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Shore and cliff sensitivity to accelerating sea level rise

FCERM Research & Development Programme

Research report: Method report

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Contents

1 Introduction

1.1 Report context

This method report describes the main concepts of the ‘Shore and cliff sensitivity to accelerating sea level rise’ (SC120017) project. It explains what conservative sensitivity indicators are, how they were derived and their strengths and weaknesses. We use example applications to show the types of setting where the new method may be most effective.

We have published this guide alongside a technical report (Environment Agency, 2025d) and a quick start guide (Environment Agency, 2025b). The technical report includes descriptions of the modelling and post-processing used to derive the indicators, including the assumptions, limitations and the treatment of uncertainty. The quick start guide provides step-by-step instructions to use the spreadsheet tool (Environment Agency, 2025a). The tool is to estimate the effect of sea level rise on cliff toe erosion at sites around the coast of England and Wales.

1.2 Background

Sea level rise is accelerating, and this will tend to increase coastal recession. Relatively few tools are available to quantify this effect. The method most widely recommended in the UK has emerged from work on shores characterised by deep beaches. Therefore, a need has been identified for work on the response of coastal cliff shores, where the dynamics of the shore platform and cliff toe (rather than those of the beach) govern the response to sea level rise. Such coasts are relatively common; Emery and Kuhn (1982) estimated that around 80% of the marine coasts of the earth are backed by sea cliffs, and it is reasonable to suppose that shore platform dynamics are important to a significant proportion of these.

Predicting coastal cliff recession is complex and uncertain. It typically involves modifying a ‘baseline’ historic rate of retreat by factors that represent the effects of sea level rise and, if necessary, other changes in the coastal system.

1.3 Findings

This study offers new and spatially varying estimates of the sea level rise factor, for the coastline of England and Wales. They are presented as **conservative indicators of cliff toe recession sensitivity to UKCP18 projected relative sea level rise** and can be found in the accompanying spreadsheet tool (Environment Agency, 2025a). The sensitivity indicators account for:

- changes in profile shape caused by sea level rise, and the time over which this occurs

- regional variations in tidal range, history of relative sea level change and wave climate
- growth in wave height

The sensitivity indicators also provide a new perspective on cliff toe sensitivity, but do not represent a definitive answer. They were derived from simplified and idealised representations of a single concept of shore profile behaviour and, necessarily, assumptions and compromises were made in quantifying them. They take no account of local variations in the physical state of the cliff, such as its height and the sediment content of the geological strata. Also, geological strength is not represented explicitly, with baseline recession being used as a proxy instead.

The strengths and limitations of the sensitivity indicators are different to those of existing methods. It is hoped that they will be of particular value at locations where the current methods are poorly suited. They are intended to provide conservative results in the face of unavoidable uncertainty. It is stressed that we cannot fully know how far they deviate from the ‘true’ answer. This is partly due to a lack of observational data against which predictions can be tested. The indicators were produced through mass simulations with a numerical modelling tool called SCAPE (Walkden and Hall, 2005), as described in the accompanying technical report (Environment Agency, 2025d). As noted above, simplifications were necessary in these simulations, and so site-specific modelling should provide better answers in many locations (SCAPE is freely available for that purpose at suitable sites, see Walkden (2019).

Our technical report explains:

- the broader rationale for the study
- the methods, modelling tool and model inputs used to derive the indicators
- an overview of what the results reveal about spatial and temporal variations in sensitivity

This method report gives:

- an explanation of the main concepts on which the work was based
- demonstrations of how the sensitivity indicators may be used to estimate cliff recession in appropriate settings
- a discussion of strengths and limitations relative to existing methods
- guidance on the types of setting where the new method may be most valuable

2 Main concepts

This project addresses cliff/platform shores at a national scale and provides a broad picture of sensitivity rather than local detail (as discussed in Environment Agency, 2025d). For simplicity, the coast was divided into adjoining regions (shown in Figure 2-1), without considering the prevalence of cliffs, and the response of each was explored through 2-dimensional modelling. Largely enclosed areas, such as estuaries, were not included.

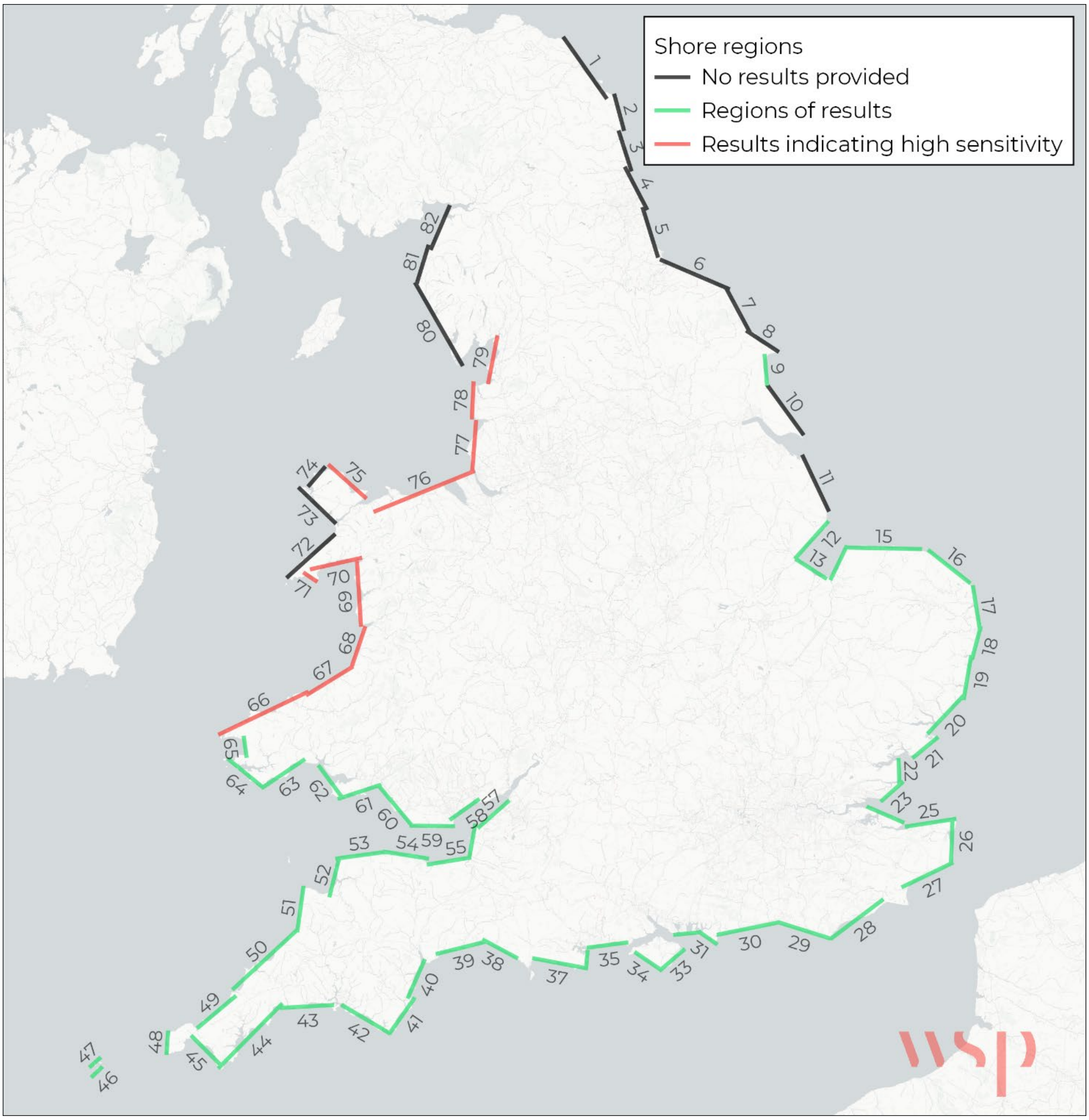

Figure 2-1: Map showing the model regions around the coast of England and Wales - black lines indicate regions where results could not be calculated, red lines show areas of particularly high sensitivity, green lines indicate regions of results. Regions 14, 24, 32, 36 and 56 are not labelled, but exist in (clockwise) sequence

Figure 2-1 shows the regions numbered in a clockwise direction starting from the Berwick-upon-Tweed area, around the whole coast of England and Wales and finishing on the south of the Solway Firth (Cumbria) - they are numbered from 1 through to 82.

2.1 Behavioural response to sea level rise

Figure 2-2: Photo showing a cliff/platform shore, Glamorgan, South Wales

This study deals with shores where, like the example in Figure 2-2, the cliff, beach and platform all retreat as a result of wave action on the shore. In this particular case, the cliff and beach are only subject to wave attack for a small proportion of the time. Most of the wave momentum works on the shore platform, which erodes and reshapes as a result.

This reshaping depends on sea level, and faster rates of sea level rise are expected to lead to steeper platforms (for example, Ashton and others, 2011). A degree of lag is also expected in the profile response; it will take some time for any change in the patterns of wave forces across the shore to be reflected in the shape that they carve into the platform, even if the geology is relatively soft (for example, Hands, 1984, Bray and Hooke, 1997). SCAPE was designed to represent these behaviours, as illustrated in as illustrated in Figure 2-3, which shows one of the simulations carried out for this study

These behaviours are different from those associated with dune/beach shores, where profiles are typically conceptualised as responding to sea level rise without changing shape and without lag (for example, Bruun 1962; Bray and Hooke, 1997).

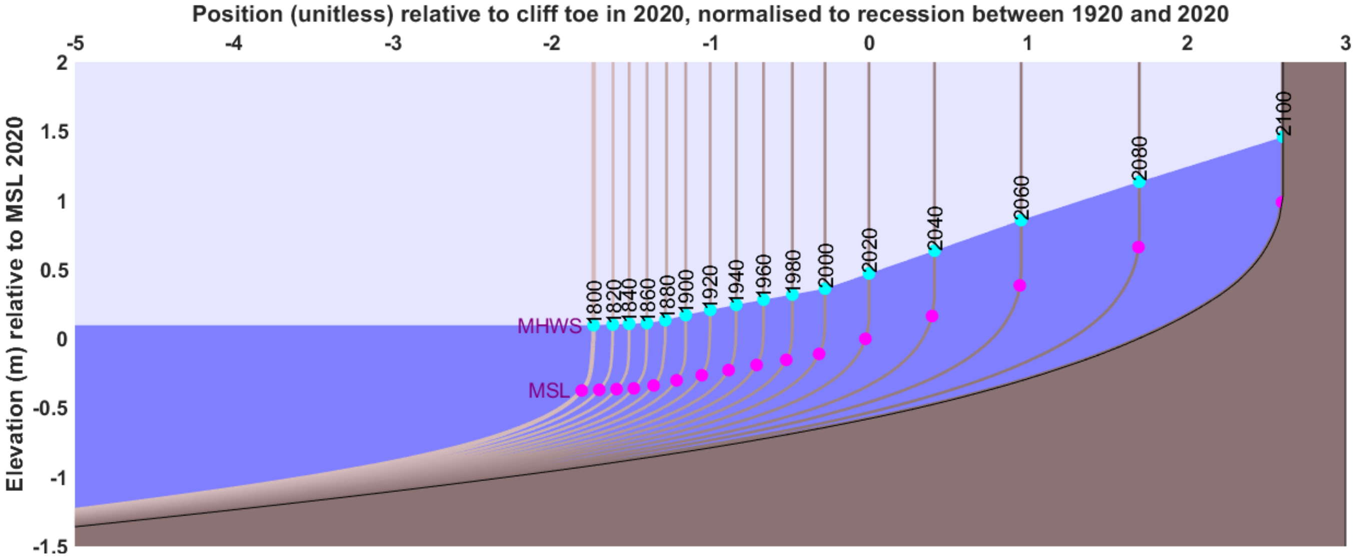

Figure 2-3: Example model output showing cliff response to sea level change. Note that: (1) the x-axis has been normalised to the cliff retreat between 1920 and 2020, (2) zero on the x-axis has been aligned to the cliff toe position in 2020, and (3) the magenta dots represent the (rising) mean sea level

SCAPE models respond to changes in the rate of relative sea level rise. Figure 2-3 shows a sequence of output profiles, in 20-year stages from 1800 to 2100, responding to sea level change at the Isle of Purbeck (95th percentile of the UKCP18 RCP 8.5 sea level projection, region 36 in Figure 2-1). The profiles during the early 19th century are similar and equally spaced. Accelerated sea level rise can be seen by the end of that century, and the profile shape begins to respond. The higher sea levels allow waves to break on higher elevations in the profile. These are steeper, and so the waves break more aggressively, and are better able to erode material. As a result the profile retreats more quickly, but also responds by changing shape. The sea level change and the resulting recession through the 20th century are noticeably higher than those of the 19th century, but the change occurs more rapidly through the 21st century. The last stage of the simulation (the last 20 years) shows the same retreat as was seen in the first 140 years (in other words, a 7-fold increase has occurred) and the profile has become noticeably steeper.

2.2 Regionalised simulations

Although SCAPE can be used to represent 3-dimensional coasts (see, for example, Walkden and Hall, 2005; Dickson and others, 2007; and Walkden and others, 2015), that approach was beyond the resources available to this large-scale study. Instead, a 2D approach was adopted, in which regions of shore (typically several 10s of kilometres in length) were treated as one unit. The regions, which are shown in Figure 2-1, were primarily defined on the basis of shoreline angle, as described in the technical report (Environment Agency, 2025d). This regionalised approach sacrificed local detail to gain general understanding of the importance of variations in tidal range, history of relative sea level change and wave climate. This simplification made the study possible, but has important implications, particularly with respect to the representation of geology and beaches.

The 2-dimensional treatment meant that alongshore interactions between adjacent areas could not be captured. Where these are important, it is recommended that bespoke 3-dimensional modelling be considered.

