Overstrand to Walcott Strategy Study

CliffSCAPE modelling and clifftop recession analysis

Part II: Technical Support Information

Report EX 4692
June 2003

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This report describes work commissioned by North Norfolk District Council whose representative was Mr Peter Frew. The HR Wallingford job numbers were CDR3212 and CDR3214. The work was carried out by Dr Jim Hall and Dr Mike Walkden of the University of Bristol. The HR Wallingford project manager was Mr Paul Sayers.

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Summary

Overstrand to Walcott Strategy Study

CliffSCAPE modelling and clifftop recession analysis

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A numerical model study of a section of the North Norfolk coast has been conducted to predict the effect of alternative strategic coastal management options, including ‘do nothing’, ‘do minimum’ and higher cost schemes. The study combined a regional-scale version of the cliffSCAPE soft cliff and platform erosion model with a stochastic model of coastal landsliding.

CliffSCAPE provides a prediction of the response of the shoreline (cliff toe) to changes in coastal management and other long term coastal changes (for example climate change). The stochastic model uses predictions from cliffSCAPE together with information from cliff surveys to generate a probabilistic prediction of cliff location that can be used in the economic appraisal of strategic coastal management options.

This study was the first application of cliffSCAPE as a regional modelling tool for soft cliff shorelines. The results of the validation process are very positive, indicating a good match between model output and historic records of shore recession over three eras spanning a total of 87 years. However, cliffSCAPE has previously been applied at only one other coastal site (the Naze on the Essex coast) and has never been applied to such a long length of coastline as examined in this study. Thus, the results may be considered experimental, as cliffSCAPE still requires testing and validation on a wider range of coastal sites.

The cliff evolution modelling has been used to predict future changes in clifftop position under a range of management scenarios. The models indicate that the cliff system is strongly influenced by sediment transport rate, with recession rates in particular areas strongly dependent on both current and historic management decisions both locally and up-drift.

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1. INTRODUCTION

This report describes a model study of the North Norfolk coast between Overstand and Mundesley. The objective of the study was to predict the effect of alternative strategic coastal management options including 'do nothing', 'do minimum' and higher cost schemes. The model study combined two modelling approaches:

- a regional-scale version of the cliffSCAPE soft cliff and platform erosion model
- a simple stochastic model of coastal landsliding.

CliffSCAPE provides a prediction of the response of the shoreline (cliff toe) to changes in coastal management and other long term coastal changes (for example climate change). The stochastic model uses predictions from cliffSCAPE together with information from cliff surveys to generate a probabilistic prediction of cliff location that can be used in the economic appraisal of strategic coastal management options.

2. THE CLIFFSCAPE MODEL

CliffSCAPE is a model of the process of shore platform lowering and cliff toe recession that governs the retreat of soft coastlines and their response to coastal management interventions. As well as representing the in-situ shore platform and cliff toe, cliffSCAPE models the mobile beach, its role in protecting or abrading the platform and the contribution that cliff and platform sediments make to the mobile beach. A regional-scale version of cliffSCAPE (cliffSCAPE-RS) is available to model long sections of coast for strategic assessment purposes, whilst the local-scale version can better resolve the effects of individual beach control and coast protection structures. Because of the strategic nature of the current study, cliffSCAPE-RS was chosen for the analysis.

A flow chart of cliffSCAPE-RS modelling tool is shown in Figure 1. CliffSCAPE-RS describes a two-dimensional shore section, which is made quasi-3D by using a series of such sections and allowing interaction between them. The model time-step is 12.47 hours, i.e. one tidal period. Every time-step wave and tide data are sampled from synthetic time-series, which in this study were generated by HR Wallingford. The synthetic wave data was generated for one offshore point, grid reference 636836, 350606, which is approximately 18 km due north of Walcott. The waves are refracted using Snell's Law and shoaled over a topography that represent, in a simplified way, site bathymetry. A cross-shore distribution of longshore sediment transport is calculated using tidal changes in water level and a distribution under static conditions published by McDougal and Hudspeth (1984). A similar approach provides a cross-shore erosion distribution function. Potential sediment transport at each shore section is calculated using the CERC equation (Shore Protection Manual 1984). The cross-shore distribution of drift is compared to the beach width to discern what proportion of the potential transport actually occurs. The magnitude of erosion at different elevations across the shore is calculated using the duration of submersion during the tidal cycle, location within the surf zone and local slope. These are combined with the expression provided by Kamphuis (1987) for shore recession rate due to wave attack, and a distribution of erosion due to random waves under static water-level conditions obtained from Skafel & Bishop (1994) and Skafel (1995). Kamphuis' expression provides the magnitude of recession; the results of Skafel are used to distribute it over the platform. Kamphuis' expression was chosen because it provides an expression in which wave breaking processes are well represented at the level of abstraction appropriate for the model. Material strength is represented by a variable R, which is found during calibration by comparing average historical recession rates to measured values. Although Kamphuis justifies his expression he does not provide values for R or link it to measurable geotechnical parameters. The beach is considered to protect the profile when it is of adequate thickness. Following field measurements of Ferreira (2000) this was defined as a depth of sand exceeding one-fifth of the wave height. If a thinner beach is present then its protective capability is assumed to vary linearly with depth of sand.. Once the whole profile has been recalculated overhanging material above the cliff toe is assumed to collapse to form talus; a constant cliff angle was assumed for the calculation of talus volume. Talus was assumed to have one-tenth of the strength of intact material. Not all of the material eroded from the talus was assumed to contribute to the beach volume. The fraction of beach material was determined by the British Geological Survey.

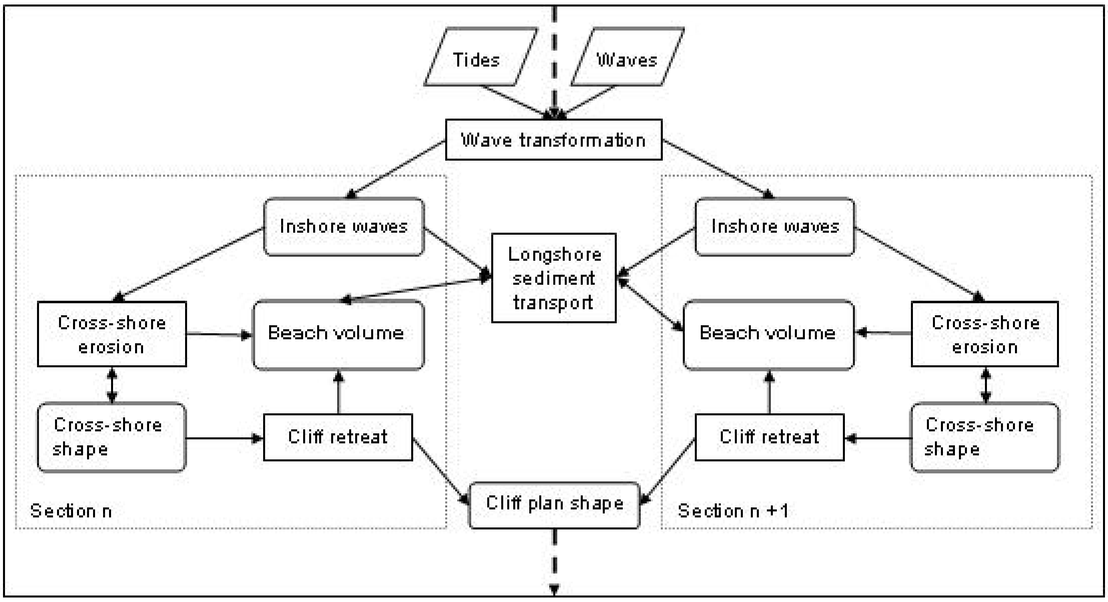

Figure 1 Flow chart representation of cliffSCAPE

CliffSCAPE provides predictions of shore profile and cliff plan-shape evolution. The latter is of most interest for strategic-scale studies.

The relationship between measurable properties of a shore platform and its resistance to erosion by the sea is unknown (Walkden *et al*, 2002). Any shore platform erosion model therefore has to be calibrated against historic recession rates. CliffSCAPE is attractive in that, whilst it has to be calibrated in order to reproduce past average recession rates, differences in recession up and down the coast or across the shore platform are predicted by the model and can be compared with measurements. In this study, comparison between differentials in average recession rates along the north Norfolk coast were used as the main criterion for model evaluation; model output was compared to long-term recession rates published by Cambers (1976).

3. SETUP OF THE CLIFFSCAPE MODEL FOR THE NORTH NORFOLK COAST

CliffSCAPE is based on concepts of system equilibrium. Before a cliffSCAPE model can be expected to behave in a realistic manner it must be allowed to develop towards a 'balanced'. This applies to both alongshore and cross-shore form; sediment released from the cliff must match sediment moved away by longshore transport and the interaction between cross-shore shape and erosion (and inundation due to rising sea-levels) result in an unchanging profile. As with the real coast, if the form is out of balance then subsequent erosion will be too high or too low. The first step in this process is to produce a single cliff profile using local wave, tide and sea-level rise conditions. The initial profile is assumed to be a vertical cliff plunging into deep water, i.e. intentionally far from equilibrium, and the model is run to simulate response to many hundred of years of wave and tide action. Once this cliff profile has stabilised it is reproduced to generate multiple sections, in this case there were 63. These were arranged side-by-side along a baseline to form a quasi three-dimensional coast with a model distance between them of 500 metres. The baseline projected at an angle of 300 degrees (west-north-west) from grid reference 640835,327250, which was its intersection with the first and most southerly profile. Appropriate offsets were introduced to represent the coast plan shape, as illustrated in Figure 2 and a beach was introduced (the exchange of beach material is calculated mid-way between sections). The model was then set to run again to allow the profiles to respond to the presence of the beach, and also for balance to be reached in the coast plan shape. At this stage the material strength parameter (*R*) was selected. A value was chosen to match the model output to known average historic rates. In North Norfolk the geology varies, becoming harder north of Cromer. This was represented with an increase in *R* by a factor of three north of Cromer. Other input parameters required by cliffSCAPE are summarised in Table 1.

Table 1 Input parameters for cliffSCAPE RS

Input	Value	Units
Run duration	453	A
Step size	Tidal period	
Baseline angle	120	Degrees
Offshore contour depth	7.75	Metres
Angle of offshore contour	Variable	Degrees
Rate of sea-level rise	2 pre-2003 then variable	mm/A
Material resistance	Calibration variable	$m^{9/4}s^{3/2}$
CERC coefficient	0.77	
Groyne construction	Dates and locations	
Seawall construction	Dates and locations	
Revetment construction	Dates and locations	
Groyne removal	Dates and locations	
Seawall removal	Dates and locations	
Revetment removal	Dates and locations	
Groyne damage	Dates and locations	
Groyne imporvement	Dates and locations	
Beach Bruun constant	0.19	
Cliff sand contents	Variable	%
Cliff top elevation	Variable	m AOD
Wave heights	Variable with time	Metres
Wave periods	Variable with time	Seconds
Wave directions	Variable with time	Degrees
Tidal amplitude	Variable with time	Metres

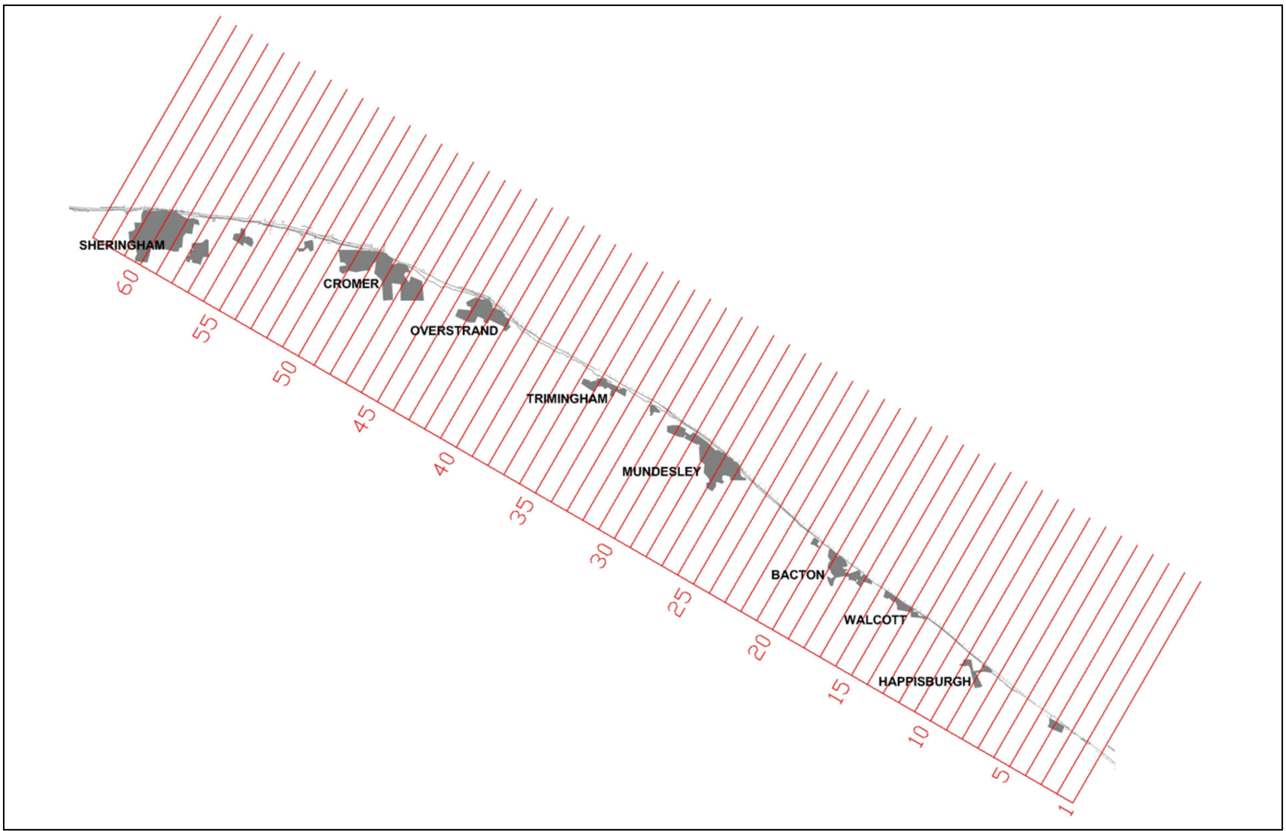

Figure 2 The study site plan shape and cliffSCAPE cross-section positions

After the material strength had been calibrated coastal structures were introduced to the model. Three types were represented in the following way;

- seawalls - a position behind which the cliff profile was not allowed to retreat.
- groynes - a 50% reduction in CERC coefficient of sediment transport.
- revetments - a line behind which wave energy was reduced by three-quarters.

The locations of the structures and the dates that they were installed were established in a study by a local engineer, Peter Lawton. The model spacing was large relative to the construction detail provided, so some averaging and simplification was necessary.

4. MODEL VALIDATION

4.1.1 Profile development

Figure 3 shows 'snapshots' of profile evolution, every 25 years at Mundesley. The dots indicate the limits of beach coverage, i.e. the beach covers the platform between the dots. The axes have been distorted by a ratio of about 1:25, which makes the platforms appear artificially steep. Later profiles are higher due to rising sea-levels.

The early profiles (towards the right of the figure) are all similar. The cliff face is very steep, and its junction with the platform is located at approximately the upper limit of the beach. Below this junction the platform slope becomes increasingly gentle, with a marked change a little below the lower limit of beach coverage. The effect of the construction of a seawall in 1910 can be seen in the convergence of the later profiles into a vertical line. This reveals the face of the seawall in front of which the platform continues to drop. The continuing lowering of the platform represents an increase in the vulnerability of the seawall and the cliff it protects.

