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Shore and cliff sensitivity to accelerating sea level rise

Research report: Scoping stage technical report

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Contents

Executive summary

This project addresses the question of how future sea level rise will increase rates of coastal erosion around England and Wales. Rather than providing future rates of erosion, which may become outdated if sea level projections change, the project aims to help practitioners and coastal managers better account for the effect of sea level rise on erosion rates. It addresses how this effect should be expected to vary from place to place. The study is also exploring the process of ‘coastal catch-up’, whereby the loss of coastal protection structures results in a (perhaps temporary) period of increased recession.

The focus of the study is on the very common type of shore where morphology is strongly influenced by a shore platform. Such features are often covered by beaches and backed by cliffs. The study does not deal with shores composed of a deep beach as these have received much attention from other studies.

This scoping technical report describes how a new method was developed and tested. The approach was carried forward into the main project as explained in the main technical report (Environment Agency, 2025c).

Historic sea level rise and tidal range are highlighted as being particularly important in determining coastal sensitivity. The sensitivity of shores of this type (not subject to external changes such as a trend in beach volume or coastal protection works) is found to be lower than might be expected using older methods. Partly as a consequence, the expectations of the total range of sensitivity to accelerating sea level rise across England and Wales should also be reduced.

Catch-up processes were found to be very strong (at the studied site). This finding is attributed to reductions in local beach volume caused by local and larger scale coastal protection. This suggests that, although the site studied appears to be approaching an equilibrium condition, this may not, in fact, be the case. Future losses may be being increased by ongoing coastal management in neighbouring areas.

The main contribution of this scoping report is a series of recommendations for further work and for development of the methodology to be used in the main project (see, Environment Agency, 2025c).

Important note

Work on project SC120017 ‘Shore and cliff sensitivity to accelerating sea level rise’ began in 2013, and this scoping report was written at an early stage.

There may be inconsistencies in the data sets and methods used at different times.

Read this scoping report with the accompanying project outputs. For updated references, see the main technical report (Environment Agency, 2025c).

1 Introduction

The overall purpose of this project is to derive a consistent set of indices of erosion acceleration for the coasts of England and Wales to predict erosion due to accelerated sea level rise expected over the next century. The behaviour of the shoreline under scenarios of accelerating sea level rise at a national scale will be modelled to provide the coastal management community with a national-scale mapping of time-varying indices.

The study’s aim is to improve understanding of the response of the very common type of coast characterised by a shore platform, normally backed by a cliff and (often) with a perched beach (Figure 1).

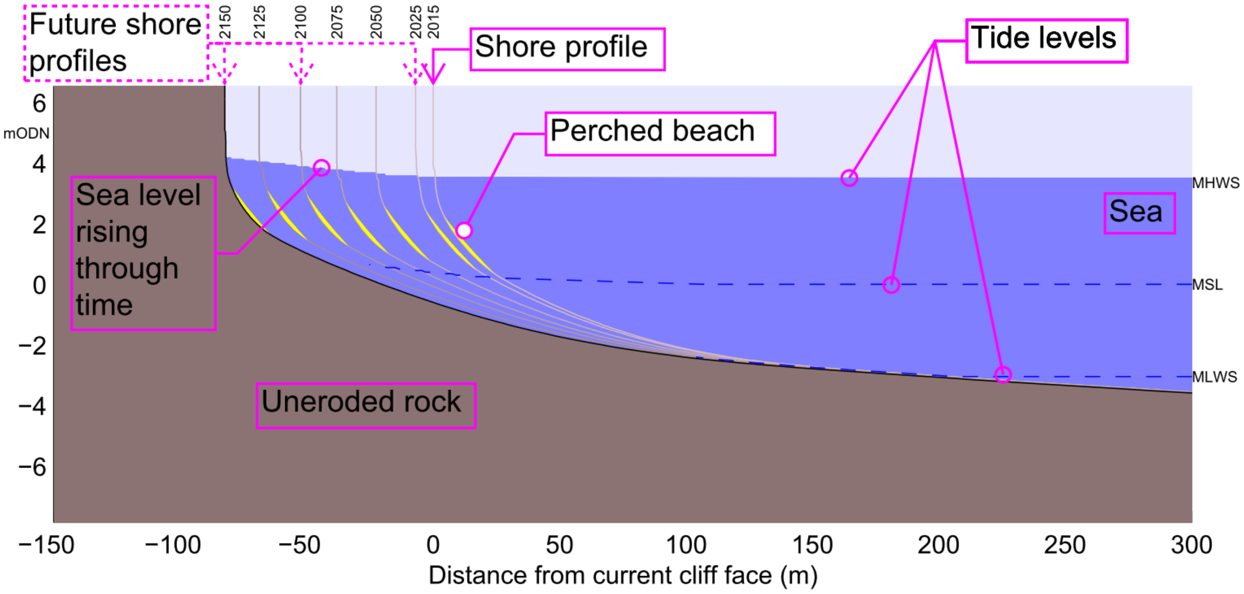

Figure 1: Illustration of the shore type and dynamic behaviour studied in this project

Figure 1 shows shore profile predictions from 2015 to 2150 based on rock erosion and sea level rises. The x-axis shows the distance from the current cliff face in metres (from -150 metres to 300 metres). The y-axis shows the level above and below sea level in metres from +6 metres above to -6 metres below with mean Ordnance Datum Newlyn (mODN). The following elements are labelled in the figure:

- sea level rising through time
- uneroded rock
- the shore profile
- the perched beach
- tide levels

Marked across the figure are the mean high-water springs (MHWS), mean sea level (MSL) and mean low water springs (MLWS).

The response of this type of shore is particularly uncertain due to a lack of previous attention in the scientific literature. The work is based on applying a numerical modelling tool called ‘Soft Cliff And Platform Erosion’ (SCAPE) (Walkden and Hall, 2005) to explore the behaviour of eroding shore profiles under conditions of changing sea levels. The 2-dimensional (2D) version is used to represent specific shore regions.

To make the task of representing whole regions of shore tractable, it was necessary to develop a generalised approach to SCAPE 2D shore profile modelling. This generalised approach involved simulating conditions without a beach present and using default conditions for certain model parameters, including rock strength. A large set of sensitivity tests were performed to inform the development of this approach.

The results are expressed in terms of a Recession Sensitivity Indicator (RSI) – represented numerically by the symbol ω. The RSI is defined as the ratio of the shore erosion expected under accelerated sea level rise divided by the recession expected (all other things being equal) if 20th century erosion rates were to continue into the future.

RSI values were calculated by using SCAPE to ‘hindcast’ historic shore profile erosion, to simulate present day conditions (using representative waves, tides and known rates of historic sea level rise) and to ‘forecast’ future erosion under assumed trajectories of increased sea level rise. The forecast results were then expressed relative to projections based simply on 20th century erosion rates.

This project is seeking to understand how this RSI varies with coastal location. Its intention is not to produce actual recession rates or projected shoreline positions around the coastline of England and Wales, but to enable others to do so in a more consistent and evidence-based way.

The project has also studied the response of such shores to the loss of coastal defence structures and the coastal ‘catch-up’ that may result. This aspect of the work was relatively minor in terms of the overall project effort, but provided very illuminating results.

1.1 Project stages and objectives

The project was carried out in 2 stages.

1.1.1 Scoping stage (stage 1)

The objectives of the scoping stage were to:

1. identify the preferred modelling methodology for generating the required indices and their associated uncertainties, alongside the strategy for discretisation of the coast of England and Wales
2. examine the issue of coastal catch-up following seawall failure or removal by designing modelled tests to look at the relationship between catch-up distance and seawall age; residual life; platform level; sea level rise and beach volume
3. demonstrate the suitability of the proposed modelling strategy by applying it to 5 case study sites

The scoping stage objectives were met through a set of generalised sensitivity tests and 5 dedicated case studies of specific coastal locations (see section 2). Scoping stage findings are summarised in sections 3.2 and 3.3, respectively. The main contribution of this report is a set of recommendations for consideration in the main project (see section 4).