Clearly, this regionalisation masks local differences in geology. This problem is managed by (1) assuming geology to be constant across the shore and (2) by using the historic recession rate as a proxy for geological strength. This is discussed in more depth in section 1.5 of the technical report (Environment Agency, 2025d). It means that the sensitivity indicators are expressed relative to (normalised to) a historic 'baseline' recession. The baseline period has been set to the last 100 years (1920 to 2020) to encompass one century of change. This approach is similar to that used in Sunamura's Shore Platform Geometrical Model (Sunamura, 1992) and the modified Bruun rule (Dean, 1991); this is discussed below in section 5.2.1.

Beaches were not included to prevent the number of simulations becoming unmanageable. This was justified on the basis of sensitivity testing, which showed a similar response from shores with beaches of limited volume to those with no beach. That work is discussed in section 6 of Environment Agency (2025d), and its implications are returned to in section 5.3 of this method report. In addition, no attempt was made to calibrate each model to local conditions; each was run in a simplified, idealised way. The outputs of such models were compared to those of calibrated models in the scoping stage of this study (noting that the main output of interest was sensitivity to accelerating sea level rise, rather than absolute recession rate or shore profile shape). It was found that the simplified simulations gave sufficiently comparable and conservative results (see Environment Agency, 2025c and 2025d).

Similarly, although SCAPE can be used to represent the effects of some coastal protection measures, including seawalls, revetments, groynes and beach nourishment (see, for example, Walkden and Hall, 2005; Dawson and others, 2009; Walkden and Hall, 2011; Walkden and others, 2016; and WSP, 2019), these were not included. The scope of this study was restricted to the effects of relative sea level change in the absence of such interventions.

2.2.1 Wave growth

This study focuses on the sea level rise aspect of climate change. It was considered important to also account for the possibility of growth in wave conditions, to reduce the chances of underestimating future recession.

The UKCP18 wave projections are not as fully quantified as their sea level rise projections, and this necessitated a greater level of interpretation, which is described in section 3.5.2 of the technical report (Environment Agency, 2025d).

A conservative estimate of wave growth was derived and applied to all simulations from 1990. This assumed that wave heights (both 'average' and 'extreme') would grow by up to 20% by the end of the 21st century, and then remain at that level. Wave periods were assumed to grow by the square root of the wave height increase, to preserve wave steepness. The models also accounted for the effect of sea level rise on inshore depth-limited wave heights.

2.3 Variation between regions

As noted above, one of the main aims of the work was to quantify and map spatial variation in indicators of cliff toe sensitivity to accelerated sea level rise. These account for regional changes in:

- tidal range
- wave climate
- history of sea level change
- future relative sea level change as described by UKCP18 projections, which include isostatic adjustment of ground levels

The results are reported in Environment Agency (2025d).

This aim was only partially met. Issues were encountered in quantifying relative sea level change during the last 10,000 years (the late Holocene). A conservative approach was taken in defining them, in line with the general approach taken to managing uncertainty within this study, and this seems to have led to overestimating them in northern areas. As a result, the models showed a physically unrealistic situation in which sea levels retreated down shore platforms during recent millennia, 'abandoning' cliffs, which, therefore, showed no recession (see section 5.3 of Environment Agency, 2025d). No results can be provided in these regions unless the models are run with more realistic representations of Holocene sea level change. The affected areas are marked with black lines in Figure 2-1.

In other areas, particularly high sensitivity was found, due to sea levels in recent millennia slowly declining or remaining near static. These led to long-term shallowing of the profile, wide dissipative shore platforms and low recession rates. This, in turn, led to high measures of sensitivity (see section 5.5 of Environment Agency, 2025d). Those regions are marked with red lines in Figure 2-1, and further comment is made in section 5.4.

3 Rapid assessment example

This example demonstrates the use of indicators of cliff toe sensitivity averaged over decades to conservatively estimate future retreat of the cliffs of Blue Anchor in Somerset. A single sea level rise trajectory is assumed, and results are calculated for 2070.

It is stressed that this is an example of one possible way of applying the sensitivity indicators; it is not presented as a template for a holistic assessment of cliff recession.

3.1 Setting

The Blue Anchor cliffs are around 400 metres in length, and have formed in Mercia Mudstone; a relatively homogenous and iron-rich sedimentary rock.

Figure 3-1: Aerial photograph of the Blue Anchor cliffs with map insert to show location

The cliffs here are around 20 metres high, and typically fail through shallow landslides driven by wave scour. These landslides deposit piles of poorly-sorted debris (talus cones) at the cliff toe (Figure 3-2), which have little strength and rapidly erode when subjected to wave attack.

Figure 3-2: Photo showing an example of the talus cones at the Blue Anchor cliffs

The cliff toe is partially protected by a coarse (gravel/cobble) beach, which gives way to a sandy beach. Both are perched on a shore platform, which is generally exposed seaward of the sand, and outcrops through the beach deposits (Figure 3-3).

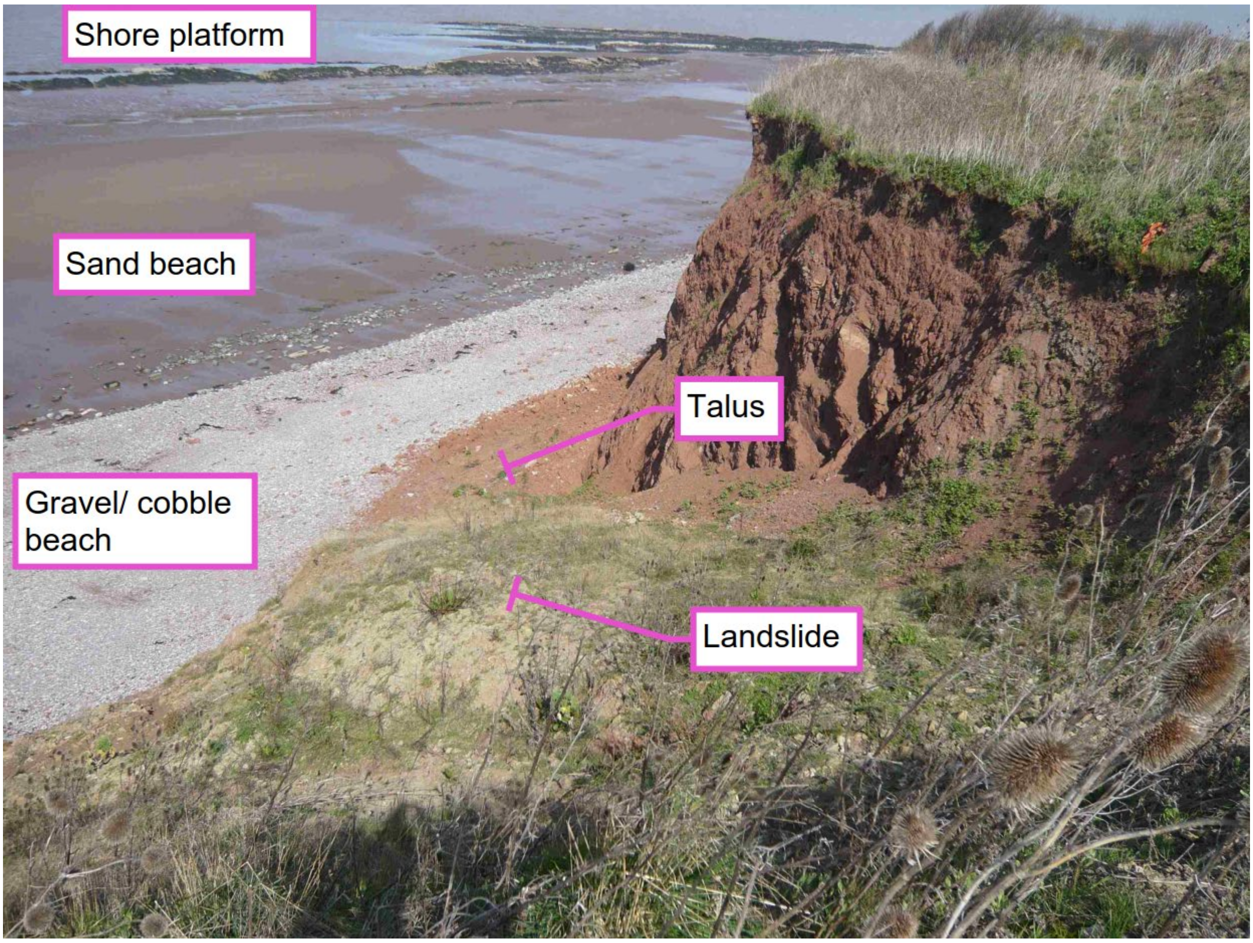

Figure 3-3: Photo showing the Blue Anchor cliff with labels to show the gravel/cobble beach, sand beach, shore platform, talus and landslide

The shore platform (Figure 3-4) plays a crucial role in protecting the cliffs from wave attack. Most wave energy is dissipated across the shore platform; only a small proportion reaches the cliff toe.

Figure 3-4: Two photos showing views of the Blue Anchor shore platform

3.2 Calculations

The trajectory of sea level rise assumed for this example is the upper limit (95th percentile) of the RCP 8.5 scenario; the UKCP18 projection for that scenario, for this part of Somerset, is shown in Figure 3-5.

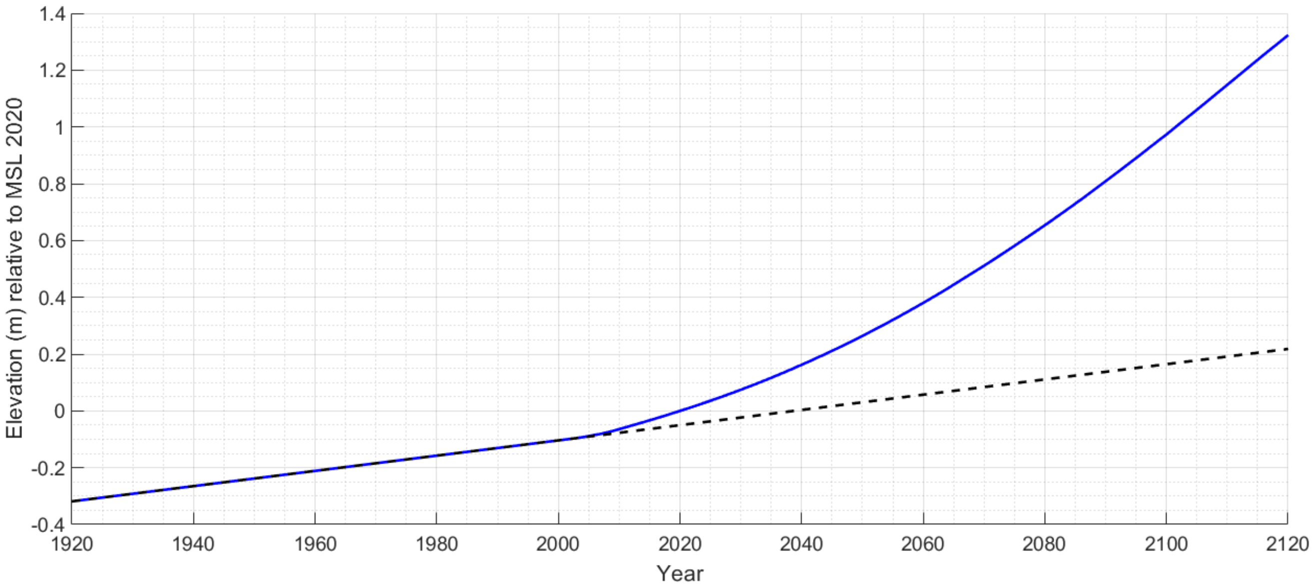

Figure 3-5: Graph showing the UKCP18 sea level rise trajectory for the upper limit of the RCP8.5 scenario as a blue line. The 20th century trend is extrapolated and shown as a dashed black line

Figure 3-5 shows elevation on the y-axis in metres relative to MSL 2020, and on the x-axis years from 1920 to 2120. The total sea level rise projected for 2120 under this scenario is around 4.6 times the sea level rise that would have been expected from the recent historic rate (which is projected on the graph as a dashed black line).

The map in Figure 2-1 was used to identify the region that these cliffs are within (region 55). A screenshot of the indicators of cliff toe sensitivity including that region is shown in Figure 3-6. These data can be found in the accompanying spreadsheet tool (Environment Agency, 2025a). This dataset contains annual sensitivity indicators for 3 percentiles (5th, 50th and 95th) of 3 RCP scenarios (RCP 2.6, RCP 4.5 and RCP 8.5).

This example uses the 95th percentile values for the 2050s, 2070s and 2120s, so for 2055 the cliff toe sensitivity indicator is 0.62 (Column AT, Row 210). Corresponding values for 2075 (Column AT, Row 210) and 2125 (Column AT Row 280) are 1.11 and 2.85. Each represents an acceleration of the baseline cliff toe recession (the recession that occurred during the 100 years between 1920 and 2020).

