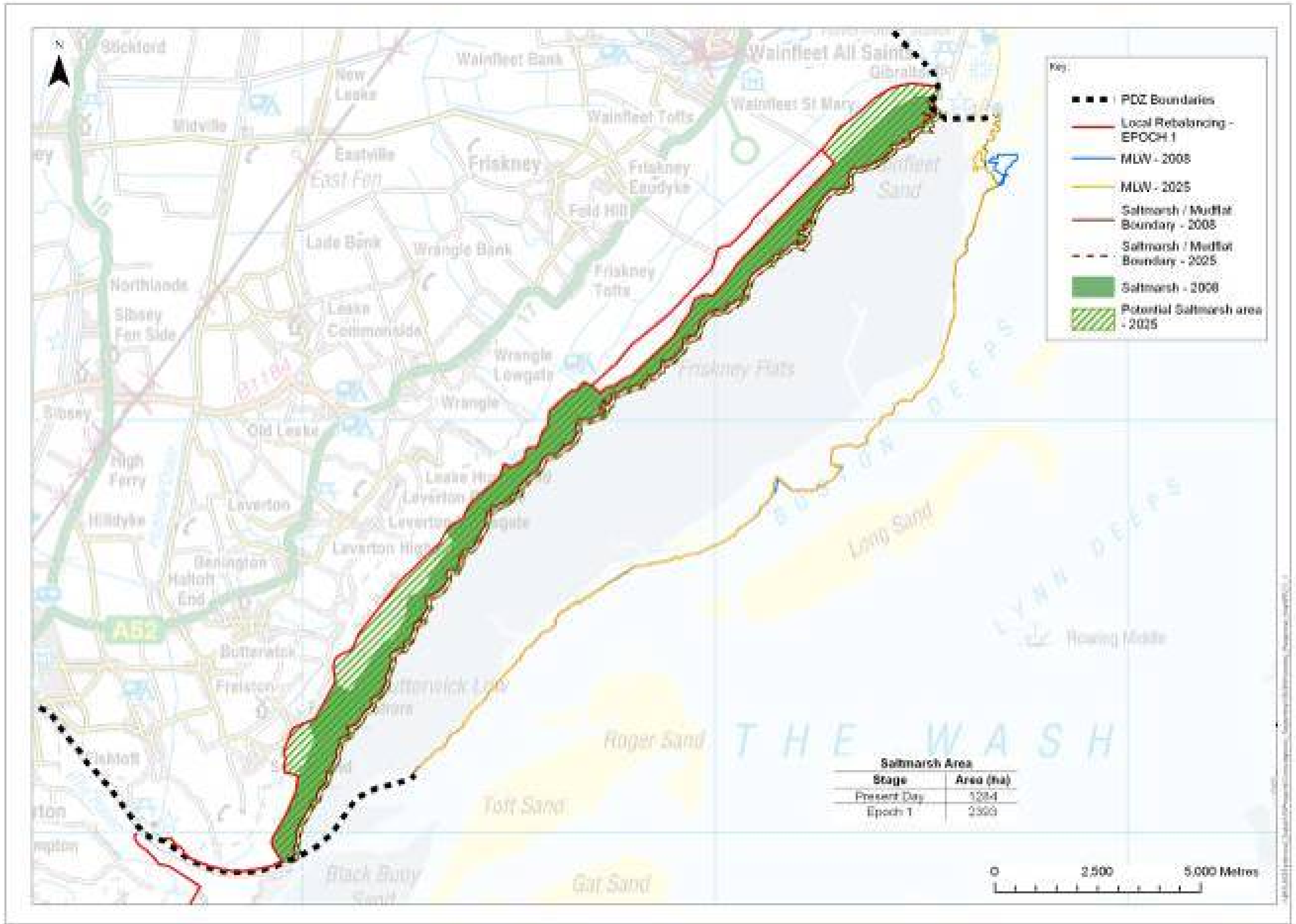


Figure F5.14 PDZ1.1 Local rebalancing epoch 2

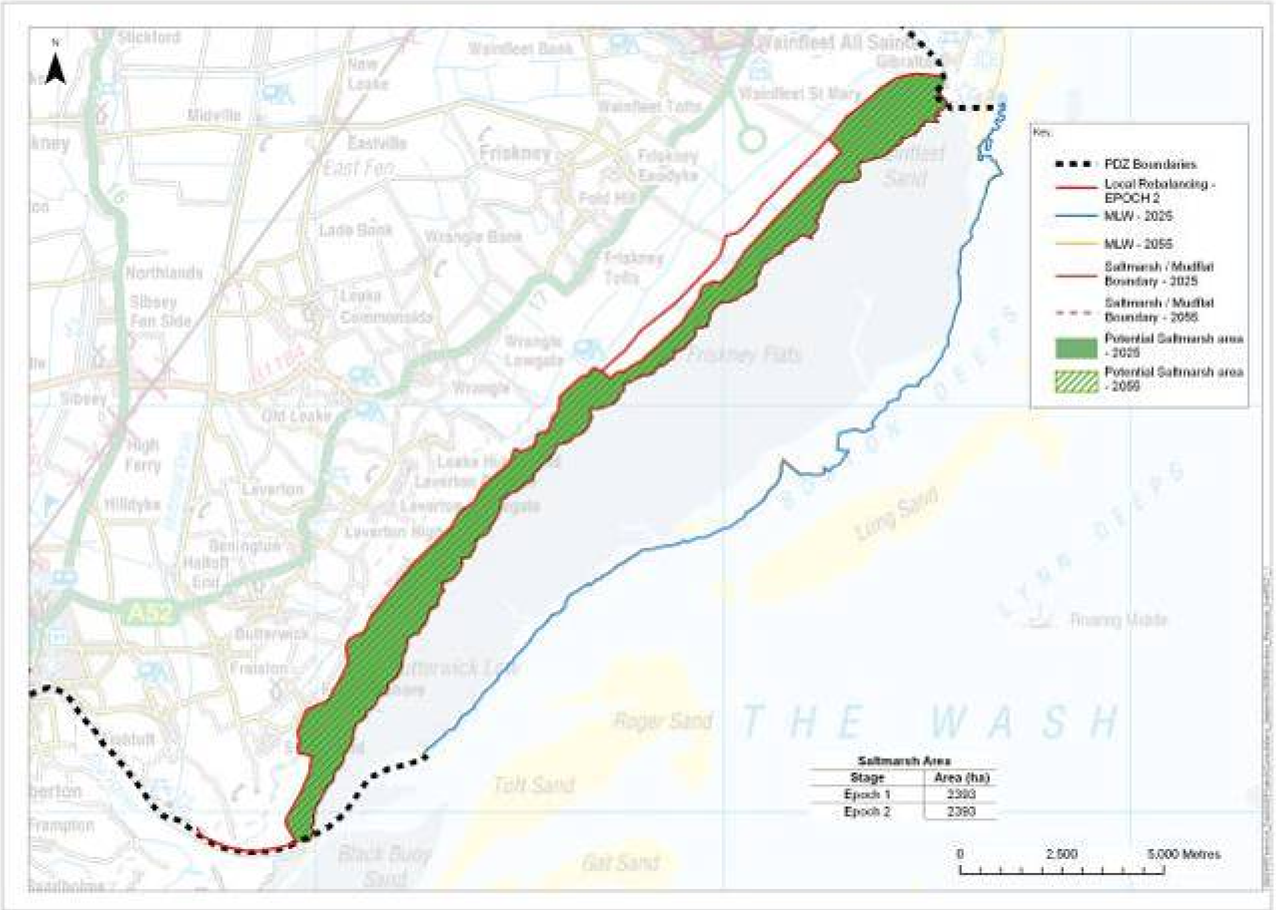
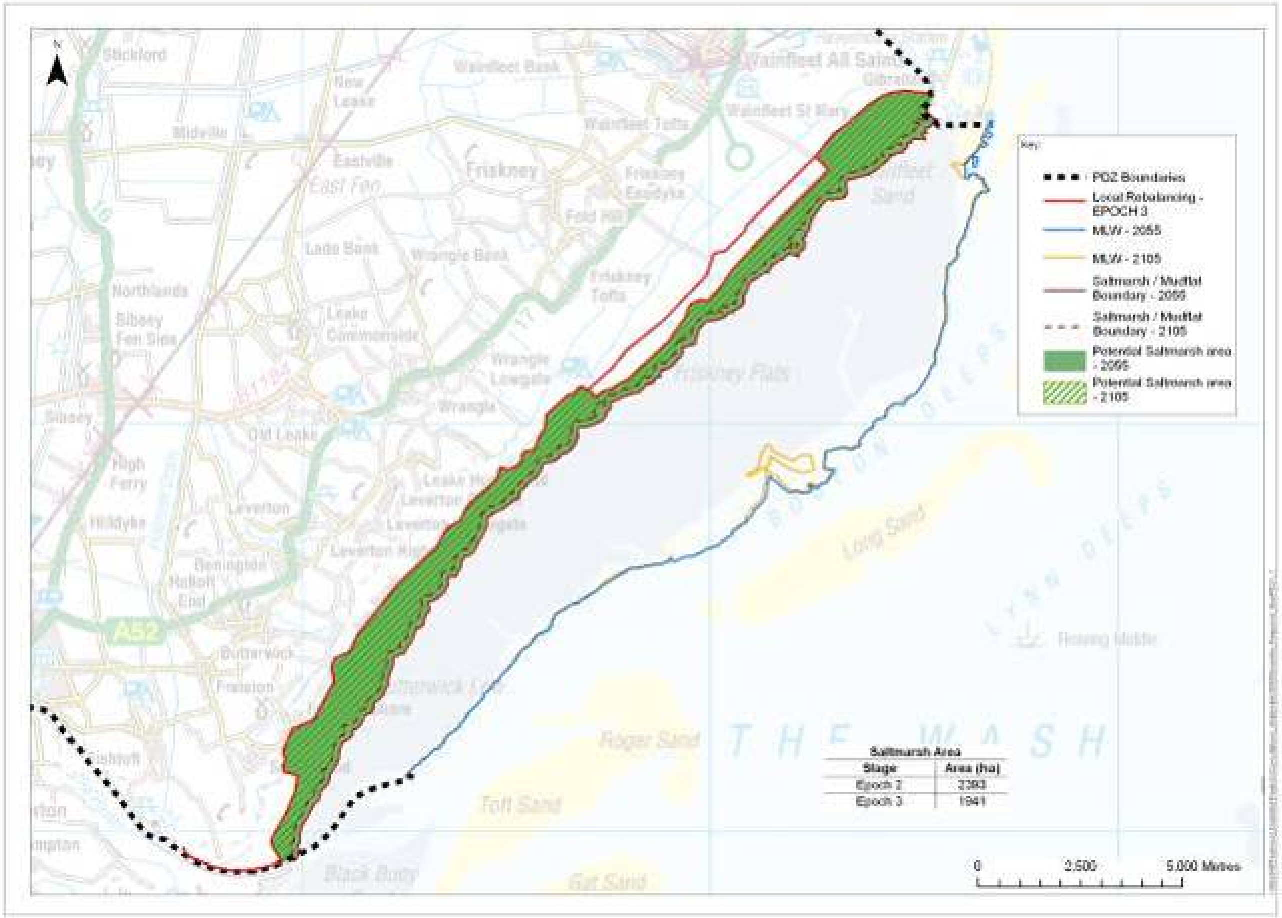


Figure F5.15 PDZ1.1 Local rebalancing epoch 3



F5.4 River Witham to River Nene (PDZ1.2)

F5.4.1 Introduction

This area belongs to PDZ1, so it has the following four Policy Packages for appraisal:

- Maximum landward realignment: Landward Managed realignment to the maximum extent per epoch as defined in the Playing Field, including land use adaptation as required;
- ‘Habitat led’ realignment: Setting a target size for the increase of intertidal habitat per epoch and find the most appropriate locations to achieve this;
- Hold the line: keep the existing alignment for all locations and for all three epochs;
- Local rebalancing: rationalise the alignment of the defence (if needed) to optimise the value for agriculture, habitats and other interests.

This sub-PDZ has a small number of villages supported by the small town of Kirton. There has been much accretion in this area with much of the sediment that enters the Wash being deposited along this sub-PDZ. The intertidal flats are wider compared with those along sub-PDZ1.1.

The eastern limit of the sub-PDZ is bound by the River Witham (The Haven) and the western limit by the River Nene.

Figure F5.16 outlines the location and boundaries of the sub-PDZ.

Further detail of the characteristics of the sub-PDZ are summarised in table F5.3. These are given in more detail in the Baseline Scenarios report.

Figure F5.16 PDZ1.2 Boundaries

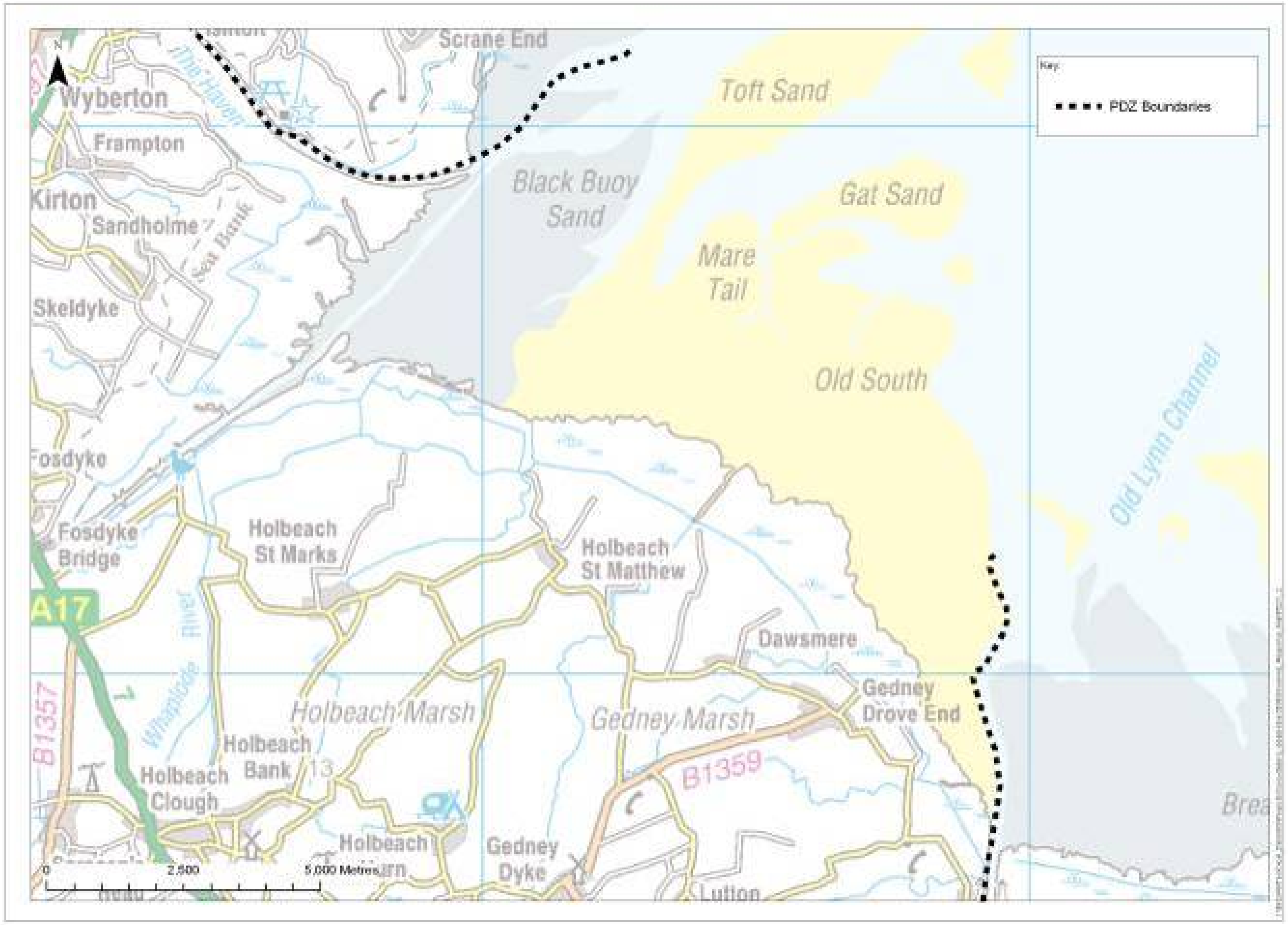


Table F5.3 PDZ1.2 Baseline Information

Geomorphological Components	*Black Buoy Sand, Toft Sand, Roger Sand, Mare Tail and Gat Sand* – sand banks connected to the intertidal area of this sub-PDZ. *Lynn Deeps* – controls the low water mark along the sub-PDZ and feeds incoming sediment for the sub-PDZ. *Clay Hole* – as with sub-PDZ1.1 but also traps sediment explaining the mature saltmarsh. *Crabs Hole* – River Nene outfall resulting in large width of mature saltmarsh.
Historic Change	There has been a long-term net accretion of saltmarsh along this sub-PDZ. This in turn has influence on the low water mark and contributed in moving it seawards.
Recent Change (1991-2006)	The Environment Agency monitoring has shown both vertical and horizontal accretion. This is variable across the upper saltmarsh, accretion of the lower saltmarsh and strong accretion along the upper mudflat.
Tidal Currents	Tidal currents can be relatively strong in the Wash due to its large tidal range. Average current velocities are between 0.8 and 1.0ms^{-1} (HR Wallingford, 1972).
Current Residuals	The net water transport of this sub-PDZ is complex. There is 50,000m^3/m/tide directed to the south-west, 30,000m^3/m/tide to the east-south-east and 21,000m^3/m/tide directed to the south-east. This results in an overall movement of south-south-west onto the sub-PDZ.
Sediment	Sources: Holderness Coast, Humber Estuary, North Norfolk coast, North Sea, the Wash mouth floor, River Witham, River Welland and River Nene outfalls. Sinks: Toft Sand, Roger Sand, Long Sand and the intertidal area. Transport of sediment is primarily suspended with sediment deposited with low tidal velocities.
Processes	Tide levels at Sutton Bridge (mCD): MHWS 3.80m, MHWN 2.00m, MLWN -1.20m, MLWS -2.00. Extreme water levels range from 4.84m for 1:1 yr at River Welland to 6.35m for 1:100 yr at River Nene. Waves: mean wave height (Hs) 0.61m, mean wave period (Tz) 3.30s, waves are predominantly from an offshore direction approaching from the north to north-east.
Existing Management	Sea banks are the prime defence along the sub-PDZ with residual life estimates between 15 and 25 years. There are some locations that are supported by a secondary defence line. The defences are maintained by the Environment Agency.
Intertidal Development	Saltmarsh vertical accretion rates = 4.0mmyr^{-1} Mudflat vertical accretion rates = -2.0mmyr^{-1} Horizontal accretion = 7.1myr^{-1} Defra sea level prediction based on 1991 to 2006 = approx. 4.0mmyr^{-1}

F5.4.2 Future Development Independent of Policy Packages

For epoch 1 both the saltmarsh and mudflat accretion rates will keep exceeding the rate of sea level rise resulting in the seaward movement of the saltmarsh/mudflat boundary, but a landward movement of the mean high and low water marks due to sea level rise. Additional sediment will be available for transport up and down the coast to adjacent PDZs.

Into epoch 2, there will be no further seaward movement of the saltmarsh/mudflat boundary due to the rate of sea level rise; the mean high and low water marks will continue to move landward. As with sub-PDZ1.1, despite the lack of horizontal accretion/erosion of the saltmarsh/mudflat boundary, it is expected that the vertical accretion across the saltmarsh would continue during epoch 2 as there would not be significant inundation of the saltmarsh on every high tide (i.e. there would be sufficient inundation and velocities across the saltmarsh to promote sedimentation, but not enough to cause erosion).

For epoch 3 the rate of sea level rise will be above the sedimentation rate predicted. Both the saltmarsh and the mudflat will still accrete vertically but at a much reduced rate to previously due to increased water depths, leading to the generation of larger waves and erosion of the shoreline. The mean high and low water mark will continue to move landward causing, as will the saltmarsh/mudflat boundary leading to coastal squeeze.

F5.4.3 Impacts: Maximum landward realignment

Epoch 1 (present day to 20205)
The analysis is based on the assumption that the new formal defence lines will be brought up to standard first, after which the existing frontline defences will be breached in various locations. The Maximum landward realignment during epoch 1 varies across the sub-PDZ. In some areas it does not differ from the present defence line whereas in the others there will be up to a 1km retreat in the defence line.

Epoch 1 will be dominated by vertical and horizontal accretion of both the saltmarsh and mudflats, and realignment will create an increased intertidal area, which is likely to have developed into saltmarsh by the end of the epoch.

This movement for Maximum landward realignment is illustrated in figure F5.17.

Epoch 2 (2025 to 2055)
There is a significant realignment of the shoreline landward in this epoch. This extensive realignment will lead to a very wide foreshore with the potential for strong wave dissipation and continued vertical accretion. This is

not likely to have a large impact on the wider SMP area, as the sub-PDZ is constrained as its western and eastern extents by the river outfalls.

This movement for Maximum landward realignment is illustrated in figure F5.18.

<u>Epoch 3 (2055 to 2105)</u>
This epoch has no further defence realignment in this PP, therefore this epoch will be characterised by further development of the saltmarsh within the realigned areas. This will further reduce wave energy for the realigned defences, although this trend will start to be counteracted by the background development of coastal squeeze in this epoch. Note that there is uncertainty regarding how quickly the young saltmarsh in the formerly defended areas will develop, and this will greatly affect its potential to effectively dissipate wave energy.

This movement for Maximum landward realignment is illustrated in figure F5.19.

F5.4.4 Impacts: 'Habitat-led' realignment

<u>Epoch 1 (present day to 2025)</u>
There is no 'Habitat-led' realignment in this epoch for this sub-PDZ. This means that there will be the same situation as with Hold the line during this epoch (therefore vertical and horizontal accretion) as there will also be no significant influence on this sub-PDZ following implementation of the same PP in the adjacent sub-PDZs (this PP only has localised impacts, and does not affect neighbouring PPs).

The movement for 'Habitat-led' realignment is illustrated in figure F5.20 (which is the figure for the Hold the line policy package).

<u>Epoch 2 (2025 to 2055)</u>
There is no 'Habitat-led' realignment in this epoch for this sub-PDZ, and overall the PP only causes localised impacts which rules out changes caused by adjacent sub-PDZs, so again there will be the same situation as with Hold the line during this epoch.

The movement for Habitat Led Realignment is illustrated in figure F5.21 (which is the figure for the Hold the line policy package).

<u>Epoch 3 (2055 to 2105)</u>
'Habitat–led' realignment remains at the current defence line except for the southern limit of the River Welland where the defence will be moved landward: the mudflat that protrudes from the River Welland will increase on the southern side of the river. This will gradually develop into new saltmarsh towards the end of the epoch.

Under a Hold the line PP for this sub-PDZ, by the end of this epoch the saltmarsh could have eroded up to the existing defence line around the area of realignment. Therefore the realignment associated with this PP will have a significant positive effect on wave dissipation.

The movement for Habitat Led Realignment is illustrated in figure F5.22.

F5.4.5 Impacts: Hold the line

Epoch 1 (present day to 2025)

The background processes as described in section F5.4.2 lead to increased saltmarsh width and height in this epoch, but the increase is small compared to the existing situation. Sea level rise and possible increased storminess may increase loading on the defences, but this is to some extent counteracted by the accretion of the intertidal area causing increased wave dissipation.

This development is illustrated in figure F5.23.

Epoch 2 (2025 to 2055)

The background processes as described in section F5.4.2 lead to stabilised saltmarsh width in this epoch. Loading on the defence line will increase due to expected climate change, but the wide foreshore will still strongly dissipate wave energy, although this dissipation will gradually become less effective towards the end of the epoch.

This development is illustrated in figure F5.24.

Epoch 3 (2055 to 2105)

The background processes as described in section F5.4.2 lead to reduced saltmarsh width in this epoch. In some places there is almost no saltmarsh left in front of the defences (leading to significant increase in loading and the requirement to strengthen them to Hold the line). In other areas there is still a significant saltmarsh width with associated effect on wave impact.

This development is illustrated in figure F5.25.

F5.4.6 Impacts: Local rebalancing

Epoch 1 (present day to 2025)

In the Local rebalancing package there are significant landward and seaward realignments in epoch 1. The banks between the Rivers Witham and Welland will be moved seaward, the northern banks of the River Welland will be moved landward, and there is a section of landward realignment near Gedney. The landward realignment along the Welland will lead to the possibility of mudflat and saltmarsh development in this area. To the south of the River Witham, the seaward realignment of the defences would create land for agriculture, at the expense of intertidal area. This will take place against the background processes of accretion as described in section F5.4.2.

Figure F5.26 illustrates this movement.

Epoch 2 (2025 to 2055)
There will be no further realignments in this epoch. The newly intertidal land between Witham and Welland will continue to develop, against the background of the stabilising foreshore developments as described in section F5.4.2 Shoreline response will generally be similar to that described in section F5.4.2, although the increased intertidal areas will continue to develop and will act to dissipate wave energy.

Figure F5.27 illustrates this movement.

Epoch 3 (2055 to 2105)
Continuing into epoch 3, this package again contains no further realignment. The defences of the reclaimed land on the south bank of the Witham will experience increased loading due to climate change (although the foreshore is not expected to erode in that location). The two areas of landward realignment will have matured, and provide a buffer against the background development of eroding foreshore, maintaining significant width and associated wave dissipation along most of the frontage.

Figure F5.28 illustrates this movement.