The findings of this scoping technical report are supported by 2 unpublished reports – a project scoping report (Environment Agency, 2025a) and a case study analysis report (Environment Agency, 2025b).

1.1.2 Main stage (stage 2) objectives

The further objectives for the main project are to:

4. generate a set of indices for appropriate coastal types located around England and Wales, which will cover the 100-year planning horizon and also go beyond this century to capture the trajectory of recession due to accelerated sea level rise
5. develop guidance on the application of the indices for both basic and more refined uses
6. publicise and disseminate the findings of the research to ensure awareness and uptake of resulting products

The long-term information generated under objective 4 will be of great use to those involved in planning large-scale coastal infrastructure projects such as the nuclear power industry.

The guidance developed under objective 5 will be tested by a number of representatives from selected maritime authorities.

The reader is directed to the main technical report (Environment Agency, 2025c) for further details.

2 Project elements

2.1 Scoping stage tasks

2.1.1 Task 1: Project initiation

The study began with a project inception report (Royal HaskoningDHV, 2013), which dealt with data acquisition, project risks and the project deliverables. It also presented a communication and dissemination plan.

2.1.2 Task 2: Project scoping

During Task 2, the project developed and described the model-based methods from which the coastal erosion indices were to be derived.

A high-level review of hydrodynamic conditions (waves, tides, sea level rise and surge) around the coasts of England and Wales was also carried out to identify their ranges and spatial variability. This information was needed to constrain subsequent sensitivity testing and to inform planning of the spatial discretisation (segmenting the coast into units) for the main project.

Views on future sea level rise were also considered to identify a range of potential future sea level rise trajectories across and beyond the 21st century. These were not intended to precisely represent expected future conditions, but to encompass and extend across the range of possible conditions. Future growth in wave conditions was also specified based on the best available information at the time – including results of UK Climate Projections 2009 (UKCP09) and guidance provided by the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency.

This task also explored the relative importance of changes in sea level rise in comparison with changes in rainfall.

Sensitivity testing was carried out (for an idealised coast) to explore the sensitivity of shore erosion to accelerated sea level rise under variations in surge, wave conditions, historic sea level rise and tide. In addition, a series of methodological sensitivity tests were performed to explore variations in grid size, rock strength and lower shore downwearing.

The study then developed an initial view of how the coastline of England and Wales might best be discretised to generate Recession Sensitivity Indicator (RSI) values during the main project stages.

The results of this work are described in the project scoping report (Environment Agency, 2025a).

2.1.3 Task 3: Case study analysis and scoping stage technical report

A series of case studies were carried out to trial the proposed methodology for quantifying the RSI. Five case study sites were identified:

- Birling Gap (Sussex)
- Carl Crag (Cumbria)
- Happisburgh (Norfolk)
- Holderness (Yorkshire)
- the Nash shore (Glamorgan)

The Happisburgh site was chosen as a site of recent coastal ‘catch-up’. The others were selected to be broadly representative of the hydrodynamic conditions found along the coastline of England and Wales. The investigation of coastal catch-up at Happisburgh included examining how catch-up distance might vary with changes in the seawall age, residual life, platform level, sea level rise and beach volume.

The results of the Nash site were used to demonstrate how the derived RSI values can be combined with information on historic recession to project future change. Those results were also compared with projections made using the method underpinning the National Coastal Erosion Risk Map published in 2012 (NCERM).

The results from Task 3 are presented in the case study analysis report (Environment Agency, 2025b).

2.2 Main stage tasks

2.2.1 Task 4: Generation of sensitivity indicators for England and Wales

Elements of the scoping stage (mainly the methodological development, sensitivity testing and review of hydrodynamic conditions) will be used to construct a large set of model simulations. These will be used to simulate coastal sensitivity to accelerated sea level rise for appropriate coastal types located around England and Wales for the chosen discretised regions. The results will be processed to provide tables of indices of erosion for every decade and each trajectory of sea level rise. The sensitivity indicators will cover the 100-year planning horizon and also go beyond this century.

2.2.2 Task 5: Reporting the practical guide

During the main project, an end-user focused workshop was held to demonstrate and further explore how the results could be used and in what formats they might best be provided. The reported material was drawn together into a technical guide on how to use the derived sensitivity indicators.

A further technical report, developed from the scoping report and this report, was also prepared, containing a fuller description of these coefficients as functions of hydrodynamic conditions (Environment Agency, 2025c). This will support more refined applications at a more localised scale and provide practical advice on estimating shore/cliff response to removing cliff toe structures.

2.2.3 Task 6: Dissemination

Dissemination events will be organised during Task 6, alongside the production of dissemination materials.

A dissemination meeting will be held to promote the new guidance to Environment Agency staff, local authorities and staff at other relevant non-governmental organisations. Two webinars will be held for technical staff unable to attend the dissemination meeting. The presentations (as Microsoft® PowerPoint slides) will be made available for subsequent use in regional workshops.

3 Scoping stage findings

3.1 Introduction

The outputs of the scoping stage deepened understanding of the nature of shore profile response to accelerated relative sea level rise and provided insights highly relevant to practical coastal management. This section records particularly revealing aspects of the study, focusing on the outcomes of the sensitivity testing, the findings of the case studies, and the exploration of coastal catch-up.

3.2 Sensitivity testing

3.2.1 General sensitivity of shore recession

The tests revealed relative insensitivity to:

(1) beach volume (below a threshold)
(2) rock resistance
(3) lower shore downwearing

They also showed coastal sensitivity to accelerated relative sea level rise increasing with lower:

(4) rates of historic relative sea level rise
(5) wave heights
(6) tidal range

Finding (1) arises because of a mode of behaviour that means that beaches below a threshold volume do not influence the rate of shore recession. This behaviour seems, initially, counter-intuitive since the presence of a beach clearly reduces the energy expended on the consolidated profile on which it rests. Although the introduction of a beach does reduce the amount of energy impinging on the platform and cliff, it also tends to steepen the part of the consolidated profile on which it rests (as the lower unprotected platform continues to erode). The beach also becomes wider and thinner, and this gradually increases the number of waves able to penetrate to the platform. Significantly, those waves that do penetrate are better able to erode the consolidated surface because it has steepened. This is described more fully in the scoping report (Environment Agency, 2025a). In this context, finding (1) is reasonable.

Finding (2) is more challenging because it arises from the relationship between wave power and rock strength used within the model (the basis of which was proposed by Kamphuis, 1987). Geology clearly influences both the recession rate and the processes through which that recession occurs. To gain benefits (in regional or national-scale coastal management terms) from numerical modelling, it is necessary to adopt an abstract description of the erosive processes. The approach taken here was to adopt descriptions of wave-driven erosion that are abstracted to the degree that they are not tied to a specific erosion process or geological strength parameter. The expression of Kamphuis (which was adapted by Walkden and Hall, 2005) has this characteristic. Although it was proposed during a study of recession of glacial till bluffs at the Great Lakes in North America, it is not tied to specific processes of erosion. It was developed to describe erosion as a function of:

- wave power in the breaking zone
- the rate of energy dissipation
- the energy contained in each breaking wave

Because the expression is not process-specific, it should be a rational abstraction of the capacity of waves to erode material from a range of rock types beyond the glacial tills of the original Kamphuis study.

Experience suggests that the model captures reasonably well the aggregated erosional processes for a variety of sites, as shown, for example, in the case study analysis report (Environment Agency, 2025b) as well as by Walkden and Hall (2005); Dickson and others (2007); Appeaning-Addo and others (2008); Dawson and others (2009); Royal Haskoning (2010, 2011); Brooks and Spencer (2012); and Carpenter and others (2014).