	A	AQ	AR	AS	AT	AU	AV	AW	AX	AY	A
1	RCP->	RCP 8.5	RCP 8.5	RCP 8.5	RCP 8.5	RCP 8.5	RCP 8.5	RCP 8.5	RCP 8.5	RCP 8.5	RCP
2	Percentile ->	95th Percentile	95th Percentile	95th Percentile	95th Percentile	95th Percentile	95th Percentile	95th Percentile	95th Percentile	95th Percentile	95th Pe
3	Sensitivity->	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Nor
4	**Year**	Region 52	Region 53	Region 54	Region 55	Region 56	Region 57	Region 58	Region 59	Region 60	Regic
203	2048	0.51	0.49	0.49	0.48	0.49	0.45	0.48	0.50	0.47	0.5
204	2049	0.53	0.51	0.51	0.50	0.51	0.47	0.50	0.53	0.49	0.5
205	**2050**	0.55	0.53	0.53	0.52	0.53	0.48	0.53	0.55	0.51	0.5
206	2051	0.57	0.55	0.55	0.54	0.55	0.50	0.55	0.57	0.54	0.5
207	2052	0.60	0.57	0.58	0.56	0.57	0.52	0.57	0.59	0.56	0.6
208	2053	0.62	0.59	0.61	0.58	0.59	0.54	0.59	0.61	0.58	0.6
209	2054	0.64	0.61	0.63	0.60	0.61	0.56	0.61	0.64	0.60	0.6
210	2055	0.67	0.64	0.65	0.62	0.64	0.58	0.64	0.66	0.62	0.6
211	2056	0.69	0.66	0.67	0.64	0.66	0.60	0.66	0.68	0.64	0.7
212	2057	0.71	0.68	0.69	0.67	0.68	0.62	0.68	0.70	0.66	0.7
213	2058	0.74	0.70	0.72	0.69	0.70	0.64	0.70	0.73	0.68	0.7
214	2059	0.76	0.72	0.74	0.71	0.72	0.66	0.72	0.75	0.71	0.7
215	**2060**	0.79	0.75	0.76	0.73	0.75	0.68	0.75	0.78	0.73	0.7
216	2061	0.81	0.77	0.79	0.75	0.77	0.70	0.77	0.80	0.75	0.8
217	2062	0.84	0.80	0.81	0.78	0.79	0.72	0.79	0.83	0.78	0.8
218	2063	0.86	0.83	0.84	0.80	0.82	0.74	0.82	0.85	0.80	0.8
219	2064	0.89	0.85	0.86	0.82	0.84	0.77	0.84	0.88	0.83	0.9
220	2065	0.92	0.88	0.89	0.85	0.87	0.79	0.87	0.91	0.85	0.9
221	2066	0.95	0.91	0.91	0.87	0.90	0.81	0.90	0.94	0.87	0.9
222	2067	0.97	0.93	0.94	0.90	0.92	0.83	0.92	0.97	0.90	0.9
223	2068	1.00	0.96	0.97	0.92	0.95	0.86	0.95	1.00	0.92	1.0
224	2069	1.03	0.99	1.00	0.95	0.98	0.88	0.98	1.03	0.95	1.0
225	**2070**	1.06	1.02	1.02	0.97	1.00	0.90	1.00	1.05	0.97	1.0

RCP2.6 5th% | RCP2.6 50th% | RCP2.6 95th% | RCP4.5 5th% | RCP4.5 50th% | RCP4.5 95th% | RCP8.5 5th% | RCP8.5 50th% | RCP8.5 95th%

Figure 3-6: Screenshot from the accompanying spreadsheet tool showing indicators of cliff toe recession sensitivity for RCP 8.5 and the 95th percentile

Baseline recession rates are typically calculated from historic maps or aerial photography or adopted from previous coastal studies. The Futurecoast project was commissioned by Defra in 2002 and information was made available via the National Network of Regional Coastal Monitoring Programmes website in 2018 (National Network of Regional Coastal Monitoring Programme, 2018). The data set also includes estimates of historic cliff retreat. In this case, a baseline rate was taken from WSP (2020), which compared 1902 Ordnance Survey mapping with aerial photography from 2018, provided by the Southwest Regional Coastal Monitoring Programme. The average recession of the Blue Anchor cliffs between those dates was found to be 30.6 metres, which provides a trend (recession rate) of 0.26 metres per year (Figure 3-7).

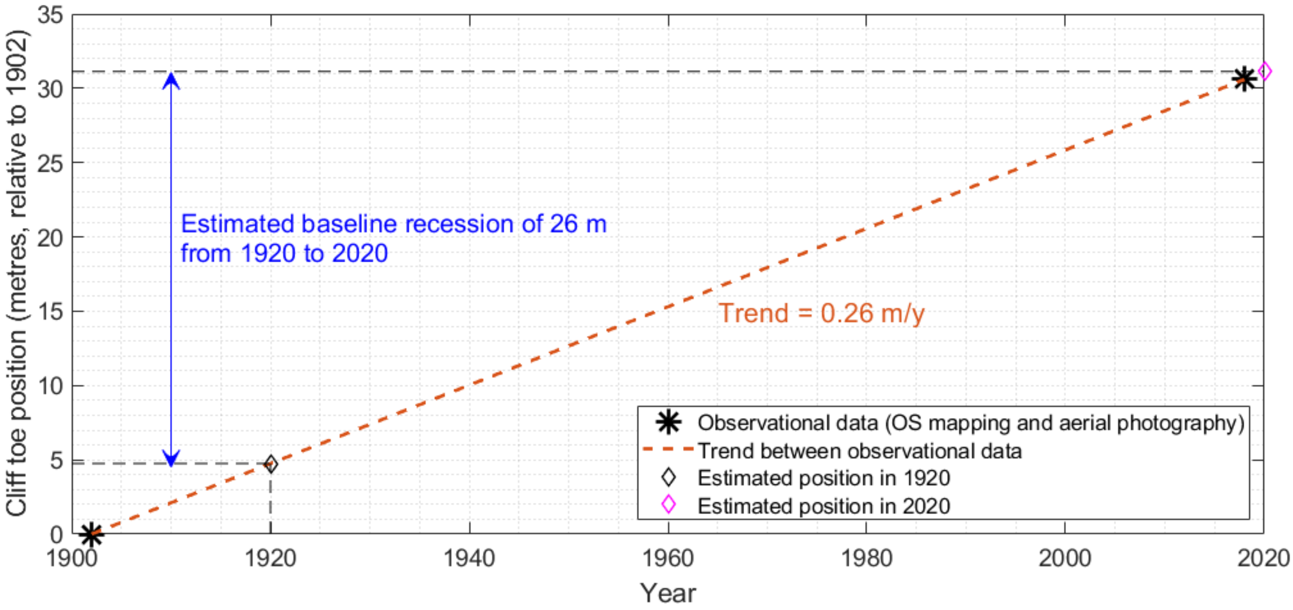

Figure 3-7: Graph showing the baseline recession estimate for the Blue Anchor cliff toe

Figure 3-7 shows on the y-axis cliff toe position (in metres relative to 1902) from 0 to 35 metres and on the x-axis years from 1900 to 2020. The trend has been used to estimate a recession distance of 26 metres for the baseline period (the 100 years between 1920 and 2020).

In Table 3-1, this baseline rate is multiplied by sensitivity indicators taken from Figure 3-6 to conservatively estimate future recession for the 2050s, 2070s and 2120s.

Table 3-1: Estimates of baseline and future recession of the Blue Anchor cliff toe, assuming (in column F) continuation of historic rates of change and (in column G) the 95th percentile of the UKCP18 RCP8.5 relative sea level projection

(A) Historic recession rate in metres per year	(B) Estimated baseline recession (for the 100 years to 2020) in metres	(C) Future year	(D) Indicator of cliff toe sensitivity (from Figure 3-6) unitless	(E) Estimation period (column C minus 2020) in years	(F) Estimated recession if historic rates were to continue (multiple of columns A and E) in metres relative to cliff toe position in 2020	(G) Conservatively estimated recession accounting for sea level change (multiple of columns B and D) in metres relative to cliff toes position in 2020
0.26	26	2055	0.62	35	9 m	16 m
0.26	26	2075	1.11	55	14 m	29 m
0.26	26	2125	2.85	105	27 m	74 m

Note for Table 3-1: the results in column G should be viewed as conservative upper estimates, for reasons discussed in the technical report (Environment Agency, 2025d) and in section 5 of this method report.

4 General assessment example

The previous section demonstrated a very simple application of the indicators of cliff toe sensitivity. The following shows a more detailed assessment, which accounts for:

- recession data from a different baseline period
- uncertainty in historic recession rate
- detail in cliff toe position
- different adjoining geological units
- different future years

As before, this example adopts the upper limit of the UKCP18 RCP 8.5 sea level trajectory. Results are provided for 3 epochs; the 2050s, the 2080s and the 2120s.

It is reiterated that this is an example of one possible way of applying the sensitivity indicators; it is not presented as a template for a holistic assessment of cliff recession.

4.1 Setting

This example includes the cliffs from Blue Anchor (which were described in the previous section) to Watchet, a shoreline distance of around 4 km (Figure 4-1). East of Blue Anchor the cliffs are shaped from Langport Member and Blue Lias Formation mudstone and limestone; interbedded sedimentary rock formed in shallow lime-mud seas (as defined by the British Geological Survey Geology Viewer). This meets the Mercia Mudstone of Blue Anchor at a sub-vertical fault (Figure 4-2).

Figure 4-1: Annotated aerial photograph showing 4 cliff behavioural units (CBU) boundaries (red lines) along the coast starting at Blue Anchor along to Warren Farm, then Holiday village and ending at West Watchet.

Figure 4-2: Photograph showing the Blue Anchor fault where mudstone and limestone meet Mercia Mudstone

The geology east of the Blue Anchor fault is diverse in the aspects of lithology that influence resistance to wave attack, including strength and stratification. As a result, the cliffs show greater variability in their processes of erosion and failure and are more irregular in form than those of Blue Anchor. WSP (2020) identified 3 cliff behavioural units (CBUs), in addition to the Blue Anchor unit, named Warren Farm, Holiday Village and West Watchet (Figure 4-1 and Figure 4-3). The CBU concept is essentially a means of segmenting alongshore extents of cliffed coast in terms of their behaviour (Lee and Clark, 2002). The purpose of this example is to illustrate the prediction of cliff recession, rather than the application of the CBU concept, and so the definition of the units will not be described here.

Figure 4-3: Photograph showing the view from the West Watchet cliff behavioural unit (CBU), across the Holiday Village CBU to the eastern end of the Warren Farm CBU

Underneath the diversity of these cliffs, the basic elements of the shore profiles are similar to those of Blue Anchor; a cliff toe exposed to occasional wave attack, beach deposits or varying grain size and a wide shore platform.

Figure 4-4a: Photograph showing Warren Farm shore platform

Figure 4-4b: Photograph showing Warren Farm beach

Figure 4-4c: Photograph showing Holiday Village cliff behavioural units

Figure 4-4d: Photograph showing West Watchet cliff behavioural units

A significant deviation from this pattern is found towards the western end of Warren Farm, where a large complex landslide obscures the toe, and apparently has done for many decades (Figure 4-5).

Figure 4-5: Photograph showing the Warren Farm complex landslide

4.2 Historic retreat

As with the previous example, information on the historic retreat of the cliff toe is taken from WSP (2020). In that study, recession distances were calculated along a series of shore-normal transects (10 metres apart) to provide a population of estimates. Example transects are shown in Figure 4-6 and Figure 4-7, and the cliff toe recession distances from all the transects are shown in Figure 4-8.

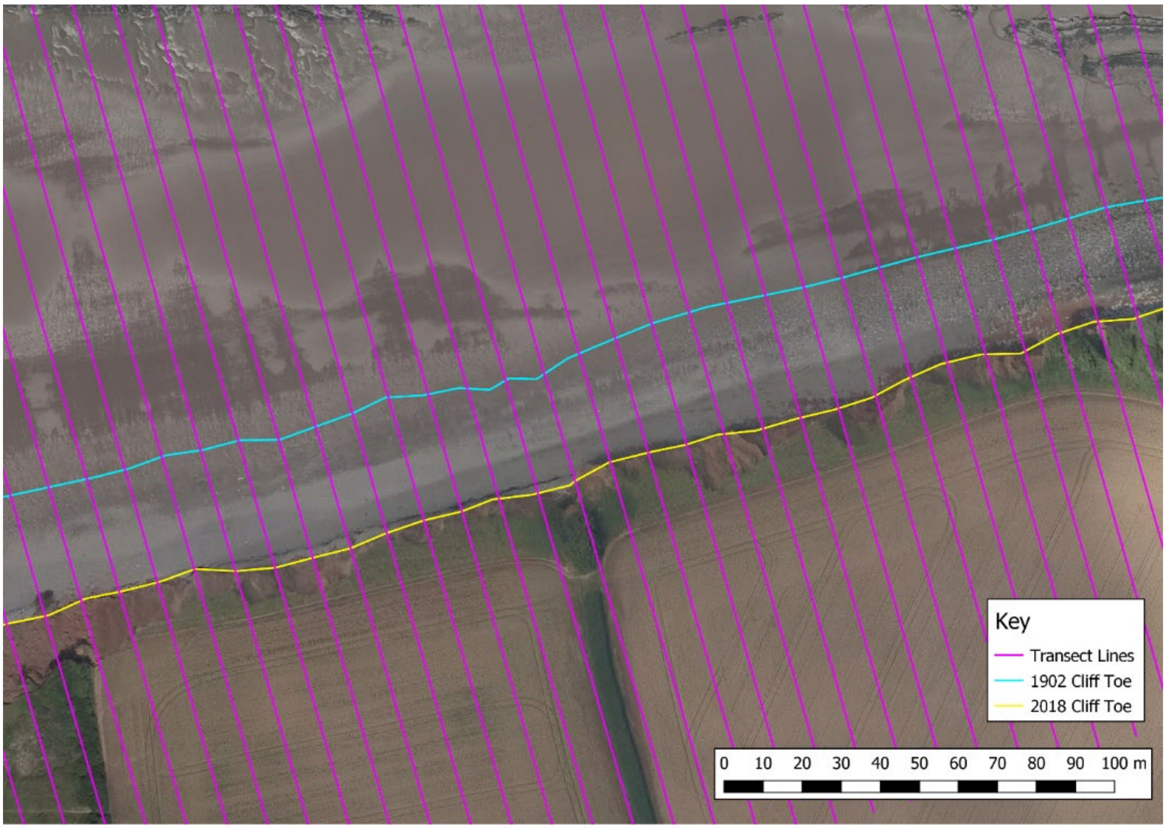

Figure 4-6: Aerial photograph with overlays shows example transects (pink lines) through the Blue Anchor cliffs. The cliff toe position is shown for 1902 (blue line) and 2018 (yellow line)