Figure F5.17 PDZ1.2 Maximum landward realignment epoch 1

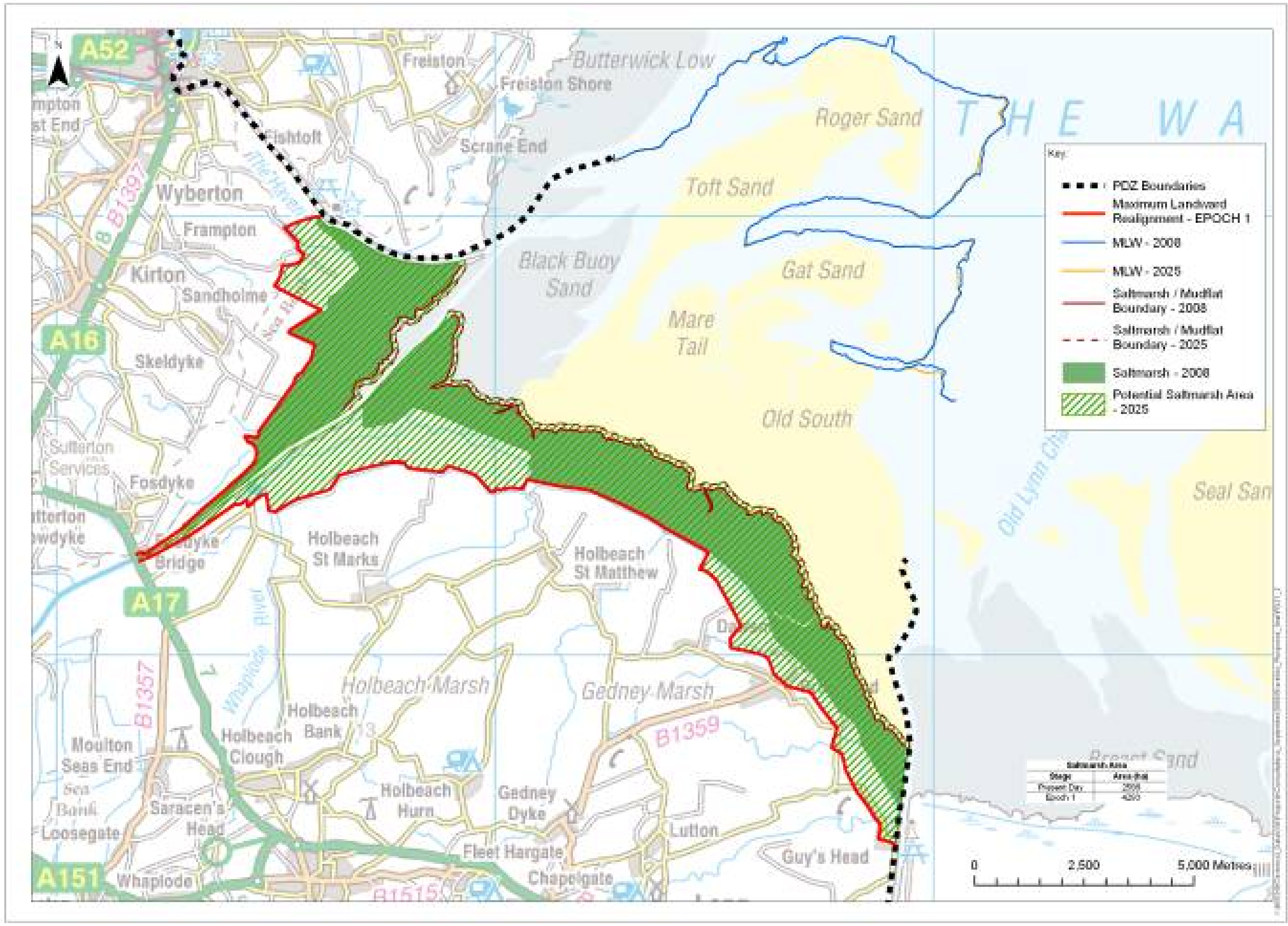


Figure F5.18 PDZ1.2 Maximum landward realignment epoch 2

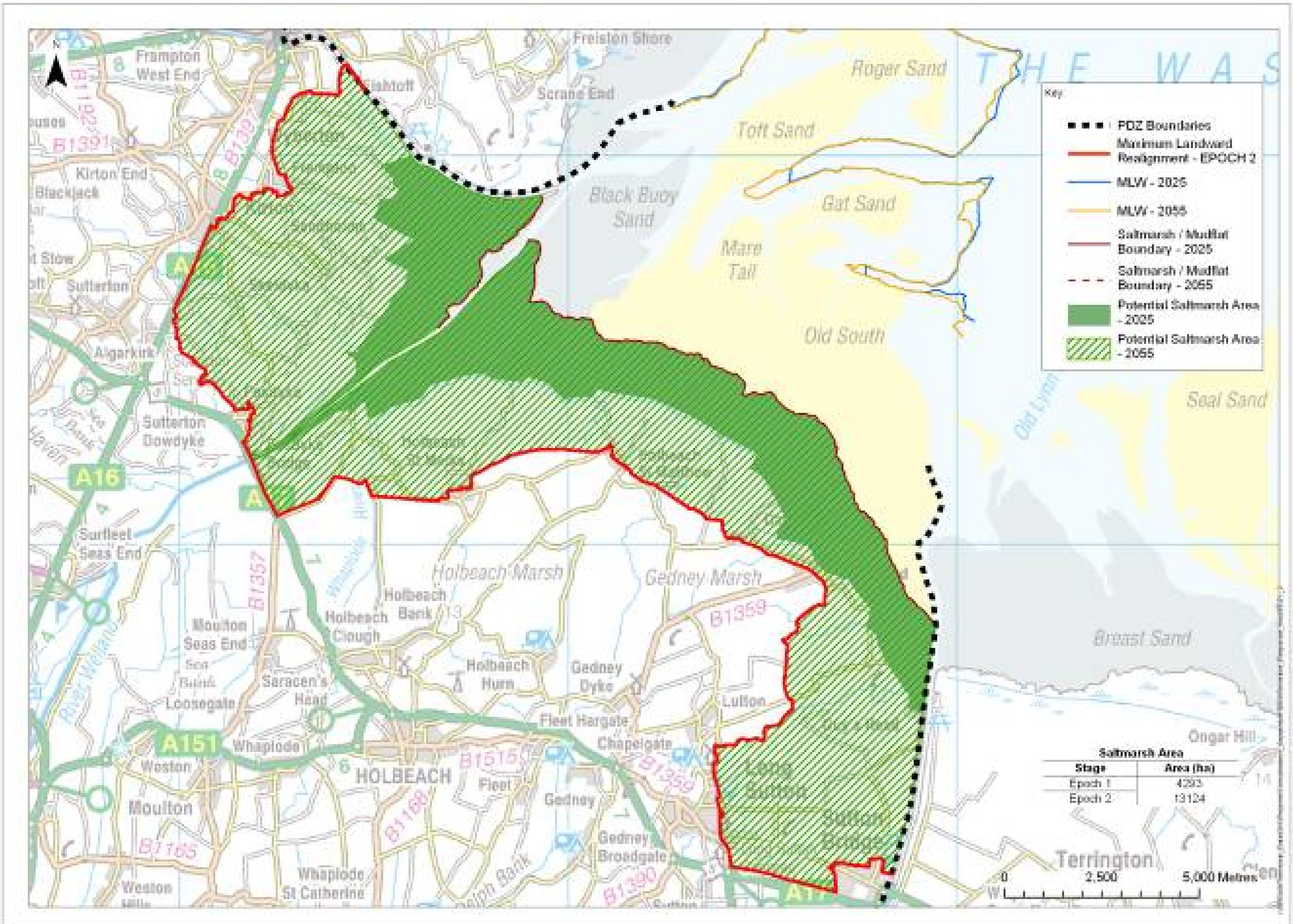


Figure F5.19 PDZ1.2 Maximum landward realignment epoch 3

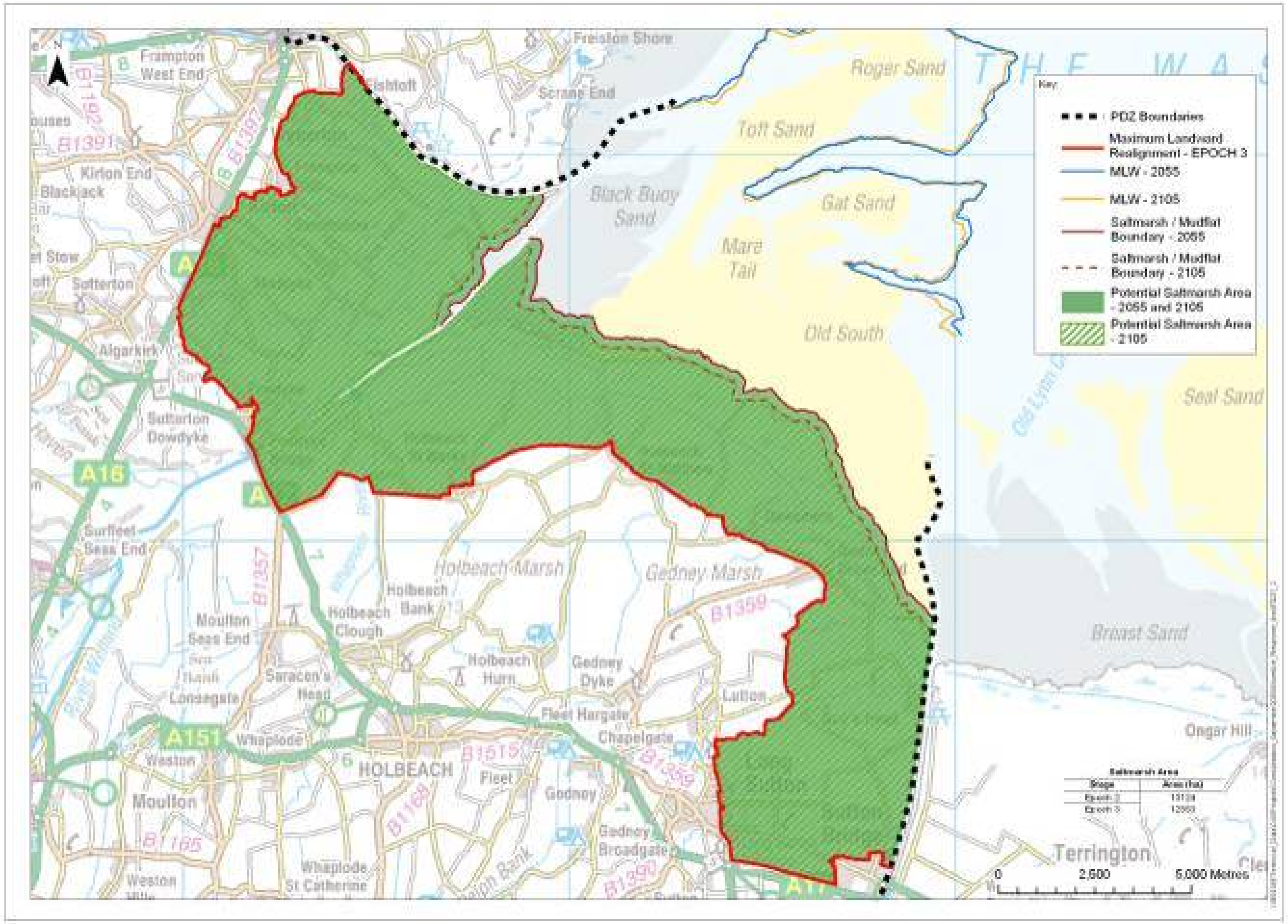


Figure F5.20 PDZ1.2 ‘Habitat-led’ realignment epoch 1

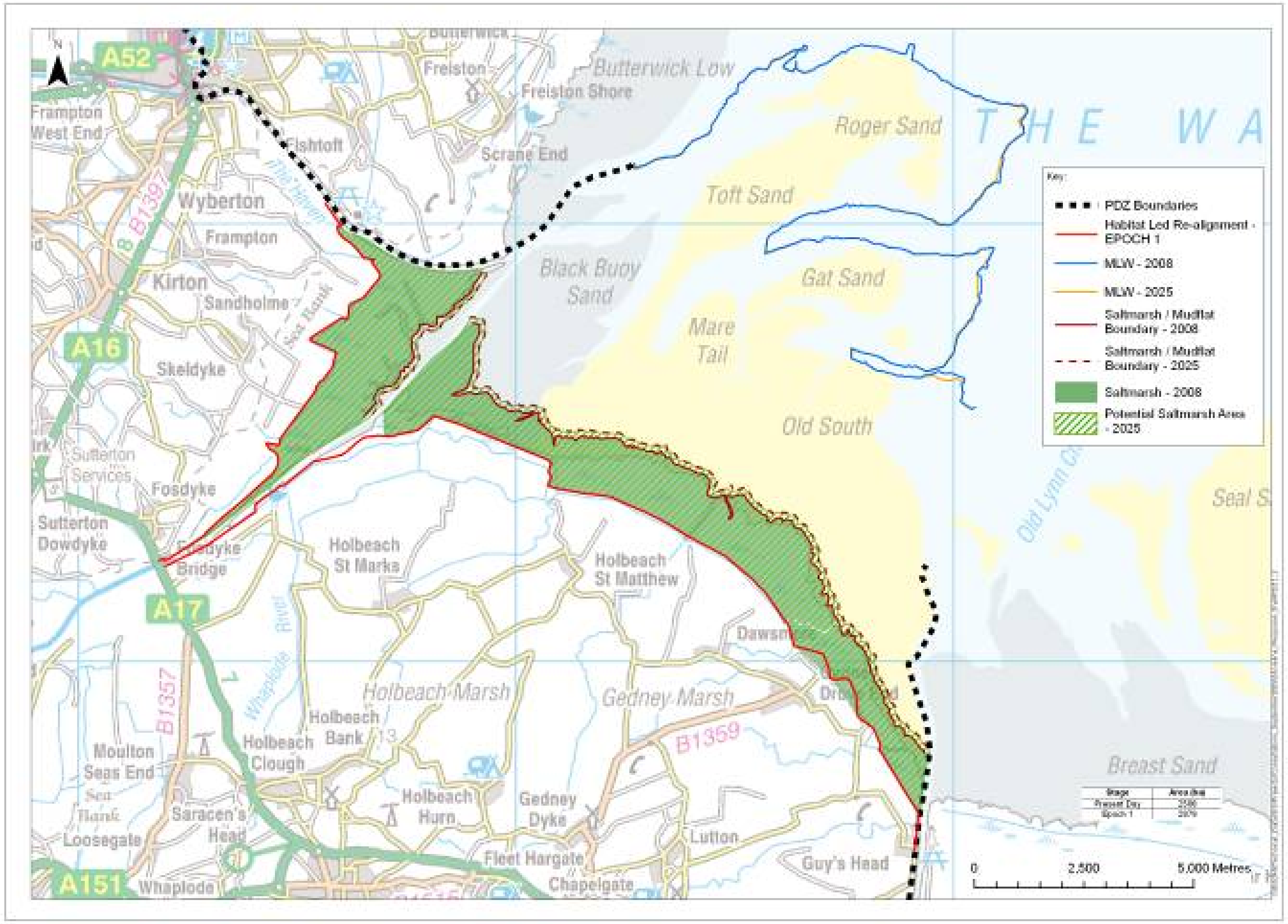


Figure F5.21 PDZ1.2 'Habitat-led' realignment epoch 2

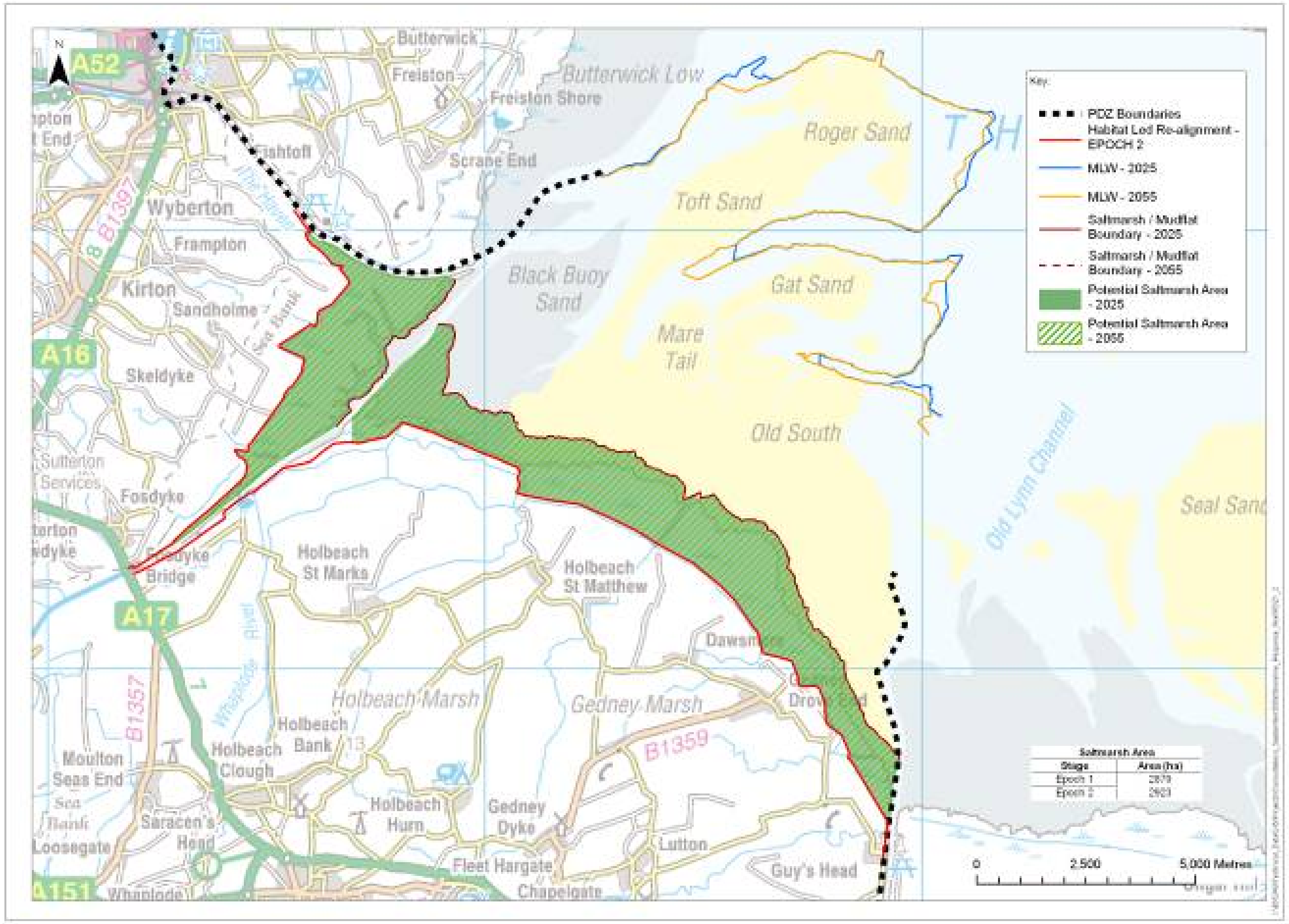


Figure F5.22 PDZ1.2 ‘Habitat-led’ realignment epoch 3

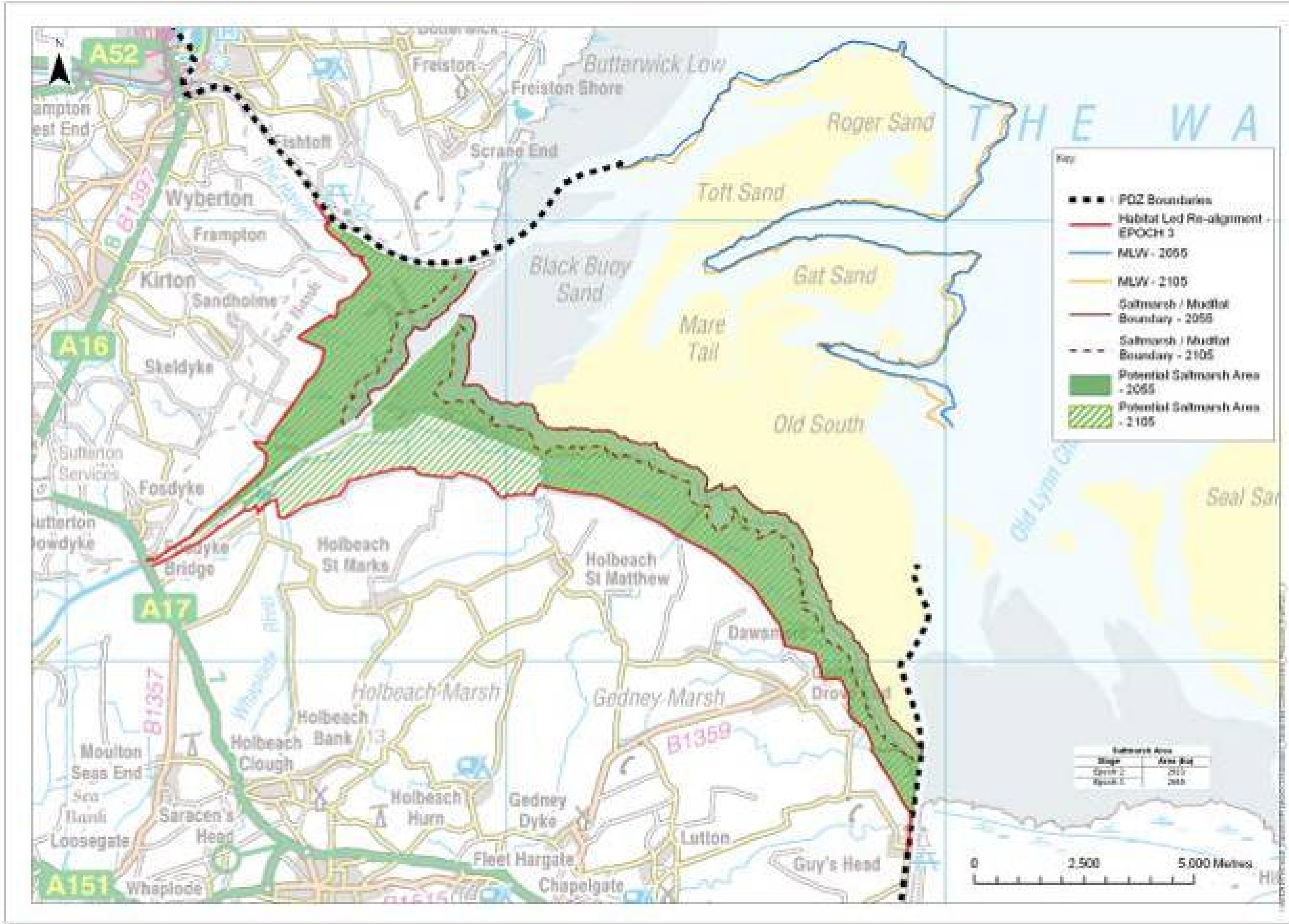


Figure F5.23 PDZ1.2 Hold the line epoch 1

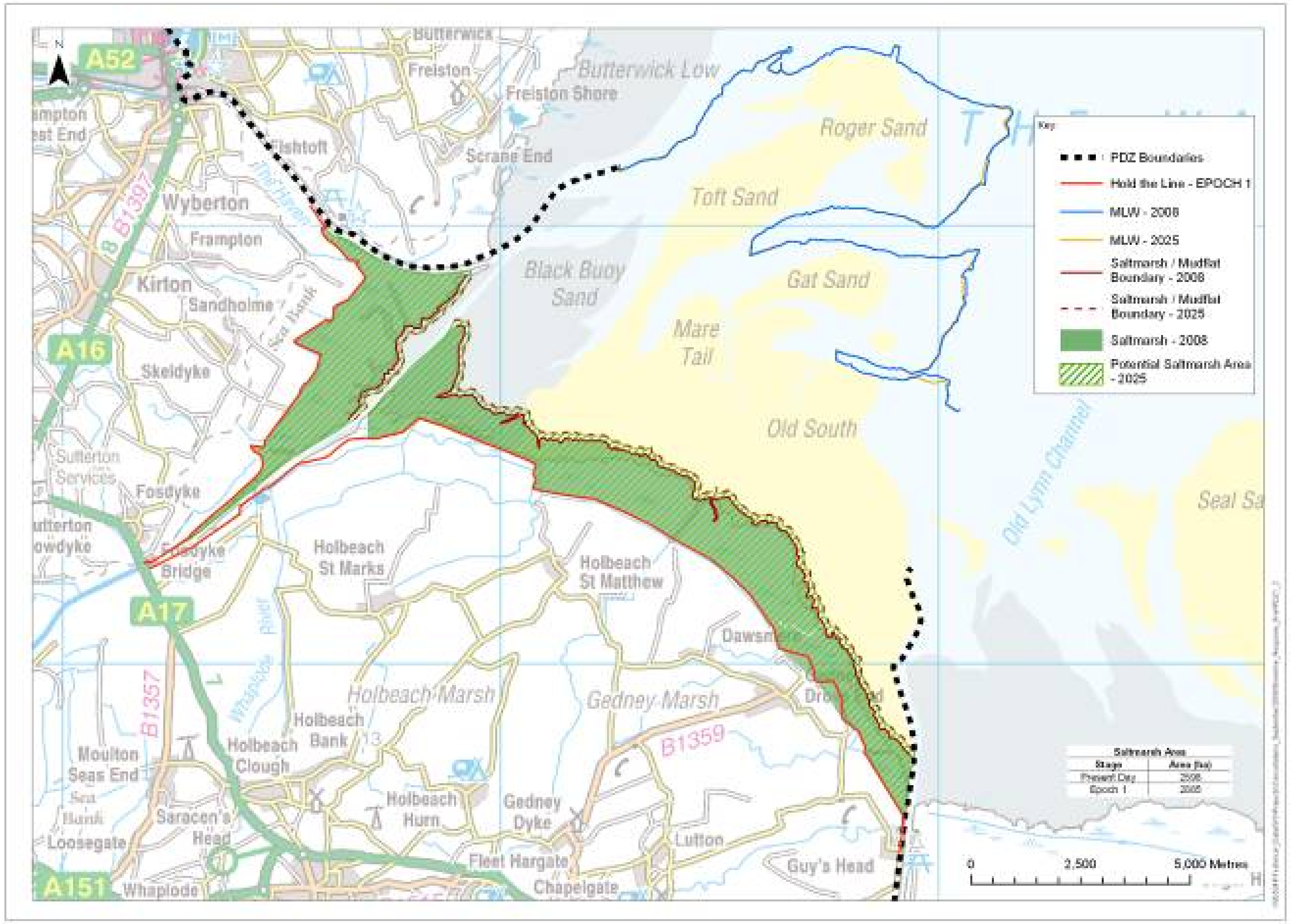


Figure F5.24 PDZ1.2 Hold the line epoch 2

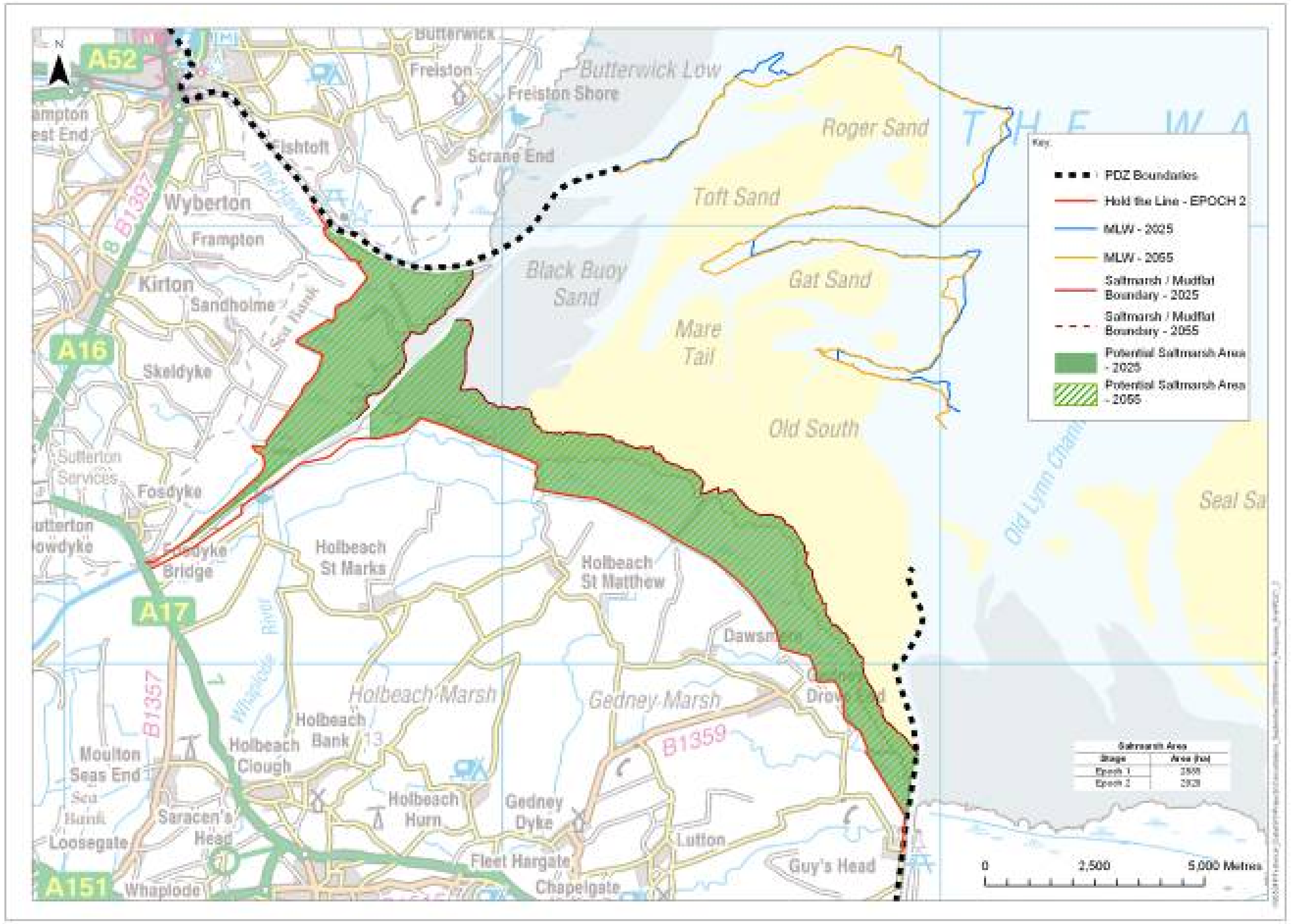


Figure F5.25 PDZ1.2 Hold the line epoch 3

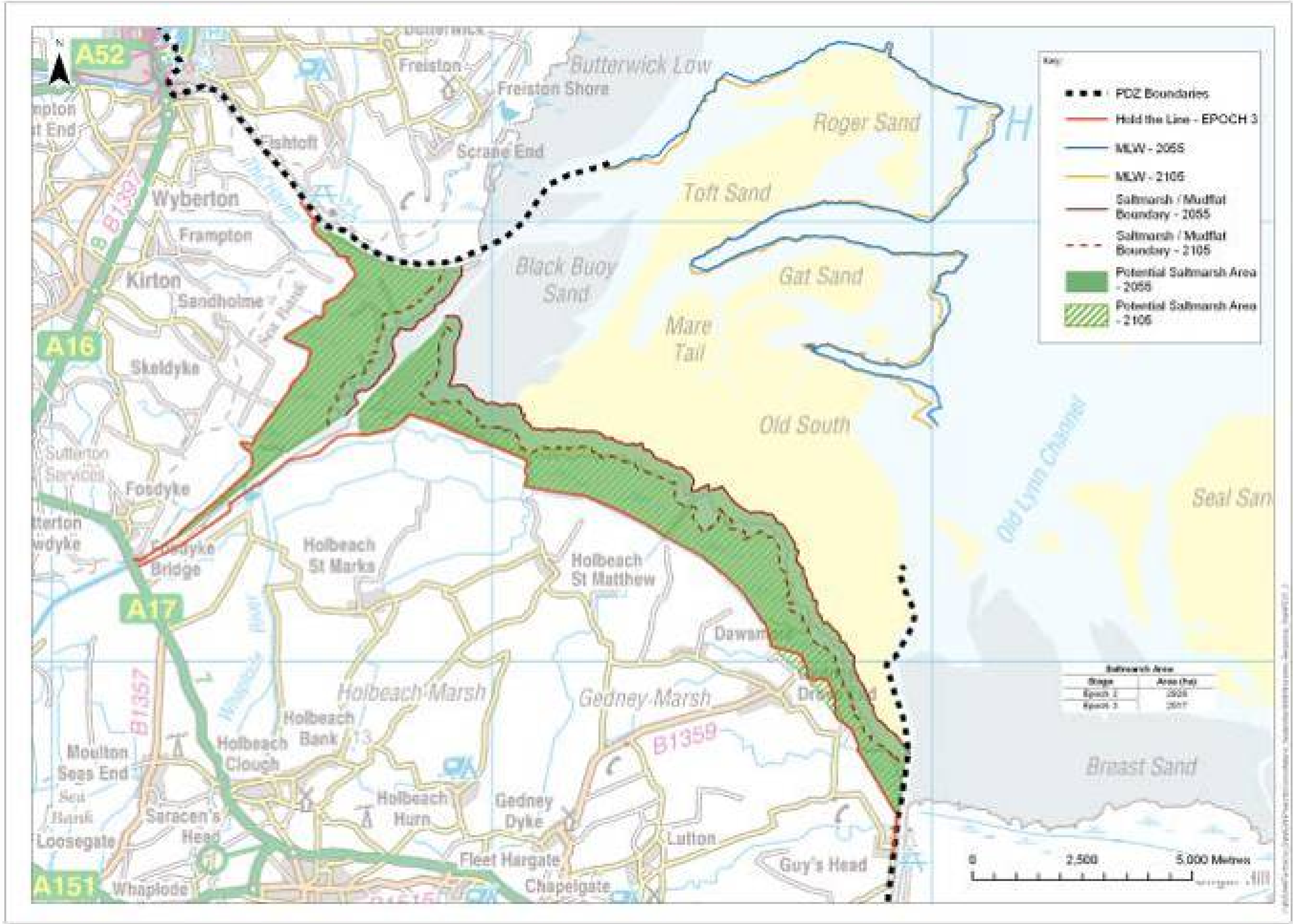


Figure F5.26 PDZ1.2 Local rebalancing epoch 1

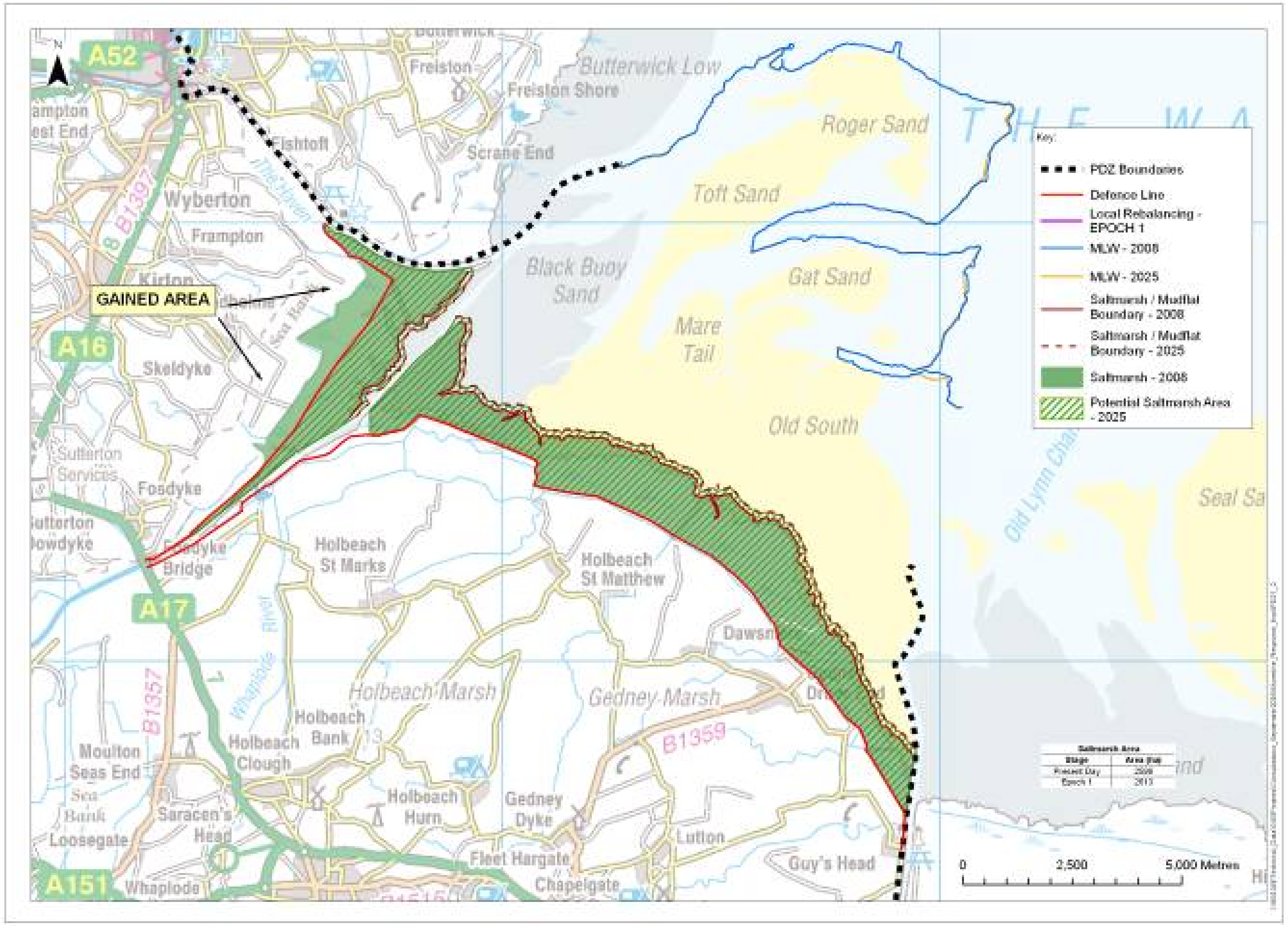


Figure F5.27 PDZ1.2 Local rebalancing epoch 2

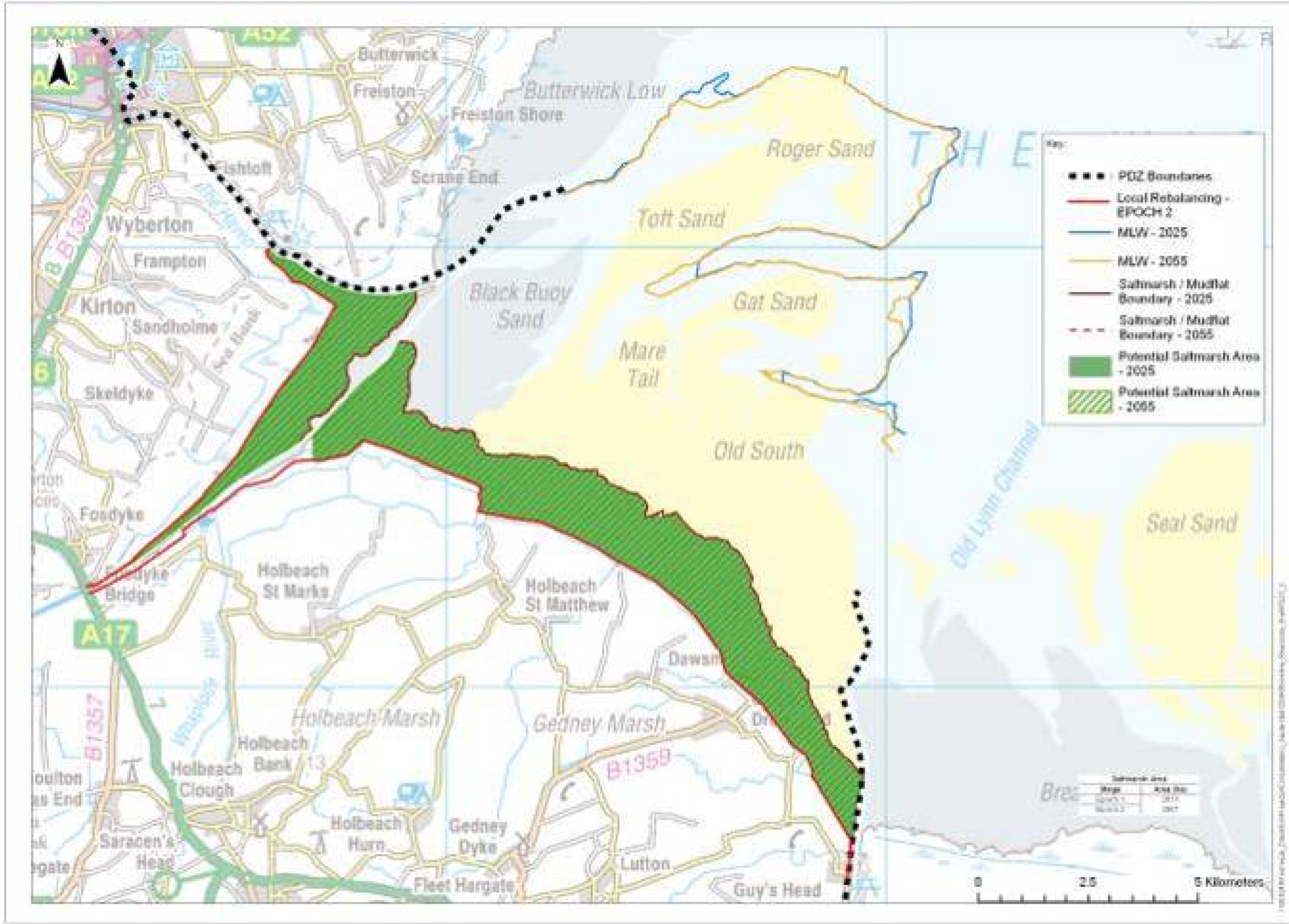
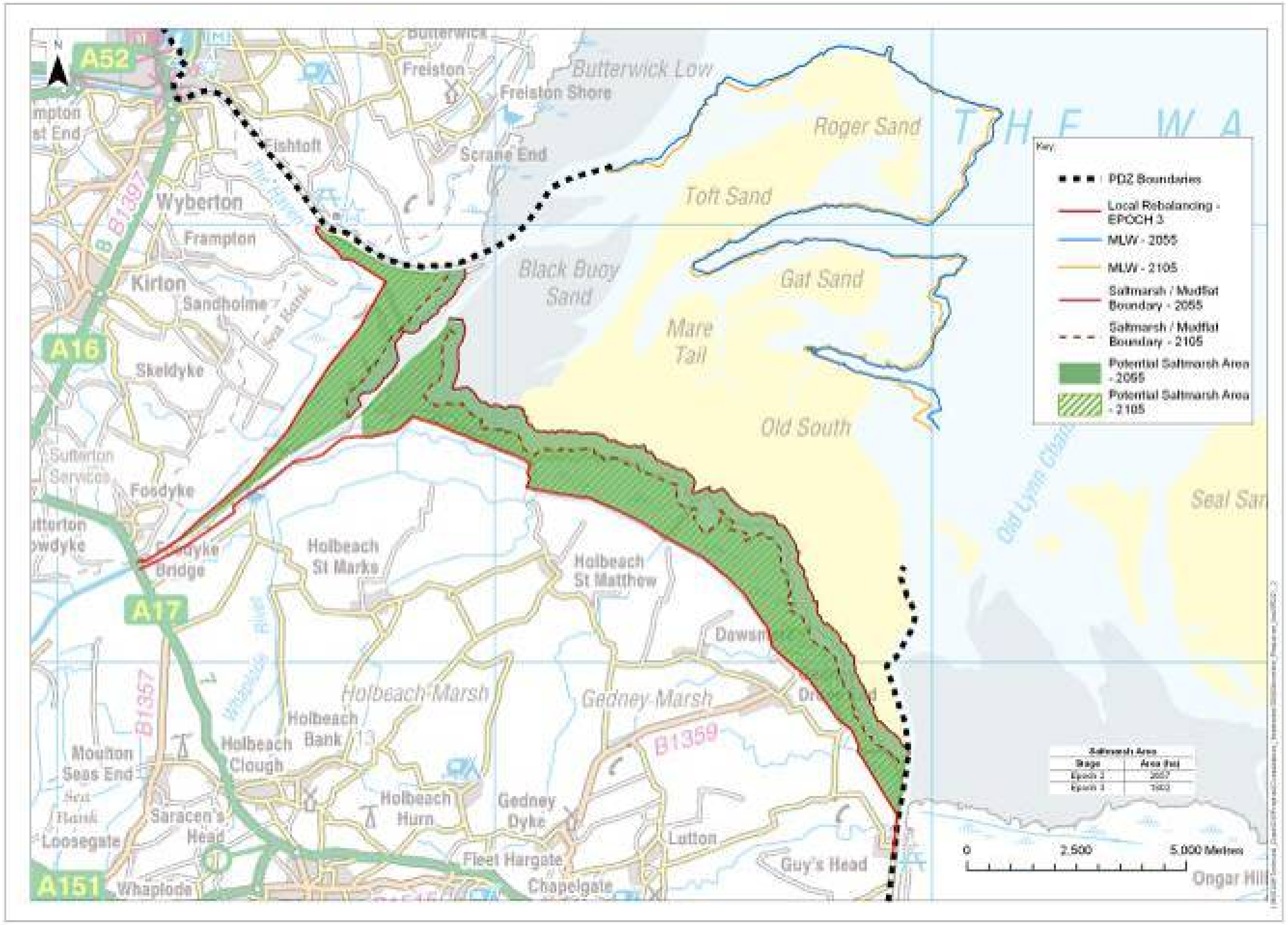


Figure F5.28 PDZ1.2 Local rebalancing epoch 3



F5.5 River Nene to Wolferton Creek (PDZ1.3)

F5.5.1 Introduction

This area belongs to PDZ1, so it has the following four Policy Packages for appraisal:

- Maximum landward realignment: Landward Managed realignment to the maximum extent per epoch as defined in the Playing Field, including land use adaptation as required;
- 'Habitat led' realignment: Setting a target size for the increase of intertidal habitat per epoch and find the most appropriate locations to achieve this;
- Hold the line: keep the existing alignment for all locations and for all three epochs;
- Local rebalancing: rationalise the alignment of the defence (if needed) to optimise the value for agriculture, habitats and other interests.

The principal town in this sub-PDZ is King's Lynn. There is also the smaller town of Terrington St. Clement and several smaller villages.

The reclaimed intertidal flats here are now protected by grassed earth embankments with up to 4 kilometres of intertidal flats extending from the shoreline also containing areas of saltmarsh.

The River Nene is at the western limit of the sub-PDZ and Wolferton Creek outfall at the eastern end. In the centre of the sub-PDZ is the River Great Ouse outfall that controls the bird's foot delta of Seal Sand.

Figure F5.29 outlines the location and boundaries of the sub-PDZ.

Further detail of the characteristics of the sub-PDZ are summarised in **table F5.4**. These are given in more detail in the Baseline Scenarios report.

Figure F5.29 PDZ1.3 Boundaries

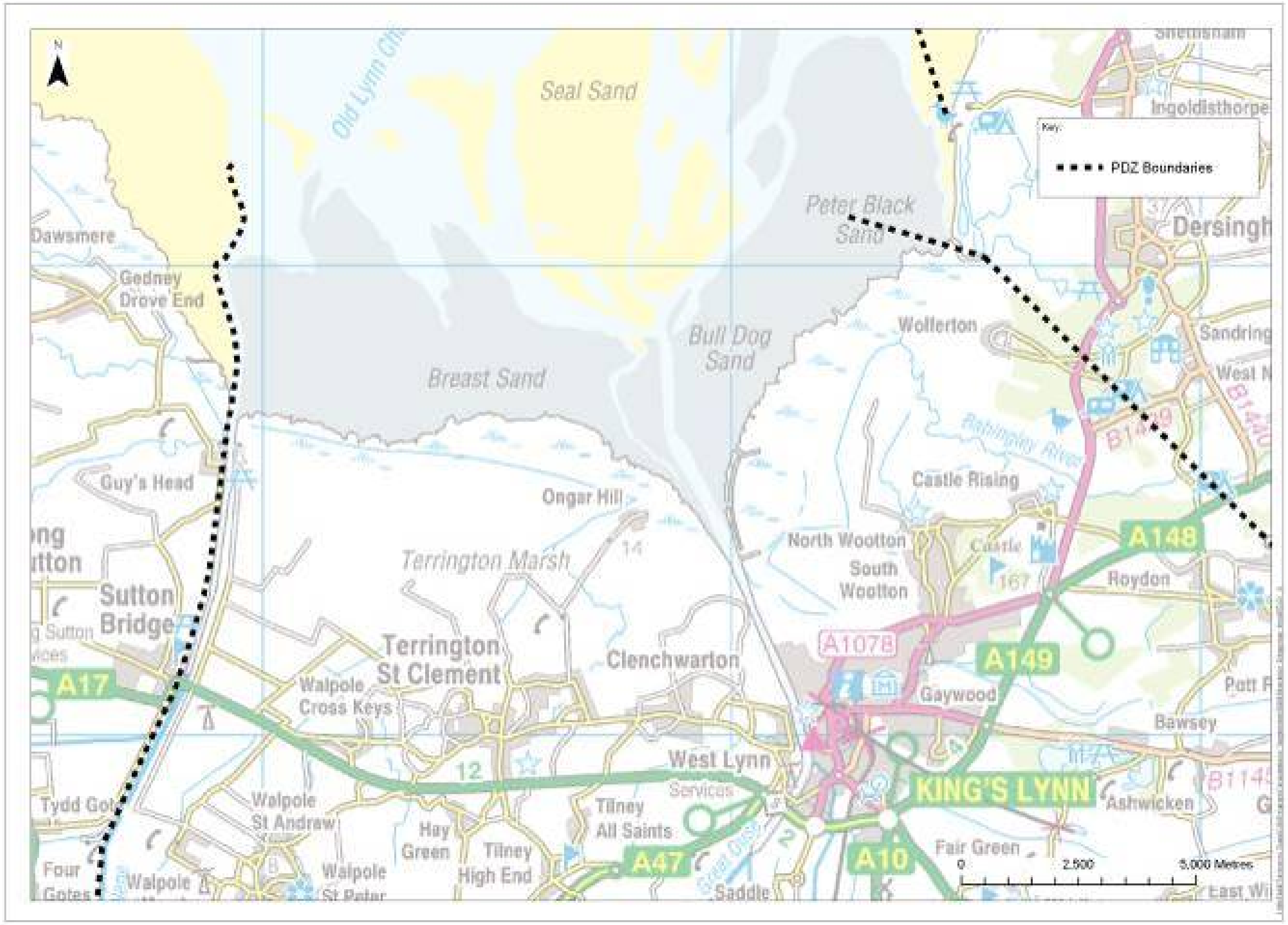


Table F5.4 PDZ1.3 Baseline Information

Geomorphological Components	*Seal Sand* – forms a bird's foot delta of the River Great Ouse that is generally exposed at low water. *Lynn Deeps* – controls the low water mark along the sub-PDZ and feeds incoming sediment for the sub-PDZ. *Intertidal flats* – wide area that decreases both erosion rates and the probability of flooding. *River Nene and Great Ouse outfalls* - form a series of deltaic deposits and transient flow channels.
Historic Change	In general, over the past 100 years, there is a general trend of accretion and seaward movement of the low water mark with variable accounts of retreat along areas of the coastline.
Recent Change (1991-2006)	More recently the sub-PDZ has experienced both horizontal and vertical accretion of the saltmarsh/mudflat boundary with both the saltmarsh and mudflat areas having increased. As with previous areas, locations where drainage channels are crossed exhibit local vertical erosion across the boundary.
Tidal Currents	Tidal currents can be relatively strong in the Wash due to its large tidal range. Average current velocities are between 0.8 and 1.0ms^{-1} (HR Wallingford, 1972).
Current Residuals	With a complex net water transport system for this sub-PDZ, it is suitable to summarise that the overall movement is directly south-south-west onto the sub-PDZ.
Sediment	Sources: Holderness Coast, Humber Estuary, North Norfolk coast, North Sea, the Wash mouth floor, River Nene and River Great Ouse outfalls. Sinks: Seal Sand and intertidal area. Transport of sediment is primarily suspended with sediment deposited during low tidal velocities.
Processes	Tide levels at King's Lynn (mCD): MHWS 3.77, MHWN 1.97, MLWN -1.23, MLWS -2.03. Extreme water levels range from 4.88m for 1:1 yr at River Nene to 6.43m for 1:1000 yr at River Great Ouse. Waves: Mean wave heights (Hs) 0.61m, mean wave period (Tz) 3.30s, waves are predominantly from an offshore direction approaching from the north to north-east.
Existing Management	The sub-PDZ is completely defended by grassed earth embankments with residual lives of between 10 and 25 years. These are maintained by the Environment Agency. They are expected to fail at the end of epoch 1 or the beginning of epoch 2. Secondary defences are present in this area but were no longer maintained after the new front line defences were constructed.
Intertidal Development	Saltmarsh vertical accretion rates = 17.0$mmyr^{-1}$ Mudflat vertical accretion rates = 63.0$mmyr^{-1}$ Horizontal accretion = 8.9myr^{-1} Defra sea level prediction based on 1991 to 2006 = approx. 4.0$mmyr^{-1}$

F5.5.2 Future Developments Independent of Policy Packages

For epoch 1 both the saltmarsh and mudflat accretion rates will keep exceeding the rate of sea level rise resulting in the seaward movement of the saltmarsh/mudflat boundary, but a landward movement of the mean high and low water marks due to sea level rise. It is important to note that coastal squeeze does not appear to be occurring to the same extent as for PDZ1.1 and PDZ1.2, mainly due to the fact that there has not been the degree of reclamation as along these PDZs, where land claim has encroached too far onto the former mudflat.

Into epoch 2, there will be no further seaward movement of the saltmarsh/mudflat boundary due to the rate of sea level rise; the mean high and low water marks will continue to move landward. Despite the lack of horizontal accretion/erosion of the saltmarsh/mudflat boundary, it is expected that the vertical accretion across the saltmarsh would continue during epoch 2 as there would not be significant inundation of the saltmarsh on every high tide (i.e. there would be sufficient inundation and velocities across the saltmarsh to promote sedimentation, but not enough to cause erosion). As with epoch 1, this PDZ will not be subject to the same degree of coastal squeeze during epoch 2 compared to PDZ1.1 and PDZ1.2.

For epoch 3 the rate of sea level rise will be above the sedimentation rate predicted. Both the saltmarsh and the mudflat will still accrete vertically but at a much reduced rate to previously due to increased water depths, leading to the generation of larger waves and erosion of the shoreline. The mean high and low water mark will continue to move landward causing, as will the saltmarsh/mudflat boundary, leading to coastal squeeze.

F5.5.3 Impacts: Maximum landward realignment

<u>Epoch 1 (present day to 2025)</u>
The majority of this sub-PDZ will be allowed to retreat by 1km with the central area having a greater retreat of up to 2km. The central area of the sub-PDZ will therefore release much more sediment for transport to other areas of sub-PDZ1.3 as well as to the adjacent PDZs. There is likely to be continued vertical accretion across both the saltmarsh and mudflat, and also continued horizontal accretion of the saltmarsh, allowing the saltmarsh/mudflat boundary to continue to move seaward. The newly breached backshore area will begin the process of saltmarsh development, but the speed at which this occurs is uncertain.

This movement is illustrated in figure F5.30.

<u>Epoch 2 (2025 to 2055)</u>
Due to the land classifications and presence of established settlements across this sub-PDZ, the Managed realignment area is much greater than on most PDZs. The greater area for energy dissipation will promote deposition

of sediment and further increase the vertical accretion rates across the newly breached backshore and saltmarsh. It is likely that there will also be continued vertical accretion across the mudflat. However due to sea level rise, there is not likely to be any horizontal landward or seaward movement of the saltmarsh/mudflat boundary. As with epoch 1, there is uncertainty regarding the development of saltmarsh on the newly breached backshore areas. It is also important to note that localised erosion is likely to occur in areas where the sub-PDZ crosses drainage channels.

This movement is illustrated in figure F5.31.

Epoch 3 (2055 to 2105)

During this epoch, the areas realigned in epoch 2 will continue to evolve into saltmarsh, although again the rate of development is uncertain. As a result of predicted sea level rise, rates of vertical accretion across both the saltmarsh and mudflat will be reduced. There will also be horizontal erosion resulting in the saltmarsh/mudflat boundary moving landward.

This movement is illustrated in figure F5.32.

F5.5.4 Impacts: ‘Habitat-led’ realignment

Epoch 1 (present day to 2025)

Similarly to sub-PDZ1.2, in this sub-PDZ realignment remains the same as for the Hold the line Policy Package and therefore referral can be made to the Hold the line package in section F5.5.5. To summarise, there will be continued vertical accretion across the saltmarsh and mudflat, and continued horizontal accretion, leading to a seaward movement of the saltmarsh/mudflat boundary.

The ‘Habitat-led’ realignment shoreline response is illustrated in figure F5.33.

Epoch 2 (2025 to 2055)

Again, this realignment will result in the same situation as for the Hold the line Policy Package. Therefore there will be continued vertical accretion across both the saltmarsh and mudflat, but due to sea level rise there is not likely to be any movement (either landward or seaward) of the saltmarsh/mudflat boundary.

The ‘Habitat-led’ realignment shoreline response is illustrated in figure F.34.

Epoch 3 (2055 to 2105)

Under the ‘Habitat-led’ realignment Policy Package for this sub-PDZ, there will be small-scale realignment of the frontline defence to the east of the River Nene. Due to the localised nature of this realignment, the shoreline response in epoch 3 will be the same as for the Hold the line Policy Package in epoch 3 (as described in section 4.3.3). There will be reduction of vertical accretion across the saltmarsh and mudflats, and erosion of the saltmarsh/mudflat boundary, leading to an overall reduction of saltmarsh area.

The Habitat Led Realignment shoreline response is illustrated in figure F5.35.

F5.5.5 Impacts: Hold the line

Epoch 1 (present day to 2025)
The coastal response for the epoch will remain similar to both sub-PDZ1.1 and sub-PDZ1.2. There will be continued accretion of the saltmarsh. Intertidal development over this sub-PDZ is more advanced and complicated than the other two sub-PDZs leading to localised erosion in the upper saltmarsh and accretion of the upper mudflat squeezing the saltmarsh and mudflat together. The saltmarsh/mudflat boundary would move seaward and vertical accretion across both the saltmarsh and mudflat would continue. This is further discussed in the Baseline Scenarios report.

This is illustrated in figure F5.36.

Epoch 2 (2025 to 2055)
A combination of sea level rise and holding the line will result in neither accretion nor erosion of the saltmarsh/mudflat boundary on this sub-PDZ. There would be continued accretion across both the saltmarsh and mudflat.

This is illustrated in figure F5.37.

Epoch 3 (2055 to 2105)
During this epoch the saltmarsh/mudflat boundary will be forced landward by the increasing water levels but prevented from too greater a landward movement from the defences holding the line as the policy suggests. This results in coastal squeeze.

This is illustrated in figure F5.38.

F5.5.6 Impacts: Local rebalancing

Epoch 1 (present day to 2025)
Similarly to sub-PDZ1.2, this sub-PDZ Local rebalancing remains much the same to holding the line. Overall this epoch will be characterised by continued vertical accretion across the saltmarsh and mudflat, and horizontal accretion leading to a seaward movement of the saltmarsh/mudflat boundary.

The shoreline response to Local rebalancing is illustrated in figure F5.39.

Epoch 2 (2025 to 2055)
Again, this Policy Package will result in much the same situation as if the line was held. A combination of sea level rise and holding the line will result in neither horizontal accretion nor erosion of the saltmarsh/mudflat boundary on

this sub-PDZ. However there is likely to be continued vertical accretion across the saltmarsh and mudflat.

The shoreline response to Local rebalancing is illustrated in figure F5.40.

Epoch 3 (2055 to 2105)

Into epoch 3, the saltmarsh/mudflat boundary will be forced landward by the increasing water levels but prevented from too greater a landward movement from the defences. This results in coastal squeeze. There is likely to be reduced vertical accretion across the saltmarsh and mudflat, and even a tendency for erosion.

The shoreline response to Local rebalancing is illustrated in figure F5.41.

