MUSSELBURGH COASTAL CHANGE ASSESSMENT

FINAL REPORT (February 2024)

Dynamic Coast analysis to inform East Lothian Council Flood Scheme

MacDonell, C., Hurst, M., Rennie, A., Hansom J. & Naylor, L. (2024) Musselburgh Coastal Change Assessment. East Lothian Council & Dynamic Coast.

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1 Executive Summary

1. East Lothian Council (ELC) propose a range of flood risk management measures to address coastal change and fluvial flooding in Musselburgh. **Our report supports ELC's work** by providing an updated coastal change analysis (superseding that of Dynamic Coast, 2021) to inform assessment **of coastal erosion and erosion-enhanced flood risks**. Coastal erosion is noted within the Council's Risk Register and thus even if the Council were not proposing flood risk management works, coastal change and erosion-enhanced flooding risks are worthy of careful consideration, in support of the Council's Planning and Climate Change Act duties.
2. Updated beach surveys conducted in 2022 and 2023 show that erosion has dominated much of the upper beach since 2018. Whilst longer-term comparisons note fluctuating change along the coast, future projections, based on new calibrated rates, support earlier research from Dynamic Coast (2021) that **coastal erosion is a current and growing concern.** This has implications for ELC's proposed flood risk management structures and parts of the town's coastal frontage. Musselburgh is not unique in this regard: in 2021 Dynamic Coast identified 46% of Scotland's beaches to be currently eroding, with erosion enhanced flood risk a growing risk that needs to be addressed. Recent Environment Agency work anticipates a 90% increase in repair costs for coastal assets due to climate change (Environment Agency 2020).
3. Further to recent changes at Musselburgh, in October 2023, **Storm Babet** caused beach sediment loss and erosion of the vegetation edge at the upper beach, with longshore redistribution of beach sediment to the west. In places, this storm caused the equivalent of five years' worth of erosion over a couple of days and removed around 4,000 m^3 of sediment from the Musselburgh beaches. Whilst substantive change has occurred, fortunately this storm coincided with a neap tide. However, if such a storm had coincided with spring tides, then the impacts would be far more severe (as was evident elsewhere across Scotland the following week). Whilst Storm Babet has not significantly compromised the existing flood management structures or natural defences (dunes etc), the natural resilience of the beach has been reduced, particularly adjacent to the existing defences in the west, and adjacent to the proposed hybrid defence in the east near Mountjoy Terrace. For this reason, the evidence suggests that Council officers have **little time to waste in planning short-term coastal resilience measures**, including nature-based enhancements.
4. **Our monitoring and future modelling of the coast suggests that a wider and currently unaddressed future erosion risk** remains, and that the Council are justified to have this on their Risk Register. In the absence of any new coastal management works, as sea levels continue to rise, recent fluctuation and erosion of the Mean High Water Spring line is expected to be replaced by more consistent erosion that may **threaten the Musselburgh Flood Protection Scheme's proposed flood defences and other assets along the town's coastal frontage**. Under a High Emissions Scenario (the trajectory of current global emissions), enhanced coastal impacts are expected within the next ten to twenty years if no coastal management takes place. Under Low and Medium emission scenarios the anticipated impacts are less and will impact later.
5. **We suggest that the Council consider a range of coastal resilience measures be developed and appraised as part of ELC's proposed Coastal Change Adaptation Plan** (CCAP). Whilst this report suggests management options for ELC to consider, a risk-based, dynamic adaptive approach which takes into consideration intergenerational community aspects is recommended. This would enhance the future resilience of the coast and enable the local coastal community to cope with substantial longer-term change, as recommended within Scottish Government Guidance. This may involve planning for the future coast to move inland in the medium to long term and to progressively plan to relocate affected coastal assets to lower risk locations.
6. We suggest that establishing a **monitoring programme for the beaches at Musselburgh is essential to inform the Council officers, so that they know when a range of erosion and flood risk adaptation options should be actioned** in the short to long-term. This would be an integral part of the proposed CCAP.

Please note there is a Glossary of key terms and acronyms in the Technical Annex.

2 Introduction

Purpose of this document

This report provides a review of recent and future shoreline change at Musselburgh, undertaken by the University of Glasgow (UoG) and Dynamic Coast, in partnership with East Lothian Council (ELC). The results supersede the Dynamic Coast (2021) analysis and better informs past, recent, and anticipated future coastal changes under a range of climate scenarios. Whilst this work has been commissioned to inform the Council's proposed flood risk management scheme, coastal change presents a current risk that is worthy of careful consideration, in support of the Council's planning and climate change act duties. The anticipated change to the future shoreline position has been compared with the positions of natural and built assets within the existing coastal zone to identify potential implications for erosion and thus associated flood risk. This analysis aims to support ELC to consider any consequential resilience and adaptation actions, as part of the Flood Risk Management Scheme, and inform their wider forthcoming Coastal Change Adaptation Plan.

Structure of this document

In the following sections we report on the three key tasks outlined in the Statement of Requirement

- Task 1: Historic Coastal Change Assessment (Section 2)
- Task 2: Modelling Future Coastal Change Scenarios (Section 3)
- Task 3: Identifying Coastal Change Management and Adaptation Options (Section 4)

Details of methods and associated supporting information, have been provided in a Technical Annex at the end of the document. This annex also provides additional information, analysis, and visualisations.

Context

Rising sea levels caused by climate change have the potential to increase Musselburgh's coastal erosion and flood risk during this century. The extent of this increase is uncertain and will depend upon global efforts to control increasing atmospheric temperature due to carbon greenhouse gas emissions (Figure 1).

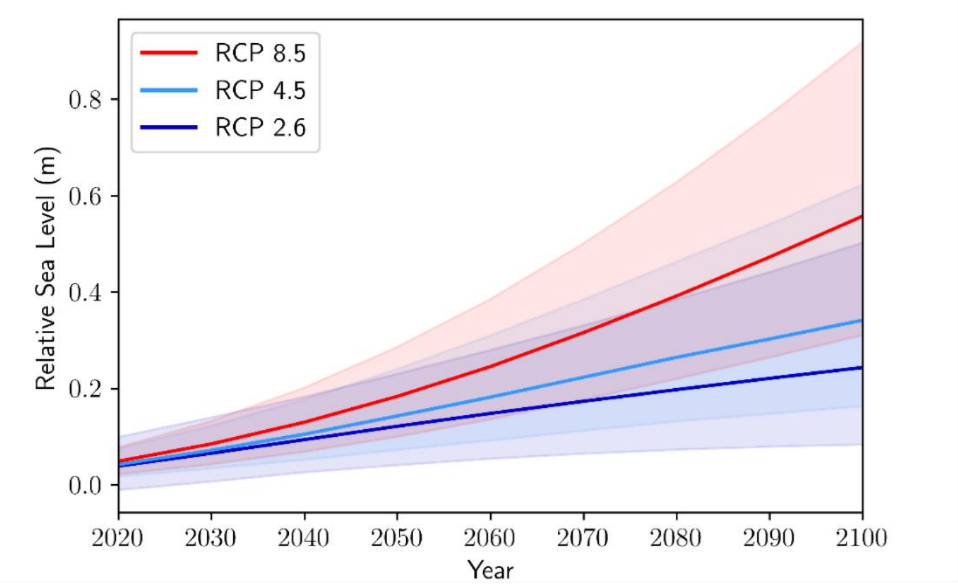

Figure 1: UCKP18 Future Sea Level for Musselburgh under various scenarios for future greenhouse gas emissions. Solid lines show the most likely trajectory for each scenario while the shaded regions show the 90% confidence interval. These projections are based on the Met Office's UK Climate Projections (UCKP18; (Met Office, 2019)).

Dynamic Coast has provided the best available means of understanding the potential for coastal erosion and erosion-enhanced flooding on a national and regional scale in Scotland. University of Glasgow and Dynamic Coast are working with ELC to better understand coastal change at Musselburgh in order to provide updated evidence to support the council's flood risk management obligations and plans, but this research also informs the councils wider coastal change adaptation duties.

Datasets

The following datasets were used to update our understanding of coastal change, following the Dynamic Coast National Coastal Change Assessment (published 2021):

Table 1: Additional survey datasets which have been used to update analysis of coastal change at Musselburgh.

Date	Name	Original Product Type	Derived Products
May 2018	Fugro LiDAR (commissioned by ELC)	Digital Elevation Model	MHWS contour
Summer 2020	Scottish Phase 5 LiDAR	Digital Elevation Model (partial coverage only; west of harbour)	MHWS contour
October/November 2022	L&M Survey Services (via Jacobs)	Topographic survey (GNSS)	Digital Elevation Model / MHWS contour
12th October 2023 (prior to Storm Babet)	University of Glasgow Musselburgh 1 survey	Digital Elevation Model (Structure-from-Motion)	MHWS contour
27th & 31st October 2023 (post Storm Babet)	University of Glasgow Musselburgh 2 survey	Digital Elevation Model (Structure-from-Motion)	MHWS contour

3 Task 1: Historic Coastal Change Assessment

Task 1 aims to appraise the available information on recent coastal change in order to complement the earlier national-scale analysis (DynamicCoast.com). This includes detailed surveys of the upper beach, which can provide protection during storms, alongside change assessment of the lower beach and wider change elsewhere. This analysis is used in Task 2 to inform future coastal change.

Several independent approaches have been used to investigate historic coastal change, using a range of coastal indicators and across a range of timescales. The coastal indicators used are:

i. the position of Mean Low Water Springs (MLWS);
ii. the position of Mean High Water Springs (MHWS); and
iii. the position of the seaward edge of coastal vegetation (VE).

Volumetric changes have been calculated between the dates of the three-dimensional (3D) topographic surveys. Such a mixed method approach serves to cross-validate and provide confidence to inform the trajectory of coastal change at Musselburgh.

MHWS from LiDAR & topographic survey from ELC & UoG

Data Statement

Assessment of shoreline change in the Dynamic Coast 2 project was based on available mapped positions of MHWS at that time, the most recent of which was from 2015/2016 Scottish Government Phase 3 LiDAR. Here, MHWS contours were derived from several more recent surveys, namely a LiDAR survey conducted in 2018 by Fugro, a topographic survey conducted in 2022 by L&M Survey Services (licensed via Jacobs) and Scottish Government Phase 5 LiDAR (though coverage is incomplete). During this research UofG conducted an unoccupied aerial vehicle (UAV) topographic survey on 12th October 2023. Storm Babet occurred shortly after, and UofG returned to complete a second, post-storm UAV survey to assess storm impacts (27th & 31st October 2023).

Key Results

Rates of change first published by the Dynamic Coast (2021) are shown in Figure 2. These data suggested that the eastern part of the area to the mouth of the River Esk, was experiencing erosion at rates of up to -1.9 m/yr (note that negative values (shown in pink to red) indicate erosion and positive values (shown in shades of blue) indicate accretion). The colour pallet has been updated since Dynamic Coast (2021), with blue replacing green (for accretion), to assist readers with common forms of colour blindness.