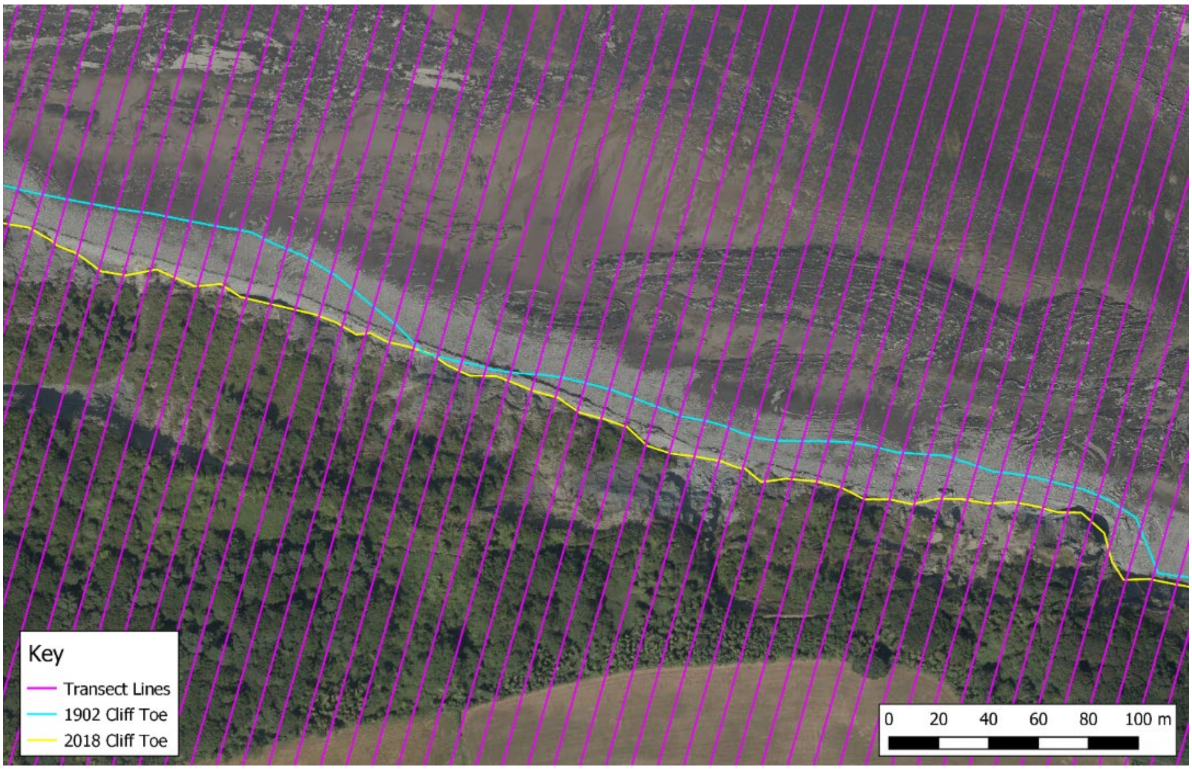

Figure 4-7: Aerial photograph with overlays shows example transects (pink lines) through a section of the Warren Farm area, showing the cliff toe position in 1902 (blue line) and 2018 (yellow line)

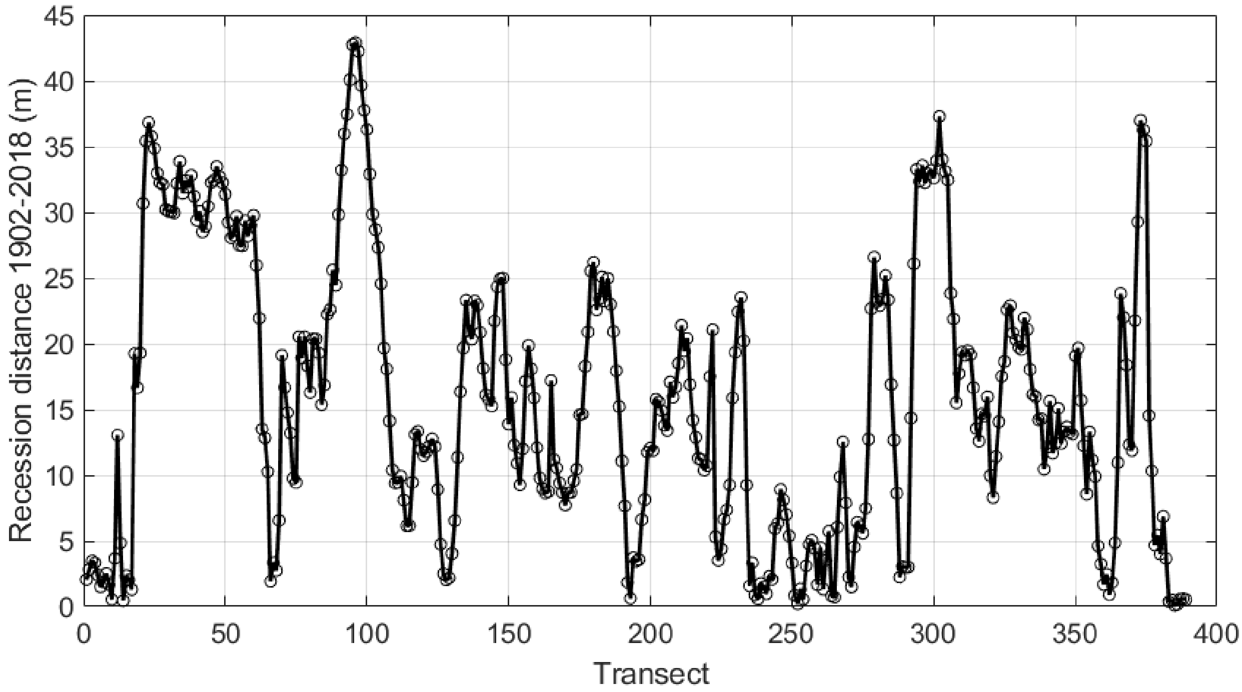

Figure 4-8: Graph shows cliff toe recession 1902 to 2018 at 10 m intervals, across the 400 transects starting from the west at Blue Anchor

Figure 4-8 shows considerable alongshore variability in the recession for many reasons, including differences in lithological conditions, topography and wave exposure. WSP (2020) used the 4 cliff behavioural units described above to manage this, and the recession observations assigned to each are indicated in Figure 4-9.

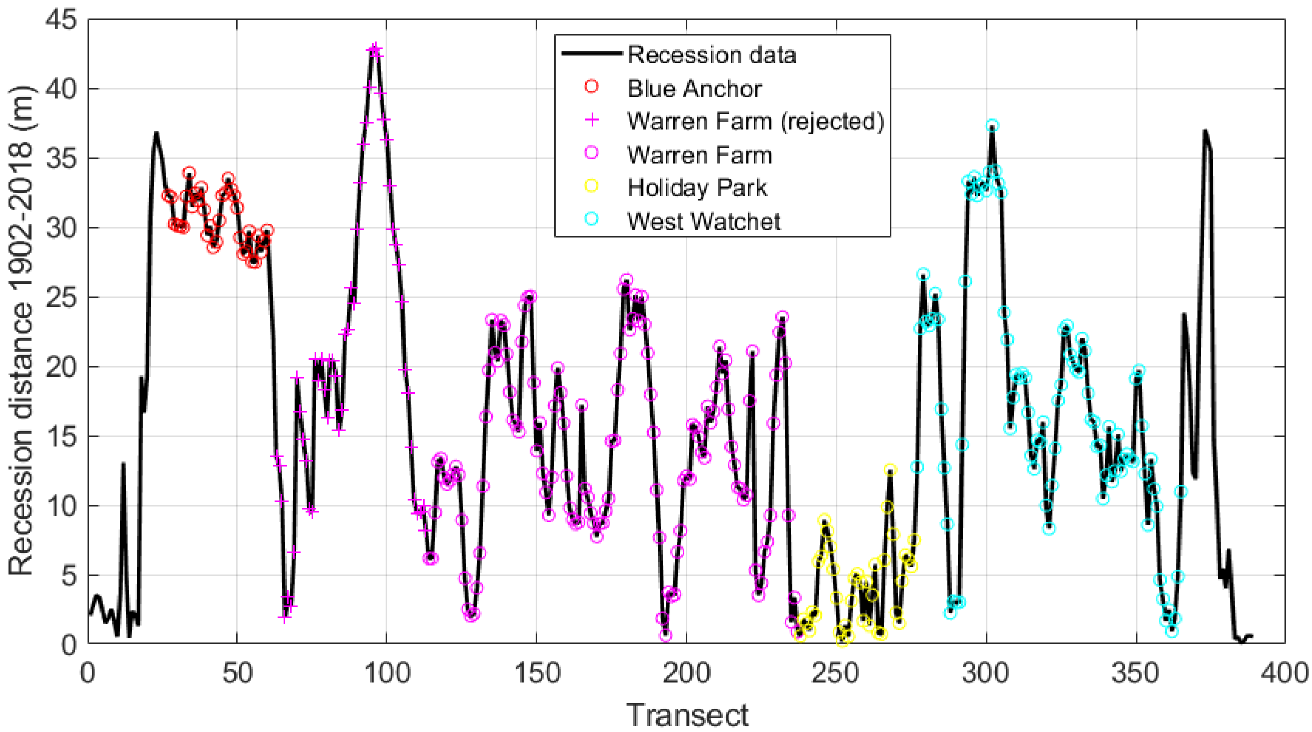

Figure 4-9: Graph shows cliff toe recession (in metres) from 1902 to 2018 grouped by cliff behavioural unit against 400 transects (spaced at 10 m intervals) from Blue Anchor to West Watchet

The following information from Figure 4-9 is noted, namely that:

- the cliffs at the lowest and highest transect numbers were considered likely to be influenced by coastal defences, and so the data in these areas were rejected
- data from the western side of the Warren Farm CBU (indicated with magenta crosses) were rejected because the large landslide in this area (shown in Figure 4-5) made estimates of toe recession rates unreliable
- a significant trend was identified in the West Watchet CBU such that recession was greater in the west (lower transect numbers) than in the east (higher transect numbers) – this trend was accounted for by adopting different recession rates for each

WSP (2020) used this grouping to estimate the changes shown in Table 4-1.

Table 4-1: Position of the cliff toe in 1902 relative to 2018, with negative values indicating a seaward position

Cliff behavioural unit	Position minimum (m)	Position mean (m)	Position maximum (m)
Blue Anchor	-29.3	-30.6	-31.8
Warren Farm	-9.2	-13.6	-18.0
Holiday Village	-2.2	-4.2	-6.2
West Watchet (Left Hand Side)	-18.7	-24.7	-30.7
West Watchet (Right Hand Side)	-3.6	-9.6	-15.6

Note for Table 4-1: the variability in the Blue Anchor CBU is significantly less than in the other units, reflecting the greater lithological heterogeneity in this area.

4.3 Future retreat

As with the previous example, future cliff retreat is conservatively estimated by combining the historic recession (Table 4-1) with the indicators of cliff toe sensitivity provided for this region. This example involves more detailed use of the sensitivity indicators, and so this section begins with some background on how they were derived.

Figure 4-10 shows outputs from one of the SCAPE simulations run for region 55, which includes the Blue Anchor to Watchet area.

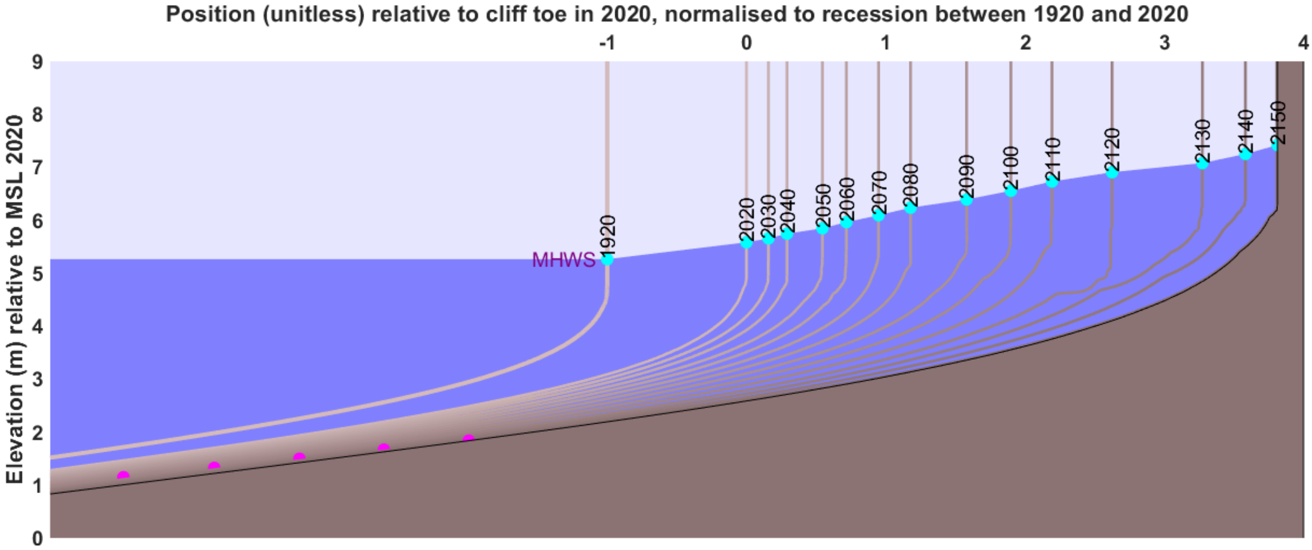

Figure 4-10: Graph displaying the profiles from one SCAPE simulation of the upper shore profile in region 55 (the Blue Anchor to Watchet area), under the 95th percentile of the UKCP18 RCP 8.5 sea level projection

Figure 4-10 shows a series of shore profiles (each is date stamped), progressing through time from 1920 to 2020 in 20-year stages; each is marked with a date. The y-axis is elevation in metres relative to MSL 2020. The x-axis represents horizontal position, normalised to the recession (in metres) that occurred in the model between 1920 and 2020 (which has been adopted as the baseline period). Zero on this axis is aligned to the position in 2020. The rising sea level is represented by magenta dots, representing mean sea level, and cyan dots represent the rising mean high-water spring.