Figure F5.30 PDZ1.3 Maximum landward realignment epoch 1

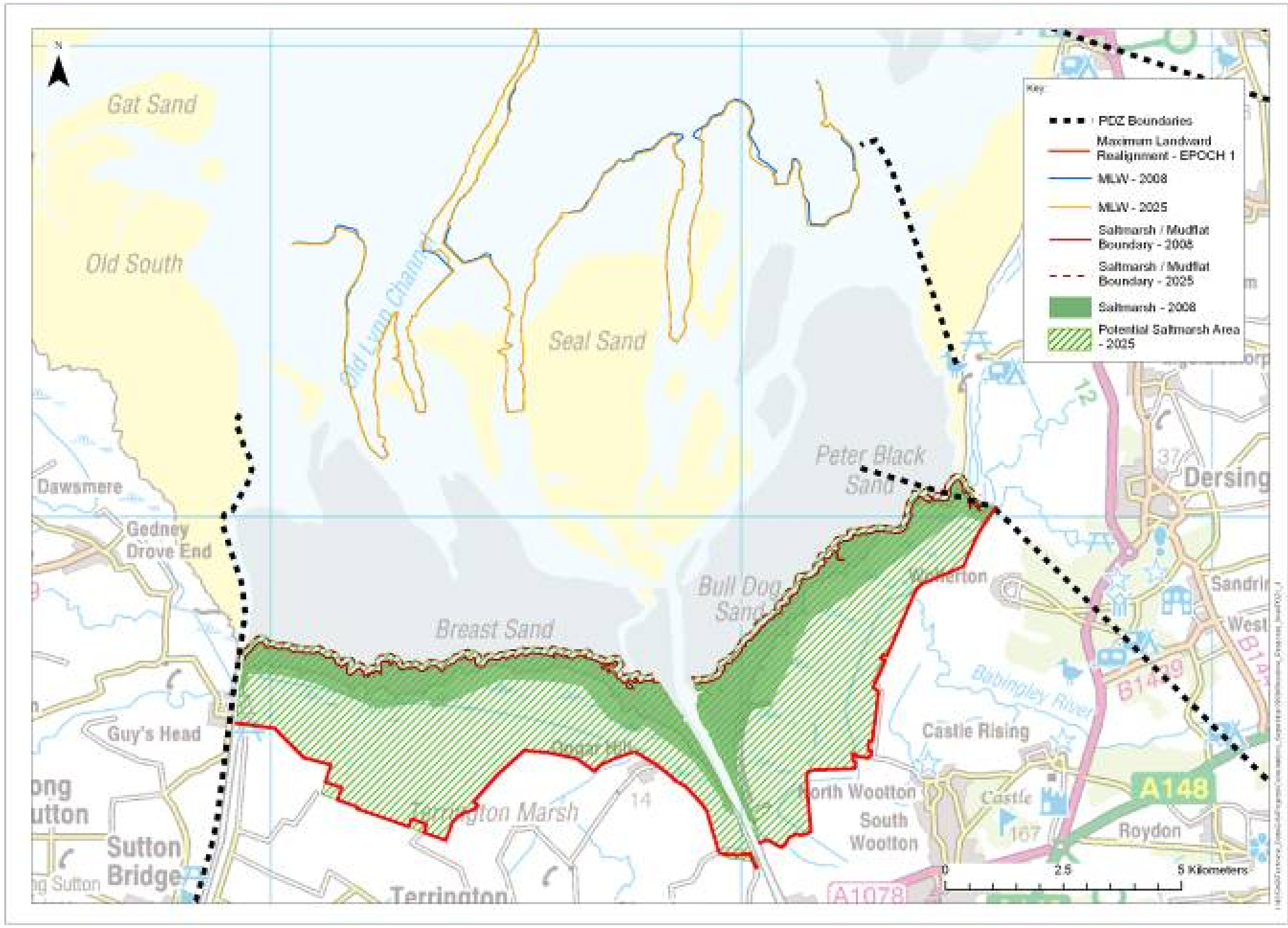


Figure F5.31 PDZ1.3 Maximum landward realignment epoch 2

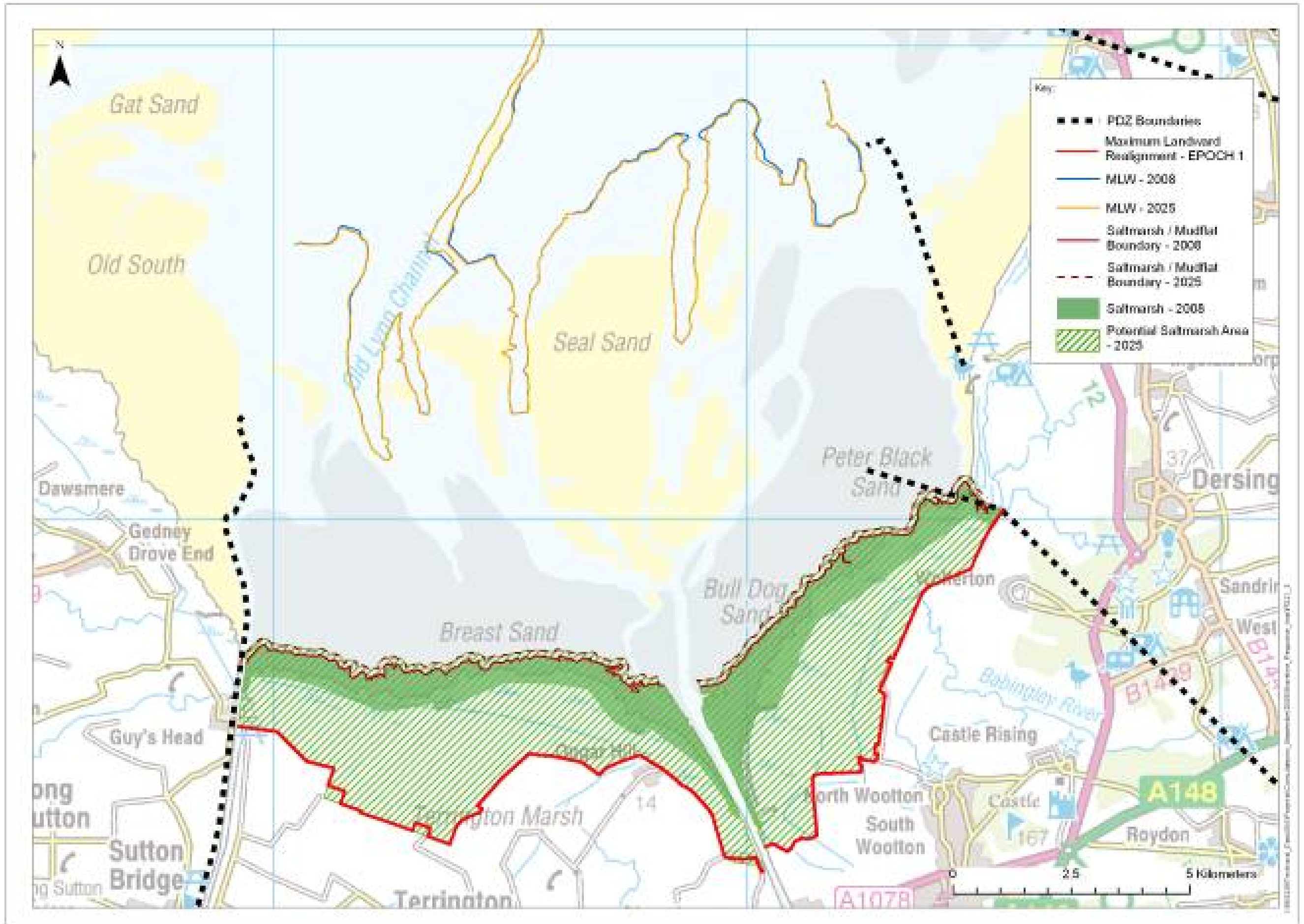


Figure F5.32 PDZ1.3 Maximum landward realignment epoch 3

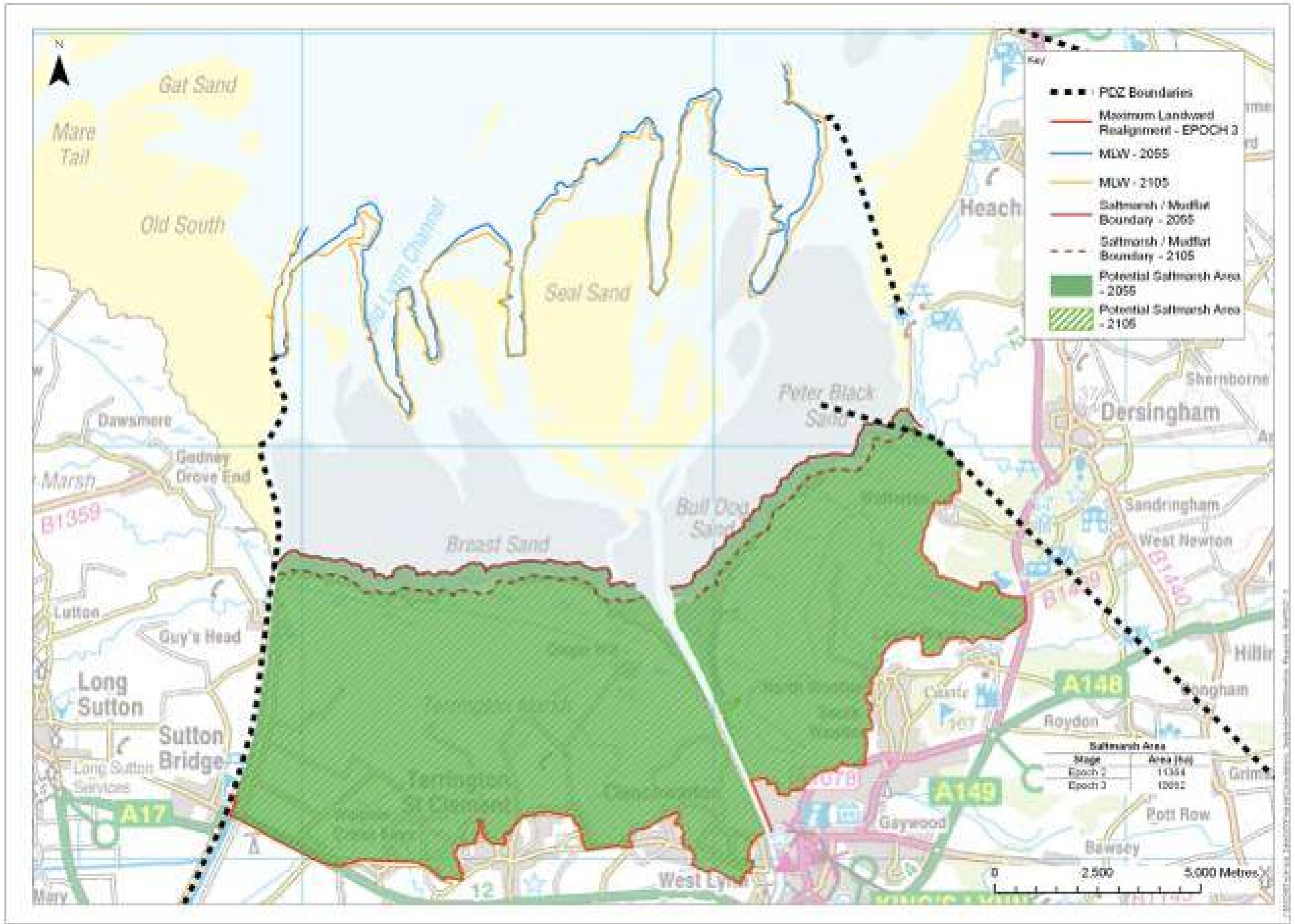


Figure F5.33 PDZ1.3 ‘Habitat-led’ realignment epoch 1

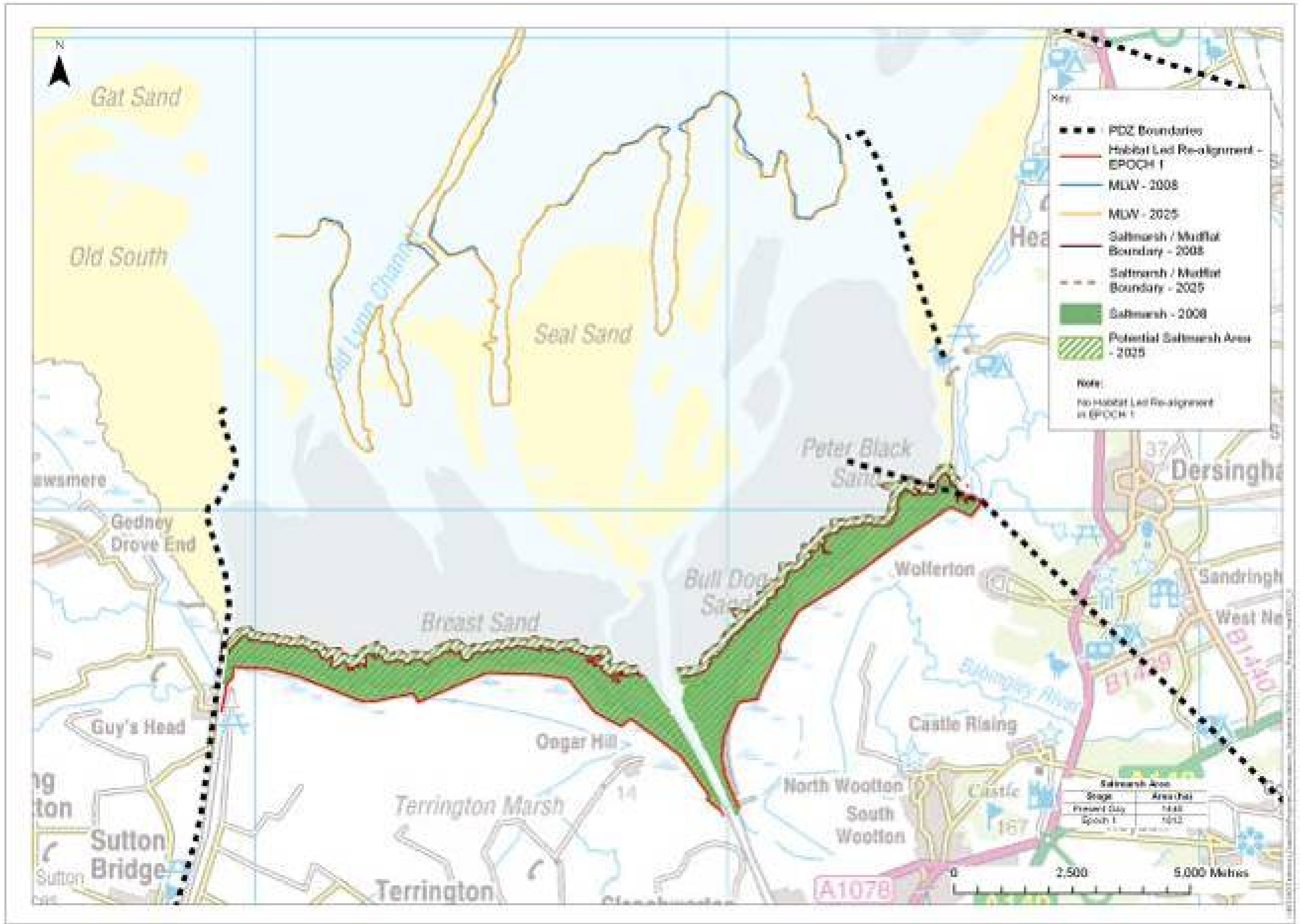


Figure F5.34 PDZ1.3 'Habitat-led' realignment epoch 2

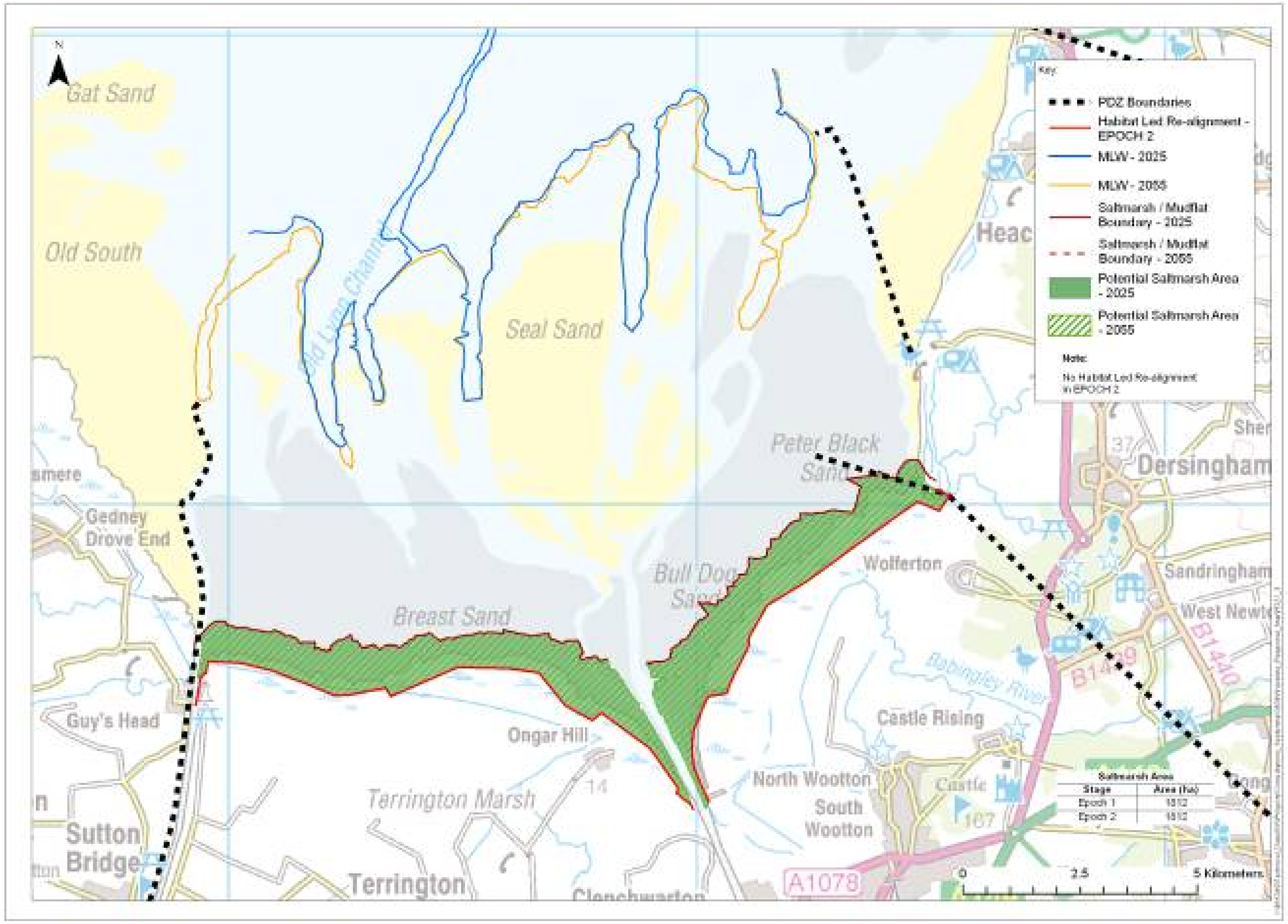


Figure F5.35 PDZ1.3 'Habitat-led' realignment epoch 3

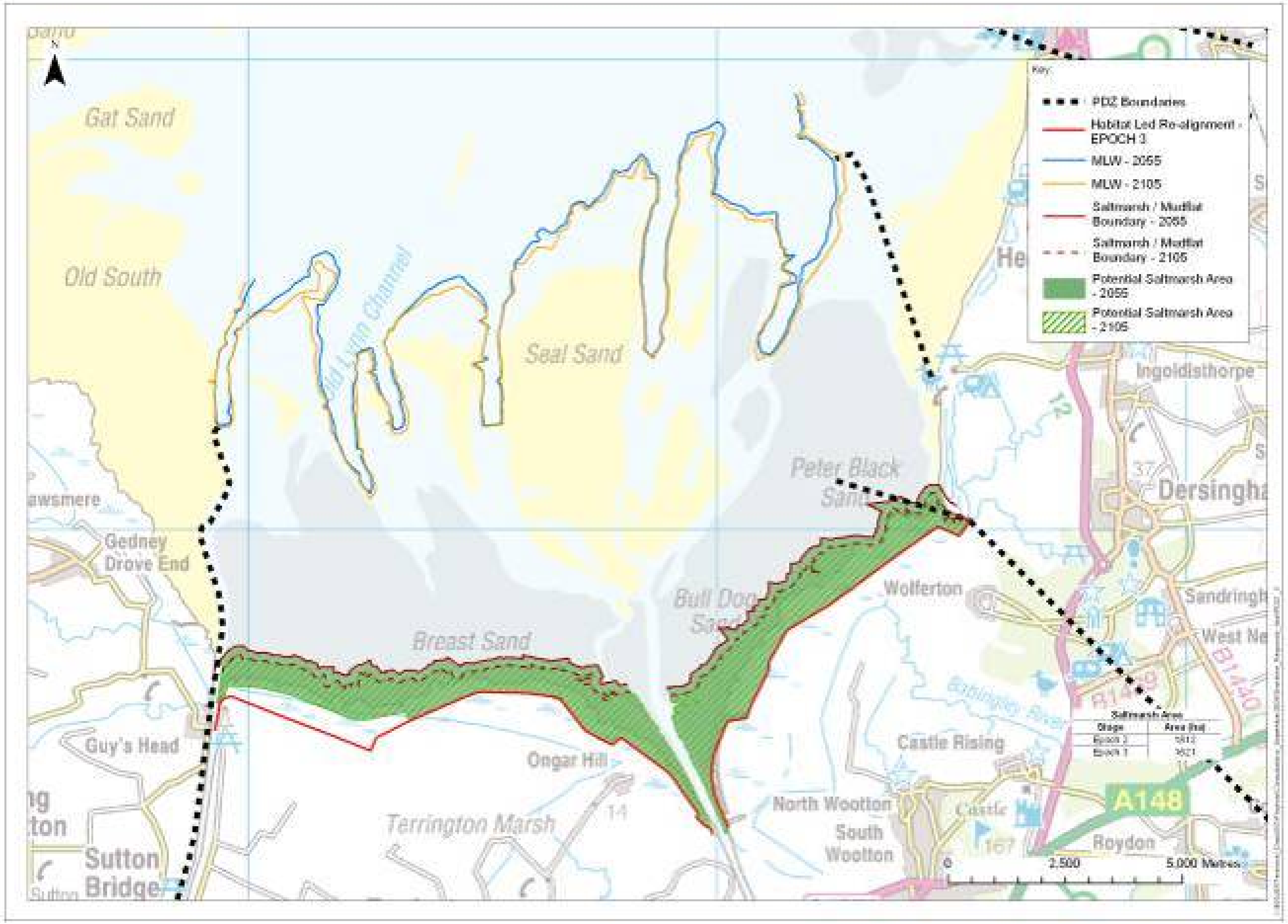


Figure F5.36 PDZ1.3 Hold the line epoch 1

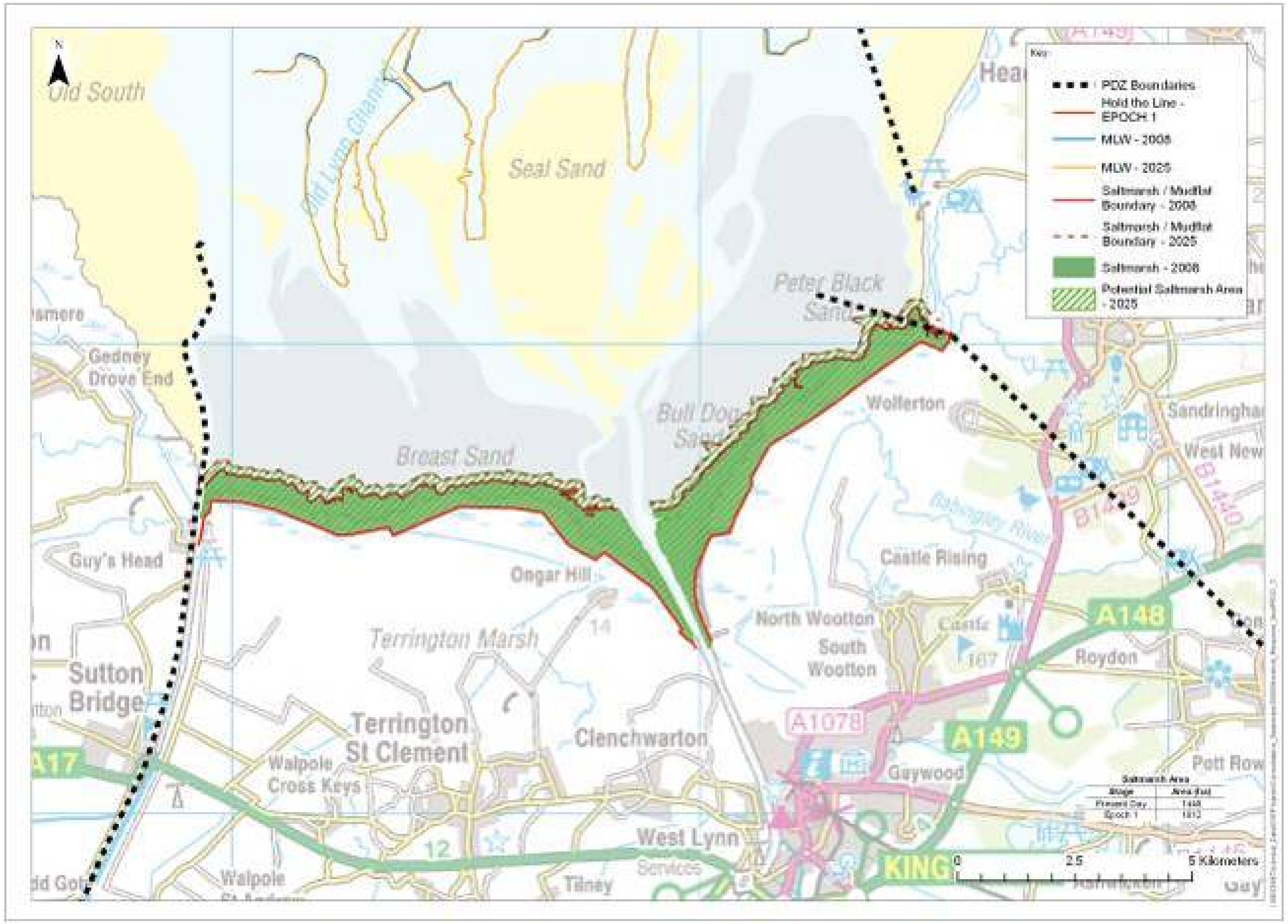


Figure F5.37 PDZ1.3 Hold the line epoch 2

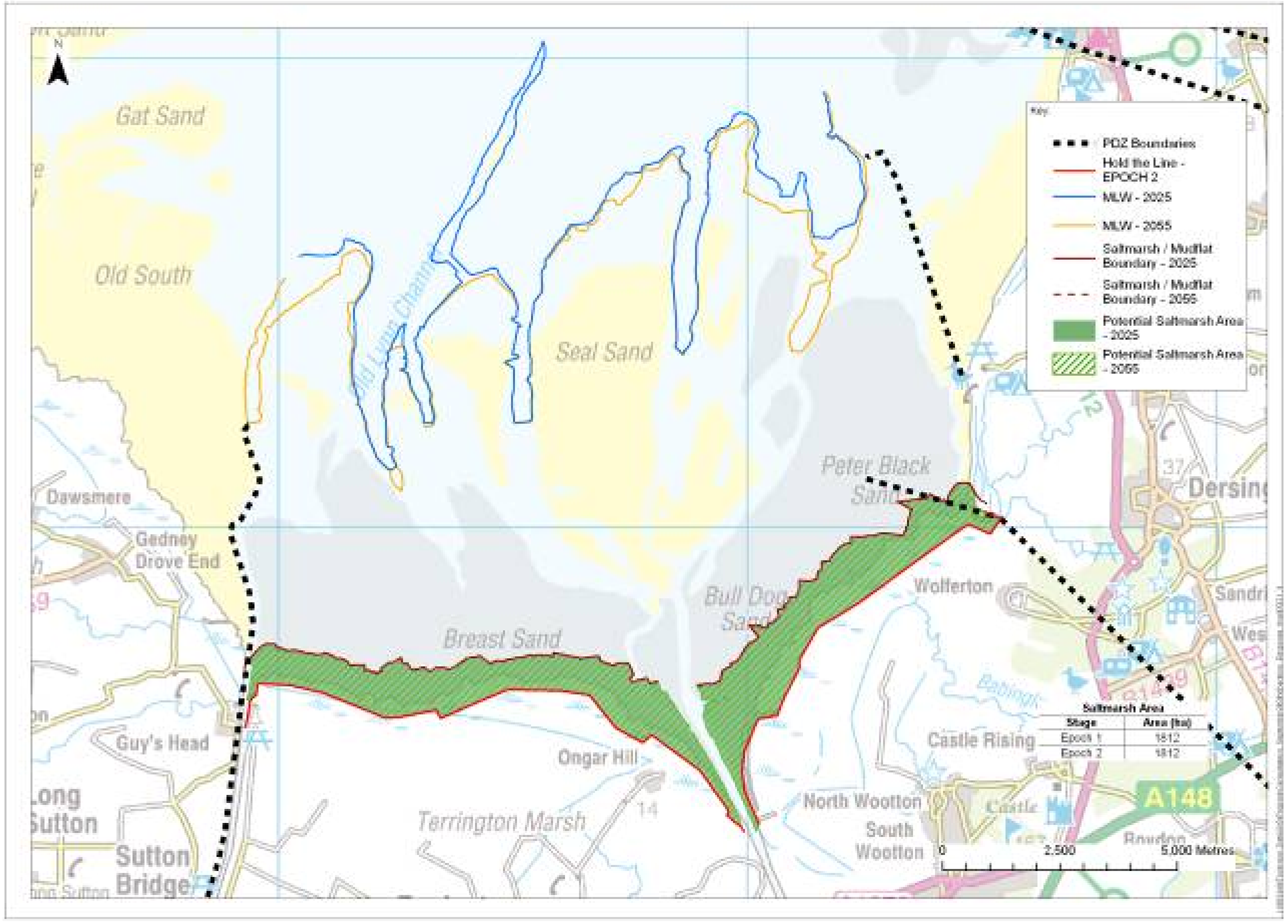


Figure F5.38 PDZ1.3 Hold the line epoch 3

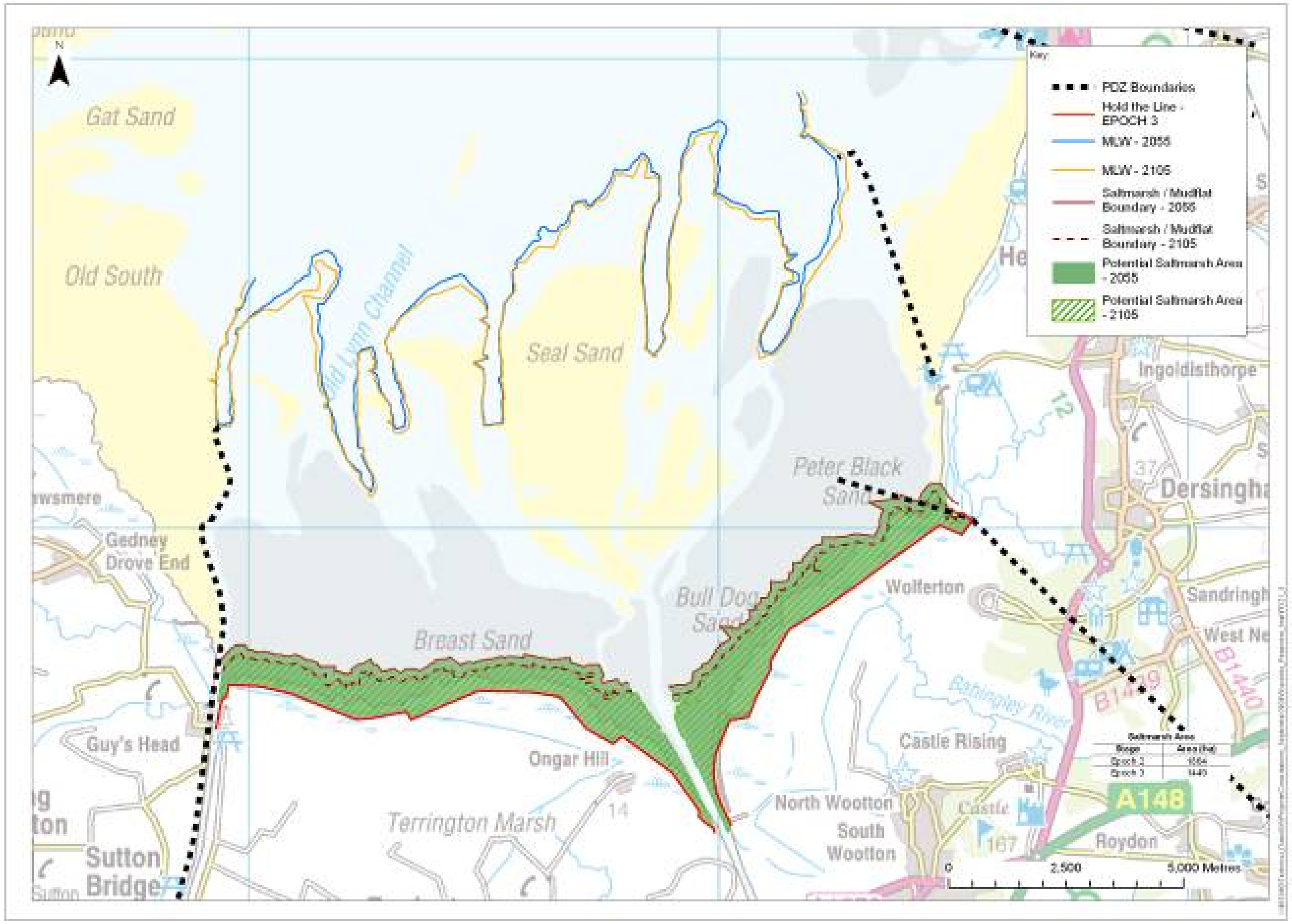


Figure F5.39 PDZ1.3 Local rebalancing epoch 1

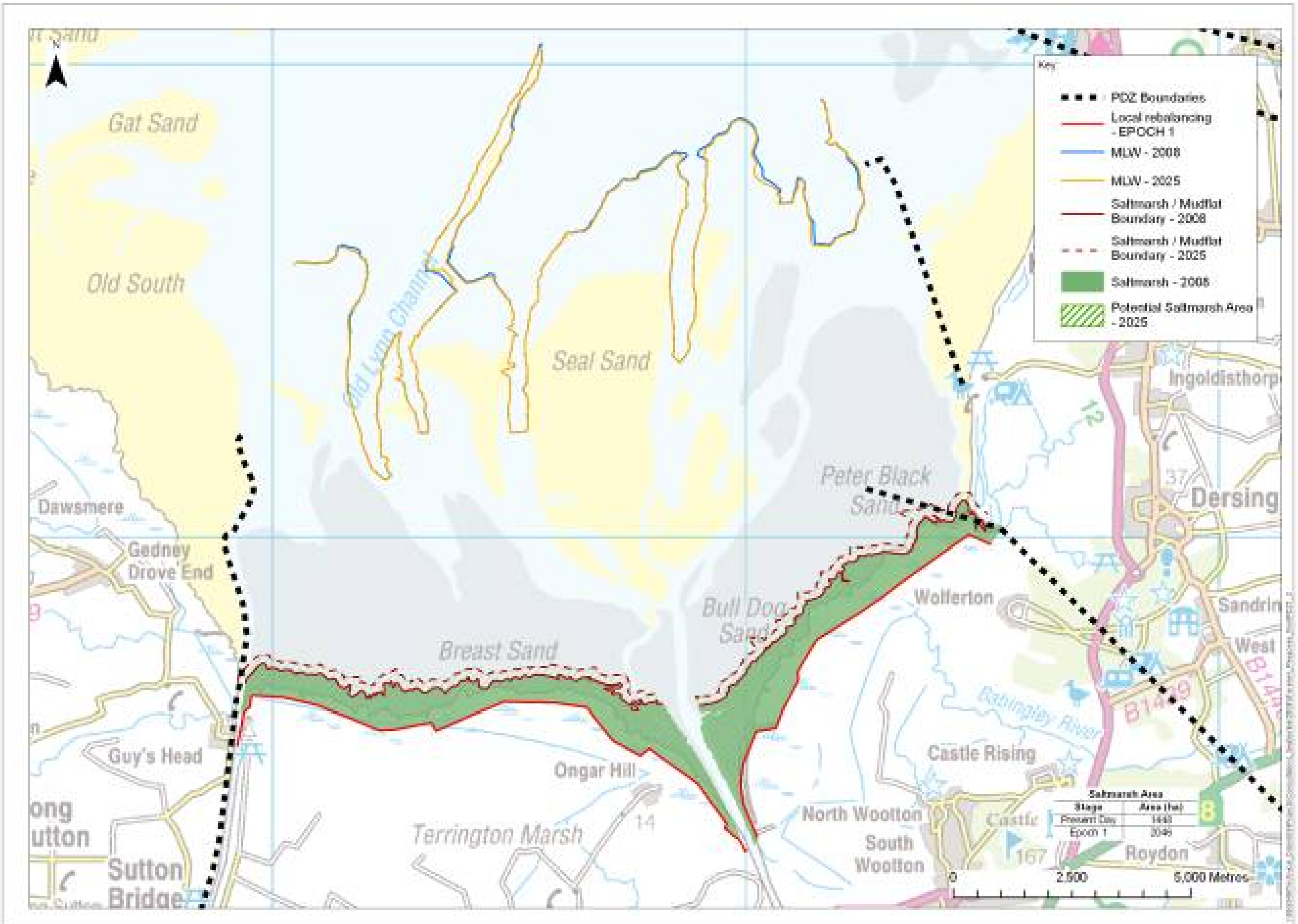


Figure F5.40 PDZ1.3 Local rebalancing epoch 2

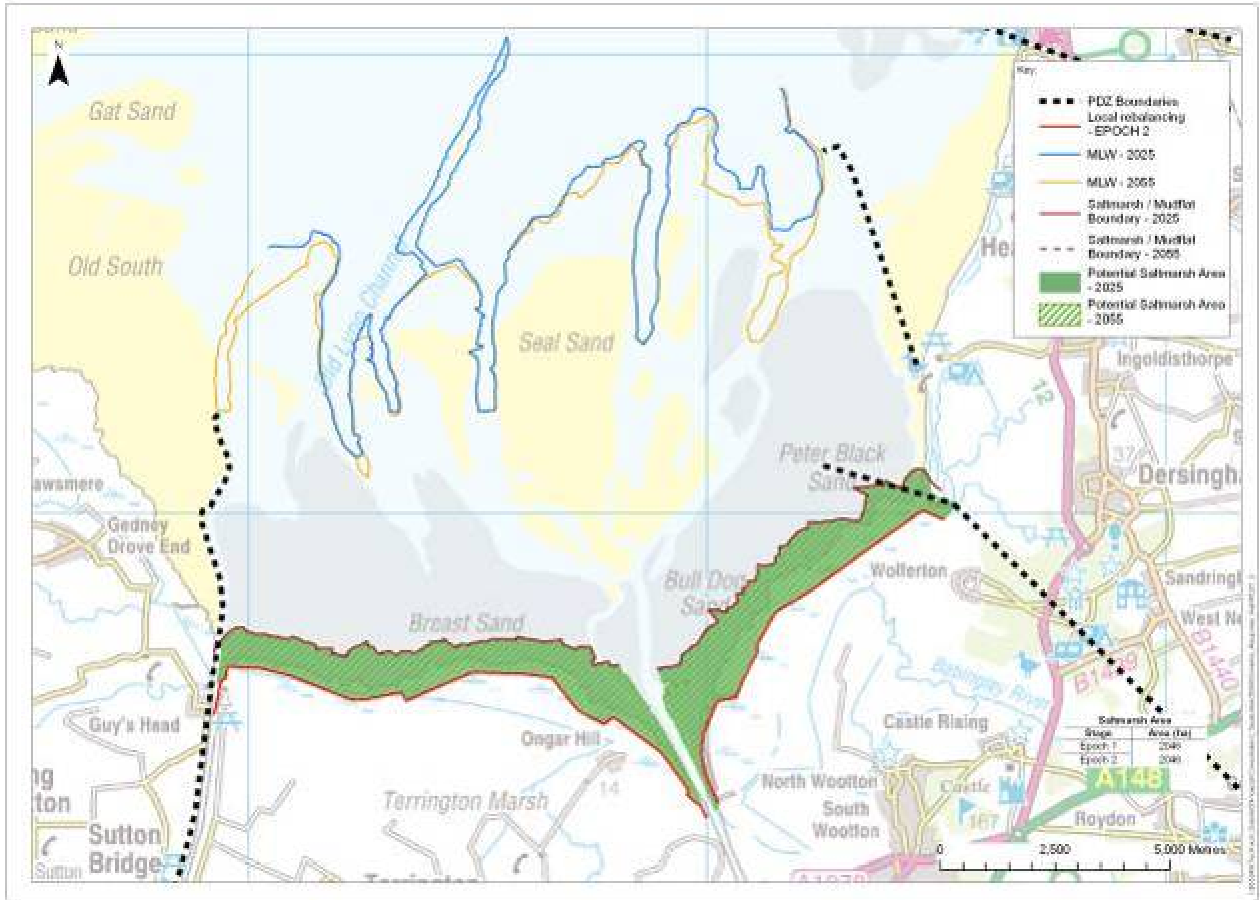
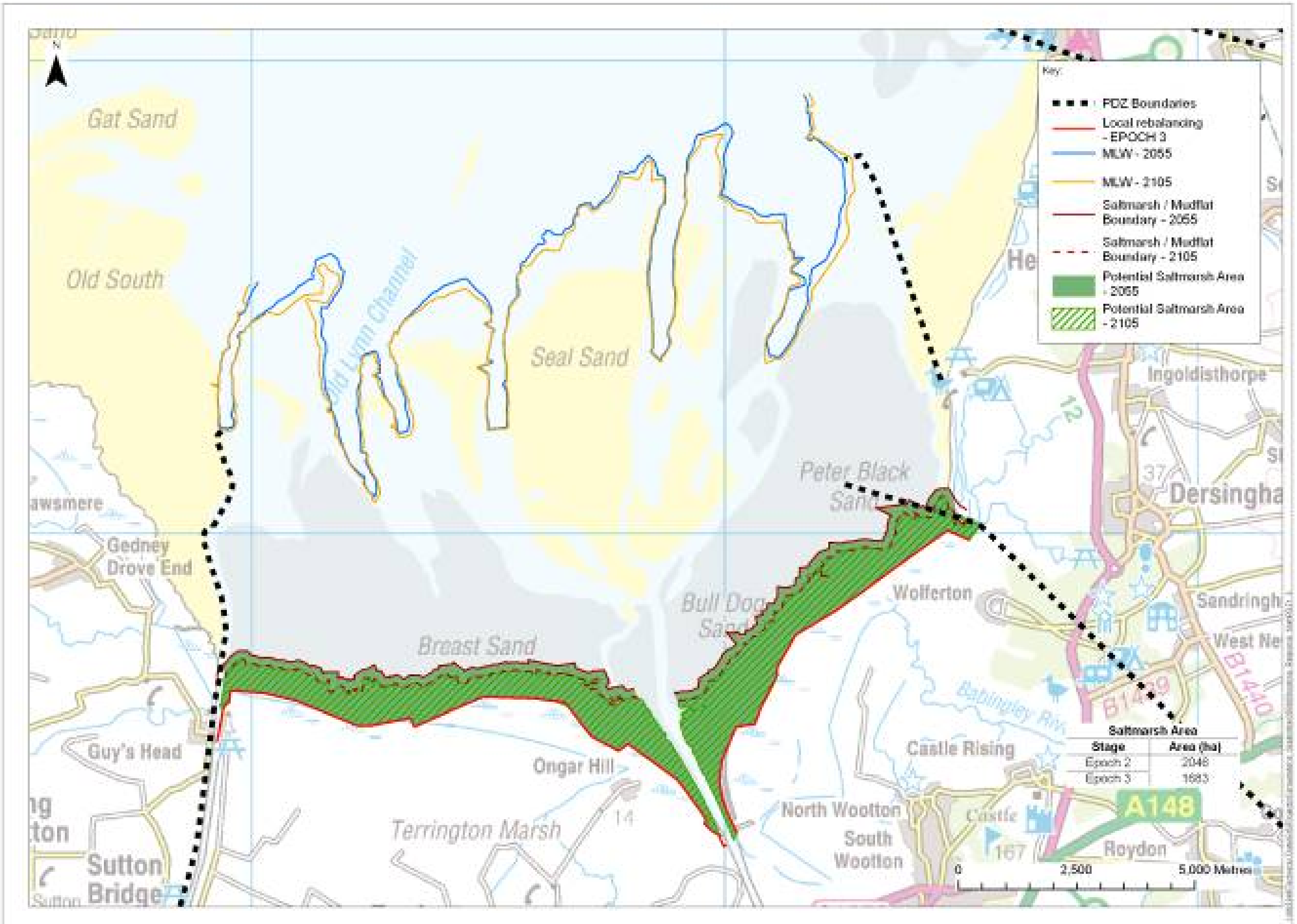


Figure F5.41 PDZ1.3 Local rebalancing epoch 3



F5.6 Wolferton Creek to South Hunstanton (PDZ2)

F5.6.1 Introduction

For this PDZ, there are four Policy Packages that are taken forward to appraisal:

- Maximum landward realignment: Landward Managed realignment to the maximum extent per epoch as defined in the Playing Field, including land use adaptation as required;
- Realignment to existing second line of defence: abandoning the first defence line (shingle bank) following adaptation of land use in between the lines;
- Wide defence zone: optimising the use of the two lines as combined defence, including adaptation of land use in between the lines;
- Hold the line: keep the existing alignment for all locations and for all three epochs.