Uncertainty around the physical processes does raise the question of the range of conditions for which the model may be valid, particularly for harder rock shores. Conditions at harder shores deviate more from those studied in the work on which the model is based. Similarly, assumptions drawn during model development were made with softer rock sites in mind. It seems reasonable that the model will perform less well at hard rock sites. This is difficult to test because hard rock shores respond so slowly that any particular example may well have been formed over hundreds of thousands of years, and, therefore, several sea level highstands. In this context, uncertainty about (among other things) starting conditions, climatic conditions and sea level change becomes profound and it is difficult to see how a realistic test simulation could be run. However, an important controlling feature within the model is feedback between the profile slope and erosive potential. Steeper slopes are likely to undergo greater recession than more gentle slopes; this is true for hard rock shores as well as soft ones.

Further scientific work could be carried out to explore the consequences of different forms of the relationship between wave power and recession rate, and perhaps also different feedback relationships between slope and erosion. This seems a reasonable medium-term aspiration for the interested scientific community. Given current knowledge, it seems reasonable to accept finding (2) and proceed given that:

- the shores of greatest concern tend to be ‘softer’ (and the model was developed for these)
- although the error in the RSI seems likely to increase with rock strength, the absolute error (that is, in linear metres) may well decrease strongly because the recession rates are smaller

Finding (4) is relatively plausible; many geomorphologists would intuitively expect that the sites that had been subject to low rates of historic relative sea level rise would respond more than those that had formed with a more rapidly rising sea. It is also strongly implied by the equation relating historic and future equilibrium recession rates, provided by Walkden and Dickson (2008) and derived analytically by Ashton and others (2011).

Findings (5) and (6) (that lower wave heights and lower tidal range increase sensitivity) are less intuitive, although they arise for reasons very similar to those governing finding (4). This is most simply explained in terms of a coastal site at which the rate of relative sea level rise increases instantly from one constant rate to another. Although real world situations (and the sensitivity tests) involve gradual changes in rates of rise, the explanation for both situations is essentially the same. A site that is subject to a constant rate of relative sea level rise (and unchanging geology, beach, tidal characteristics, wave climate and so on) will develop a dynamically stable shore profile. The gradient of this profile will vary across it from very steep at the cliff face, to the gently sloping ‘relic’ zone of the profile, below the influence of wave attack.

If the relative sea level rise were to change suddenly to a higher (steady) rate, the equilibrium recession rate would also increase. This would not happen instantaneously; the new equilibrium rate would be reached only after the new equilibrium profile had emerged. This would involve the steepening of the entire active profile and this could only occur through erosive processes. The time necessary for the transition to the new equilibrium rate will be approximately equal to the time necessary for the active zone of wave attack to rise above the top of its position at the moment of the increase in relative sea level rise (that is, the time needed to rise by the height of the active zone). The height of the active zone is directly related to the tidal range and to the height of the incident wave climate. It follows that it will take less time for sites with smaller waves and smaller tides to respond fully to a sudden change in the rate of relative sea level rise (that is, they will be more sensitive).

This also helps to explain finding (3). Downwearing processes act below the active zone of wave attack and so do not influence the duration of the response to accelerated relative sea level rise. Subsequent case study work shone more light on the importance of such downwearing processes and this is covered further in section 3.3.3. The fact that relative sea level rise changes slowly, and that we are exploring conditions before equilibrium has been reached is a complication, but does not change the basic argument.

3.2.2 Historic relative sea level rise

The results of relative sea level rise sensitivity tests showed the importance of accounting for the historic variation in relative sea level rise. They also implied that the period at which relative sea level rise is assumed to begin should not be the early 21st century but the late 19th century. This presents a challenge for the concept of the RSI, which must necessarily be based on recession rates observed over the 20th century (that is, after relative sea level rise started to accelerate and, therefore, changes in recession rate had begun). Although a challenge, this should not undermine the concept as long as this limitation is made clear and there is a clear definition of the historic recession rate on which the RSI is based (for example, ‘average recession over the 20th century’). However, this does introduce a complication for a national-scale application of this modelling approach in the main stage of the project. It may not be possible to assume equilibrium conditions at the end the hindcast period, necessitating multiple hindcasts (each with a different sequencing of input conditions).

Possibly a larger problem associated with historic recession rates is that their variability was found to be quite large. This suggests that the:

- typical around 100-year timeframe over which historic rates are calculated may be rather short
- uncertainty that this introduces into the projection of future rates may be larger than previously thought

This is best managed in the simulations by running multiple hindcasts from which a set of estimates of 20th century recession rates may be extracted for averaging.

3.3.3 Rainfall

Simulations were run to explore the relative importance of accelerated relative sea level rise compared with increased future rainfall. These also provided insights into the coastal recession behaviours that might be expected from increased rainfall. They illustrated, for example, that the consequences of a particularly ‘wet’ year should be expected to be transient; if no failure happens to occur before the cliff has drained, then the event is ‘forgotten’ by the system.

A systemic change in rainfall climate has a much stronger and longer lasting effect. Over shorter timeframes, the effect may be substantially larger than that due to accelerated relative sea level rise. However, over time the erosion driven by accelerated relative sea level rise becomes much more significant. This is illustrated in Figure 2. This shows results from 3 sets of conditions representing:

- no change in relative sea level rise rate or rainfall
- increased relative sea level rise rate after year 100
- increased relative sea level rise rate with increased rainfall after year 100

The cliff recession that would have occurred under the first condition is represented by the straight line (extending from year 0 to year 300 of the simulation). Losses due to accelerated relative sea level rise are only approximated by the yellow area, while the green area represents losses due to increased rainfall.