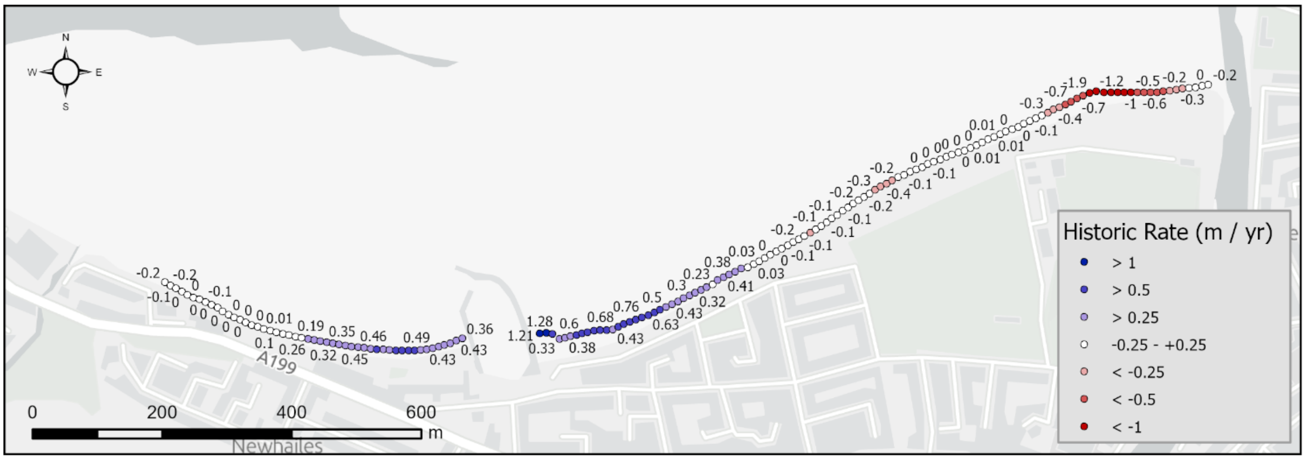

Figure 2: Map showing rates of coastal change between 2003 and 2015/2016 as published in Dynamic Coast (2021), where erosion is shown in red and accretion is shown in blue, minimal change in white. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack. Fisherrow Harbour manually added for context (and all following maps).

Figure 3 provides an update to the 2021 published data above (Figure 2), showing how MHWS has changed between 2018 (Fugro LiDAR) and 12 October 2023 (first UofG survey, pre-Storm Babet). Annual rates of change are shown as colour-coded points along the latest MHWS position. Figure 2 and Figure 3 show that increased erosion is evident across parts of the upper beach to the east of the harbour, particularly adjacent to Mountjoy Terrace and the playing fields. Accretion has also occurred across central sections in front of the Promenade.

West of the harbour there is minimal accretion transitioning into moderate erosion at the western edge of Murdoch's Green, to the beach access from the Edinburgh Road cul-de-sac adjacent to the current rock boulder defence structure. Please note these updated recent rates, exclude the impacts of Storm Babet, which are considered separately below (Figure 5).

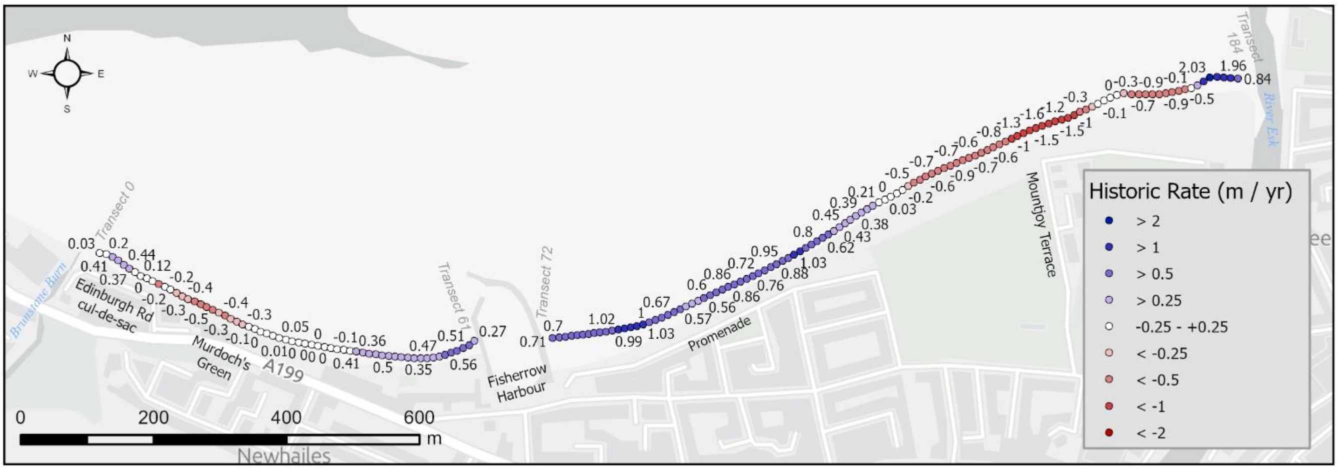

Figure 3: Map showing rates of coastal change between 2018 and 12th October 2023 (prior to Storm Babet), where erosion is shown in red and accretion is shown in blue, minimal change in white. Note these recent rates of change update those published as part of the Dynamic Coast reports (2021; Figure 2). Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

A direct comparison of the rates of change in Figure 2 and Figure 3 are shown in Figure 4 from west (Transect 0) to east (Transect 184) on the same (10 m spacing transects previously used by Dynamic Coast 2. This also shows the changes described above, Mountjoy Terrace being located at Transect 152, and the Promenade stretching between Transects 72 and 122. The erosional area to the west of the harbour occurs between the start of the DC2 data (Transect 12) and Transect 26 (western end of Murdoch's Green). There has been greater change over the recent period for both accretion and erosion than occurred between 2003 to 2015.

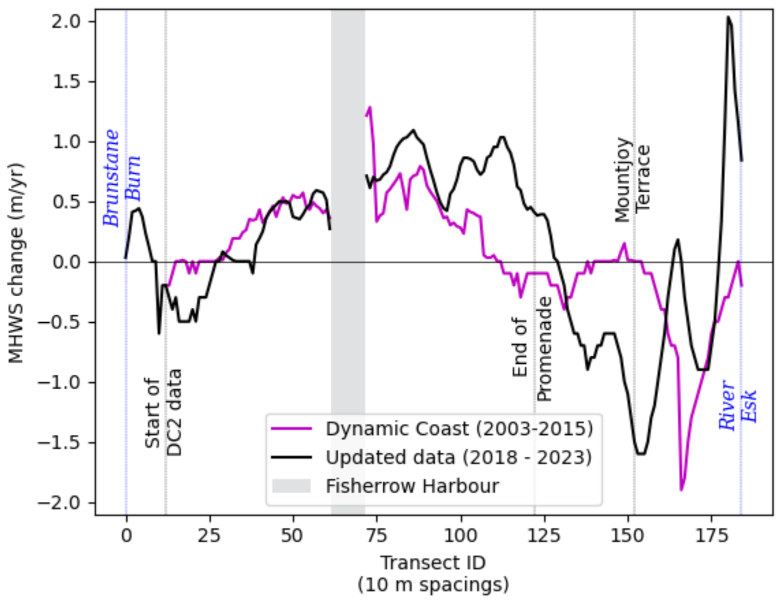

Figure 4: Plot showing changes to MHWS comparing the 2003-2015 changes in pink (as published in 2021) and the recent change between 2018 and 12th October 2023, in black. Note that the previously published MHWS change rate transects (10 m spacing) did not extend fully to the west of the site (Brunstane Burn; Transect ID 0), the start of this data is indicated by the grey dotted line. No MHWS calculations were undertaken in Fisherrow Harbour, and this is indicated by the grey polygon.

The impacts of Storm Babet are shown in Figure 5 and Figure 6. The average change in the position of MHWS between the two surveys undertaken before and after Storm Babet is -1.12 m. To the west of the harbour MHWS has retreated an average distance of -2.9 m, and the maximum retreat for MHWS is -6.85 m. Wave orientation and the presence of the harbour breakwaters has resulted in sediment being lost from the west side of the harbour, but with accretion on the eastern side of the harbour. Approximately 130 m alongshore stretch of the beach immediately east of the harbour has accreted with an average gain of 2.69 m. Immediately east in front of the promenade and as far as the playing fields, erosion dominates, with an average retreat of -1.66 m and maximum retreat of -2.51 m. Fronting the playing fields and approaching Mountjoy Terrace MHWS has built seawards with modest gains of up to 2.72 m, in contrast to the longer-term signal of retreat (Figure 2 and Figure 3). Towards the River Esk mouth the pattern fluctuates. Overall, the impact of Storm Babet has been a retreat of MHWS by approximately 1 m.

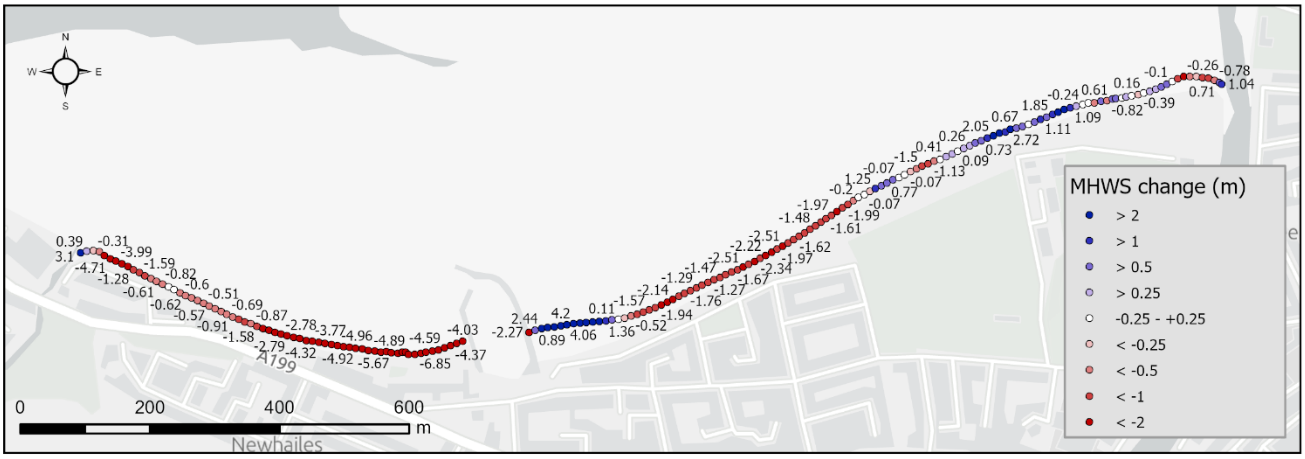

Figure 5: Map showing absolute coastal change over the period of Storm Babet in mid/late-October 2023, where erosion is shown in red and accretion is shown in blue, minimal change in white. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