This PDZ is dominated by a 6 metre high beach ridge that encloses low-lying land between itself and higher ground. Snettisham Scalp has a large mussel bed on the intertidal flat beyond the beach ridge.

Figure F5.42 outlines the location and boundaries of the PDZ.

Further detail of the characteristics of the PDZ are summarised in table F5.5. These are given in more detail in the Baseline Scenarios report.

It is important to remember when assessing the shoreline's response under the Policy Packages stated above that this PDZ is affected by sediment supply from the north. As a result, management practices in PDZ3 and PDZ4 will have an affect on the evolution of this PDZ. The main influence will be the volume of sediment released from PDZ3 and PDZ4. For the purpose of this assessment, it has been assumed that the management practices in adjacent PDZs will remain the same (Hold the line). This will actually give the 'worst-case' scenario as Hold the line means only a limited sediment supply moving southwards along the PDZ from the undefended cliffs to the north of PDZ4. All other Policy Packages (apart from Hold the line) for PDZ3 and PDZ4 will in fact provide an increased volume of sediment, which will increase the sediment available for shingle ridge development and growth of the spit to the very south of this PDZ.

Figure F5.42 PDZ2 Boundaries

Table F5.5 PDZ2 Baseline Information

Geomorphological Components	*Lynn Deeps* – controls the low water mark along the PDZ and feeds incoming sediment for the PDZ. *Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand* – provide a degree of shelter to a small intertidal area to the north. *Intertidal flat* – energy dissipation to decrease erosion and flood risk. *Snettisham Scalp* – additional shelter to the intertidal area*. Beach ridge* – encloses low-lying ground.
Historic Change	Historically, the shingle ridge has moved landwards and has now been restricted by rising land. The intertidal area has both advanced and retreated with a trend towards narrowing since 1890. The coastline between Wolferton Creek and Snettisham Scalp has seen overall accretion.
Recent Change (1991-2006)	Beach volumes have indicated a general increase in volume since 1992. The lower sand flats in front of Heacham show a trend of horizontal erosion with their upper beaches stabilising.
Tidal Currents	Tidal currents can be relatively strong in the Wash due to its large tidal range. Average current velocities are between 0.8 and 1.0ms^{-1} (HR Wallingford, 1972).
Current Residuals	Net water transport of the water column for this PDZ is north-north-east with levels of 10,000m^3/m/tide to 14,000m^3/m/tide. This is parallel to the coast.
Sediment	Sources: Holderness Coast, Humber Estuary, North Norfolk coast, North Sea, the Wash mouth floor, River Nene and River Great Ouse outfalls. Sinks: Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand and the intertidal area. Transport of sediment is primarily suspended with sediment deposited with low tidal velocities.
Processes	Tide levels at Hunstanton (mCD): MHWS 3.65, MHWN 1.85, MLWN -1.25, MLWS -2.85. Extreme water levels at Snettisham Scalp range from 4.86m for 1:1 yr to 6.37m for 1:1000 yr. Waves: Mean wave heights (Hs) 0.61m, mean wave period (Tz) 3.30s, waves are predominantly from an offshore direction approaching from the north to north-east.
Existing Management	There are grassed earth embankments protecting the majority of this stretch of coastline with beach nourishment works having been implemented in specific areas.

F5.6.2 Future Development Independent of Policy Packages

Throughout all epochs, this PDZ will generally experience continued erosion due to its exposure, but there is the potential for accretion to the northern end of the PDZ, and also along some localised stretches. The southern section of the PDZ is likely to experience increased erosion rates as it is more exposed to north-westerly storms. Into the later epochs, sea level rise is likely to cause increased erosion. This erosion will release sediment which will then be exchanged with the offshore banks, and generally move in a southward direction and be deposited to the very south of this PDZ, building up the spit at Snettisham Scalp.

F5.6.3 Impacts: Maximum landward realignment

<u>Epoch 1 (present day to 2025)</u>
The Playing Field defines that as a minimum all dwellings and the A149 will be kept defended in epoch 1, as adaptation or relocation of these features is not considered realistic within this timeframe. As a result this PP will be the same as the Hold the line PP in epoch 1 – both the shingle ridge and earth embankment will be held to allow time for adaptation.

<u>Epoch 2 (2025 to 2055)</u>
The main change into epoch 2 for this Policy Package will be the cessation of protection of the three caravan parks and holiday homes, with both the shingle ridge and earth embankment being breached or abandoned. As a result, there will be no formal man-made defences in this PDZ, and the intertidal area will extend up to the higher ground. As the shingle ridge rolls back, it will revert back to its natural profile, which is characterised by a reduced crest height and wide berm width. This will mean that there will be increased rates of overtopping across the shingle ridge, leading to increased flooding of the former backshore, and as a result this area will continue to make the transition to saltmarsh, but the rate at which this occurs is uncertain.

It is important to note that ceasing to defend the shingle ridge in epoch 2 has the potential to change the state of the coastal lagoons, and therefore may affect its role in supporting a large population of migrating and wading birds.

<u>Epoch 3 (2055 to 2105)</u>
Into epoch 3, there will be no change in defence position; therefore the trends described in epoch 2 will continue. The saltmarsh development on the former backshore will continue and the shingle ridge will continue to roll back. A considerable amount of sediment will be available for transportation to the adjacent PDZs during this epoch.

A schematic summary diagram of what is predicted over all three epochs is presented in figure F5.43 and the shoreline response for this Policy Package for the three epochs is presented in figure F5.44, figure F5.45 and figure F5.46.

F5.6.4 Impacts: Realignment to Existing second Line of Defence

Epoch 1 (present day to 2025)
Along this PDZ, if realignment to the existing second line of defence was undertaken, this would mean landward realignment to the grassed earth embankment and cessation of management of the shingle ridge. The lower and middle beach profile would erode and the shingle ridge would begin to roll back and regain its natural profile. As a result it is likely that the grassed embankment would require maintenance and monitoring for overtopping from sea level rise.

It will be important to consider the impacts upon the freshwater reserves (environmentally designated sites) at Snettisham Scalp that are currently situated behind the first defence line. The freshwater reserves in the area will gradually become saline through overtopping and breach.

Epoch 2 (2025 to 2055)
This epoch contains no further change of defence alignment. As explained above, realigning would mean reliance upon the grassed embankment as the shingle ridge would roll back and possibly even merge with the earth embankment towards the end of the epoch. It is likely that the embankment will require additional toe protection and potentially an increase in crest height in this epoch.

Epoch 3 (2055 to 2105)
Again, this epoch contains no further change of alignment. Reliance on the grassed embankment alone may present risks to the coastline. There will be a slightly larger area for wave energy dissipation approaching the embankment but as sea levels rise, the mean high and low water mark will move landward. Greater water depths will allow larger waves to reach the embankment, which are more likely to overtop the grassed embankment. As with epoch 2, the embankment will need to be monitored closely with respect to sea level rise, and further works may be required to maintain the standard of protection.

A schematic summary diagram of what is predicted over the three epochs for this PDZ is provided in figure F5.47.

F5.6.5 Impacts: Wide defence zone

Epoch 1 (present day to 2025)
This Policy Package involves the collaboration of both the sand/shingle ridge and the grassed embankment as defences. The area in between these two lines of defence would be occasionally inundated when the shingle ridge is

either overtopped or breached. Therefore, the area is predominantly dry except during storm surges. This will continue to be the case for epoch 1.

During storm conditions, the area between the two lines of defence would act as a temporary flood water retaining zone. Following an overtopping or breach event, the flood water would either drain back over the ridge or down through the shingle into the water table.

As with realignment to the second defence line, this option could threaten the coastal lagoons along this PDZ, depending on the standard of protection for the primary line.

Epoch 2 (2025 to 2055)
To maintain this defence option through epoch 2 would lead to the natural progression of greater overtopping of the first line of defence during high spring tides and storm events. These will become more frequent as sea levels rise. As a result, for this PP the level of management will need to increase.

Epoch 3 (2055 to 2105)
In epoch 3 the processes would be similar to epoch 2, but to a larger extent. Erosion will be an increasing problem for the PDZ specifically as the mean high and low water marks move landward with sea level rise. When restricted by the sand/shingle ridge, the water will forcibly attack the shingle ridge, which will also become more susceptible in general to the rising water levels. Overtopping will continue to increase in frequency and as a result there will be the level of management will need to increase further.

A schematic summary diagram of predicted shoreline evolution for all three epochs is provided in figure F5.48.

F5.6.6 Impacts: Hold the line

Epoch 1 (present day to 2025)
The northern zone of this PDZ has previously seen accretion of the middle and lower beach with continued erosion of the upper profile.

The shingle ridge would maintain its current standard of protection throughout epoch 1. However, towards the south of the PDZ, the constant erosion means that the ridge is under repeated stress and will require monitoring and reprofiling and renourishment on a regular basis (potentially more regular than is undertaken currently). Constant nourishment will lead to an over-steepened ridge profile that increases the risk of failure.

Epoch 2 (2025 to 2055)
The developments in epoch 2 are a continuation from those in epoch 1. The shingle ridge will be under increasing pressure, and it may be necessary to

consider harder man-made coastal protection in order to maintain the standard of protection.

Epoch 3 (2055 to 2105)

The developments in epoch 3 are a continuation from those in epoch 1 and 2, but with a greater impact.

This is the same coastal processes and movement as with the With Present Management scenario discussed in the Baseline Scenarios assessment (see section F3).

Figure F5.43 PDZ2 Maximum landward realignment Schematic

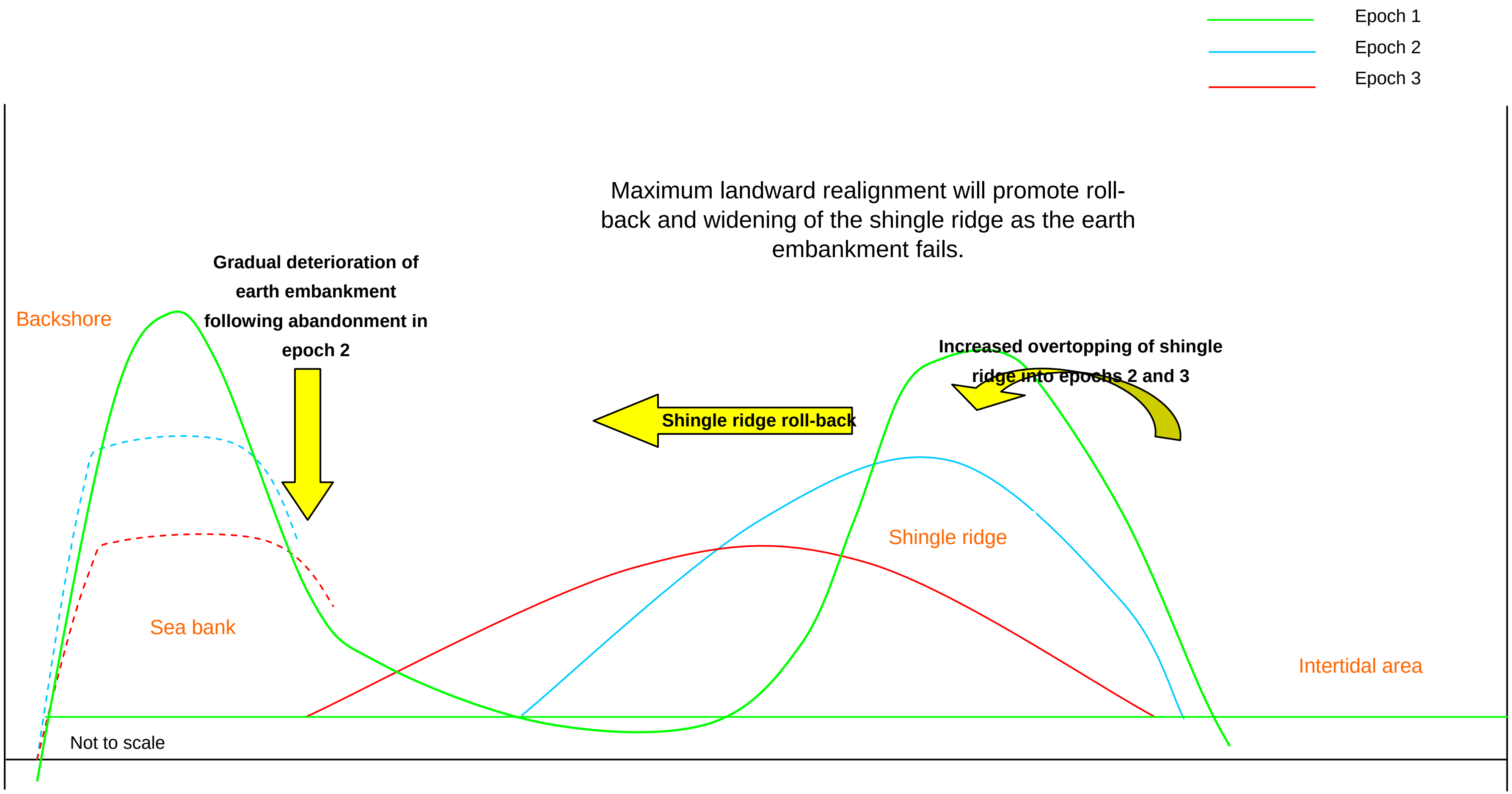


Figure F5.44 PDZ2 Maximum landward realignment epoch 1

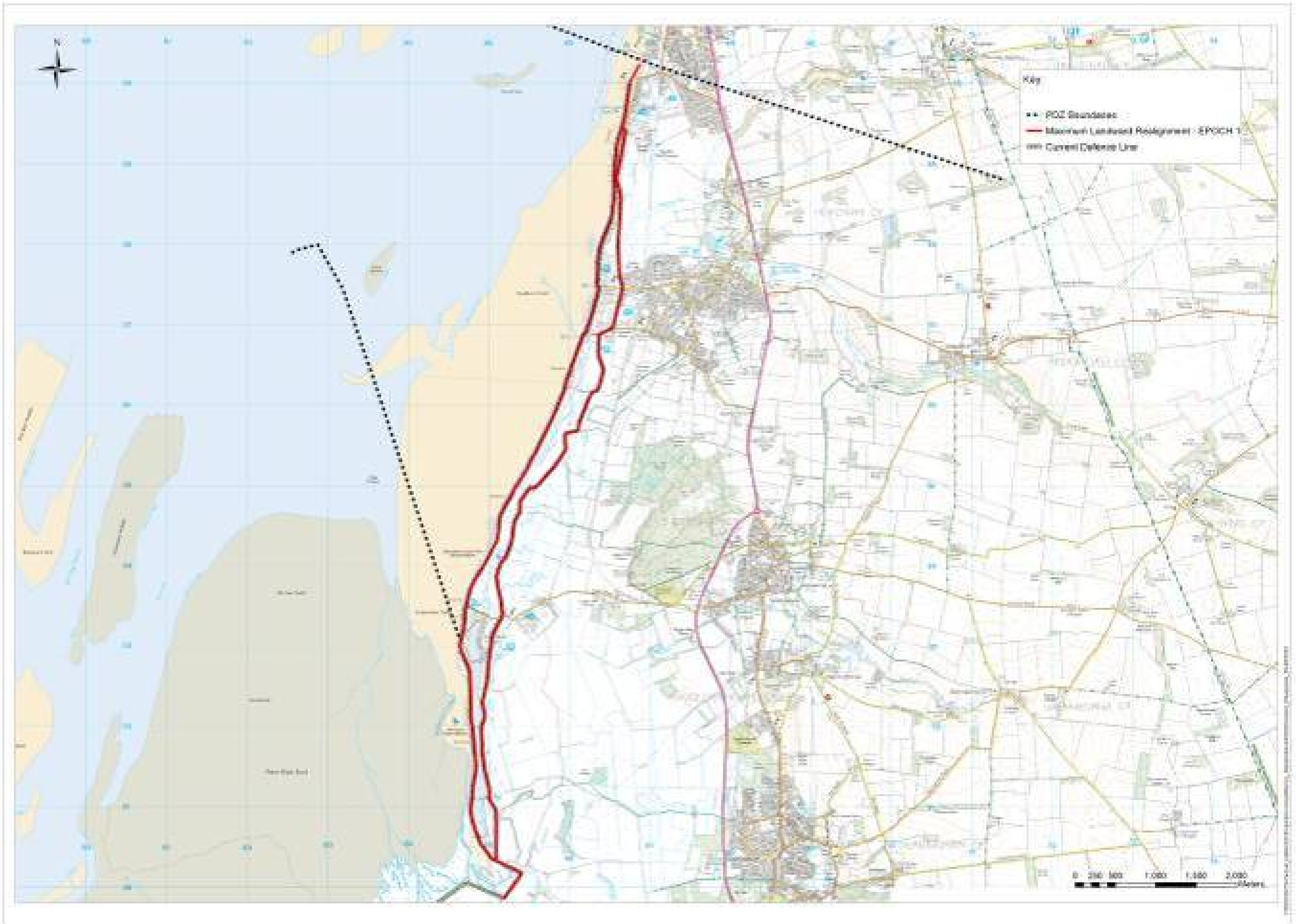


Figure F5.45 PDZ2 Maximum landward realignment epoch 2

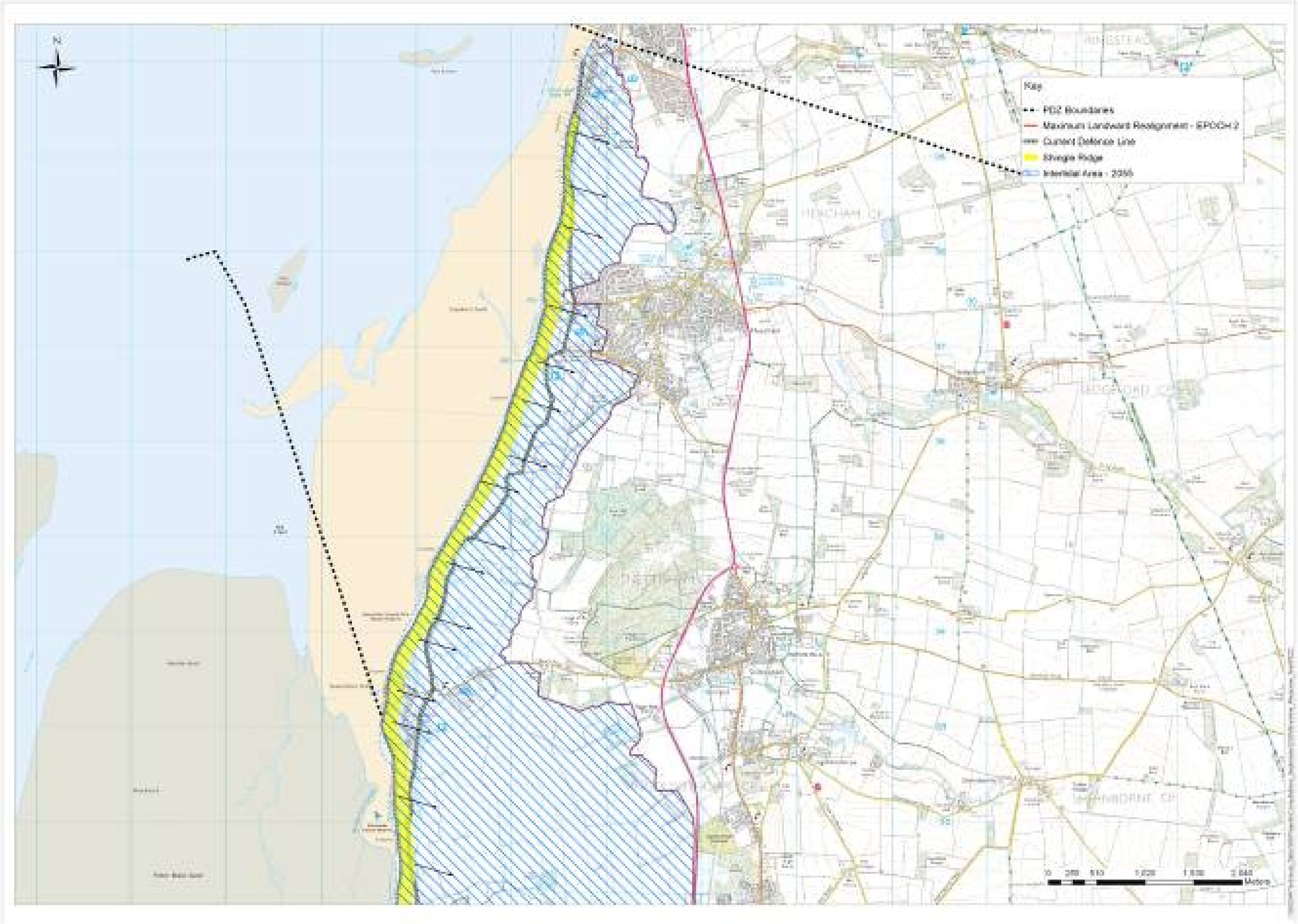


Figure F5.46 PDZ2 Maximum landward realignment epoch 3

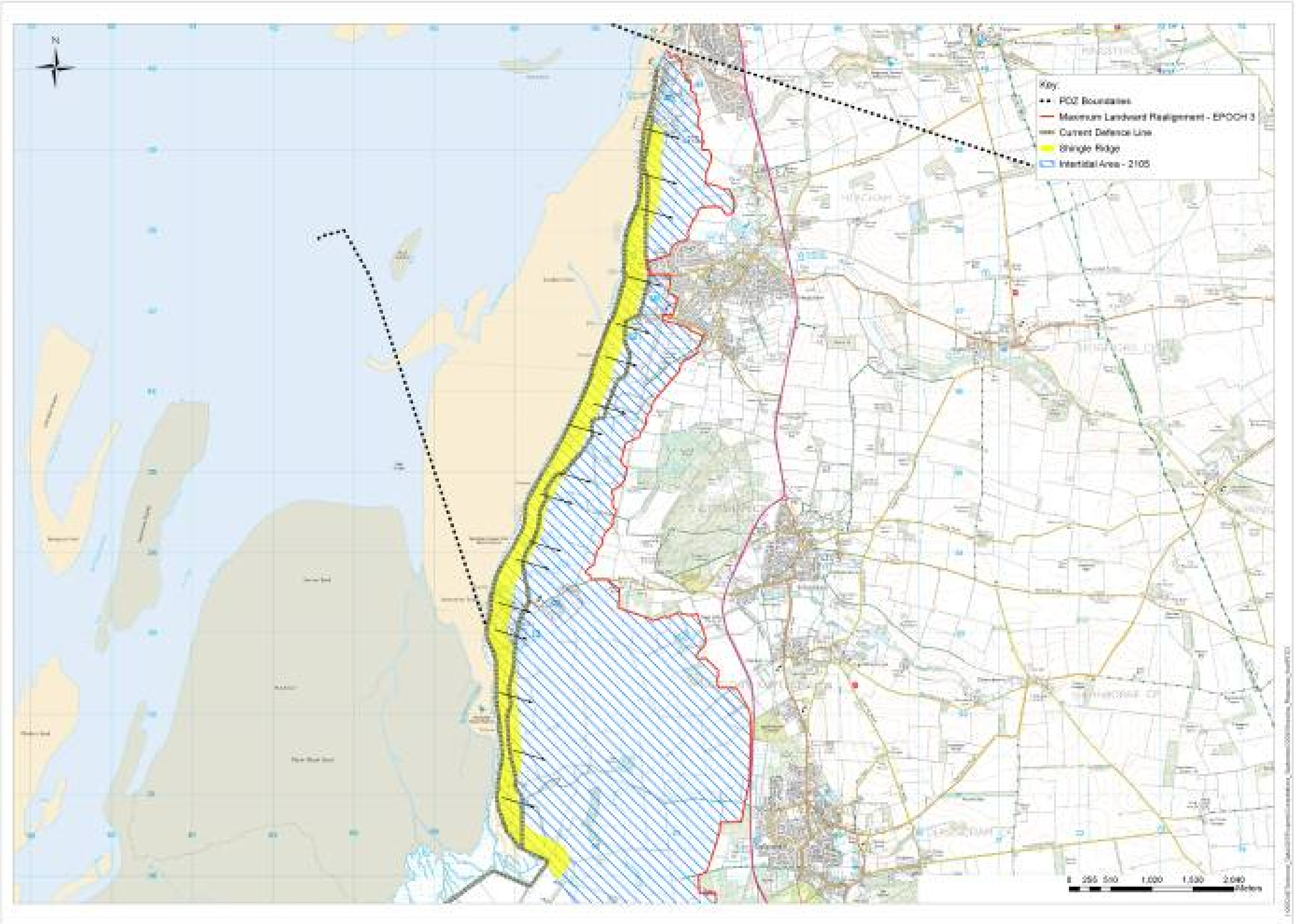


Figure F5.47 PDZ2 Realignment to existing 2nd line of defence Schematic

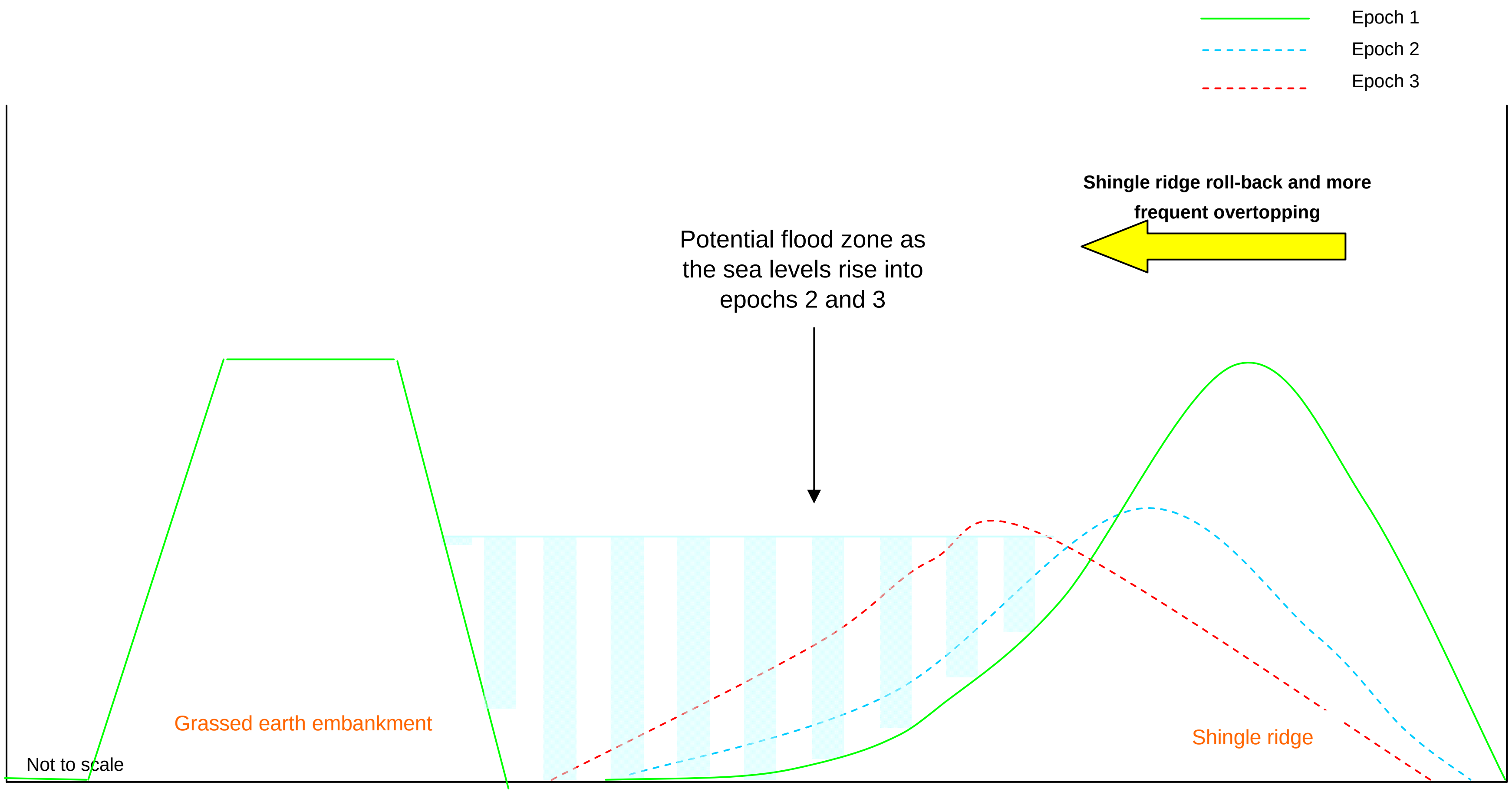
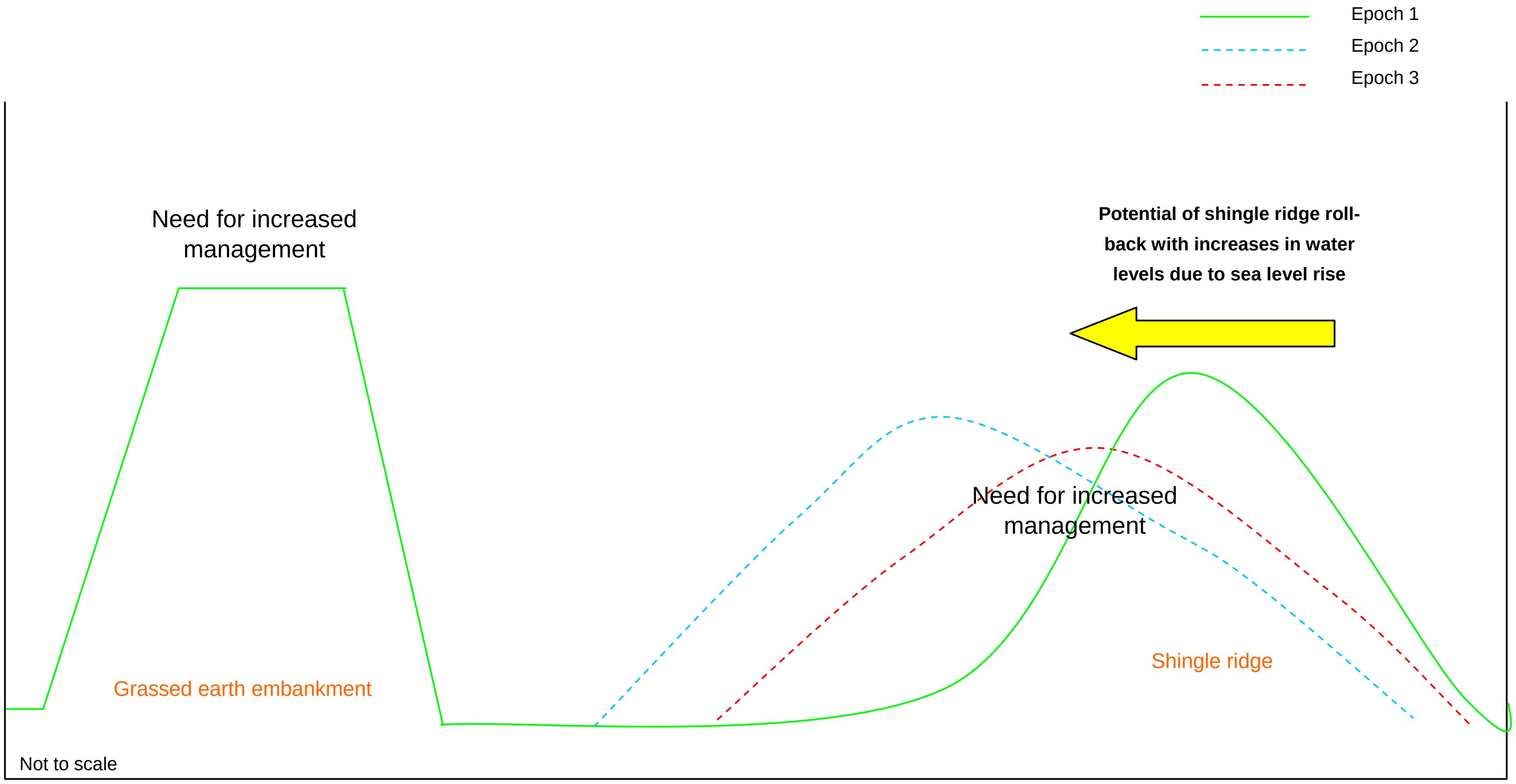


Figure F5.48 PDZ2 Wide defence zone Schematic



F5.7 Hunstanton Town (PDZ3)

F5.7.1 Introduction

For this PDZ, there are three Policy Packages that are taken forward to appraisal:

- No active intervention: apply this policy for all three epochs, including land use adaptation as required;
- No active intervention up to limit: apply this policy up to the point where it threatens features on top of the cliffs (road, dwellings) and then Hold the line;
- Hold the line: keep the existing alignment for all frontages and for all three epochs.

This PDZ deals with the defended high ground in front of Hunstanton itself. Figure F5.49 outlines the location and boundaries of the PDZ.

Further detail of the characteristics of the PDZ are summarised in table F5.6. These are given in more detail in the Baseline Scenarios report (Royal Haskoning, 2008).

For this PDZ it has been assumed that there is no erosion of the cliffs under the Hold the line policy and no erosion following implementation of management after No active intervention (No active intervention up to a Maximum). This does not, therefore, take into account erosion due to storm events and weathering.

Table F5.6 PDZ3 Baseline Information

Geomorphological Components	*Old Hunstanton Cliffs* – at the northern limit of the SMP area and constrain the mouth of the Wash and releases some material to the beach. *Lynn Deeps* – controls the low water mark along the PDZ and feeds incoming sediment for the PDZ. *Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand* – provide a degree of shelter to a small intertidal area to the north. *Intertidal flat* – energy dissipation to decrease erosion and flood risk*. Beach ridge* – encloses low-lying ground.
Historic Change	The cliffs have been receding at a slow rate due to chalk undercutting and small landslides. The glacial till area of the cliffs was receding until defended by a seawall in 1928.
Recent Change (1991-2006)	Recent change has seen retreat of the cliffs of approximately $0.2myr^{-1}$. Sunk Sand has increased in size to the south-west and south-east whilst Thief Sand, Sunk Sand and Ferrier Sand have suffered from erosion on their northern ends.
Tidal Currents	Tidal currents can be relatively strong in the Wash due to its large tidal range. Average current velocities are between 0.8 and $1.0ms^{-1}$ (HR Wallingford, 1972).
Current Residuals	Net water transport of the water column for this PDZ is north-north-east with levels of $10,000m^3$/m/tide to $14,000m^3$/m/tide. This is parallel to the coast.
Sediment	Sources: Holderness Coast, Humber Estuary, North Norfolk coast, North Sea, the Wash mouth floor, The Haven and River Welland outfalls. Sinks: Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand and the intertidal area. Transport of sediment is primarily suspended with sediment deposited with low tidal velocities.
Processes	Tide levels at Hunstanton (mCD): MHWS 3.65, MHWN 1.85, MLWN -1.25, MLWS -2.85. Extreme water levels at Heacham range from 4.81m for 1:1 yr to 6.33m for 1:1000 yr. Waves: Mean wave heights (Hs) 0.61m, mean wave period (Tz) 3.30s, waves are predominantly from an offshore direction approaching from the north to north-east.
Existing Management	The weak rock cliffs provide a natural coastal defence for a number of properties in the area. The chalk section of cliffs (in the northern part of the PDZ) is undefended while the southern glacial till is protected by a seawall and landscaped backshore. There are a series of Groyne to reduce the southward littoral drift and the south beach has concrete stepwork revetment, a promenade and wave wall protection.

F5.7.2 Impacts: No active intervention

Epoch 1 (present day to 2025)

The defences are predicted to fail towards the end of epoch 1 or beginning of epoch 2. Failure is likely to occur either by excessive overtopping, which would cause washout and inundation, or by undermining of the toe of the defence, which would cause instability. As a result, during epoch 1, these defences will continue to provide residual protection, but will quickly deteriorate following loss of the toe. Defence failure is likely to be focused in key areas where defence condition is particularly poor.

The onset of erosion of the higher ground towards the end of this epoch is likely to result in an increased volume of sediment that will naturally nourish the beaches in front of this PDZ and into PDZ2.

The potential erosion is illustrated in figure F5.50.

Epoch 2 (2025 to 2055)

Into epoch 2 the localised areas of failure will begin to spread along the entire defence length as the wall ‘un-zips’ laterally from the localised failure sections. This process is likely to be rapid following failure of the localised section. From this point, the shoreline will begin to regain its cliff-like appearance, and attempt to erode back to its natural profile that is in line with the cliffs to the north. As a result the erosion rate in the epoch is likely to be high. This increased erosion would, however, provide an increased sediment volume to the beaches to the south and would aid to improve the erosion trend of the beaches in front of this PDZ and into PDZ2

The potential erosion is illustrated in figure F5.51. For the purpose of this figure, as with the Baseline Scenarios report, it has been assumed that cliff regression will commence at the start of epoch 2 at a rate of $0.53myr^{-1}$ (an average of the epoch 2 erosion rates for PDZ4).

Epoch 3 (2055 to 2105)

Erosion rates experienced are likely to be similar to those along PDZ4. It is important to stress here that this is an uncertainty, but for the purpose of the figures, an average erosion rate from PDZ4 has been applied to this PDZ. As with epochs 1 and 2, erosion of the higher ground will continue to provide sediment to the beaches in front of this PDZ, and into PDZ2.

The potential erosion movement is illustrated in figure F5.52. For the purpose of this figure, as with the Baseline Scenarios report, it has been assumed that cliff regression along this PDZ will be $0.75myr^{-1}$ between 2055 and 2085 and $0.94myr^{-1}$ between 2085 and 2105 (an average of the epoch 3 erosion rates for PDZ4).

F5.7.3 Impacts: No active intervention up to a limit

Epoch 1 (present day to 2025)
For the southern part of the PDZ, the line will need to be held from the beginning of the epoch due to the dwellings and roads that will need protecting.

For epoch 1, using the cliff erosion rates stated in the Baseline Scenarios report (based on Leatherman's equation 1990), the 'maximum' extent will not be reached in the first epoch in the northern part of the PDZ. As a result cliff erosion will be allowed to continue.

The beach will therefore continue to become steeper as the intertidal zone continues to narrow. The cliff will continue to erode, with the central zone of the currently undefended chalk section being the subject of increased wave attack and therefore increased erosion rates. The southern area of the currently undefended chalk cliffs, where the mean high water mark is closest to the toe of the cliffs, may also experience increased regression rates.

The predicted erosion movement is illustrated in figure F5.53.

Epoch 2 (2025 to 2055)
For the southern part of the PDZ the line will continue to be held.

For epoch 2, using the cliff erosion rates stated in the Baseline Scenarios report (based on Leatherman's equation 1990), the 'maximum' extent of the B1161 may be reached towards the end of the epoch. As a result, the cliffs in this section may need to be defended towards the end of this epoch.

The predicted erosion movement is illustrated in figure F5.54.

Epoch 3 (2055 to 2105)
For the southern part of the PDZ the line will continue to be held.

Using Leatherman's (1990) equation for cliff recession leads to the conclusion that an increased proportion of the cliff top features along the northern section of this PDZ will come under threat in the course of this epoch. Therefore, a policy of Hold the line will be needed from towards the end of epoch 2 (in time to prevent damage), for a large proportion of the central section.

The predicted erosion movement is illustrated in figure F5.55.

F5.7.4 Impacts: Hold the line

Epoch 1 (present day to 2025)
Holding the line along this PDZ would result in the current defences (sea wall and Groyne) that protect the high ground being maintained and improved where necessary in order to maintain the current standard of protection.

The trend of lowering beach levels along this PDZ is likely to continue.

The response is illustrated in figure F5.56.

Epoch 2 (2025 to 2055)
Similar trends will be experienced as during epoch 1.

The response is illustrated in figure F5.56.

Epoch 3 (2055 to 2105)
Similar trends will be experienced as during epoch 1. It is possible that the underlying glacial deposits will become exposed across the Hunstanton beach, and nourishment may be required to allow continued tourist activities in the area.

The response is illustrated in figure F5.56.

F5.8 Hunstanton Cliffs (PDZ4)

F5.8.1 Introduction

For this PDZ, there are three Policy Packages that are taken forward to appraisal:

- No active intervention: apply this policy for all three epochs, including land use adaptation as required;
- No active intervention up to maximum: apply this policy up to the point where it threatens features on top of the cliffs (road, dwellings) and then Hold the line;
- Hold the line: keep the existing alignment for all frontages and for all three epochs.

The Old Hunstanton sea cliffs are between 10 and 20 metres in height. The lower sections of the cliff expose cretaceous ferruginous sandstones (Carstone) that is covered with Red Chalk adjacent to White Lower Chalk. A sandstone platform fronts the cliffs. The offshore bank of Sunk Sand reaches out for approximately 4 kilometres from the coast and is exposed at low water.

Figure F5.49 outlines the location and boundaries of the PDZ.

Further detail of the characteristics of the PDZ are summarised in table F5.7. These are given in more detail in the Baseline Scenarios report (Royal Haskoning, 2008).

For this PDZ it has been assumed that there is no erosion of the cliffs under the Hold the line policy and no erosion following implementation of management after No active intervention (No active intervention up to a Maximum). This does not, therefore, take into account erosion due to storm events and weathering.