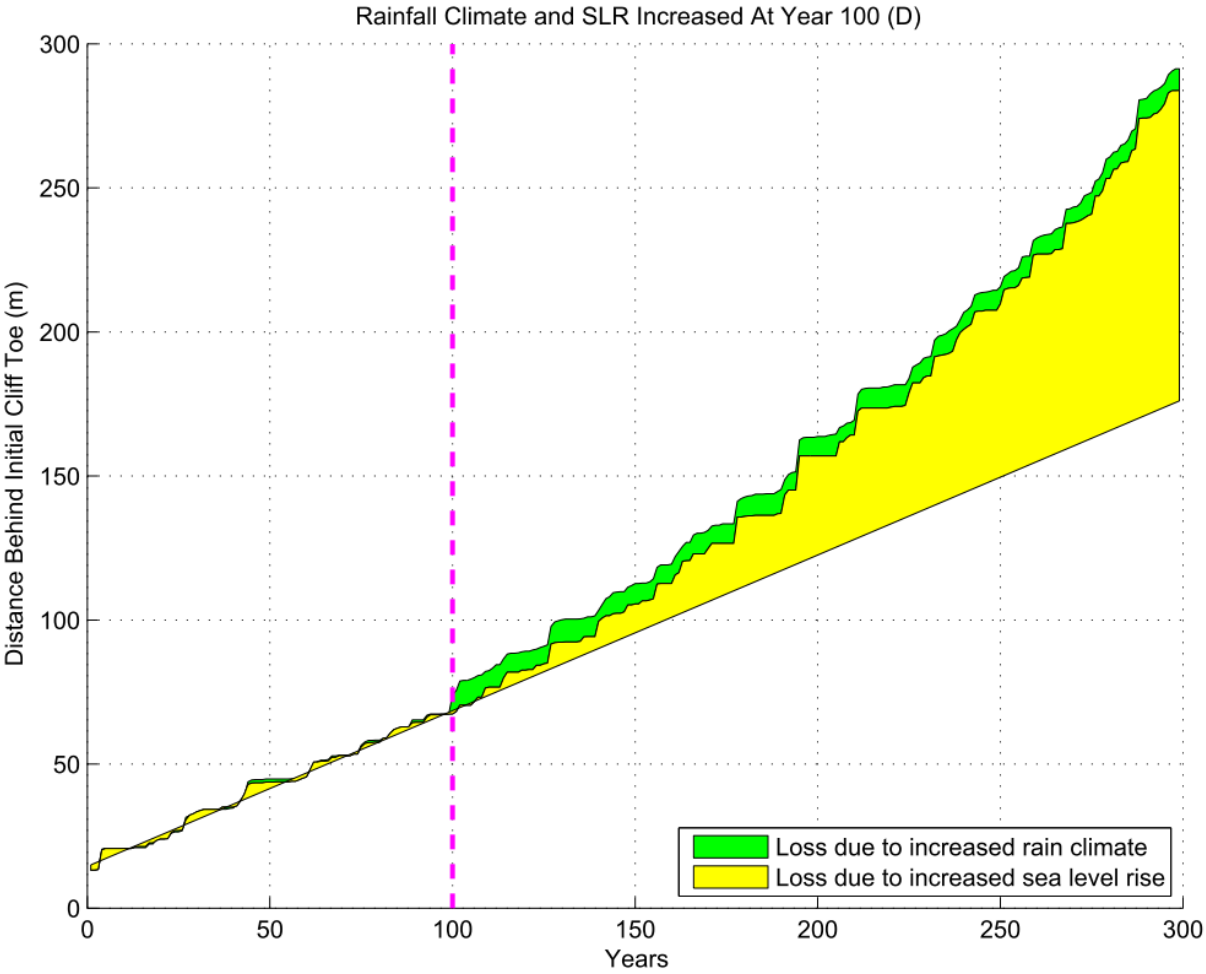

Figure 2: Cliff top losses caused by an increase in rainfall (green) and increased relative sea level rise (yellow) after year 100

The y-axis in Figure 2 shows the distance behind the initial cliff toe in metres (from 0 to 300 metres). The x-axis shows the time in years (from 0 to 300 years). At 100 years, the rainfall climate and sea level increased. This graph shows how the cliff top losses increased at this point. Cliff top losses due to sea level rise increased continuously over time.

Following changes to the model inputs (in year 100, marked with a pink dashed line), the losses due to increased rainfall are initially greater. After 3 or 4 decades (in this simulation), the losses due to an accelerated relative sea level rise have risen to the same scale. From then on, the relative sea level rise losses exceed those associated with rainfall increase and rise to become much more substantial.

These simulations were driven using hypothetical illustrative input conditions but, nevertheless, the results capture the basic behaviours of coastal cliffs and show relatively realistic relationships between cliff top and toe. While relative sea level rise was assumed to increase gradually, the increase in rainfall was assumed to occur instantaneously and this may result in overestimating the impact of rainfall in early decades.

3.3 Case studies

The purpose of the case studies was to:

- trial the generalised 2D modelling approach proposed for the main stage of the project
- to extend the number of sites at which SCAPE 2D had been applied to build understanding of the associated benefits and potential issues

Studies at 5 sites, each selected to provide different insights into the processes of coastal erosion and how they may be represented, are described in Environment Agency (2025b).

The modelling methodology was tested by constructing both calibrated and generalised models of the sites. The results of both were used to calculate RSI values and the results were compared. Where the results were similar, it was concluded that the generalised approach was accurate enough. The generalised models were run with local wave, tide and relative sea level rise data, but did not include a beach, and default values were used for many parameters, including rock strength.

The Nash shore case study in Glamorgan provided a good example of a shore with minimal human influence. It, therefore, offered the best means of testing whether the sort of generalised SCAPE 2D model approach proposed for the main stage of the project would give reliable results. A comparison was also made between the model output here and the projections of recession made by the first generation (2012) National Coastal Erosion Risk Map (NCERM) project for this site.

Earlier sensitivity testing had indicated that shores with a historically low, or negative, rate of relative sea level rise should be most sensitive to accelerated relative sea level rise (Environment Agency, 2025a). A site in the north of England or Wales was, therefore, considered crucial to the study. The Carl Crag shore in Cumbria was chosen; the results of this model should provide a reasonable estimate of the upper bound of coastal sensitivity to the accelerated relative sea level rise. This case study also allowed some exploration of the effects of shoreface downwearing on coastal sensitivity.

The Birling Gap site in Sussex was chosen, in part, because SCAPE 2D had not previously been applied to chalk cliffs. The main challenge that emerged at this location was to deal with the effects of human intervention, such as the historic construction at Newhaven, on beach volume. This was overcome by modifying the model to allow a time-varying beach input and by calibrating simultaneously to recession rate and beach volume.

The Holderness site in the East Riding of Yorkshire was selected because it is relatively far north and because the ‘rock’ (till) formed relatively recently, offering the potential for a relatively simple geomorphic history. In the event, the site could not be adequately represented with SCAPE 2D. Further investigation would be needed, beyond the scope of this project, to provide a realistic representation of that coast.

The Happisburgh case study site in Norfolk was chosen because it is an excellent recent example of shore response to the loss of structures. Although the Happisburgh model was run under scenarios of relative sea level rise, its main purpose was to allow sensitivity testing to explore the recession processes that control how (and how quickly) a shoreline responds following the removal of coastal protection. This element of work was carried out in less depth than the more detailed exploration of responses to accelerated relative sea level rise elsewhere in the project, but it provided interesting and potentially important results.

3.3.1 Model inputs

Assembly of the model inputs required for hindcasting (historic relative sea level rise, tide levels and wave climate) was relatively straightforward (see Environment Agency, 2025b). Importantly, sensitivity testing revealed that statistical resampling of extreme waves and water levels was not necessary to calculate the RSI. Although extreme waves are the most energetic, they do less work, overall, in reshaping the shore compared with smaller, more common conditions.

Input conditions for future conditions were more problematic. Understanding of the effect of climate change on wave conditions is very limited and so this was necessarily represented with some uncertainty in the case studies.

More importantly, the baseline year of the trajectories of future relative sea level rise provided by UKCP09 (and adopted at the time of this scoping study) seems questionable. The baseline year is 1990, so that by 2014, a seemingly large amount of change would have occurred, apparently at odds with observational data (a baseline year of 2013 was assumed in the site studies). The project’s sea level rise trajectories and the baseline year were revisited through discussion with the Met Office’s Hadley Centre at the start of the main project (Environment Agency, 2025c).

3.3.2 NCERM (2012) data comparison

The RSI estimates derived for the Nash shore were converted into projections of erosion before being compared with the 2012 NCERM and Shoreline Management Plan 2 (SMP2) projections. Due to a localised error in the NCERM, it was found to predict zero recession at this site and so the methodology underpinning the NCERM – as reported in the outputs of the Risk Assessment of Coastal Erosion (RACE) project (Halcrow, 2007a) – was followed to generate projections for the comparison.

An approximately 50% reduction in predicted erosion resulting from the new RSI-based approach was found relative to the RACE-based predictions. Sensitivity testing also revealed very large differences in the behaviour of the 2 methods. Changing sediment size, increasing the rate of projected relative sea level rise and lowering the cliff height all increased the recession projected using the RACE method and the relative difference to the RSI results. Very different responses to variation in rock strength were also found, with the RACE-based method proving to be insensitive.

An important reason for the different behaviours exhibited by the 2 methods is that the RACE method is based on ‘Bruun’ concepts (Bruun, 1962), which were developed for beach shores and then adapted for cliff sites. In contrast, the SCAPE-based RSI values represent rock/consolidated profile development more directly. If the site had had a substantially fuller beach with more connection between cliff sediment content and beach volume, the performance of the RACE methodology would probably have been better.

SCAPE–RSI based projections of shore erosion should fit readily within the framework developed to produce the 2012 NCERM. This has been established through a review of that framework (as defined by the RACE project) and discussions with the technical team responsible for producing the NCERM. The outputs of this project should, therefore, be compatible with subsequent NCERM revision processes.

