Coastal Change Management Areas (CCMAs) – Methodology and Adoption

Work Package 2: CCMA Method

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Work Package 2: CCMA Method

Executive Summary

WP1 provided an overview of CCMA legislation, techniques, case studies in England and shortfalls in current methods. WP2 presents approaches to CCMA development using two case studies in the Taw-Torridge Estuary and East Devon as examples to explore the types of data available and the role they play in developing a CCMA.

For North Devon, existing Level 2 Strategic Flood Risk Assessments have been made available, for Bideford and Barnstaple, providing detailed modelling output for different future flood scenarios. Areas that do not benefit from Level 2 coverage are, at present, managed through a Level 1 SFRA whereby climate change impacts are represented by re-classifying the return periods for existing flood extents. Comparison with projected sea level rise impacts indicates this method under predicts future scenarios for 2100. Using existing up-to-date LiDAR datasets new flood extents can be quickly and easily generated and kept relevant with EA flood data. These maps can then be combined with neighbouring Level 2 SFRAs for a comprehensive CCMA.

For eroding cliff systems, past retreat rates provide key indicators for future behaviour. When past retreat rates are combined with predicted future sea level rise, it is possible to estimate future cliff line positions using predictive formulae from the scientific literature. The detail provided by LiDAR analysis allows for variable along-coast retreat rates to be calculated, reflecting the fact that cliff retreat rates vary within a given area. In the examples presented, retreat distance of more than double (118 m) the long term SMP projections (55 m) are presented. LiDAR data enable contemporary cliff retreat rates to be calculated accurately (as used here, covering a 10-year period), however due to the short temporal extent of presently available LiDAR, it is recommended that historic aerial image analysis is also be incorporated where possible, for a more comprehensive estimate of historic retreat rates.

Methods for sandy, gravel and defended coastlines are presented which also rely on suitable survey data and, where possible, multiple epochs to explore historic retreat. For defended coastlines, future management policies may be subject to change and, therefore, we propose that they are included in the CCMA designations by forecasting the future shoreline position without the defences present.

Both case studies have focused on developing a straightforward method using the latest data and analytical approaches. WP1 highlighted the strengths and weaknesses of the existing Shoreline Management Plans that underpin current management practices, and will undoubtedly remain a vital reference when considering the extents of any future CCMA lines. The semi-automated and data-driven methods for CCMA definition presented here help to standardise their definition, however it is clear

that expert judgement, local knowledge and multi-agency collaboration will ultimately be required to finalise any CCMA.

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1. Introduction

This report is the second work package (WP2) of the SWEEP Coastal Change Management Area (CCMA) project, intended to present an optimised methodology for determining the extents of a CCMA based on the best available methods in the literature. The document uses two case studies from contrasting coastal environments to demonstrate how the proposed methodology can be applied in different areas. WP3 will implement the methodology developed in WP2 to determine CCMAs for two areas in southwest England.

1.1. Aims and Objectives

The aim of WP2 is to develop a repeatable and scientifically robust approach for determining the extents of a CCMA that can be applied using existing datasets and generic (i.e. non-specific) data analysis software. The focus will be on establishing a clear set of guidelines and logical workflow for the development of new CCMAs, which it is hoped will make the techniques straightforward to apply by LPAs (or consultants they have appointed) for future CCMA designation beyond the example cases in this report. The available datasets and approach will, in part, be informed by WP1 and will develop in collaboration with the project stakeholders as the project evolves. Existing datasets, that will likely be central to the approach, include:

- National Coastal Erosion Risk Mapping (NCERM) data
- Environment Agency Flood Zone data
- Plymouth Coastal Observatory Regional Mapping Program (LiDAR, Aerial Imagery, cliff lines)
- UCKP18 sea level rise (SLR) projections
- Shoreline Management Plans (SMP)

The UK Environment Agency (EA) already work with LPAs to map coastal erosion, and the EA NCERM data and local SMPs provide a wealth of background information on how erodible or floodable a section of coastline is considered to be. However, a key objective of this report is to estimate coastal flooding and erosion extents under future climate scenarios using the latest UKCP18 data to predict SLR along the coast, which is vital in order to predict coastal change into the future.

Two main coastal environments will be considered in this report; (a) wave-dominated erodible coastline and (b) tide-dominated floodable estuaries. A methodology will be developed to calculate coastal recession rates and potential flooding extents in the face of rising sea levels from two case study examples in southwest England. The case study sites represent complex regions, which should allow a generalised and robust methodology to be developed, enabling the approach to be up-scaled to the whole of the southwest region or beyond if necessary in the future.

1.2. Coastal Mapping

WP1 provided an overview of approaches that have been taken to develop CCMAs at coastal authorities around the UK. In general, the approach has been to rely on the Shoreline Management Plan (SMP) which provides the main source of analysis for predicted future shoreline positions for a range of epochs; short-term (0 to 20 years); medium-term (20 to 50 years); Long-term (50 to 100 years) erosion scenarios. The SMPs were developed by incorporating datasets including the National Coastal Erosion Risk Mapping (NCERM) and Futurecoast. At the time of these projects, coastal monitoring datasets were in their infancy and for many areas historic mapping and low-resolution aerial imagery were the primary data sources available.

The development of systematic regional monitoring programs (www.channelcoast.org) around the coastline, combined with improvements in mapping and imaging technology (for example, aerial imagery, terrestrial and aerial LiDAR), have enabled contemporary coastal change to be more accurately measured. These additional datasets provide improved spatial and temporal resolution which allows us to improve our ability to accurately define past rates of retreat, which is a fundamental component of forecasting future coastal retreat (Collins and Sitar, 2008, Earlie *et al*., 2015).

The geomorphologically diverse coastline of SW UK adds complexity to coastal monitoring and the mapping of coastal retreat. While soft cliffs can exhibit relatively rapid and easily measurable retreat, the timescale over which noticeable retreat occurs can be decades to centuries for hard-rock coastlines, and the episodic nature of retreat in such locations adds uncertainty to estimates of long-term retreat. With a large proportion of cliffed coastline in the UK, these features are of national interest as highlighted by Brooks and Spencer (2012) " *A UK Government review in 2002 concluded that 'in order to manage coastal cliffs it is important to have access to accurate and reliable information on past and future cliff recession patterns and trends' and that this requires the development of 'analytical methods of predicting cliff erosion rates for the wide variety of differing situations around the coast"*.

The availability and resolution of terrestrial and airborne LiDAR datasets provides a reliable geospatial dataset that has been used widely for volumetric analysis of cliff and shoreline change (Adams and Chandler 2002; Young and Ashford 2006; Brock and Purkis 2009; Young *et al*. 2009; Lim *et al*. 2011). This report seeks to develop methodologies that make the most of the more accurate datasets now available, and best available analytical techniques from the scientific literature to predict future coastal positions.

2. Case Study: Cliff Backed Coastline

This section will describe the methodology used to define future coastline position for eroding coastal cliffs. The approach firstly quantifies rates of historic cliff retreat using geomorphic change detected from airborne LiDAR, and secondly, formulae for future cliff retreat that consider the effects of accelerating SLR will be applied under a future SLR scenario to project the expected cliff retreat to the year 2100. All output will be compared with current SMP data and management policies.

2.1. Site description

A methodology to define a CCMA extent along an eroding coastline was developed using a 4-km stretch of coast between Sandy Bay and Budleigh Salterton, East Devon, UK in V1 of the WP2 report. To better address the method detail we have updated the demonstration site to the East Devon area used for WP3 (Figure 2-1). The coast is predominantly orientated to the south-southeast and is exposed to easterly waves originating in the English Channel, and is broadly sheltered from large westerly waves originating in the Atlantic Ocean. The aerial imagery in Figure 2-1 shows a complex coastline, representative of the wider area.

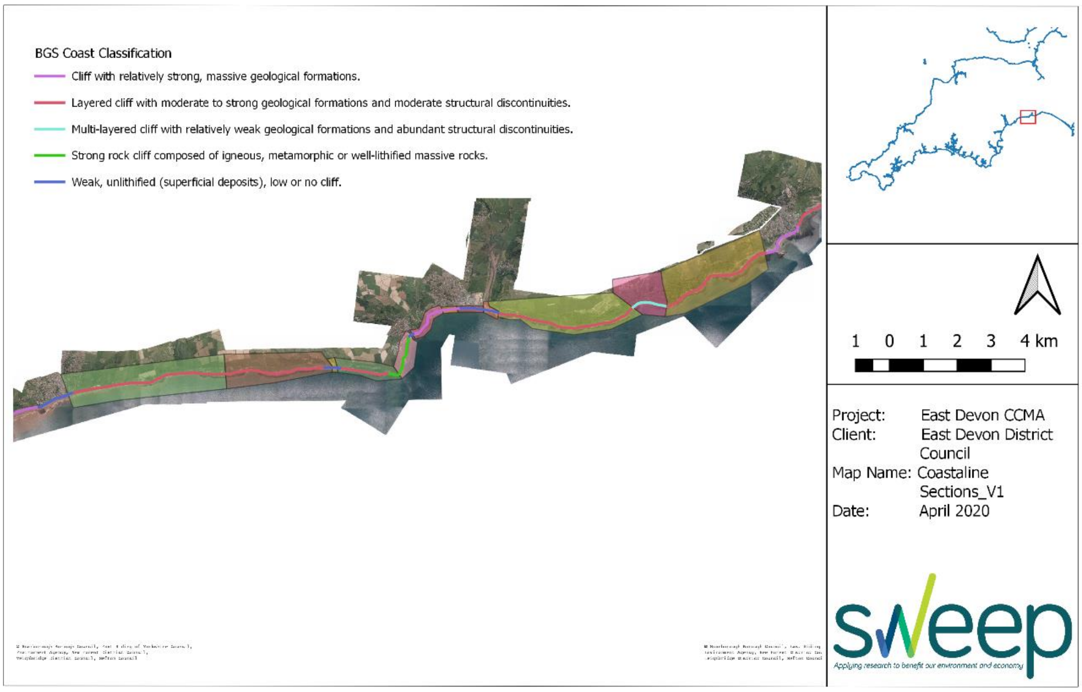


Figure 2-1. Case study location between Sidmouth and Lyme Regis in East Devon, UK. The map also indicates the separate regions and coastal classifications discussed in the text.

2.2. Data Sources

Airborne LiDAR

Airborne LiDAR data with a nominal vertical accuracy of 15-cm (Sallenger *et al*., 2003) and 1-2 m horizontal resolution are freely available from the Channel Coastal Observatory (CCO). In the presented case study, LiDAR data were obtained from CCO for the earliest and most recently available time periods (2007 and 2017). The 10-year LiDAR epoch enables the quantification of volumetric changes (Young and Ashford, 2006), historic cliff recession rates (Earlie *et al*., 2014), and future projection of cliff recession (Ashton *et al*., 2011; Brooks *et al*., 2014), which all feed into the methodology for defining CCMAs on eroding coastlines.

Once an area of interest was selected, LiDAR data were downloaded in a georeferenced 1-m resolution raster format as an unfiltered (i.e. surface rather than bare-earth model) .txt File, which consists of multiple 1 x 1 km tiles containing XYZ data (available from http://www.channelcoast.org). The LiDAR data were then input and prepared within a GIS platform (QGIS v10.6). Once the data were input, an area polygon *(clip extent)* was created to clip a suitable area for each stretch of coastline from both the LiDAR data epochs. The multiple tiles were then merged into one raster data set per time-period (e.g. 2007 and 2017), the merged raster(s) were clipped to the polygon area extent, and the raster datasets were output in an ascii (text) format required for further analysis (in this case using Matlab).

Georeferenced Aerial Imagery

Georeferenced aerial imagery is available as a Web Map Service (WMS) plug-in for ArcGIS and QGIS from the CCO (available from: http://www.channelcoast.org/ccoresources/wms/). The aerial imagery was principally used to identify the cliff-top position.

Cliff line polyline

A contemporary cliff line position associated with the most recently available LiDAR data is required for this analysis, as it provides a baseline from which cliff change can be computed and cliff retreat can be projected. Cliff line position has been mapped by the CCO over a number of epochs since 2009 using aerial imagery. While this was deemed suitable for most of the cliff retreat analysis in this project, the cliff line was manually adjusted in some places (as described below) to better reflect the line of active coastal retreat (rather than the location of maximum cliff elevation), and in locations where multiple CCO cliff lines existed due to a stepped cliff being present, as a single cliff line is required for the present analysis.

Sea level records/projections

Long term tide gauge records are available at a number of locations around the UK and are archived (https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/) by the British Oceanographic Data Centre. These represent the best available observations of past sea level rise; however, some gauges exhibit more 'noise' than others and some degree of line fitting is required to obtain a sea level rise value over the period of interest. Sea level rise projections into the future are available for the UK from the United Kingdom Climate Projections dataset (currently UKCP18), and we chose to use the 'high emissions, 50th percentile' climate scenario, in line with Environment Agency common practice.

Historical Aerial Photos and Historic Maps (pre-2008)

As discussed in WP1, one of the principle sources for historic shoreline assessments, developed as part of the Futurecoast and NCERM projects, were historic maps and aerial imagery. Such historic maps are not usually available free-of-charge, and re-visiting such analysis would be extremely time consuming, and was beyond the scope of this project. However, suitable historic information can usually be found within the SMP reports adopted for each area.

2.3. Data Preparation

Within the GIS platform that the source data (LiDAR layers/Cliff lines) are managed, it is important to split the coastline up into suitable sections for further analysis. This has two purposes:

1) Makes the size of the data being examined more manageable in subsequent processing

2) Links the coastal sections to geomorphological types and orientations which are likely to respond in a similar fashion.