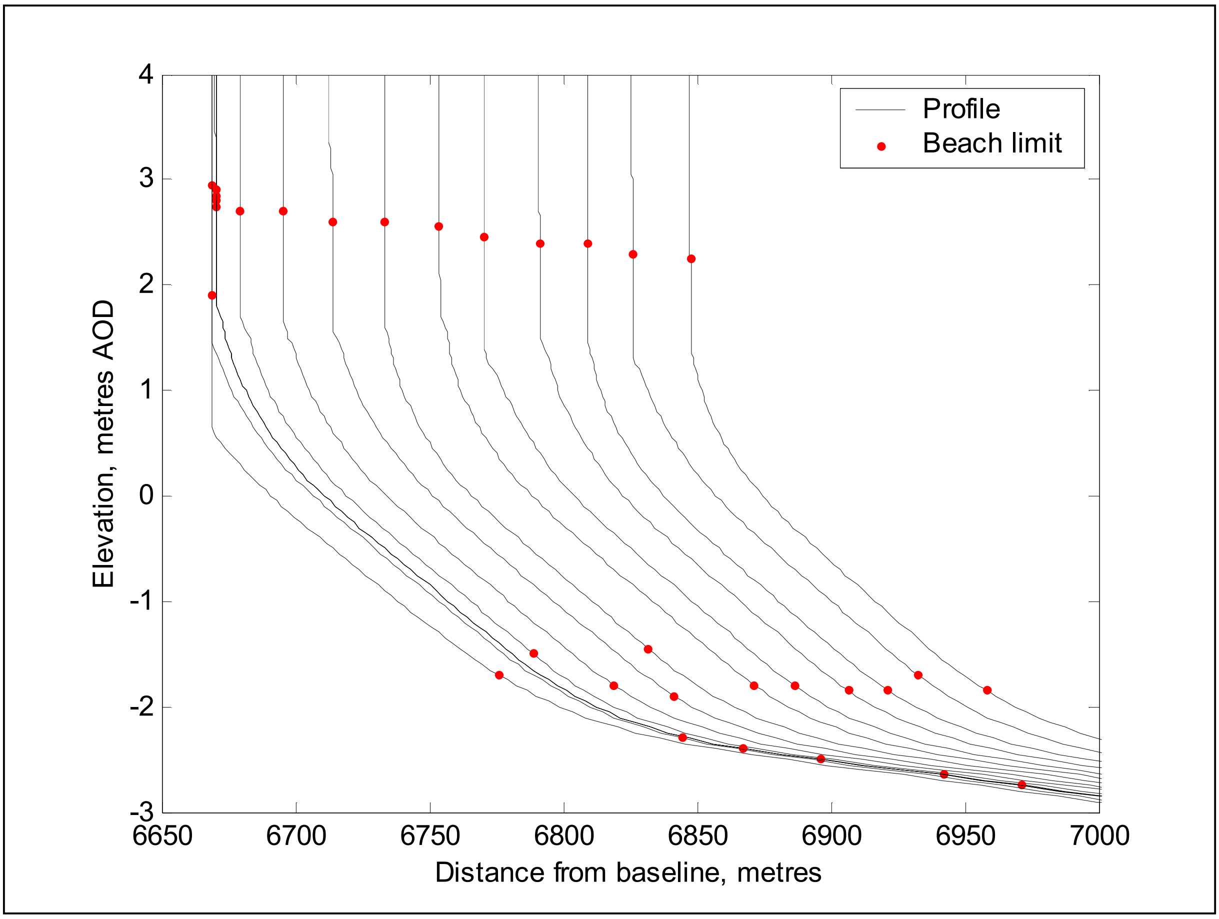

Figure 3 Model profile evolution at Mundesley, 25 year stages from 1600 to 2000

Most of the later profiles show much wider beaches, the largest being about 300 m, indicating an increase in the volume of the beach. This probably results from both the construction of groynes at this location and increased updrift recession between Mundesley and Overstrand.

The last profile represents the present day situation and has been compared to measurements. It was found that the platform level close to the seawall was well represented, but the gradient is too shallow in the model. Consequently the rest of the platform is too high. Site investigations reveal that at 30 m from the wall the platform is about 0.5 m deeper than is predicted in the model. This misrepresentation of the platform elevation seems to be a general problem along the model coast, although data describing the actual platform is very scarce. This is a disappointing aspect of the simplistic representation of cross-shore processes.

Although greater accuracy in the prediction of the platform level is desirable, it is not necessarily critical to model performance. The primary need is for the model to be capable of predicting planshape evolution.

4.1.2 Plan shape development

Model planshape evolution was compared to the historic development of the North Norfolk coast, as measured by Cambers (1976).

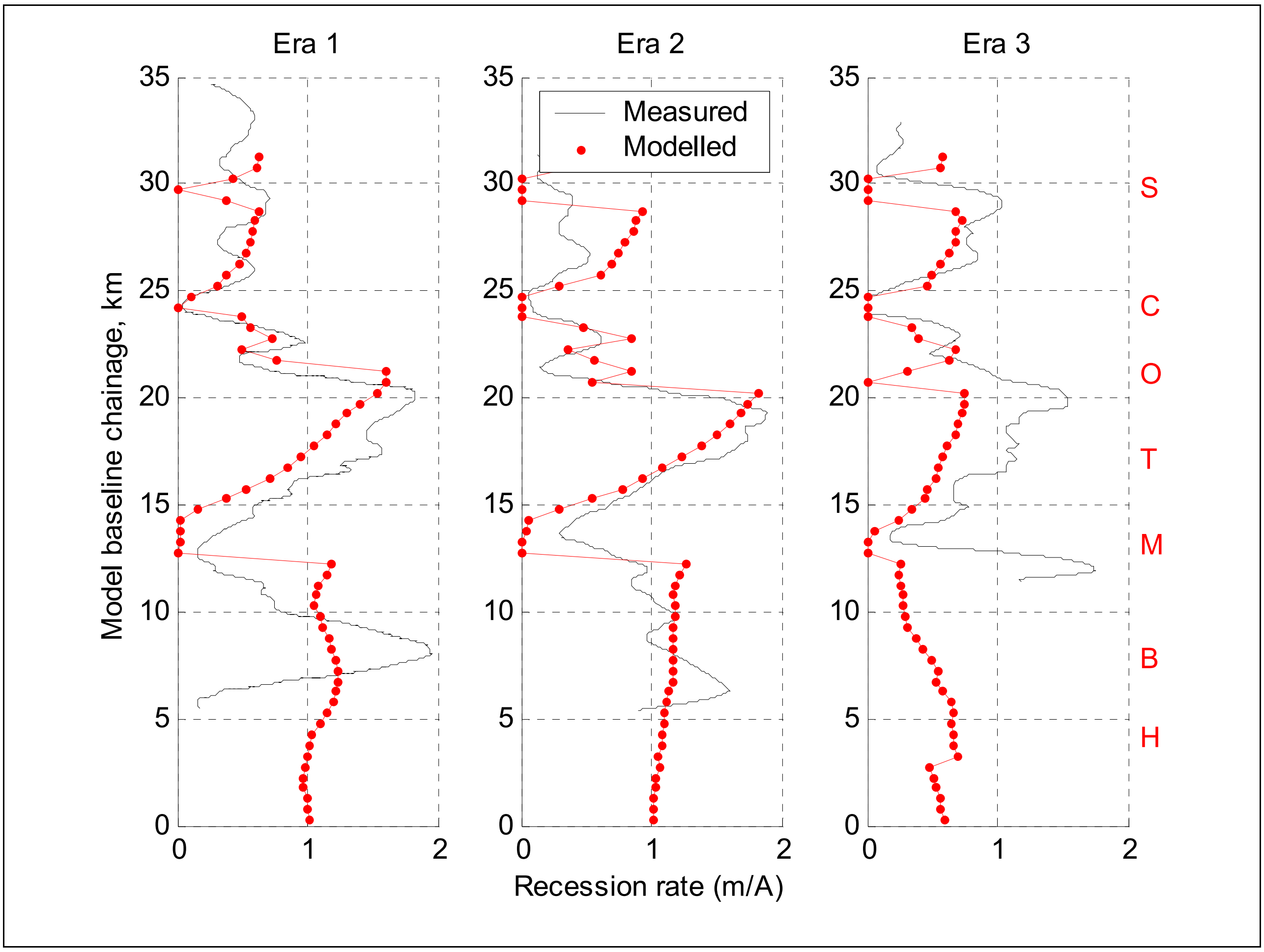

Figure 4 Comparison between model recession rates and measurements provided by Cambers

The comparison, which is shown in Figure 4 is made over three eras, 1880 – 1905, 1905 – 1946 & 1946 – 1967. There is some asynchrony between the model output and the historic measurement period for eras 2 and 3 since data was output from the model at 5 year intervals, e.g. era 2 last from 1905 to 1945. The dots on the line for predictions each represent a model section. The results are good, both in terms of magnitude and temporal and spatial variation. The fit is least good in era three, which is disappointing since this is the most recent. The cause is not clear but it can be attributed, in part, to the short duration of this era, (21 years) and some asynchrony between the recession periods (1946-1967 measured and 1945-1970 modelled). In addition there is an anomaly in the measured data at Overstrand (Chainage 21 km). A seawall has been present there since 1920, but the measured recession over the period 1946 – 1967 is given as approximately 0.7 m/A. The measured data also shows high recession south of Mundesley in the third era that contradicts local knowledge.

Although the comparison is good for the primary area of interest, from Overstrand to Mundesley, less confidence is established in the representation of the south of the region. The cause of this is uncertain, although it can be attributed in part to the proximity of the southern boundary and the use of only one wave point. The problem is also compounded by the lack of reliable calibration data south of Mundesley after 1946. However, it is also the case that any misrepresentation of any area of the model will be propagated downdrift. Since the southern area is downdrift of the rest of the model it is likely to show the largest errors.

The good match obtained over the main part of the region lends confidence in the model performance and provides a good basis for making future predictions.

4.2 5Scenario testing

A total of 19 future management scenarios were modelled, which are summarised in Table 2. These were used to explore the implications of structure failure, removal, maintenance and improvement and different rates of sea-level rise. Groyne removal, damage and improvement was represented within the model by varying the CERC coefficient, and therefore sediment transport rate, e.g. 20% model groyne damage was represented by a 20% decrease in its effect on the sediment transport rate. The rate of sea-level rise post-2002 assumed for all scenarios, except Scenarios 6a-6d, was 6 mm/A.

Table 2 Summary of scenarios

No.	Management scenario	Notes
1	Open Coast	Remove all seawalls and groynes in January 2003
2	Do Nothing	Structures removed at the mean estimate of residual life
3	SMP policy options	SMP policy option, groynes and seawalls held in present alignment & condition
4	Revised SMP policy options	As scenario 3 but Do Nothing at Trimingham
5a	SMP policy options with groyne modification	20 % increase in groyne efficiency at C, O, T, M & B
5b	SMP policy options with groyne modification	20 % increase in groyne efficiency at C, O, M & B
5c	SMP policy options with groyne modification	20 % increase in groyne efficiency at C, M & B
5d	SMP policy options with groyne modification	20 % increase in groyne efficiency at C and B
5e	SMP policy options with groyne modification	20 % increase in groyne efficiency at C
6a	Do nothing	4 mm/A Sea-level rise
6b	SMP policy options	4 mm/A Sea-level rise
6c	Do nothing	2 mm/A Sea-level rise
6d	SMP policy options	2 mm/A Sea-level rise
7a	Do nothing	Minimum residual life estimate
7c	Do nothing	Maximum residual life estimate
8a	SMP policy options with groyne modification	Groyne efficiency reduced by 20% at O, T, M & B, increased by 20% at C
8b	SMP policy options with groyne modification	Groyne efficiency reduced by 20% at T increased by 20% at C
9a	SMP policy options with groyne modification	Groyne efficiency increased by 40% at O, T, M & B, increased by 20% at C
9b	SMP policy options with groyne modification	Groyne efficiency increased by 40% at O & M, increased by 20% at C

N.B. C, O, T, M & B refer to Cromer, Overstrand, Trimingham, Mundesley and Bacton respectively.

The models provide cliff toe position every year at every section. These were processed to provide recession distance and average recession rate for each scenario. A full set of results is given in Appendix 1. Key representative results are described below.

4.2.1 Scenario 1, 'Open coast'

The first scenario to be tested was 'Open Coast' in which all model structures were removed at the beginning of 2003. Historically these structures have resulted in the formation of anthropogenic headlands. Removal of the structures might be expected to result in the rapid removal of these features. A benefit of releasing the coast in this way would be the resulting supply of large amounts of sediment from the cliff to the beach. The modelled consequences of the 'Open Coast' scenario are shown in Figure 5.

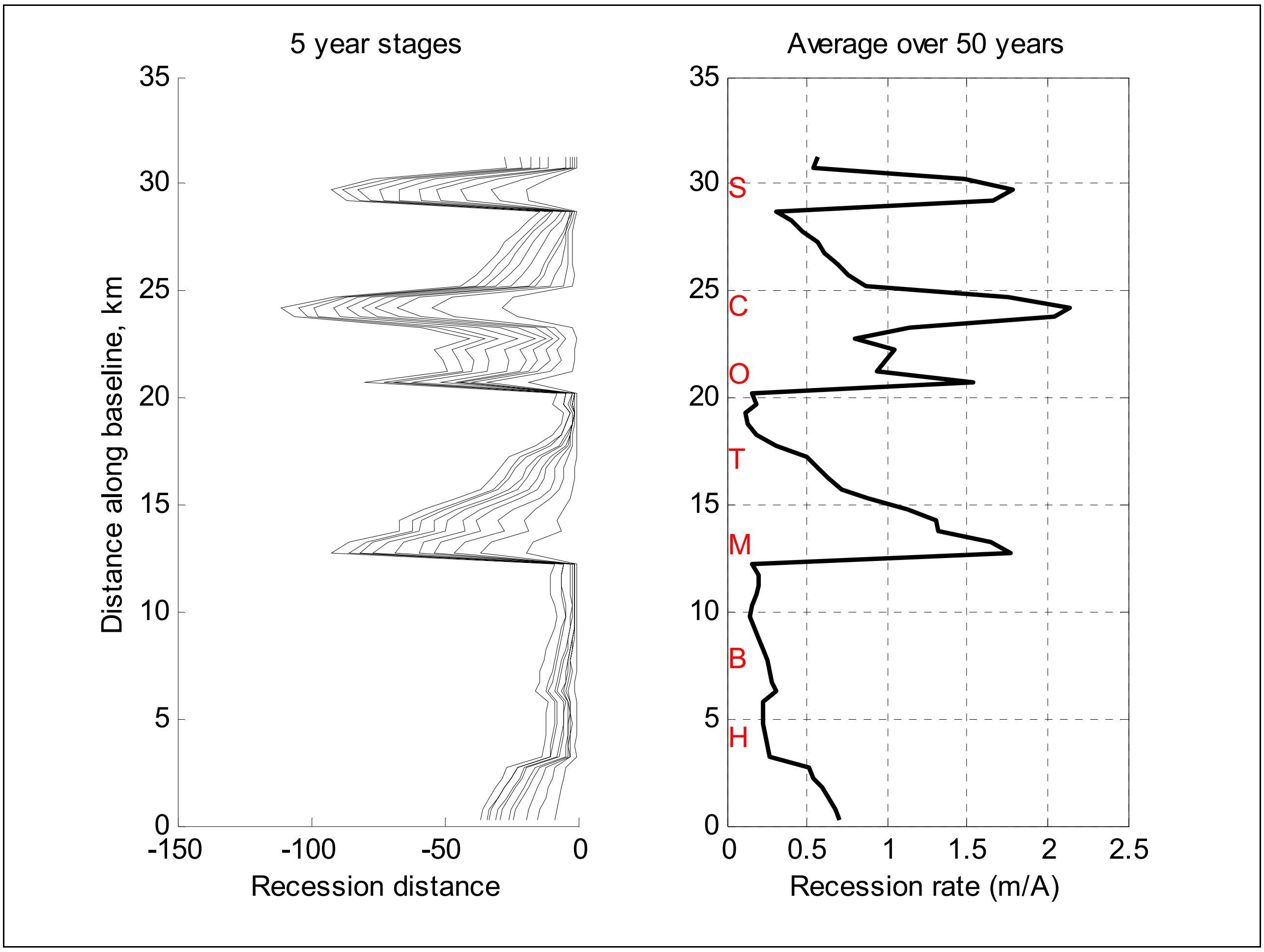

Figure 5 Recession resulting from an 'Open coast' management policy (scenario 1)

The first graph in Figure 5 shows the cumulative cliff toe recession over 50 years from the 2003 position in five year increments. The average recession rate over this period is shown in the second graph.