3.3.3 Significance of lower shore downwearing

The lower sections of SCAPE shore profiles sometimes emerge at an erroneously high level. This is normally attributed to non-wave (perhaps tidal) processes acting to lower the shore and is compensated for in the model by introducing a ‘lower shore downwearing’ term. This was the case in the Carl Crag case study. Given earlier sensitivity testing, it was expected that the calculated RSI at this site would be insensitive to including this term. In fact, the RSI values resulted in an overestimation of erosion of around 15% by 2100.

The reason for this different result is not completely clear and it is difficult to identify precisely without further exploratory simulations. However, the most likely source of the different response is the change in the treatment of historic relative sea level rise that was made between the sensitivity tests and the site-specific simulations. Sea level rise was treated in a linear manner in the sensitivity tests, whereas it was represented as varying with time in the Carl Crag simulations. In addition, the sensitivity tests included rates of historic relative sea level rise as low as 1 mm a year, but did not include falling sea levels, which have occurred along the Cumbrian coast.

This finding has significance for the main stage of the project because it suggests that, at some sites, the generalised RSI values that will be predicted will overestimate future shore recession. If this overestimation is associated with the linearisation of relative sea level rise, then it might be generally expected at all sites where shoreface lowering is significant. However, if the overestimation is associated with recent sea level fall at this site, then the overestimation may be limited to only those sites where shoreface lowering is significant in northern areas of England and Wales. It is not, therefore, necessary to include lower shore downwearing processes in the generalised approach. This omission is likely to introduce a modest source of conservatism to the analysis, which will affect a subset of real sites.

It should also be noted that the shoreface lowering rates used here are likely to be overestimations (for reasons explained in Environment Agency, 2025b). If shoreface lowering is, in reality, less than the value of 5 mm a year imposed in these simulations, then the levels of overestimation described here would also be lower.

3.3.4 Three-dimensional effects

As noted above, the project is addressing the problem of coastal response to relative sea level rise by representing shore profile change through time in a 2D way. This is reasonable given the current state of knowledge about such change and is also necessary to make the problem tractable (given resource limitations).

Three-dimensional representation is possible but is more involved; see, for example, the SCAPE 3D simulations described by Walkden and Hall (2005); Dickson and others (2007); and Walkden and Hall (2011). That approach also generates more complex results that can complicate the task of uncovering basic dynamic behaviour.

Difficulties arose at 2 of the case study sites due to this 2D treatment. At Birling Gap, a site which was initially selected as one in a ‘natural’ condition, it emerged that long-term (century-scale) changes in average beach volume had a strong influence on recession rates in the 20th century. It further emerged that the scale of these effects was significantly greater than the (predicted) scale of influence of future relative sea level rise.

As an exercise in modelling Birling Gap (and the chalk cliffs), the case study was a success in that historic change and the current profile form were represented quite well. In terms of testing the concept proposed for the main stage of the project, however, the benefits of the work were limited to providing evidence that the approach would have worked at sites like Birling Gap that had not been subject to long-term systemic change in beach volume.

Essentially, to understand future recession rates at Birling Gap, it is more important to understand past and future changes in beach volume, and their effect on the shore profile and its recession rates, than it is to understand the site’s response to accelerated relative sea level rise.

Three-dimensional effects limited the 2D modelling of the Holderness shore more profoundly. It was recognised at the outset that 3D effects were important at Holderness. However, the attractions of the site (its northern location, high recession rates and the recent formation of its tills) made the attempt worthwhile. Moreover, the intertidal beach at Holderness is shallow; the glacial tills below it are exposed to direct wave attack in processes very similar to the conceptual basis of SCAPE.

As the modelling progressed, however, it became clear that the Holderness beach is strongly divided into upper and lower sections. Although the formation of the intertidal zone (made up of the top part of the lower beach, the till platform and the perched upper beach) occurs through the kind of wave-driven erosion captured within SCAPE, the overall recession of this zone is governed by subtidal processes of sediment transport and till erosion. It follows that the sensitivity of shoreline retreat to accelerated relative sea level rise should also be governed by the response of subtidal sediment transport balances and erosion processes, which SCAPE 2D does not capture. As a consequence, the output of the SCAPE modelling was poor, and it was determined that meaningful results could not be achieved with the approach adopted within this study.

The Holderness case study and the results of the Birling Gap model illustrate limitations in the generalised 2D approach. The Birling Gap modelling was still very informative in that it demonstrated that, at sites undergoing a significant trend in beach volume, the effect of accelerated relative sea level rise is likely to be small relative to effects driven by the changing beach. It follows that, at such sites, the problem of accelerated relative sea level rise will be a relatively minor (though still necessary) element of the assessment of future recession. Furthermore, the project provides a new method of accounting for the accelerated relative sea level rise element, and doing so in a rapid and efficient way. At such sites, the new method should provide a much better means of estimating (at the very least) the lower limit of response.

3.3.5 Overall sensitivity to accelerated relative sea level rise

The case studies included sites in the very north of England, in the south, and also within the Severn Estuary with its high tidal range. Their results should, therefore, provide a good indication of the total range of (RSI) results to be expected for the coastlines of England and Wales during the main stage of the project.

Figure 3 shows RSI projections for 3 of the case study sites. Only the central – and arguably the more realistic – of the 3 sea level trajectories is included for simplicity. Figure 4 shows an example of the calculation of shore recession from those RSI values (assuming an arbitrary 0.2 m per year historic recession). The projections in Figure 4 are obtained simply by multiplying the values in Figure 3 by a baseline projection (shown in blue) representing continuation of the historic rate. The baseline year for these simulations has been taken as 2013; data before 2025 are subject to a high degree of uncertainty and so are not presented. Data have been extracted and presented in 10-year intervals – a shorter timestep would have resulted in fewer smooth lines, although the same trends.

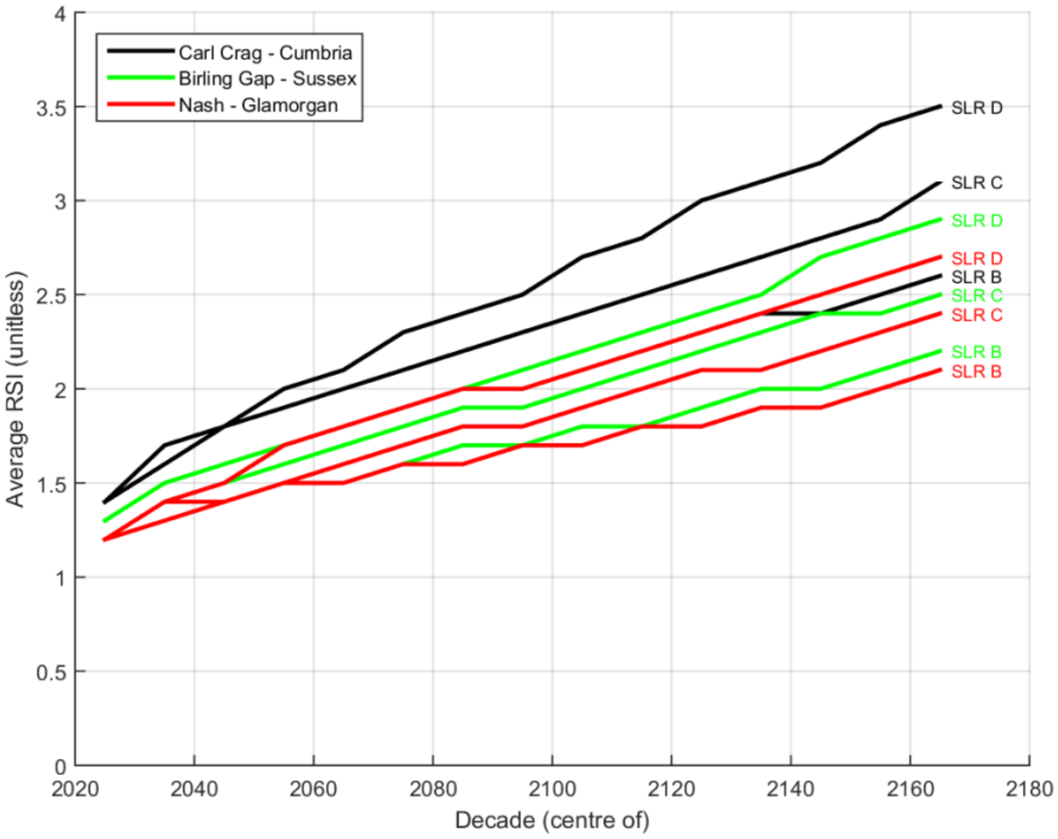

Figure 3: Generalised RSI values derived for 3 of the case study sites for the central relative sea level rise (SLR) trajectory only