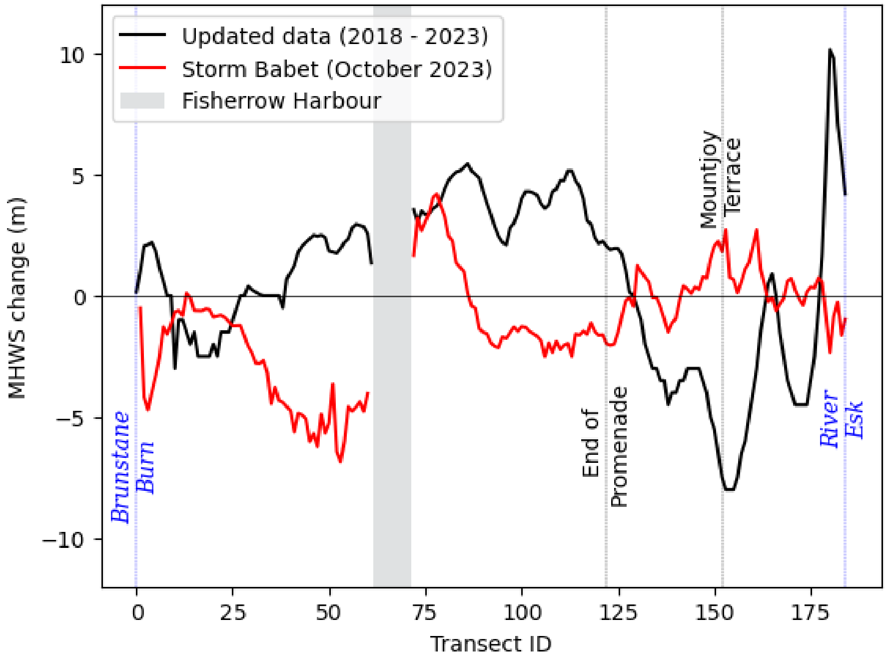

Figure 6: Plot showing the observed changes primarily resulting from Storm Babet. Accretion as positive values and erosion as negative values. Please note that these are shown as absolute change in metres, rather than annual rates of change (m/yr). This analysis was informed by change shown in MHWS surveys up to the 12th of October 2023 (black line) and then change of MHWS position between 12th and 27th/31st of October 2023 (red line).

The magnitude of change during a single storm can be large, with changes in the position of MHWS above 5 m (both in erosion and accretion) observed due to Storm Babet. The impact of storms are superimposed on the longer-term trajectory of change, and it is expected there will be some post-storm recovery during more moderate conditions. Subsequent sections of the report will consider the potential implications of various future climate change scenarios, and the approach used is calibrated to recent observed rates of change. It is important to note that rates of coastal change have varied through time. In Figure 7, we explore the use of the most benign rates of change (using the lowest observed erosion rate) to inform a best-case scenario, and the most malign rate of change (using the highest observed erosion rate) to inform a worst-case scenario. Whilst rates could be derived from any period we have data for (i.e. 1890s to 2023), the authors feel it is reasonable to only use rates since the year 2000, derived from the most accurate coastal surveys, to inform the best / worse-case assessment of 'recent change'. And further, these rates will also be selected where the same minimum period of 4-years, as was used in Dynamic Coast 2021, to avoid any excessive influence of individual storm events.

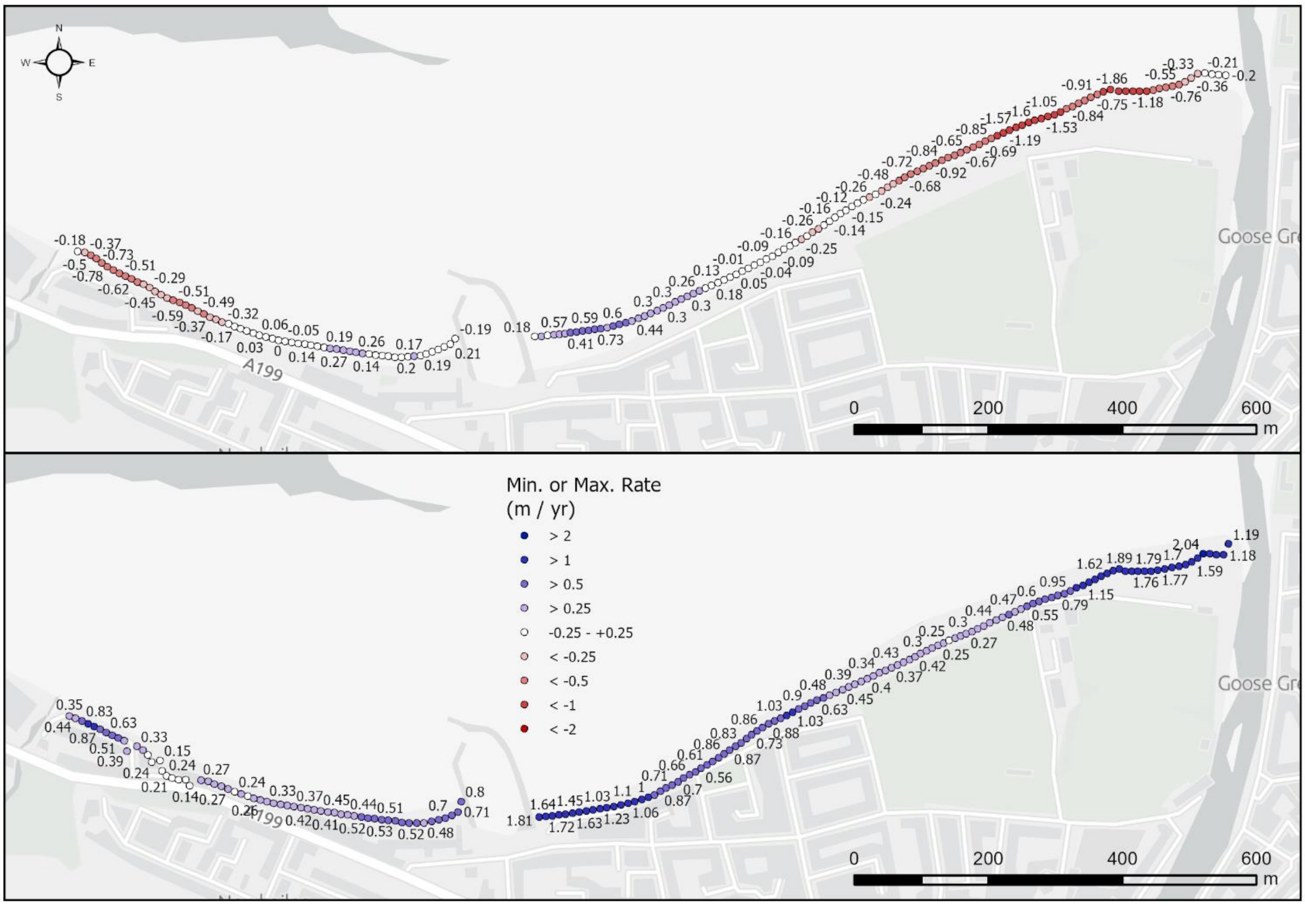

Figure 7: Map showing the minimum / worst case (top) and maximum / best case (bottom) rates of change observed on each transect, since 2000 (minimum 4-years between two given surveys). Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Implications

Recent observations of change to the position of MHWS from topographic surveys in 2018 and 2023 reveal that erosion remains a concern for beaches at Musselburgh. With the exception of the area immediately east of the harbour, the majority of the beach has experienced some degree of erosion over the recent period, either prior to, or following Storm Babet. There is a substantial variability, particularly in the short-term with many areas experiencing the same magnitude of changes occurring during Storm Babet as the net changes observed over a 5-year window (back to 2018). Whilst this is, of itself, not surprising, when the proximity of existing and proposed coastal assets (buildings and flood management structures, for example) are considered then erosion should be regarded as a risk and concern, both now and in the future.

MLWS, MHWS and Vegetation Edge from Satellite Imagery

Standard methods of coastal change detection (reported in MHWS from LiDAR & topographic survey from ELC & UoG) rely on direct measurement of the beach, this is often labour intensive, and therefore costly. Whilst the methods above are regarded as the most reliable at identifying change, other less accurate methods can offer interesting insights at lower costs. This next section outlines data from these other approaches based on satellite imagery, which serve to complement traditional survey methods.

Data Statement

Water edges (MLWS & MHWS) and vegetation edge (VE) positions have been derived from satellite images. The lowest sections of any foreshore are only exposed for limited periods of time each month. This practical barrier has resulted in MLWS not being updated regularly across much of the Scottish coast. To overcome this, MLWS change rate is based on change in mapped positions of Ordnance Survey MLWS in 1850 and 2019 using the Coast X-Ray technique used during Dynamic Coast 2 (Fitton, et al., 2021). The Coast X-Ray tool allows the identification of individual satellite images during particular tidal elevation conditions. MHWS and VE have been derived using PlanetScope imagery (3m resolution; November 2016 - present) processed using new software developed at University of Glasgow (Muir, et al., 2023), that extends the capabilities of an existing coastal earth observation tool, CoastSat (Vos, et al., 2019). The upper water edge extracted from these images has been corrected using observed beach slope and is equivalent to the position of MHWS. Rates of change were quantified by regression analysis to establish the long-term average rate over the period 2016-present.

Key Results

Figure 8 shows the changing position of MLWS, MHWS and Vegetation edge derived from Earth Observation techniques. These novel remote sensing techniques are increasingly being used internationally to supplement (rather than replace) the more traditional surveying techniques. They are of value as they may be used as an efficient, and low-cost early warning monitoring system to help inform trigger points for coastal change adaptation planning, especially at the regional level. Caution is urged however, in that the vegetation edge can appear to retreat inland when sand inundates it, which is not the same as mechanisms of marine erosion. This is perhaps what might be driving the apparent landward retreat of the vegetation edge immediately to the east of the harbour in Figure 8.

Figure 8 also informs perceptions of coastal change. Understandably, the changing position of tidal extents is very noisy (in macrotidal locations such as the Musselburgh shore) and may be influenced by tidal cycles rather than real coastal change. For this reason, the mean position of tides is used, but this is hard to identify on the ground. More readily identifiable is the position of the vegetation edge, even though it too may vary seasonally. The stability and gains of the vegetation edge in many areas at Musselburgh suggests dune resilience, despite erosion of the upper beach over the recent period (2015-2023). However, a combination of stability of vegetation edge, together with landward movement of MHWS results in a squeezing and steepening of the upper beach.

Finally, Figure 8 compares the extent of a MLWS from satellite imagery; this has been compared with the Ordnance Survey published position of MLWS. Even allowing for methodological errors in both datasets and subtle low beach gradients, erosion remains apparent across much of the lower foreshore over this time period.