Figure F5.49 PDZ3 and PDZ4 Boundaries

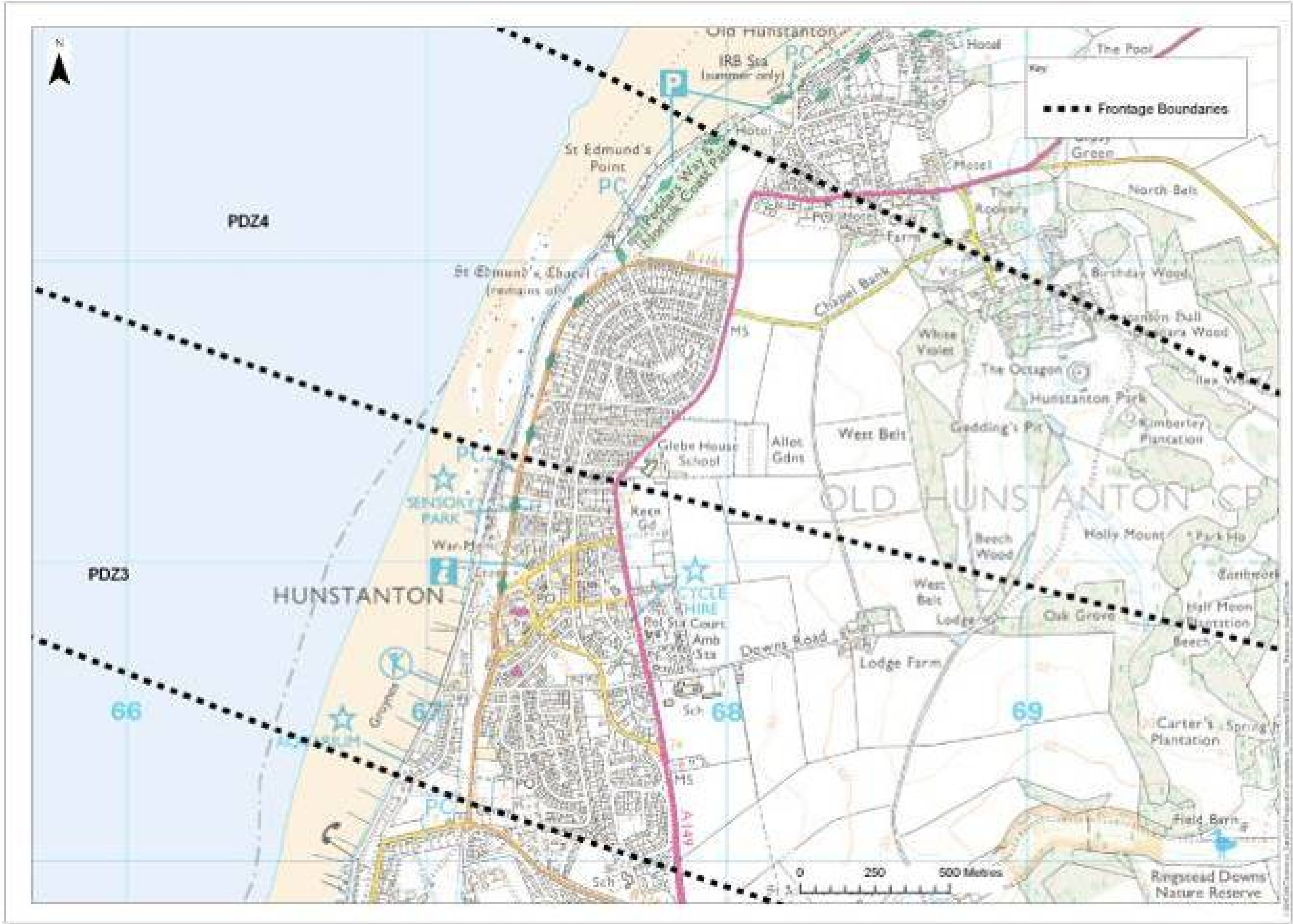


Table F5.7 PDZ4 Baseline Information

Geomorphological Components	*Old Hunstanton Cliffs* – at the northern limit of the SMP area and constrain the mouth of the Wash and releases some material to the beach. *Lynn Deeps* – controls the low water mark along the PDZ and feeds incoming sediment for the PDZ. *Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand* – provide a degree of shelter to a small intertidal area to the north. *Intertidal flat* – energy dissipation to decrease erosion and flood risk. *Beach ridge* – encloses low-lying ground.
Historic Change	The cliffs have been receding at a slow rate due to chalk undercutting and small landslides. The glacial till area of the cliffs was receding until defended by a seawall in 1928.
Recent Change (1991-2006)	Recent change has seen retreat of the cliffs of approximately $0.2myr^{-1}$. Sunk Sand has increased in size to the south-west and south-east whilst Thief Sand, Sunk Sand and Ferrier Sand have suffered from erosion on their northern ends.
Tidal Currents	Tidal currents can be relatively strong in the Wash due to its large tidal range. Average current velocities are between 0.8 and $1.0ms^{-1}$ (HR Wallingford, 1972).
Current Residuals	Net water transport of the water column for this PDZ is north-north-east with levels of $10,000m^3$/m/tide to $14,000m^3$/m/tide. This is parallel to the coast.
Sediment	Sources: Holderness Coast, Humber Estuary, North Norfolk coast, North Sea, the Wash mouth floor, The Haven and River Welland outfalls. Sinks: Seal Sand, Old Bell Middle, Blackguard Sand, Silver Sand and Sunk Sand and the intertidal area. Transport of sediment is primarily suspended with sediment deposited with low tidal velocities.
Processes	Tide levels at Hunstanton (mCD): MHWS 3.65, MHWN 1.85, MLWN -1.25, MLWS -2.85. Extreme water levels at Heacham range from 4.81m for 1:1 yr to 6.33m for 1:1000 yr. Waves: Mean wave heights (Hs) 0.61m, mean wave period (Tz) 3.30s, waves are predominantly from an offshore direction approaching from the north to north-east.
Existing Management	The weak rock cliffs provide a natural coastal defence for a number of properties in the area. The chalk section of cliffs (in the northern part of the PDZ) is undefended while the southern glacial till is protected by a seawall and landscaped backshore. There are a series of Groyne to reduce the southward littoral drift and the south beach has concrete stepwork revetment, a promenade and wave wall protection.

F5.8.2 Impacts: No active intervention

Epoch 1 (present day to 2025)

During epoch, the beach is expected to continue to become steeper as the intertidal zone continues to narrow. The Baseline Scenarios report looks in detail at the future predicted cliff recession rates of this area using an equation formulated by Leatherman (1990).

It is likely that the central zone of this PDZ will be the focus of wave attack and erosion. There is also potential for the southern section to experience high regression rates as the mean high water mark is closest to the toe here.

Erosion across the whole of the PDZ in this epoch will continue to provide an increased volume of sediment to the Hunstanton beach area.

The potential erosion is illustrated in figure F5.50.

Epoch 2 (2025 to 2055)

As with epoch 1, the future cliff recession rates have been predicted using the equation formulated by Leatherman (1990), as detailed in the Baseline Scenarios report. This increased erosion would, however, provide an increased sediment volume to the beaches to the south and would aid to improve the erosion trend in PDZ2 and PDZ3.

The potential erosion is illustrated in figure F5.51. For the purpose of this figure, as with the Baseline Scenarios report, it has been assumed that cliff regression along the southern section will commence at the start of epoch 2 at a rate of $0.53myr^{-1}$ (an average of the epoch 2 erosion rates for the northern section).

Epoch 3 (2055 to 2105)

With continued No active intervention it is likely that the cliff top amenities, including properties, would be at risk from cliff recession if no work was carried out. The eroded materials would supply the beaches in the southern area of this PDZ (and also PDZ2 and PDZ3).

The potential erosion movement is illustrated in figure F5.52. For the purpose of this figure, as with the Baseline Scenarios report, it has been assumed that cliff regression along the southern section will be $0.75myr^{-1}$ between 2055 and 2085 and $0.94myr^{-1}$ between 2085 and 2105 (an average of the epoch 3 erosion rates for the northern section).

F5.8.3 Impacts: No active intervention up to a limit

Epoch 1 (present day to 2025)

For epoch 1, using the cliff erosion rates stated in the Baseline Scenarios report (based on Leatherman's equation 1990), the 'limit' will not be reached in the first epoch. As a result cliff erosion will be allowed to continue.

The beach will therefore continue to become steeper as the intertidal zone continues to narrow. The cliff will continue to erode, with the central zone of the currently undefended chalk section being the subject of increased wave attack and therefore increased erosion rates. The southern area of the currently undefended chalk cliffs, where the mean high water mark is closest to the toe of the cliffs, may also experience increased regression rates.

The predicted erosion movement is illustrated in figure F5.53.

Epoch 2 (2025 to 2055)

For epoch 2, using the cliff erosion rates stated in the Baseline Scenarios report (based on Leatherman's equation 1990), the 'limit of the B1161 may be reached around the southern section of this PDZ. As a result, the cliffs in this section may need to be defended towards the end of this epoch.

The predicted erosion movement is illustrated in figure F5.54.

Epoch 3 (2055 to 2105)

Using Leatherman's (1990) equation for cliff recession leads to the conclusion that an increased proportion of the cliff top features along the central section of this PDZ will come under threat in the course of this epoch. Therefore, a policy of Hold the line will be needed from towards the end of epoch 2 (in time to prevent damage), for a large proportion of the southern and central section.

The predicted erosion movement is illustrated in figure F5.55.

F5.8.4 Impacts: Hold the line

Epoch 1 (present day to 2025)

Holding the line along this PDZ would involve continued maintenance of the sea wall and Groyne protecting the higher ground and undertaken improvements where necessary in order to maintain the current standard of protection.

The trend of lowering beach levels along the southern glacial till section of this PDZ is likely to continue.

The response is illustrated in figure F5.56.

Epoch 2 (2025 to 2055)

Similar trends will be experienced as during epoch 1. The areas of this PDZ in addition to PDZ2 and PDZ3 would become more apparent in this epoch as annual sediment supplies are reduced.

The response is illustrated in figure F5.56.

Epoch 3 (2055 to 2105)
Continuing to Hold the line in this epoch would have similar impacts upon this PDZ and PDZ2 as in epoch 2. It is possible that the underlying glacial deposits will become exposed across the Hunstanton beach, and nourishment may be required to allow continued tourist activities in the area.

The response is illustrated in figure F5.56.

Figure F5.50 PDZ3 and PDZ4 No active intervention epoch 1

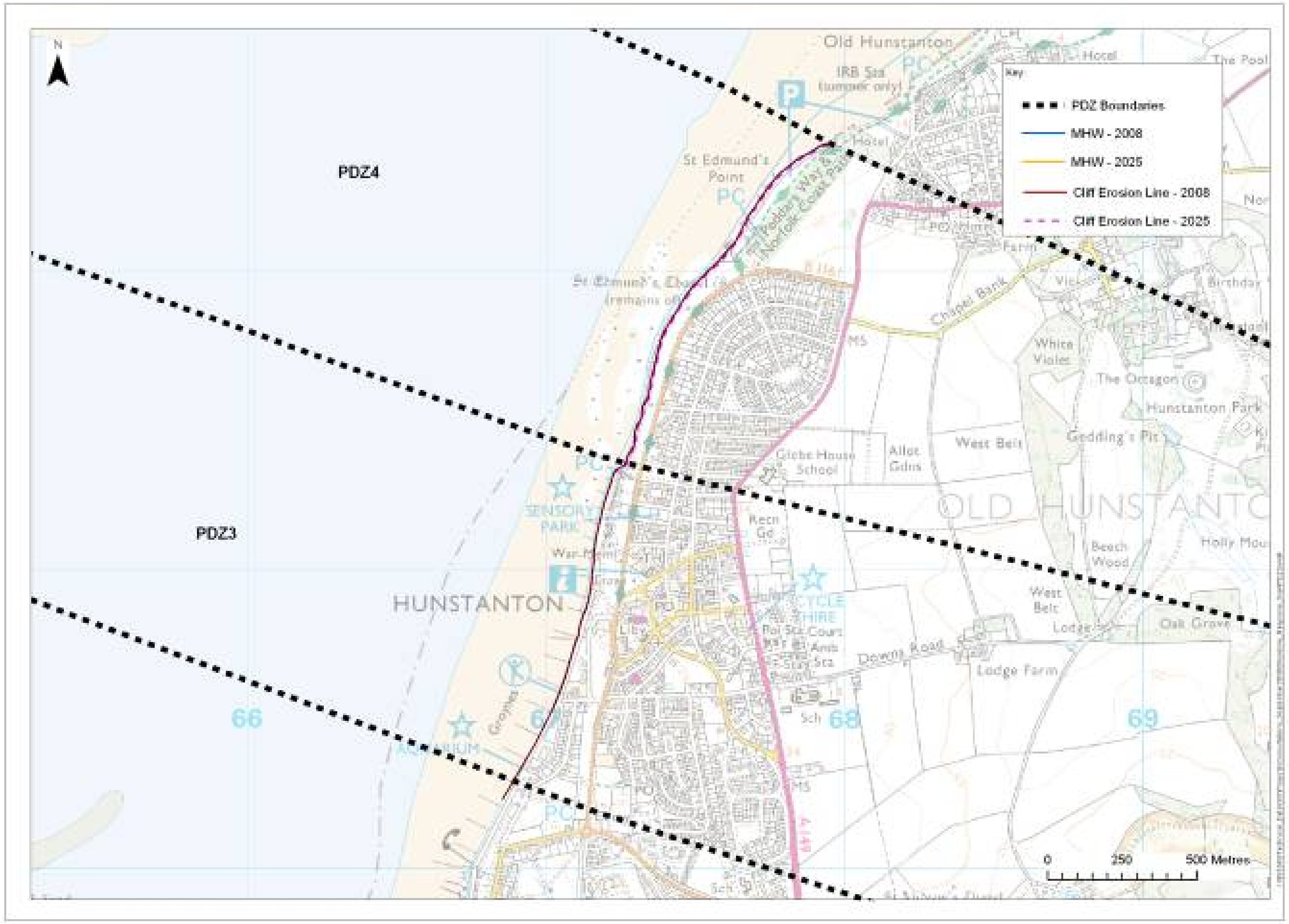


Figure F5.51 PDZ3 and PDZ4 No active intervention epoch 2

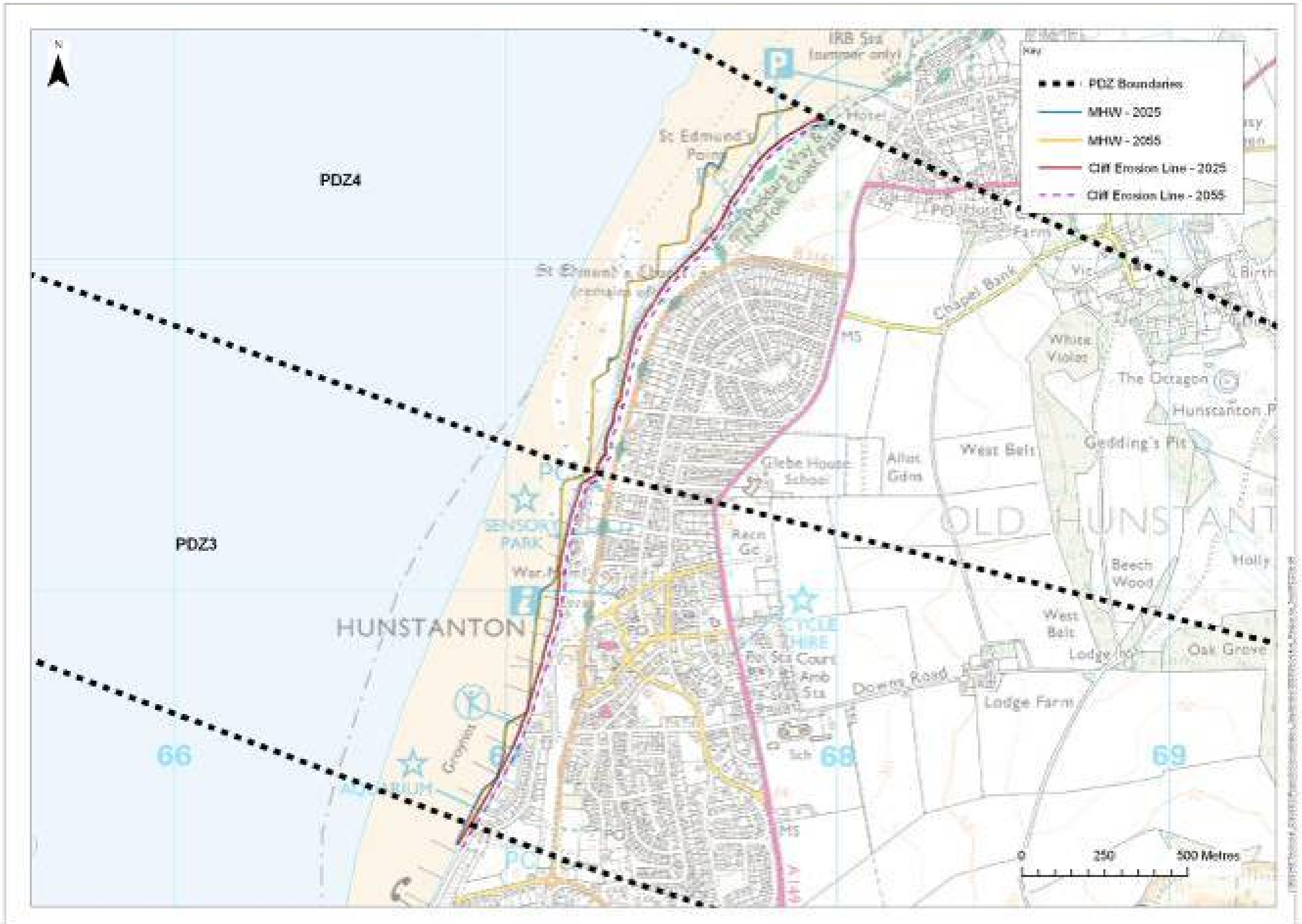


Figure F5.52 PDZ3 and PDZ4 No active intervention epoch 3

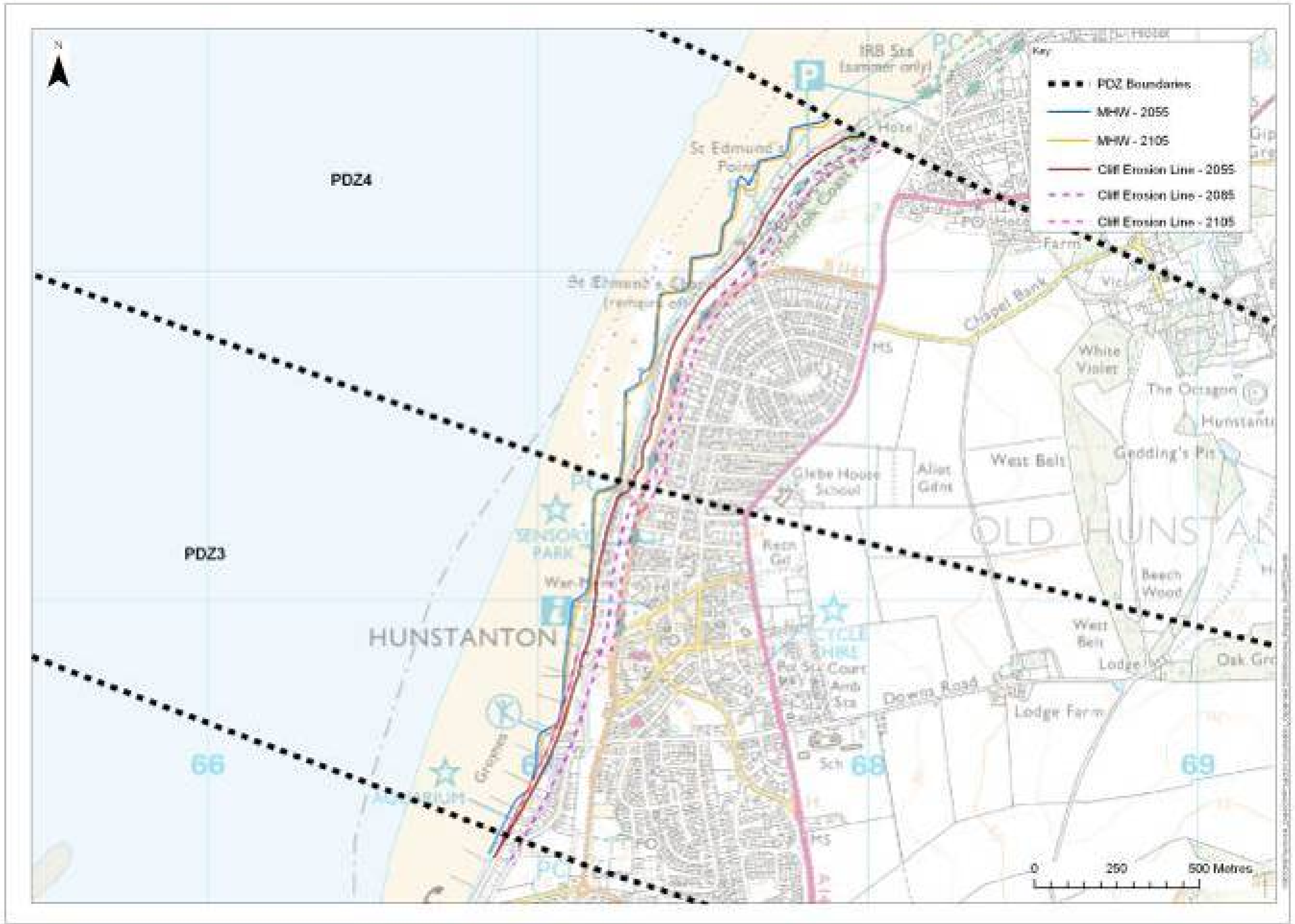


Figure F5.53 PDZ3 and PDZ4 No active intervention up to a limit epoch 1

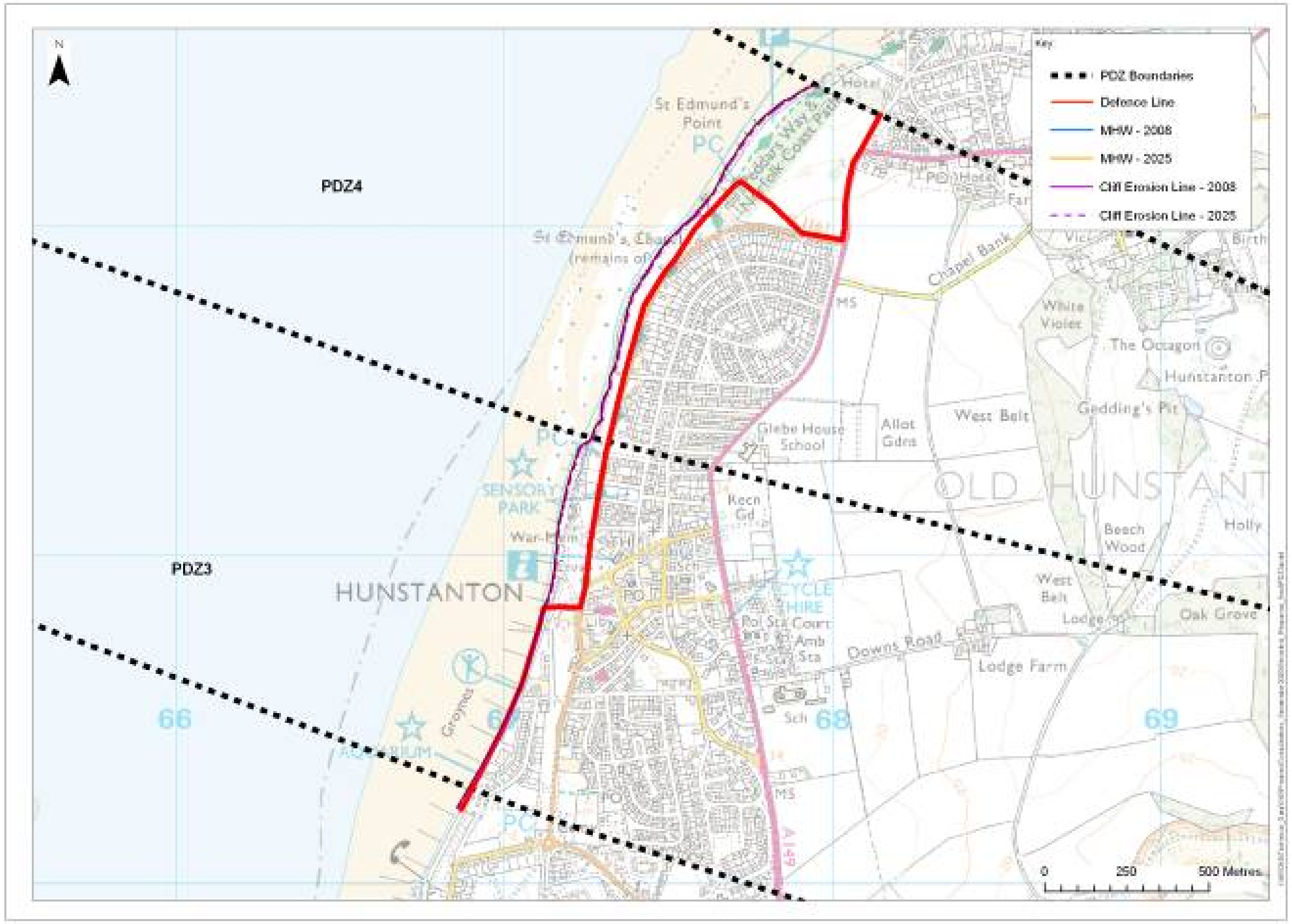


Figure F5.54 PDZ3 and PDZ4 No active intervention up to a limit epoch 2

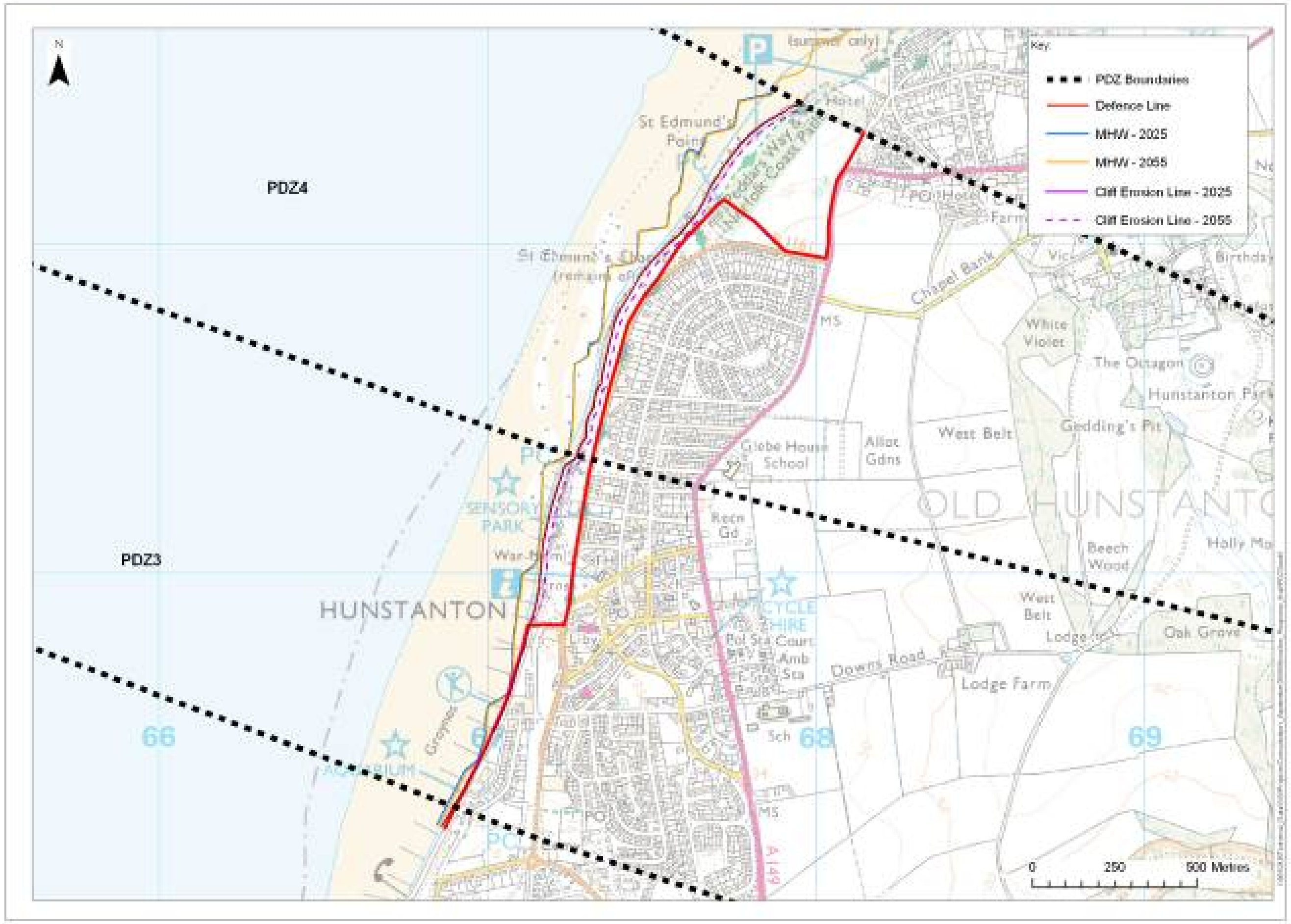


Figure F5.55 PDZ3 and PDZ4 No active intervention up to a limit epoch 3

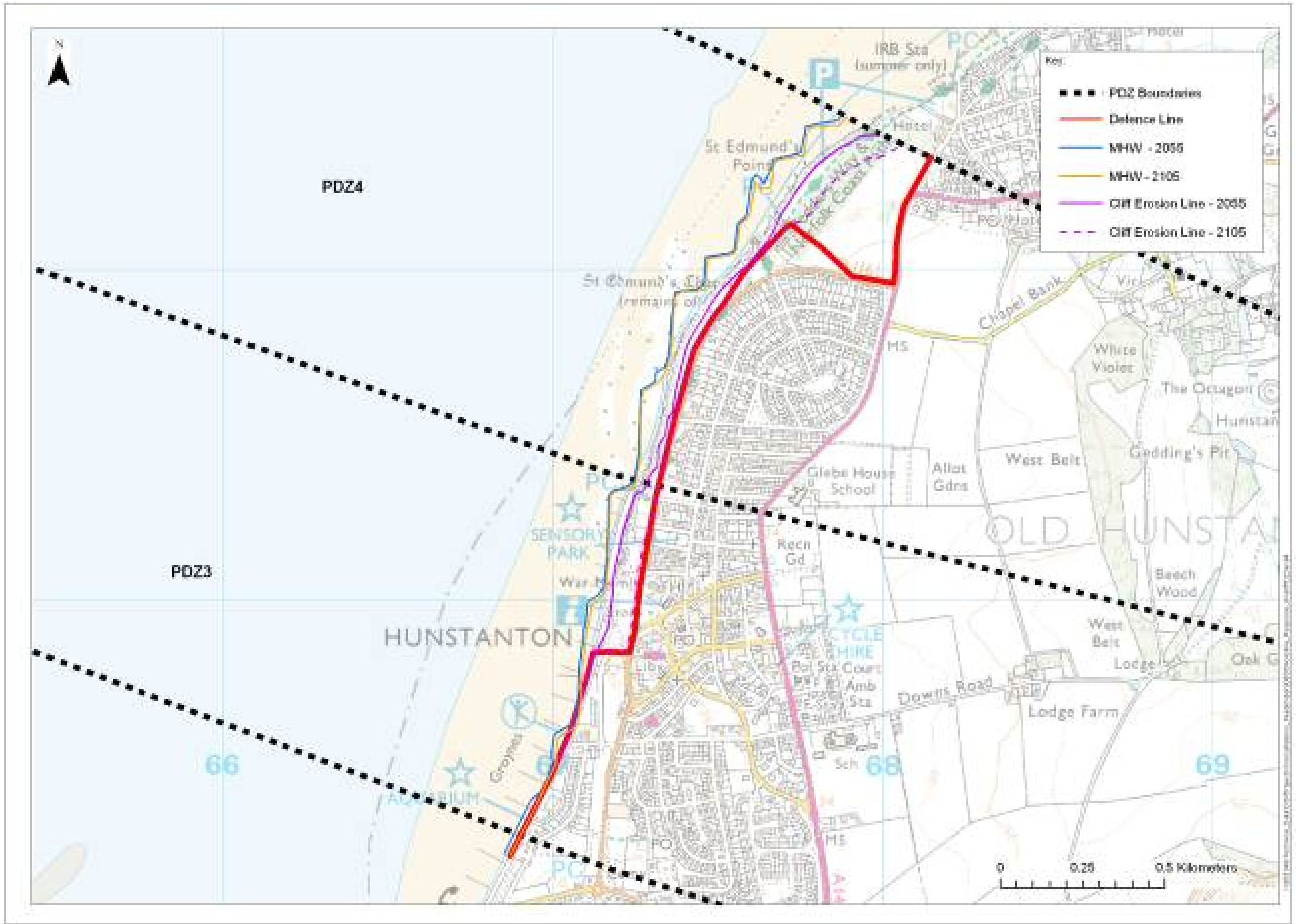
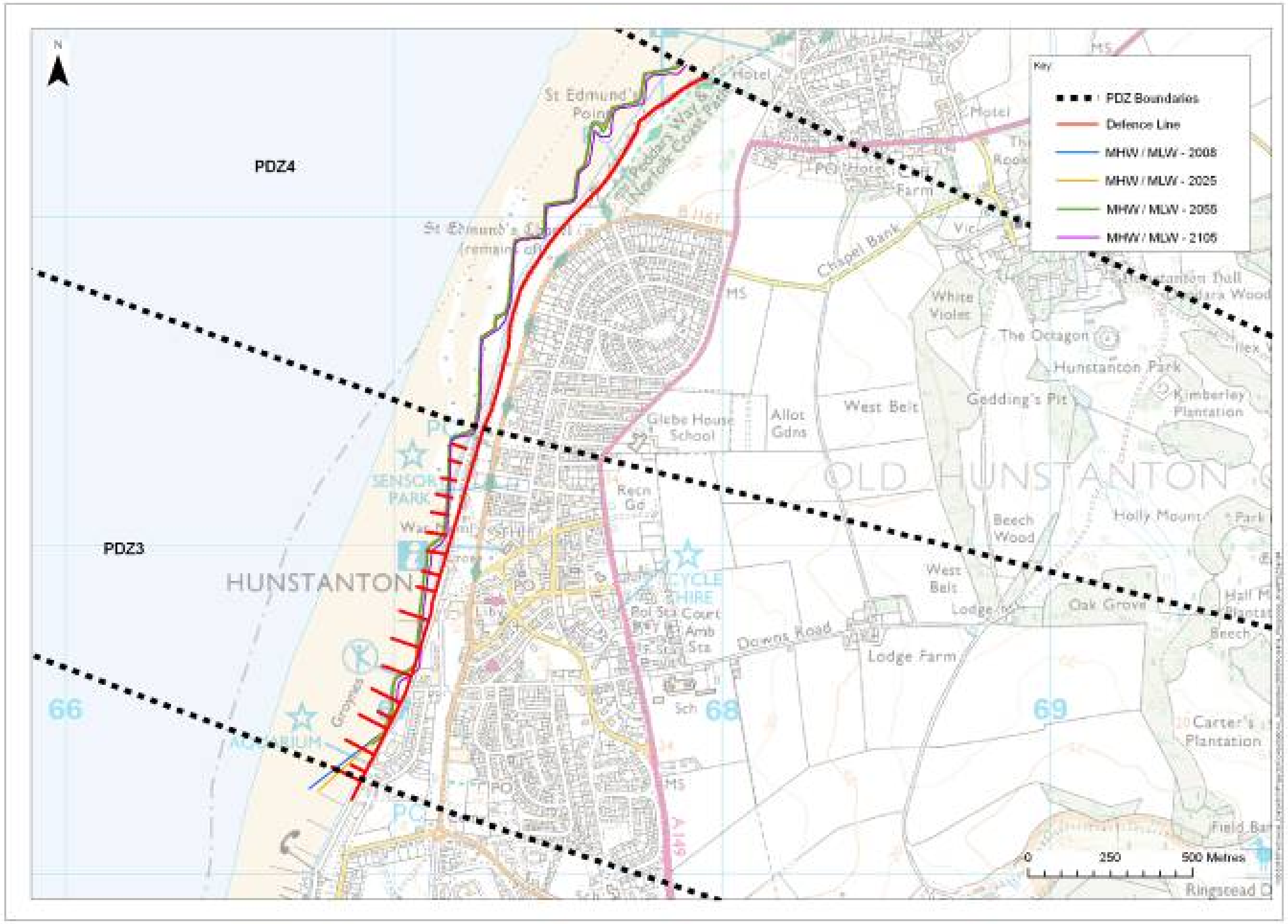


Figure F5.56 PDZ3 and PDZ4 Hold the line epochs 1 to 3



F5.9 Conclusions

F5.9.1 PDZ1 Gibraltar Point to Wolferton Creek

Background Developments

Throughout PDZ1.1, PDZ1.2 and PDZ1.3, there is overall vertical and horizontal accretion of both the mudflats and saltmarsh during epoch 1, although coastal squeeze will continue to occur as the mean low water mark gradually moves up the beach profile due to sea level rise (leading to an overall loss of mudflat area). This vertical growth of the saltmarsh is likely to continue into epoch 2 but as epoch 3 approaches with higher water levels, both horizontal, and to some extent vertical, erosion will take precedence and saltmarsh erosion will occur at the seaward edge, leading to an overall reduction in saltmarsh area, and the classic coastal squeeze situation.

Maximum landward realignment

The current defences will be breached and realigned in some instances in epoch 1, but where they remain in the same position they will be strengthened and managed as appropriate. As a result, epoch 1 will be dominated by continued vertical and horizontal accretion of both the saltmarsh and mudflats, and realignment will create an increased intertidal area, which is likely to have developed into saltmarsh by the end of the epoch. Into epochs 2 and 3, realignment will be extensive, creating a large intertidal area which will have developed substantially into saltmarsh by the end of the third epoch, thus reducing loading on the newly realigned defences.

'Habitat-led' realignment

The required realignments are fairly small-scale, and therefore coastal response is similar to that of Hold the line. Accretion will dominant in epoch 1 and 2 and erosion will increase into epoch 3 as sea levels rise. The relatively wider foreshore will allow a small increase in wave energy dissipation, leading to reduced defence loading, which will have a relatively small positive effect by counteracting the increased pressure expected in epoch 3.

Hold the line

Shoreline response under the Hold the line policy package will be as described per the 'Background Developments' above. This policy package will put an increasing amount of pressure on the defences, and they will need to be strengthened and improved as sea levels rise.

Local rebalancing

This policy package is characterised by realignment at three locations between Gibraltar Point and Wolferton Creek, and advance at one location between the Rivers Witham and Welland. As a result, the shoreline response will therefore be similar to that described as per the 'Background Developments' above, but with a small increase in natural defence to reduce loading on the man-made defences at the realigned locations.

F5.9.2 PDZ2 Wolferton Creek to South Hunstanton

Maximum landward realignment

In epoch 1, the current defences will be held (both the shingle ridge and earth embankment) to ensure continued protection of the caravan parks and holiday homes throughout epoch 1. Into epoch 2 the caravan parks and holiday homes will no longer be protected, although the area will have undergone adaptation in epoch 1. Throughout epochs 2 and 3, the shingle ridge will continue to rollback and undergo natural reprofiling. Into the later epochs there will also be a trend of more frequent overtopping of the shingle ridge, flooding the backshore areas. Ceasing to defend the shingle ridge in epochs 2 and 3 will result in the current coastal lagoons become increasingly saline, which will affect its role in supporting a large population of migrating and wading birds.

Realignment to existing 2nd line of defence

Moving the primary defence function to the 2nd line in this Policy Package will lead to a large change in the beach profile. There would be erosion of the shore with the shingle ridge being allowed to roll back naturally to the earth embankment. It is also important to note the significant change to the coastal lagoons in this PDZ as they would be frequently flooded with salt water. Into the later epochs there would also be a need to increase protection to the second line of defence (earth embankment) to ensure that the standard of protection is maintained.

Wide defence zone

The development of the shingle ridge and the area in between depends on more detailed decisions with regard the standards of protection of each line. Assuming that the shingle ridge's role is mainly to reduce wave impact on the secondary line, it is likely that the area between the 1st and 2nd defence lines will gradually develop into a saltmarsh over the epochs as overtopping of the shingle ridge increases as a result of rising sea levels and increased wave heights.

Hold the line

Holding the line would induce continued accretion in the north, but erosion in the south. Defences will need to be maintained as sea levels rise and erosion persists. This will become particularly important towards the end of epoch 2 and into epoch 3 when there is the potential for erosion to occur along the whole PDZ due to the predicted levels of sea level rise.

F5.9.3 PDZ3 Hunstanton Town

No active intervention

This Policy Package will cause the beach to become steeper during epoch 1 and the cliffs will begin to erode. This will be increased into epoch 2 and 3 with erosion rates dramatically increasing leading to loss of cliff top amenities and key infrastructure links.

<u>No active intervention up to a limit</u>
This policy allows the PDZ to react naturally to sea level rise up to a point. For this PDZ this just over half of the PDZ will be allowed to erode naturally up to epoch 3, whereas the southern half of the PDZ will effectively be Hold the line.

<u>Hold the line</u>
Holding the line reduces wave attack on the beach and cliffs but reduces the amount of sediment available for transport to other PDZs and offshore. Reduced sediment supplies could have an impact upon the processes within PDZ2 and PDZ3.

F5.9.4 PDZ4 Hunstanton Cliffs

<u>No active intervention</u>
This Policy Package will cause the beach to become steeper during epoch 1 and the cliffs will continue to erode. This will be increased into epoch 2 and 3 with erosion rates dramatically increasing leading to loss of cliff top amenities and key infrastructure links.

<u>No active intervention up to a limit</u>
This policy allows the PDZ to react naturally to sea level rise up to a point. The beach will become steeper in epoch 1 but intervention will be expected during epoch 3 to prevent cliff top amenities being affected by erosion. This will be strengthened towards the end of epoch 3 as wave attack becomes more severe.

<u>Hold the line</u>
Holding the line reduces wave attack on the beach and cliffs but reduces the amount of sediment available for transport to other PDZs and offshore. Reduced sediment supplies could have an impact upon the processes within PDZ2 and PDZ3.

F6 FROM POLICY APPRAISAL TO PREFERRED POLICY

F6.1 Introduction

As discussed in section E5.1 of appendix E, following the first two cycles of policy appraisal, **tentative** PPs were identified for PDZ1 and PDZ2 and **preferred** PPs were identified for PDZ3 and PDZ4. Section E5 reports on the process that was followed to move from these interim policies to the final plan and policies presented in the draft and final SMP. The aim of this section will be to provide more detail with respect to the information provided in appendix E, focusing on the coastal processes and shoreline interactions as opposed to the effect on the tentative PPs. The following section will be subdivided into PDZ1 and PDZ2. The overall conclusions from this work, and how these have informed the development of the draft and final policies, are provided in appendix E (section E5).

F6.2 PDZ1 Gibraltar Point to Wolferton Creek

The main gaps and uncertainties for PDZ1 concerned:

- The development of salt marsh and mud flat in the medium and long term, and the current level of uncertainty around this;
- The role of the foreshore in flood defence;
- The impact of policies on sand banks in the Wash.

These issues are described in the following sections. Section E5.2 in appendix E describes the implications for policy development.

F6.2.1 Future Intertidal Development

<u>This section summarises the final position arrived at in the course of the SMP process, based on a number of subsequent assessments. The draft and final Plan and policies described in the draft and final main SMP document are based on these insights.</u>

<u>Background</u>

For the first and second rounds of policy appraisal (as discussed in appendix E, sections E3 and E4) the target habitat compensation per epoch for the 'Habitat-led' realignment PP was determined by taking the intertidal area as being between the defence line and the mean low water mark. To calculate the reduction in intertidal area due to sea level rise per epoch, the Defra (2006) sea level rise guidance rates were then applied to the mean low water mark. This water level per epoch was then overlain onto the bathymetry and the loss was calculated. The compensation area target size as derived using this method is provided in table F6.1.

Table F6.1 Existing Compensation Area Target Size

Epoch	Intertidal Flat Loss / Compensation Area (hectares)
1	117
2	555
3	947

Following discussions with Natural England, it became apparent that further detail was required with respect to future intertidal development and therefore habitat loss. This further detail concerned the definition of saltmarsh and mudflat, and quantifying the loss of both habitats over the three epochs. It was also decided that it is necessary to determine an 'envelope of potential change' to illustrate the large uncertainty surrounding intertidal development in the Wash. It was agreed that this would be undertaken by developing two conceptual models to illustrate an 'erosional' and 'accretional' future. This section will detail how the conceptual models were developed for the two possible futures and the potential 'envelope of change' resulting from the model results.