Figure 3 presents the average Recession Sensitivity Indicator (RSI) on the y-axis ranging from 0 to 4 (unitless). The x-axis represents time in years, spanning from 2020 to 2180 at the midpoint of each decade. The line graph illustrates RSI projections for 3 case study sites: Carl Crag in Cumbria (black lines), Birling Gap in Sussex (green lines), and Nash in Glamorgan (red lines). For each case study there are 3 central sea level trajectories: SLR B, SLR C, and SLR D. All projections show increases in RSI values, but vary depending on the assumed historical recession rates and the specific sea level rise trajectories.

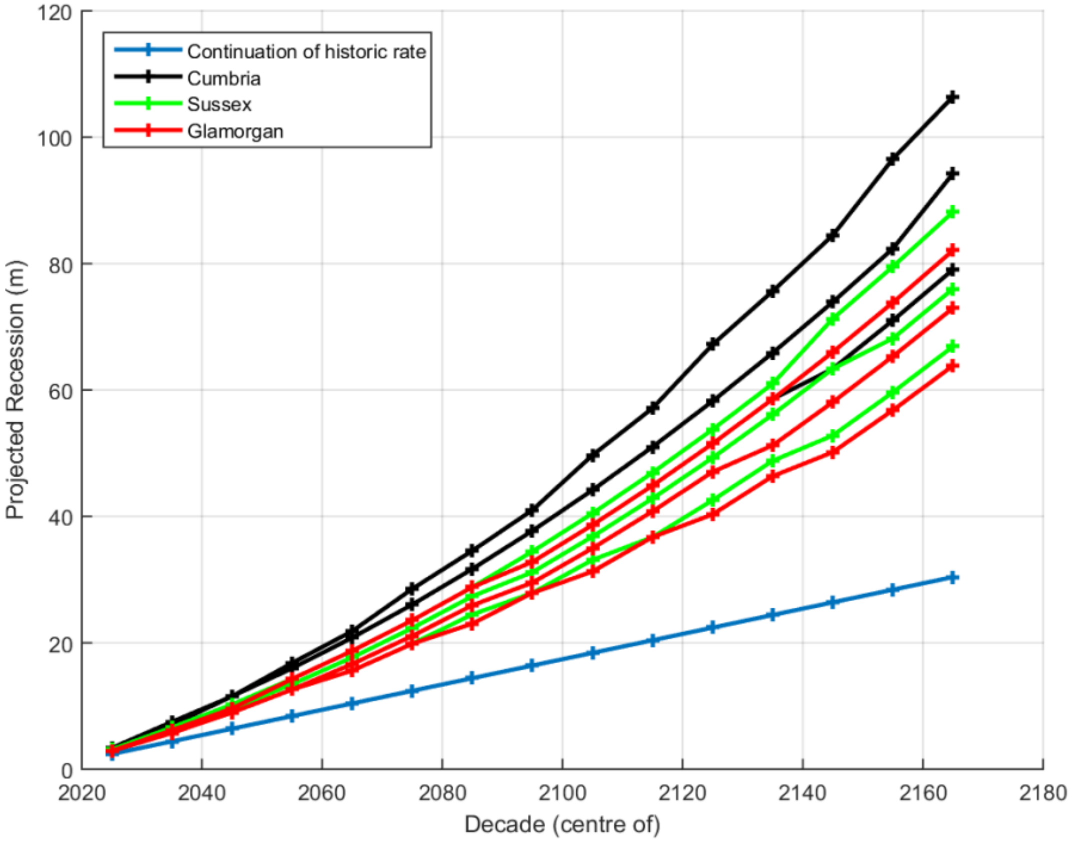

Figure 4: Example projections of shore recession made using the RSI values from Figure 3 (a historic recession rate of 0.2 m per year has been assumed)

Figure 4 plots the projected recession in metres (from 0 to 120 metres) on the y-axis, by the midpoint of each decade (from 2020 to 2180) on the x-axis for 3 case study sites (Carl Crag, Cumbria (black plot); Birling Gap, Sussex (green plot); Nash, Glamorgan (red plot) and the continuation of the historic rate (blue plot).

As expected, the Cumbrian example shows the greatest sensitivity (and, therefore, recession) because of its historically low (and negative) rates of relative sea level rise.

Based on historic sea level change, the Glamorgan coast might be expected to be the next most sensitive. However, it shows the lowest recession, and it appears that the high tidal range along the Glamorgan coast is slowing its response.

In terms of absolute erosion, the difference from place to place is not particularly great. For example, the total range of recession by 2100 under the central projection (SLR C in Figure 3) is around 9 m from approximately 32 m (Glamorgan) to approximately 41 m (Cumbria). This range is, of course, dependent on the assumed historic erosion rate and sea level rise trajectory. If, for example, a historic rate of erosion of 0.5 m is assumed, then under SLR D, the total range in erosion is between 113 m and 89 m (a range of 24 m).

Such ranges seem modest, given the long timeframes. They reflect the general reduction in future recession projected following this approach compared with previous (Bruun-based) methods. Such a reduction is shown in section 2.5.3 of the case study analysis report (Environment Agency, 2025b). It arises from assumptions inherent in the Bruun approach that are not correct for shores of the type addressed in this study. These are:

- conservation of profile form
- conservation of sediment volume
- instantaneous response to sea level rise

In addition, the Bruun method assumes the existence of a ‘depth of closure’ – an extremely difficult concept to translate to coasts where behaviour is strongly influenced by a shore platform.

3.4 Coastal catch-up

Processes of coastal catch-up (accelerated recession resulting from the removal of coastal protection structures) were examined in the Happisburgh case study.

Analysis of Environment Agency LiDAR (light detection and ranging) data and shore profiles shows that the Happisburgh shore has responded very strongly to the failure of coastal protection structures. The ‘natural’ recession rate that occurred at Happisburgh before defences were constructed is not known precisely, but historic mapping suggests it was around 0.5 m per year. The Environment Agency reports erosion of up to 140 m after structure failure since the early 1990s. It is, therefore, very likely that the response of the Happisburgh shore has been to ‘overshoot’ rather than ‘catch-up’. The factor of ‘overshoot’ is estimated to be up to around 4.7, that is, the maximum recession in 2013 was around 4.7 times that which would be expected from predictions based on historic rates. It should be noted that catch-up and overshoot behaviours are not distinctly different, but represent different scales of the same response.

Catch-up is associated with the development of a step in the shore platform surface level across the defence structure as the shore platform seaward of the structure erodes downwards. It was not possible to accurately determine the typical size of this step at the north of Happisburgh (where structures still exist) in 2013, but it has been estimated to be between 1.5 m and 4 m.