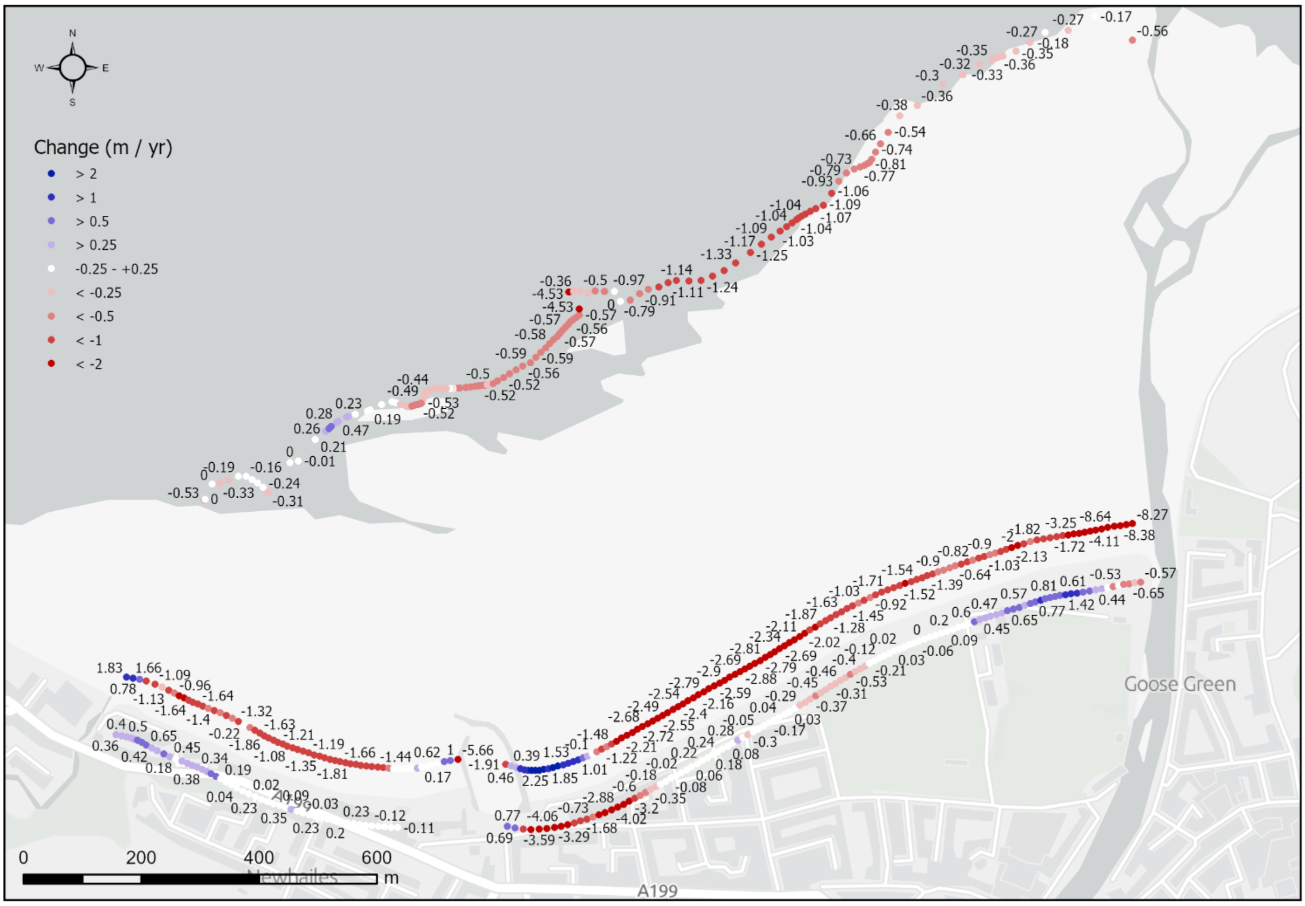

Figure 8: Map showing the average rates of MLWS (most seaward), MHWS (middle) and vegetation edge (VE; most landward) change rates colour coded as points and labelled: erosion dominates. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Implications

There is a dominant signal of erosion revealed by observations of MHWS and VE derived from satellite images in the period 2016-present. Lower erosion rates and some areas of accretion of vegetation edge suggest that the coastal vegetation is providing some natural resilience, despite narrowing and steepening of the mid-upper beach. Narrowing of the foreshore due to the landward migration of MLWS reduces the potential for the dissipation of wave energy and therefore more wave energy can be delivered to the beach during high-energy (storm) conditions.

Volumetric Change Analysis

Single metric indicators such as MHWS are useful measures for shoreline change at national and regional scales and facilitate assessment of future shoreline change. However, analysis of time series 3D datasets provides richer insights into the system behaviour and variability of volumetric changes across the entire active coastal zone (from MLWS to supra-tidal coastal vegetation). This is particularly important when considering coastal systems which provide a natural capital flood protection function to inland areas, such as Musselburgh.

Data Statement

Rasterised Digital Elevation Model (DEM) datasets from different time periods are compared, to quantify topographic changes through time. Using existing methodologies and Geomorphic Change Detection software (Wheaton, et al., 2010), the inherent uncertainties in the various DEMs are considered. In this instance, a probabilistic thresholding technique (80%) was used to establish change considered to be real (i.e. beyond the noise & uncertainty of the two input datasets). This technique can identify surface lowering (erosion) or surface rising (deposition). Any change identified can also be spatially aggregated to provide estimates of volumetric change, for example the volume of sediment lost or gained either across the whole coastal stretch or across smaller unit areas (Figure 11 & Figure 12). Such coastal changes and volumes are important when considering the relative resilience of coastal landforms and serve to inform management strategies, such as beach nourishment involving specific volumes of sediment to be added.

Key Results

Whilst Dynamic Coast (2021) used 2005 and 2013 Digital Elevation Models, here we have compiled five further datasets from 2018, 2020, 2022 and two from 2023. This allows different three-dimensional comparisons to be made spatially, including those over the last five years (Figure 9); and with a separate assessment of the impact of Storm Babet (Figure 10).

Figure 9 shows the height changes across the two beaches over the period 2018 to 12th October 2023, with surface lowering (erosion) shown as red and surface gains (accretion) as blue. Figure 9A and Figure 9B relate to the area east of the harbour, whilst Figure 9C and Figure 9D relate to the area west of the harbour. Adjacent to Mountjoy Terrace (Figure 9B), the upper beach has seen up to 1.5 m surface lowering, however there are more localised gains within the dunes (shown in blue) and linear features on the foreshore below the beach toe. Towards the Drying Green and approaching the eastern side of the harbour, the general trend has been positive with both the beach face and dunes building up to 1m of sediment (Figure 9A).

To the west of the harbour (Figure 9) The upper beach has seen noisy changes, where localised gains and losses are evident. Slightly lower down the beach face gains are evident above the beach toe (typical values + 0.2 m, shown as pale blue areas). Further west, however lower beach face losses are evident (pale pink areas, ~-0.3 m) again with the greatest change on the lower beach face, just above the beach toe. There is larger localised lowering at the mouth of the Brunstane Burn.

Overall, Figure 9 indicates erosion at the east and west extremities of the beach with some accretion in the middle and along the upper beach.

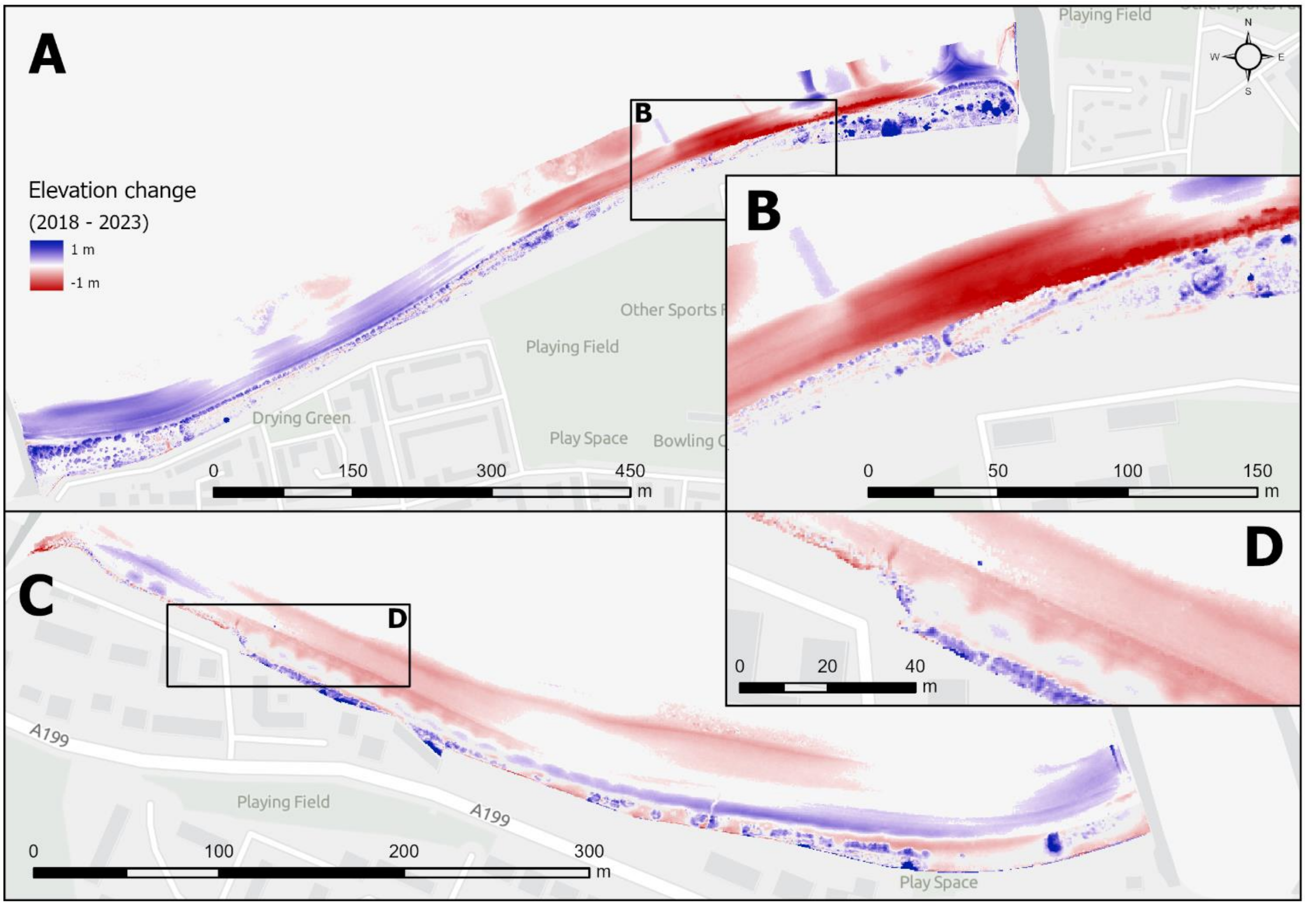

Figure 9: Geomorphic Change Detection analysis over 5-year period between 2018 and 2023. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Figure 10 shows the three-dimensional changes that occurred due to Storm Babet, with surface lowering (erosion) shown as red and surface gains (accretion) as blue. Whilst there are pockets of upper beach gains, the dune edge has been clipped back during the storm (red feature within Figure 10B). West of the playing field along the Promenade, the upper beach has lowered slightly, but gains dominate towards the eastern harbour wall. These gains are likely associated with the wave orientation and presence of the harbour, acting like a groyne, holding sediment from moving further alongshore from east to west. Readers should note that the apparent (blue) triangular gains northwest of the Drying Green are an artefact from a data error.

West of the harbour (Figure 10C), the pattern of change is more consistent. The upper beach appears to have lowered (up to 1 m in height), whilst the lower beach has gained (up to 1 m in height). This cut-fill pattern isn't unexpected with the high-energy, destructive waves likely to have dominated during Storm Babet, entraining sand from the upper beach, and depositing it lower down during backwash. Assuming constructive waves dominate in the coming months, some of this sediment may return to the upper beach. Some upper beach clipping is also evident and highlighted within the Figure 10D.