Erosional Future

Baseline Scenarios

The development of Baseline Scenarios (section F3) quantified the loss of saltmarsh habitat (horizontal erosion of the saltmarsh/mudflat boundary) over the three epochs under a scenario of With Present Management. Firstly a rate of movement of the saltmarsh/mudflat boundary was calculated using aerial photographs from 2001 and 2006. This was achieved using the saltmarsh/mudflat boundary lines defined by the Environment Agency's (EA) Shoreline Management Group for their Coastal Trends Analysis of the Wash (EA SMG 2007) for 2001 and 2006.

For all frontages, this analysis identified that the saltmarshes of the Wash had been accreting horizontally since 1991. Given the predicted rate of sea level rise it was then assumed that this horizontal accretion would continue into epoch 1 at a similar rate to 1991-2006. The vertical accretion across both the saltmarsh and mudflat was also predicted to continue at similar rates to 1991-2006.

Into epoch 2, the substantial predicted increase in the rate of sea level rise (Defra 2006) was predicted to cause increased water depths across the mudflat and consequently larger waves and increased pressure on the saltmarsh/mudflat boundary. However, due to the fact that the rate of vertical accretion across the saltmarsh and mudflats was likely to keep pace with sea level rise, the saltmarsh/mudflat boundary was assumed to be able to hold its position. As a result, the net horizontal rate in the course of epoch 2 was assumed to be zero.

Into epoch 3 further increased water depths, decreased vertical accretion on the mudflat and saltmarsh, and significant landward movement of the mean high and low water marks, would mean that there would be erosion of the saltmarsh/mudflat boundary. This was predicted to lead to an overall loss of saltmarsh area. In order to produce mapping for the Baseline Scenarios task, the rate of erosion (landward movement) of the saltmarsh/mudflat boundary was assumed to be equal to the accretion (seaward movement) rate for epoch 1. This is with the exception of frontage D (Terrington, Wootton and Wolferton) where the saltmarsh was assessed to be more stable than the other frontages, and therefore erosion of the saltmarsh/mudflat boundary was predicted only back to its 2006 position (giving a rate of $-3.38myr^{-1}$).

The horizontal and vertical rates used to produce the mapping for the Develop Baseline Scenarios report are shown in table F6.2 and table F6.3.

Table F6.2 Baseline Scenarios Saltmarsh/Mudflat Boundary Movement (negative number = erosion, positive number = accretion)

Frontage	Saltmarsh/mudflat Boundary Horizontal Rate (myr^{-1})		
	Epoch 1	Epoch 2	Epoch 3
A (Wainfleet and Friskney)	+ 6.6	0.0	- 6.6
B (Leverton, Butterwick and Freiston)	+ 4.9	0.0	- 4.9
C (Frampton, Holbeach and Gedney)	+ 7.1	0.0	- 7.1
D (Terrington, Wootton and Wolferton)	+ 8.9	0.0	-3.4

Table F6.3 Baseline Scenarios Saltmarsh and Mudflat Vertical Change (negative number = erosion, positive number - accretion)

Frontage	Saltmarsh Vertical Rate (myr^{-1})			Mudflat Vertical Rate (myr^{-1})		
	Epoch 1	Epoch 2	Epoch 3	Epoch 1	Epoch 2	Epoch 3
A (Wainfleet and Friskney)	+ 0.007	Accretion (rate not specified)	Reduced accretion	+ 0.002	Accretion (rate not specified)	Reduced accretion
B (Leverton, Butterwick and Freiston)	+ 0.007			+ 0.006		
C (Frampton, Holbeach and Gedney)	+ 0.004			- 0.002		
D (Terrington, Wootton and Wolferton)	+ 0.017			+ 0.063		

This analysis is, however, only indicative and the rates stated in table F6.2 and table F6.3 are not very suitable to be used in isolation to determine the target size for habitat compensation. As a result, an additional literature review was undertaken to attempt to provide a more quantitative approach.

Long-Term Intertidal Profile Evolution (Pethick 2002)

Pethick (2002) studied the long-term intertidal profile evolution at three study sites in the Wash SMP2 area. There are two sites on the north-western side (Wrangle Flats and Butterwick Low, which lie in frontage B) and one on the southern edge (Breast Sand, which lies in frontage D). Pethick used predictive modelling (MUDPACK) to assess the development of a potential instability across the saltmarsh and mudflat over the next 50 years.

The MUDPACK model is based on a theory developed by Roberts et al (2000) which states that an equilibrium can exist between the mudflat shape and the hydrodynamic forcing. If this equilibrium exists, there will be stable mudflat morphology. The main influence over whether this equilibrium does in fact exist is sediment movement. Under an equilibrium situation there will be no net sediment transport.

Instead of focusing on sediment transport, MUDPACK looks at the balance of forces at the mudflat surface. This balance is between the stress applied by waves and tidal flows and the resistance to such stress by the inherent strength of the sediment comprising the mudflat surface. In extreme events the stresses on the mudflat are high and are greater than the inherent strength of the sediment. This leads to erosion of the mudflat surface. As the surface elevation of the mudflat decreases, the wave stress at the mudflat surface also decreases, leading to decreased rates of erosion. After the extreme event, the mudflat surface then recovers and deposition is able to occur. The key to whether a mudflat will continue to erode is whether it can recover from one erosional event before it is hit by another.

Pethick's basis for the predictive MUDPACK modelling was based on trends observed between 1994 and 2002. The main conclusions derived from the analysis of these trends are as follows. These trends were used as the main inputs to the modelling.

- Intertidal mudflat eroded vertically at rates of between 0.02 and 0.036 myr^{-1}.
- Saltmarsh accreted vertically at rates of between 0.0009 and 0.02 myr^{-1}.
- This overall change indicates a steepening of the entire intertidal profile.
- The saltmarsh/mudflat boundary underwent rapid horizontal advance (indicating overall saltmarsh growth) at rates of between 3.0 and 5.6 myr^{1}.

From this analysis, Pethick concluded that such a large contrast between the saltmarsh/mudflat boundary advance and erosion of the mudflat (leading to a steepening of the profile) had produced an unstable situation that was about to change.

The results from the predictive modelling are shown in table F6.4. These results show the average movement of the saltmarsh/mudflat boundary over the period 2000-2050. A positive number denotes a seaward movement (i.e. accretion) and a negative number denotes a landward movement (i.e. erosion). The results are taken from the model run that used a constant rate of sea level rise of 6mmyr^{-1}. This rate is approximately equivalent to an average of the predicted Defra (2006) sea level rise for epochs 1 and 2 (epoch 1 is 4mmyr^{-1} and epoch 2 is 8.5mmyr^{-1}). The MUDPACK predicted intertidal rates of vertical change are also shown in table F6.5. This is again assuming a constant rate of sea level rise of 6mmyr^{-1}.

Table F6.4 MUDPACK Results Saltmarsh/Mudflat Boundary Horizontal Movement (Pethick 2002) (negative number = erosion, positive number = accretion)

Location (Environment Agency profile no.)	MUDPACK predicted saltmarsh/mudflat boundary movement (average 2000-2050) (myr^{-1})
Wrangle Flats (L3B5)	- 0.90
Butterwick Low (L3A5)	- 2.31
Breast Sands (N0D3)	- 3.92

Table F6.5 MUDPACK Results Intertidal Vertical Change (Pethick 2002) (negative number = erosion, positive number = accretion)

Location (Environment Agency profile no.)	MUDPACK predicted vertical change (average 2000-2050) (myr^{-1})		
	Upper intertidal	Mid intertidal	Lower intertidal
Wrangle Flats (L3B5)	- 0.0042	- 0.0064	- 0.0027
Butterwick Low (L3A5)	- 0.0008	- 0.0002	- 0.0008
Breast Sands (N0D3)	- 0.0077	- 0.0016	- 0.0170

The MUDPACK modelling has shown that the potential instability predicted by Pethick using the 1994-2002 data, and therefore reversal of the saltmarsh/mudflat boundary advance, would occur within the next 50 years (therefore by 2052). The modelling has also shown that this instability is likely to occur even without sea level rise.

Pethick believes that in the Wash, sea level rise is not correlated with an overall increase in erosion rates. He predicted that a more rapid rate of sea level rise would actually lead to lower rates of mudflat erosion on the upper intertidal. The same was predicted for the rate of movement of the saltmarsh/mudflat boundary. The main cause of this inverse relationship between the rate of sea level rise and erosion of the intertidal zone is due to the decrease in bed shear stress in deeper water as a result of sea level rise.

The modelling suggests that the gradient of the lower intertidal slopes will increase, but the gradient of the upper intertidal slopes will decrease. The impact of the flatter upper intertidal slopes will be to cause the saltmarsh/mudflat boundary to move landwards.

Contrary to the modelling results presented in table F6.4, Pethick also suggests that the likely saltmarsh/mudflat boundary erosion will not necessarily bring about saltmarsh vertical erosion. This is due to the resilience of a vegetated saltmarsh surface to vertical erosion, and this erosion is only likely to occur under exceptional wave and tidal conditions.

Reconciliation

Table F6.6 provides a summary of the predictions made in both the Baseline Scenarios report, and by Pethick (2002) following the predictive MUDPACK modelling. Note that the rates shown are an average for the entire 50-year period and for the Wash SMP2 area.

Table F6.6 Comparison between Baseline Scenarios and Pethick (2002) (negative number = erosion, positive number = accretion)

Intertidal Profile Change	50-year average predicted rate (myr^{-1})	
	Baseline Scenarios	**Pethick (2002)**
Saltmarsh/mudflat boundary	+ 0.14	-2.38
Saltmarsh vertical trend	Accretion	Accretion
Mudflat vertical trend	Accretion	- 0.0048

Pethick (2002) believed that the potential instability, due to significant intertidal profile steepening, would occur imminently (i.e. towards the beginning of the 50 year period), leading to saltmarsh/mudflat boundary erosion throughout the 50-year period.

Pethick's predictions were, however, based on data recorded between 1994 and 2002 only, and for three specific sties around the Wash. However since publication of this report, an additional 4 years of data has been recorded and analysed (2002 to 2006) by the Environment Agency. For the purpose of this report, all of the Environment Agency's profiles were analysed and this new data has shown that there has been continued saltmarsh/mudflat boundary seaward movement (accretion). As a result, Pethick's modelling output rates are now seen as a providing a worst case scenario.

As a result of this additional data, it can be assumed that the intertidal development as put forward in the Baseline Scenarios report remains a more accurate prediction of the future development. However, as epoch 3 rates (both saltmarsh/mudflat horizontal erosion and mudflat vertical erosion) in the Baseline Scenarios report were only indicative, Pethick's predictive modelling rates can be used to provide a more accurate prediction. In addition the Baseline Scenarios report did not specify the rate of mudflat vertical erosion in epoch 2, and as a result Pethick's predictive modelling rates will also be used here.

As a summary, the origin of the rates to be used for the purpose of determining the total saltmarsh and mudflat compensation area per epoch is provided in table F6.7.

Table F6.7 Origin of Intertidal Development Rates

		A (Wainfleet and Friskney)	B (Leverton, Butterwick and Freiston)	C (Frampton, Holbeach and Gedney)	D (Terrington, Wootton and Wolferton
Saltmarsh/mudflat boundary horizontal movement (myr^{-1})	Epoch 1	Baseline Scenarios			
	Epoch 2	Baseline Scenarios			
	Epoch 3	Pethick (2002)			
Mudflat vertical movement ($mmyr^{-1}$)	Epoch 1	Baseline Scenarios			
	Epoch 2	Pethick (2002)			
	Epoch 3	Pethick (2002)			

Note that saltmarsh vertical accretion/erosion rates are not discussed in the above section. Following Pethick's analysis, it is assumed that the saltmarsh will continue to accrete throughout the three epochs. The rates, however, remain unspecified as this will not affect calculations of the overall loss of saltmarsh using GIS.

The rates based on the sources stated in table F6.7 are provided in table F6.8.

Table F6.8 Summary of Intertidal Rates (as taken from sources discussed in table E6.7)

<table>
<tr><th></th><th></th><th>A (Wainfleet and Friskney)</th><th>B (Leverton, Butterwick and Freiston)</th><th>C (Frampton, Holbeach and Gedney)</th><th>D (Terrington, Wootton and Wolferton</th></tr>
<tr><td rowspan="3">Saltmarsh/mudflat boundary horizontal movement (myr^{-1})</td><td>Epoch 1</td><td>+ 6.60</td><td>+ 4.90</td><td>+ 7.10</td><td>+ 8.90</td></tr>
<tr><td>Epoch 2</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>Epoch 3</td><td colspan="2">-1.61</td><td colspan="2">-3.92</td></tr>
<tr><td rowspan="3">Mudflat vertical movement ($mmyr^{-1}$)</td><td>Epoch 1</td><td>+ 2.00</td><td>+ 6.00</td><td>-2.00</td><td>+ 63.00</td></tr>
<tr><td>Epoch 2</td><td colspan="2" rowspan="2">-3.50</td><td colspan="2" rowspan="2">-17.00</td></tr>
<tr><td>Epoch 3</td></tr>
</table>

For the saltmarsh/mudflat boundary horizontal movement in epoch 3, and the mudflat vertical movement in epochs 2 and 3 (see table F6.7 and table F6.8), Pethick's rates, which were based on a constant sea level rise of $6mmyr^{-1}$, will have to be extrapolated so that they are consistent with the Defra sea level rise guidance. This extrapolation will be achieved using the following equation. This equation is based on Leatherman's (1990) historical projection model.

$$\text{Future recession rate} = \frac{\text{historical recession rate}}{\text{historical sea level rise}} \times \text{future sea level rise}$$

In terms of extrapolating Pethick's modelling results into the future, the above equation can be interpreted as follows:

$$\text{Future recession rate} = \frac{\text{recession rate (Pethick's modelling)}}{\text{SLR as assumed by Pethick for model run}} \times \text{future sea level rise}$$

Calculation of the epoch 3 saltmarsh/mudflat boundary horizontal movement rates are provided in table F6.9 and calculation of the mudflat vertical movement epoch 2 and 3 rates are provided in table F6.10.

Table F6.9 Derivation of epoch 3 Saltmarsh/Mudflat Boundary Horizontal Movement

Frontages	Pethick (2002) Saltmarsh/Mudflat Change 2000-2050 (myr^{-1})	Pethick (2002) Sea Level Rise 2000-2050 (myr^{-1})	Epoch 3 Average Sea Level Rise (Defra 2006) (myr^{-1})	Calculated Epoch 3 Saltmarsh/Mudflat Change (myr^{-1})
A and B	- 0.90	0.006	0.013	**- 1.95**
	- 2.31	0.006	0.013	**- 5.01**
C and D	- 3.92	0.006	0.013	**- 8.49**

Table F6.10 Derivation of epochs 2 and 3 Mudflat Vertical Erosion

Frontages	Pethick (2002) Lower Mudflat Vertical Change 2000-2050 ($mmyr^{-1}$)	Pethick (2002) Sea Level Rise 2000-2050 ($mmyr^{-1}$)	Defra (2006) Sea Level Rise		Calculated Mudflat Vertical Change	
			Epoch 2 ($mmyr^{-1}$)	Epoch 3 ($mmyr^{-1}$)	Epoch 2 ($mmyr^{-1}$)	Epoch 3 ($mmyr^{-1}$)
A and B	- 2.7	6.0	8.5	13.0	**- 3.8**	**- 5.9**
	- 0.8	6.0	8.5	13.0	**- 1.1**	**- 1.7**
C and D	- 17.0	6.0	8.5	13.0	**- 24.1**	**- 36.8**

Summary

A summary of the saltmarsh/mudflat boundary and mudflat rates discussed in the above section are provided in table F6.11.

Table F6.11Summary of Intertidal Rates

		A (Wainfleet and Friskney)	B (Leverton, Butterwick and Freiston)	C (Frampton, Holbeach and Gedney)	D (Terrington, Wootton and Wolferton
Saltmarsh/mudflat boundary horizontal movement (myr^{-1})	Epoch 1	+ 6.60	+ 4.90	+ 7.10	+ 8.90
	Epoch 2	0.00	0.00	0.00	0.00
	Epoch 3	-3.48		-8.49	
Mudflat vertical movement (mmyr^{-1})	Epoch 1	+ 2.00	+ 6.00	-2.00	+ 63.00
	Epoch 2	- 2.45		- 24.10	
	Epoch 3	- 3.80		- 36.80	
Future Mean Low Water (mODN)	Epoch 1	-2.11	-2.19	-2.04	-2.75
	Epoch 2	-1.78	-1.86	-1.06	-1.77
	Epoch 3	-0.93	-1.01	1.44	0.73

Constraints
There are two main constraints with respect to unconstrained accretion across the saltmarsh and mudflat: the presence of tidal channels and the availability of sediment.

The first constraint is the presence of tidal channels in the Wash. There are a number of these tidal channels (Boston Deeps, Lynn Deeps etc) and these are clearly visible from bathymetry plots. These tidal channels were formed, and are maintained, as a result of inflow and outflow during the each tide. Due to the strength of flows throughout the channels these will be a limiting factor in the mudflat's continued seaward growth (i.e. the mudflat edge would get to a point and would then accrete no further). The actual lay-out of the channels may develop in the course of the epochs, but for this assessment the current lay-out is used as a best estimate.

The second constraint is the limited availability of sediment. If there is insufficient suspended sediment within the Wash system, then the saltmarsh and mudflats will not be able to continue to accrete. Evans and Collins (1975) and Ke et al (1996) stated that the net suspended supply passing through the entrance and deposited into the Wash embayment is approximately 6,800,000 tonnes/year. This equates to 3,700,000 m^3/year assuming a density of 1.8 t/m^3 (which is an average of fluid mud density and packed mud density). The net positive number indicates that there is more suspended sediment travelling into the Wash than is travelling out, which is in line with the current accretional trend across the Wash embayment. For the purpose of this assessment it has been assumed that the total volume of sediment available will remain constant throughout the three epochs, although in reality it has the potential to change as a result of a number of factors, such as change in management practices to the north of the Wash or increased sea level rise leading to changing sediment patterns or increased cliff erosion along the Holderness coast.

These constraints were calculated and the impact on the intertidal rates (table F6.11) was assessed. The new rates, taking into account the two constraints, are provided in table F6.12.

Table F6.12 Summary of Intertidal Rates – Erosional Future With Constraints

		A (Wainfleet and Friskney)	B (Leverton, Butterwick and Freiston)	C (Frampton, Holbeach and Gedney)	D (Terrington, Wootton and Wolferton
Saltmarsh/mudflat boundary horizontal movement (myr^{-1})	Epoch 1	+ 6.60	+ 4.90	+ 7.10	+ 8.90
	Epoch 2	0.00	0.00	0.00	0.00
	Epoch 3	-3.48		-8.49	
Mudflat vertical movement ($mmyr^{-1}$)	Epoch 1	+ 2.00	+ 6.00	-2.00	+ 63.00
	Epoch 2	- 2.45		- 24.10	
	Epoch 3	- 3.80		- 36.80	
Future Mean Low Water (mODN)	Epoch 1	-2.11	-2.19	-2.04	-2.00
	Epoch 2	-1.78	-1.86	-1.06	-1.77
	Epoch 3	-0.93	-1.01	1.44	0.73

These rates were applied to the current saltmarsh/mudflat boundary as defined by the Environment Agency (2006). The area between the saltmarsh/mudflat boundary and the current defence line was taken as the saltmarsh habitat area, and the gain/loss was calculated per epoch.

The mudflat (defined as being between the saltmarsh/mudflat boundary and the mean low water mark) vertical change rates were applied to the existing Digital Terrain Model (DTM) along with the predicted level of mean low water per epoch.

Results

The total change of saltmarsh and mudflat habitat per epoch was calculated and the results are provided in table F6.13 and are illustrated diagrammatically in figure F6.1.

Table F6.13 Total Habitat Change – Erosional Future

Epoch	Total intertidal change (ha)		
	Saltmarsh	Mudflat	Intertidal
1	+1,110	-878	+231
2	0	-769	-769
3	-2855	-7214	-10,069
Totals	**-1745**	**-8861**	**-10,607**

Figure F6.1 Erosional Future Schematic

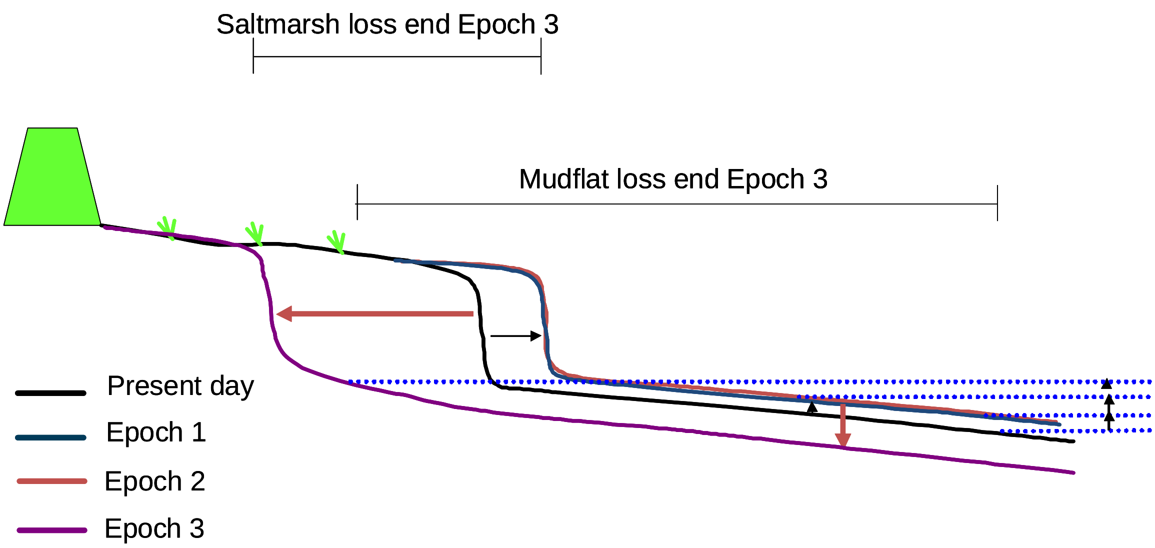


Table F6.13 provides an overview of the entire Wash SMP2 area over the three epochs; however it is important to note that the analysis was actually carried out for each individual frontage and the values presented are totals of the four frontages.

The erosional future shows an overall gain of intertidal habitat in epoch 1, mainly due to the assumption that the current trends of intertidal development will continue (i.e. continued vertical accretion across the saltmarsh and mudflat at a faster rate than sea level rise). Into the second epoch the erosional model predicts a significant loss of mudflat due to the fact that vertical erosion is assumed to be occurring across the mudflat, which is further exacerbated by sea level rise. Into the third epoch, there will be continued loss of mudflat, but at greater rates, leading to a greater loss of mudflat area. The model also assumes erosion of the saltmarsh/mudflat boundary in epoch 3, thus leading to overall loss of saltmarsh area.

Accretional Future

Methodology

The first step in developing an accretional conceptual model was the present day rates as discussed in the Baseline Scenarios report. This was the same starting point as for the erosional conceptual model. They were derived from the Environment Agency's profile monitoring data and represent an average rate across each profile for each defined frontage. A summary of these rates is provided in table F6.14.

Note that the rate of saltmarsh vertical accretion has not been included because it is not needed for the calculation. The boundaries for the two areas are defined as follows:

- Saltmarsh: from seabank to the saltmarsh/mudflat boundary;
- Mudflat: from saltmarsh/mudflat boundary to the mean low water (MLW) mark. The horizontal location of the MLW mark can change due to two factors: vertical movement of the mudflat surface and sea level rise. Both factors have been taken into account.

Table F6.14 Present day situation (negative = erosion, positive = accretion)

Frontage	Saltmarsh/mudflat boundary horizontal movement (myr^{-1})	Mudflat vertical movement (myr^{-1})	Mean Low Water (mODN)
A	6.6	0.002	-2.15
B	4.9	0.006	-2.15
C	7.1	-0.002	-2.15
D	8.9	0.063	-1.63

It needs to be noted that horizontal accretion of saltmarsh comes at the expense of mudflat area (which may or may not be compensated by seaward movement of the MLW mark).

Future Rates

The accretional model will assume a continuation of the above trends into the future, but with two factors that could limit expansion: the presence of the channels and the availability of sediment (which are discussed separately in section 4). In order to correctly extrapolate these rates to take into account sea level rise, the following equation was used (based on Leatherman's 1990 historical projection model, as used in our earlier assessments):

$$\text{Future accretion/erosion rate} = \frac{\text{historical accretion/erosion rate}}{\text{historical sea level rise}} \times \text{future sea level rise}$$

Note that the use of this equation is based on the (uncertain) assumption that current trends are largely driven by sea level rise. The equation was only used to extrapolate rates for epochs 2 and 3. For epoch 1 it was assumed that current rates would remain the same (see table F6.14) due to the fact there is not expected to be an increase in the rate of sea level rise until epoch 2. As with the earlier assessments, sea level rise rates have been taken from the Defra (2006) guidance as more up to date information (such as scenarios put forward by the UKCIP) was not available at the time of assessment. The Defra (2006) rates of sea level rise used in this assessment are provided in table F6.15.

Table F6.15 Defra (2006) sea level rise

Time Period	Net Sea Level Rise (myr^{-1})
1990 – 2025	0.004
2025 – 2055	0.0085
2055 – 2085	0.012
2085 - 2115	0.015

Table F6.16 and table F6.17 provide the results of this extrapolation exercise for the saltmarsh/mudflat horizontal movement and the mudflat vertical movement respectively. Table F6.18 provides the position of MLW in the future, combining the mudflat rates from table F6.17 with the sea level rise rates shown in table F6.15 provides an overview of the total seaward saltmarsh/mudflat boundary movement by the end of each epoch for each frontage. This will mean a continued growth of the saltmarsh in all three epochs.

Table F6.16 shows the extrapolated rates for the saltmarsh/mudflat boundary and table F6.19 shows the overall movement of the boundary per frontage per epoch. The future horizontal position of the mean low water mark (shown in table F6.19) was calculated using the extrapolated vertical movement of the mudflat's surface shown in table F6.17 relative to sea level rise. This was undertaken by raising the Digital Terrain Model (DTM) across the mudflat and then plotting the MLW mark for that epoch (table F6.18). This gives the relative movement of the MLW mark taking into account mudflat vertical accretion and sea level rise.

Table F6.16 Saltmarsh/mudflat boundary horizontal movement extrapolated rates

Frontage	Saltmarsh/mudflat boundary horizontal movement (myr^{-1})			
	Present day	Epoch 1	Epoch 2	Epoch 3
A	6.6	6.6	14.0	21.8
B	4.9	4.9	10.4	16.2
C	7.1	7.1	15.1	23.4
D	8.9	8.9	18.9	29.4

Table F6.17 Mudflat vertical movement extrapolated rates

Frontage	Mudflat vertical movement (myr^{-1})			
	Present day	Epoch 1	Epoch 2	Epoch 3
A	0.002	0.002	0.004	0.007
B	0.006	0.006	0.013	0.020
C	-0.002	-0.002	**0.000**	**0.000**
D	0.063	0.063	0.134	0.208

Table F6.18 Future Mean Low Water

Frontage	Mean Low Water (mODN by end of Epoch)			
	Present day	Epoch 1	Epoch 2	Epoch 3
A	-2.15	-2.11	-1.98	-1.65
B	-2.15	-2.19	-2.32	-2.65
C	-2.15	-2.04	-1.78	-1.12
D	-1.63	-2.75	-6.51	-16.25

Table F6.19 Total saltmarsh/mudflat boundary movement

Frontage	Epoch	Saltmarsh/mudflat boundary movement (m)
A	1	125
	2	421
	3	1086
B	1	93
	2	312
	3	809
C	1	135
	2	453
	3	1172
D	1	169
	2	567
	3	1469

A comparison between table F6.15 and table F6.17 shows that the mudflat across frontages B and D are building up at a greater rate than the rate of sea level rise, and therefore on this basis it is expected that the mudflat's seaward edge across these two frontages would move in a seaward direction (thus increasing the area of mudflat at the seaward edge). The opposite is true for frontage A and C where the rate of mudflat vertical accretion is less than the rate of sea level rise, and therefore the mudflat's seaward edge is likely to move in a landward direction (thus reducing the area of mudflat from the seaward edge).

Table F6.17 also shows that current trends across the mudflat indicate that frontage C is experiencing vertical erosion, whereas the other frontages are experiencing vertical accretion. It is thought that this vertical erosion is a local effect and is not related to sea level rise as with the other frontages, although the processes occurring here are complex and largely unknown. It would therefore be unrealistic (and not fitting in the conceptual model) to assume that the erosion would continue and therefore increase in the later epochs. As a result, for epoch 1 we have assumed that this rate will remain the same (i.e. continued erosion of the mudflat), but into epochs 2 and 3 we have set the vertical movement rate to zero (neither erosion nor accretion) for frontage C only (as shown by the bold red numbers in table F6.17). Note that there will still be a change of mudflat area because of the change in saltmarsh / mudflat boundary and the change of MLW level.

As discussed in section 2.1 the area of mudflat in the future will be defined at its landward edge by the saltmarsh/mudflat boundary and at its seaward edge by the mean low water mark. The vertical mudflat change rates were applied to the existing DTM along with the predicted mean low water per epoch. This gave an overall relative accretion or erosion of the mudflat's surface relative to the rate of sea level rise.

Initial Results

The above information was used to plot the total saltmarsh and mudflat area for each frontage using GIS. Table F6.20 provides of overview of the mudflat change specifically (including details of whether the mudflat is being lost at its seaward or landward edge). Table F6.21 provides an overview of the results.

Table F6.20 Mudflat loss

Frontage	Mudflat landward edge change			Mudflat seaward edge change			Overall mudflat change		
	E1	E2	E3	E1	E2	E3	E1	E2	E3
A	-156	-484	-1,268	0	-28	-38	-156	-512	-1,306
B	-143	-442	-969	-14	14	22	-157	-429	-948
C	-362	-868	-1,784	-85	-218	-200	-447	-1,086	-1,983
D	-448	-1,051	-2,562	2,125	3,021	5,135	1,667	1,970	2,572
							916	**-57**	**-1,665**

Table F6.21 Total Intertidal Change – Accretional Future (unconstrained)

Epoch	Total Habitat Change (ha)		
	Saltmarsh	Mudflat	Intertidal
1	1,110	916	2,025
2	2,846	-57	2,788
3	6,583	-1,665	4,918
Totals	**10,538**	**-806**	**9,732**

Table F6.21 provides an overview of the four frontages (PDZ1) over the three epochs; however it is important to note that the analysis was actually carried out for the four individual frontages and the values presented are totals of the four frontages. Frontages A and C appear to experience erosion at the mudflat's seaward edge (as the rate of vertical accretion does not keep up with sea level rise) whereas frontages B and D generally keep up with sea level rise, or in fact continue to accrete at a faster rate than sea level rise, thus leading to an overall increase in mudflat at its seaward edge (although this is balanced out by the significant loss at the seaward edge). The tables also show the there is a relatively large accretion trend across frontage D which could be unrealistic as the development is likely to become constrained at some point. This potential constraint is dealt with in more detail in section 4.

Constraints
As with the erosion future, an assessment was undertaken to see whether the constraints in the form of tidal channels and sediment availability would have an effect on the unconstrained future development of the intertidal area. As a first step the total volume of sediment required to sustain the level of accretion across both the saltmarsh and mudflats as shown in table F6.21 was calculated. The results are presented in table F6.22.

Table F6.22 Volumetric analysis assuming unconstrained accretion

Frontage	**Total volume sediment required Epoch 1 (m^3/yr^-)**		**Total volume sediment required Epoch 2 (m^3/yr^-)**		**Total volume sediment required Epoch 3 (m^3/yr^-)**	
	Saltmarsh	**Mudflat**	**Saltmarsh**	**Mudflat**	**Saltmarsh**	**Mudflat**
A	41,053	84,720	80,667	159,456	126,800	163,944
B	37,632	182,214	73,667	330,799	96,900	321,770
C	95,263	-187,016	144,667	0	178,400	0
D	117,895	7,378,938	175,167	14,273,753	256,200	16,839,276
Totals	**7,750,698**		**15,238,174**		**17,983,290**	

This table shows that even in the first epoch, the total volume of sediment required for the accretion (7,750,698m^3/yr) was double the available sediment (3,700,000m^3/yr). The numbers in table F6.22 show that frontage D is the cause of the large values. This is due to the fact that the present day vertical accretion rate across the mudflat for frontage D is very high: 63$mmyr^{-1}$. Note that this high rate is not caused by one large result for one profile, but does in fact represent the current trend across the entire frontage. The role of frontage D is also illustrated by the plots of the position of the saltmarsh/mudflat boundary and the MLW level per epoch, as calculated in GIS. Figure F6.2, figure F6.3 and figure F6.4 show that frontages A, B and C would not be constrained by the tidal channels. Note that in these figures "WASH BASE" refers to the present position of the saltmarsh/mudflat boundary and mean low water. "WASH_EPOCH1", "WASH_EPOCH2" and "WASH_EPOCH3" refers to the position of the saltmarsh/mudflat boundary at the end of epoch 1, 2 and 3 respectively. However for frontage D (figure F6.5) it is obvious that the calculated epoch 2 and 3 MLW positions are in deep water and therefore not realistic.

Figure F6.2 Frontage A Unconstrained Accretion

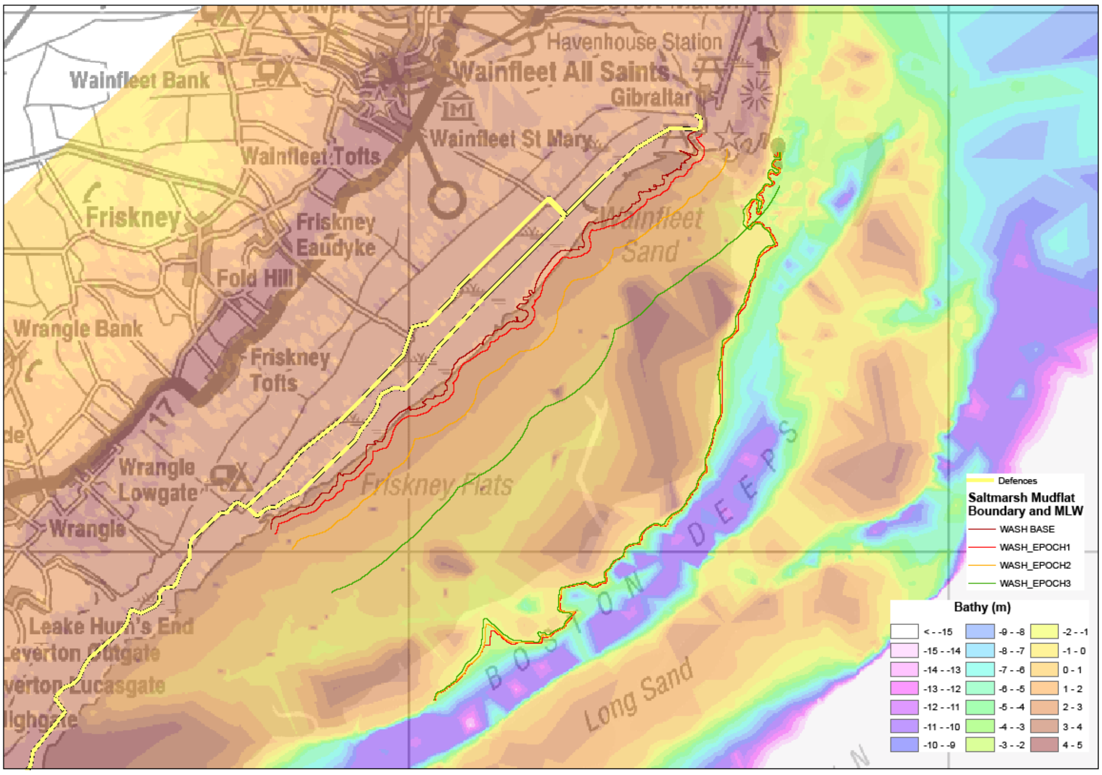


Figure F6.3 Frontage B Unconstrained Accretion

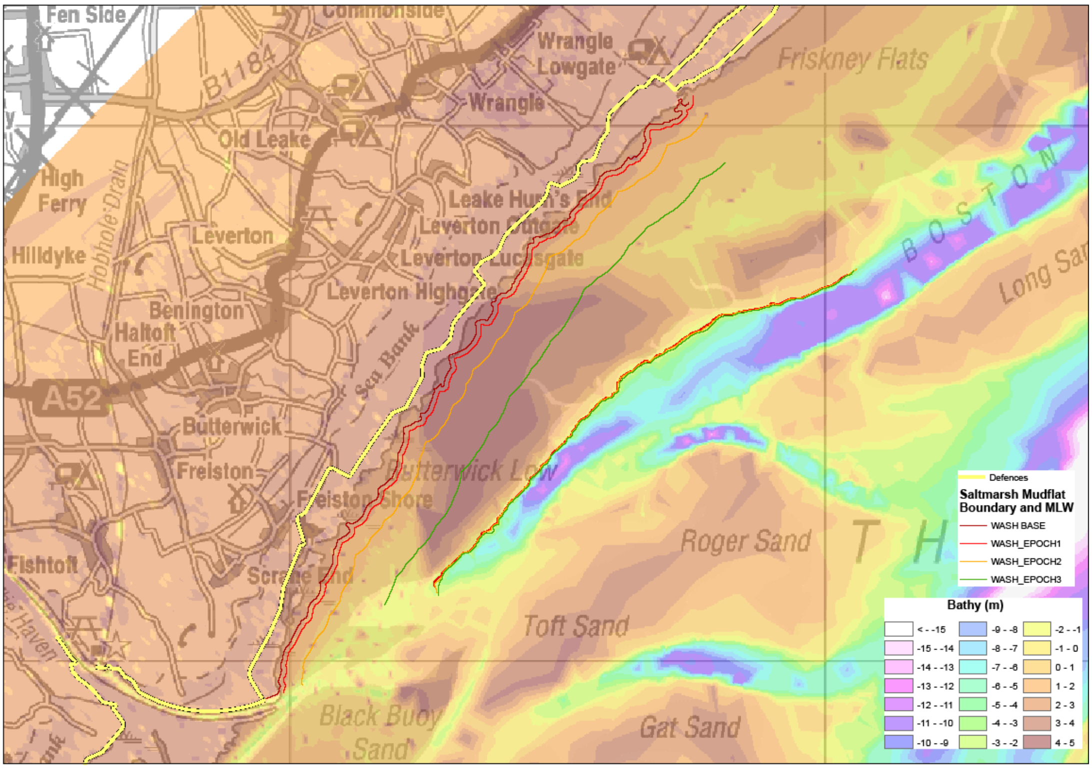


Figure F6.4 Frontage C Unconstrained Accretion

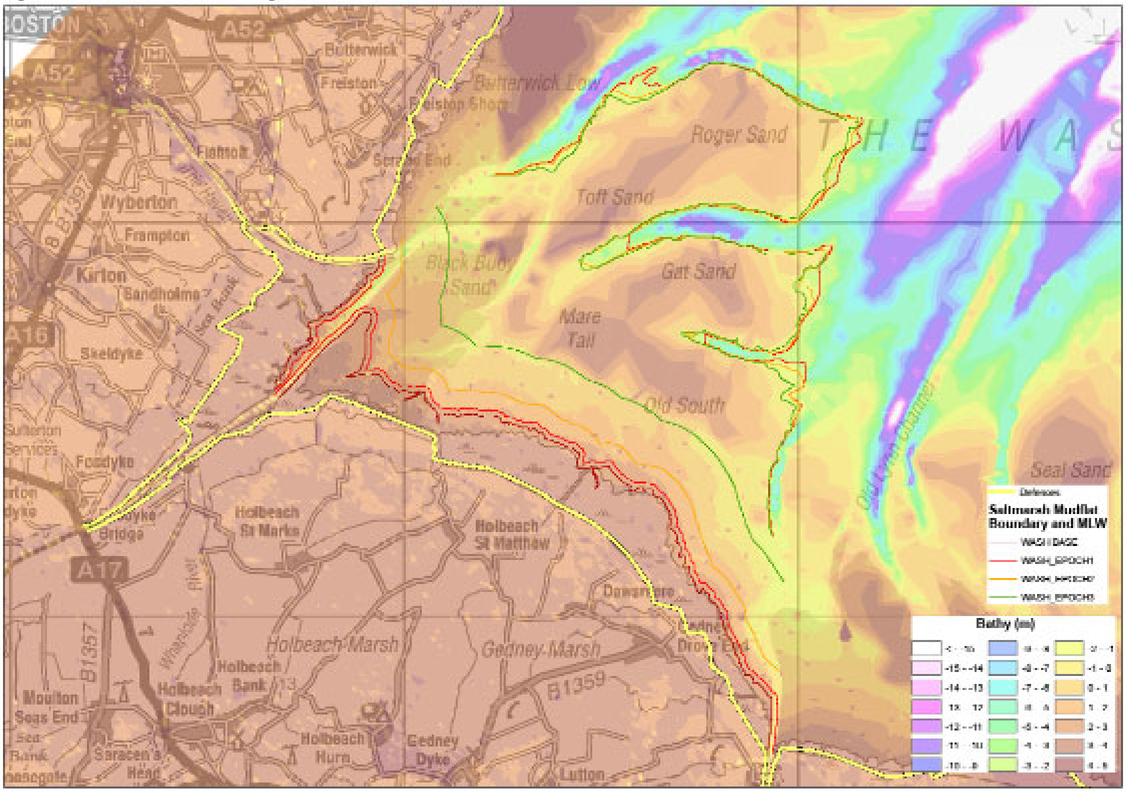
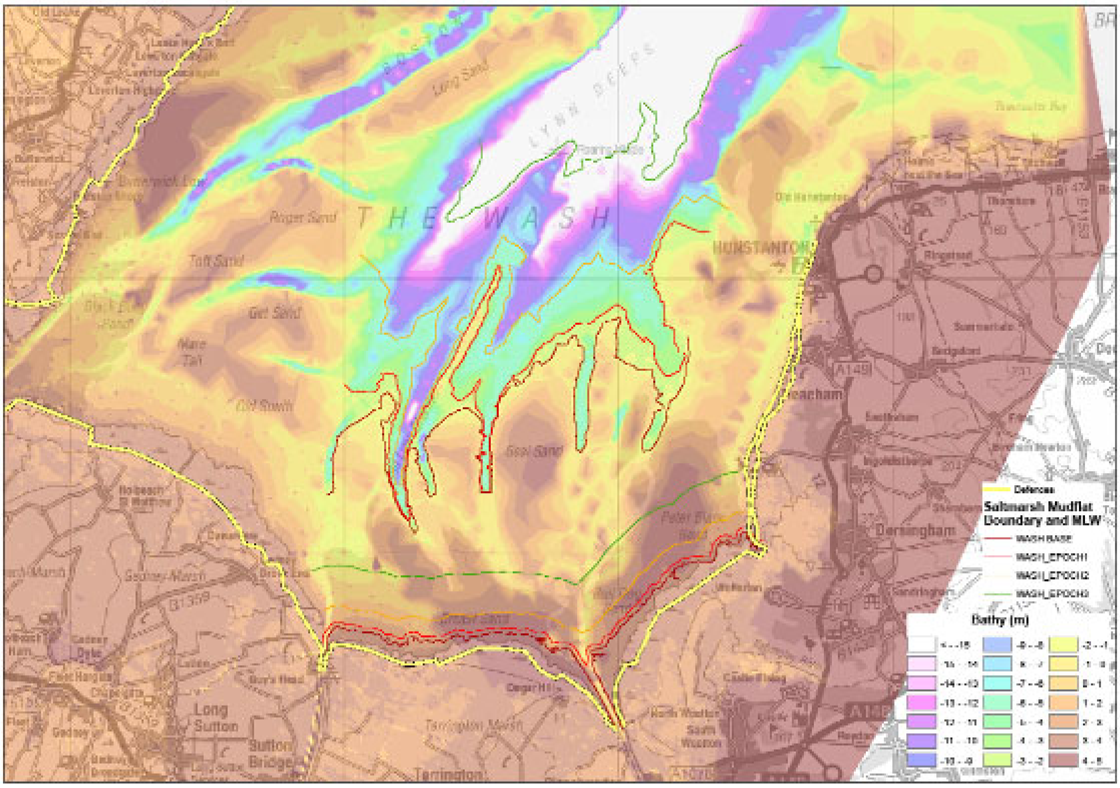


Figure F6.5 Frontage D Unconstrained Accretion



The influence of both constraints could lead to an infinite number of combinations of rates and positions per epoch. For this assessment, one possible scenario was developed based on the assumption that the MLW position reaches a location around the channel edge at the end of epoch 1, based on the available sediment, and that the MLW position remains constant in epoch 2 and 3 (requiring mudflat growth to keep pace with sea level rise).