The first point is self-explanatory and is often required when working with spatial datasets. Point 2 concerns a key component of the way the coastline is assessed. As discussed in WP2, cliff retreat is episodic and spatially variable, therefore, future retreat rates for any given area are best informed by considering the maximum historic retreat along the surrounding cliff area. This is a more robust approach than considering retreat at each location in isolation, provided the neighbouring cliff is of a similar geomorphological type, and the cliff has a similar wave exposure. Dividing the coastline into sections also allows a transition between the differing methods required to project cliff retreat and beach retreat, as different retreat rate equations need to be applied for each case. To inform where the coastline is divided into differing sections, we utilised the Coastal Vulnerability Dataset from the British Geological Survey (BGS). This dataset has been compiled by geologists (engineering and coastal) and the BGS to provide a range of GIS layers that identify areas susceptible to flooding and coastal erosion for Great Britain within 1 km of the coast. It is expected that this dataset would be available to councils, or the Environment Agency and so be of relevance for future CCMA work. Of primary interest to us is the ‘Backshore (Erosion Susceptibility)’ layer;

“The erosion susceptibility assessment considers a number of geological engineering properties of cliff sections around the GB coastline using the discontinuities and excavatability datasets (part of the BGS Civils data suite), and the BGS Permeability dataset”.

BGS used a scoring system to capture the range of geological and engineering properties to be applied to the various rock layers within the cliff. The scores were summed and used to produce an overall level of erosion susceptibility. The output that has been adopted within our region includes five different BGS classifications:

1) *Cliff with relatively strong, massive geological formations.*
2) *Layered cliff with moderate to strong geological formations and moderate structural discontinuities.*
3) *Multi-layered cliff with relatively weak geological formations and abundant structure discontinuities.*
4) *String rick cliff composed of igneous, metamorphic or well-lithified massive rocks.*
5) *Weak, unlithified (superficial depositions), low or no cliff.*

The above classification scheme and the need for ‘manageable’ data sizes were the primary parameters used to split the East Devon region into 13 sections shown in Figure 2-7. However, as the method described in the following sections calculates the maximum retreat rate from the surrounding cliff area, if the BGS dataset were not available for a given region it would be possible to simply divide the coastline into sections that have a similar overall orientation (i.e. dividing at large headlands), are either cliff or open beach, and are of a manageable data size.

2.4. Step 1: Cliff-top detection

The aim of locating the cliff-top is to provide a coastal baseline from which to compute the rate of retreat, and in order to generate perpendicular profiles which determine the direction in which the cliff is expected to retreat. The cliff line polygon associated with the most recent LiDAR epoch was obtained from the CCO, and then manually adjusted where necessary using the associated aerial imagery where it was deemed that the CCO cliff line did not represent the line of active coastal retreat. The division between vegetated and un-vegetated areas was used to identify the adjusted cliff line, as this shows where recent coastal change has occurred (i.e. vegetation has not had time to establish since the last cliff retreat event). This approach avoids heavily vegetated, wooded, or even inhabited areas of coast that have not experienced contemporary coastal change being located seaward of the cliff line, which would have been the case if the raw CCO cliff lines were used. The cliff line adjustment was also informed to some degree by the LiDAR data, which was used as a cross-reference to visually identify the change in slope associated with the cliff top using a profile tool in the GIS platform. The digitized cliff-top vector (for example, Figure 2-2) was then used as a baseline from which shore-normal transects could be generated.

Figure 2-2. Example coastline section with manually digitised cliff line (red). The line is defined through a combination of vegetation boundaries and change in slope from LiDAR elevations.

Future methodological development may seek to automatically identify the cliff-top and cliff-toe, as has been achieved in recent research efforts (e.g. Payo *et al.*, 2018). However, initial attempts at using an automated approach highlighted the complexities of defining the cliff-top from elevation data alone;

some cliffs do not feature an obvious change in slope, or feature multiple changes in slope, and the vegetation line was therefore found to more reliably indicate the position of the cliff-top.

2.5. LiDAR Change Analysis

GIS platforms are designed for spatial analysis and excel at providing tools for analysing data such as LiDAR. To calculate the past rate of cliff retreat we use the difference in cliff volume (the ‘geomorphic change’) between different LiDAR epochs, however, the LiDAR measurement accuracy needs to be considered and accounted for in this analysis. Geomorphic Change Detection (GCD) tools are readily available within GIS platforms and allow the user to define the following parameters:

- Measurement error, for example, 0.15 m is generally associated with LiDAR
- Confidence level, for example 95 %ile for thresholding what is actual geomorphic change

GCD tools therefore create a new Digital Elevation Model (DEM) of the Difference (DoD) between two LiDAR surfaces, which shows the geomorphic change that can be considered real (with 95%) and not a result of measurement error. This DoD surface was exported for each cliff section and used to compute the volumetric cliff change for each of the extracted profile lines described in the following section.

2.6. Step 2: Profile Extraction

To calculate cliff change and determine the direction of cliff retreat at each along-coast location, a smoothed version of the cliff line was created. The digitised cliff-top was smoothed using a moving-average filter with a window size of 80 m, to remove small-scale variations in cliff orientation (e.g. Payo *et al*., 2018), with the objective of ensuring that any point along the cliff line represents the overall orientation of the coastline at that location. The smoothed cliff-top was resampled to a node spacing of 10 m, but this value could be increased depending on the expected level of along-coast variability in recession in the region of interest, with smaller values (10’s of meters) being necessary for locations with sudden changes in coastal retreat rate and larger values being acceptable for locations with less variability in recession. Finally, the smoothed cliff line was used to generate a series of regularly-spaced transects, each located at one of the cliff line nodes (i.e. at 10 m intervals) and oriented perpendicular to the cliff line at that location (Figure 2-3). Data from the two chosen LiDAR epochs, as well as the DoD surface were then extracted along each transect, providing a series of profiles from which to assess the rate of coastal retreat (Figure 2-3, lower panel, and Figure 2-4).

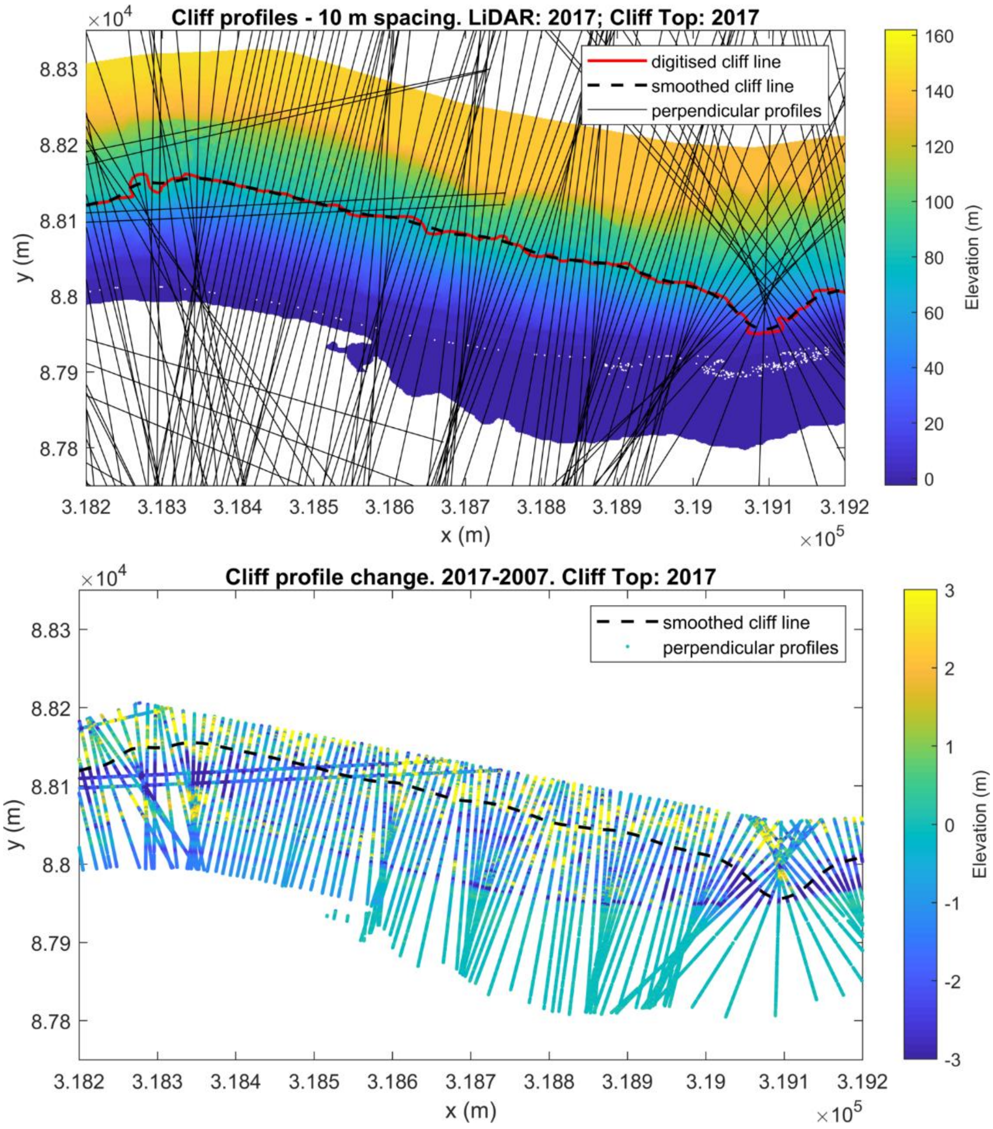


Figure 2-3. Example profile extraction for a section of East Devon cliff. Upper panel: 2017 LiDAR data overlaid with the digitised cliff line (red), the smoothed cliff line (dashed), and the perpendicular profiles used to calculate cliff change and determine retreat direction. Lower panel: geomorphic change extracted along each of the perpendicular profiles shown in the upper panel.

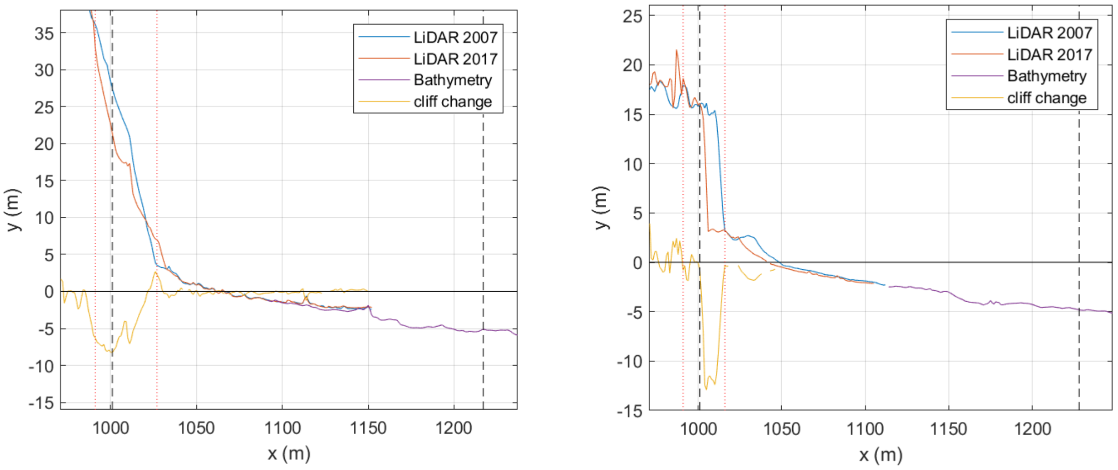


Figure 2-4. Two examples of LiDAR (blue and red) and geomorphic change (yellow) profiles extracted from two different locations (left and right panels) in East Devon over two epochs (2007 and 2017). The vertical dotted lines show the landward and seaward extents of the cliff used to calculate cliff change volume, while the vertical dashed lines show the position of the cliff top (left dashed line) and the estimated Depth of Closure (right dashed line), respectively. Bathymetry profiles (magenta) are also shown, but were not used in the present analysis.

2.7. Step 3: Calculating Past Retreat

For each profile along the cliff-top, volumetric analysis was undertaken on a section of the extracted profile extending 10 m landward of the digitised cliff-top position and seaward down to MHWS + 2 m elevation (Figure 2-4). The seaward extent was defined such that the active beach profile would not be considered in the cliff change analysis. The inland extent is not critical to the results, as the digitised cliff line should come from the latest LiDAR epoch and therefore cliff erosion is not expected landward of the digitised cliff line. The volume of geomorphic change (herein called volumetric erosion) was calculated from the extracted DoD between these landward and seaward extents, by trapezoidal integration of the DoD values. Positive changes were ignored in this calculation, as they represent vegetation growth, or accumulation of loose material at the base of the cliff, and therefore are not part of the cliff itself.

The computed volumes were then used to calculate **past retreat rates** for each of the extracted profiles using the following equation (Young and Ashford, 2006; Earlie *et al*., 2014).

$$R1 = \frac{V}{ZcLcTc} \tag{1}$$

Where; R1 = linear retreat rate (m/yr), V = volumetric erosion (m^3), Zc = the cliff height for each profile between MHWS + 2 m and the highest point between the landward and seaward cliff extents, Lc= longshore length of cliff (here fixed as 1 m), and Tc = time interval between data (the exact number of decimal years).

2.8. Step 4: Predicting Future Retreat

The rate of landward cliff recession is expected to increase in the future if SLR accelerates as is predicted by UKCP18, as higher sea levels increasingly allow the erosive action of the sea to act on the cliff. As such, it is important when predicting the future position of the coastline to define CCMA regions to consider how SLR may change into the future.