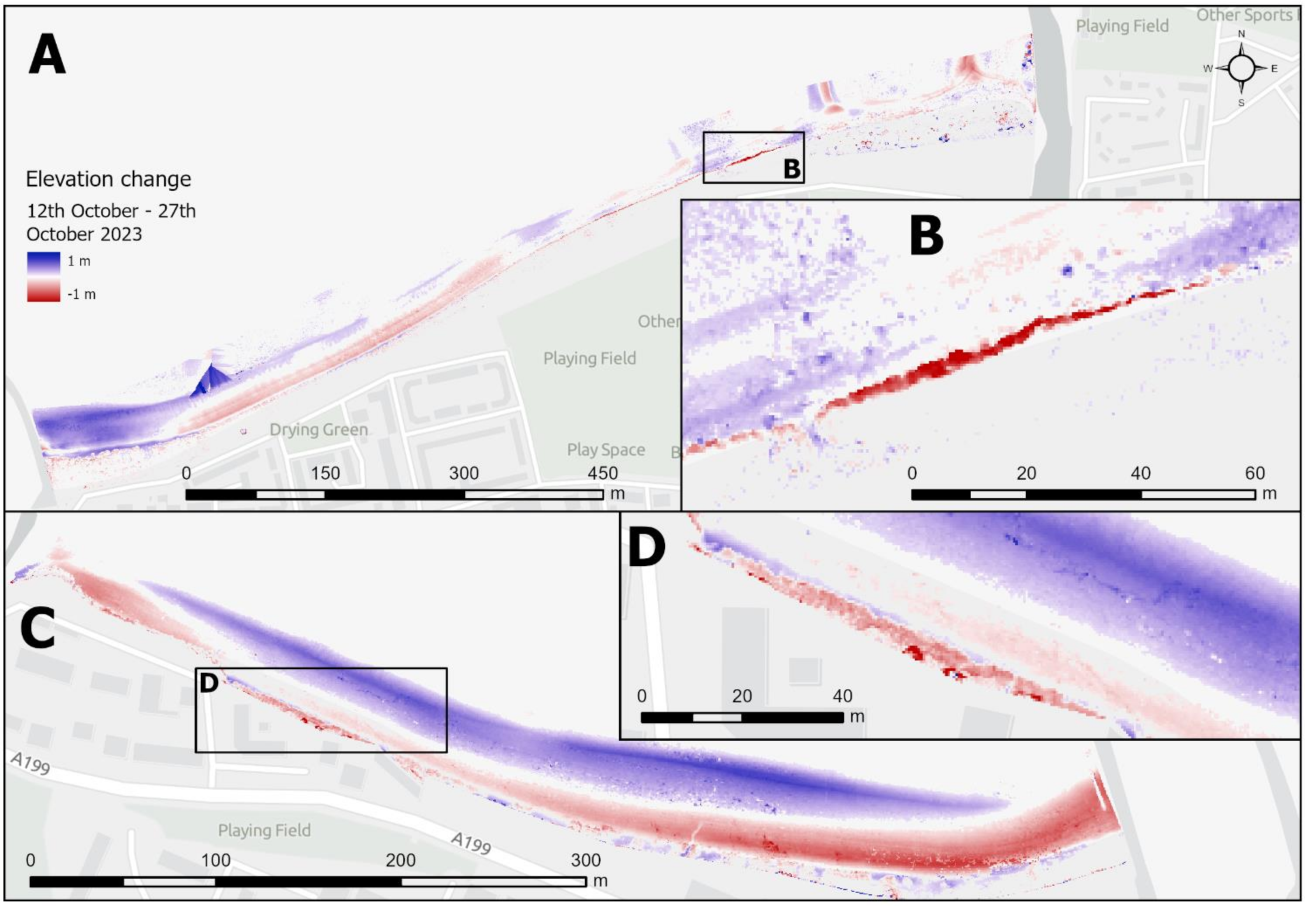

Figure 10: Geomorphic Change Detection analysis between a survey of the 12th of October 2023 and a second survey on 27th & 31st of October 2023, after Storm Babet. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

As part of the Geomorphic Change Detection software, an area with a calculated DEM of Difference (DoD), can be further segmented into smaller areas for more localised analysis of the areas and volume of erosion, accretion, and net differences. To further explore any alongshore or cross-shore patterns at Musselburgh, both the east and west beach sections have been segmented into three cross-shore zones (lower beach, upper beach and vegetation/dunes) and 11 alongshore zones (from west (River Esk) to east (Brunstane Burn; due to likely alongshore drift direction into the Firth of Forth), as shown in Figure 11.

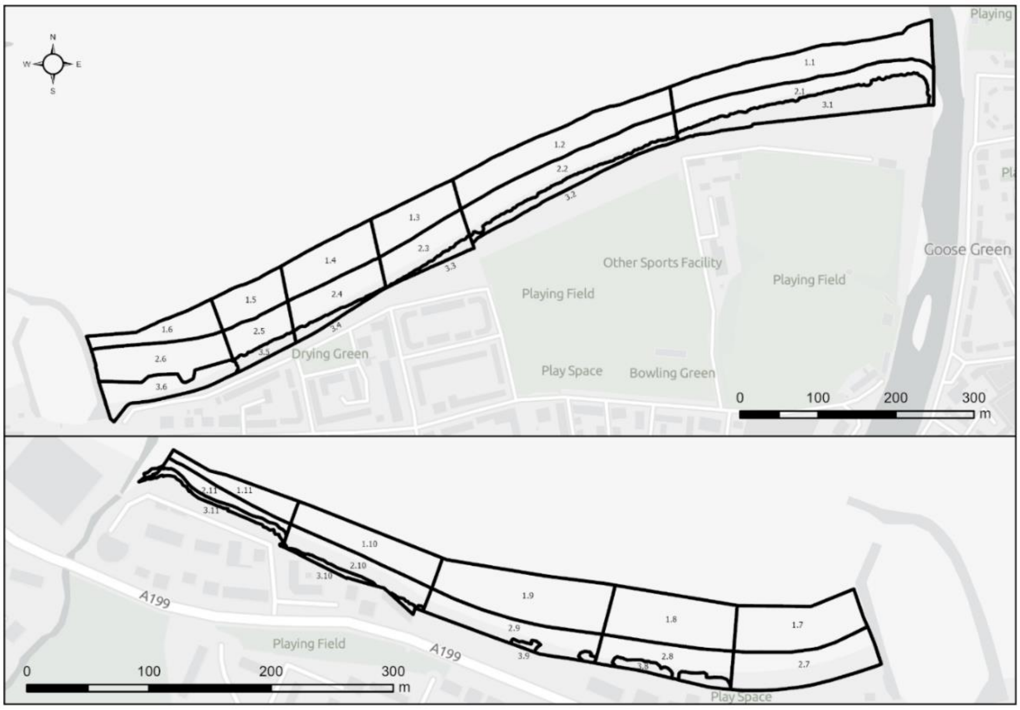

Figure 11: Geomorphic Change Detection, budget segmentation zones. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

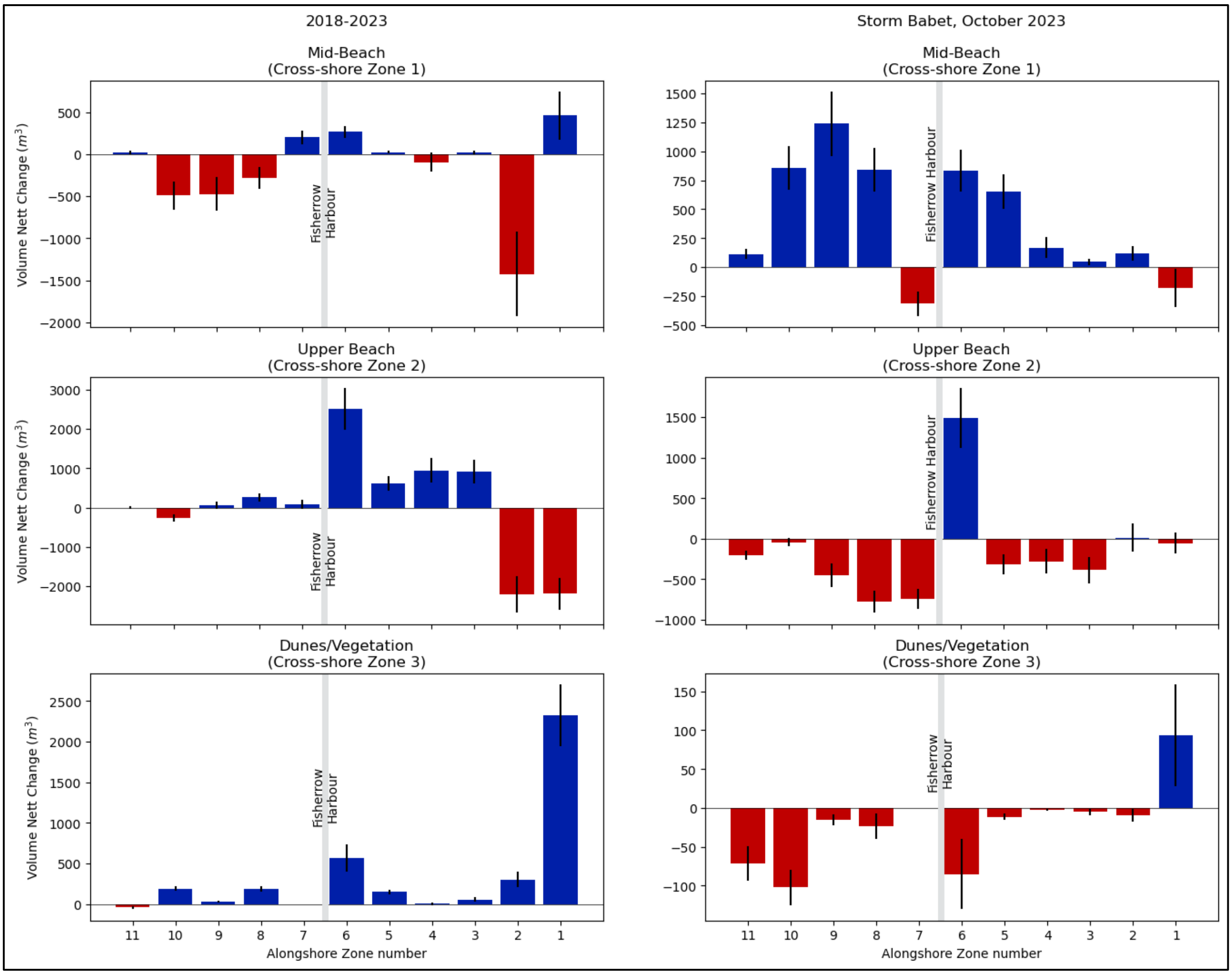

Figure 12: Bar chart showing net volume changes in budget segmentation zones, comparing the overall volumetric change (2018-2023; left column) to volumetric changes during the period around Storm Babet (October 2023; right column). The plots are oriented geographically with west (Alongshore Zone 11; Brunstane Burn) on the left and the east (Alongshore Zone 1; River Esk) on the right. Fisherrow Harbour is indicated by the grey line.