The large overshoot raises the question of whether such a response should be generally expected at sites where coastal protection is discontinued. To provide evidence to help answer that question, a series of SCAPE simulations were used to explore processes of coastal catch-up. Data recorded at Happisburgh were used to both constrain these simulations and to test the realism of their output. The simulations were not, however, similar enough to Happisburgh to be considered a direct model. The main reasons for this lack of similarity are the difficulty in establishing in a 2D model:

- the correct relationship between rock strength and beach volume
- the scale of alongshore effects of neighbouring coastal management on beach volumes

The results suggested that a decrease in average beach volume (believed to have occurred when the Happisburgh structures were installed) strongly promotes step development and ultimately catch-up processes carrying the shoreline landward of the position it would have been reached if structures had not been built (that is, causing a net loss of land). Wave reflection was also found to play a role in this behaviour, but its effect seemed relatively minor.

The work suggests that coastal catch-up leading to net loss of land will be most severe where coastal protection – either locally or at distance – reduces local beach volumes.

3.4.1 Dependency of catch-up on seawall age and residual life

Results suggested, as expected, that the longer a structure is present, the greater the catch-up distance will be. This is due to the increasing size of the step in platform level across the structure. In these simulations, the duration of catch-up was unaffected by seawall age (and, therefore, residual life). It should be noted that the duration of the catch-up/overshoot was shorter in the model than in reality (that is, the model profile eroded more quickly). This will be due, in part, to imperfect representation in the model, but may also be attributed to the 3D nature of the Happisburgh embayment and the progressive failure of defences that occurred there (as opposed to the modelled instantaneous failure).

3.4.2 Dependency of coastal catch-up on platform level

Catch-up depends strongly on the level of the shore platform seaward of the structure at the time of failure. As time progresses the platform lowers, providing conditions for greater catch-up. However, the simulations showed relative insensitivity between platform level and overshoot. Although increased structure lifetime results in a lower platform level, this did not result in a noticeable relationship with overshoot distance.

3.4.3 Response to relative sea level rise

Shore response to accelerated relative sea level rise was found to be slow relative to processes around catch-up/overshoot. The magnitude of the response is also smaller. The results support a view that the 2 processes may be treated in isolation and added together when deriving projections of future coastal recession.

3.4.4 Relationship with beach volume

Beach volume appears to have a very strong influence on catch-up/overshoot distance. If the beach volume remains constant (on average), then net loss of land is minimised (though still happens). Sensitivity tests on the beach volume showed factors of overshoot as large as (and greater than) those observed at Happisburgh. This occurs because the reduced beach volume provides less protection to the shore platform fronting the structure. Waves are then more frequently able to penetrate the beach to attack and lower the platform. The relationship between overshoot and beach volume appears to be quite non-linear; the response increases as the beach volume becomes smaller. The coastal management implications of these observations are considered further below.

4 Recommendations

4.1 Introduction

The work completed during the scoping stage of this project represents a significant and practical step forward in better understanding shore response to accelerated sea level rise and to the loss of structures. There is much scope for additional development, however, and so this section makes a series of recommendations for further work and methodological refinement within and beyond the main stage of this project.

It should be stressed that this project does not tackle all the challenges commonly encountered when predicting future shore position, but instead focuses on the extremely important challenges of shore sensitivity to accelerated relative sea level rise and, to a more modest extent, coastal response to structure removal. The study is looking specifically at shores with a perched or absent beach – a coastal type that is very common, but which has tended to be neglected in previous studies.

It should also be noted that this project is not intended to provide future shoreline positions, but to enable those to be produced in a more transparent and evidence-based way.

The recommendations made in this section are based on the observations described in section 3 and the results described in previous outputs from this project (Environment Agency, 2025a, 2025b).

4.2 General recommendations

4.2.1 The methodology developed during the scoping stage should be carried forward for national-scale application

Current methods of accounting for coastal response to accelerated relative sea level rise tend to be Bruun-based (see, for example, Halcrow, 2007a, 2007b). However, the results of this study have shown:

- a tendency for overprediction in a Bruun-based approach when applied to ‘cliff’ sites
- questionable sensitivities in response to variations in parameters such as rock strength, cliff height and sediment size

These shortcomings seem to arise from the fact that the basic assumptions underpinning the Bruun method do not generally hold for cliff/platform shores. The new approach adopted here was designed from the outset to represent cliff/platform processes and, as a result, these were found to exhibit more realistic behaviours for this shore type.

This study suggests that the time required for a shore of this type to respond fully to a change in relative sea level rise may be around 1,000 years, although this response is non-linear. This means that, over coastal management timeframes, responses will be ‘transient’ and so dynamic models are required to predict them. Furthermore, these models must represent processes in an aggregated way to be able to deal with geological variation. The methodology tested in the scoping stage is a means of bringing some of the benefits offered by a dynamic numerical model to practical coastal management without the associated time and expense.

4.2.2 Research should continue into aggregated scale representation of shore profile development

This project builds on previous investment in the development and testing of a specific numerical modelling tool (SCAPE). Its strength and usefulness have been demonstrated through a series of projects, including this one. It, therefore, seems reasonable for the scientific community to develop more aggregated scale systems-based models like SCAPE. That research should include a branch that explores different formulations of the relationship between wave erosive forces, profile slope and rock strength. Those formulations should explore other ways of representing those relationships in terms that are sufficiently aggregated to allow the generalised representation of coastal erosion for a range of rock types. Similarly, that work should develop understanding of the cross-shore distribution of erosion under breaking waves, ideally using site observations.

4.2.3 Research into coastal catch-up should continue

The results of this study suggest that the erosion consequences of coastal catch-up following the loss of coastal protection structures can be substantial. The Happisburgh case study has shown that a model-based approach can reveal useful information on the scales of the possible responses and the geomorphic interactions that control it. The results were striking in that:

- they revealed a surprisingly large catch-up response (essentially one of overshoot)
- the problem at Happisburgh is likely to be growing despite the removal of local defences and the emergence of an apparently more stable embayment

Further work is recommended in this area to better quantify:

- the benefits that defences are currently providing (that is, to reduce potential underestimation of catch-up behaviours)
- the increasing future local and neighbouring ‘damages’ caused by defence maintenance through growth in the extent of catch-up and overshoot

It is also recommended that coastal monitoring programmes should record beach volumes and shore platform levels at structures, particularly at coastal protection structures. It is likely that the ability to predict catch-up processes will depend on the availability of data on these shore profile characteristics and how they have developed over time.

It would be particularly valuable to make a survey of platform levels before coastal protection structures are removed (or fail) to allow a more detailed assessment of the shore response. Areas of Norfolk, north of Happisburgh – where defences are beginning to fail – might be suitable for this.

4.2.4 Further work should be carried out to map the range of applicability of the method

The method developed for the main stage of this project provides a new and science-based means of accounting for coastal sensitivity to accelerated relative sea level rise. This is a significant contribution, given the shortage of science-based methods available to deal with this important problem.

The simplifications adopted to allow the method to be applied at a national scale introduce limitations to the range of applicability of the output. It is recommended that further work be carried out to deepen understanding of these limits.

Further work is needed, perhaps by an academic institution, into the transitional behaviour around recession sensitivity from being governed by the reshaping of the consolidated profile to being governed by redistribution of beach sediments (that is, from 'SCAPE like' to 'Bruun like' behaviour).

In addition, more understanding is needed of the importance of 3D effects (via beach transport and volume) on coastal sensitivity to accelerated relative sea level rise. Large-scale 3D effects are complex but can be modelled to a degree (for example, using the quasi-3D version of SCAPE).

4.3 Recommendations for the main stage of the project

4.3.1 Model discretisation

It is recommended that approximately 50 points should be modelled, relatively equally spread but with greater resolution in the north and within the Bristol Channel.

The greatest sensitivity in the RSI resulted from variation in historic linear relative sea level rise. Differences in tidal range were ranked next in importance. These findings suggested that a relatively even spread of output points should be selected for the main project, with perhaps more concentration in the north of Wales and England, and within the Bristol Channel and Severn Estuary. The case study simulations, which used time-varying rates of historic relative sea level rise, showed that the total range of shore sensitivity calculated during the main stage is likely to be quite modest.