This figure gives a good impression of the acceleration in shore retreat as the sea level rises. For example, if future recession were similar to the historic recession, then the cliff shown in 2120 would be aligned with position 1.0 on the horizontal axis (that is, the same distance to the right of the 2020 position as the 1920 position was to its left). In fact, the 2120 position is close to 2.6, showing the cliff face moving around 2.6 times the distance it moved between 1920 and 2020.

Figure 4-10 represents one of the set of 100 simulations that were run for this condition for region 55. The average output of the full set is shown as the solid line in the graph in Figure 4-11.

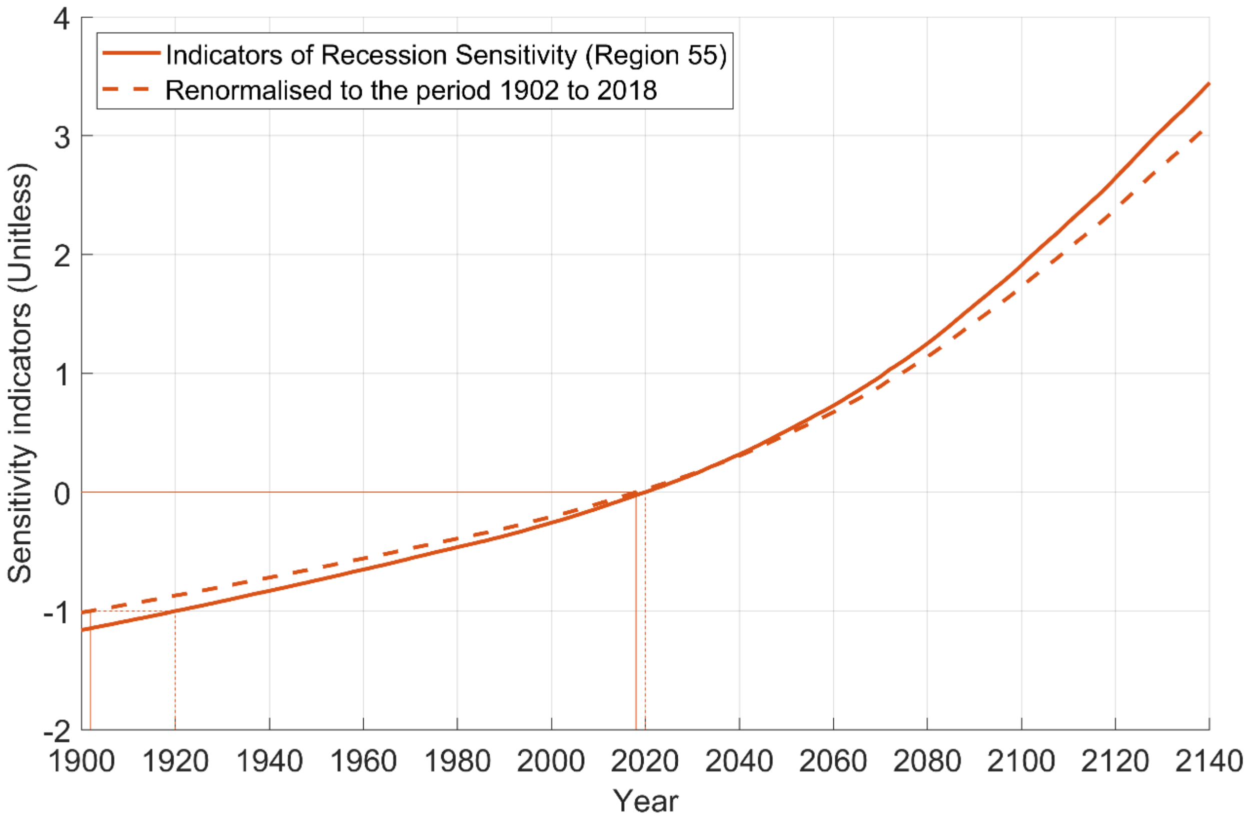

Figure 4-11: Graph showing indicators of cliff toe sensitivity for the Blue Anchor to Watchet area under the upper limit of the local UKCP18 RCP8.5 sea level trajectory (average of 100 simulations)

Figure 4-11 represents the recession of the cliff toe through time, between 1900 and 2140. It has been aligned and normalised to the baseline period, so that the cliff is at position -1.0 in 1920 and 0.0 in 2020.

The dates at which cliff toe positions were captured at the site (1902 and 2018) do not precisely match this baseline period, and the curve in Figure 4-11 has been adjusted accordingly, so that the cliff is at position -1.0 in 1902 and 0.0 in 2018; the result is shown as a dashed line.

This re-baselined curve was then then scaled to the data in Table 4-1 to project cliff toe positions for each of the cliff behavioural units.

For example, Table 4-1 records that, for the Warren Farm unit, the 1902 cliff toe position was between -9.2 metres (lower estimate) and -18.0 metres (upper estimate) from its 2018 position, with a mean estimate of -13.6 metres (where negative values indicate a seaward position). Those positions are shown in Figure 4-12 as black crosses (for the limits) and a black diamond (for the mean estimate) close to the left-hand side of the graph.

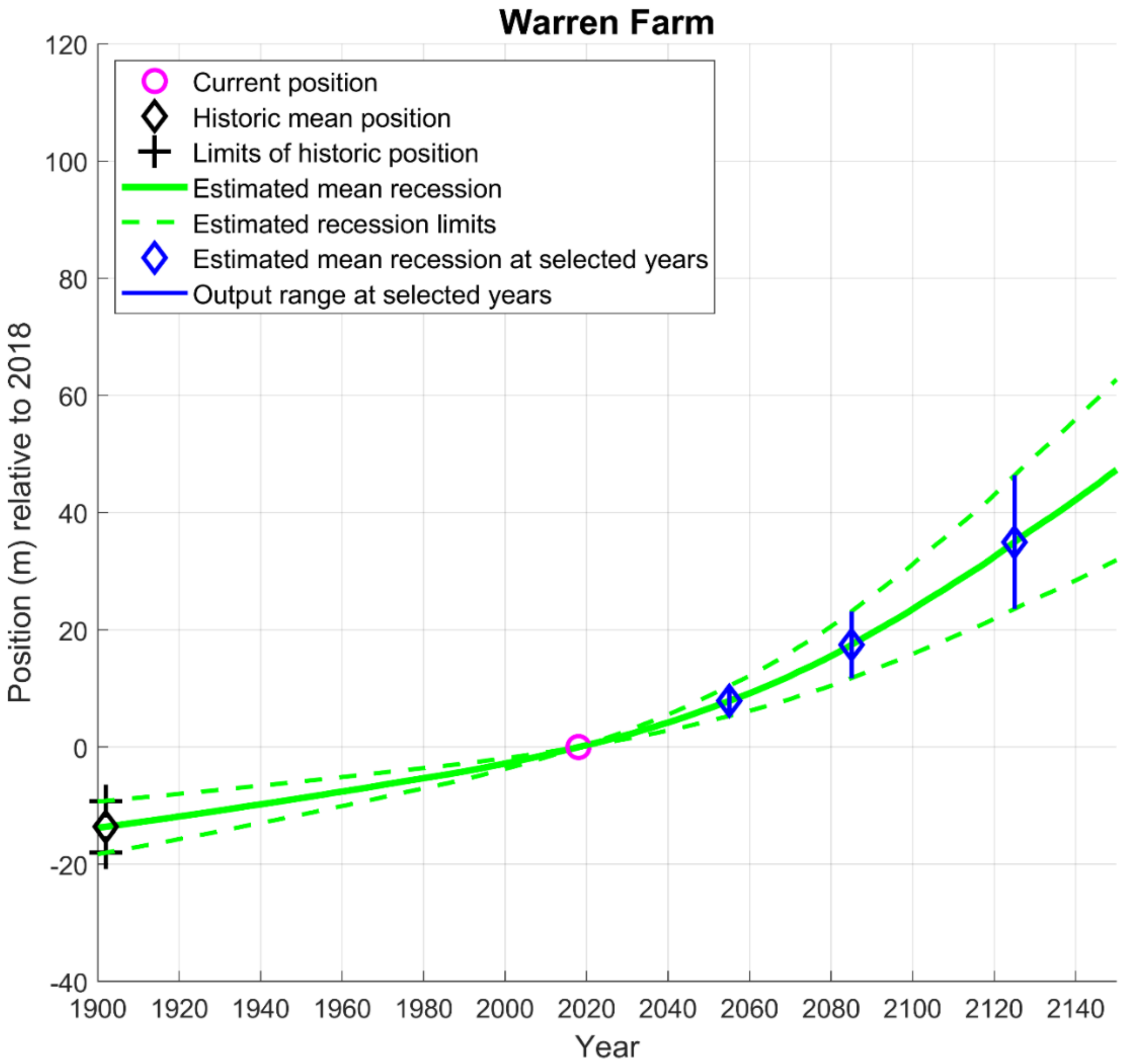

Figure 4-12: Graph showing the results from Figure 4-11 scaled to the recession data for the Warren Farm cliff behavioural unit

Figure 4-12 shows position (in metres) relative to 2018 on the y-axis against the year from 1900 to 2140 on the x-axis. The curves extending from the historic mean position and limits of historic position are copies of the dashed line in Figure 4-11, which have been scaled to pass through zero in 2018. The parts of these curves that fall to the right-hand side of the year 2018 can be treated as projections of future cliff toe position. The recession projected for the future years selected for this study (2055, 2085 and 2125) are illustrated in blue and are also shown in Table 4-1.

Equivalent graphs for the other units are shown as Figure 4-13 to Figure 4-16; all have been plotted to the same axes to aid comparison.

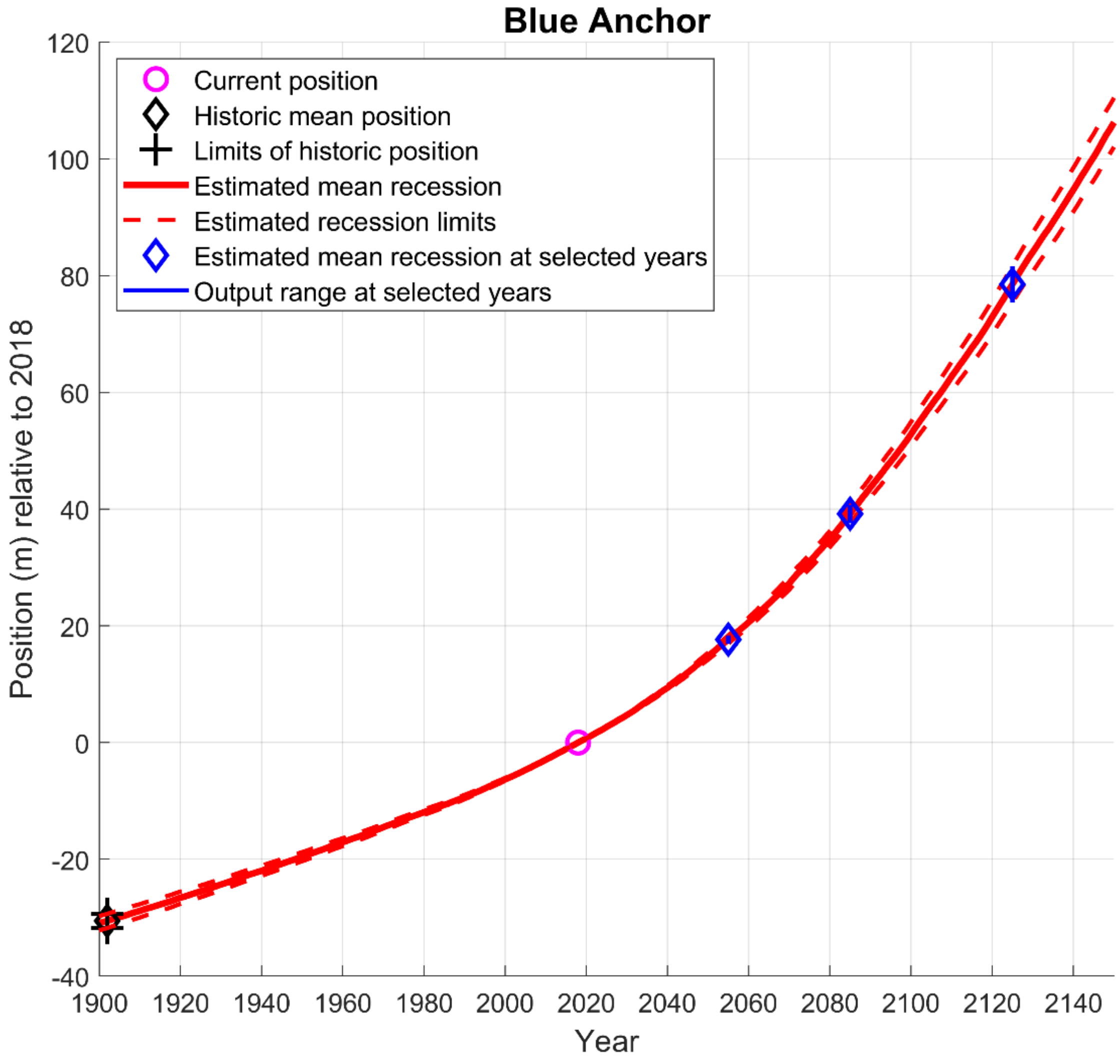

Figure 4-13: Shows the results from Figure 4-11 scaled to the recession data for the Blue Anchor cliff behavioural unit.

In Figure 4-13 the projected future change is higher for the Blue Anchor unit than the Warren Farm unit because of its softer geology and, therefore, the greater historic change. The limits of the projections, shown as dashed lines, are closer together, reflecting the low variability of the historic changes.