A summary of the above rates and future MLW levels, taking into account the constraint provided by the tidal channels and the availability of sediment, is provided in table F6.23 and table F6.24 (values in red show those which have changed from the original assessment in section 2.2).

Table F6.23 Mudflat vertical movement extrapolated rates

Frontage	Mudflat vertical movement (myr^{-1})			
	Present day	Epoch 1	Epoch 2	Epoch 3
A	0.002	0.002	0.004	0.007
B	0.006	0.006	0.013	0.020
C	-0.002	-0.002	0.000	0.000
D	0.063	**0.024**	**0.009**	**0.013**

Table F6.24 Future mean low water

Frontage	Mean Low Water (mODN)			
	Present day	Epoch 1	Epoch 2	Epoch 3
A	-2.15	-2.11	-1.98	-1.65
B	-2.15	-2.19	-2.32	-2.65
C	-2.15	-2.04	-1.78	-1.12
D	-1.63	**-2.00**	**-2.00**	**-2.00**

Table F6.25 presents the total change of saltmarsh and mudflat area with the tidal channel and volumetric constraints applied. The development of the intertidal area under the accretional model is shown diagrammatically in figure F6.6

Table F6.25 Mudflat loss with constraint

Frontage	Mudflat landward edge change			Mudflat seaward edge change			Overall mudflat change		
	E1	E2	E3	E1	E2	E3	E1	E2	E3
A	-156	-484	-1,268	0	-28	-38	-156	-512	-1,306
B	-143	-442	-969	-14	14	22	-157	-429	-948
C	-362	-868	-1,784	-85	-218	-200	-447	-1,086	-1,983
D	-448	-1,051	-2,562	331	0	0	-117	-1,051	-2,562
Totals							**-878**	**-3,078**	**-6,799**

Figure F6.6 Accretional Future Schematic

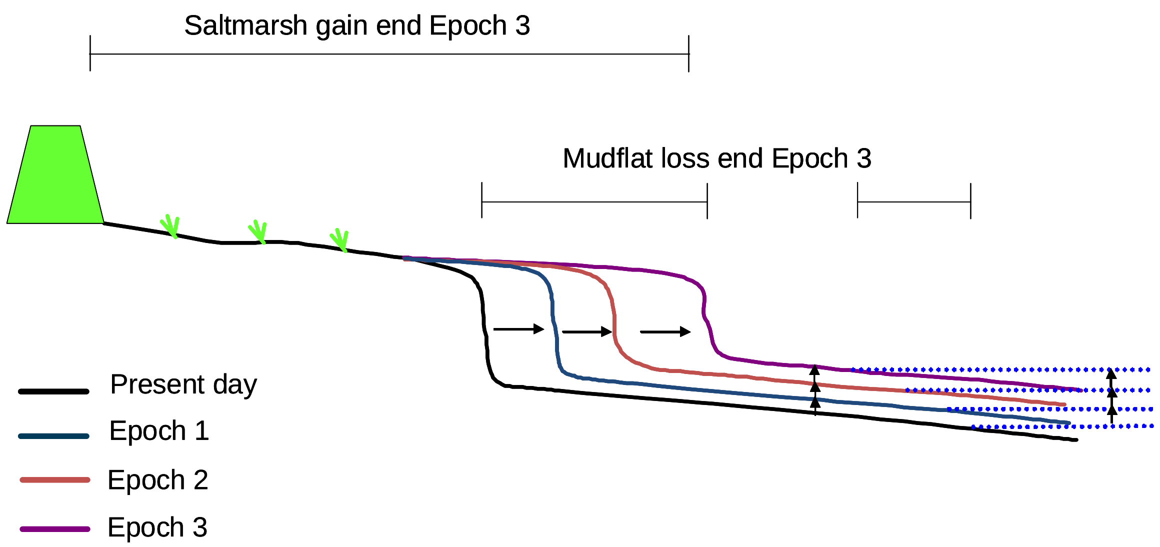


Table F6.26 Total area change including tidal channel constraints

Epoch	Total intertidal change (ha) WITH CONSTRAINT			Total intertidal change (ha) WITHOUT CONSTRAINT		
	Saltmarsh	Mudflat	Intertidal	Saltmarsh	Mudflat	Intertidal
1	1,110	-878	231	1,110	916	2,025
2	2,846	-3,078	-233	2,846	-57	2,788
3	6,583	-6,799	-216	6,583	-1,665	4,918
Totals	**10,538**	**-10,756**	**-217**	**10,538**	**-806**	**9,732**

Table F6.27 Accretional model results (including constraints)

Time Period	Ratio of Saltmarsh vs. Mudflat of Total Intertidal	Approximate Saltmarsh Width (m)	Approximate Mudflat Width (m)
Present day	15% / 85%	850	4900
Epoch 1	18% etc	1040	4750
Epoch 2	26%	1500	4250
Epoch 3	46%	2600	3100

Table F6.26 provides an overview of the four frontages (PDZ1) over the three epochs; however again it is important to note that the analysis was actually carried out for the four individual frontages and the values presented are totals of the four frontages. Table F6.27 also provides further analysis of the results presented in table F6.26 and focuses on the proportion of intertidal area that is saltmarsh or mudflat for each epoch. It also gives an idea of the approximate width of saltmarsh and mudflat across the entire PDZ (assuming an approximate length of PDZ1 of 60km and assuming that the saltmarsh and mudflat would be distributed evenly across the PDZ).

Frontages A and C appear to experience erosion at the mudflat's seaward edge (as the rate of vertical accretion does not keep up with sea level rise) whereas frontage B generally keeps up with sea level rise, or in fact continue to accrete at a faster rate than sea level rise, thus leading to an overall increase in mudflat at its seaward edge (although this is balanced out by the significant loss at the seaward edge). These trends are the same as those presented for the unconstrained scenario in section 3. The major difference is that we have assumed that the rate of vertical accretion across the mudflat for frontage D is equal to the rate of sea level rise in the later epochs and therefore there is no increase or decrease of the mudflat at is seaward edge.

One of the main findings from table F2.26 is that although this constrained accretional model assumes continued vertical accretion of the mudflat, we will actually see an overall loss of mudflat area in epochs 2 and 3. In epoch 1 the mudflat appears to be growing horizontally at a faster rate than it is being reduced at its landward edge (due to saltmarsh horizontal accretion). Note that this trend is not applicable to all frontages, and at some locations the mudflat is already being reduced at its landward edge faster than it is accreting at its seaward edge. Into epochs 2 and 3 however, the mudflat is being reduced at its landward edge as the saltmarsh advances seaward (accretes). The horizontal seaward movement of the saltmarsh/mudflat boundary is at a greater rate than that of the mudflat's seaward edge and therefore there is an overall loss of mudflat. This is only apparent for frontages A and C.

More 'accretional'?

Throughout this section the word 'accretional' has been used to describe this new conceptual model to predict the future development of the intertidal area throughout PDZ1. However, the results of the model, as presented in table F2.26, show that even under this 'accretional' scenario there will still be overall loss of intertidal area, and in particular loss of mudflat area, due to the predicted rates of sea level rise. This new model, and the erosional model developed in March 2009, is therefore intended as a realistic extreme and more accretional (or indeed more erosional at the other end of the scale) scenarios are also possible.

A more accretional scenario would involve assuming either a faster rate of vertical mudflat accretion, or by assuming a slower rate of sea level rise (deviating from Defra guidance). A faster rate of vertical mudflat accretion would either reduce/halt the landward movement of the MLW mark up the intertidal area (depending on the rate), or if the rate was greater than the rate of sea level rise, the MLW mark would actually be pushed seawards, thus creating a larger area of mudflat.

A slower rate of sea level rise would cause two effects. It would potentially allow mudflat vertical accretion to outpace sea level rise across all frontages across the three epochs, therefore leading to an overall growth in mudflat at its seaward edge. However this would also mean that the future rates of vertical accretion would also be reduced (due to the way in which they were extrapolated related to the rate of sea level rise). The overall effect on the development of the frontage is dependent on the degree of sea level rise reduction (compared to the current rate of vertical accretion) and will vary for each frontage.

Alternatively it is also possible to assume approximately the same development across the mudflat (although with slightly increased vertical accretion), but with significantly reduced horizontal movement of the saltmarsh/mudflat boundary. This would lead to an overall (limited) gain of saltmarsh and mudflat throughout the three epochs.

<u>Sensitivity Analysis</u>

Methodology

Development of this 'envelope of change' with respect to the intertidal development acts as a sensitivity analysis as it quantifies the range of potential futures within the Wash SMP area. In addition a specific sensitivity analysis was undertaken for the erosional conceptual model to illustrate how one end of the extreme is also sensitive to external factors (sea level rise in particular).

The Defra (2006) sea level rise rates were used as a basis for the Sensitivity Analysis. The Defra rate was then increased by 3 mm per year and decreased by 3 mm per year in order to give two new groups of Sensitivity rates. These are provided in table F6.28.

Table F6.28 Sensitivity Analysis Sea Level Rise Rates

Epoch	Length (yrs)	Defra (2006) rate (my^{-1})	Sensitivity Analysis	
			+ 3$mmyr^{-1}$	- 3$mmyr^{-1}$
1 (present day - 2025)	19	0.004	0.007	0.001
2 (2025 - 2055)	30	0.0085	0.012	0.006
3a (2055 - 2085)	30	0.012	0.015	0.009
3b (2085 - 2105)	20	0.015	0.018	0.012

The process as defined under the 'Reconciliation' heading in the Erosional Model section was repeated using these new rates. The outcomes of this process were saltmarsh/mudflat boundary movement and mudflat vertical rates for the two Sensitivity scenarios. These are presented in table F6.29 and table F6.30.

It is important to note that not all of the rates will have changed from those calculated as part of the new method, as shown in table F6.26. For some of these developments, sea level rise only plays a limited part as a driver. The saltmarsh/mudflat boundary horizontal movement rates for all frontages in epochs 1 and 2 are not strongly dependent on the rate of sea level rise as they are based on simple extrapolation of the recent Environment Agency monitoring. The same can be applied to the mudflat vertical rates in epoch 1. It may be argued that this is based on an implicit assumption that the rate of sea level rise in epoch 1 will be similar to the rate in the last 15 years, and hence a different sea level rise rate would lead to different changes. The main reason for the assumption that rates will be similar to present, despite an increase or decrease in the rate of sea level rise, is that the entire geomorphic system is generally accreting both horizontally and vertically in response to recent land reclamation. Sea level rise is likely to have an impact, but this impact is limited. Note that if the impact of changes in sea level rise would be taken into account in this assessment, it would lead to lower (not higher) sensitivity of mudflat area to changes in sea level rise: the direct 'geometrical' effect of higher mean low water (landward movement of low water mark) would be counteracted by an increased morphological effect. In general, it is important to remember that the Wash is a natural geomorphic system, and how it will respond to sea level rise is a large uncertainty.

The saltmarsh/mudflat boundary horizontal movement rates in epoch 3 and the mudflat vertical rates in epochs 2 and 3 are based on a mixture of results derived from Pethick's modelling and on the Baseline Scenarios report, however both involve extrapolation of base rates into the future epochs using sea level rise. As a result these values will differ from those calculated as part of the new method. The amended values are shown in bold in table F6.29 and table F6.30.

Table F6.29 Sensitivity Analysis Summary of Intertidal Rates for Habitat Compensation

		A (Wainfleet and Friskney)	B (Leverton, Butterwick and Freiston)	C (Frampton, Holbeach and Gedney)	D (Terrington, Wootton and Wolferton
Saltmarsh/mudflat boundary horizontal movement (myr^{-1})	Epoch 1	+ 6.60	+ 4.90	+ 7.10	+ 8.90
	Epoch 2	0.00	0.00	0.00	0.00
	Epoch 3	**-4.30**		**-10.60**	
Mudflat vertical movement ($mmyr^{-1}$)	Epoch 1	+ 2.00	+ 6.00	-2.00	+ 63.00
	Epoch 2	**- 3.40**		**- 32.60**	
	Epoch 3	**- 4.70**		**- 45.90**	

Table F6.30 Sensitivity Analysis Summary of Intertidal Rates for Habitat Compensation - 3 mm/yr

		A (Wainfleet and Friskney)	B (Leverton, Butterwick and Freiston)	C (Frampton, Holbeach and Gedney)	D (Terrington, Wootton and Wolferton
Saltmarsh/mudflat boundary horizontal movement (myr^{-1})	Epoch 1	+ 6.60	+ 4.90	+ 7.10	+ 8.90
	Epoch 2	0.00	0.00	0.00	0.00
	Epoch 3	**-2.70**		**-6.70**	
Mudflat vertical movement ($mmyr^{-1}$)	Epoch 1	+ 2.00	+ 6.00	-2.00	+ 63.00
	Epoch 2	**- 1.60**		**- 15.60**	
	Epoch 3	**- 3.00**		**- 28.90**	

Results

Following the necessary GIS analysis, the total change of saltmarsh and mudflat per epoch was calculated and the results are provided in table F6.31. This table also includes results from the original Method 2 calculations for easy comparison.

Table F6.31 Total Habitat Change (hectares)

Epoch	Erosional Future		Sensitivity Analysis			
			+3 $mmyr^{-1}$		-3 $mmyr^{-1}$	
	Saltmarsh	Mudflat	Saltmarsh	Mudflat	Saltmarsh	Mudflat
1	1181	195	1181	59	1181	426
2	0	-1842	0	-2018	0	-1305
3	-2925	-7214	-3263	-13109	-1569	-5068
Totals	**-1744**	**-8861**	**-2082**	**-15068**	**-388**	**-5947**

One point to note here is that although there is no change in the **rate** of mudflat vertical movement for epoch 1 as a result of this Sensitivity Analysis (see table F6.29 and table F6.30), the **overall loss** of mudflat in epoch 1 will change due to the increase/decrease in sea level which has been incorporated into the GIS analysis.

Overall Conclusions

At this point it is useful to draw comparisons with the erosional model that was developed in March 2009. This comparison is illustrated diagrammatically in figure F6.7 and figure F6.8.

The accretional scenario has predicted an increase in saltmarsh throughout the three epochs whereas the erosional scenario predicted an increase in saltmarsh area in the first epoch and then a loss of saltmarsh into the later epochs. In terms of mudflat, the accretional scenario has predicted a gradual loss of area over the three epochs due to the predicted increase in the rate of sea level rise and the significant increase of saltmarsh area (which acts to reduce the mudflat at its landward edge), whereas the erosional scenario actually predicts a loss of mudflat over the three epochs, but not to the same extent as with the accretional scenario due to a gain of mudflat at its landward edge (due to erosion of the saltmarsh in the third epoch).

For the accretional scenario the current ratio of 15% saltmarsh and 85% mudflat is predicted to change to almost a 50:50 ratio. For the erosional scenario, assuming onset of saltmarsh erosion, the ratio of saltmarsh and mudflat could remain similar to the current situation (15% saltmarsh and 85% mudflat). In reality it is expected that the future is likely to be a combination of the erosional and accretional scenarios, but not necessarily on a linear scale between the two. For example, it is within the range of possible futures that both the total intertidal area remains roughly constant, but also the saltmarsh / mudflat ratio.

Analysis of both the accretional and erosional models has shown that the movement of the saltmarsh/mudflat boundary has the greatest impact on the total area of saltmarsh or mudflat for each epoch. The movement of the mean low water mark (an indicator of accretion or erosion of the mudflat at its seaward edge) is negligible in comparison to the saltmarsh/mudflat boundary movement. For example a significant seaward movement of the saltmarsh/mudflat boundary (i.e. accretion of the saltmarsh) can cause a significant loss of mudflat at its landward edge. In some cases this landward edge loss is greater than the growth at the seaward edge (caused by vertical accretion outpacing sea level rise) which leads to an overall loss of mudflat area. Loss or gain of saltmarsh is extremely important for the sustainability of flood defences (see separate note).

The movement of the saltmarsh/mudflat boundary is therefore an important indicator of whether habitat compensation through realignment will be required in the later epochs. For example if there is a significant seaward movement of the boundary, there is likely to be a loss of mudflat, which would trigger localised realignment requirements. If there was a landward movement of the boundary, this would result in growth of mudflat area (the extent to which is dependent on the movement of the low water mark) but loss of saltmarsh which would also trigger the need for localised realignment. There is also the important issue of whether there is a need to maintain a certain ratio of saltmarsh to mudflat from a habitats perspective, however close monitoring of the saltmarsh/mudflat boundary movement will ensure that this can be done.

Figure F6.7 Accretional Intertidal Development

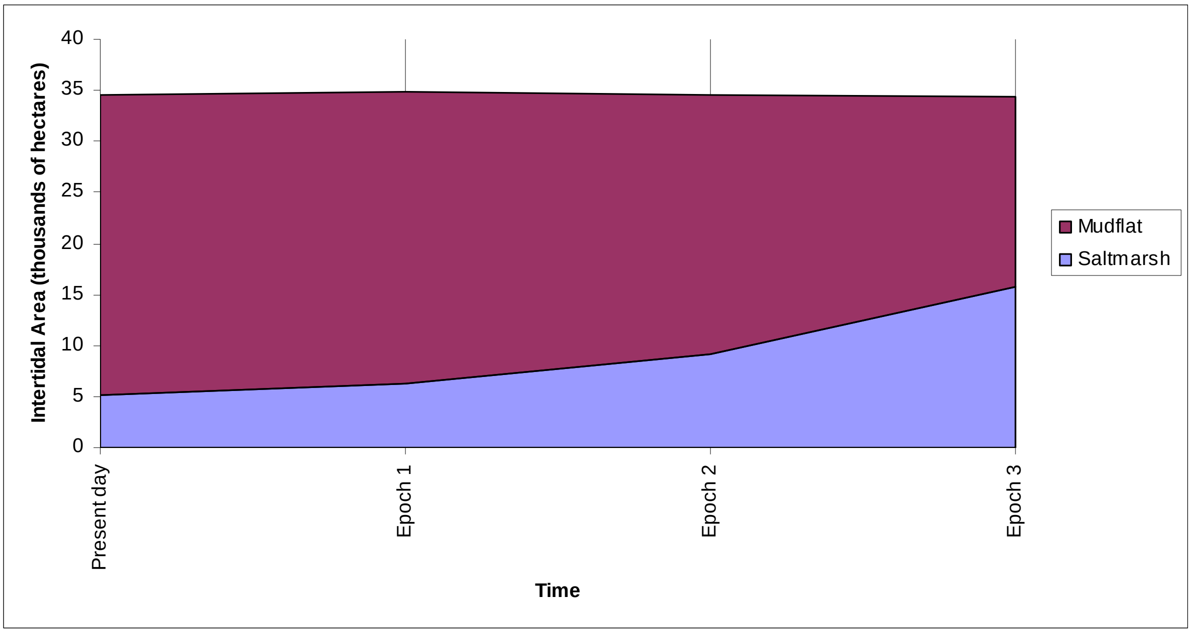
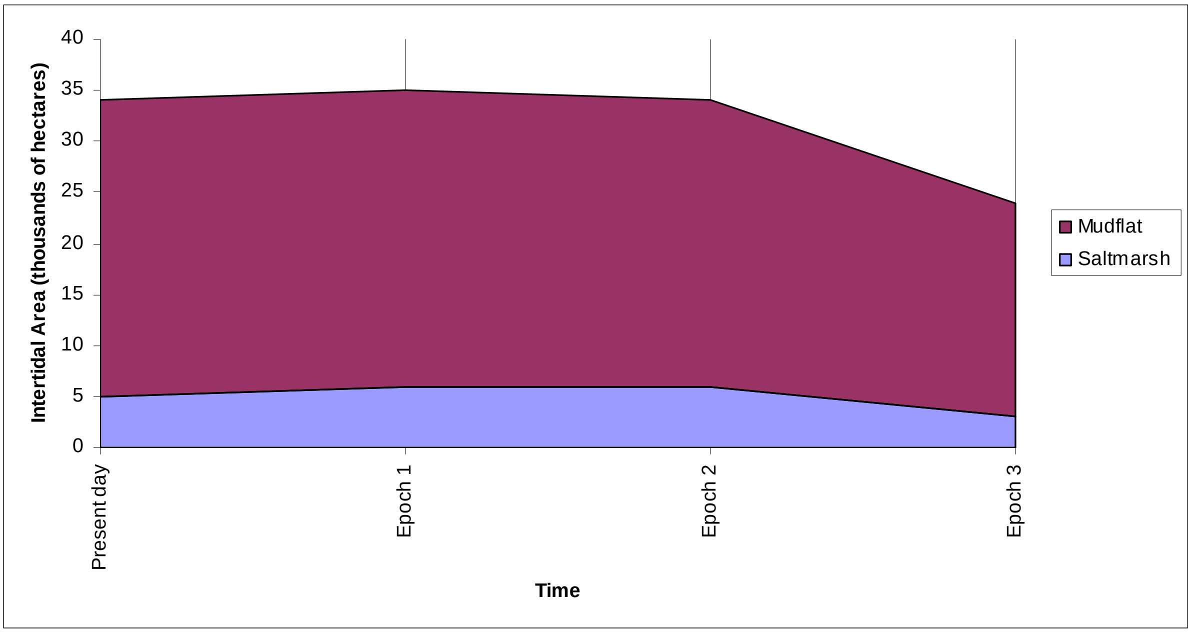


Figure F6.8 Erosional Intertidal Development



F6.2.2 Role of Foreshore in Flood Defence

<u>Background</u>

Saltmarsh has an important flood defence function, mainly because it reduces water depth on the foreshore, which limits the height of the waves that can reach the banks. This section provides an initial assessment of how a loss of foreshore in The Wash (in a potential 'erosional future' as described in section F6.2.1) would influence the likelihood of flooding, and what the possible responses could be. The impact on policy development is described in appendix E (section E5.2.2).

Saltmarsh as a Natural Defence

The natural saltmarsh that has developed, and is still developing, within the Wash estuary, not only provides an important habitat for a large number of species, but also acts as a significant natural defence. The saltmarsh absorbs incoming wave energy before it reaches the toe of the man-made defences (earth embankments) and therefore minimises pressure on the banks themselves. An increased width of saltmarsh is able to absorb an increased amount of wave energy and therefore provides greater natural protection, and vice versa.

Saltmarsh starts to form when it is covered less than about 450 tides per year. Therefore the saltmarsh is covered at spring tides but not neap tides. At these normal levels the water depths are small and therefore the waves are attenuated prior to reaching the earth embankments. On extreme events (such as the design standard of 1:200 per year) the water levels will be high and the associated water depths will mean that the waves are likely to reach the earth embankments, despite the high foreshore. Their height will still be reduced though by the reduced water depth.

The level of mud flats is around low water and they are covered every tide. The tidal range is in the order of 6m, so at high or extreme water levels the water depth can be 6m or more, enabling waves of a significant height to pass toward the shore.

The saltmarsh has a number of other smaller positive impacts on flood defence: the higher ground level causes a slight reduction in extreme water levels, and the extra roughness of saltmarsh vegetation has some impact on waves and water levels. These are expected to be much smaller than the depth limitation effect. They are therefore not calculated at this stage, but could be assessed in more detail beyond the SMP. In addition, the presence of saltmarsh means that there is no deep channel that can erode the toe of the bank: the saltmarsh vegetation and the higher ground levels provide protection against migration of deep channels toward the banks.

Embankment Failure
Failure of the earth embankments can result in flooding of the land behind, either through a breach or through excess water overtopping the earth embankment. A breach is likely to cause catastrophic flooding, whereas overtopping causes more gradual onset of flooding. Note that overtopping can also cause breach by eroding the crest, landward slope or toe.

A breach in an embankment can be caused by a combination of different factors. These include:-

- *Front face erosion*
- *Overtopping and erosion of the back face*
- Settlement of material
- Piping of water through embankment
- Third party damage
- Local surface slips
- Geo-technical failure - deep slip

The presence of saltmarsh will reduce the waves but not (or hardly) the water levels. Only the first two factors (highlighted in italic font) are caused by waves, so only they are relevant for this assessment.

As far as overtopping is concerned, it is mainly the crest level that determines the standard of protection: a higher crest reduces overtopping. In practice, the crest height is often determined based on the wave run-up: the vertical level on the seaward slope that is reached by the waves in the design storm.

As far as front face erosion is concerned, it is mainly the material of the slope that determines design: grass banks can withstand wave attack up to waves of about 1m, but don’t tend to develop well when they are regularly inundated by saline water.

Physical Conditions

The waves that occur at the Wash seabanks can be either swell waves generated offshore or locally generated wind waves. The behaviour of waves is affected by a number of conditions:

- Wind strength;
- Wind direction;
- Fetch length;
- Duration that the wind has been blowing;
- Storm offshore creating swell waves; and
- Water depth.

Wave buoy measurements in the mouth of The Wash during one year have shown a maximum wave height of 2.81m. For this initial assessment this is used as a good indication for the incoming deep water waves during extreme events. Note that the wave height is defined as the height between the top and bottom of the wave.

The water depth is of course crucial for this assessment; all these other conditions are not affected by the Wash SMP. Waves are limited in height by the depth of water they travel though, because they break from a certain point and thereby lose energy. The breaker index H_s/D_b that describes this varies from 0.5 to 0.78; this means that the significant wave height can't be more than 0.5 to 0.78 times the water depth. For this work the breaker index will be taken as 0.6.

In addition to wave height, the wave length (or wave period) is also a very important factor in wave attack on structures, as this defines the volume of water in a wave and the quantity of water that can attack the structure at once. Therefore waves with longer periods are likely to cause more problems. The Coastal Process and evolution note suggests wave periods of 2.5-4s. Initially 4s will be used in calculations, but the sensitivity for longer periods (likely for more extreme events) will be checked. The period or length of waves is not significantly affected by breaking or depth variation, and therefore the values measured in the middle of the Wash can be used as a good indication for the wave period near the seabanks.

A more accurate assessment of waves could be made through the transformation of wave data from buoys or calculation of locally generated wind waves.

Information on water levels is summarised in table F6.32 and table F6.33.

Table F6.32 Tidal Levels for Admiralty Port in the Wash

Location	Tidal level (mODN)			
	MHWS	MHWN	MLWN	MLWS
King's Lynn	3.77	1.97	-1.23	-2.03
Wisbech Cut	3.80	1.90	-1.00	no data
Port Sutton Bridge	3.80	2.00	-1.20	-2.0
Tabs Head	3.30	1.90	-1.30	-3.0
Boston	3.93	2.83	-1.17	-2.47

Table F6.33 Summary of Extreme Tidal Level Results (Mott MacDonald 2006 and Royal Haskoning 2007 (*italics*))

Site	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
Burgh Sluice	4.26	4.45	4.63	4.76	4.90	5.03	5.21	5.34
Mouth Witham	4.82	5.30	5.49	5.64	5.78	5.93	6.12	6.27
Mouth Welland	4.84	5.32	5.51	5.66	5.80	5.95	6.14	6.29
Mouth Nene	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35
Mouth Nene	*4.88*	*5.37*	*5.57*	*5.71*	*5.86*	*6.01*	*6.21*	*6.35*
*Mouth Great Ouse**	*4.93*	*5.43*	*5.63*	*5.78*	*5.93*	*6.08*	*6.28*	*6.43*
Snettisham Scalp	*4.86*	*5.36*	*5.56*	*5.71*	*5.86*	*6.02*	*6.22*	*6.37*

Future Intertidal Development

Currently the saltmarsh within the Wash is generally advancing seawards. It is expected that this trend will continue in the short term, but in the medium and long term there is a significant amount of uncertainty surrounding the future development. This is discussed in more detail in section F6.2.1.

Climate Change

Climate change is taken as recommended by DEFRA climate change supplementary guidance note, see table F6.34. These are the same rates as used throughout the SMP and all associated assessments. It means that mean sea level is predicted to have risen by about 1.1 m in 2105.

Table F6.34 Latest Sea Level Rise Allowances for the East Coast (Defra 2006)

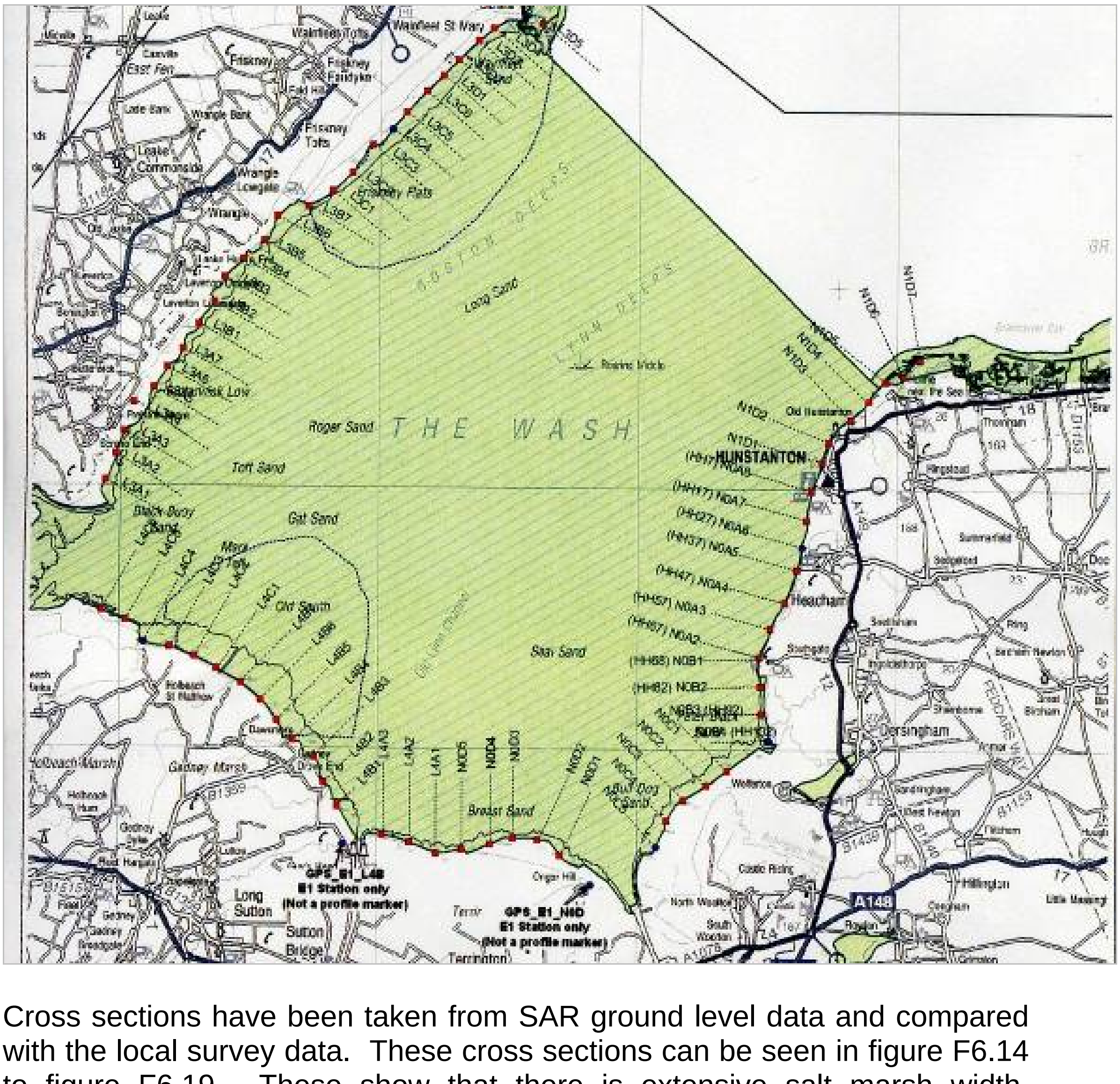
Administrative Region	Assumed Vertical Land Movement ($mmyr^{-1}$)	Net Sea Level Rise ($mmyr^{-1}$)			
		1990 – 2025	2025 – 2055	2055 – 2085	2085 – 2115
East of England	-0.8	4.0	8.5	12.0	15.0

Climate change could also lead to increased storminess and other factors that could influence the performance of the flood defences. These have not been included in this initial assessment.

Study Sites

This task looked at six representative sites, which were suggested by the Environment Agency. These are identified using the Beach Monitoring profile naming method. These are L3D3, L3B6, L3A2, NOD1, NOC5 and NOC1; their location is shown in figure F6.9.

Figure F6.9 Environment Agency Monitoring Profiles



Cross sections have been taken from SAR ground level data and compared with the local survey data. These cross sections can be seen in figure F6.14 to figure F6.19. These show that there is extensive salt marsh width, typically 800m (300-1500m) in front of the earth embankments, currently advancing on average 1m/year. The earth embankments have crest heights between 6.1 and 7.2mODN. The salt marsh height varies around MHWS at 3.7mODN.

For this initial analysis, the seaward slope angle has been assumed at 1 in 3. The relevant characteristics of the six sites are summarised in table F6.35.

Table F6.35 Geometry of Example Sites

Site	Foreshore height [m+OD]	Foreshore width [m]	Slope angle [ver:hor]	Crest height [m+OD]
L3D3	3.8	825	1:3	6.9
L3B6	3.6	780	1:3	6.1
L3A2	3.3	350	1:3	7.2
NOD1	3.6	1450	1:3	7.2
NOC5	3.8	1100	1:3	6.7
NOC1	3.8	760	1:3	6.6

Step 1: Impact on Flood Defence

Step 1 of the analysis is how loss of foreshore would reduce the performance of the flood defences. This requires the following sub-steps:

- Current performance of the defences:
  - o What are the current design values for water level and waves?
  - o What does that mean for the wave-run up?
- How much will design water levels and waves increase as a result of climate change?
- How does this reduce the performance of the defences?

Current performance of the defences

The water levels and wave heights were taken from the information in section 2.

The results are summarised in table F6.36:

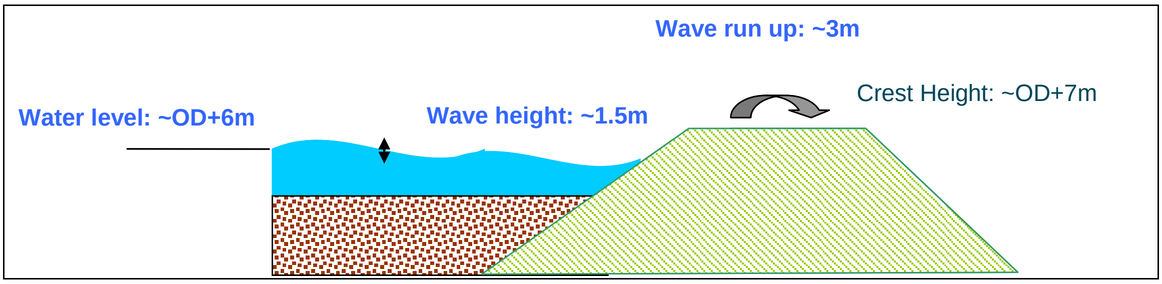
- The water depth is simply the 1:200 year water level (6 m above OD) minus the foreshore height from table F6.35.
- The wave height is 0.6 x the water depth (the maximum possible wave height), unless this exceeds the assumed incoming deep water wave height of 2.81m. That appears not to be the case for the existing situation with presence of saltmarsh.
- The wave run-up is calculated with a formula that uses water level, wave information and defence geometry. The calculations were carried out with the latest guidance for wave run-up called Euro-top.

Table F6.36 Current Performance of the Defences (2006)

Site	Water depth [m]	Wave height [m]	Wave run-up [m above crest]
L3D3	2.2	1.32	2.4
L3B6	2.4	1.44	3.4
L3A2	2.7	1.62	2.5
NOD1	2.4	1.44	2.3
NOC5	2.2	1.32	2.6
NOC1	2.2	1.32	2.7

These values are not intended to provide a value judgement on the current performance of each of these defences: that would require more detailed study (such as the 2007 Strategy study for Wash Banks, which showed that the majority of the defences can currently withstand a 1:200 per year storm event). In this analysis, the values for the wave run-up are just used as a baseline. In section 3.2 the wave run-up is recalculated for the situation in 2105 with and without saltmarsh; based on that section 4 presents the defence height needed to reduce the wave run-up to the baseline figures in table F3.36.

Figure F6.10 Illustration of Current Defence Performance



Future performance of the defences
This analysis only looks at the end of the SMP horizon, which is the year 2105. By that time, it is expected that mean sea level will have risen by about 1m. This analysis assumes that extreme water levels will see the same increase (it is possible that there will be a larger increase because of increased storminess causing increased surges, but this is uncertain). As this analysis is primarily concerned with the relative impact of foreshore loss only, the impact of this assumption is limited.

The analysis looks at two future scenarios for foreshore development:

- In the ‘accretional future scenario’, it is assumed that the saltmarsh grows vertically with the same rate as the mean sea level, which means that the water depth in extreme events, and hence the wave height, remains as in the current situation. The water level will have increased, so in this scenario the increase in wave run-up is equal to sea level rise.

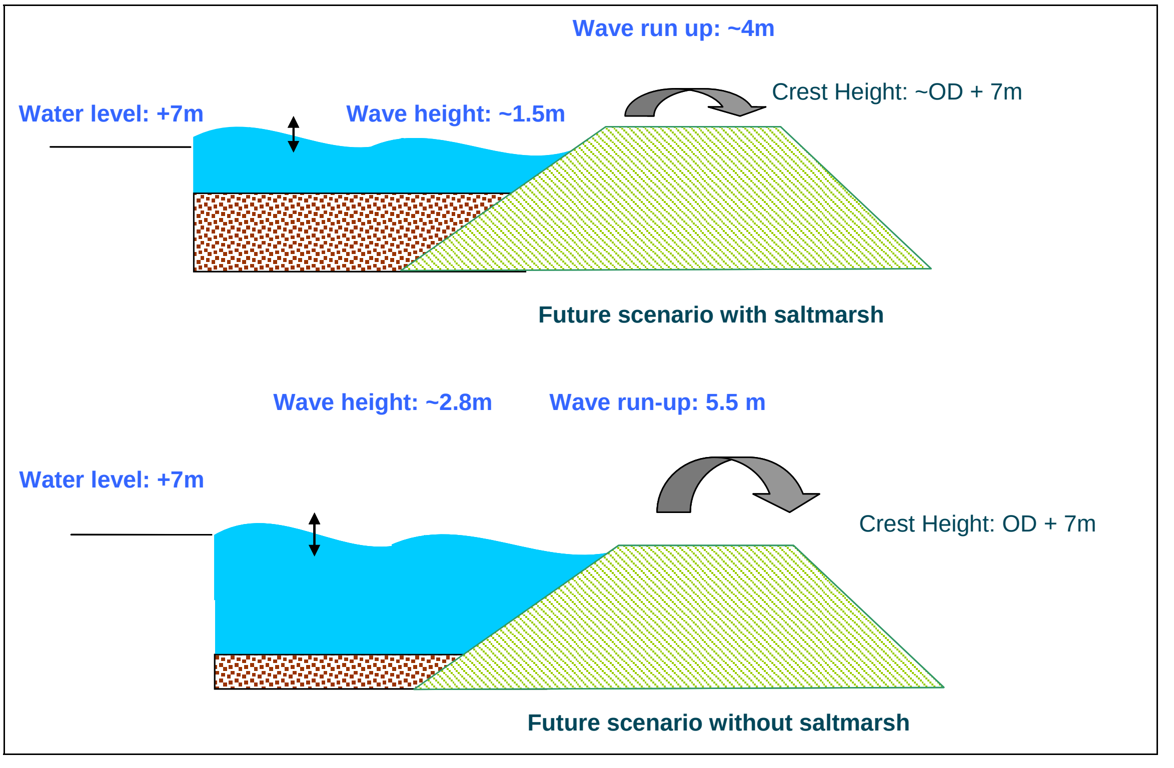
- In the 'erosional future scenario', it is assumed that all saltmarsh has been eroded away down to mean low water level. This means that the water in front of the defence in extreme events will be much deeper, allowing much bigger waves to reach the earth embankments. The maximum wave height is still limited to the observed deep water wave height of 2.81m, as assumed in section 2.3. In this scenario the increase in wave run-up is much larger: equal to sea level rise plus increased wave impact.

Table F6.37 Future Performance of the Defences (2105)

Site		Water depth [m]	Wave height [m]	Wave run-up [m above crest]	Impact of saltmarsh loss
L3D3	With saltmarsh	2.2	1.32	3.5	1.5m
	Without saltmarsh	7.1	2.81	5.0	
L3B6	With saltmarsh	2.4	1.44	4.5	1.3m
	Without saltmarsh	7.1	2.81	5.8	
L3A2	With saltmarsh	2.7	1.62	3.6	1.1m
	Without saltmarsh	7.1	2.81	4.7	
NOD1	With saltmarsh	2.4	1.44	3.4	1.3m
	Without saltmarsh	7.1	2.81	4.7	
NOC5	With saltmarsh	2.2	1.32	3.7	1.5m
	Without saltmarsh	7.1	2.81	5.2	
NOC1	With saltmarsh	2.2	1.32	3.8	1.5m
	Without saltmarsh	7.1	2.81	5.3	

The results show that the loss of saltmarsh for these six sites leads to an increase of wave run-up between 1.1m and 1.5m. A quick sensitivity analysis shows that this additional wave run-up is very sensitive to the wave period. The assumed value of 4s (based on 1 year of measurements) is relatively low, certainly for extreme events. If the deep water wave period were 6.7s (which would be a normal period for non-broken 2.8m high waves), the increase in wave run-up is about 2.5m.

Figure F6.11: Illustration of Performance of Current Defences in 2105 Conditions

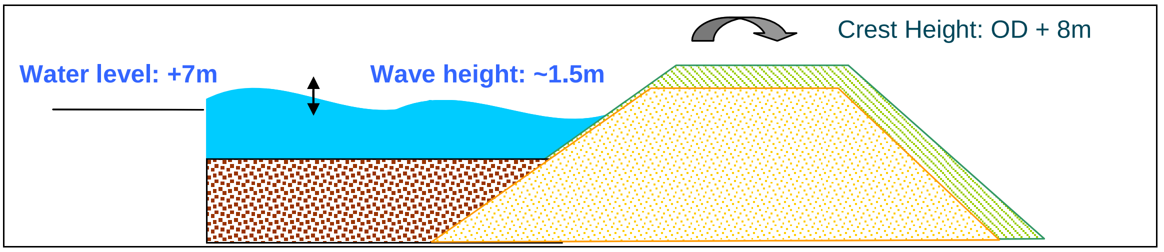


The results from table F6.36 are illustrated in figure F6.11.

Step 2: Measures needed to sustain current standard
Based on the results in section 3, this section determines indicative defence designs that would be needed in 2105 to achieve the same level of protection as in the current situation. The analysis shows that the six sample sections vary, but that the differences are limited. Because of the initial nature of this assessment, the analysis from this point is only carried out for one representative section: section NOD1. This cross-section was selected because the additional wave-run up due to loss of saltmarsh is 1.3m, which is in the middle of the range from 1.1m and 1.5m that is shown by table F6.37.