There are a number of equations available in the literature for predicting future cliff retreat rates. Brooks and Spencer (2012) assessed the efficacy of four such models on the Suffolk coast, and following this work, **we utilise the generic retreat equation proposed by Ashton *et al.* (2011)** which captures the general behaviour predicted by the four equations. The cliff retreat equation predicts the **future retreat rate R_2 (m/yr),** as a function of the **historic cliff retreat rate R_1 (m/yr)** and the **past and future SLR rates S_1 and S_2, respectively (mm/yr):**

$$R_2 = R_1 \left[{S_2}/{S_1}\right]^m \qquad (2)$$

The exponent m in Eq. 2 determines how the cliff retreat rate will change as SLR accelerates, and can range from: 1 ('instant response') which implies that cliff retreat rate will scale directly with the rate of SLR; 0.5 ('damped feedback') which implies that cliff retreat rate will increase by the square-root of the increase in SLR rate; and 0 ('no feedback') where the past retreat rate simply continues into the future, regardless of any acceleration in SLR. To calibrate m accurately requires accurate knowledge of historic sea level rise and cliff positions from a distant point in the past (for example 100 years would be sufficient). While sufficiently long and accurate records of sea level are available for this region, historic maps carry an unknown level of uncertainty and accuracy, and as such they were not deemed sufficient to calibrate m for this project. Instead, we use an m value of 0.5, following the widely used cliff retreat model 'SCAPE' of Walkden and Hall (2005). Therefore we assume that cliff retreat accelerates as sea level rise accelerates, and does so by the square-root of the increase in SLR rate.

Eq. 2 was calculated at each alongshore cliff node (10 m intervals) using R_1 as defined in Section 2.7, and S_1 calculated using 10 years (2007 – 2017) of **sea level data from the Newlyn tide gauge**, to match the LiDAR epoch, which gave a contemporary SLR rate of 2.54 mm/yr. Exponent **m was fixed at 0.5**, as previously mentioned. S_2 was defined for each year from 2017 up to 2100 using **UKCP18 SLR rates, and using the median (50th percentile) values from the RCP8.5 'high emissions' climate scenario** (Figure 2-5). This gives a rate of sea level rise per year, and therefore a rate of cliff retreat can be calculated for each year into the future. Summing these cliff retreat rates over the number of years then yields a cliff retreat distance for each year up to 2100, and for each position along the length of the cliff line (Figure 2-6).

Episodic and localised cliff retreat that is common in hard rock coastlines could result in highly variable along-coast cliff retreat rates over the 10-year epoch studied here, yet over many decades homogeneous cliffs would be expected to retreat in an overall uniform manner. Therefore, to provide a more homogeneous future retreat behaviour, **the maximum predicted retreat distance within 50 m of each location along the cliff was used to define the local cliff retreat** (i.e. using a moving-maximum filter over a 100 m window size). The effects of this are demonstrated in Figure 2-6 (lower panel), where the raw and moving-maximum retreat values are compared for each future epoch for an example section of the East Devon cliff line.

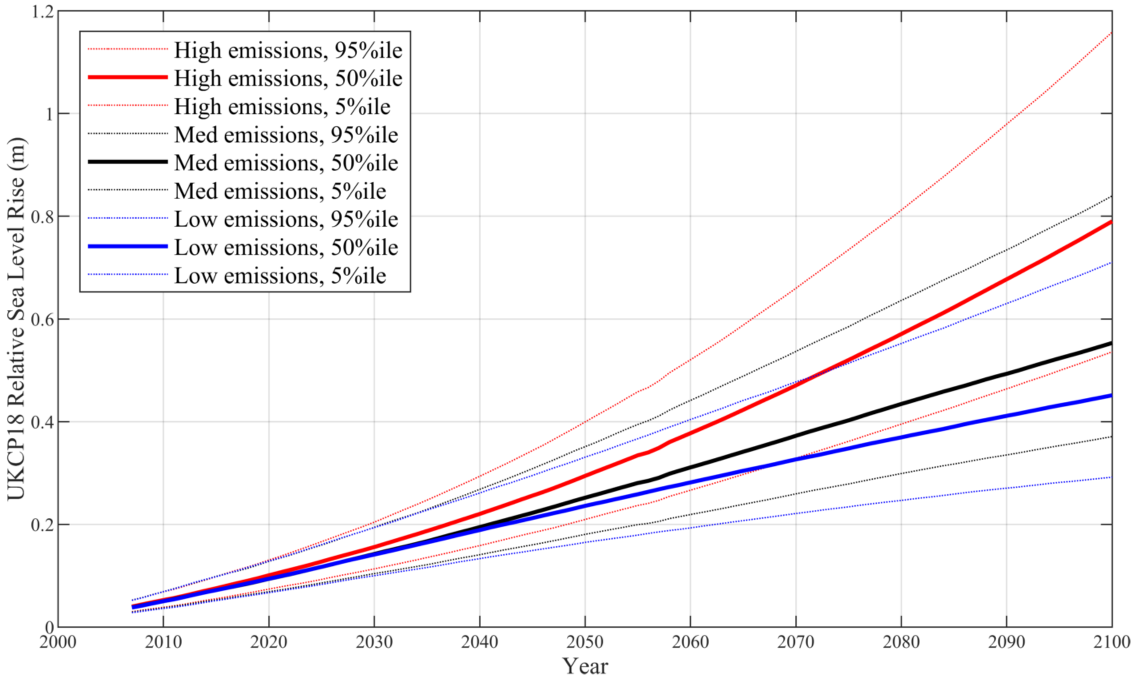


Figure 2-5. Sea level rise projections for East Devon under different future emissions scenarios, from UKCP18. The High emissions, 50%ile scenario was used for this project to predict future cliff retreat.

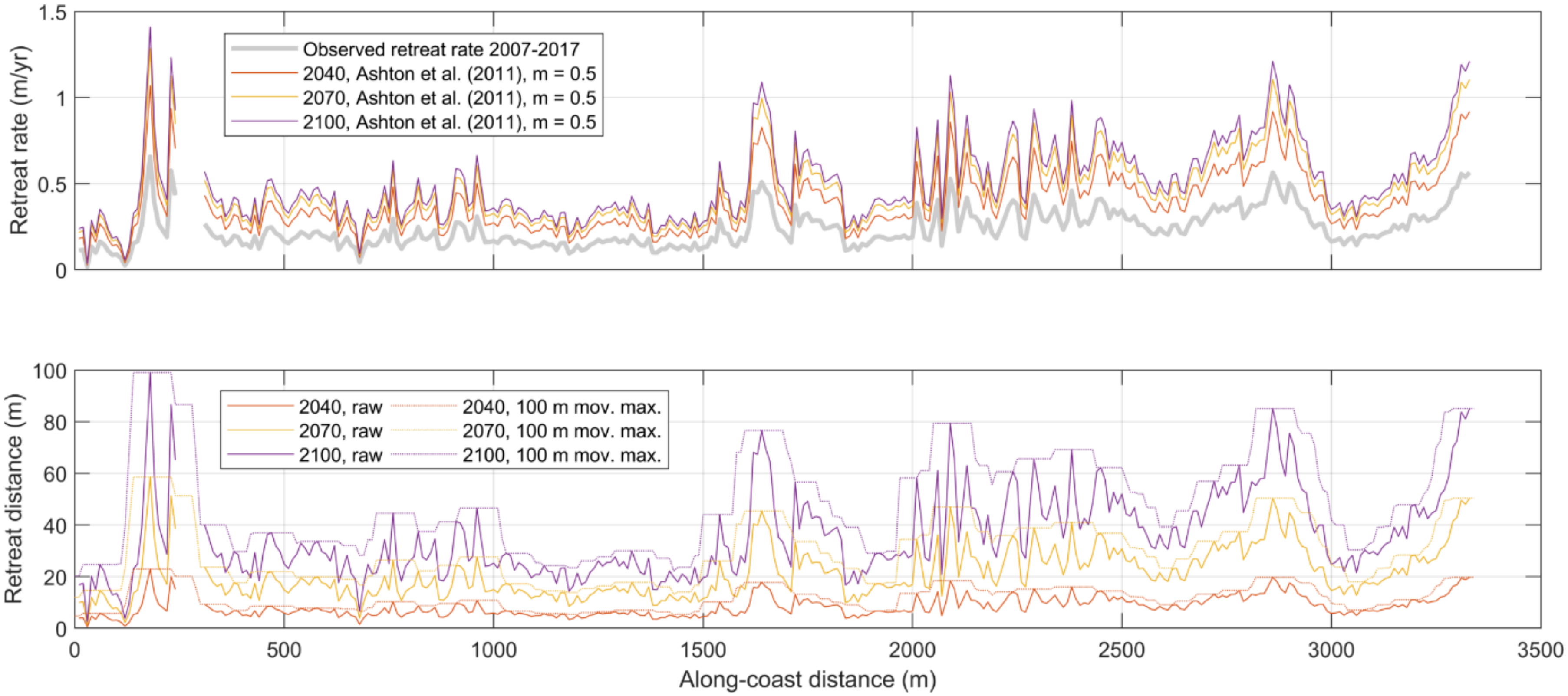


Figure 2-6. Upper panel: predicted future rate of cliff retreat for an example section of East Devon cliff, compared to the contemporary observed cliff retreat rate. Lower panel: predicted future cliff retreat distance from the 2017 digitised cliff line, including the raw retreat distance (solid lines) and the distances after applying a 100-m moving maximum filter (dotted).

Figure 2-7. Aerial image showing the current cliff top position (blue line) and the predicted cliff position for the three epochs; short (green), medium (orange) and long term (red). The dashed lines indicate the associated buffer lines. The black line indicate the long term SMP prediction.

2.9. Step 5: Generate future cliff lines

The predicted retreat distances were next used to **generate future cliff lines for the years 2040, 2070, and 2100 (**Figure 2-7**)**. At each location along the cliff, the angle of the perpendicular profile and the retreat distance at that position were combined to calculate a retreated cliff coordinate for that location, using trigonometry. The future cliff lines were then smoothed to remove noise, and to deal with any areas where the retreated cliff line overlaps with itself, which can occur where narrow headlands 'erode' from opposing sides. This was achieved using a moving-average filter, with a window size that varied along the coast, equal to the retreat distance at each location. Therefore, if a location was predicted to retreat 30 m inland, the smoothed coordinate was determined from the average of all coordinates 15 m either side of that point.

A set of alternative future cliff lines was also generated which incorporated a 'buffer' distance, as discussed in Section 5, which added an additional 10% or 10 m (whichever was larger) onto the predicted retreat distances. All future cliff lines were Quality Controlled in GIS, and the separate cliff sections (Section 2.3) were merged to produce a final complete retreat line for each epoch to be saved as a GIS '.shp' file.

2.10. Step 5: SMP, LPA & EA Input

The generation of a future cliff line position is a significant step in the development of a CCMA boundary; however, the proposed method needs to be combined with additional supporting data, as presented in the SMP (Halcrow, 2011). In particular, while LiDAR provides comprehensive coverage and acceptable levels of spatial resolution and accuracy, the temporal resolution tends to be limited due to the cost of data capture, and therefore it is likely at slowly-eroding, hard-rock coastlines that the long-term retreat rate may not be represented sufficiently by the retreat observed over 10 or even 20 years of LiDAR data. In such cases, the SMP assessment provides a useful benchmark for comparison, as these were determined using a different methodology incorporating historic mapping.

Using the methods presented in this section of the report, the predicted rate of future cliff retreat is dependent on the historic retreat rate at each location, and therefore varies along the coast. In comparison, the current SMP projection applies a uniform erosion rate to the future cliff-top. For the section of coastline in Figure 2-7 the long term scenario predicts ~55 m retreat. It is expected that the existing SMP method would therefore underestimate future retreat in some places, while overestimating it in other places, both of which are highly undesirable for planning purposes.

The SMP for this region states;

“The long term policy is to continue No Active Intervention along this undefended section of cliffed coast, allowing it to continue to evolve naturally.

Erosion of the cliffs would continue, although sea level rise is likely to lead to this rate increasing during this period, with total erosion of 40 to 55m predicted by 2105. Towards Straight Point, where recession is only as a result of infrequent small scale cliff falls, less than 10m of recession is predicted by 2105. These cliffs could however, be more sensitive to sea level rise and any increase in precipitation, potentially leading to an increase in the frequency of cliff failure events. There is, also a slight risk that relict landslides could be reactivated. Therefore monitoring is recommended to monitor this potential risk”

The total retreat rates for the different SMP epochs are presented in Table 2-1, which shows that, for the study region, the SMP predicts 55 as maximum, which is far lower than the maximum of 118 m predicted using the LiDAR analysis methods described in this section of the report.

Table 2-1. Summary table showing the different SMP shoreline change rates currently defined, and the variable retreat rate generated using the new method.

Method	Short term 2011-2025	Medium Term 2011-2015	Long Term 2011-2100
SMP Upper Final Line	8 m	20 m	55 m

Revised Cliff Retreat range (incl SLR)	8 m – 28 m	20 m – 70 m	32 m – 118 m

It is important that the CCMA region identified is compared against SMP projections, and is discussed with the EA and relevant LPAs to ensure adoption is likely. For consistency and to keep the methodology clear **we have not adjusted our retreat lines to incorporate existing SMP lines**. The SMP uses a different baseline shoreline position and a fundamentally different methodology, and is therefore not directly comparable. Instead, we encourage LPAs to consider both the SMP future cliff lines and the cliff lines generated in this project. Where uncertainty arises as to which line to use in planning decisions, the most conservative (furthest inland) estimate would be a safe benchmark. We consider the lines generated in this project to be derived from more precise and accurate data, using the most up to date sea level rise projections, and use the best available cliff retreat formulae from the literature. However, the cliff lines generated in this project become more uncertain where stretches of cliff have experienced little or no cliff retreat over the 10-year LiDAR epoch used, and the 'buffered' cliff lines, or the SMP lines should be considered as a failsafe in such locations.