As expected the recession is greatest at locations that were previously protected. In the model this occurs because the platform level at anthropogenic headlands tends to be unnaturally low, as seen in Figure 3 allowing more direct wave attack on the cliff toe.

The recession rate between Overstrand and Trimingham is low, presumably due to increased protection from large amounts of sand released from Overstrand to Cromer. The same effect probably causes the low recession rates south of Mundesley, though model performance close to this southern boundary is reduced, as discussed in section 4.

It can be seen that the greatest cliff retreat occurs in the first ten years; as time goes by the recession rate drops. This indicates the initial excursion from equilibrium form, which decreases as the shoreline is allowed to evolve and recession rates tends to equalise.

4.2.2 Scenario 2, 'Do Nothing'

In the 'Do Nothing' scenario the structures were assumed to collapse and have no more effect after the mean estimate of residual life. The results are shown in Figure 6 and are similar to those of the 'Open Coast' scenario, which are also shown. This is because the residual life of most of the structures is much shorter than 50 years. The greatest difference between the two is seen in the early years. At Sheringham, for example, there is no recession for the first 20 years, but very high recession rates immediately after.

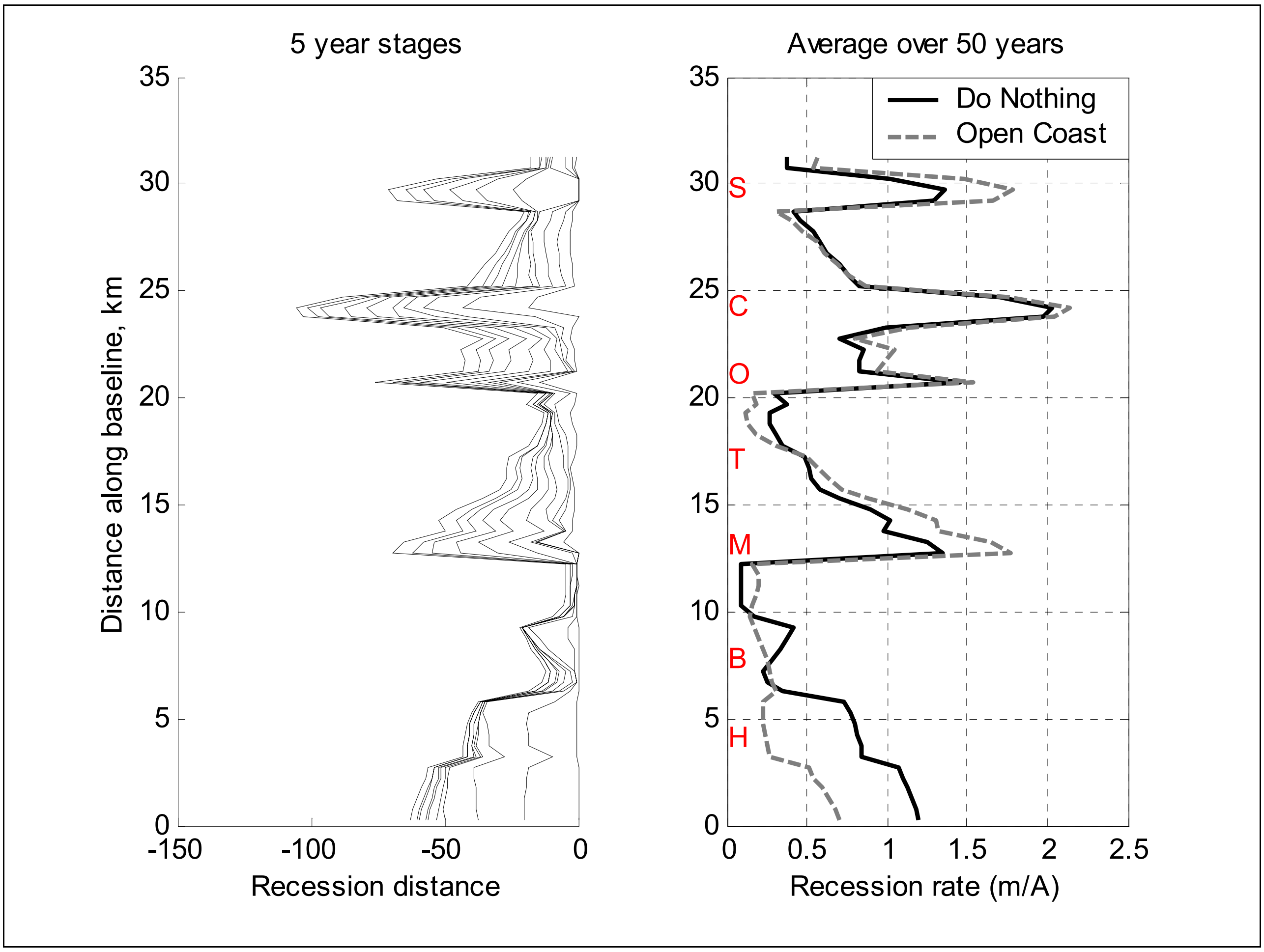

Figure 6 Recession resulting from a 'Do Nothing' management policy (scenario 2)

4.2.3 Scenario 3, 'SMP policy options'

The 'SMP policy options' scenario assumed a continuation of current management practice under which structures are maintained. The expected result of this policy is that the settlements would continue to emerge from the cliff line as anthropogenc headlands, separated by bays. The results of this scenario are shown in Figure 7. There are areas between Sheringham and Cromer and Overstrand and Trimingham where the recession rate under the 'Do Nothing' scenario is greater than the 'Open Coast' scenario. This probably reflects increased protection resulting from the greater volumes of beach sediment released by the latter scenario.

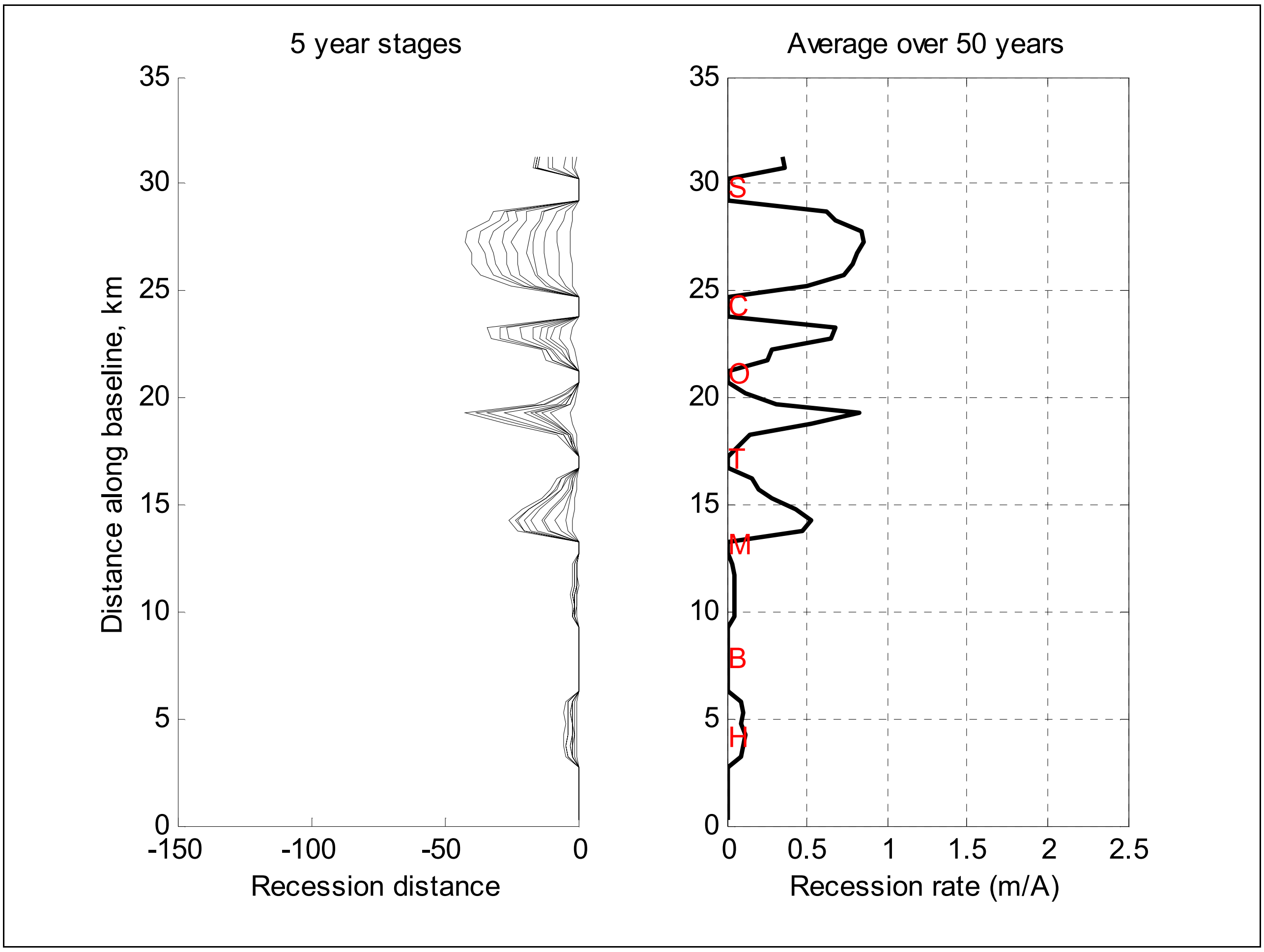

Figure 7 Recession resulting from a 'SMP policy options' management policy (scenario 3)

It can be seen that, as expected, the maintenance of the seawalls prevents recession at the settlements, but the cliff continues to retreat between them.

The model shows very little recession south of Mundesley. This is due to a large accumulation of sand in this area which ultimately results in wide berms of around 30 – 40 metres. This apparently excessive beach volume may be a result of the unrefined representation of the effects of groynes, and/or boundary conditions.

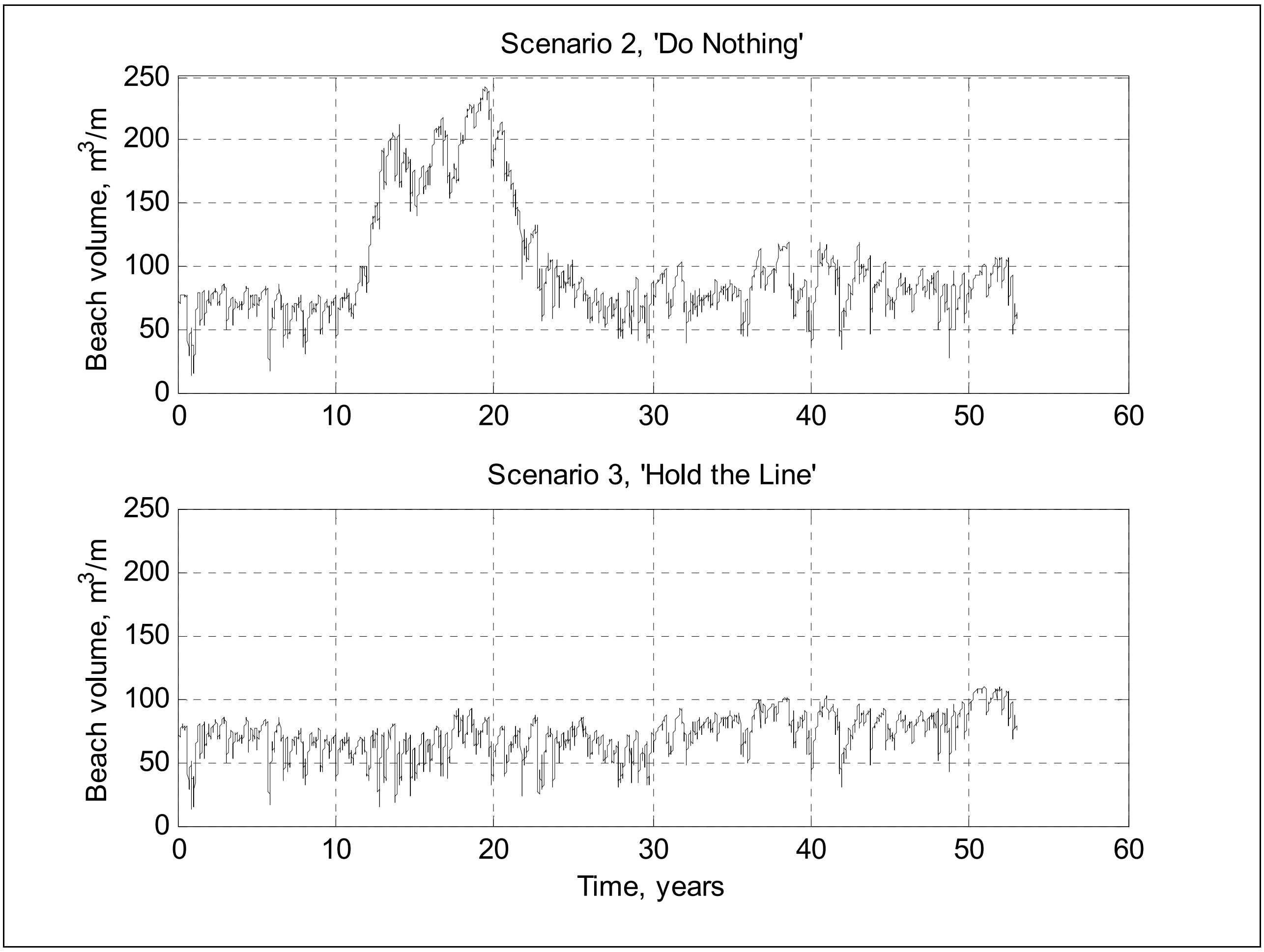

Figure 8 Beach volume at section 58 under scenarios 2 and 3

Figure 8 shows the difference in beach volume at model section 58, which is north of the centre of Mundesley, under scenarios 2 and 3. A large transient increase in beach volume can be seen under the 'Do Nothing' management option between years 12 and 25, resulting from the collapse of updrift structures.

4.2.4 Scenario 4, 'Revised SMP policy options'

Figure 9 shows the results of scenario 4, 'Revised SMP policy options', which was identical to scenario 3 except that the structures at Trimingham were not maintained. For comparative purposes the 50 year average recession rate for scenario 3 is also shown in a dotted line.
Allowing Trimingham to retreat in this scenario benefits the coast north of Mundesley as the beach volumes there are larger.