In the scenario with saltmarsh, the only intervention needed would be to raise the crest by 1.1m to keep up with sea level rise. This is based on the noted assumption that the saltmarsh accretes vertically at the same rate as the sea level. In addition, it is based on the existing geometry so it doesn't take defence deterioration into account. Raising the crest by 1.1m will require about 3m extra horizontal space.

Figure F6.12: Defence Raising to Sustain Defence Performance ('with saltmarsh scenario')



In the scenario without saltmarsh, there are two fundamental options:

- Strengthen the defence on its current alignment; there are various ways to achieve this, but for this assessment we have assumed a simple raising of the crest to reduce wave overtopping to its current level. Based on the analysis above, we have assumed that a crest raising of 3.5m would be needed (which covers both sea level rise and increased wave attack), requiring about 10m of extra horizontal space. In addition, the more exposed seaward slope will require a hard revetment.
- Carry out a landward realignment. For this assessment we have assumed that the realigned defence will be subject to limited wave attack, equal to the scenario with saltmarsh. The wave attenuation will partly be caused by newly created saltmarsh, and partly by the breached defences which may largely remain in place (as is the case in Freiston shore). We have also made the practical assumption that the realigned defence will be constructed on an existing secondary line. These are present along most, but not all of the frontage. Along a part of the frontage (north of Wrangle) it may be possible to realign to the little ridge of high ground. Overall, these assumptions are likely to provide the right ballpark figures.

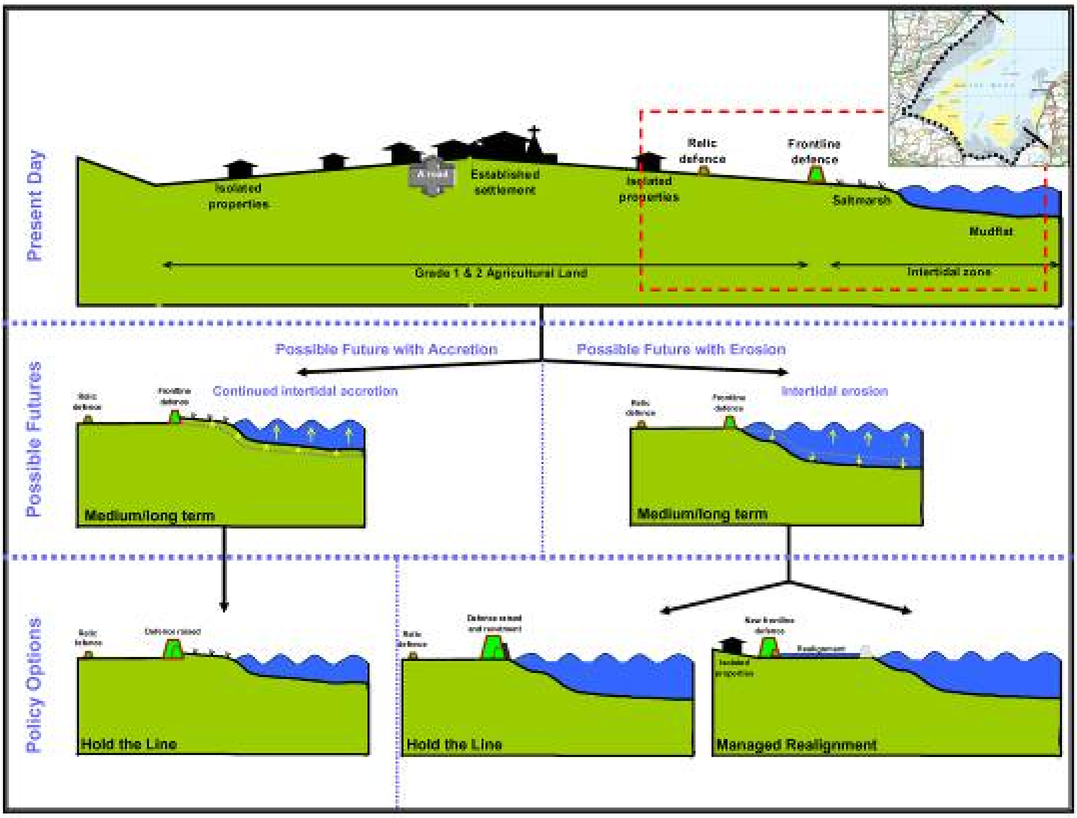
Figure F6.13 includes an overview of these options, within the overall context of the scenarios.

There are technical design limitations to increasing embankments by large steps at a time, associated with the settlement and compaction of the new material. In addition, the weight of the raised embankments will be significant and the ability of the ground to support this additional material needs to be carefully considered to prevent deep failures. It is likely that banks of this size need to be built up over a number of years to enable consolidation of both the embankment and the underlying ground before it is subject to any significant loadings. A general approximation is that banks can only be raised by 3m at a time before they will fail. In practice this scenario would happen gradually so it will be possible to carry out the measures in multiple smaller steps.

Alternative options for holding the line in the 'without saltmarsh scenario' would be:

- A sea bank with a seaward berm (typical for Dutch sea banks: wider, but requires a much lower crest);
- A sea bank with hard revetment on crest and landward slope, which would increase overtopping resistance and therefore reduce the need to raise the crest;
- A concrete sea wall.

Figure F6.13: Overview of Scenarios and Options



<u>Step 3: Estimate of ballpark costs</u>

This section provides ballpark costs for the policy options shown at the bottom of figure F6.13. It focuses on the two options in the erosional future scenario, and uses the Hold the line option in the accretional future as a baseline.

The costs are based on the assumption that the work would be carried out for 10 km lengths of shoreline, and that the improvement from the current structure to the structure required in 2105 happens in one project. This is of course not realistic, but it is considered sufficient for this analysis, which only aims to provide ballpark and relative costs.

Approach and source of information
The ballpark cost estimate is based on the Environment Agency's Flood Risk Management Estimating Guide – Unit cost database 2007. This document provides unit costs for construction projects, based on a more than 300 completed projects. The unit costs are based on March 2006 prices.

For embankments, the Guide provides costs per m^3 of fill. It provides cost ranges for three project sizes, and it lists 'key issues' that would affect the cost. For this analysis, assuming 10km long projects, the volume of material easily puts it in the largest project size. The unit costs significantly decrease with project size; on the other hand, the location of the works may lead to higher mobilisation and material transport costs. On balance, the 'average' cost has been used, which is £24 per m^3 of material. For large projects, the range of the unit costs is plus or minus 30%. The volume of fill required for a particular height of raising has been calculated based on an existing height of 3.6m, a slope angle of 1:3 and a crest width of 5m. For the existing secondary lines which would form the basis for a realigned defence in the erosional scenario, we have assumed that the crest is 2m lower than the crest of the frontline defence.

For revetments, the Guide provides costs per cubic metre of material. For the erosional scenario with Hold the line option (the only one assessed to require revetment), a typical embankment would require protection of approximately 5m of the slope, with a thickness of approximately 1.5m. Again assuming a project length of 10km, the resulting material volume leads to a unit cost of £27 per m^3 of material.

Costs
The numbers in table F6.38 indicate that there is a large difference in costs between the erosional and accretional futures. Within the erosional future, the costs for Managed realignment are significantly lower than those for holding the line. Note however that this is based on construction costs only; the estimate does not include the potential costs required for compensation of land owners (in a realignment option) or habitat compensation (in a Hold the line option).

Table F6.38 Ballpark costs per 10km of shoreline

Future scenario	Policy Option	Embankment cost [million £]	Revetment costs [million £]	Total costs [million £]
Accretional	Hold the line	5	0	5
Erosional*	Hold the line	13	2	15
	Managed realignment	11	0	11

*the estimate does not include the potential costs required for compensation of land owners (in a realignment option) or habitat compensation (in a Hold the line option).

Conclusions

The analysis shows that for both scenarios (with and without saltmarsh), the defences will need raising to keep pace with the expected sea level rise of just over 1m up to 2105. In addition, a loss of saltmarsh would allow much larger waves to reach the earth embankments. Holding the defence in its current alignment would require crest raising of approximately 3.5m (including 1m for sea level rise), plus a revetment on the lower slope. There are various alternatives, but they would be similarly extensive. If the defence was realigned, it may be possible to upgrade existing relict secondary defences; these would still need significant crest raising and strengthening to meet the requirements (approximately 3m), but there would be no need for a revetment.

The ballpark cost estimate shows that foreshore loss is very expensive. In addition, comparing the two high level options for the situation without saltmarsh, the construction costs of landward realignment are significantly lower. However, the estimate only includes construction costs, and not the potential costs required for compensation of land owners (in a realignment option) or habitat compensation (in a Hold the line option).

Recommendations

The analysis in this note is only indicative. In the coming years this should be built upon, as part of the Action Plan and in combination with monitoring and study of the expected development of the foreshore in The Wash.

More detailed assessments would be needed to increase the accuracy of the following elements:

- Level of wave penetration with and without present of saltmarsh in extreme events, including joint probability, local wind wave generation, impact of climate change on storminess
- More detailed assessment of location specific characteristic
- Design of solutions, including geotechnical considerations and construction stage issues
- Costing
- Gradual change in time (instead of current situation and 2105 only)
- Using saltmarsh width and height as a variable (instead of yes / no only)

These studies should not be a stand-alone study, but should be fully integrated in the overall plan to develop medium- and long-term policies for PDZ1.

Figure F6.14 N0D1 Cross Section

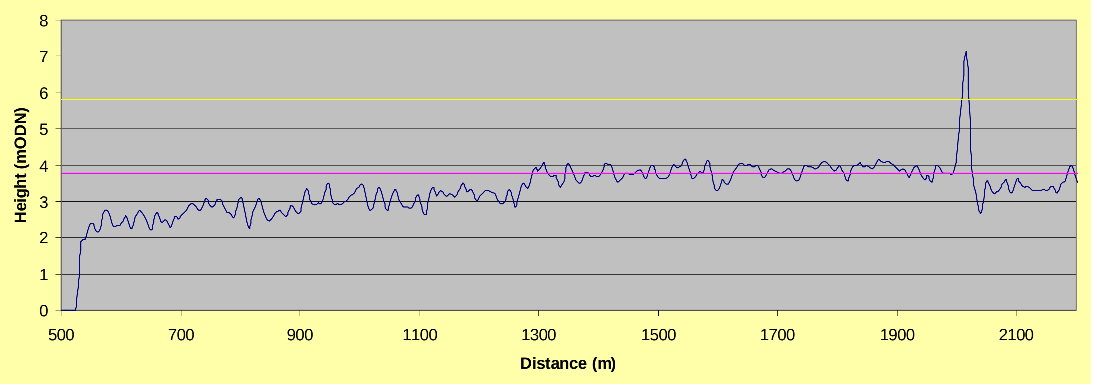


Figure F6.15 N0C1 Cross Section

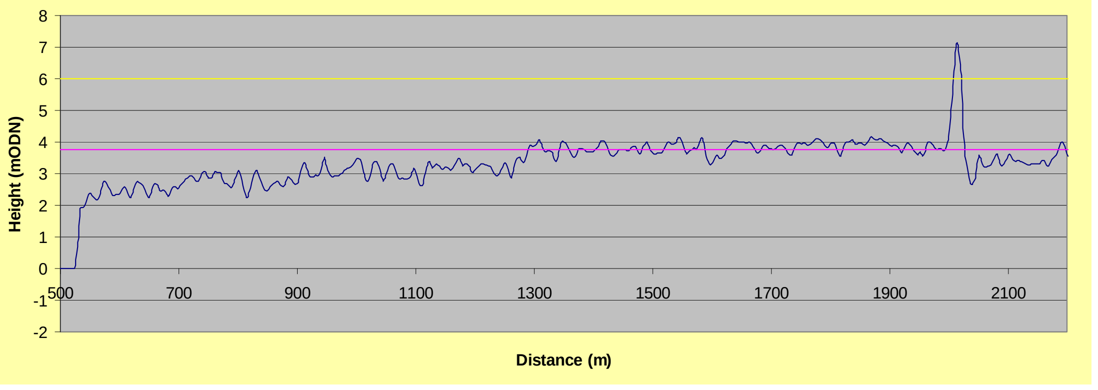


Figure F6.16 N0C5 Cross Section

Figure F6.17 L3A2 Cross Section

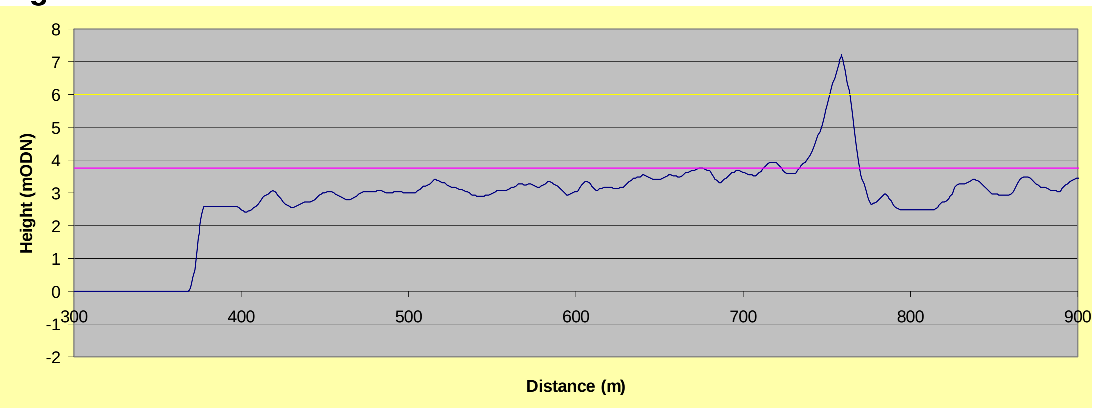


Figure F6.18 L3B6 Cross Section

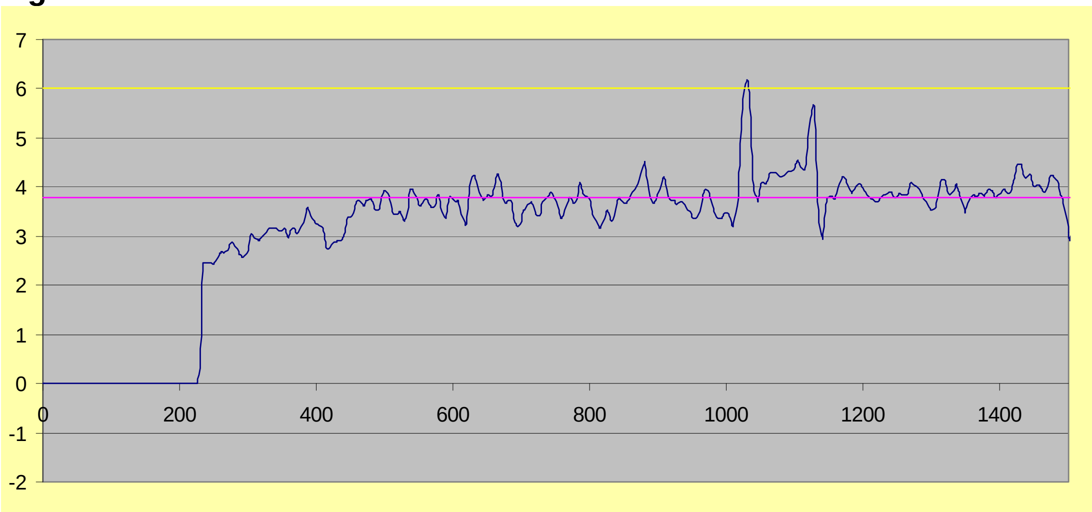
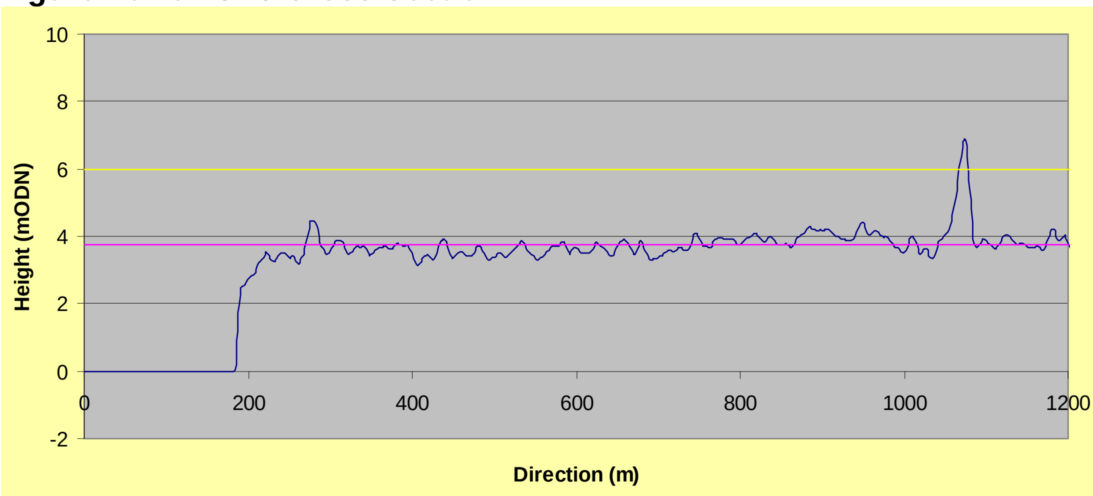


Figure F6.19 L3D3 Cross Section



F6.2.3 Impact of Defences on Offshore Banks

Background

This section aims to establish the effect of the flood defences on the sand banks of the Wash SMP2 area. The impact on policy development is described in appendix E (section E5.2.3). In terms of 'sand banks', this note will focus on those accumulations of sediment which are not covered at low water (so those defined by the Mean Low Water mark) and which are detached from the main intertidal expanse (the saltmarsh and mudflats). The sand banks in the Wash are generally known by individual names, notably:

- Inner Dogs Head;
- Long Sand;
- The Ants;
- Bar Sand;
- Roger Sand;
- Toft Sand;
- Thief Sand;
- Seal Sand;
- Pandora Sand;
- Blackguard Sand;
- Stylemans Middle;
- Silver Sand; and
- Sunk Sand.

Sand banks are generally formed from medium or coarse sand, establishing in areas where there is an abundant supply of sediment and where the currents are strong enough to move this sediment. They can be seen as a sediment sink and therefore store large volumes of sand. Dyer and Huntley (1999) developed a descriptive classification scheme to unify the approaches of marine geologists and physical oceanographers. This classification emphasised the formation and present hydrodynamic setting of the sand bank in relation to the longer-term development. This classification defines the sand banks of the Wash as Type2A, which describes linear ridge-like features formed in the mouth of wide estuaries. These banks are aligned parallel to the axis of main tidal flow and are located between the mutually evasive ebb and flood dominated channels, having a tendency to migrate away from their steeper face.

In terms of their geomorphological functioning, the sand banks have a major influence on the physical processes and sediment flow patterns within the Wash embayment. As a result, they influence the erosion and accretion of materials at the shoreline. They also act to provide a certain degree of sheltering to the intertidal areas.

The Wash SMP2 area has a number of environmental designations. The sand banks discussed in this note also have specific environmental designations associated with them. They are designated as a Special Area of Conservation (SAC) Annex I habitat (1140 mudflats and sandflats not covered by seawater at low tide) under the EU Directive (92/43/EEC) on the Conservation of natural habitats and of wild fauna and flora. The biota associated with this designated habitat includes large numbers of polychaetes, bivalves and crustaceans.

It is important to note that the sublittoral areas of the Wash are also an extremely important habitat and have a number of environmental designations, but that this note only deals with the sand banks themselves (those areas which are exposed at low water).

Past Development

There is a specific lack of literature that discusses the past development of the sand banks of the Wash. Between 1828 and 1971 the major banks did not change position, but a change in size did occur. The movement of the low water mark along the intertidal profile does appear to be affected by the movement of the offshore sand banks.

Future Development

This brief assessment of the future development of the sand banks has been carried out assuming that With Present Management is maintained throughout the Wash SMP2 area. This is Hold the line (HTL) for all frontages.

Assuming that the current trained river outfalls continue to be maintained, it is likely that the banks' position relative to the seaward edge of the intertidal area will remain the same. However, with sea level rise, the mean low water mark will move landward up the intertidal profile and will also gradually reduce the amount of sand bank exposed at low water. This increase in total volume of water flowing through the main tidal channels also has the potential to deepen the channels themselves and cause the sand banks to migrate away from their steep faces (because the steep face in the tidal channels is being actively eroded by the increasing discharge produced by the growth of the tidal prism). This will further act to reduce the total size of the sand bank. However it has to be noted that this increase in tidal prism is relatively small in comparison to a situation of landward defence realignment or even full-scale No active intervention.

However, due to the specific type of biota currently found on the sand banks, it is not expected that there will be a significant negative impact on the biological communities.

Biota of the Wash Sandbanks

The Wash is the second-largest area of intertidal flats in the UK, comprising extensive fine sands and drying banks of coarse sand. This diversity of substrates, coupled with variety in degree of exposure, means that there is a high biological diversity relative to other east coast sites (Murby, 1997). The biota of the Wash includes large numbers of polychaetes, bivalves and crustaceans. Salinity ranges from that of the open coast in most of the area (supporting rich invertebrate communities) to estuarine close to the rivers.

In addition to this, the Wash supports the largest numbers of migrating waterfowl of any site in the UK, as well as possessing the largest common seal colony in England.

Descriptions of biological communities in such naturally dynamic environments are complicated by the fact that many species are found in a number of different habitats; what is more, as the sediment moves about so does the associated wildlife. Generally, however, the intertidal flats cover about 40% of the total area of the Wash, supporting a community characterised by lugworms, with cockles, baltic tellin, mussels, the tiny mud-snail *Hydrobia ulva*, the crustacean *Corophium volutator* and several species of polychaete. The primary communities of the Wash are presented in table F6.39.

Table F6.39 Primary Communities of the Intertidal mudflats and Sandflats of the Wash (Natural England 2008)

Community type	Specific sub-communities
Sand & gravel communities	• Burrowing amphipods and polychaetes (often lugworm) in clean sand shores (LGS.S.AP.P); • Dense sandmason worm beds (LGS.S.Lan); • Red algae and piddocks on intertidal fossilised peat (MLR.R.Rpid); and • Mussel beds (SLR.MytX).
Muddy sand communities	• Baltic tellin & lugworm in muddy sands (LMS.MS.MacAre); • Baltic tellin, lugworm and sand gaper in muddy sand (LMS.MS.MacAre.Mare); • Cockle beds (LMS.PCer); and • Seagrass beds (LMS.ZOS.Znol).
Mud communities	• Ragworm, baltic tellin & lugworm in muddy sand or sandy mud (LMU.SMu.HedMac.Are);

Community type	Specific sub-communities
	• Ragworm, baltic tellin and Pygospio elegans in sandy mud (LMU.SMu.HedMac.Pyg); • Ragworm, baltic tellin and sand gaper in sandy mud (LMU.SMu.HedMac.Mare); • Ragworm and oligochaetes in low salinity muds (LMU.Mu.HedOl); and • Ragworm and peppery furrow shell in reduced salinity muds (LMU.Mu.HedScr)

As previously described, the biota of the Wash sandbanks is very dependent upon the substrate type and therefore, changes in the substrate will lead to shifts in the biological communities.

<u>Impact of Flood Defences</u>

As can be seen from the above discussion, the only negative effects associated with continued HTL will be as a result of 'natural' sea level rise. There is only likely to be a small increase in tidal prism which is unlikely to have a significant effect on the erosion of the main tidal channels.

Further negative impacts would be experienced if the more 'extreme' policies were implemented. For example, a policy of full scale Advance the line (AtL) (which has been discounted for this SMP) would act to squeeze the entire geomorphic system, but is likely to have more of an effect on the intertidal area (saltmarsh and mudflat) than the functioning of the sand banks. Alternatively, implementation of large landward Managed realignment or even a full scale No active intervention (NAI) policy (which has also been discounted for this SMP) would initially lead to a large increase in tidal prism, with associated increased erosion of the channel sides and likely erosion of the sand banks. Into later epochs, as sedimentation increases across the saltmarsh and mudflat, there is likely to be a relative decrease in tidal prism again and therefore decreased erosion of the channel sides and therefore of the sand banks, but this decrease will not compensate fully for the initial increase of tidal prism due to realignment.

The most important management change with respect to the sand banks would be implementing a policy of No active intervention with respect to the river outfalls. Ceasing to maintain the currently trained outfalls would change the total geomorphic functioning of the Wash embayment. It would cause the system to be characterised by a number of meandering channels, with less of an influence of the flood and ebb channels.

In addition, there could be a theoretically conceivable impact of continuation of flood defence (either at the current alignment or further landward) through the reflection of wave energy back into the centre of the Wash which could have the potential to cause erosion of the sand bank and hence alter the percentage of substrate type on the bank itself, which will in turn affect the biota. However, this would require a combination of circumstances which is unlikely: it would require the defences to be near vertical sea walls right in front of deep water, and relatively close to the sandbanks. This would require an Advance the line policy without compensation for coastal squeeze, plus a particular and unlikely choice of defence type. Such a solution is not considered a realistic option in the SMP. The fact that the Wash is a low energy embayment also means that the amount of wave energy available to be reflected back from the defences is minimal.

Conclusions

In conclusion the available information and knowledge does not provide any indication that continuation of flood defence (at the current alignment or further landward) will have a negative impact on the sand banks and their biota.

However, it has to be noted that there is a distinct lack of literature relating to the development of the sand banks in the Wash and how they are predicted to respond to sea level rise. It is therefore extremely difficult to be certain about the effects of Hold the line, and then to go a step further and quantify these effects.

If we were to assume continued Hold the line throughout epoch 1, the tidal prism will continue to decrease slightly or remain as it is, and therefore erosion of the channel sides and therefore sand banks, is likely to stay the same, or even decrease, depending on the effects of sea level rise. Into epoch 2, assuming relatively small-scale realignment to compensate for habitat loss, there will be an increase in tidal prism, and, coupled with sea level rise, there is the potential for erosion of the channels and therefore erosion of the sand banks.

F6.3 PDZ2 Wolferton Creek to South Hunstanton

As far as shoreline interactions and responses are concerned, the main gaps and uncertainties for PDZ2 concerned the impact of the tentative policies on the saline lagoons and on Snettisham Scalp.

F6.3.1 Introduction

The RSPB reserve at Snettisham Scalp attracts around 25,000 visitors per year. The reserve consists of former gravel pits, now known as ‘lagoons’. These lagoons contain a specific salinity and depth of water. They are an important refuge for internationally important birds, with over-wintering and breeding birds accumulating in and around the pits during storms and at high tide. The spit at Snettisham Scalp (also referred to as the 'Scalp') is also an important shingle vegetation habitat for invertebrates and certain species of birds.

This section will provide a brief description of the coastal processes and current management practices along the frontage. It will also provide an overview of how the frontage can be expected to react in the future to different management practices, namely continuing the existing management practices, No active intervention and implementing the Wide defence zone policy.

F6.3.2 Coastal Processes and Current Management Practices

Coastal Processes

The spit at Snettisham Scalp (shown in figure F6.22) appears to have been present since 1945. There is a general consensus that sediment movement along the Hunstanton-Heacham frontage is from the north to the south. This north-south littoral drift is driven by waves predominantly approaching the frontage from the north to north-east during storm events. It is therefore believed that the erosion trends in the north and accretion trends in the south produced by this littoral drift are not necessarily caused by sediment movement in inter-storm periods. The material that moves south along the frontage is clastic material derived from cliff failure and erosion events to the north.

This southward movement of sediment has resulted in a general growth of the Scalp. This movement has been noted since 1945 and has been the only apparent change in beach morphology along the frontage. The rate of this southward sediment movement has been described as 'rather sluggish' (Posford Duvivier 2001), with rates of approximately 600m^3/yr being quoted (Halcrow 1989 in SGS Environment 1996). The relatively slow southward movement has been attributed to the attenuation of waves by nearshore banks and shallows. This southward movement also creates a lee area directly to the south of the Scalp which is likely to experience erosion, losing approximately 1,500m^3/yr (Posford Duvivier 2001).

Environment Agency Management Activities

History

- The sediment transport in the area between Hunstanton and Snettisham is from north to south, and the sediment tends to naturally accrete at a point known as the Snettisham Scalp. In order to maintain beach levels and profiles between Hunstanton and Snettisham it is necessary to undertake annual recycling. This involves the excavation of accreted material from the Snettisham Scalp and transporting it to the areas of erosion between the Hunstanton boat ramp in the north and Snettisham in the south.

- In 1988 the Environment Agency, then the National Rivers Authority, adopted a strategy for defences between Hunstanton and Wolferton Creek. This included a beach nourishment scheme between the powerboat ramp (in Hunstanton) to Snettisham Scalp, and a new cross-bank to the south of Snettisham which formed the southern most boundary of the scheme.
- Nourishment commenced in 1988, but 1:10yr storms in 1990 caused a re-shaping of the beach and as a result the programme of nourishment had to be re-analysed and re-designed. The scheme was completed to the new design profile in 1991.
- From 1993 recycling was carried out every year. As a result of analysis of regular monitoring (which looked at beach levels, sediment size and ecological aspects) the Environment Agency reduced the amount of material taken from the spit to allow for some recovery of volumes of material at the spit.
- In August 1998, designs for hard defence works for Heacham North Beach, Heacham Dam and south of Snettisham Scalp were completed and tenders were received. A design was also completed for future beach nourishment for Heacham South Beach and Snettisham Beach. However construction was postponed due to an absence of funding, but finally commenced in autumn 2001.
- In 2001 the Strategy Appraisal report completed by Royal Haskoning recommended "Option 4 – Nourishment and Sea Walls" that consisted of:
    - Beach nourishment at Heacham/Hunstanton.
    - Seawall improvement at Heacham.
    - Revetment improvements at Snettisham.
- Since implementation of the strategy in 2001, the following works have been undertaken in the area:
    - 2005 – Beach nourishment works at Heacham and Snettisham (approximately 196,000m^3 imported material placed on beach).
    - Annual shingle re-cycling from Snettisham Scalp at the southern end of the frontage back to the beach to the north (total volume of shingle recycled to date is shown in table 1).
    - Environmental monitoring.
    - Beach surveys.
    - Beach maintenance works in response to shingle 'cliffing' etc.

Table F6.40 Total Quantities of Shingle Recycled to Date

Year	Volume (m^3)
1993	58,000
1994	33,700
1995	31,600
1996	7,000
1997	6,600
1998	9,620
1999	8,992
2000	8,016
2001	5,988
2002	3,570
2003	6,396
2004	18,465
2005	5,442
2006	10,374

- A PAR was undertaken in 2007 in order to bridge the gap before the Strategy review (planned for 2012). Three options were identified in the PAR as summarised below.
    - Option 1 – Do nothing, or walk away and abandon the 2001 management Strategy.
    - Option 2 – Undertake limited beach management over the next 5 years (only reactive maintenance, beach survey and commitment to environmental monitoring.
    - Option 3 – continue to manage the beach and recycle shingle annually in order to maintain the design profile, as stated in the 2001 strategy.
- The 2007 PAR update identified Option 3 as the preferred option. The project commenced in 2007, with the first annual recycling of shingle occurring in February 2008. The volume of shingle recycled annually is not specified, but records of annual recycled volumes are kept.

Management and Existing Defences

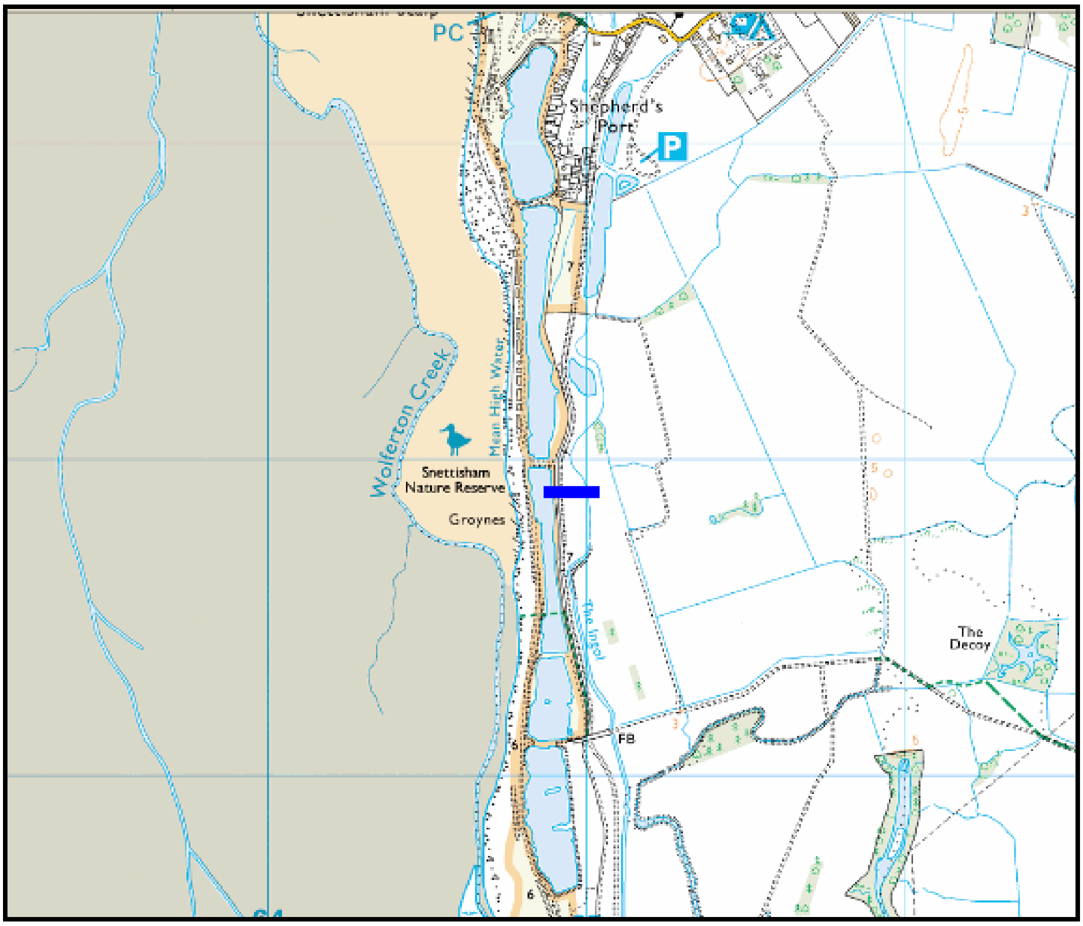
- The entire stretch of this coastline is managed by the Environment Agency, apart from a section directly in front of Hunstanton town which is managed by King's Lynn and West Norfolk Borough Council (these are coastal defences as opposed to flood defences).
- The sea defences between Hunstanton and Heacham consist of a mixture of concrete seawalls, flexible concrete revetment and a shingle ridge. There is also a second line of defence located landward of, and parallel, with the first shingle ridge/sea wall line. Together these defences protect a considerable area of low-lying land.
- Specifically in front of the Snettisham Lagoons there is mainly a maintained shingle ridge which protects the lagoons, and then a sea bank

landward of the lagoons themselves. There is a short section (approximately 550m) of sea wall/revetment structure which, as mentioned above, was constructed as part of the 2001 scheme. This defence type is shown in figure F6.20.

- The Environment Agency cross bank at the southern end of the sea defence scheme which divides the lagoons, is shown in figure F6.21. To the north of the cross bank maintenance of the shingle ridge is classified as higher priority by the Environment Agency compared with maintenance of the ridge to the south. This is due to the considerable value of tourist facilities and properties that are located to the north.
- Due to this higher priority in the north, the cross bank was constructed to compartmentalise the tourist area and to ensure that breach of the shingle ridge in the south would not cause damage to the bungalows located to the north of the cross bank.
- As a result of this difference in management priority between the north and south, the history discussed above generally applies to the area to the north of the cross bank. To the south, the shingle ridge is maintained sporadically by the RSPB, with occasional help from the Environment Agency (for instance when plant is already on site and available).
- The RSPB have also paid for the Environment Agency to install culverts running from the lagoons, under the beach, with outfalls towards the MLW mark. The aim of the culverts is to re-establish optimal water levels in the lagoons for the bird population following periods of high rainfall.

Figure F6.20 Sea Wall at Snettisham Scalp (looking southward)

Figure F6.21 Cross Bank at Snettisham Scalp (shown by a blue line)



F6.3.3 Impact of Management Scenarios on Saline Lagoons and Snettisham Scalp

<u>With Present Management</u>

The RSPB and Natural England have thus far generally supported the principle of recycling along the frontage, but do not want the spit to decrease significantly due to the potential loss of the bird reserve located at the saline lagoons and other environmental factors associated with loss of habitat on the spit itself.

A number of EIAs undertaken for elements of the 1997 preferred strategy of beach nourishment coupled with hard defence works (same management practice that is currently being undertaken) concluded that for the nourishment aspect, during the operation phase, "the stability and future of Snettisham Scalp will be more secure as a result of the scheme" (Posford Duvivier 2001 p.52).

No active intervention

In contrast, doing nothing along the entire Hunstanton-Heacham may alter the 'natural' drift of beach material and there is the potential for tidal inlets to develop. It has to be emphasised here that this 'do nothing' refers to full do nothing along both the shingle ridge and the earth embankment immediately landward of the ridge. Under this scenario, the Scalp may gradually reduce in size as a result of erosion if sediment supply to it was to diminish (Royal Haskoning 2001). Ceasing management of the shingle ridge would also have a negative effect on the saline lagoons as there would be increased overtopping and an increased risk of breach of the ridge itself. This would dramatically alter the salinity and depth of the water in the lagoons, both of which are key factors in ensuring continued use of the saline lagoons by overwintering and breeding birds. In addition, under this scenario it is highly likely that overtopping of the ridge and therefore inundation of the saline lagoons would occur during storm events or high tides, and therefore the site may not be available as a roost area at exactly the time when it is most required. This scenario was ruled out by the CSG at the beginning of policy appraisal due to the significant loss of communities and environmental assets.

Wide defence zone

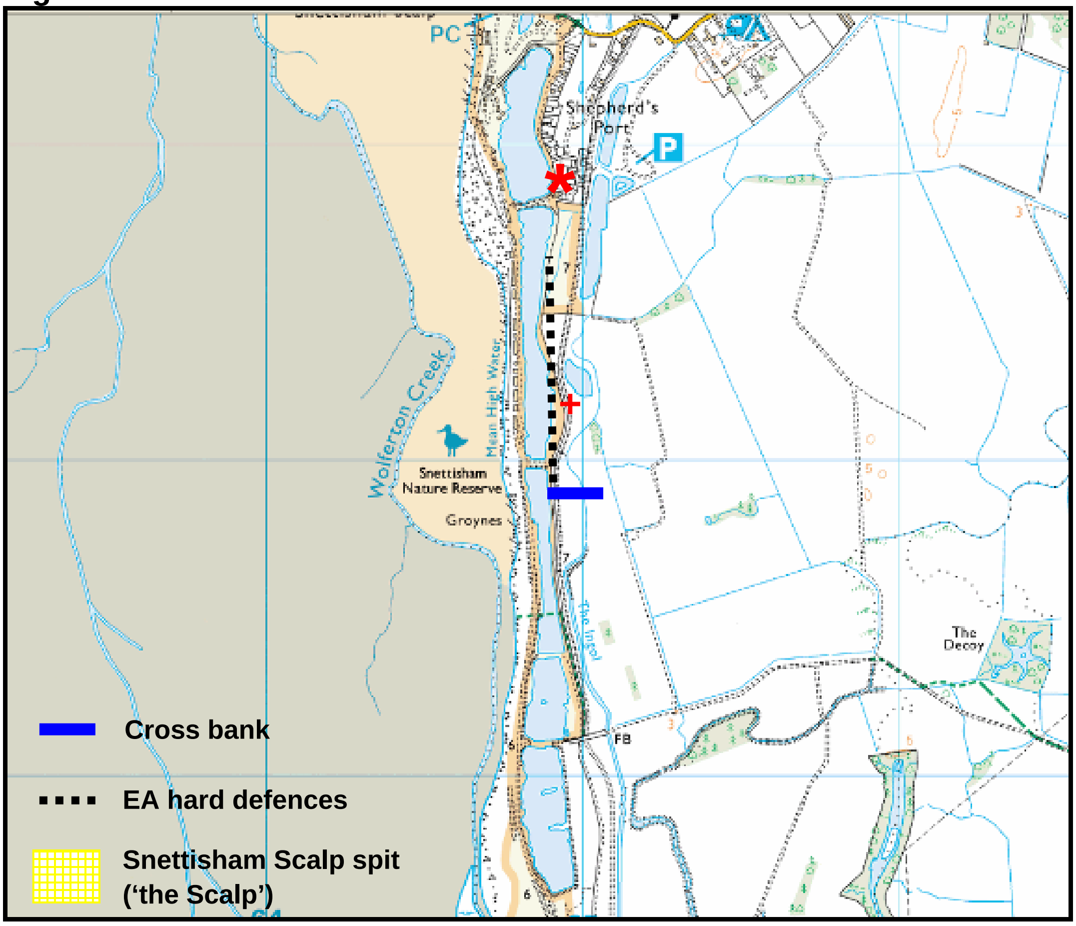
Gradually reducing the amount of material taken from the spit for placement on the beaches to the north in epochs 2 and 3 would initially result in an increase in volume at the spit. However this accretion is likely to be constrained, as it is predicted that a situation is likely to be reached when the influence of the waves/tidal flows will prevent further accretion of the spit. At this point, the additional sediment is likely to be lost from the system, potentially offshore (Jacobs 2007).

Moving southward towards the Scalp, the Wide defence zone policy has beneficial consequences for the shingle spit itself and the saline lagoons. Ceasing the maintenance of the shingle ridge in epoch 2 will allow the spit to continue to build and gradually there will be in an increase in vegetated surface across the spit. This will provide an increased area of habitat for invertebrates and certain bird species. The build up of the spit will also act to provide increased protection to the saline lagoons directly east of the spit itself (the most northerly lagoons, denoted by a red asterisk on figure F6.22). As a result, from our understanding of the coastal processes along this frontage, it is believed that the salinity and water depth across this lagoon will be maintained.

In terms of the lagoon immediately north of the cross bank (denoted by a red cross on figure F6.22), the hard defences will remain and continue to be maintained during epoch 1, thus providing continued protection to the lagoon directly to the east. Into epoch 2 maintenance of the defences will be ceased as the intent of management will be NAI for the frontline. As are result there will be the need for adaptation of these bungalows during epoch 1 in parallel to the adaptation required for the bungalow and holiday parks to the north of the Scalp. However, the hard defences will continue to provide residual protection to the lagoons into epoch 2. Towards the end of epoch 2 it is expected that the spit will have built up sufficiently to provide the required level of protection to the lagoons into epoch 3. It should be noted here that there is uncertainty regarding the future development of the spit, particularly into epoch 3, and therefore it is essential that monitoring is undertaken to record the spit's development and provide a basis for future analysis.

For the lagoons to the south of the cross bank, their existence is not necessarily reliant on management practices to the north, as at present the shingle ridge is not maintained to the extent that it is to the north of Snettisham Scalp. As a result, the ridge currently acts sufficiently as a natural flood defence and is only reprofiled on an ad hoc basis, usually following storm events. Ceasing management practices to the north is only likely to enhance their function as greater protection will be provided by the increasing Scalp (the area to the south has the potential to be sheltered by prevailing waves during storm conditions). However our understanding allows us to predict that this improvement is likely to be counteracted by the effects of climate change. The result will be no net change in the function of the Scalp and therefore of the saline lagoons. If there was significant damage to the ridge following a storm event, the RSPB may have to undertake some ad hoc management, but this is not likely to be needed at more regular intervals than what is carried out at present.

Figure F6.22 Illustration of Features



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