Implications

Considering the period between 2018-2023 (Figure 9 and left-hand graphs on Figure 12) losses dominate the mid beach though there are areas of more modest gain. Net change for the mid beach is -1,774 m^3 over this period. Upper beach losses are evident at the far eastern (-4,398 m^3) and towards the western end of the beach (-271 m^3). The central sections of the upper beach appear to be benefiting from this sediment (5,379 m^3), with modest gains, peaking towards the east of the harbour. As expected, the vegetated dune areas have shown almost exclusive gains, averaging ~168 m^3 per zone, indicating long-term growth and stabilisation in these areas. This is likely to be the key indicator from the community's perspective that *'much of the beach isn't eroding'*. However, it is clear that some areas of the foreshore have been experiencing erosion and steepening during this period and that erosion is a concern.

Considering the impact of Storm Babet (Figure 10 and right-hand graphs on Figure 12) the losses are evident on the upper beach and dune areas. The release of sediment from these stores is not unexpected and is likely to be fuelling gains immediately east of the harbour and lower down the profile (i.e. the mid beach). Erosion of the dune crest and building up of the beach toe is a typical response to storm impacts. The western-most area of lowering of up to 0.5 m (Figure 10), resulted in the retreat of MHWS ca. 4.7 m landward (Figure 5). These changes are in close proximity to the proposed coastal flood protection structures, which are an upgrading of the existing rock armour at this location. Adjacent to the eastern end of the defences (Links View), the beach has changed little (<3 m of movement to MHWS) over the last twenty years. Nevertheless, erosion is anticipated here in the future (Figure 13) and coastal management options should be considered here.

Assuming the impact of Storm Babet is typical of a storm at neap tide then the intertidal may be expected to recover over time from this disruption since the volumes of sediment lost from the upper beach are balanced by those gained by the lower beach. However, the results also point to an inherent vulnerability of the upper beach to such storms, given the role that the upper beach plays in preventing erosion-related coastal flooding. Had Storm Babet occurred on a spring tide or if an equivalent storm is encountered in the future on a higher sea level than the present, then the protective role provided by the sediment in the upper beach could be compromised, placing landward assets at increased risk.

4 Task 2: Modelling Future Coastal Change Scenarios

Task 2 takes the observed rates of recent coastal change and projects them forward to consider future erosion risks under various scenarios. It also considers the position of key community assets (buildings, roads, utilities etc.) against any anticipated coastal change.

Modelling future coastal change under RCP2.6, 4.6 and 8.5 Emissions Scenarios

Data Statement

Future shoreline change was anticipated following the same approach used in Dynamic Coast (Hurst, et al., 2021). Climate change scenarios are taken from the UKCP18 (Palmer, et al., 2018) projection of sea level rise for representative concentration pathway (RCP) scenarios for future greenhouse gas emissions (Figure 1). We model a low, medium, and high emissions scenario (RCP 2.6, 4.5 and 8.5 respectively). Historic observations of shoreline change (change in position of MHWS derived from topographic survey data) are extrapolated forward in time using the modified Brunn Rule method (Hurst, et al., 2021) according to these climate scenarios. We also perform these analyses using both minimum and maximum historic shoreline change rates derived in MHWS from LiDAR & topographic survey from ELC & UoG (Figure 7). Further scenarios were evaluated using the extent of current defences and structures proposed as part of the Musselburgh Flood Protection Scheme.

Key Results

Using the rates of change calculated between the 2023 (prior to Storm Babet) and 2018 shoreline datasets (Figure 3), the anticipated future positions of MHWS can be updated for each emission scenario. The MHWS positions under each Emissions Scenario (RCP2.6, 4.6 and 8.5), and a do-nothing management strategy (assuming current defences/structures), are shown in Figure 13.

The High Emissions Scenario (RCP8.5) is used for discussion purposes, unless otherwise stated. Whilst it is not a certainty that we'll continue along this emissions pathway, it is pragmatic when considering the precautionary principle and our current trajectory. This is a concept acknowledged within Scottish Planning Policy (Scottish Government, 2023; Section 5.10), essentially where there is doubt, we should err on the side of caution. It is important to note that although the results presented below indicate a given future, management and adaptation approaches may alter this, based on locally relevant monitoring and trigger points.

As part of meetings and site visits with East Lothian Council and our own onsite observations it was established that pre-existing defence structures were present in the area that were not included in the national-scale Dynamic Coast assessment from 2021. These included walls with beach frontage to the west of the harbour, as well as a sea wall extension running parallel with the Promenade which is now part-obscured and overgrown with dune vegetation. These defence structures have been added to the future change scenarios (see Figure 13-Figure 16).

As can be seen in Figure 13, further to the east beyond Links View between the playing fields and the River Esk (where the shore is natural with no backing defences), erosion is anticipated to propagate inland as sea levels rise. The only other area of natural erosion beyond the 25-metre defence buffer is adjacent to the beach access on Edinburgh Road cul-de-sac.

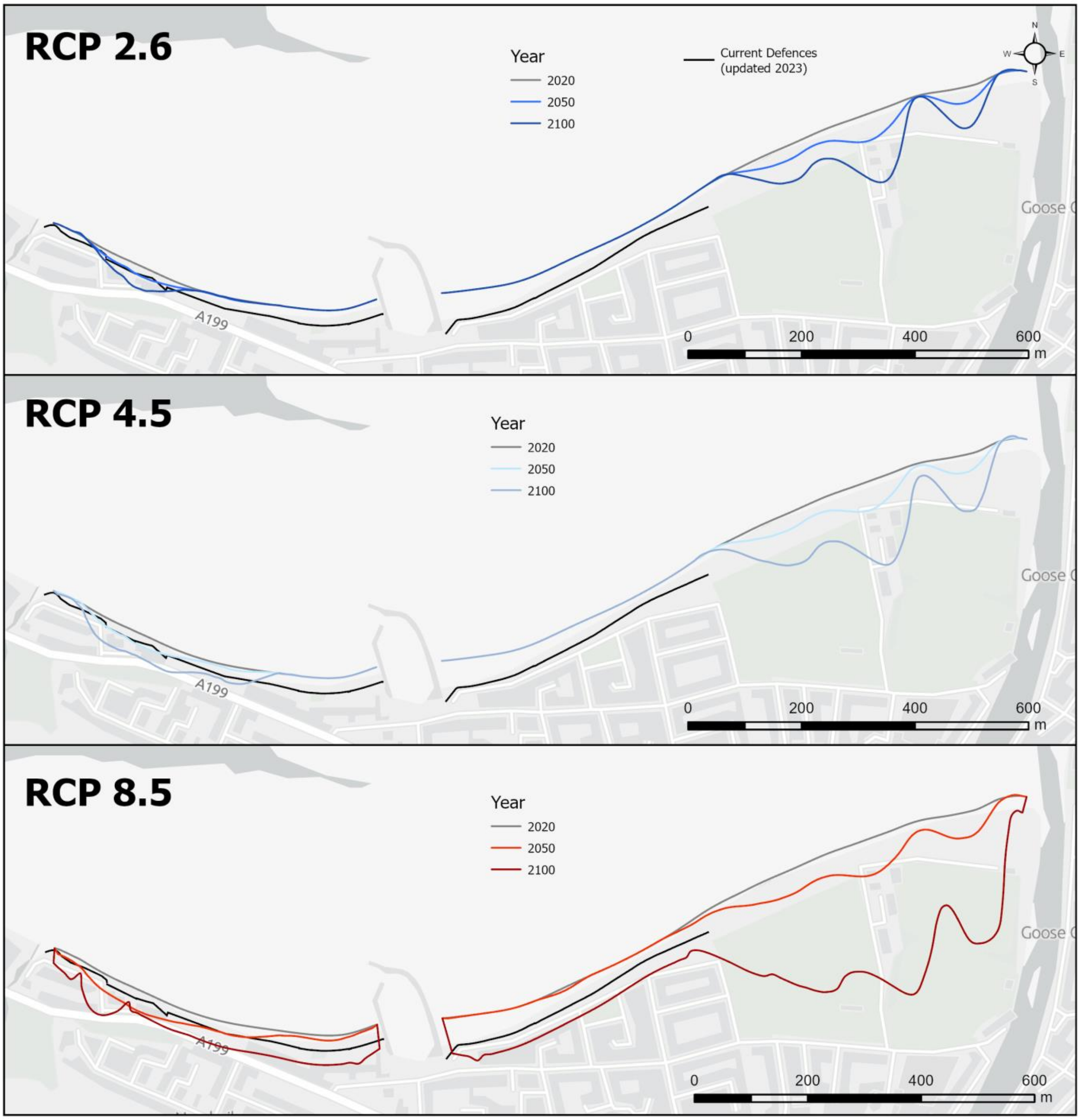

Figure 13: Future MHWS position based on Low, Medium and High Emissions scenarios informed by best available long-term observations of shoreline change (2018-2023). Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Figure 14 shows the difference between Dynamic Coast 2 predictions and the update provided here for RCP8.5 with these added defences and change calibrated to observations in the period 2018-2023. The extent of MHWS predictions behind defences is limited to 25 metres landward of the defences. This 25-metre buffer was also used during Dynamic Coast (following the methods of Hurst et al., 2021 & Muir et al., 2021) and was selected to demonstrate a possible extent to which MHWS may migrate landward if a defence structure was to fail, irrespective of the current condition of the structures.

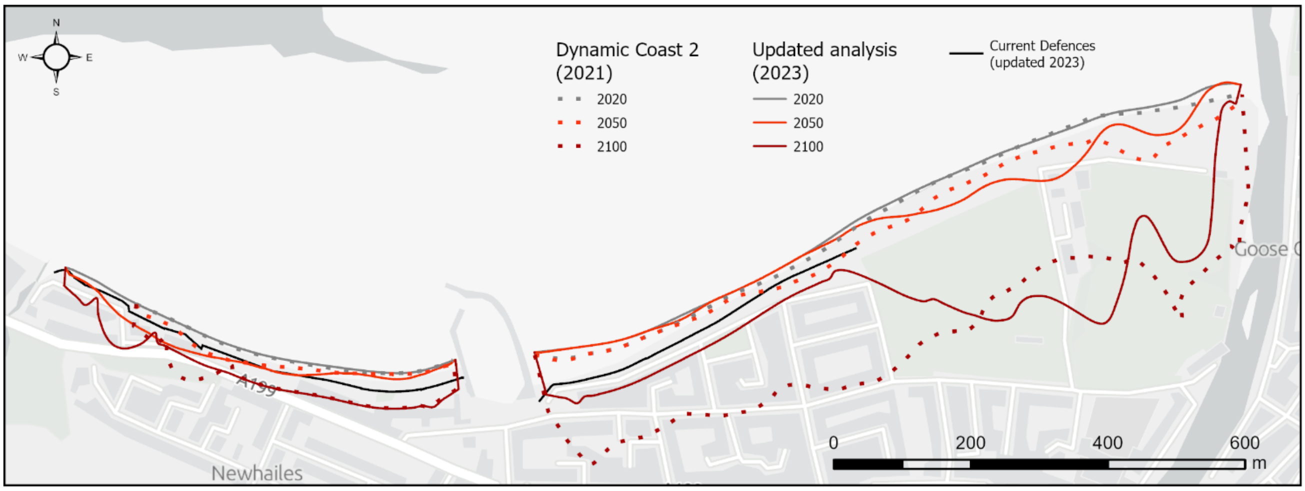

Figure 14: Comparison of updated future MHWS predictions against those published during Dynamic Coast (2021). Both examples are based on RCP8.5 and a do-nothing management strategy. The earlier (2021) results are shown in dashed lines, full lines are the latest predictions using the additional defence structures data and updated MHWS predictions from 2018-2023. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Figure 15 shows us a comparison of the future MHWS position predictions (using RCP8.5 climate scenario) with the variation in previously observed rates of MHWS change (Figure 7), compared to the regular rate used by the methodology (Figure 3). This analysis indicates that the predictions created using the regular rate (Figure 15, centre; using MHWS positions from 2018 & 12th of October 2023) most closely match the worst (minimum) rate. This reinforces the view that in recent times (2018-2023) we have begun to experience some of the most erosional changes in MHWS position (at least since 2000).