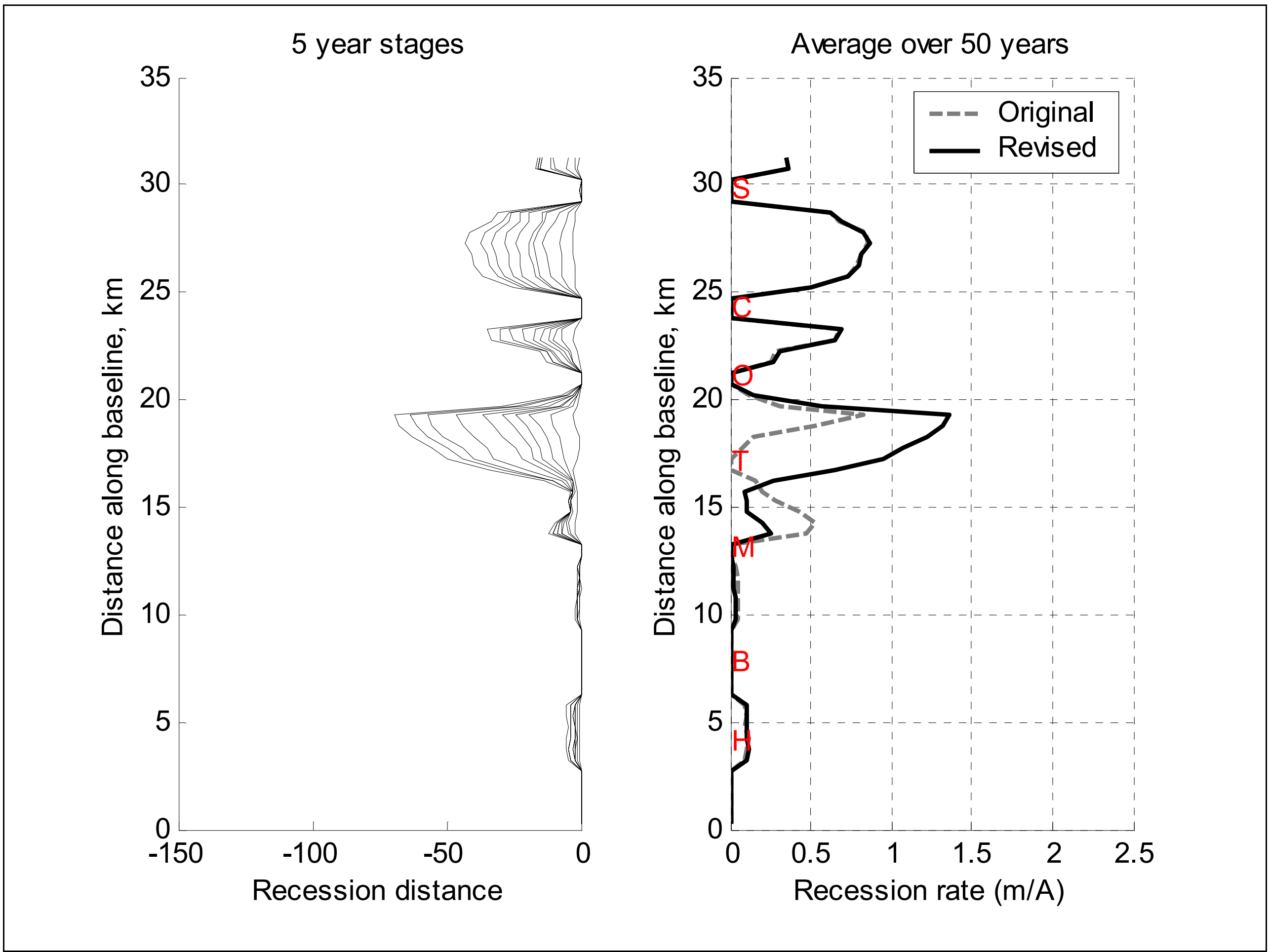

Figure 9 Recession resulting from a revised 'SMP policy options' management policy (scenario 4)

4.2.5 Scenarios 5a – 5e, 'SMP policy options with Groyne Modification'

In scenarios 5a to 5e the effect of improving groyne performance was explored. Improved groynes might be expected to increase the level of protection of the local cliffs but promote recession of downdrift areas. This behaviour was observed in the model results, as shown in Figure 10.

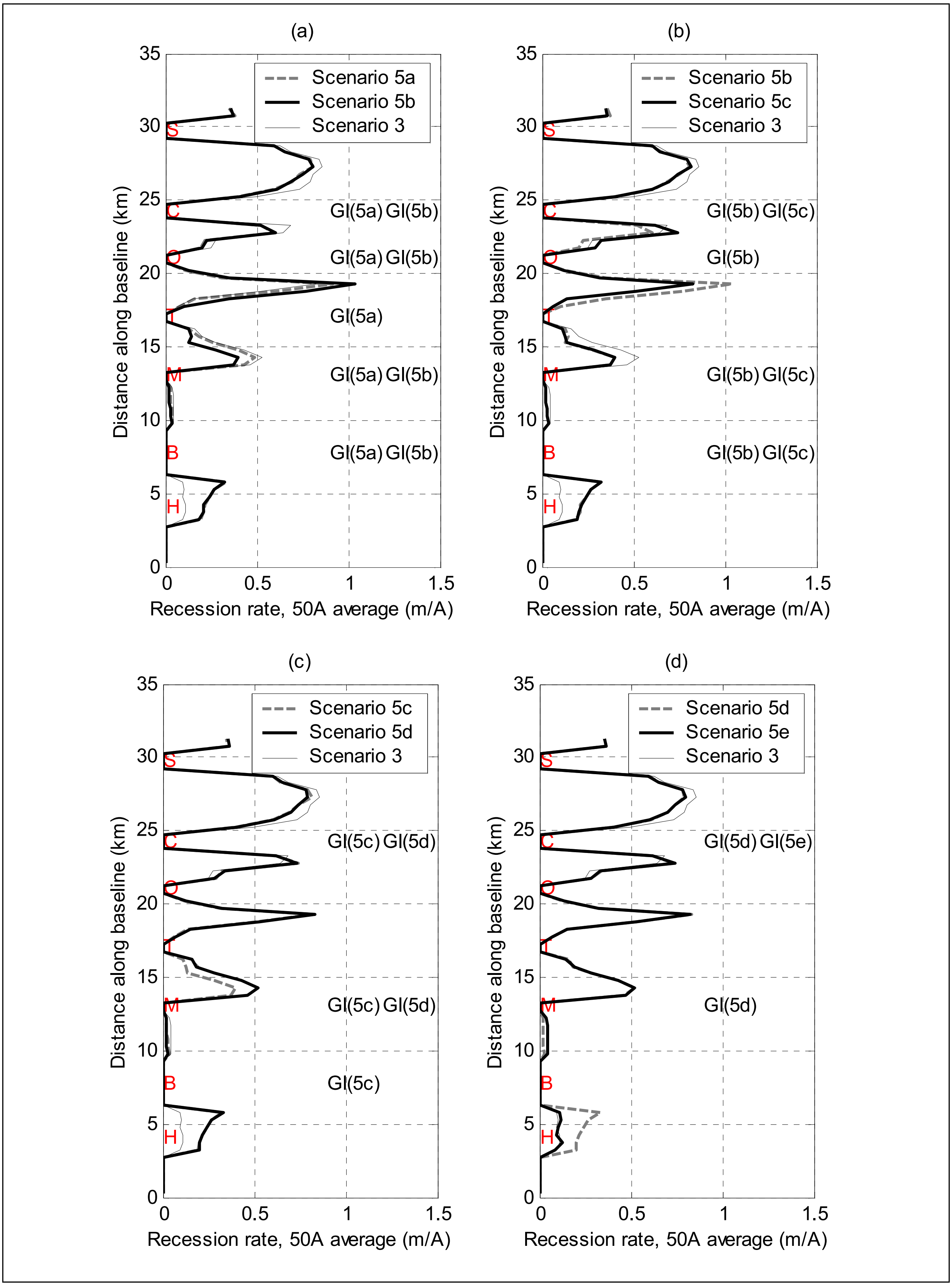

Figure 10 Results of scenarios 3 and 5a to 5d, 'SMP policy options with groyne modifications', 'GI' indicates a location of groyne improvement.

In Figure 10 (a) to (d) the effects of different options of groyne improvement can be seen. In each case there is a beneficial and detrimental effect of land lost to recession. For example in Figure 10 (a) the difference in average recession rate between scenario 5a and scenario 5b is shown. These indicate groyne improvement at Trimingham reducing updrift recession, but promoting it on the downdrift side.
The impact of sediment restriction seems to be limited to a relatively short downdrift area. This seems unrealistic, and may be indicative of the simplistic means of groyne representation.

4.3 6Sensitivity tests

Eight scenarios were used to explore model sensitivity to rate of sea-level rise and structure residual life. These are summarised in Table 3.

Table 3 Summary of sensitivity tests

No.	Testing sensitivity to…	Management option	Assumptions
6d	Rate of sea-level rise	SMP policy options	2 mm/A Sea-level rise
6b	Rate of sea-level rise	SMP policy options	4 mm/A Sea-level rise
3	Rate of sea-level rise	SMP policy options	6 mm/A Sea-level rise
6c	Rate of sea-level rise	Do nothing	2 mm/A Sea-level rise
6a	Rate of sea-level rise	Do nothing	4 mm/A Sea-level rise
2	Rate of sea-level rise & Residual life	Do Nothing	6 mm/A Sea-level rise & mean residual life estimate
7a	Residual life	Do nothing	Minimum residual life estimate
7c	Residual life	Do nothing	Maximum residual life estimate

4.3.1 Sensitivity to rate of sea-level rise

Six scenarios were run to study the implications of accelerated sea-level rise, which was expected to cause a significant increase on recession rates. The average recession rates predicted under these scenarios are shown in Figure 11. Two management policies were assumed, ‘SMP policy options’ and ‘Do Nothing’. Although a retreat rate was found to increase with accelerated sea-level rise the effect was small.

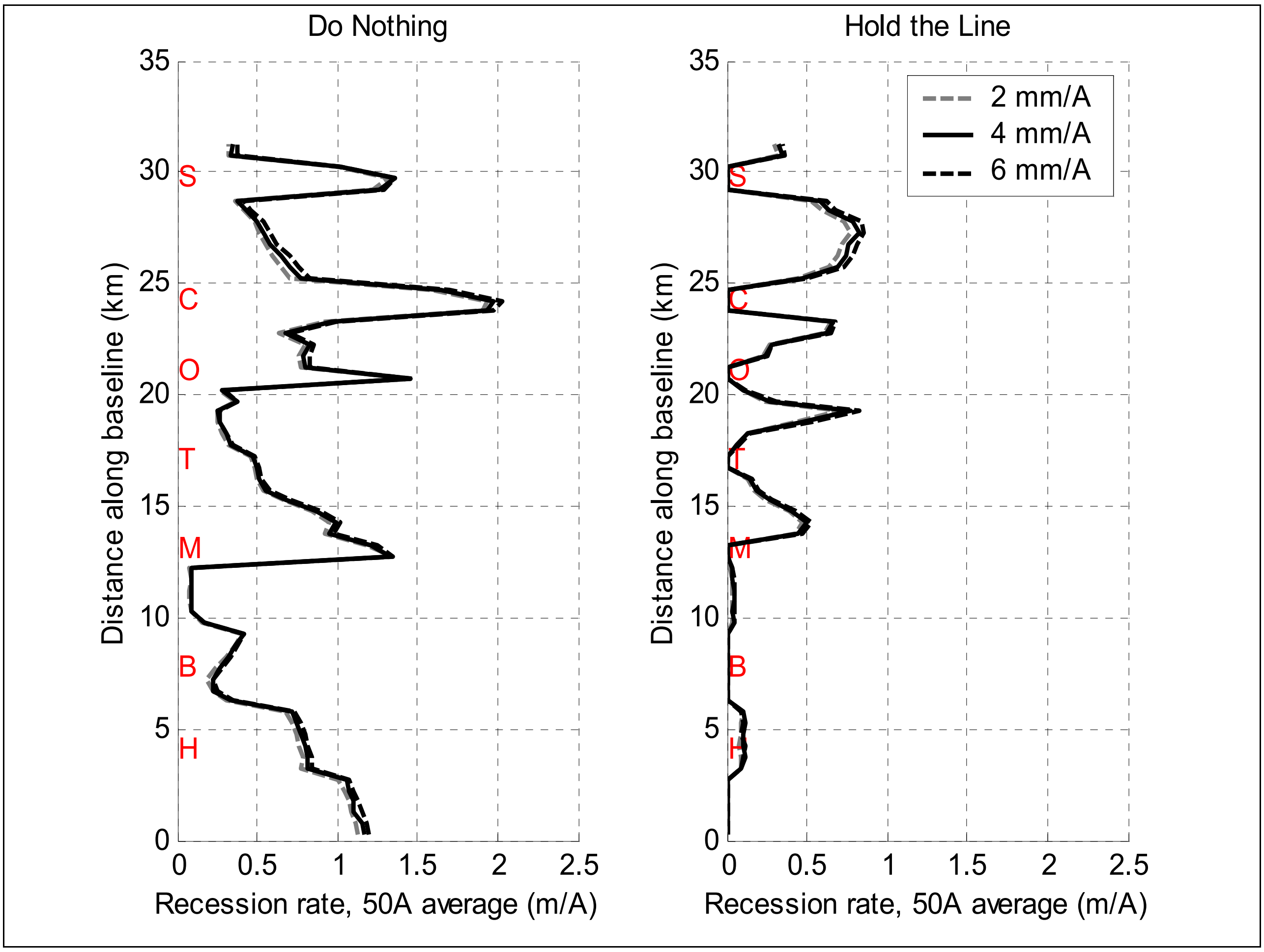

Figure 11 Average recession rates resulting from different rates of sea-level rise (SLR), (scenarios 2, 3, 6a, 6b, 6c, & 6c).

Although this insensitivity is, at first, counterintuitive, it is reasonable. This region of coast is curved, which results in a changing angle of wave attack along the shore. The longshore sediment transport rate depends on this angle so it also changes, becoming gradually larger with distance from Sheringham. This positive gradient in sediment transport rate tends to reduce the beach volume, i.e. at any section of this coast more sand tends to move out towards the south than in from the north. This would result in the beaches being totally removed, leaving behind the underlying platform, if it were not for the supply of sand from retreating cliffs. If left to evolve naturally the rate of sand supplied from a section of cliff would tend to be equal to the difference in net beach sediment transport rate across that section. The process by which this balance is maintained is simple; if the difference in sediment transport rate increases, the beach volume drops and larger waves attack the cliff causing increased recession resulting in the release of more cliff sediments. Conversely, if the differential in sediment transport rate drops then the beach lowers more slowly, and is able to provide more protection than it would otherwise. Consequently cliff erosion and retreat reduces and the rate of sand supply from the cliff falls.

In this description it can be seen that the retreat rate is simply an aspect of a larger system of sediment balancing, which is dominated by the differential sediment transport rate.

Accelerated sea-level rise can not cause a significant increase in retreat rate in such a system. If it did then the beaches would grow continuously from the increased cliff sediment supply since the unchanged longshore sediment transport rates would not be washing away all the material being supplied.