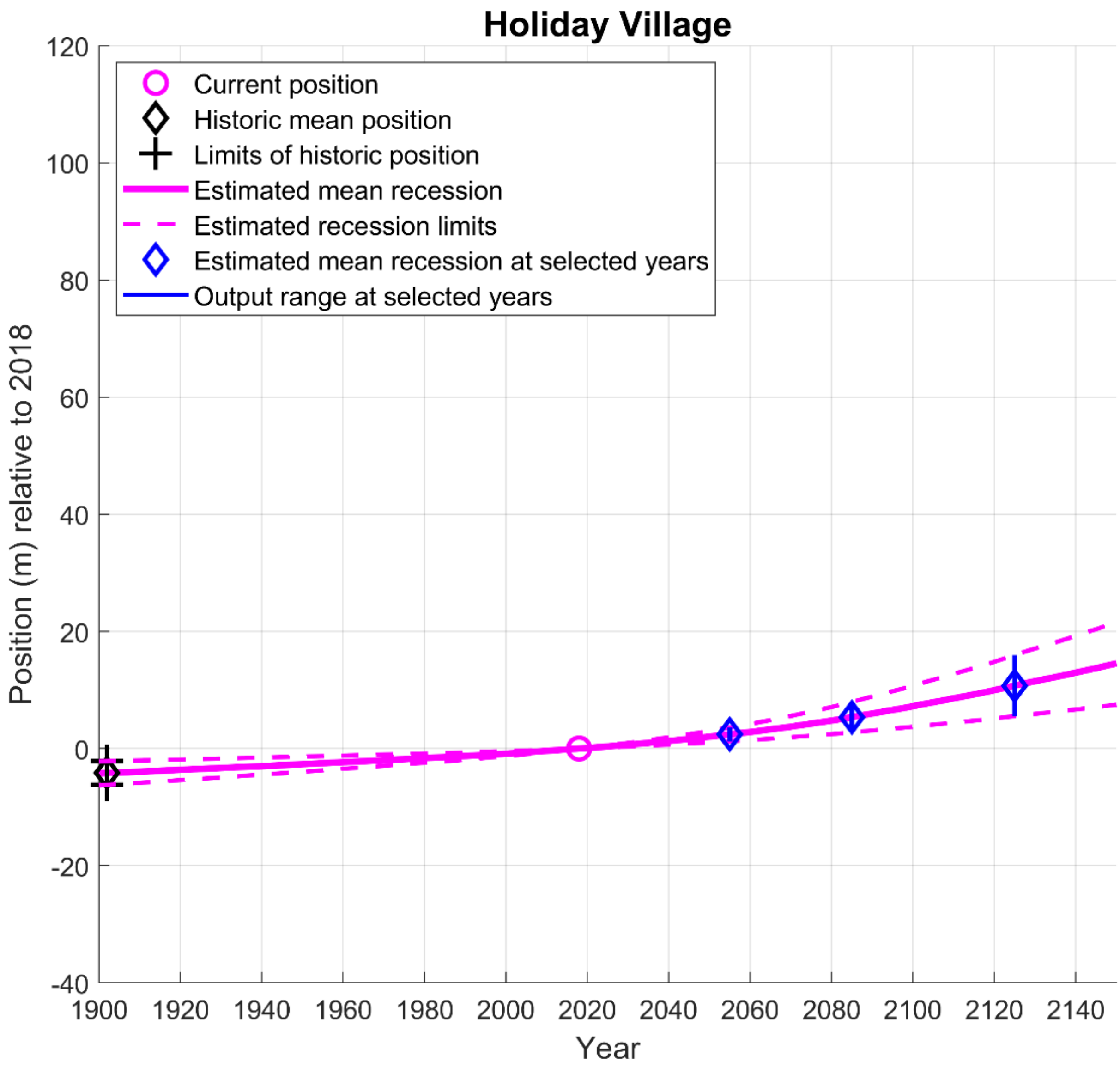

Figure 4-14: Shows the results from Figure 4-11 scaled to the recession data for the Holiday Village cliff behavioural unit

In Figure 4-14 the relatively small Holiday Village unit has exhibited low historic change due to resistant geology, but has relatively high uncertainty. As a result, the projections show high variability around a small average recession.

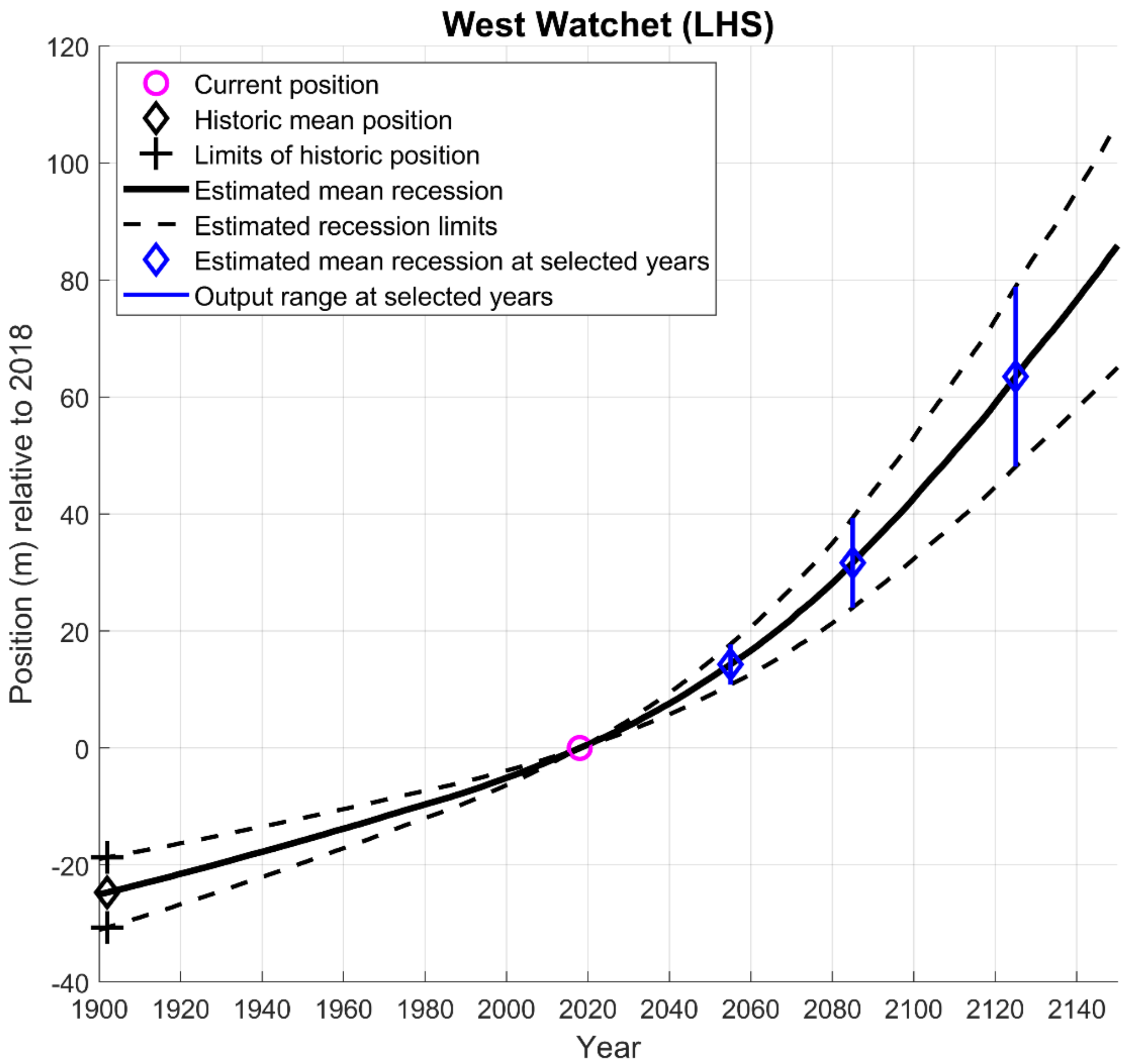

Figure 4-15: Presents the results from Figure 4-11 scaled to the recession data for the west (left-hand side) of the West Watchet cliff behavioural unit

In Figure 4-15 the uncertainty range (that is, the distance between the upper and lower limits) is the same throughout the West Watchet unit, but the observed historic change and projected future change are greater at the western end of the unit (the left-hand side when facing the sea, Figure 4-15), than at the eastern end (Figure 4-16).

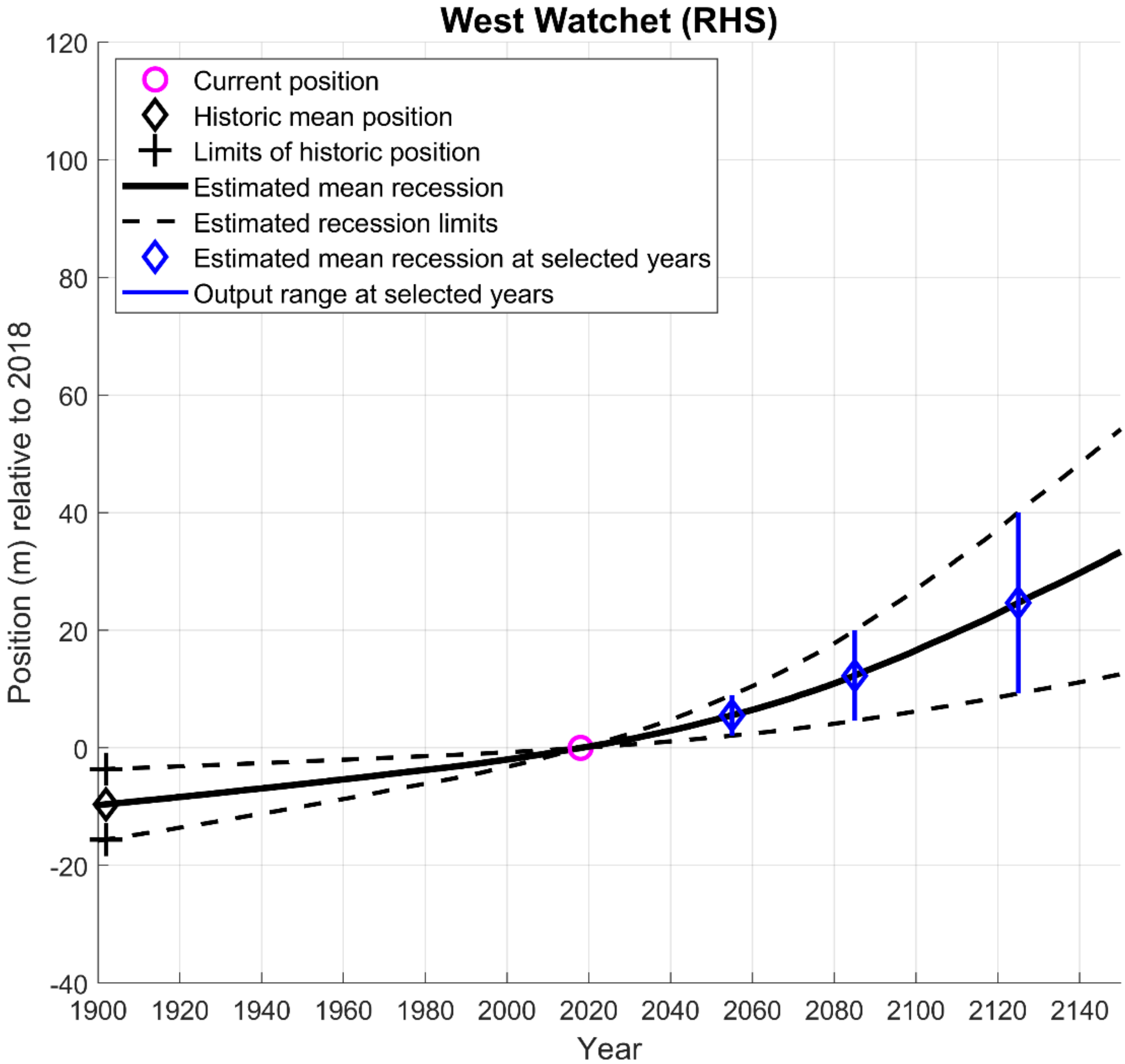

Figure 4-16: Shows the results from Figure 4-11 scaled to the recession data for the east (right-hand side) of the West Watchet cliff behavioural unit