2.11. Summary Steps for Cliff Backed Coastline

For this project, the preparation of spatial data was undertaken in QGIS, and the majority of the cliff retreat analysis was undertaken in Matlab. The steps below provide a guide to the key steps involved, and are written for generic use with any data analysis or GIS platforms. It should be stressed that while the analysis methods aim to be transparent and conceptually simple, their implementation is not trivial and approximately 1000 lines of Matlab code were required to undertake the analysis.

1. **Load the earliest available, and most recent LiDAR datasets** (usually individual tiles) and, if necessary, merge tiles into one raster data set per time-period (e.g. 2007 and 2017).

2. **Conduct a 'geomorphic change detection'** (GCD) analysis using the two LiDAR epochs, thresholding the LiDAR changes at 15 cm (nominal accuracy of LiDAR), and 95% confidence level. This results in a GCD surface that shows where significant geomorphic changes have occurred between the two LiDAR epochs.

3. **Create an area polygon (clip extent)** and clip a suitable area for each stretch of coastline from both the LiDAR data epochs and the GCD surface. The coastline should be divided into sections of largely similar geological type, orientation (i.e. divide at large headlands), and of manageable data size. Output the coastal sections in ascii (text) format for further processing.

4. **Use aerial imagery to digitise the cliff-top line**. Use imagery from the same period as the latest LiDAR epoch (e.g. 2017), and digitise along the line that divides the vegetated and un-vegetated regions, indicating the line of active coastal retreat. Where the line of active retreat is not obvious, use the latest LiDAR to confirm where the most significant change in slope occurs (i.e. using a profile tool in GIS). Cliff lines from CCO provide a good starting point, but often require manual adjustment to represent the line of active coastal retreat.

5. **Generate perpendicular coastal profiles along the cliff line.** Smooth the cliff-top line with a moving-average filter; a window size of 80 m was found to produce a good balance between removing small-scale variations in cliff orientation while still representing the overall orientation of the coastline.

6. **Create perpendicular profiles to the smoothed cliff line** at (e.g.) 10 m along-coast spacing. The cross-shore extent should be sufficient to reach at least the toe of the cliff and at least 10 m inland of the cliff line. Generate coordinates along each profile at (e.g.) 1 m resolution.

7. **Extract LiDAR and GCD data along each of the perpendicular profiles**. Use the coordinates of the perpendicular profiles to extract data from the LiDAR and GCD surfaces.

8. **Calculate past cliff retreat rate at each profile location** by calculating area of negative cliff change (lost cliff area) between the top of the beach (part of profile coinciding with an elevation = MHWS + 2 m) and the top of the cliff (part of the profile that is 10 m inland of the digitised cliff line). Calculate the maximum cliff height between these two locations, then calculate cliff retreat rate using Eq. 1.

9. **Predict future cliff retreat rate at each profile location** using Eq. 2, informed by the past cliff retreat rate, the best available measurements of past sea level rise (e.g. long-term tide gauge records), and the best available projections of future sea level rise (e.g. UKCP18 or similar). We adopted the 'high-emissions, 50th percentile' future SLR scenario from UKCP18.

10. **Generate future cliff lines for the years 2040, 2070, and 2100**. At each location along the cliff, use the angle of the perpendicular profile and the predicted retreat distance to calculate a retreated cliff coordinate for that location using trigonometry.

11. **Smooth and clean the retreated cliff line**. A moving-average filter, with a window size that varies along the coast, equal to the retreat distance at each location, was found to provide an appropriate level of smoothing without removing maximum retreat locations.

3. Case Study: Floodable Estuary

This section will describe the proposed methodology used to define future shoreline position for an estuarine/tide dominated coast. In such environments, shoreline change, and erosion are expected to play a far smaller role in determining the CCMA than enhanced coastal flooding, as storm surge is considered the main coastal hazard. The focus here is about the enhanced/modified flood risk, not necessarily a modified coastline position. The approach will examine data sources relevant to the region and existing flood mapping, where available. Secondly, areas of improvement will be identified and methods by which future climate change scenarios can be incorporated will be addressed. As discussed in WP1 the current focus for CCMAs is on permanent submergence, however, we shall adopt a method for inclusion of areas where flood risk is significantly enhanced due to SLR.

3.1. Site Description

The Taw Torridge estuary, North Devon, represents a large estuarine system forming the mouth of the rivers Taw and Torridge (Figure 3-5). From a development perspective the area is dominated by Bideford and Barnstaple as the central urban populations. Both of these towns are located on the riverbanks and have developed historically through shipping and trade.

As identified above, a broad Level 1 SFRA was published in 2009 as an overview of the flood risk for North Devon Council (NDC) and Torridge District Council (TDC). This document covers a wide remit looking at the catchment as a whole, historic flood events and likely fluvial and tidal flood events. More recently, TDC commissioned a Level 2 SFRA assessment to focus on identified and potential development sites (Figure 3-1). In 2010, Royal Haskoning also undertook a Level 2 SFRA for Barnstaple (Figure 3-2) with similar objectives to undertake more detailed modelling of sites earmarked for future development/growth.

Figure 3-1. Overview map showing the river Torridge, Bideford, "Extreme flood zone" (EA Flood zone 2 or 3) and identified development sites to be addressed in the Level 2 SFRA (Hyder, 2010).

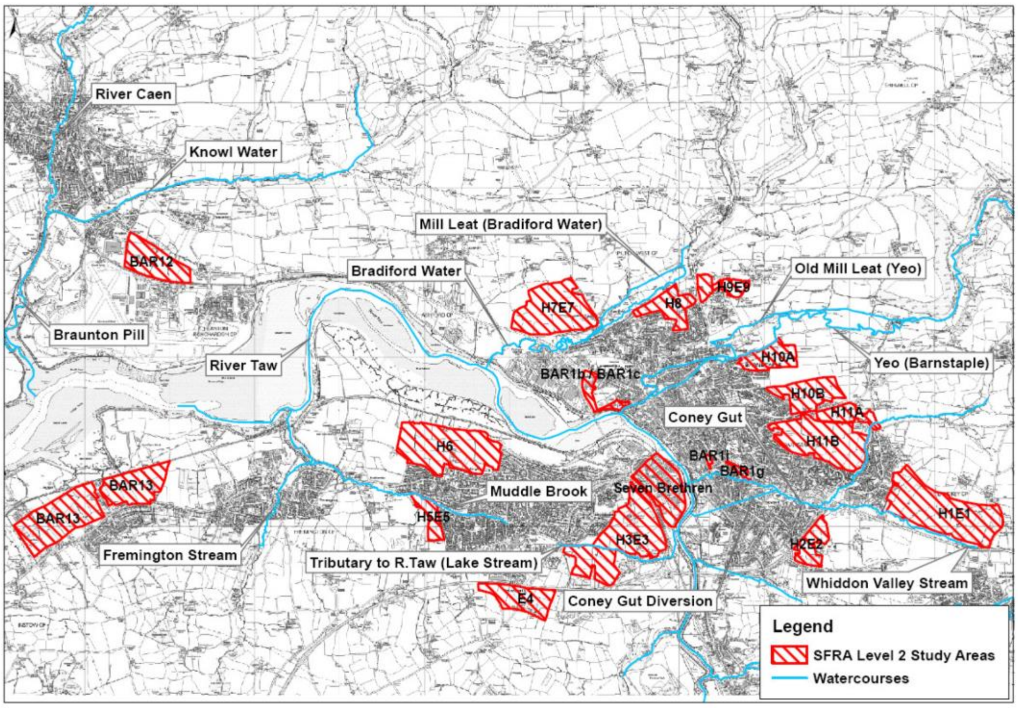


Figure 3-2. Overview map showing the river Taw and identified potential development sites to be addressed within the Level 2 SFRA undertaken on behalf of NDC (Royal Haskoning, 2010)

3.2. Data Sources

- Most recent aerial LiDAR
- Most recent aerial imagery
- EA Flood Map for Planning

From the EA; *"The Flood Map for Planning (Rivers and Sea) includes several layers of information. It is our best estimate of the areas of land at risk of flooding, when the presence of flood defences are ignored and covers land between Zone 2 & 3 and the extent of the flooding from rivers or the sea with a 1 in 1000 (0.1%) and 1 in 200 (0.5% or greater) chance of flooding each year for Flood Zone 2 and 3 respectively. This dataset is designed to support flood risk assessments in line with Planning Practice Guidance; and raise awareness of the likelihood of flooding to encourage people living and working in areas prone to flooding to find out more and take appropriate action."*

The dataset is maintained by the EA and updated four times a year. Zones are based on flood models which use the EA Extreme sea water level dataset from 2008. This has now been replaced by the Coastal Flood Boundary Conditions for the UK (2018), published May 2019. Future Flood Zone releases should include the most recent Coastal Flood Boundary datasets; however, these **DO NOT INCLUDE SLR.**

- NCERM data

See WP1 for a summary of NCERM data and how it was developed.

- Strategic Flood Risk Mapping (SFRM)

As introduced in WP1, there are two levels to SFRAs. For a Level 1 SFRMs, existing EA Flood Zone data are used to asses areas for development/infrastructure where the threat of flooding is low (not within Flood Zone 2 or 3)- this does not account for climate change impacts. For areas where this threat is greater a Level 2 SFRA is required. For Level 2 SFRMs more detailed modelling, including climate change scenarios, is required for planning sites.

In North Devon there are two main areas that have benefited from Level 2 SFRM: Bideford and Barnstaple.

- Barnstaple 2015 flood modelling includes 3 main scenarios available as GIS layers; 1:100 Fluvial, 1:200 Fluvial and 1:200 Tidal events. 1 m has been applied to represent SLR up to 2100.
- Bideford includes 12 different scenarios, available as GIS output. A table of these are shown in Appendix A. Of those presented there are two which are of most interest to the current project: 8b) Wave overtopping with sea-level rise and 10) Impact of climate change on tidal flooding. Both of these represent a 1:200 yr return period tide level + SLR, where 1 m has been applied

to represent SLR, in accordance with Defra’s 2006 prediction for the next 100 years (Hyder, 2010).

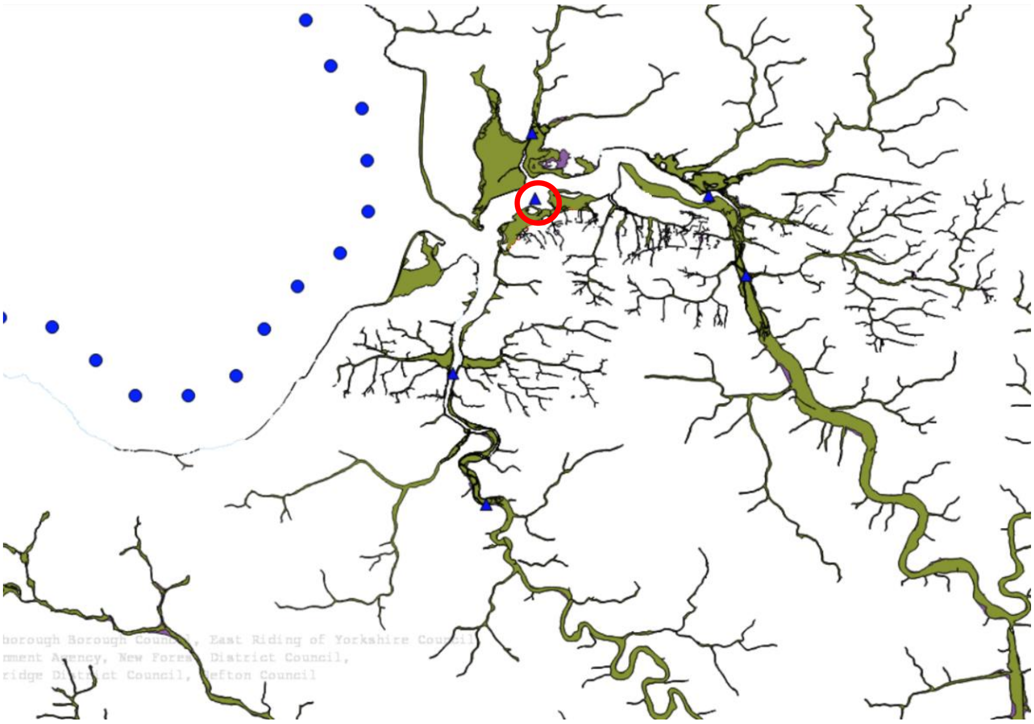


Figure 3-3. Spatial map showing Flood Zone 3 (green) and Flood Zone 2 (green and purple) for the Taw Torridge Estuary and surrounding rivers. Blue circles indicate the Coastal Flood Boundary Extreme Sea Level points and blue triangles show the Estuary points. The red circle identified the estuarine node discussed within the text.

As stated in WP1, for Level 1 SFRA, it has been accepted that Zone 2 can be re-classified as Zone 3 when climate change scenarios need to be considered. This means that what is currently a 1:1000 yr flood event becomes a 1:200 yr event due to sea-level rise. We would argue that without closer examination there is a danger this approach is not sufficiently conservative to provide informed long term CCMA mapping.

For most urban/developed areas, exposed to flood risk, a Level 2 SFRA will have been undertaken, which must include some provision for climate change scenarios. Where these studies have been undertaken within a reasonable time frame, and the SLR projections used are in line with the most recent forecasts there is strong support for utilising these datasets where possible.