4.3.2 Sensitivity to residual life

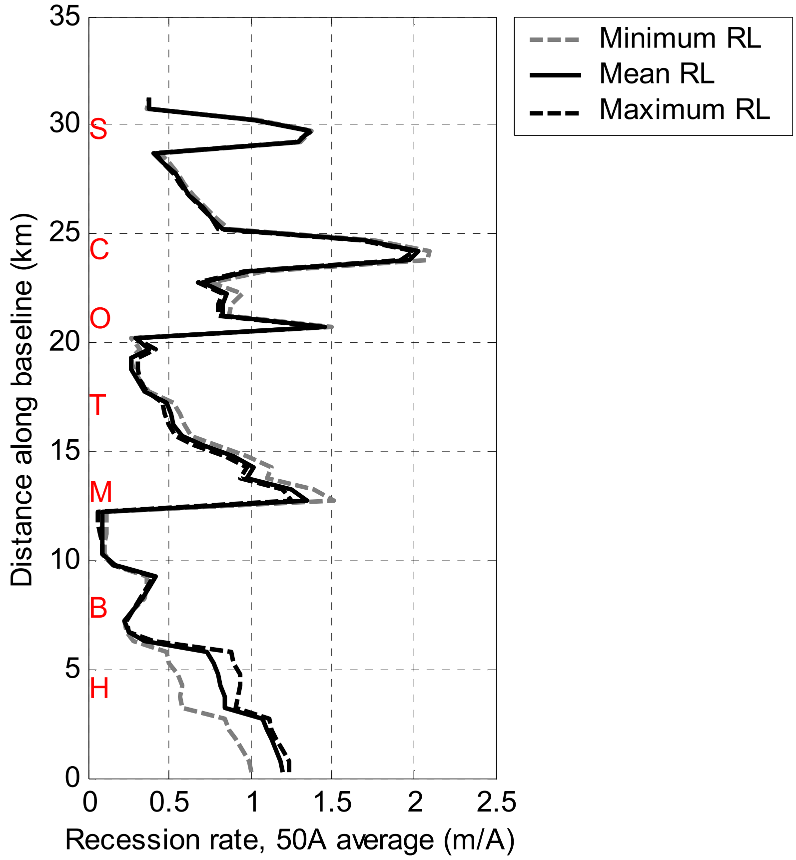

Figure 12 Average recession rates resulting from three 'Do nothing' management options, with different estimates of residual life (RL) (scenarios 2, 7a & 7c).

Figure 12 shows results from three 'Do nothing' scenarios, in which sensitivity to estimated residual life (*RL*) was explored. The 50 year average recession rate does vary with the different choices of residual life, though the relationship is not strong. This is, in part, due to the relatively small residual life of the structures (average of 6.7 years) and the smaller difference between the maxima and minima (average of 2.3 years). Despite this it can be seen that, as expected, the lower estimate of residual life results in more erosion of the anthropogenic headlands than the higher estimate. However, towards the southern boundary of the model, in the Happisburgh area, the trend is reversed. This is probably due to differences in the beach volumes at Happisburgh under the different scenarios, i.e. less residual life leads to more recession and greater quantities of sand released into the system. However, as was discussed in section 4, confidence is model behaviour south of Mundesley is reduced.

5. A STOCHASTIC MODEL OF COASTAL CLIFF LANDSLIDING

For economic appraisal of the impacts of coastal cliff recession, predictions are required of when individual cliff-top assets will be lost due to coastal landsliding. Coastal landsliding is a consequence of a combination of cliff toe recession and geotechnical processes within the cliff slope. On the north Norfolk coast landsliding on unprotected coasts proceeds by a process of marine removal of material from the cliff toe, resulting in steepening the coastal slope. Eventually the slope becomes geotechnically unstable and a landslide occurs, which reduced the coastal slope and delivers debris to the beach. The timing of the landslide is a function of the rate of removal of material from the cliff toe and other processes, primarily connected with pore pressure distributions within the cliff, that influence cliff stability. The timing of a landslide cannot be predicted precisely. However, knowledge of the rate of shoreline retreat (from cliffSCAPE) can be combined with an assessment of the geotechnical characteristics of the slope to generate an approximate prediction of cliff top location (Walkden *et al*. 2002).

The approach adopted here is based on the notion of a Cliff Behavioural Unit (CBU) as being a stretch of cliff-line which behaves in broadly the same way. Within a CBU, the cliff can be expected to fail when it reaches a average angle α_f and will, after failure, adopt an angle α_s. Of course neither α_f nor α_s can be predicted precisely. They will vary because of temporal variations in pore pressure and local variations in cliff strength and composition. Even if all the required information were available, they could still not be predicted precisely because of uncertainties in our understanding of the processes of coastal landsliding. This uncertainty in α_f and α_s has been included in the analysis by representing both values as Normally distributed random variables, with means and variances obtained from geomorphological assessment of the CBU. The situation is illustrated diagrammatically in Figure 13.

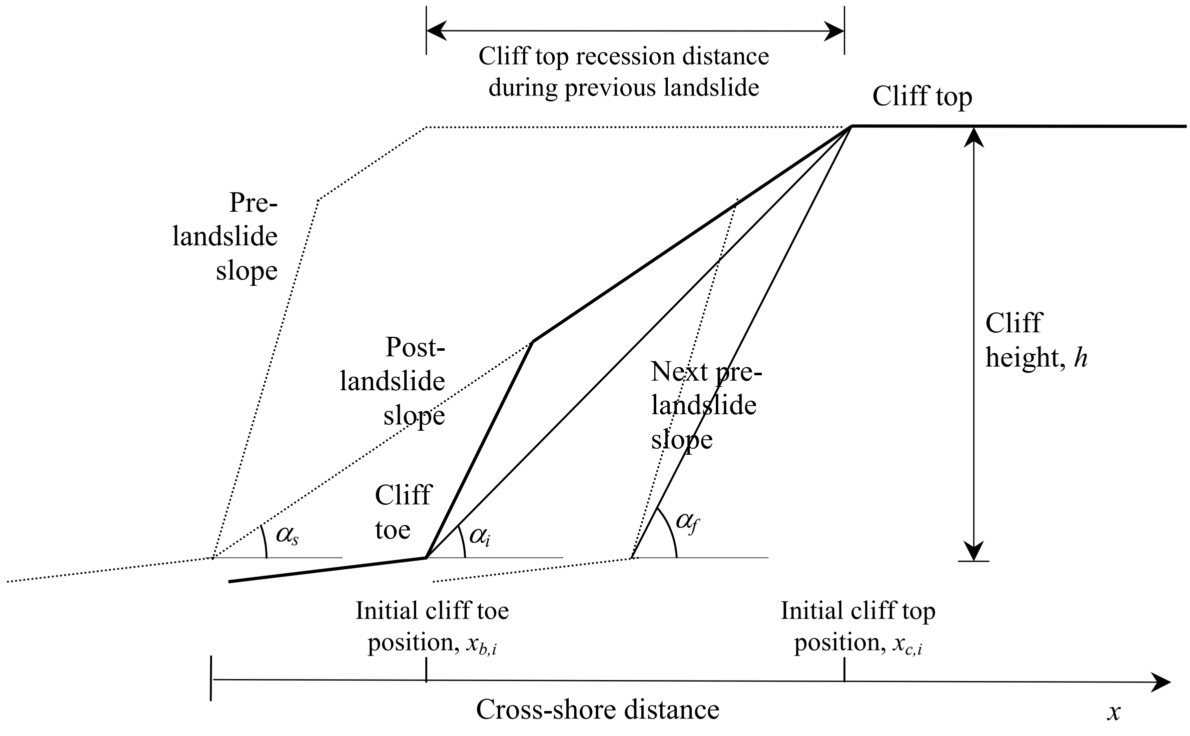

Figure 13 Diagrammatic representation of the coastal landsliding model

Further uncertainty is apparent in the initial cliff angle at the site. Within a CBU there will be a range of initial angles, whilst in this analysis (other than for very long CBUs) a prediction of cliff top recession has been generated for entire CBUs or, where appropriate, sub-sections thereof. The initial cliff angle has therefore also been represented as a Normally distributed random variable, with mean and variance based on measurements of cliff angle within the CBU.

From Figure 13 we see that the distance the cliff toe has to retreat until the first landslide is $h(\cot\alpha_i - \cot\alpha_f)$ and the distance lost between each subsequent landslide to the next is $h(\cot\alpha_s - \cot\alpha_f)$. It is therefore straightforward to simulate the cliff top recession process, given

- cliffSCAPE predictions of cliff toe recession,
- the cliff height,
- the initial cliff angle $\alpha_i \sim N(\mu_i, \sigma_i)$, *i.e.* is a Normally distributed random variable with mean μ_i and standard deviation σ_i, and
- geomorphological assessments of the pre and post landslide angles $\alpha_f \sim N(\mu_f, \sigma_f)$, $\alpha_s \sim N(\mu_s, \sigma_s)$.

Predictions of cliff top recession are generated by taking the cliffSCAPE predictions of cliff toe recession and then sampling, from the relevant distributions, first an initial cliff angle and then a sufficiently long sequence of angles α_f and α_s. Large numbers of samples of these sequences of angles are used to generate a histogram of predicted cliff top locations at given numbers of years in the future. A smooth probability density function is generated from the histogram of simulation results using a kernel density estimator (Silverman, 1986). Typical predictions are plotted in Figure 15. Note how the distribution reflects the the number of landslides that may have taken place up to a certain time in the future. The analysis was repeated for a total of 57 prediction sections, corresponding to 35 cliffSCAPE model sections. In some cases a cliffSCAPE model section lay near the boarder of two CBUs in which case the analysis was repeated with the slope parameters from both CBUs. A total of 26 CBUs were therefore assessed (see Figure 14).

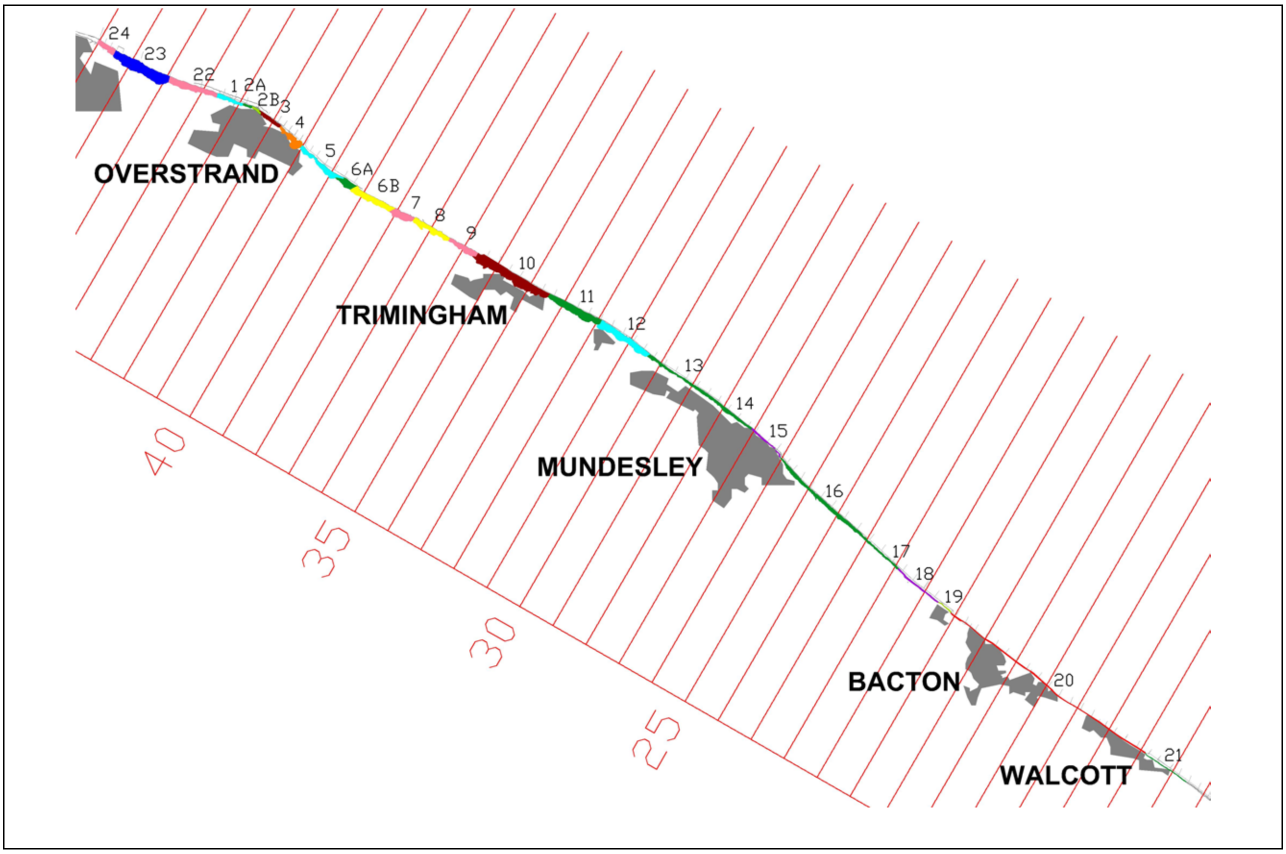

Figure 14 Layout of CBUs (coloured sections of coastline and small black numbers) with cliffSCAPE sections overlaid (red lines and large numbers)

Table 4 Cliff top recession prediction input data

Height,	$E(\alpha_i)$	$Var(\alpha_i)$	$E(\alpha_s)$	$Var(\alpha_s)$	$E(\alpha_f)$	$Var(\alpha_f)$	cliffSCAPE
8	40	51	48	7	32	3	13
6	42	25	48	7	32	3	14
6	60	0.1	41	4	31	2	14
5	60	0.1	41	4	31	2	15
5	60	0.1	41	4	31	2	16
5	60	0.1	41	4	31	2	17
4	60	0.1	41	4	31	2	18
4	60	0.1	41	4	31	2	19
6	60	0.1	41	4	31	2	20
6	32	2	34	1	30	1	20
8	32	2	34	1	30	1	21
8	29	1	29	1	38	1	21
12	30	1	29	1	38	1	22
17	48	6	50	5	45	1	22
17	40	20	39	4	31	3	22
25	37	20	39	4	31	3	23
25	39	1	39	4	31	3	24
25	41	1	39	4	31	3	25
19	36	16	39	4	31	3	26
13	37	0.1	37	1	33	1	26
13	37	0.1	37	1	33	1	27
13	35	11	40	1	35	1	27
23	37	11	40	1	35	1	28
33	41	1	43	3	36	2	29
36	37	12	43	3	36	2	30
36	28	4	30	1	25	1	30
40	28	4	30	1	25	1	31
50	30	4	30	1	25	1	32
50	33	6	33	3	30	1	32
60	38	22	33	3	30	1	33
60	22	6	25	1	20	1	33
55	22	6	25	1	20	1	34
50	23	6	25	1	20	1	35
50	23	6	25	1	20	1	36
44	28	31	35	2	20	1	36
37	38	6	40	3	35	2	36
37	38	6	40	3	35	2	37
45	27	64	38	4	20	1	38
45	35	0.1	40	3	34	2	38
53	35	0.1	40	3	34	2	39
53	40	12	40	3	34	2	39
42	37	12	40	3	34	2	40
42	32	39	43	4	25	1	40
30	30	17	43	4	25	1	41
30	19	24	30	2	18	4	41
25	20	24	30	2	18	4	42
25	29	4	30	2	25	1	42
25	30	4	30	2	37	2	42
20	30	4	30	2	37	2	43
20	41	1	40	3	37	2	43
20	28	6	33	4	23	1	43
20	23	6	33	4	23	1	44
43	25	8	29	1	24	1	44
65	30	8	29	1	24	1	45
65	22	4	28	2	21	1	45
47	31	28	28	2	21	1	46
29	33	5	33	1	30	1	47