Figure 15: Future MHWS position prediction for High Emission Scenario (RCP 8.5), taking maximum (best) and minimum (worst) historic MHWS change rates (see Figure 7; in any period from 2000-present). Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Figure 16 shows the newly proposed coastal flood management structure. These are not explicitly designed nor certified at this stage for any coastal erosion protection function but are modelled here to allow the same nominal 25 m of erosion. As can be seen, this simply reduces the extent of future predicted MHWS position to the 25-metre buffer along the whole stretch of the coast between Brunstane Burn, Fisherrow Harbour and the River Esk.

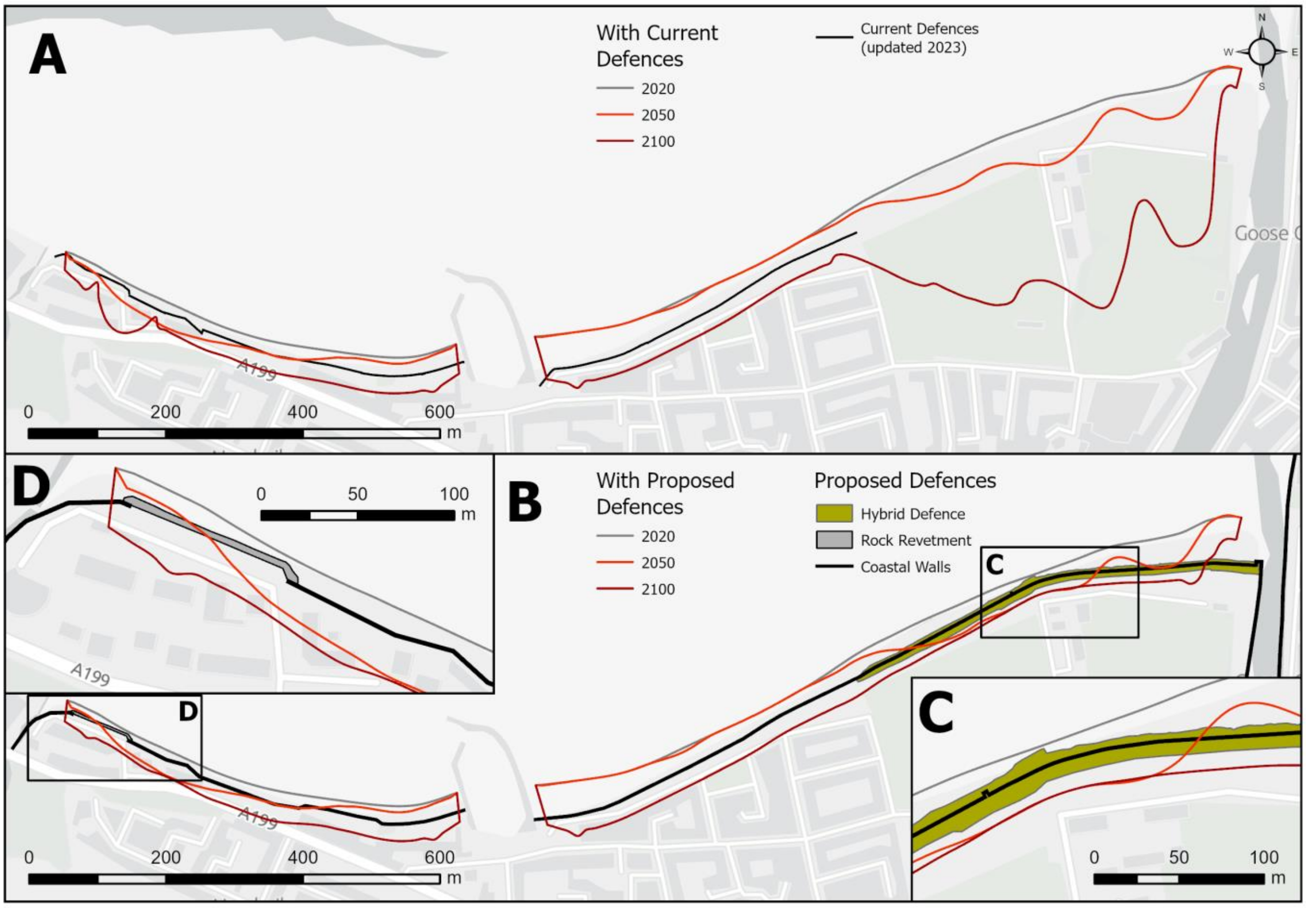

Figure 16: Maps showing the anticipated coastal erosion based on recent rate of change (between 2018 to 12th October 2023) with the known extent of existing coastal defences (Figure 17A). Figures 17B-D show ELC's proposed flood structures, which are assumed to allow a nominal 25m of erosion. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Implications

Factoring in an updated perspective of historic shoreline change, the results here are consistent with the findings of Dynamic Coast (2021) in suggesting that there will be continued shoreline erosion into the future; this anticipated to accelerate with expectations of sea level rise on the low-lying coastal area at Musselburgh.

Pragmatic application of the precautionary principle would suggest that on our current high emissions trajectory, erosion will accelerate in the coming decades, putting existing defences at risk and likely impacting the newly proposed flood defences. Coastal Change Adaptation Plans, which are explored in Task 3: Identifying Coastal Change Management and Adaptation Options, will need to consider how to continue to monitor these ongoing changes and identify trigger points for adaptation actions as these threats grow more acute.

Converting horizontal change into beach lowering rates

Much of the work on future projections depict coastal change via changes to the position of MHWS. However, coastal managers also have an interest in appreciating vertical changes in beach levels. By using the current beach slope (between dune face and break in slope onto the shore platform, measured using the pre-Storm Babet survey), and the anticipated horizontal rate of change of MHWS, a broad estimation of beach lowering rate per decade can be calculated (based on changes in decadal MHWS change rate under a high emissions scenario and in the absence of coastal management). Here we have used the regular calibration rate (Figure 3), and high emissions scenario (RCP8.5; Figure 13), assuming no changes to coastal management.

The following map (Figure 17) shows possible beach lowering rates in 2030 (Figure 17A & B) and 2050 (Figure 17C-E). This clearly shows ongoing beach lowering adjacent to Mountjoy Terrace in both 2030 (up to -17 cm/yr) and 2050 (up to -0.33 cm/yr). For context, a rate of -17 cm/yr equates over the period of a decade to a potential vertical loss of 1.7 m of sediment, approximately equivalent to the average height of an adult in the United Kingdom. The 2030 rates also show some potential for deposition, which would further corroborate views of local residents and beach users. However, by 2050 (Figure 17C-E), almost all of the beach is predicted to begin lowering, most notably there is an acceleration of rate at Mountjoy Terrace, and also west of the harbour near the Edinburgh Road cul-de-sac (up to -19 cm/yr).

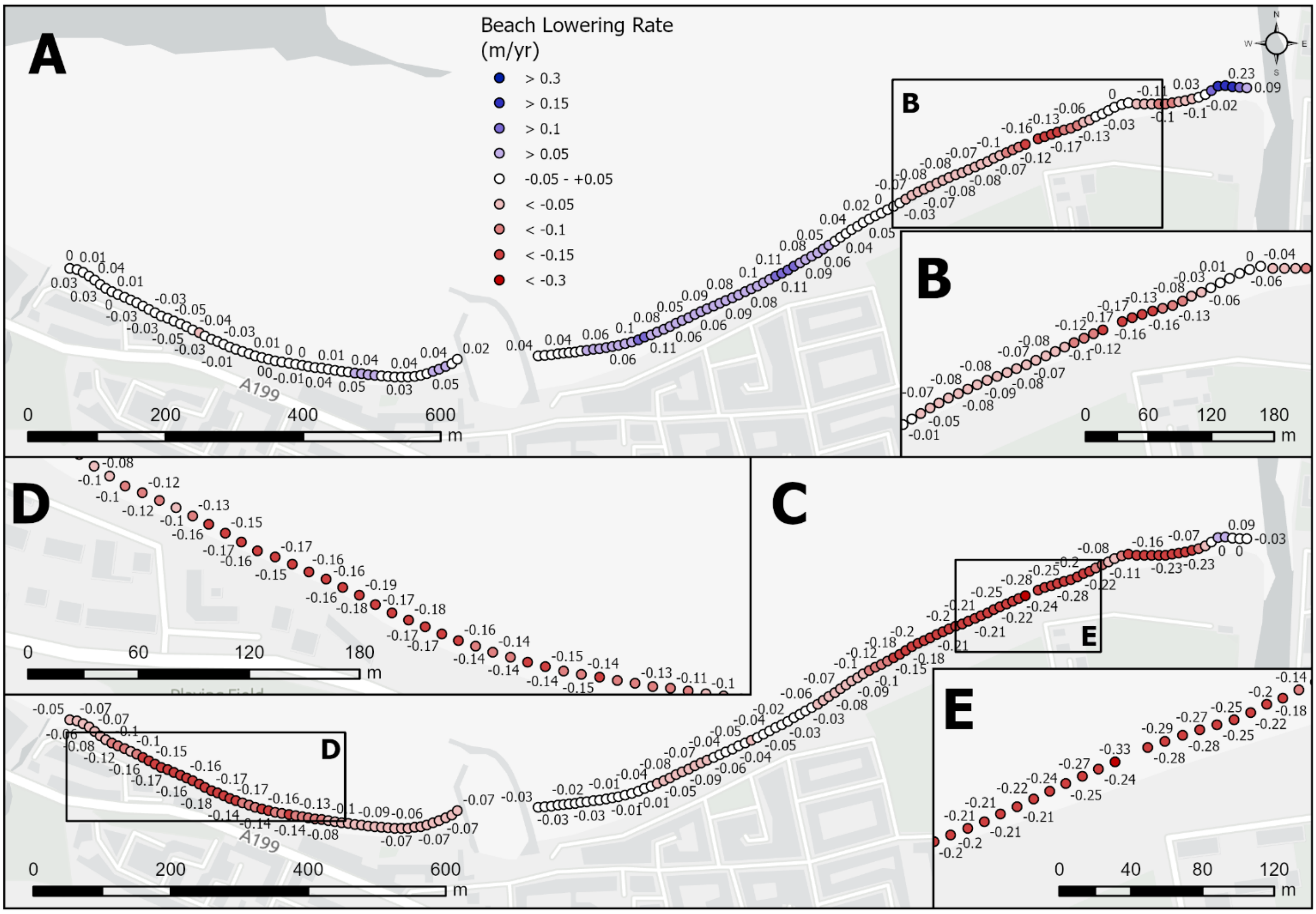

Figure 17: Maps showing a broad estimate of beach lowering based on recent rate of change (between 2018 to 12th October 2023) and current beach slope (12th October 2023). Figures 17A & B show the predicted annual rate of beach lowering between 2023 and 2030. Figures 17C-E show the predicted annual rate between 2040 and 2050. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Coastal Erosion Risk Assessment

Data Statement

Under the climate scenarios of future coastal change (including a standard historic change rate (2018-2023 pre-Storm Babet, Figure 3) and best and worst case historic change rates (see Figure 7), the areas anticipated to be impacted by erosion are intersected with built assets to identify the number and extent of these assets expected to be impacted, following the Dynamic Coast methodology (Muir, et al., 2021). This is done by creating a polygon of the anticipated coastal erosion areas using the known modern shoreline and the anticipated decadal shorelines. This is referred to as *Erosion Area* (EA), defined as landward of MHWS today, but expected to be seaward of any future MHWS. A 10 m buffer was added to this initial EA polygon, termed *Erosion Influence* (EI), to identify those adjacent areas that might be directly impacted by erosion events. A further buffer beyond EI was also created a further 50m landward, termed here the *Erosion Vicinity* (EV), to allow the identification of adjacent assets, which may be indirectly impacted by events, and flagged for further consideration by Local Authorities and asset managers.