3.3. Step 1: Relevant Data

The first stage involves obtaining the latest relevant datasets through the EA or regional monitoring program (CCO). When combining multiple data sources care needs to be given to the relative accuracy of the datasets being used. Figure 3-4 highlights discrepancies in the datasets, e.g. NCERM and Flood Zone maps not aligning with the same shoreline. While the focus of this study is to identify the *inland* extent of a CCMA, discussion with Dave Watkins at Cornwall Council have highlighted that previous planning applications have not been automatically referred to the coastal team as the proposed development site was seaward of the restricted planning zone. This has subsequently been resolved by extending the shoreline extent down to Mean Low Water (MLW).

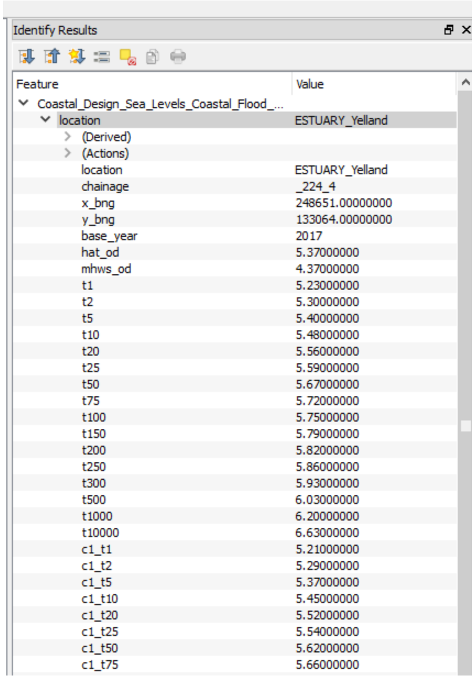
Figure 3-4. Aerial imagery of Taw-Torridge estuary with Flood Zone 3 (green) and NCERM 5 %ile buffer (red) shown. Note the poor alignment of the NCERM shoreline relative to the Flood Zone mapping

Figure 3-5 provides an overview of the three principle flood extent datasets that were incorporated into regional overview: the EA Flood Zone 3 extent (1:200 yr), Barnstaple Level 2 SFRA 1:200 yr Tidal flood extent for 2115 and the Bideford Level 2 SFRA Wave Overtopping and Tidal Flooding extent incorporating SLR. Each of these datasets provide the most detailed flood modelling information, including climate change projections (with the exception of Flood Zone 3) and should be used before additional mapping is undertaken. By identifying these regions from the outset gaps in the spatial extents can be mapped and the following analysis can be limited to these regions.

Figure 3-5. Overview map of the Taw-Torridge region showing the EA Flood Zone 3 extent (light blue), Barnstaple 1:200 Tidal flood extent for 2115 (orange) and the Bideford Wave overtopping and tidal flooding extent incorporating SLR (pink).

3.4. Step 2: Contour Extraction

The objective with the step is to use the most recent aerial LiDAR to create a new polygon relating to a future SLR scenario. As in the earlier example for eroding coasts, aerial LiDAR tiles need to be merged into a single product covering the full area of interest. This can be done within all GIS platforms, although for large areas some care needs to be taken over computing power and resolution requirements. In general, increased resolution is preferable; however, this can be computationally demanding and also result in spurious boundary edges where detailed features such as trees/hedges distort the true boundary. CCO provide unfiltered and filtered data; the latter has undergone preliminary processing to remove vegetation creating a more robust boundary and is the approach adopted by the EA for similar work. With the LiDAR data in a single layer it is possible to create a new "Flood Zone" corresponding to the future SLR elevations required. Figure 3-6 shows the data for an **EA Coastal Design Sea Level** Estuary Node which is situated close to the mouth of the Taw (Figure 3-3).



Feature	Value
Coastal_Design_Sea_Levels_Coastal_Flood_...	
location	ESTUARY_Yelland
(Derived)	
(Actions)	
location	ESTUARY_Yelland
chainage	_224_4
x_bng	248651.00000000
y_bng	133064.00000000
base_year	2017
hat_od	5.37000000
mhws_od	4.37000000
t1	5.23000000
t2	5.30000000
t5	5.40000000
t10	5.48000000
t20	5.56000000
t25	5.59000000
t50	5.67000000
t75	5.72000000
t100	5.75000000
t150	5.79000000
t200	5.82000000
t250	5.86000000
t300	5.93000000
t500	6.03000000
t1000	6.20000000
t10000	6.63000000
c1_t1	5.21000000
c1_t2	5.29000000
c1_t5	5.37000000
c1_t10	5.45000000
c1_t20	5.52000000
c1_t25	5.54000000
c1_t50	5.62000000
c1_t75	5.66000000

Figure 3-6. Example output from the EA Coastal Design Sea Level dataset which provides sea level output at specific nodes around the coastline and estuary, as shown in Figure 3-3.

The data for each node provides the current Extreme Sea Level values for the highest astronomical tides (HAT) and various return periods, e.g. 1:200 yr = 5.82 m and 1: 1000 yr = 6.2 m, that are used by the EA to generate the Flood Zone maps. As yet these do no incorporate future climate change projections. Using the current approach, adopted for Level 1 SFRA allowance for climate change impacts, would mean that the new 1:200 yr level would be 6.2 m. However, by using the node outputs shown in Figure 3-6, we can incorporate a SLR component for the period of interest. By applying 1 m SLR, in line with the neighbouring Level 2 SFRAs, Flood Zone 3 1:200 yr return level should be 6.82 m, more conservative than the current approach (Figure 3-7). This approach does make some assumptions; that the future sea level inundation curves will closely follow the current one e.g. the estuarine basin shape will not alter significantly enough to change the tidal prism.

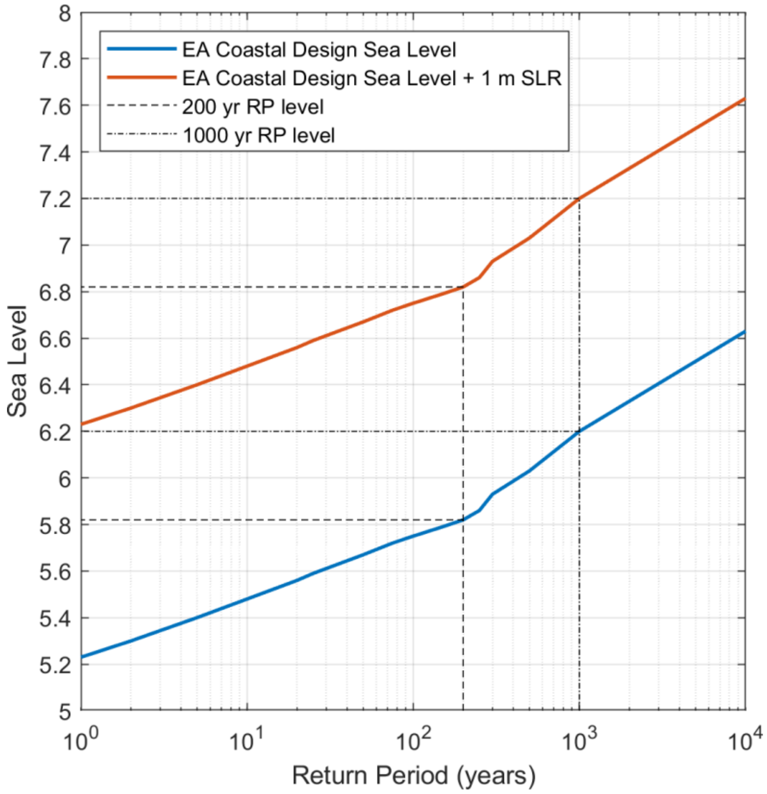


Figure 3-7. Current and future sea-level charts using the EA Coastal Design Sea Level data taken for the estuary node for the Taw Torridge (Figure 3-6). The dashed lines indicate the 1: 1000 and 1:200 return period levels which are used to represent Flood Zone 2 and 3, respectively.

By using the most recent LiDAR elevation data, the future Flood Zone 3 extent extracted and mapped onto the river banks for the areas not benefiting from more detailed SFRA Level 2 modelling (dark blue; Figure 3-8). At present the adjoining model data from Barnstaple and Bideford remain distinguishable; however, in the final version the three regions would be merged into a single layer.

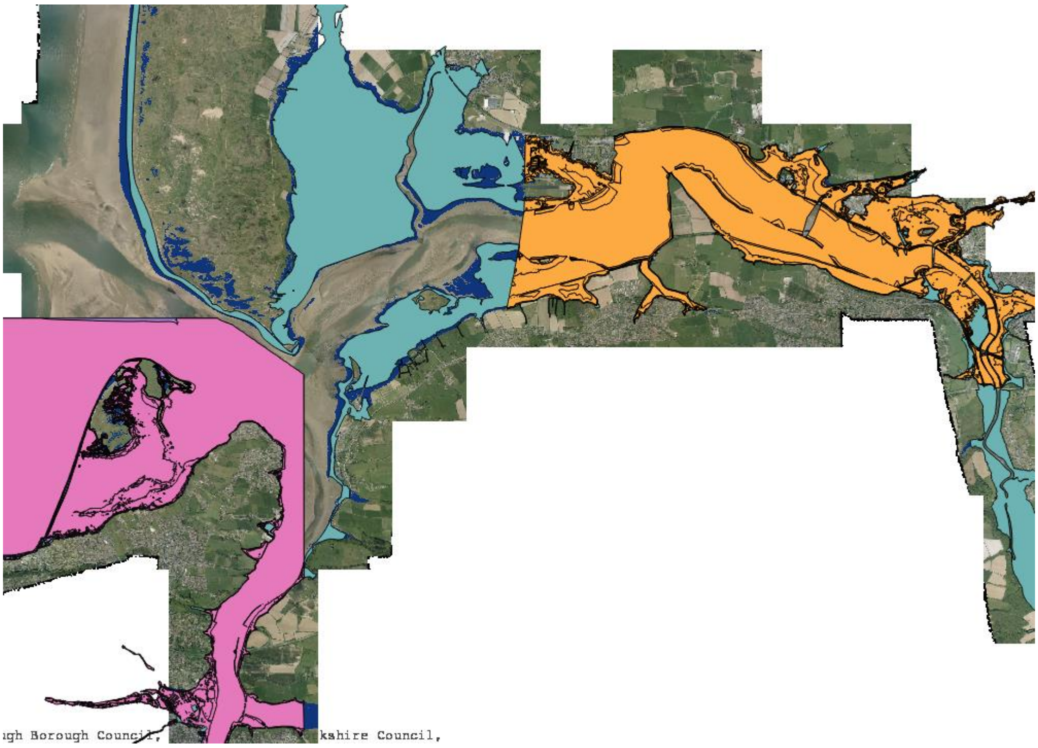


Figure 3-8. Overview map of the Taw Torridge estuary with the EA Flood Zone 3 extent incorporating the model output for Barnstaple and Bideford. The projected 2100 1:200 yr extreme sea level is also shown (dark blue) for areas that fall outside of the model extents.

3.5. Step 3: SMP, LPA & EA Input

As with the first case study, the final step in this process is to provide a single continuous line to define the region to match a given emission scenario. This will require merging the different datasets and ensuring they represent the same SLR scenarios. Once these have been developed further guidance from the SMP, LPAs and EA will feed into the final adoption of the CCMA region developed.

The long term plan for the Taw and Torridge estuaries is to allow the estuary to respond naturally to climate change, particularly in its upper reaches, while continuing to provide flood defence to people, property and infrastructure where settlements exist (Halcrow, 2010). The long term plan is to maintain existing defences to protect assets while also identifying possible realignment sites and allow the estuary to evolve naturally.

The SMP goes on to state;

Within the Taw, the infilling of the estuary with muddy sediments has progressed slowly seawards from the inner reaches of the estuary and has reached approximately Penhill Point (Pethick, 2007). Future sea level rise will lead to a continuation of this situation (in both estuaries) with the rate of sea level rise occurring at a greater rate than the rate at which the estuary is able to accrete with muddy sediment (Pethick, 2007).

There is much uncertainty about the future evolution of the Taw/Torridge Estuary as it is very sensitive to sea-level rise and other climate change impacts. There is also uncertainty regarding the source of sediment to the Taw/Torridge system. SMP1 (Halcrow, 1998) suggest that there would be a net trend of retreat of the intertidal areas over the next 50 years as a result of sea level rise; although the current trend for siltation was noted, an explanation for this trend was not offered.

No specific predictions for the estuary were made by Futurecoast (Halcrow, 2002) although it concluded that accelerated sea level rise, resulting from climate change, could have implications for the future evolution of this area in at least two ways: firstly, this would increase rates of erosion through increased exposure of the backshore, in particular those areas which have to date been partially protected by foreshore platforms.

As with the previous case study, the final step in any method is a comprehensive review of how any changes to SMP policy, over the duration of the CCMA may have a bearing on the flood extent identified. Confidence in future funding for defence and the potential to allow realignment will have impacts on the final CCMA region applied.

3.6. Summary Steps for a Floodable Estuary

While the work presented above has been undertaken using QGis, which is an open source free software, the tools mentioned are generic between GIS platforms, although exact names may vary.