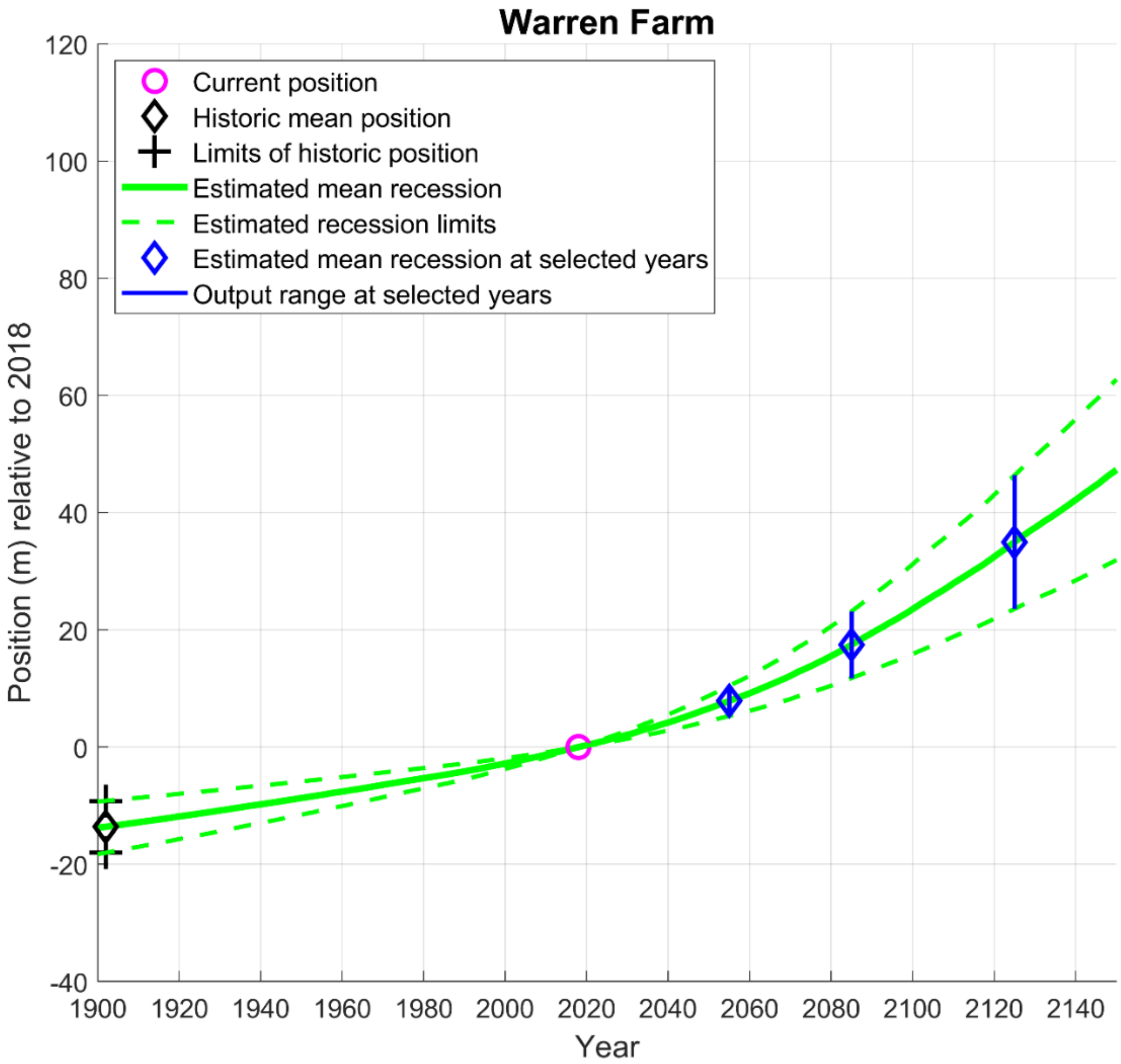

Figure 4-12 to Figure 4-16 illustrate how differences in resistance to wave attack can be accounted for, using historic change (and its variability) as a proxy. The derived projections of future recession are recorded in Table 4-2.

Table 4-2: **Projected cliff toe movement relative to its mean position in 2018 (in metres)**

Cliff unit	Year	Lower estimate (m)	Middle estimate (m)	Upper estimate (m)
Blue Anchor	2055	17	18	18
Blue Anchor	2085	38	39	41
Blue Anchor	2125	75	79	82
Warren Farm	2055	5	8	10
Warren Farm	2085	12	17	23
Warren Farm	2125	24	35	46
Holiday Village	2055	1	2	4
Holiday Village	2085	3	5	8
Holiday Village	2125	6	11	16
West Watchet (LHS)	2055	11	14	18
West Watchet (LHS)	2085	24	32	39
West Watchet (LHS)	2125	48	64	79
West Watchet (RHS)	2055	2	6	9
West Watchet (RHS)	2085	5	12	20
West Watchet (RHS)	2125	9	25	40

4.4 Mapping cliff top position

The results in Table 4-2 represent the conservatively estimated average change of the cliff toe position for the years 2055, 2085 and 2125, relative to the mean position in 2018. This must be used to estimate movement of the cliff top to inform understanding of asset vulnerability. The processes governing the relationship between cliff toe and cliff top are complex and are beyond the scope of this study. In this example, it has been assumed that the horizontal distance between the cliff toe and cliff top will not change, on average, in the future. Following this assumption, the changes in Table 4-2 can be applied to the cliff top position in 2018 to provide upper, middle and lower estimates of future movement. The figures below show example mapping of the results; in each case, a degree of smoothing was applied to erase localised details of the shape of the 2018 cliff top from the projected future alignments (see WSP, 2020 for further information).

The Blue Anchor unit (Figure 4-17) showed the greatest historic change and this resulted in the largest estimate of future recession. The uncertainty range is very narrow, and this may seem counter-intuitive. It should be recognised that (1) this reflects the very low variability found in the estimate of average historic recession, and (2) this illustration explores the consequences of only one sea level rise trajectory.

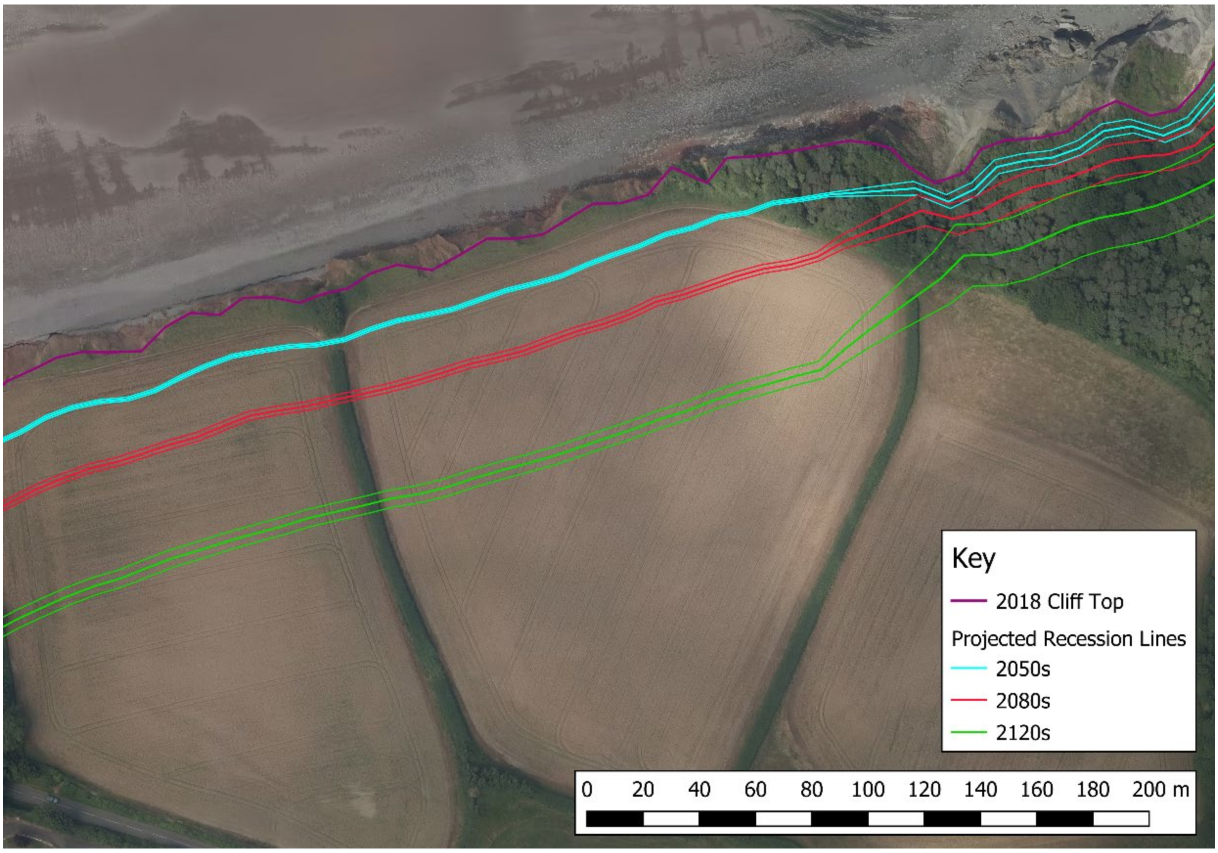

Figure 4-17: Shows the projected cliff top positions across the Blue Anchor CBU; the figure is orientated to the National Grid and uses imagery provided by the National Network of Regional Coastal Monitoring Programmes of England. The magenta line represents the 2018 cliff top. Projected recession lines are shown as follows: cyan 2050s, red 2080s, green 2120s

In Figure 4-17 the transition to the Warren Farm CBU can be seen towards the right of this figure. Overall recession distances fall, but the uncertainty bands become much wider. The increase in the level of uncertainty through time can also be seen quite clearly (the width between the lines of each year becomes progressively wider). The eastern limit of this unit, and its transition to the Holiday Village CBU can be seen in Figure 4-18.

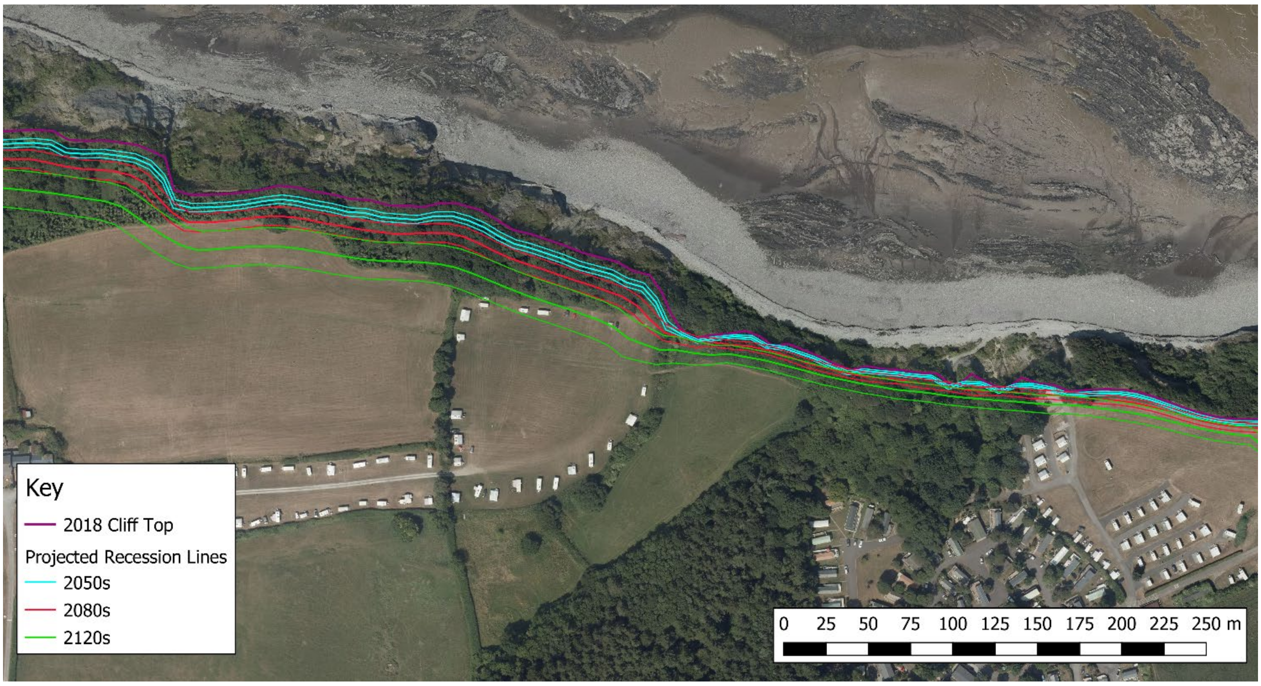

Figure 4-18: Shows the projected cliff top positions at the boundary between the Warren Farm CBU (towards the left of the figure) and the Holiday Village CBU (on the right); the figure is orientated to the National Grid and uses imagery provided by the National Network of Regional Coastal Monitoring Programmes of England. The magenta line represents the 2018 cliff top. Projected recession lines are shown as follows: cyan 2050s, red 2080s, green 2120s

In Figure 4-18 the Warren Farm CBU is on the left of this figure, so that the distances represented by the recession lines are identical to those on the right-hand side of Figure 4-17. The projections of recession become smaller as they pass into the Holiday Village CBU (on the right of the figure), although (as would be expected from Figure 4-14) the uncertainty is relatively wide.

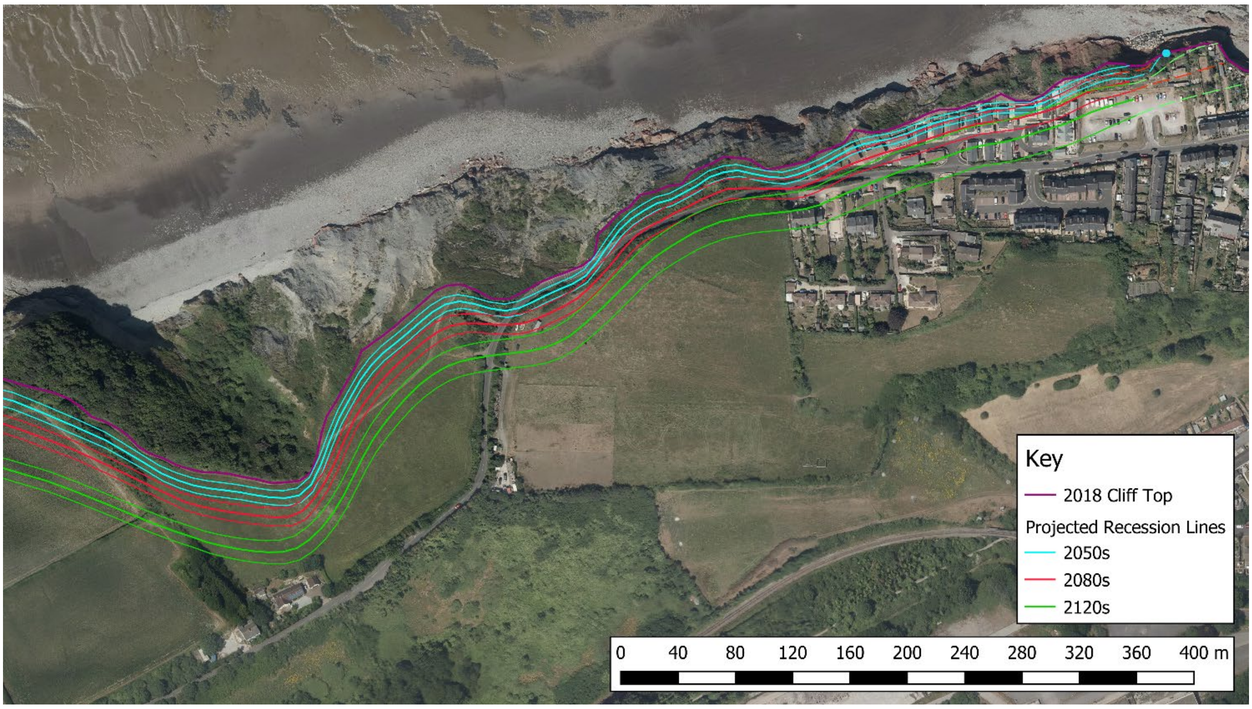

Figure 4-19: Shows the projected cliff top positions across the West Watchet CBU; the figure is orientated to the National Grid and uses imagery provided by the National Network of Regional Coastal Monitoring Programmes of England. The magenta line represent the 2018 cliff top. Projected recession lines are shown as follows: cyan 2050s, red 2080s, green 2120s

The project cliff top lines across the West Watchet CBU are shown in Figure 4-19. Here, the uncertainty bands remain constant throughout the unit, but the average projected recession reduces with distance east, reflecting the trend seen in the historic data (the cyan circles in Figure 4-9).