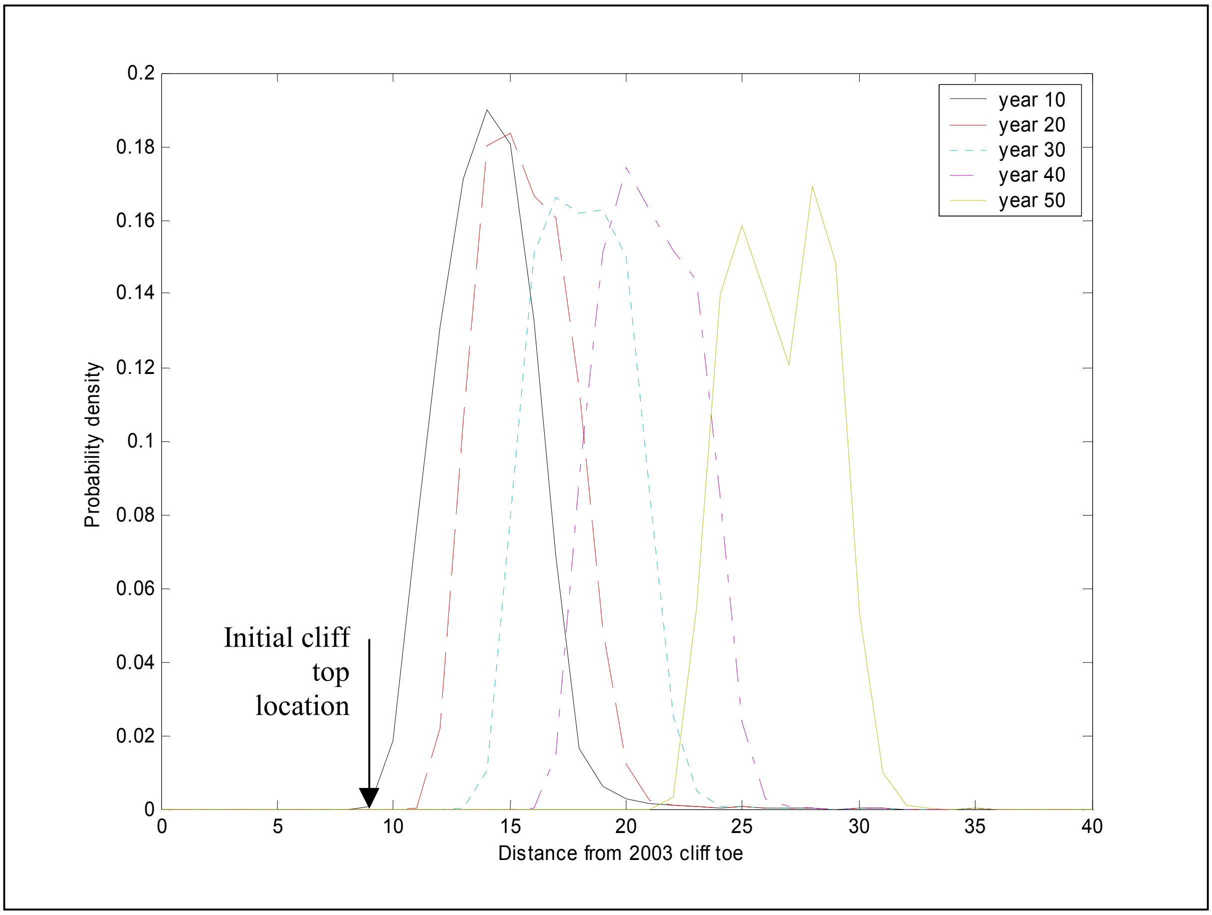

Figure 15 Typical cliff top recession predictions (cliffSCAPE section 13 in Scenario 1)

6. CONCLUSIONS

This report represents the output from the first application of cliffSCAPE-RS, a regional modelling tool for soft cliff shorelines. The results of the validation process are very positive. A good match was found between model output and historic records of shore recession over three eras spanning a total of 87 years. This comparison is particularly encouraging because the measured recession rates are highly variable in both space and time. The match was less good towards the south of the model. It is surprising and informative that a good match was achieved with historic recession rates with minimal variation of the material strength parameter (R). Appropriate recession rates emerged by representing structure installation. This lends support to the manner in which there structures were represented and implies that the erosion of the North Norfolk cliffs is not dominated by material strength, but by management practice and it's effect on sediment transport rates. However the results of scenarios 5a to 5e indicate that the way in which the groynes were represented (as a reduction in the CERC coefficient of longshore transport) may have been too simplistic. Should another model of this coast be developed this aspect should be revisited. In particular it may be beneficial to represent sand bypassing when beaches become sufficiently full.

Despite the encouraging performance of the model, the reader should be aware that cliffSCAPE has only previously been applied at one other coastal site (the Naze on the Essex coast) and has never previously been applied to a length of coastline tested in this study. The results are therefore somewhat experimental. CliffSCAPE still requires testing and validation on a wider range of coastal sites. Because the technique used is novel the results should, as with any model predictions, be interpreted and utilised with some caution. It should also be noted that the future scenarios rely on conditions that have not appeared, at least explicitly, in the historic record; a change in the rate of sea-level rise and the removal of protective structures. This is a fundamental aspect of the problem of making predictions of the Norfolk coast which would promote uncertainty in results regardless of the technique employed to obtain them. However, cliffSCAPE is a process-based modelling tool, so is designed to deal with this type of situation.

The dependence of the recession on sediment transport explains the observation of the relative insensitivity of the system to changes in rate of sea-level rise. Rising sea-levels have little direct influence on rates of sediment transport.

CliffSCAPE-RS has been successfully used to model the historic development of the North Norfolk coast, and to predict future changes under a range of management scenarios. The models have developed understanding of the cliff system as one which is strongly influenced by sediment transport rate, with recession rates in particular areas strongly dependent on both current and historic management decisions both locally and up-drift.

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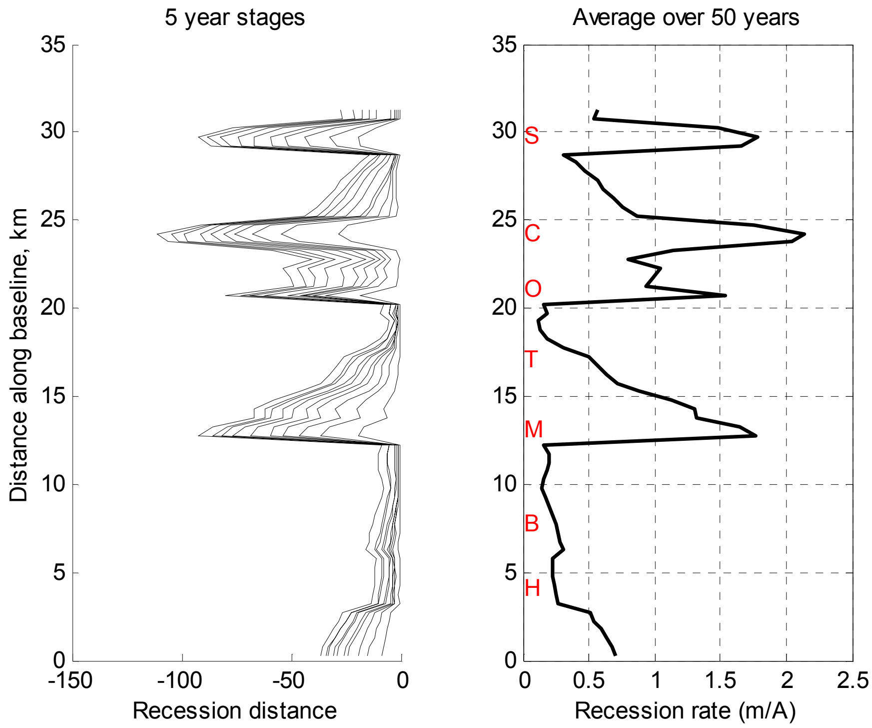
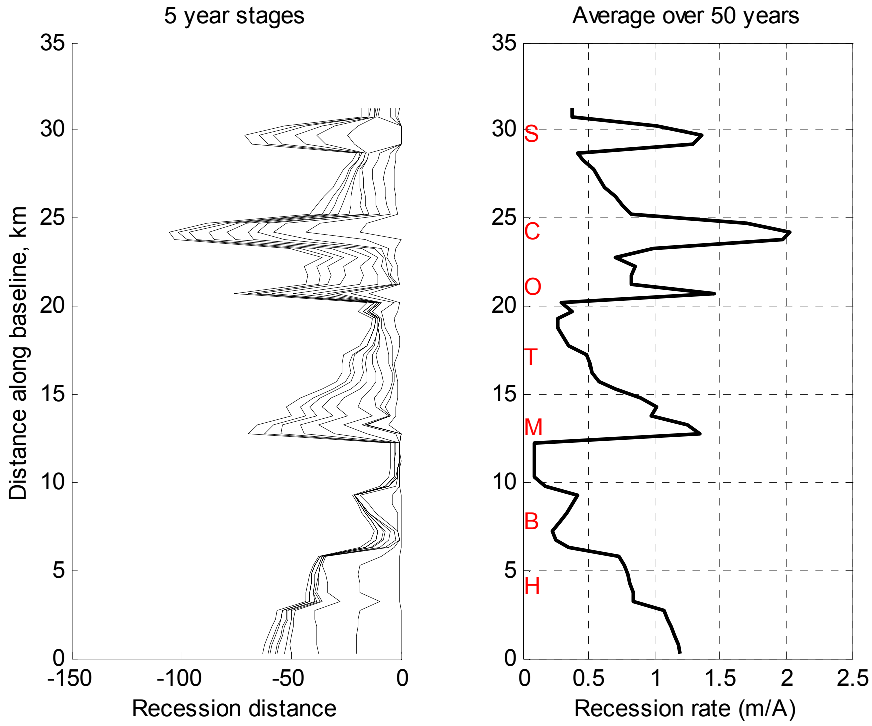
Appendix

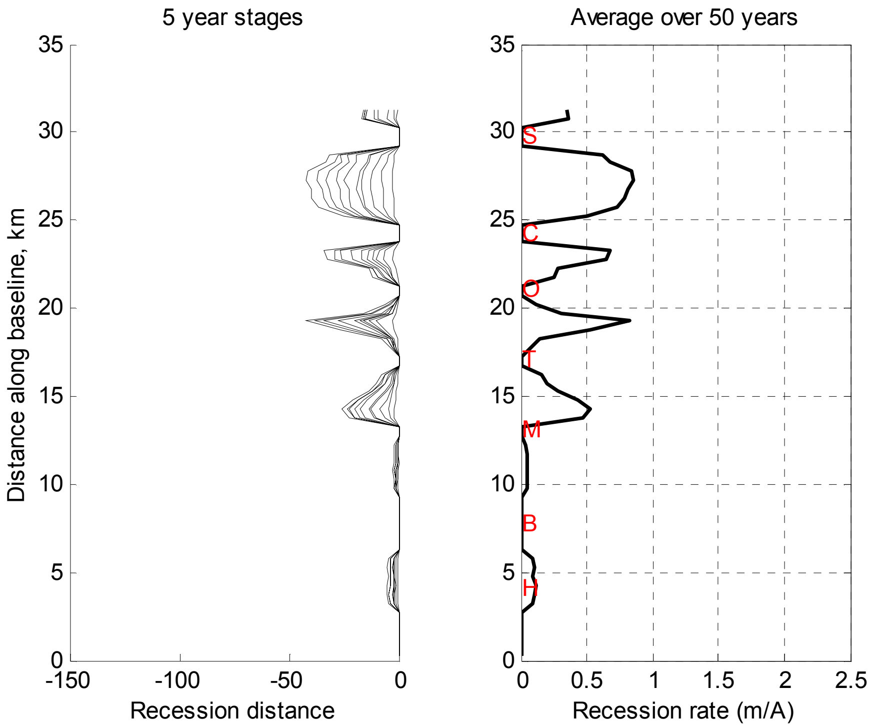
Overstrand to Mundesley Strategy Study:
cliff toe recession results



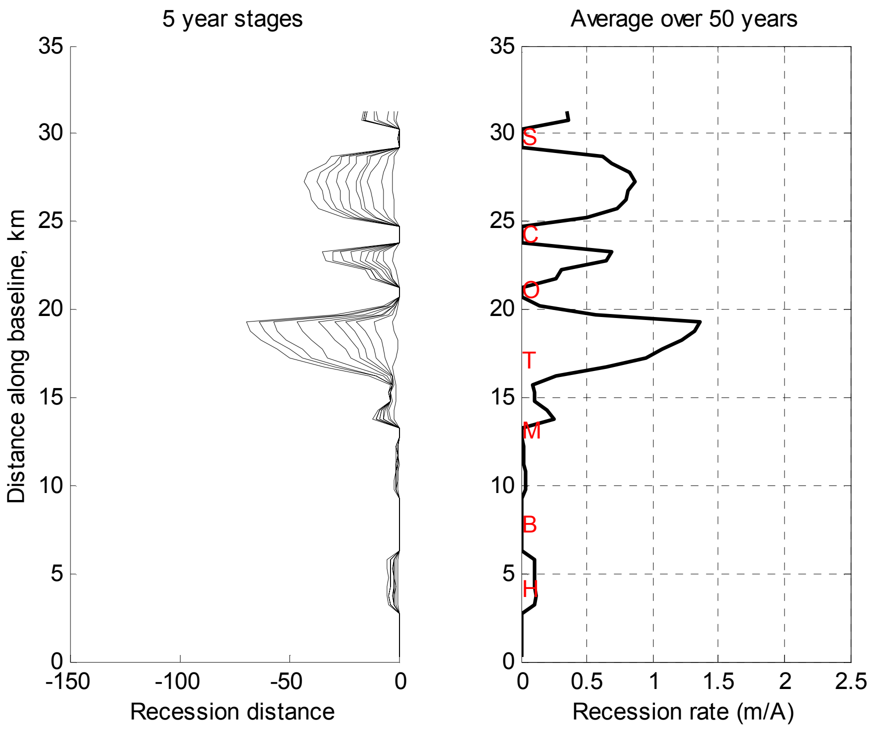
No.	Management scenario	Notes
1	Open Coast	Remove all seawalls and groynes in January 2003



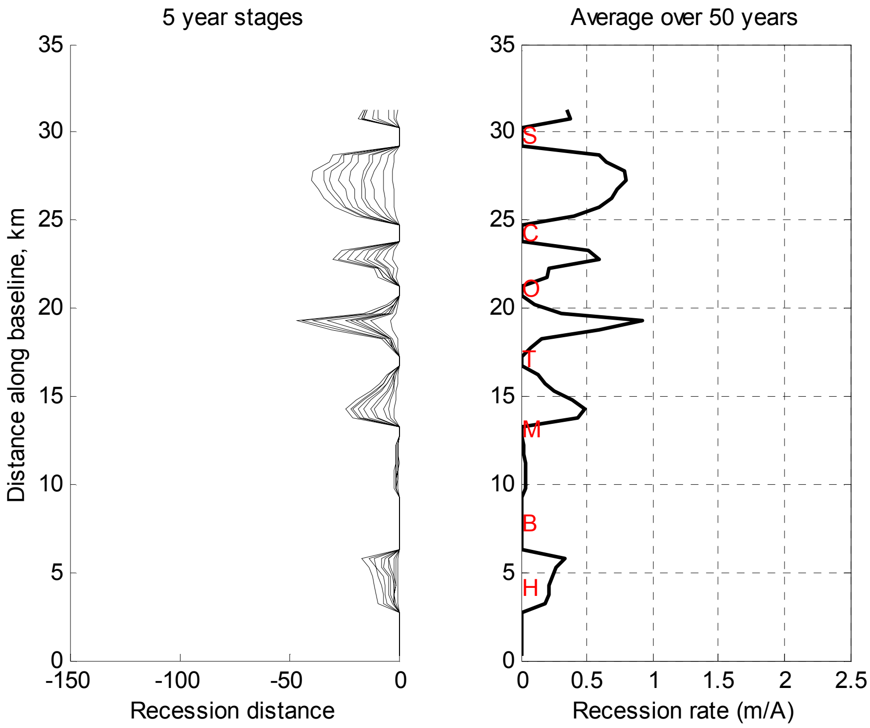
No.	Management scenario	Notes
2	Do Nothing	Structures removed at the mean estimate of residual life