Make sure Coordinate Reference System (CRS) is set throughout for all layers e.g. Ordnance Survey OSGB 36

1. **Load the most recent LiDAR datasets available** (usually individual tiles)
2. **Merge LiDAR tiles** into one layer (often best to work in batches depending on size of area) In QGis you can use **Raster- Miscellaneous-Merge**
3. Use the Raster Calculator to **find the area from '0 m' up to the required elevation** (see Step 2: Contour Extraction). e.g. " my_raster@1 " <=6.68 AND " my_raster@1 " > 0 where "my_raster" is your merged LiDAR layer. This will create a binary layer from 0 to 6.68 m.
4. **Run Raster- Polygonize tool on that layer to make it into a polygon.** It is possible to then shade that layer to indicate the projected flood zone.
5. If the area is a straightforward small region it is likely **this layer can be used as the CCMA boundary**, however, it is likely that there will be a lot of "noise" around the edge, particularly in urban areas.

6. Create a new Vector layer- as a Polygon. Edit this new layer and click around the edge of the polygonized flood area created in (4). This will allow the user to exercise judgement when view overlaid onto aerial imagery. Where the region overlaps with a Level 2 SFRA then follow the most conservative region.

7. The final step is to **add a buffer to the mapped regions**. A vertical 0.25 m buffer can be applied using the same method outlined in steps 3-7. A horizontal buffer, to accommodate the South West Coast Path is added by creating a 2 m single sided buffer. In QGis you can use “Single Sided Buffer” found under the Vector Geometry tool.

8. Save layer as a shape file (.shp) file for export into the relevant planning portal.

4. Case Study: Beaches and Sea Defences

The two case studies presented above deal with the primary modes of coastal change along cliff backed coasts and estuarine systems. Within both study areas, the Taw-Torridge Estuary and the East Devon coast, there are sections of open coastline dominated by sand and gravel beaches. Additionally, around many urban areas there are significant shorelines fronted by coastal defences. A complete CCMA needs to address all of the areas carefully to provide a complete future coastline position. Here we address methods to predict future shoreline retreat at sandy and gravel beaches, and discuss ways to deal with future coastal change at locations with sea defence structures that may not be maintained indefinitely.

4.1. Data Sources

Airborne LiDAR

Airborne LiDAR data with a nominal vertical accuracy of 15 cm (Sallenger *et al*., 2003) and 1-2 m horizontal resolution are freely available from the Channel Coastal Observatory (CCO). In the presented case study, LiDAR data were obtained from CCO for the earliest and most recently available time periods (2007 and 2017). The 10-year LiDAR epoch enables the quantification of barrier retreat, and mapping of shoreline position for sandy beaches.

Once an area of interest was selected, LiDAR data were downloaded in a georeferenced 1-m resolution raster format as an unfiltered (i.e. surface rather than bare-earth model) .txt File, which consists of multiple 1 x 1 km tiles containing XYZ data (available from http://www.channelcoast.org). The LiDAR data were then input and prepared within a GIS platform (QGIS v10.6).

Sea level records/projections

Long term tide gauge records are available at a number of locations around the UK and are archived (https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/) by the British Oceanographic Data Centre. These represent the best available observations of past sea level rise; however, some gauges exhibit more ‘noise’ than others and some degree of line fitting is required to obtain a sea level rise value over the period of interest. Sea level rise projections into the future are available for the UK from the United Kingdom Climate Projections dataset (currently UKCP18), and we chose to use the ‘high emissions, 50th percentile’ climate scenario, in line with Environment Agency common practice. It is not recommended to use UKCP18 for sea level hindcasts.

Bathymetry data

Bathymetry data are required to quantify the nearshore slope (from the Depth of Closure landward) for the Bruun Rule. Multi-beam bathymetry data were available from the CCO for the East Devon region under study in this project. In North Devon, single beam data were available from the CCO. Alternatively, it may be possible to use the freely available EMODNET data set, which provides data for the whole of Europe at reasonable (~150 m) resolution. However, in many places these data do not cover the intertidal region and close attention should be paid to check that the data reaches at least the Depth of Closure at the site of interest.

Wave data

A long time series of wave data (at least 10 years) is required for each location, in order to calculate the Depth of Closure. We chose to use the Met Office 40-year wave hindcast, which is available around the UK at 7 km resolution by request via the CEFAS WaveNet data portal (wavenet.cefas.co.uk/hindcast).

4.2. Step 1: Define Coastline Position

As with the methods used in Sections 2 and 3, it is necessary for sandy and gravel beaches to define a line which represents the coastline to be projected into the future. However, unlike the more abrupt change in slope/vegetation associated with the edge of a cliff, the shoreline of a beach is less well defined due to the daily variation of the tide, and as a result, different shoreline definitions are found in different studies. As CCMAs are concerned with the interface between the sea/ocean and the adjacent inhabitable land, we adopt the MHWS contour as a suitable coastline position for sandy beaches, which was extracted along the beach from the most recent LiDAR data. For gravel barriers, the barrier crest provides a suitable position as it represents the line of natural sea defence. This was manually digitised from recent aerial imagery and cross-referenced to LiDAR data using a profile tool in GIS to ensure the crest position was correctly identified.

4.3. Step 2: Profile Extraction

A smoothed version of the shoreline was created. The digitised shoreline or barrier crest was smoothed using a moving-average filter with a window size of 80 m, to remove small-scale variations (morphological features such as cusps), with the objective of ensuring that any point along the shoreline represents the overall orientation of the coastline at that location. The smoothed shoreline was then resampled to a node spacing of 10 m, but this value could be increased depending on the expected level of along-coast variability in recession in the region of interest, with smaller values (10’s of meters) being necessary for locations with sudden changes in coastal retreat rate and larger values being acceptable for locations with less variability in recession. Finally, the smoothed shoreline was used to generate a series of regularly-spaced transects, each located at one of the cliff line nodes (i.e. at 10 m intervals) and oriented perpendicular to the shoreline at that location (similar to Figure 2-3). Data from the chosen LiDAR epochs, as well as the bathymetry were then extracted along each transect, providing a series of profiles from which to assess the rate of barrier retreat and to determine the foreshore slope at sandy beaches (Figure 4-1).

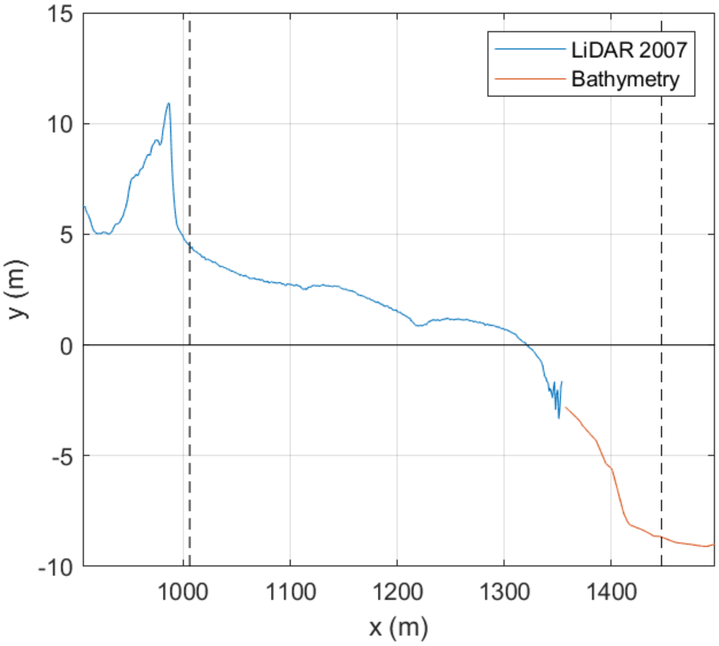


Figure 4-1. Example LiDAR and bathymetry profiles for a location on Saunton Sands, north Devon. The left and right vertical dashed lines represent the position of MHWS and the DoC at the site, respectively, which are used to define the nearshore slope for sandy beaches.

4.4. Step 3: Determine Nearshore Slope

For sandy beaches it is necessary to determine the Depth of Closure (DoC), as this was used to define the nearshore slope. This step is not required for gravel barriers. The DoC is the position on a profile at a particular site beyond which little or no sediment transport or profile change occurs (Masselink and Hughes, 2011; Valiente *et al*., 2019). We applied three different wave-based DoC equations (Hallermeier, 1981, Birkemeier, 1985, and Capobianco 1997), using wave data from a 40-year Met Office wave hindcast (at least 10 years of wave data is recommended), and used the average of the three values to represent DoC for that site, following the approach of Valiente *et al*. (2019). For each equation, the wave record is sorted in descending height order to compute the wave height that is exceeded for more than 12h a year (H_{12}). Once the DoC had been determined, its cross-shore position was found on each perpendicular profile and the nearshore slope was defined as the vertical height between DoC and MHWS divided by the horizontal distance between DoC and MHWS.

Table 4-1. Depth of Closure (DoC) equations, and example DoC values at case study site Westward Ho!

Eq. no.	Equation	Parameters	Depth of Closure
3	$DoC = 2.28\,H_{12} - 68.5\left(\frac{H_{12}^2}{gT_p^2}\right)$ Hallermeier (1981)	H12 = Non-breaking significant wave height exceeded for 12 hours per year. Tp = wave period associated to H12 g = gravitational acceleration (9.81 m/s)	5.6 m
4	$DoC = 1.75\,H_{12} - 57.9\left(\frac{H_{12}^2}{gT_p^2}\right)$ Birkemeier (1985)		4.3 m
5	$DoC = KH_{12}^{0.67}$ Capobianco (1997)	K = 3.4, for a maximum vertical variation in the profile of 0.05 m, over annual to medium temporal scale.	7.8 m
			Average = 5.9 m

4.5. Step 4: Historic Retreat Rates

For **gravel barrier** systems, such as the case study site at Westward Ho! discussed below, historic observations of the barrier crest position can be used to determine a historic retreat rate, as the barrier is expected to gradually migrate due to successive large storm events over a number of years. For **sandy beaches,** historic retreat is not computed, as changes at sandy beaches are characterised by both accretion and erosion phases. Therefore, the most recent shoreline position and LiDAR data should be used, although for sites that exhibit large seasonal variability in profile shape, consideration should be given to derive a ‘representative’ shoreline slope

4.6. Step 5a: Predicting future retreat at gravel barriers

Gravel barriers have been shown to respond to SLR through ‘rollover’ and landward retreat, which occurs as a result of large waves and elevated water levels during storms washing gravel over the barrier crest. As there is no natural mechanism for this material to re-enter the active beach profile, successive events will see a gradual landward migration of the barrier crest as the system maintains equilibrium with the forcing conditions. As such, a historic retreat rate for gravel barriers can be used to forecast future retreat under predicted SLR scenarios.

For **gravel barriers** we can use a specifically developed formula from Orford *et al.* (1995). Over time-scales of 1–100 years, the rate at which a gravel barrier will naturally retreat landward has been found to relate to the rate of local sea-level rise, as well as the characteristic size, or ‘inertia’, of the barrier (Orford *et al.*, 1995). A comparison of barrier retreat rates in Europe and Canada by Orford *et al.*, (1995) suggests that the retreat efficiency (the change in retreat rate per unit increase in the rate of SLR) is related to the barrier size or barrier inertia (cross-sectional area multiplied by crest height above mean sea-level). Increasing rates of SLR therefore increase the rate at which a gravel barrier will migrate landward, and additionally, smaller barriers will migrate faster than larger barriers (Figure 4-2). **The formula predicts the future rate of barrier retreat, R2**, from estimates of **current retreat rate R1** and past and future SLR:

$$R2 = R1 + Re(S_2 - S_1) \tag{6}$$

Where R2 = future retreat rate (m/yr), R1 = historic retreat rate (m/yr), and S_1 and S_2 are the past and future SLR rates, respectively (mm/yr, see section 2.8). **The retreat efficiency parameter, Re**, was found by Orford *et al*., (1995) to be correlated to the **barrier cross-sectional area * barrier height (termed barrier inertia, I_b)**, and can be estimated using the following equation (from Figure 4-2, right panel):

$$Re = \frac{I_b - 3403.5}{3554.4} \tag{7}$$

Therefore, by estimating the height and cross-sectional area of a gravel barrier from the perpendicular profiles extracted from the LiDAR or bathymetry data, Eq, 7 and then Eq. 6 can be used to predict the future barrier retreat rate R2.

The gravel barrier at Westward Ho! is a good example of a gravel system that has experienced gradual historic retreat that is well documented (Orford *et al.*, 1995; Pethick, 2007). By applying Eqs. 6 and 7 to Westward Ho! (Re = 0.23) We can see how different future sea-level rise scenarios can have a significant impact on the predicted future retreat compared with the historic retreat rate (Figure 4-3). At Westward Ho!, under a medium emission scenario the predicted retreat rate by 2120 would be 2.72 m/yr, which would be the equivalent of ~200m retreat from its current position (Figure 4-4). This result is in line with the SMP projections for the area, shown in Figure 4-5, which show a similar ~200-250m retreat at the southern end of the Pebble Ridge.

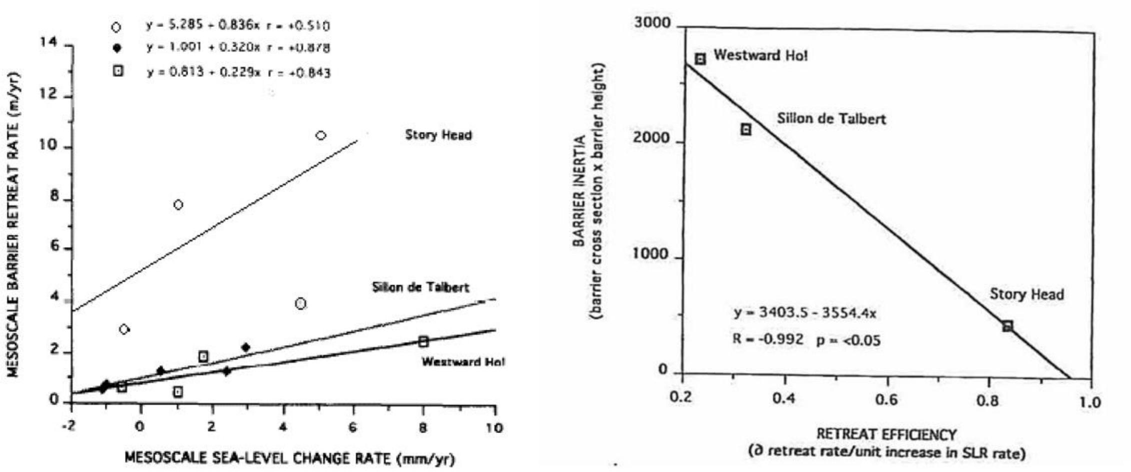


Figure 4-2, Left panel: relationship between barrier retreat rate and sea-level rise (SLR) rate determined from three gravel barriers in Europe and Canada by Orford *et al*., (1995). Right panel: relationship between the gradient of each line in the left panel (barrier 'retreat efficiency'), versus the geometry of the barrier ('barrier inertia').