Based on these findings, it seems reasonable to plan for around 50 output points, while noting that it may not be useful to report all the results if small differences were found between neighbouring points.

The vertical resolution of the models should be increased from 50 mm to 10 mm.

During the sensitivity tests, little relationship was found between the choice of vertical grid resolution and the resulting RSI. However, following the case study work, it seems likely that early ‘noise’ levels in the derived RSI might be reduced by an increase in the resolution of the grid, and so this is recommended in the main stage of the project. ‘Noise’ may be expected to reduce following this change because the models will then be subject to smaller (more frequent) step increases in sea level; this input will essentially become smoother.

4.3.2 Model inputs

Historic wave data should be represented using the recently generated WAM4 synthetic wave data produced by the Met Office and funded by the Environment Agency.

This data set has comprehensive spatial coverage, describes a 30-year period, and will be quite accessible. These data should be processed in the normal way for SCAPE modelling (monthly segmentation and semi-random concatenation preserving seasonality) to produce long (millennial) time series.

The effect of climate change on wave activity should be represented following Defra 2006 guidance.

The heights (and steepness) of future waves should be increased to represent the effects of climate change. In the absence of clear guidance on realistic changes, it seems reasonable to assume the growth defined by Defra (2006). This gives an ‘indicative sensitivity range’ of +5% to 2055 and +10% to 2115. When viewed in the light of the quite small changes in wave conditions shown in UKCP09, it seems reasonable to apply these sensitivity ranges as upper limits of probability distributions and to apply increases in a linear way.

The range of potential changes in future wave direction is also difficult to determine. It is recommended that these potential changes be assumed to follow a normal distribution, centred on zero, with limits of ±10° at the 95th percentile level. These bounds would encompass 75% of the probability and are chosen – using engineering judgement – to capture most of the probable outcomes.

Tide data should be synthesised using a modelling tool rather than being derived from tide gauge observations.

Although tide gauge data are more realistic (at least at the observations points) than synthetic data, they are more time consuming to work with and so might require a disproportionate amount of resource during a national-scale application. A synthetic approach would not include surge, which is not ideal, but the effect of this should only be to introduce a small element of conservatism into the result. Two potential software options are POLTIPS (National Oceanographic Centre Liverpool) and MIKE by DHI.

POLTIPS can be used to generate 100-year high water levels for 700 locations around the UK based on tidal harmonic constants. This would require spatial interpolation, translation of datum levels, and handling of batch runs of POLTIPS (pre-processing of job description files and post-processing of output).

MIKE by DHI also allows the generation of long time series of water levels, but is more flexible in that the user specifies the desired location and the software performs the spatial interpolation. However, this approach has the disadvantage of being based on satellite altimetry at a scale that is coarse relative to the variations in inshore water depths.

Historic relative sea level rise should be represented as ‘time varying’.

It is clear from the sensitivity tests that, at the timeframes over which the model hindcasting is made, historic sea level change should be treated as time varying. The best source of such trajectories currently available is Bradley and others (2011). These must be combined with information gathered from tide gauges on more recent changes, as reported by Woodworth and others (2009).

The impact of uncertainty in historic relative sea level rise should be explored.

During the scoping stage, historic relative sea level rise emerged as a particularly important model input. Data on this change are quite uncertain. Questions arise around the spatial and temporal variability of historic sea levels, how to join sea level curves from different sources, and when the human influence on sea level change really began. It would be desirable for these uncertainties to be captured in the model output. However, it is not clear what effect this would have on the uncertainty range surrounding the output and, moreover, the task of building broadly acceptable historic relative sea level rise trajectories is likely to be quite involved.

It is, therefore, recommended that the main project be expanded to explore the effect of this uncertainty on the output, albeit at a modest scale, aiming to provide general rather than definitive upper and lower limits for historic sea level change.

Trajectories of future relative sea level rise should be revisited in the light of very recent research.

The approach taken in the sensitivity tests to sample the possible space of sea level trajectory, rather than attempting to identify likely trajectories of future change, seems reasonable for the main project. Given recent work on sea level change, the Met Office should be consulted to help consider whether the chosen trajectories still reflect the range of possible change.

It follows from the sensitivity tests that the ‘curves’ of the relative sea level rise trajectories may well be important as well as the final sea level arrived at. The form of the curves is uncertain and should be chosen carefully. If, following consultation with the Met Office, a reasonable family of curves can be chosen, these could be implemented as an explicit source of uncertainty. Otherwise, a reasonably conservative form of curve should be applied. These discussions should also focus on the baseline year of the projections and extrapolation of conditions into the 22nd century (see section 4.4.3).

4.4 Model projections

4.4.1 Discussion with the Met Office should be used to select the most appropriate baseline year

The main project outputs will be tied to the concept of a ‘baseline year’ at which change is assumed to begin. This year is essentially defined by the projections of future sea level rise. As noted above, the science behind those projections has recently been revised. Moreover, the observational data on sea level change do not appear to correspond well with previous projections. The choice of the best baseline year should, therefore, be considered when the future sea level rise projections are being revisited.

4.4.2 A set of hindcast simulations should be run for each output point

Results from the scoping stage suggest that the stochastic variation in shore profile retreat is large enough to undermine modelled estimates of 20th century recession rates. For this reason, the case study work was adapted to include a set of hindcast simulations; this approach is recommended for the main project. These sets contained 20 simulations per site and this number should be considered the minimum.

4.4.3 Results should be reported to 2130

Results should be published for the longest period over which they may be both useful and reasonable. This period depends strongly on the reliability of the sea level projections. The UKCP09 projections extend to 2100 and so the project had first to extrapolate them before running simulations into the 22nd century. These extrapolations were based on the geometry of the trajectories, not the physics of sea level change, and so must be considered increasingly questionable for later decades.

As noted above, sea level trajectories should be revisited at the start of the main project and this may result in physics-based projections extending beyond 2100. To meet the needs of coastal management, the main project should provide results for the coming 110 years, even if this involves an element of extrapolation. These should be rounded up to the nearest decade, which would give an end date for (reported) results of 2130. It may be that results that extend beyond this date may ultimately prove useful, perhaps for the purposes of very broad-scale planning or science, and so it is suggested that the simulations should be run to 2150, but only publicly reported to 2130.

4.4.4 At least 100 forecast simulations should be run per point and per sea level rise scenario

Uncertainty bounds will be an important component of the main project and will require multiple forecast simulations. The case study simulations were run with a forecast set of

100 simulations (per site and per sea level rise scenario) and this number should be considered as the minimum.

4.4.5 Uncertainty bounds should be reported at the 5th, 12.5th, 87.5th and 95th percentiles

Prediction of future shore change is inherently uncertain and this uncertainty arises from many sources. During the main project, it will be important to represent uncertainty in the output so that it is recognised in decision-making. It must also be made clear which uncertainties are being accounted for. In brief terms, these will be uncertainties in:

- future relative sea level rise
- wave sequencing
- tide sequencing
- future change in wave direction
- stochastic fluctuations in shore profile shape

The uncertainty ranges calculated at each site should be reported; the 5th and 95th percentiles would provide reasonable estimates of these. However, the uncertainties captured within the Stage 2 simulations will represent only a subset of the uncertainties that should be included in projections of future shore change. Important uncertainties that cannot be represented include stochastic variation in cliff slope.

Providing only the 5th and 95th percentiles may become an unnecessary constraint on end users who wish to combine the results with other data on uncertainty. Less extreme bounds should, therefore, also be provided; the 12.5th and 87.5th percentiles are suggested.

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List of abbreviations

MHWS	Mean high water springs
MLWS	Mean low water springs
MSL	Mean sea level
NCERM	National Coastal Erosion Risk Map
RACE	Risk Assessment of Coastal Erosion [project]
RSI	Recession Sensitivity Indicator
SCAPE	Soft Cliff And Platform Erosion [model]
UKCP09	UK Climate Projections 2009

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