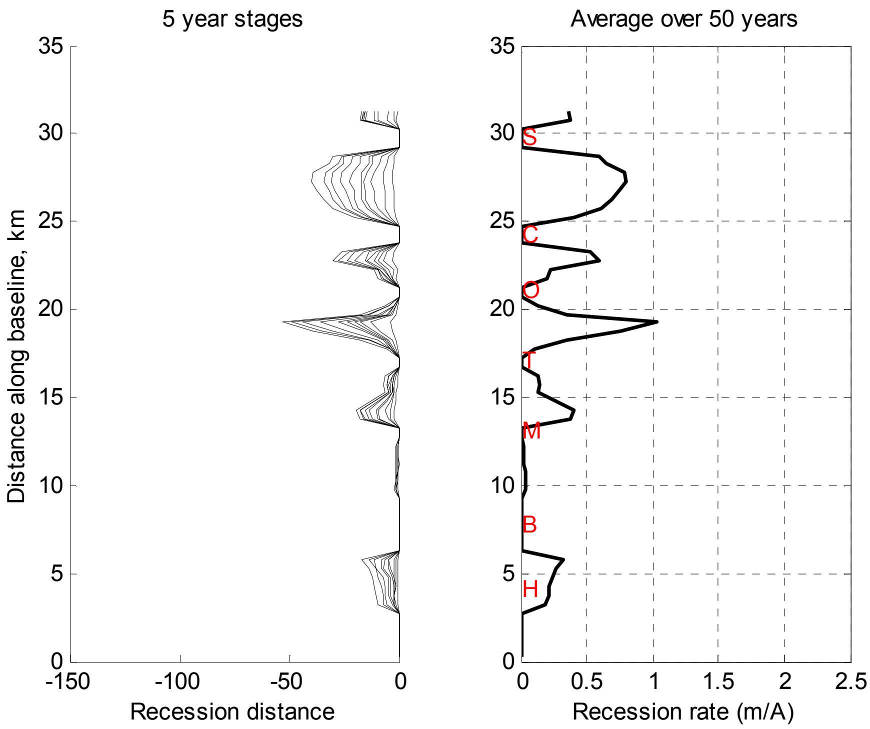
No.	Management scenario	Notes
3	SMP policy options	SMP policy option, groynes and seawalls held in present alignment & condition



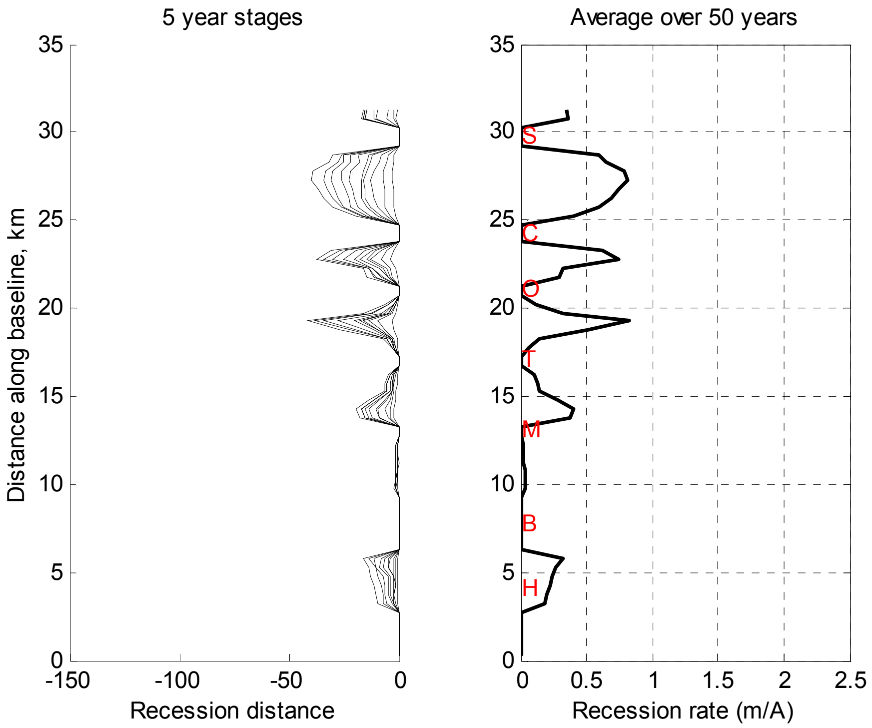
No.	Management scenario	Notes
4	Revised SMP policy options	As scenario 3 but Do Nothing at Trimingham



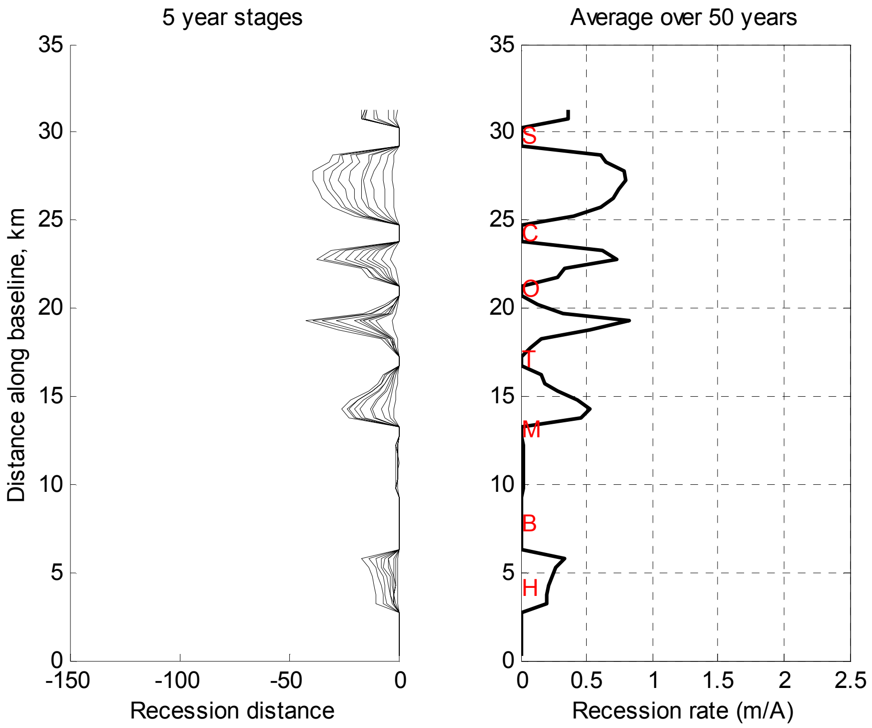
No.	Management scenario	Notes
5a	SMP policy options with groyne modification	20 % increase in groyne efficiency at C, O, T, M & B



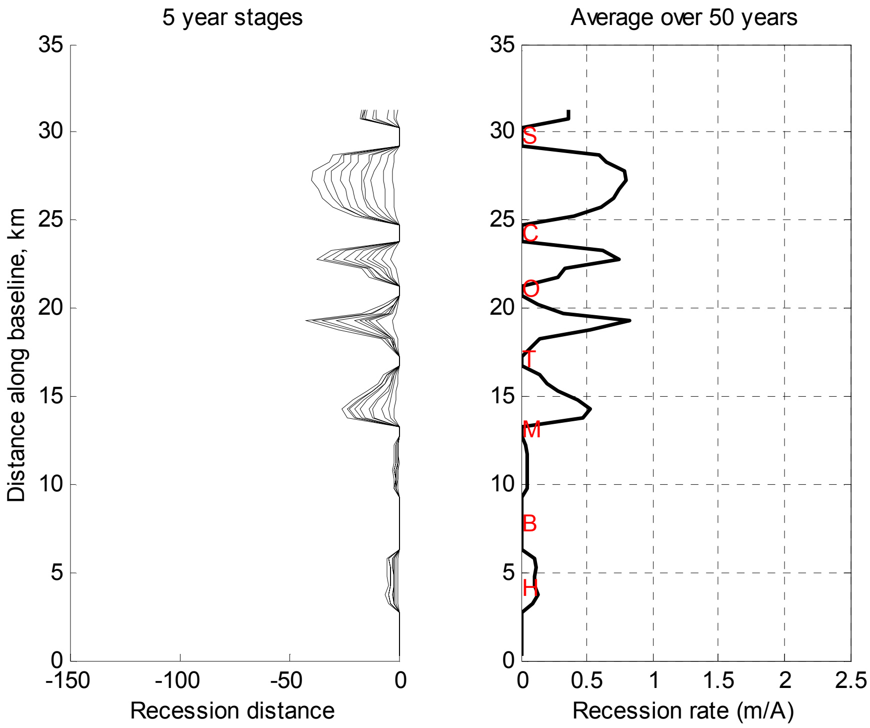
No.	Management scenario	Notes
5b	SMP policy options with groyne modification	20 % increase in groyne efficiency at C, O, M & B



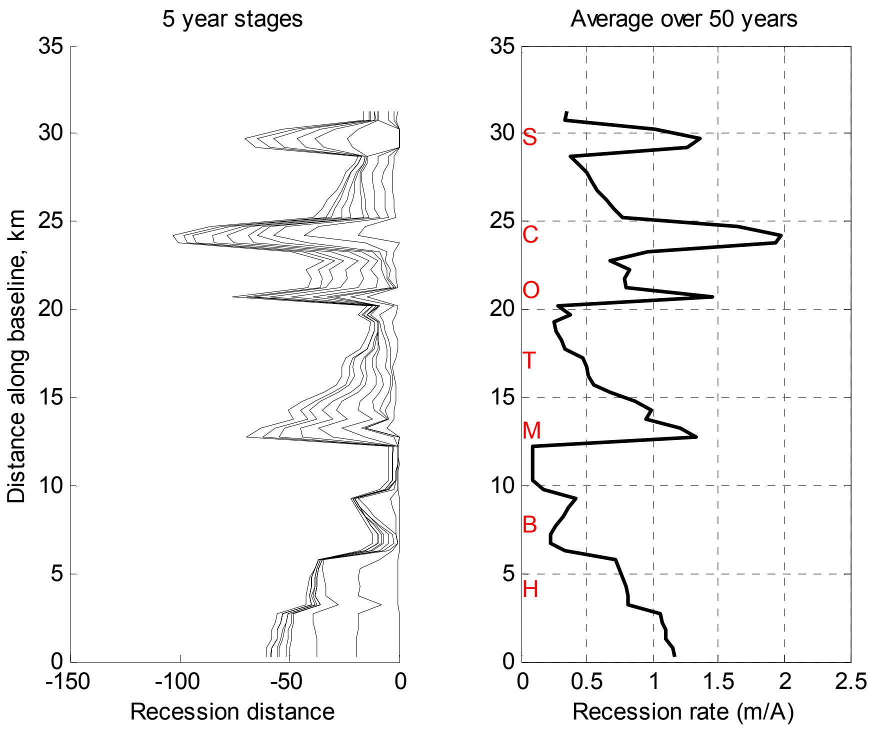
No.	Management scenario	Notes
5c	SMP policy options with groyne modification	20 % increase in groyne efficiency at C, M & B



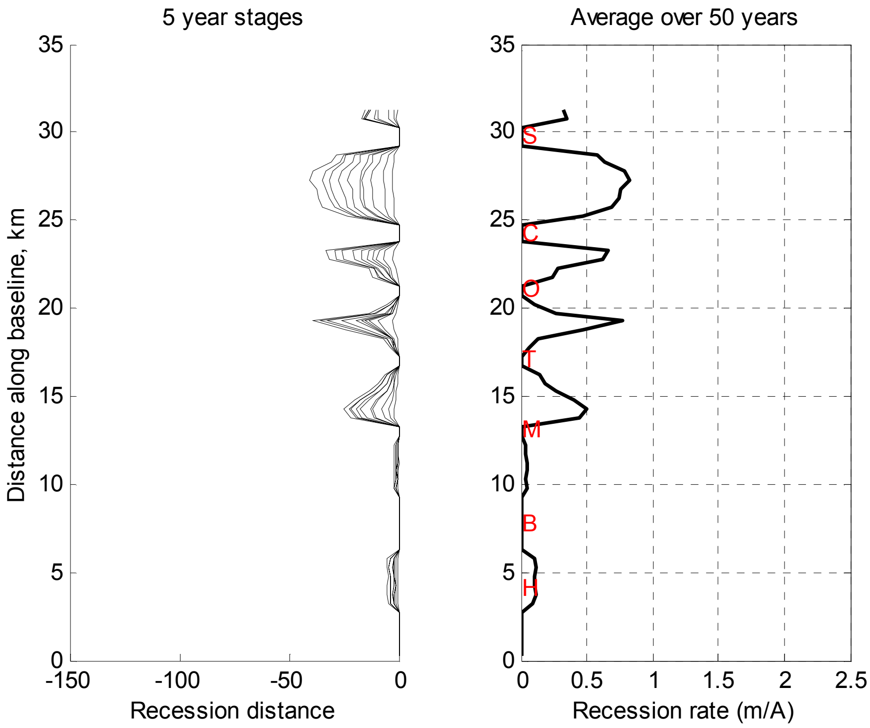
No.	Management scenario	Notes
5d	SMP policy options with groyne modification	20 % increase in groyne efficiency at C and B



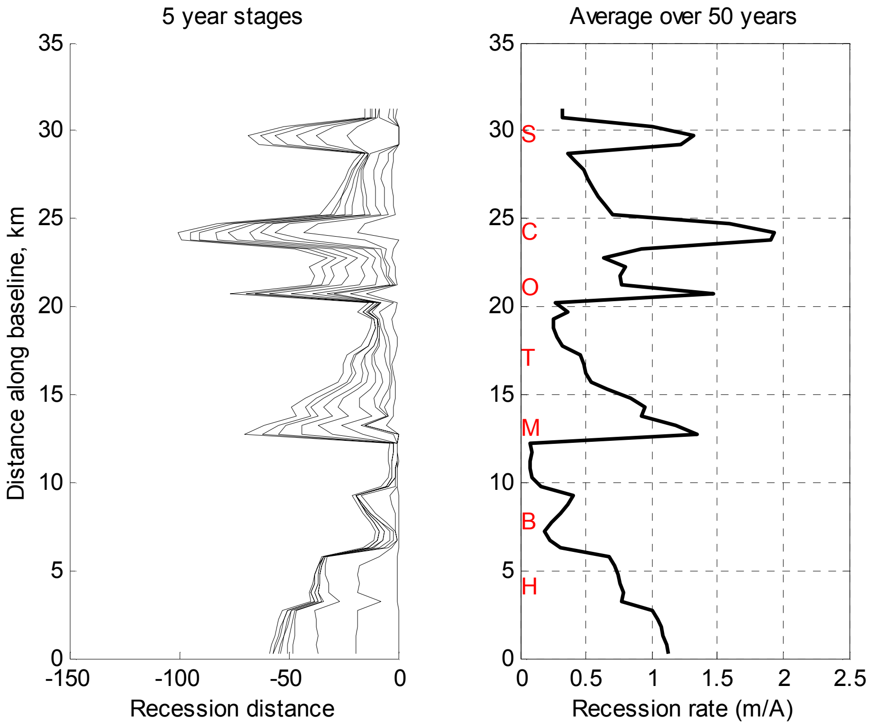
No.	Management scenario	Notes
5e	SMP policy options with groyne modification	20 % increase in groyne efficiency at C