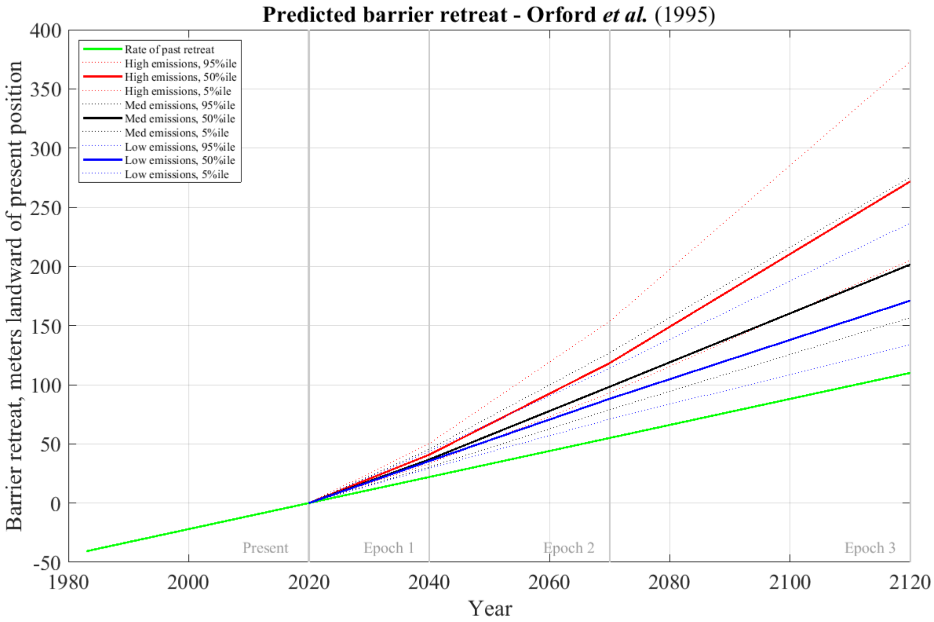


Figure 4-3. Retreat of Westward Ho! Pebble Ridge due to SLR predicted using Orford et al.'s (1995) model for different UKCP18 sea-level rise scenarios. Epoch 1 is years 2020 to 2040 (0 - 20 years), epoch 2 is years 2040 – 2070 (20 – 50 years), and epoch 3 is years 2070 – 2120 (50 – 100 years). Lower (5th percentile), median (50th percentile), and upper (95th percentile) predictions are shown for each scenario, indicating the magnitude of uncertainty in the UKCP18 sea-level rise predictions.

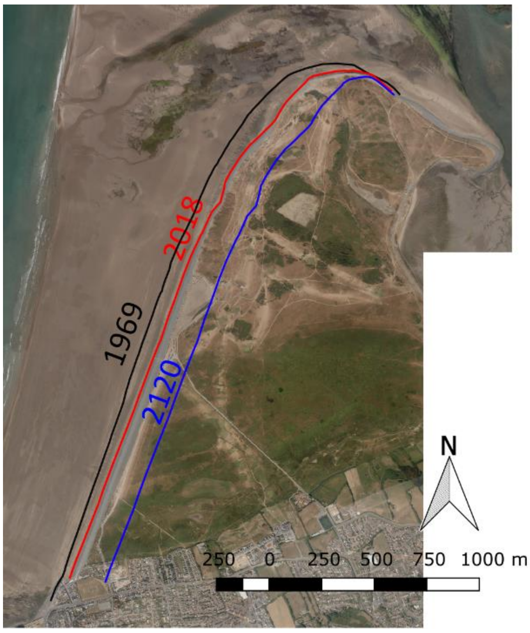
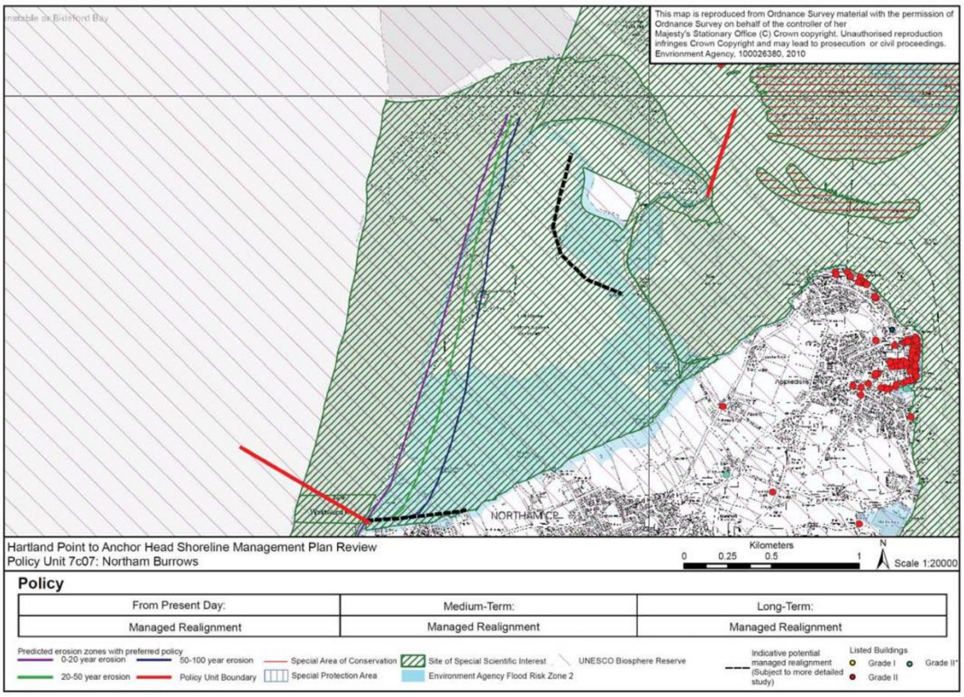


Figure 4-4. Historic barrier position (black line) current barrier position (red line) and predicted retreat distance by 2120 (blue line) at Westward Ho!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Hartland Point to Anchor Head Shoreline Management Plan Review
Policy Unit 7c07: Northam Burrows

Policy

From Present Day:	Medium-Term:	Long-Term:
Managed Realignment	Managed Realignment	Managed Realignment

Figure 4-5. Shoreline Management Plan for Westward Ho! which indicates the SMP short (purple line), medium (green line) and long (blue line) predictions of barrier position.

4.7. Step 5b: Predicting future retreat at sandy beaches

For **Sandy beaches,** the most widely used method for predicting shoreline response to SLR is the ‘Bruun rule’ (Bruun, 1962), which works on the hypothesis that as sea level rises, the shoreface moves landward through a process of upper beach erosion and lower beach accretion, whilst maintaining its equilibrium shape. This model of shoreline retreat has been critiqued in the literature, but remains the most widely used and prevalent concept to predict future shoreline position on sandy beaches. Unlike the formula for gravel barrier retreat, the Bruun rule does not require knowledge of past shoreline retreat rate.

For **sandy beaches**, The Bruun rule assumes that as sea level rises, shoreface erosion on the upper beach is balanced by shoreface accretion on the lower beach, and the resulting change in shoreline position, δy, is predicted with equation (10):

$$\delta \gamma = -S \frac{W}{h+B} \tag{10}$$

where S is the rise in sea-level (m), W is the cross-shore width of the active shoreface (here taken as the horizontal distance between MHWS and DoC), h is the height of the active shoreface (here taken as the depth of closure below Ordnance Datum Newlyn, ODN), and B is the height of the subaerial beach (here taken as the height of MHWS above ODN). Therefore future shoreline position can simply be projected using the measured shoreface slope ($\frac{W}{h+B}$) and future sea level rise S.

4.8. Step 6: Generate future shorelines

The predicted retreat distances were next used to **generate future shorelines for the years 2040, 2070, and 2100**. At each location along the shore, the angle of the perpendicular profile and the retreat distance at that position were combined to calculate a retreated coordinate for that location, using trigonometry. The future shoreline coordinates were then smoothed to remove noise, although were found to be more linear (and therefore less noisy) than the cliff lines described in Section 2. This was achieved using a moving-average filter, with a window size that varied along the coast, equal to the retreat distance at each location. Therefore, if a location was predicted to retreat 30 m inland, the smoothed coordinate was determined from the average of all coordinates 15 m either side of that point.

A set of alternative future shorelines was also generated which incorporated a ‘buffer’ distance, as discussed in Section 5, which added an additional 10% or 10 m (whichever was larger) onto the predicted retreat distances. All future shorelines were Quality Controlled in GIS and saved as a GIS ‘.shp’ file.

4.9. Step 7: Consideration of sea defence structures

The approaches outlined above, for sandy and gravel beaches, are clearly only realistically suitable for natural sites where landward migration is possible. For sites where existing **coastal defences** are in place, predicting the future shoreline position is clearly not possible, as it is often coincident with the sea defence itself. In many cases, such sections of coast are considered as HTL and therefore a CCMA is not required under NPPF guidance. As discussed in WP1, such a policy does not fully allow for future changes in shoreline management budgets and changes in policies. We propose that for areas where **coastal defences** are present, a future shoreline retreat prediction is made assuming that the sea defence is not there. Therefore, if the sea defence fails or is removed in future, at least a reasonable estimate of the future shoreline position will have been considered in the CCMA. This approach is similar to that which is adopted for flood zones, and allows for a CCMA to become a continuous zone along the coast regardless of engineered structures from which informed planning decisions can be made.

4.10. Step 8: SMP, LPA &EA Input

In line with Section 2 and 3, existing SMP future shoreline predictions can be consulted to provide an alternative estimate of the future shoreline position, and if necessary the most conservative estimate can be used to define a CCMA region. It is anticipated additional LPA and EA expert advice would also be sought to facilitate uptake of the designated CCMA regions.

4.11. Summary Steps for Beaches and Sea Defences

For this project, the preparation of spatial data was undertaken in QGIS, and the majority of the shore retreat analysis was undertaken in Matlab. The steps below provide a guide to the key steps involved, and are written for generic use with any data analysis or GIS platforms.

1. **Extract coastline position from LiDAR**. We used the MHWS contour line for sandy beaches, and the barrier crest for gravel barriers

2. **Generate perpendicular coastal profiles along the shoreline**. Smooth the shoreline; a moving-average filter with a window size of 80 m was found to produce a good balance between removing small-scale variations in shoreline orientation while still representing the overall orientation of the coastline.

   For sandy beaches:

3. **Determine nearshore slope of sandy beaches**, by calculating the DoC from a long term wave record (at least 10 years is recommended) using Eqs. 3,4, and 5, and then computing the horizontal distance between MHWS and DoC
4. **Predict future shoreline position** using the measured shoreface slope and future sea level rise using Eq. 10. Now skip to step 8

   For gravel barriers:

5. **Estimate rate of past barrier retreat at gravel barriers** using the earliest and most recently available LiDAR or historic imagery.
6. **Estimate the height and cross-sectional area** of the gravel barrier from the perpendicular profiles extracted from the LiDAR or bathymetry data
7. **Predict future barrier retreat rate** using Eqs, 6 and 7 informed by the past retreat rate, and past and future SLR rates.

For sandy beaches and gravel barriers:

8. **Generate future shorelines for the years 2040, 2070, and 2100**. At each location along the shore, use the angle of the perpendicular profile and the predicted retreat distance to calculate a retreated shoreline coordinate for that location using trigonometry.

9. **Smooth and clean the retreated shoreline**. A moving-average filter, with a window size that varies along the coast, equal to the retreat distance at each location, was found to provide an appropriate level of smoothing without removing maximum retreat locations.

5. Retreat Line Buffers

As outlined within the National Planning and Policy Framework guidance, a buffer of between 10 - 30 m is advocated along CCMA extents, in addition to the expected future position of coastal change. Previous case studies in WP1 have indicated there is variability in how this is applied and very little detail on the specific reason for the distance adopted

For our areas we have tried to adopt a clear and consistent approach that includes;

Tidal Coastlines

1. A 2 m horizontal allowance for the South West Coast Path

AND

2. 0.25 m vertical allowance to allow for uncertainties in the estimated coastal change (better reflects the neighbouring topography than a set horizontal buffer)

Erosive Coastlines

The greater of:

1. A 10 m horizontal buffer that includes the 2 m allowance for the South West Coast Path

OR

2. A variable horizontal buffer computed as 10% of the projected retreat distance for each section of coastline assessed at each epoch.

6. Summary

This report has set out to provide robust methods to predict future coastal change using data-driven analytical approaches from the scientific literature for the designation of CCMAs in different coastal environments. Using case studies covering sections of coastline in the Taw-Torridge Estuary and East Devon coastline we have explored different methods and available datasets that can be used to define CCMA areas.