5 Strengths and limitations

This study is intentionally ‘broad-brush’; it aims to provide general insights into regional sensitivity to sea level rise rather than local detail. As described above, and in the technical report (Environment Agency 2025d), this aim was pursued through broad-scale, 2-dimensional SCAPE modelling, involving idealised conceptualisations and simplified representations of physical conditions. The study does not deal with other influences on recession, such as landsliding, coastal protection interventions, alongshore influences and coastal catch-up. More detailed bespoke modelling can be expected to provide better results, and SCAPE is freely available for this purpose, where appropriate.

This method report offers a method for translating the results (conservative indicators of cliff toe recession sensitivity) into conservative estimates of future cliff retreat at suitable sites. It shows how certain local details can be accounted for, including the plan shape of the coast and alongshore variations in recession rate, which is used as a proxy for geological strength. This approach will not be valuable for all cliffed sites, and so guidance is offered below to help users identify appropriate settings.

This new method was developed to account for coastal behaviours not captured by current approaches, and so offers users a new perspective. The work is subject to general limitations arising from SCAPE, and from the simplified way that the shore system has been conceptualised. Environment Agency (2025d) discusses these in detail and recommends investment to improve SCAPE, and to develop alternative models of coastal profile response to sea level rise.

This section begins by commenting on the approach taken to managing unavoidable uncertainty, and the implications of that approach. It discusses the strengths and limitations of the proposed method, relative to currently recommended approaches. It then focuses on the importance of the beach, and how its size may be used to identify appropriate settings. Areas of particularly high sensitivity are also discussed.

5.1 Uncertainty

The prediction of cliff sensitivity to accelerating sea level rise is subject to major uncertainties. The approaches taken to manage these are described in the technical report (Environment Agency 2025d). Where more sophisticated approaches were not possible, uncertainties were managed by adopting conservative bias, conditions were chosen to be more likely to lead to overestimation rather than underestimation of sensitivity at applicable sites. It is important to note, however, that it is not yet possible to know whether the final results are conservative, or how much they deviate from the ‘true’ answer.

It is also important to recognise that there is still general (epistemic) uncertainty about the processes and behaviours that govern cliff response to sea level change. It is hoped that by providing a tool for a previously unrepresented mode of behaviour, this work reduces the consequences of this uncertainty. However, the results unavoidably reflect limitations in current understanding, and should only be applied after careful consideration.

This project has shown that uncertainty in historic (late Holocene) relative sea levels is important (see Environment Agency 2025c and Environment Agency 2025d). Exploring its consequences through model simulations, although possible, was beyond the scope of the work. A conservative approach was, therefore, taken, in which the simulations were driven with the upper end of the possible range of historic relative sea levels (see section 3.6 of Environment Agency 2025d, and section 5.4 below for further discussion of this).

A range of UKCP18 projections of relative sea level rise were adopted to account for uncertainty in climate change. A conservative scenario of wave growth was also assumed, which was based on UKCP18 findings (Palmer and others, 2018). Sensitivity testing suggested that wave growth accounted for 19% to 33% of the overall response for the high sea level projections; this proportion will be generally larger for the lower projections.

5.2 Relative strengths

As noted above, understanding of coastal cliff response to sea level change is limited. Various predictive tools have been proposed, each representing different conceptualisations of the involved processes and behaviours. These have been reviewed by previous papers and guidance documents, and it was not within the scope of this study to provide a further review. Instead, the methods recommended by those reviews have been compared to the new approach. This comparison was based on the conceptualisation of coastal behaviour that each represents.

The most commonly used conceptualisation of shore response to sea level rise was given by Bruun (1962) to describe the behaviour of beach/dune shores; this provided the predictive method known as the 'Bruun rule'. It was adapted for a range of different shore configurations, including coastal cliffs, by Dean (1991). Bray and Hooke (1997) found this modification to be "*...*the most easily applied and realistic adaptation of the Bruun rule for eroding cliffs." It is also offered or recommended by UK guidance documents, including CIRIA's Beach management manual (Rogers and others, 2007) and the Soft Cliffs Handbook (Lee and Clark, 2002). A variant was adopted for the Environment Agency's first (2012) National Coastal Erosion Risk Maps (NCERM), and, therefore, for many second-generation Shoreline Management Plans (Halcrow, 2007). The method introduced here supports the updated (2025) NCERM outputs.

A distinctly different conceptualisation led to the Shore Platform Geometric Model of Sunamura (1992), which was also recommended by the Soft Cliffs Handbook and preferred, alongside the modified Bruun rule, by Bray and Hooke.

The relative strengths and limitations of the modified Bruun method and the Shore Platform Geometric Model are compared to those of the new sensitivity indicators using the 6 criteria discussed in the sub-sections below. Comparisons are also made with the SCAPE numerical model.

5.2.1 Variations in geology

It is not yet possible to directly relate a measurable parameter of rock strength to erosive forces; a problem compounded by the highly variable nature of cliff geology. The new method avoids this problem by using historic recession rate as a proxy for geological strength, and the same approach is taken with the Shore Platform Geometric Model.

In contrast, the modified Bruun rule uses historic recession as a proxy for the historic net sediment budget; in this sense, geological strength is assumed to be unimportant. It, therefore, predicts that all cliffs, regardless of their strength, will show the 'same increase' in recession, if all other factors are equal. If, for example, it predicts an increase of one metre per year for a clay cliff, then it will give the same increase for an adjacent hard cliff, if all other factors are the same. This independence between geological strength and response to sea level change seems physically unrealistic.

It should be noted that none of the methods account for variation in geological strength across the profile. A bespoke numerical model would be needed to capture this.

5.2.2 Varying platform slope

Shore platform gradients are likely to respond to sea level rise, with higher rates leading to steeper slopes (see, for example, Ashton and others, 2011). This is important because steeper slopes allow larger waves closer to the cliff toe and are associated with higher rates of momentum flux (and, therefore, increased hydrodynamic forces). This is an important behaviour driving increased cliff recession.

The dependence of slope on rate of sea level rise is explicitly represented in SCAPE simulations (see section 2.1) and is implicitly captured in the sensitivity indicators.

In contrast, the modified Bruun method and the Shore Platform Geometrical Model are based on an assumption that the slope is unvarying.

5.2.3 Time-dependent response

Reshaping of cliff/platform shores is expected to take an appreciable time to occur (for example, Hands, 1983; Bray and Hook, 1997). This response time is calculated by SCAPE models, and so is implicitly represented in the sensitivity indicators.

In contrast, both the modified Bruun method and the Geometrical Shore Platform Model assume an instantaneous response to a change in sea level.

5.2.4 Sediment budget representation

Growth in cliff/platform recession will increase the release of beach-suitable sediments in many places. This is likely to create feedback that mitigates, to varying degrees, the growth in recession caused by sea level rise. This is explicitly represented by the modified Bruun rule, which is essentially a sediment-budget method.

However, this is not represented by the new sensitivity indicators (or the Shore Platform Geometrical Model) and this has the effect of increasing conservatism in the results they give. They are offered for sites where the beach is of limited volume or is absent. This is discussed further in section 5.3

5.2.5 Time-varying history of sea level change

Many contemporary shore platforms and nearshore profiles have been shaped over millennia, influenced by changes in sea levels over that time. This study has demonstrated the important effect this has on future sensitivity (Environment Agency, 2025d).

The SCAPE simulations were driven by time-varying historic relative sea levels, and this is captured in the sensitivity indicators. In contrast, historic sea level rise is treated as a constant in both the modified Bruun rule and the Geometrical Shore Platform Model.

5.2.6 Wave growth

As noted in section 2.2.1, (conservatively estimated) wave growth is accounted for in the sensitivity indicators.

The modified Bruun rule and the Geometrical Shore Platform Model deal solely with sea level rise, and do not account for potential wave growth.

5.2.7 Summary

The results of this assessment are summarised in Table 5-1.

Table 5-1: Results from the comparison of the relative strengths and limitations of both the modified Bruun method and the Shore Platform Geometric Model to the new sensitivity indicators using the 6 criteria. Key: A - represents historic recession rates used as a proxy for geological strength; B -represents historic recession used as a proxy for net sediment budget

Relative strenghts	Indicators of cliff toe sensitivity provided by this study	Modified Bruun rule (Dean, 1991; Bray and Hooke, 1997)	Geometrical Shore Platform Model (Sunamura, 1992)
Variations in geology	A	B	A
Varying platform slope	A	B	B
Time-dependent response	A	B	B
Sediment budget representation (note)	B	A	B
Time-varying history of sea level change	A	B	B
Wave growth	A	B	B

Note for Table 5-1: SCAPE may be used to represent beach behaviours and track sediment budgets, but those algorithms were not used to derive the sensitivity indicators.

Table 5-1 shows the strengths of the indicators of recession sensitivity relative to other approaches, where A indicates relative strength; justification for this assessment is provided in sections 5.2.1 to 5.2.7.

Exploring strengths and limitations in this way helps to develop a picture of the types of shore where the methods may be better suited. The assessment suggests that:

- the new sensitivity indicators are better suited to sites where the shore platform is eroded by wave action, its reshaping influences the rate of cliff retreat, and the beach does not limit shore retreat
- the Geometrical Shore Platform Model is intended for similar sites, but represents fewer shore platform behaviours

- the modified Bruun method is better suited to sites where the beach is very thick, and cliff recession is ultimately governed by the balancing of beach sediment budgets

The importance of the size of the beach is discussed further in the following section.

5.3 Beach size

In the previous section, and in section 2.1, a distinction was drawn between the behavioural response of cliff/platform shores and those of beach/dune shores. They described how the new method has been developed specifically for the former. In reality, many sites will fall between these extremes (beaches that are neither small, nor very deep).

The limit of applicability of the new method was explored in Stage 1 of this study, through tests in which beach volume was varied from 5 m^3/m to 500 m^3/m. The results suggested a threshold in the relationship between beach volume and sensitivity. Below this threshold, the sensitivity was found to be independent of the beach (see Figures 6.22 and 6.23 of Environment Agency, 2025d).

The threshold was associated with the beach not being wide or thick enough to protect the platform from wave action across the entirety of any tidal cycles. Under this condition, both the long-term recession rate and the sensitivity to sea level rise were independent of beach volume. Widening and deepening of the beach beyond this threshold brought enough protection to begin to influence the equilibrium recession rate and also the sensitivity to sea level rise.

This suggests that the sensitivity indicators should be similarly valid for settings where the beach is either absent or the average beach volume does not extend across the whole intertidal zone.

Where a beach extends across the whole intertidal zone, the sensitivity indicators are expected to become less valid as the average beach becomes increasingly protective of the underlying platform. It is noted that, under these conditions, the conceptualisations underpinning the modified Bruun rule become increasingly valid.

5.4 Areas of high sensitivity

As was noted in section 2.3, and illustrated in Figure 2-1, particularly high sensitivity was found in northern regions. This was associated with fairly static relative sea levels in recent millennia due to the similarity of the isostatic uplift in these areas to global sea level rise. This, in turn, led to low recession during the baseline period, and high relative future growth (see Environment Agency 2025d).

This behavioural response is plausible, and highlights the important effects that historic relative sea levels have on shore profiles. Nevertheless, these results should be used with particular care, because of the high recession estimates that may result, and the possibility that estimates of Holocene sea levels were overly conservative in northern areas (see section 6 of Environment Agency 2025d for a discussion of this).

In the absence of further work, it is noted that:

- high sensitivity should be expected in areas where relative sea levels have been fairly static over recent millennia
- the results provided for these areas may be overly conservative due to the representation of Holocene sea levels
- the high sensitivity is associated with low simulated recession during the baseline period; if low baseline recession rates are not found in reality, then the results may be misleading

This uncertainty increases the likely value of bespoke numerical modelling in those areas.

6 Acknowledgements

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The work was funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme of Defra and the Environment Agency.

Developers and adaptors of the version of SCAPE used here were Mike Walkden, Jim Hall, Mark Dickson, James Thomas and John Barnes. The modelling tool was made openly available by the Integrated Coastal Sediment Systems project (iCOASST), which was coordinated by the University of Southampton and funded by the Natural Environment Research Council.

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Projections of future sea levels to 2100 were provided by the United Kingdom Climate Projections project 2018 (UKCP18), which is part of the Met Office Hadley Centre Climate Programme funded by the Department for Business, Energy & Industrial (BEIS) and Defra.

Projections of future sea levels to 2300 were provided by the United Kingdom Climate Projections project 2018 (UKCP18), and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme of Defra, the Environment Agency, Natural Resources Wales and the Welsh Government and the flood research programme of the Scottish Environment Protection Agency.

Wave data were generated by the Met Office WAVEWATCH III model, under the Environment Agency licence.

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