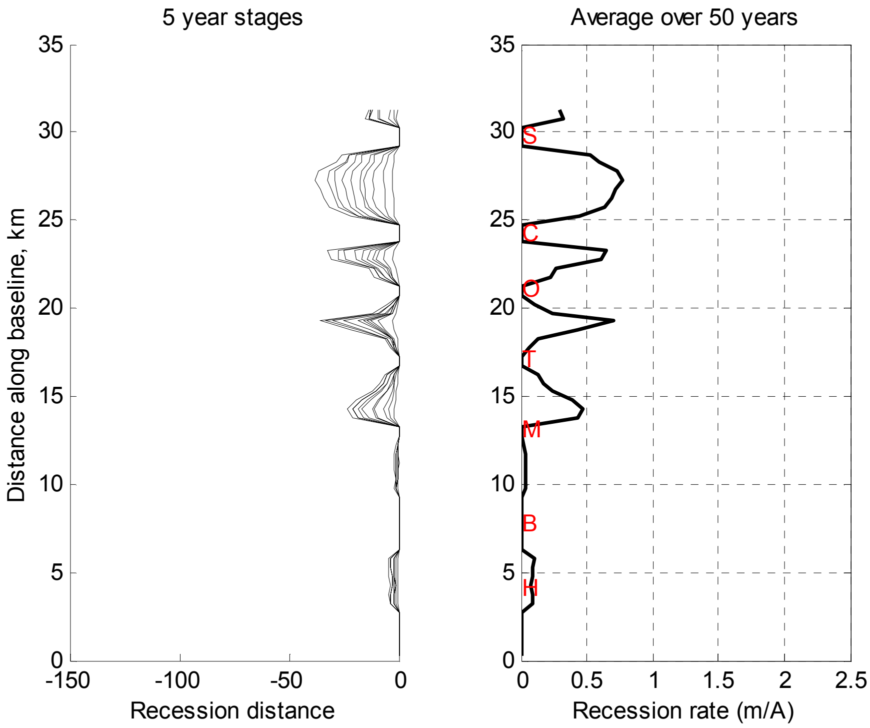
No.	Management scenario	Notes
6a	Do nothing	4 mm/A Sea-level rise



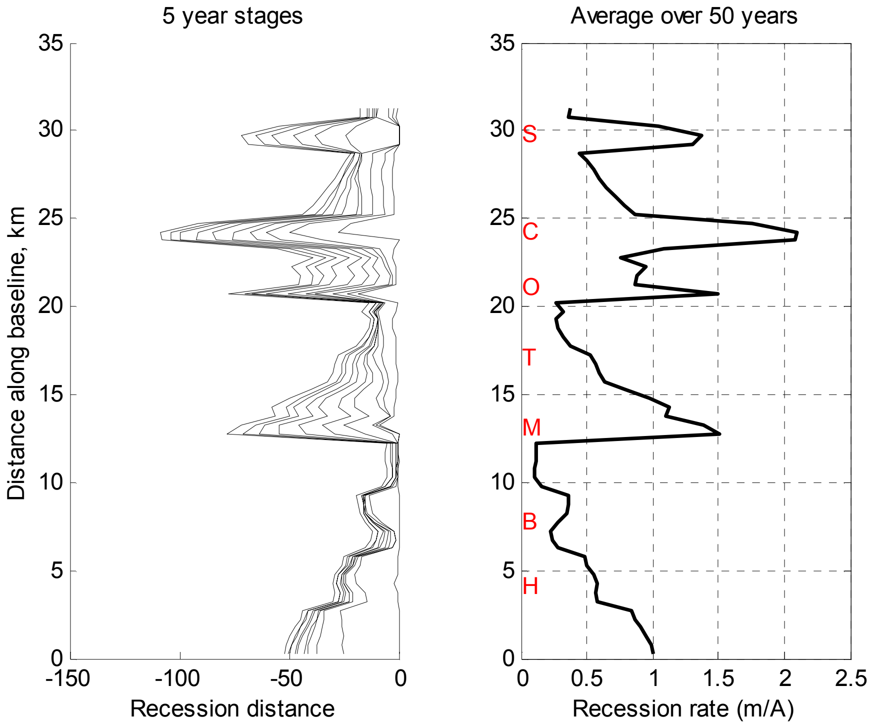
No.	Management scenario	Notes
6b	SMP policy options	4 mm/A Sea-level rise



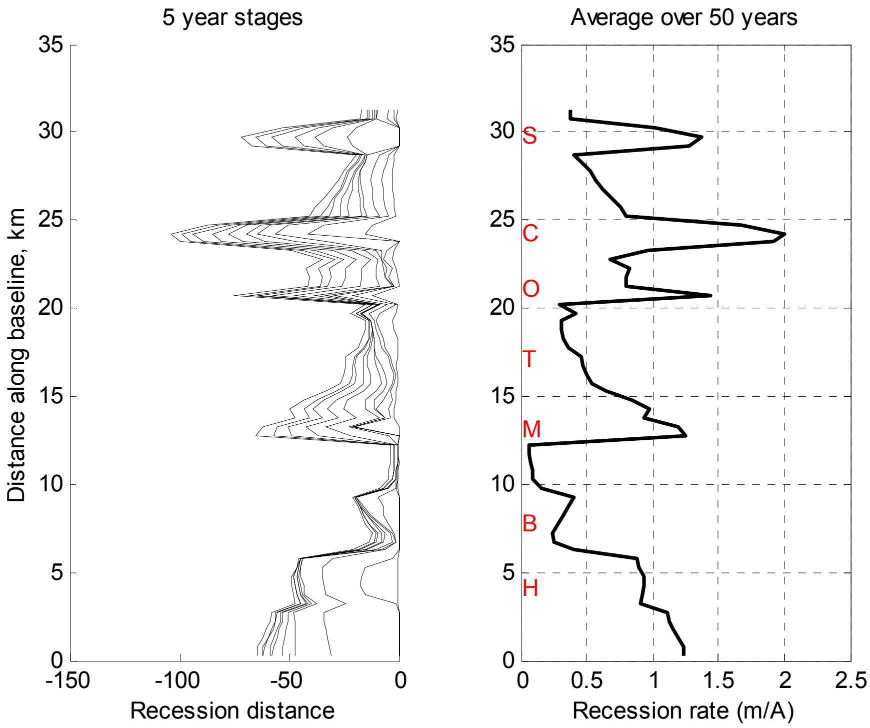
No.	Management scenario	Notes
6c	Do nothing	2 mm/A Sea-level rise



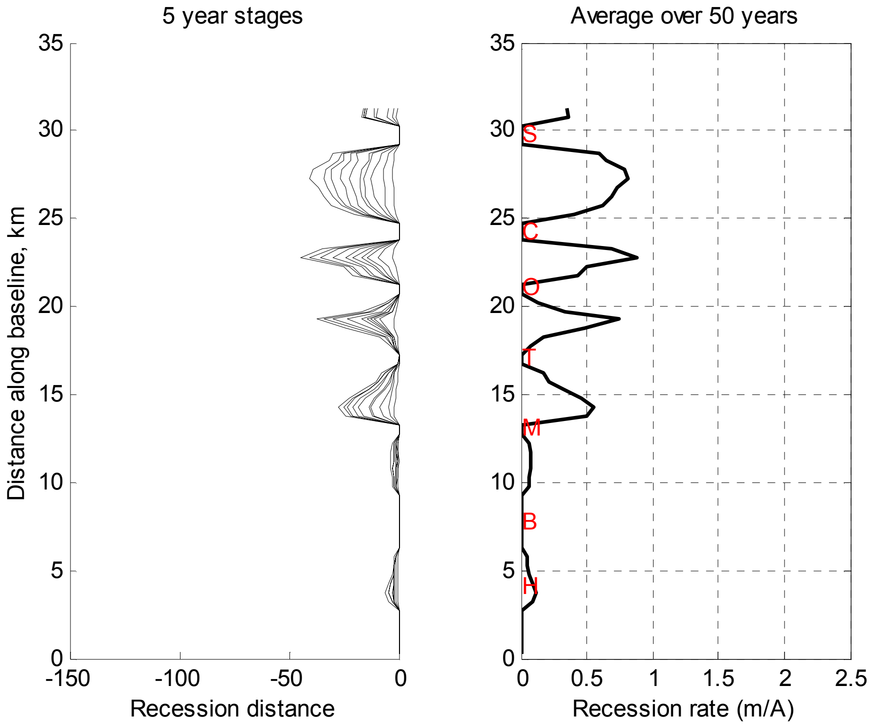
No.	Management scenario	Notes
6d	SMP policy options	2 mm/A Sea-level rise



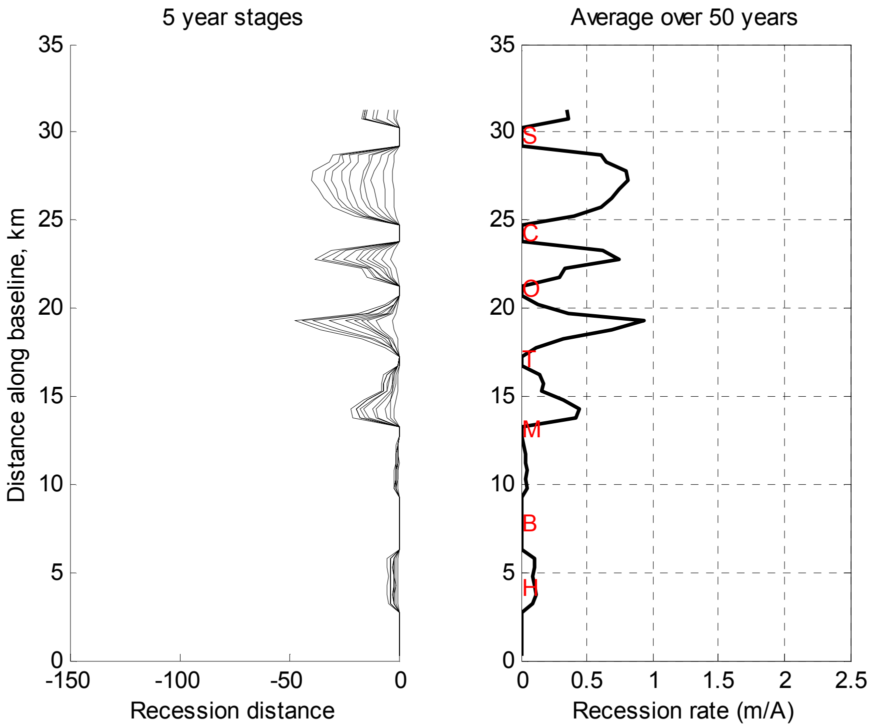
No.	Management scenario	Notes
7a	Do nothing	Minimum residual life estimate



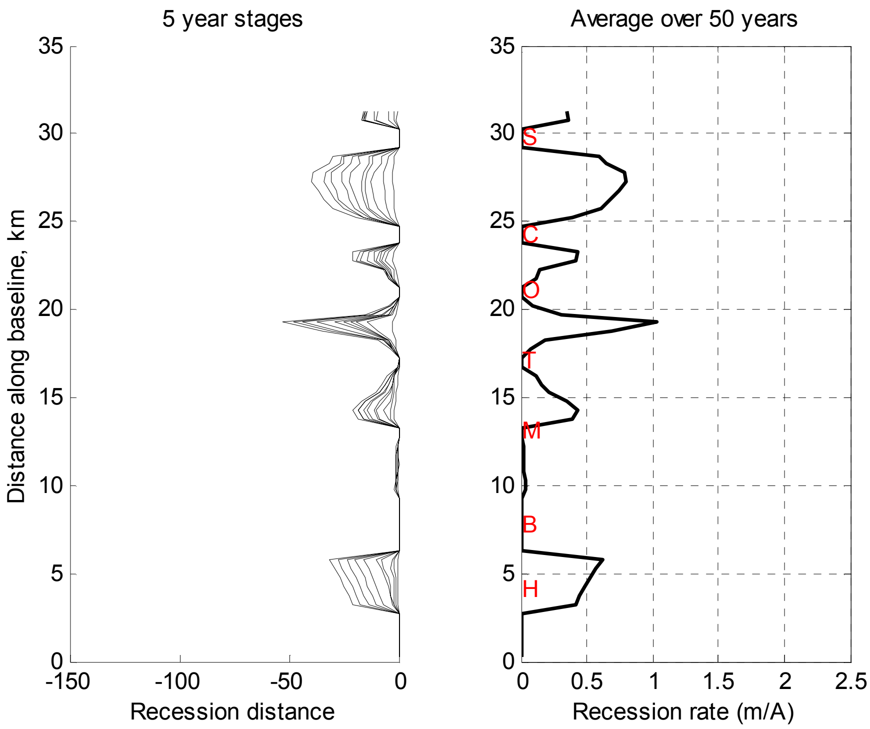
No.	Management scenario	Notes
7c	Do nothing	Maximum residual life estimate



No.	Management scenario	Notes
8a	SMP policy options with groyne modification	Groyne efficiency reduced by 20% at O, T, M & B, increased by 20% at C

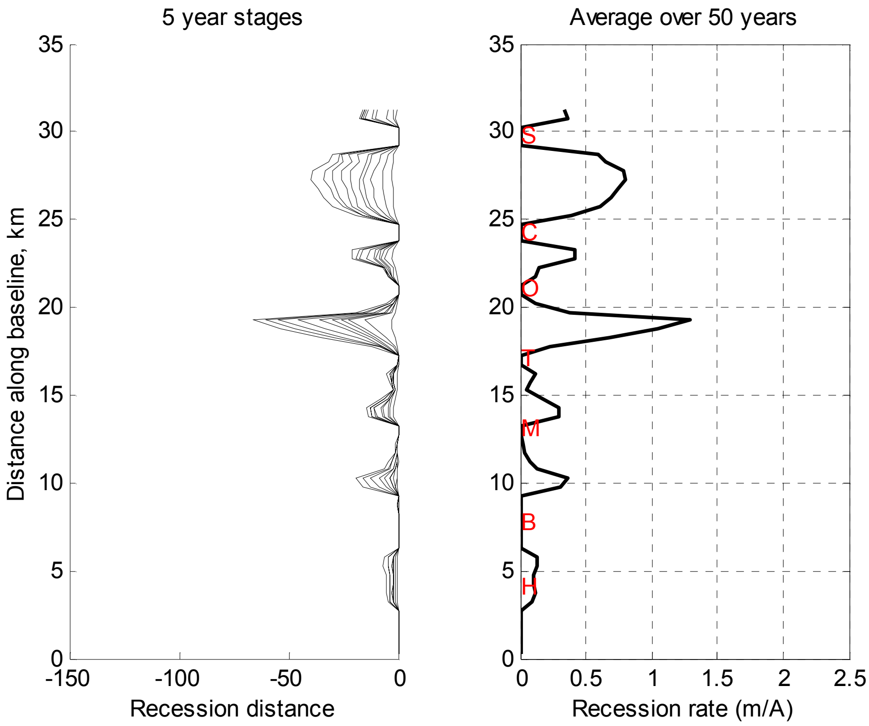


No.	Management scenario	Notes
8b	SMP policy options with groyne modification	Groyne efficiency reduced by 20% at T increased by 20% at C



No.	Management scenario	Notes
9a	SMP policy options with groyne modification	Groyne efficiency increased by 40% at O, T, M & B, increased by 20% at C

HR Wallingford



No.	Management scenario	Notes
9b	SMP policy options with groyne modification	Groyne efficiency increased by 40% at O & M, increased by 20% at C