For North Devon, existing Level 2 SFRAs have been made available for Bideford and Barnstaple, representing much of the estuarine system. Such analysis provides detailed modelling of different scenarios designed to address the principal aim of a CCMA - that is to assist LPAs in future infrastructure developments. Future flood risk gaps in the Level 2 SFRA coverage are, at present, managed through a Level 1 SFRA whereby climate change impacts are represented by re-classifying the return periods for existing flood extents. Comparison with projected SLR indicates this method under-predicts future water level scenarios for 2100. Using existing up-to-date LiDAR datasets, new flood extents can be quickly and easily generated, with the most recent extreme values analysis projections- updated regularly by the EA- with relevant SLR information. These maps can then be combined with neighbouring Level 2 SFRAs for a comprehensive CCMA.

For eroding cliff systems, historic retreat rate provides a key indicator of future behaviour. Combined with predicted acceleration in SLR it is possible to calculate future coastline positions at a user-defined resolution. In the examples presented, retreat distances of more than double (up to 118 m) the long term SMP projections (55 m) are presented. While the SMP coastal retreat predictions provide reasonable agreement with the proposed methods in some areas, the SMP predictions were found to not vary over large sections of coastline, despite large differences in the observed rates of past retreat. The proposed methods in this report aim to produce estimates of future coastal retreat that are data-driven and vary along the coast to reflect differences in geology and observed retreat. LiDAR data can be used to accurately measure cliff retreat; however, such datasets are temporally limited and, for slowly-eroding, hard-rock coastlines, historic aerial image analysis should be incorporated for more comprehensive estimates of historic retreat.

WP1 has highlighted the detail and depth of existing coastal research that underpins current management practices. While there are shortcomings within the existing SMPs – e.g. outdated climate change predictions, spatial resolution, and management policy designations – they represent a detailed analysis that should be incorporated into CCMA policy. Equally, the SFRA have been commissioned to provide the level of detail LPAs require and are therefore the best available data to support CCMA creation. The scope of this SWEEP CCMA project does not match the nature of these studies, but instead aims to explore methodologies and current datasets to address some of the shortcomings of the SMPs and SFRAs, while still making use of the existing reports where appropriate.

The key addition provided by this report compared to existing coastal change assessments, is a more comprehensive inclusion of sea-level rise effects on future coastal change, and in the use of historic retreat rates to inform the prediction of future retreat rates.

In much of what we have presented there is a tendency to move towards more automated techniques of coastline mapping to increase the repeatability between users, to increase speed, and to remove error. This should be encouraged to help standardise approaches and improve accuracy. However, it is clear when dealing with coastal systems that automation is far from simple and will often not work at all locations due to the myriad of profile types that are encountered. As such, human supervision is still considered necessary for mapping historic coastline position. Ultimately, Expert judgement from current and existing assessments, local knowledge, and multi-agency collaboration will all be highly necessary to finalise any CCMA.

6.1. CCMA Method

Sections 3, 4 and 5 have sought to outline proposed methods that can be applied to generate a CCMA for three types of coastal environment. Figure 6-1, below, provides a summary work-flow to break down the main stages required for each type of coastline likely to be incorporated as part of a CCMA. This provides a framework approach which can be applied using various data analysis/mapping software platforms. As indicated in previous sections, a GIS platform may provide the most user-friendly approach, whereas others may be more comfortable with a data analysis package such as Python® or Matlab®. Assessing historic and future coastal change requires complex analysis methods, and it is expected that regardless of the software used, a high level of proficiency in data analysis and mapping is required for such an assessment, and it should therefore be conducted by experienced GIS or data analysis experts only. While the methods outlined have been developed through case studies, there will undoubtably be some modifications/refinements required when applied to other areas.

The workflow ends with a preliminary CCMA boundary (or multiple depending on which emission scenarios and epochs are desired) that can then be explored further alongside the SMP, LPAs and further guidance from partner organisations such as the EA. It is anticipated the final output from any exercise would be a series of GIS based layers that could be incorporated into existing planning systems and used to flag up development proposals that require further assessment. The number of CCMA “lines” that are developed depends on the policy for each council. The most recent UK climate projections (UKCP18) provides three emission scenarios for future SLR prediction and for each emission scenario the retreat extent can be delineated into three epochs to reflect the approach taken by the SMP. This would, therefore, result in up to nine CCMA boundaries which can then be used for various planning applications when dealing with future proposals.

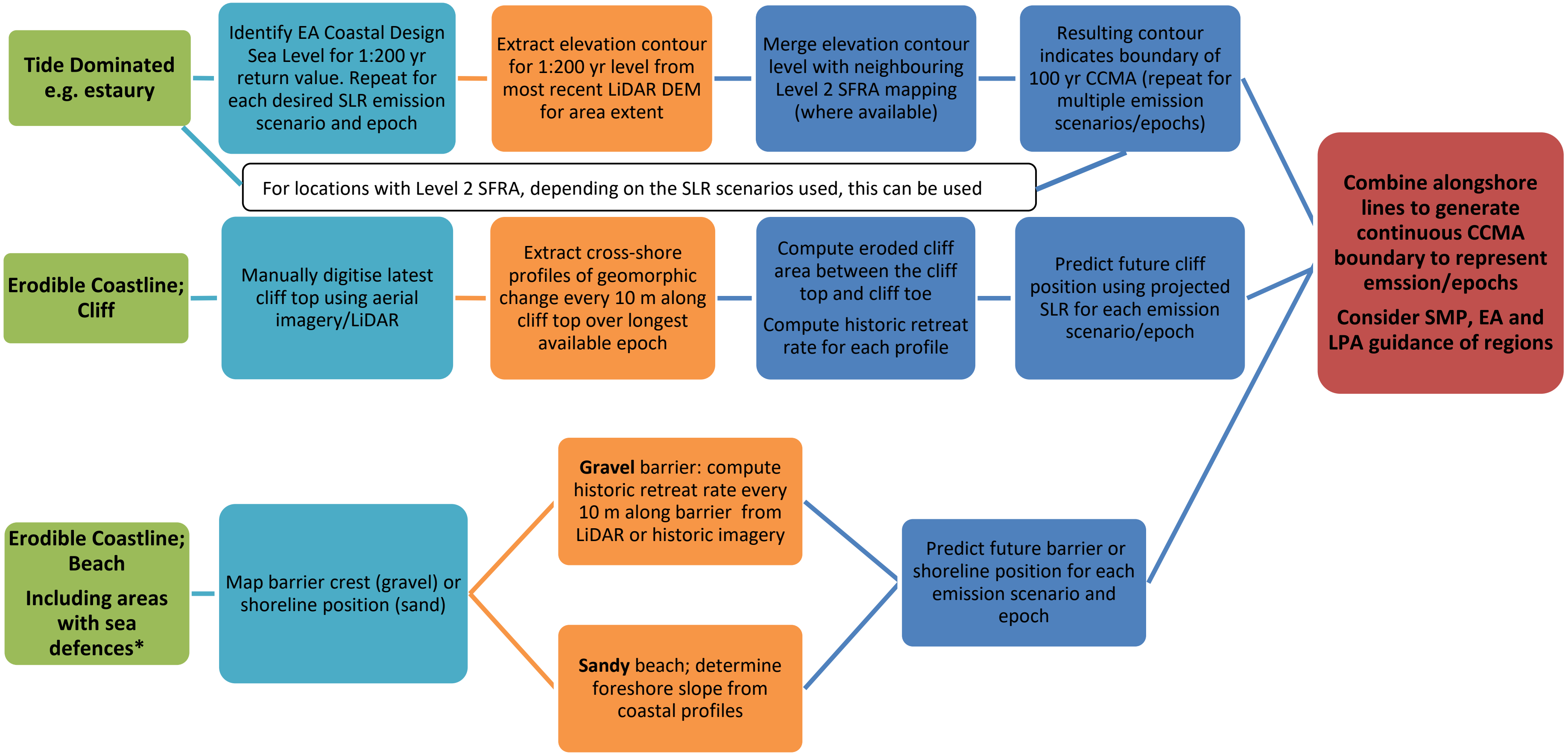

Figure 6-1. Schematic workflow of the main steps required for CCMA generation for different coast types. The final stage would involve detailed assessment of existing SMP and discussion with the LPA, EA and other relevant experts. The reader is referred back to Sections 2 (Cliff Backed Coastline), 3 (Floodable Estuaries), and 4 (Beaches and Defences) for details of the methods described.*As per Section 4 beaches backed by defences are treated as natural beaches as no method exists to incorporate defence structures.

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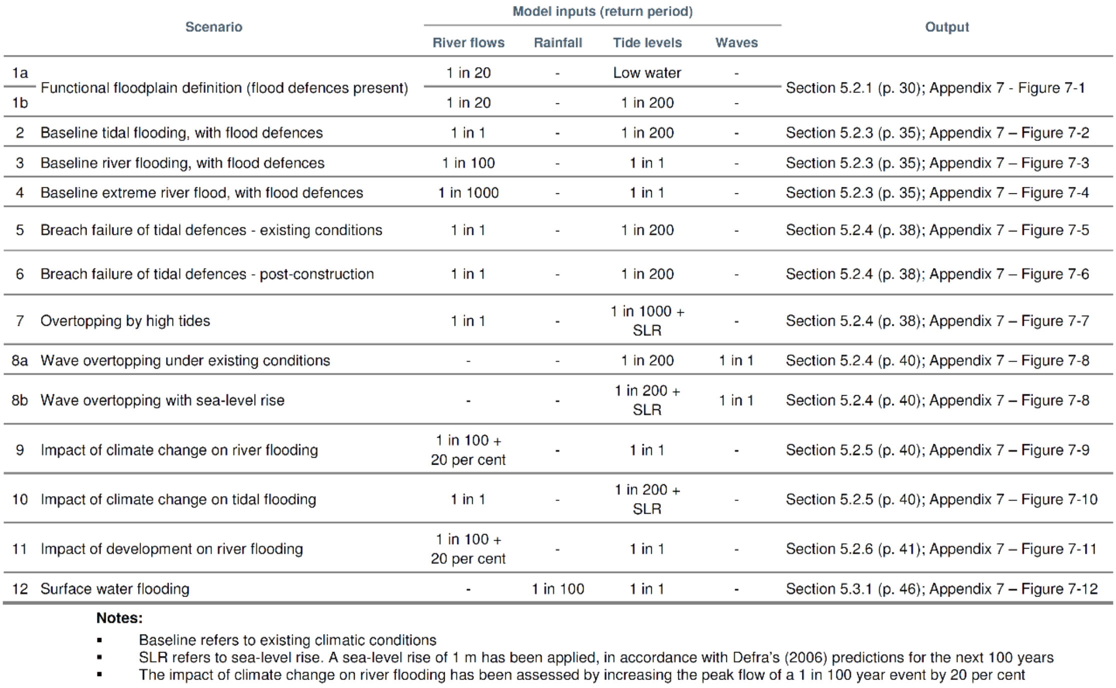
7. Appendix A

Table 7-1, Strategic Flood Risk Assessment Level 2 model scenarios as presented in Hyder, (2010).



Scenario		Model inputs (return period)				Output
		River flows	Rainfall	Tide levels	Waves	
1a	Functional floodplain definition (flood defences present)	1 in 20	-	Low water	-	Section 5.2.1 (p. 30); Appendix 7 - Figure 7-1
1b		1 in 20	-	1 in 200	-	
2	Baseline tidal flooding, with flood defences	1 in 1	-	1 in 200	-	Section 5.2.3 (p. 35); Appendix 7 – Figure 7-2
3	Baseline river flooding, with flood defences	1 in 100	-	1 in 1	-	Section 5.2.3 (p. 35); Appendix 7 – Figure 7-3
4	Baseline extreme river flood, with flood defences	1 in 1000	-	1 in 1	-	Section 5.2.3 (p. 35); Appendix 7 – Figure 7-4
5	Breach failure of tidal defences - existing conditions	1 in 1	-	1 in 200	-	Section 5.2.4 (p. 38); Appendix 7 – Figure 7-5
6	Breach failure of tidal defences - post-construction	1 in 1	-	1 in 200	-	Section 5.2.4 (p. 38); Appendix 7 – Figure 7-6
7	Overtopping by high tides	1 in 1	-	1 in 1000 + SLR	-	Section 5.2.4 (p. 38); Appendix 7 – Figure 7-7
8a	Wave overtopping under existing conditions	-	-	1 in 200	1 in 1	Section 5.2.4 (p. 40); Appendix 7 – Figure 7-8
8b	Wave overtopping with sea-level rise	-	-	1 in 200 + SLR	1 in 1	Section 5.2.4 (p. 40); Appendix 7 – Figure 7-8
9	Impact of climate change on river flooding	1 in 100 + 20 per cent	-	1 in 1	-	Section 5.2.5 (p. 40); Appendix 7 – Figure 7-9
10	Impact of climate change on tidal flooding	1 in 1	-	1 in 200 + SLR	-	Section 5.2.5 (p. 40); Appendix 7 – Figure 7-10
11	Impact of development on river flooding	1 in 100 + 20 per cent	-	1 in 1	-	Section 5.2.6 (p. 41); Appendix 7 – Figure 7-11
12	Surface water flooding	-	1 in 100	1 in 1	-	Section 5.3.1 (p. 46); Appendix 7 – Figure 7-12

Notes:

- Baseline refers to existing climatic conditions
- SLR refers to sea-level rise. A sea-level rise of 1 m has been applied, in accordance with Defra's (2006) predictions for the next 100 years
- The impact of climate change on river flooding has been assessed by increasing the peak flow of a 1 in 100 year event by 20 per cent