The tables below show the decade the various assets are expected to be first impacted, as well as the extent of potential impact by 2050 assuming no action / coastal management is taken in mitigation. The values presented are based on the recent average calibration rates (2018 to 2023 before Storm Babet; see Figure 3) and rates of change associated with storms may be far higher and thus impacts are felt earlier. Furthermore, as explored elsewhere in this report (Figure 7), best and worst-case calibration rates (since 2000) can also be used for risk assessments and in some instances will bring forward and push back the projected impacts on the assets accordingly.

It should be noted that in the tables below, although the decade of first impact on an asset may be shown as, for example 2040, the first actual impact on this asset could be anytime between 2030 and 2040.

Key Results

The first set of assets analysed were the proposed flood defence structures (frontal edge), comprising of extended coastal walls, a hybrid defence structure within the park and a renewed rock revetment at the far west of the site (see Figure 16B). Two key results appear from Table 2 below, 1) direct impact on these assets is likely to occur relatively soon, mostly around 2030-2040, but potentially earlier, and 2) although the difference between the low and medium emissions scenarios appears minimal with respect to the early extent of impact, there is a significant increase when considering the high emissions scenario, particularly for coastal walls west of the harbour and also the renewal of the rock revetment at the west of harbour. There is a much more consistent impact on the proposed extensions/upgrades to the coastal walls east of the harbour.

Table 2: Risk Assessment results under standard calibration (2018-2023 pre-Storm Babet), noting the first decade when assets are impacted, and the coastal length which has been intersected by future MHWS.

Asset	First impacted (decade)			Proposed length (m)	Extent impacted within corresponding decade (m)		
	RCP2.6	RCP4.5	RCP8.5		RCP2.6	RCP4.5	RCP8.5
Coastal Walls (west of harbour)	2040	2040	2040	578	18	25	112
Coastal Walls (east of harbour)	2040	2040	2040	1,154	101	104	124
Hybrid Defence	2030	2030	2030	639	67	67	67
Rock Revetment	2040	2040	2040	108	14	19	39

The second analysis run explored assets at risk with the current defence structures in place at Musselburgh (see Figure 3). These assets were those also analysed in the Dynamic Coast project (Muir, et al., 2021). If an asset that was covered in the 2021 analysis is not discussed or included (e.g. railways), this indicates that it is not impacted at Musselburgh in this latest analysis. Several assets are predicted to not be directly impacted by coastal erosion (EA). Following the approach taken in Dynamic Coast (2021) where if the asset is particularly sensitive (e.g. property), and there are only a few assets identified at risk, these will be noted as “less than five”, to ensure individual assets are not singled out. This risk assessment includes assets identified at risk on the natural shore and any assets that are within 25m of existing coastal defences if the shore is erosional. Such a precautionary approach ensures that we do not take for granted the future maintenance of existing artificial defences. These currently defended assets can be readily identified within the datasets, and can be excluded from the at risks totals, if the decision is taken to maintain the associated defence structure(s).

Table 3 shows that under the low and medium emissions scenario (RCP2.6 and 4.5 respectively) less than five residential properties are expected to be at risk by 2050, if no coastal management is undertaken. Under the High Emissions Scenario, again with no coastal management undertaken, around 19 residential properties are expected to be at risk by 2040. Utilities (excluding water assets) is predicted to be within the Erosion Influence zone (within 10m of actual erosion) by 2090 in the medium emissions scenario and by 2060 in a high emissions scenario. Therefore, although not shown in Table 3, this asset could still be regarded as under significant risk in the coming decades. In respect of cultural heritage assets, a battlefield is predicted to be within the Erosion Vicinity zone (between 10m and 60m of actual erosion) by sometimes around 2060 – 2080. It is also of note that the Musselburgh foreshore is also categorised as a Special Protection Area (SPA) and Site of Special Scientific Interest (SSSI).

The third and final analysis examined the impact on the same assets from our second analysis, but with the additional flood defence structures accounted for in the predicted future MHWS positions (difference shown in Figure 16). The results presented in Table 4 assumes that the new flood defence structures have a comparable level of erosion protection as the existing coastal protection. Whilst this is known not to be the case, as these structures are not designed to resist marine undermining, such a scenario provides a ‘what if’ scenario, assuming the predicted erosion is not addressed by other means. Table 4 shows a broadly similar picture for residential property, namely that up to five properties may be at risk by 2050 under low and medium emissions, but under a high emissions scenario, around 17 may be at risk from erosion, assuming no coastal management.

As one would expect if the best-case and worst-case calibrations were used for these risk assessments, fewer assets would be identified as at risk, and more at risk respectively. For reasons of brevity these are not explored here, but under the full CCAP, we recommend ELC take consideration of a range of possible future scenarios (including climate, recent calibration rate and management approach).

Table 3: Anticipated assets at risk under various emissions scenarios, assuming existing defences are maintained with no new coastal management. Left-hand columns note by which decade the asset is expected to be at risk, whilst the right-hand columns note the number and lengths of assets intersected by the 2050 MHWS line.

Asset	First impacted (decade) – Erosion Area			Units	Impact extent by 2050		
	RCP2.6	RCP4.5	RCP8.5		RCP2.6	RCP4.5	RCP8.5
Residential properties	2050	2050	2040	**#**	< 5	< 5	19
Non-residential properties	*EV by 2030*	*EI by 2090*	2060	**#**	-	-	< 5
Roads	2050	2050	2050	**m**	15	31	95
Clean Water pipes	2090	2070	2050	**m**	-	-	0.38
Gravity Pipes	2040	2040	2040	**m**	125	141	230
Rising Mains	2040	2040	2040	**m**	297	348	680
Outfalls	-	2090	2050	**#**	-	1	2

Table 4: Anticipated assets at risk under various emissions scenarios, assuming new flood protection is in place, and providing comparable protection to existing defences, but with and then there is no new coastal management. Left-hand columns note by which decade the asset is expected to be at risk, whilst the right-hand columns note the number and lengths of assets intersected by the 2050 MHWS line.

Asset	First impacted (decade) – Erosion Area			Units	Impact extent by 2050		
	RCP2.6	RCP4.5	RCP8.5		RCP2.6	RCP4.5	RCP8.5
Residential properties	2050	2050	2040	**#**	< 5	< 5	17
Non-residential properties	*EV by 2030*	*EV by 2030*	2060	**#**	-	-	-
Roads	*EI by 2060*	2070	2050	**m**	-	-	25
Clean Water pipes	*EI by 2080*	2080	2060	**m**	-	-	-
Gravity Pipes	2040	2040	2040	**m**	125	141	230
Rising Mains	2040	2040	2040	**m**	166	187	476
Outfalls	-	2090	2050	**#**	-	-	1

Implications

These analyses strongly support concerns that the erosion risks at Musselburgh have the potential to impact both existing and proposed assets unless the future risks are managed. Table 2 identifies that the hybrid defence (adjacent to the Park) is expected to be directly impacted within the next decade (i.e. now-2030), under all emissions scenarios. The Coastal Walls and Rock Revetments are both expected to be impacted by erosion between 2030 and 2040. Table 3 and Table 4 show the substantial erosion extents and the adjacent assets at risk if effective forward-looking coastal management is not implemented.

Coastal flood risks

This section reports the publicly available risk maps for flooding for the Musselburgh shore. Figure 18 shows the likelihood of coastal flood risk according to SEPA's assessment (Flood maps | Scottish Environment Protection Agency (SEPA)). Figure 19 show's SEPA's anticipated flood risk when climate change / sea level is included: by the 2080s, each year the hatched area may have a 0.5% chance of flooding. Figure 19 shows the coastal food risk, based on a blended approach, as reported on the Musselburgh flood scheme website.

The future anticipated flood risk shown in Figure 19 and Figure 20 do not factor in the potential for erosion-enhanced flooding, whereby the anticipated landward migration of the foreshore, particularly under a high-emissions scenario, could exacerbate flood risks due to wave overtopping.

Figure 18: SEPA's present day coastal flood map, each year these areas may have a 10% (dark green), 0.5% (medium green) and 0.1% (light green) chance of flooding.

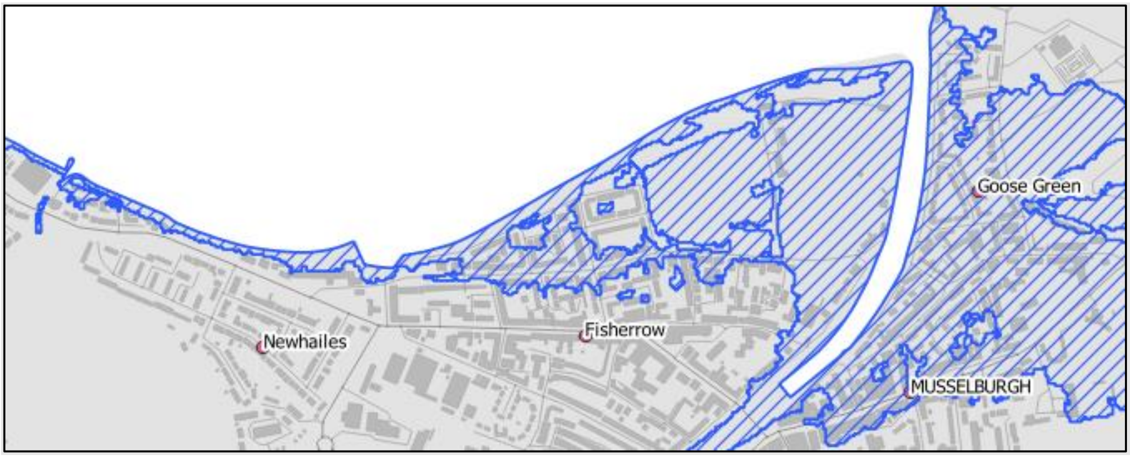

Figure 19: SEPA's future flood map for medium likelihood, by 2080 each year this area may have a 0.5% chance of flooding.

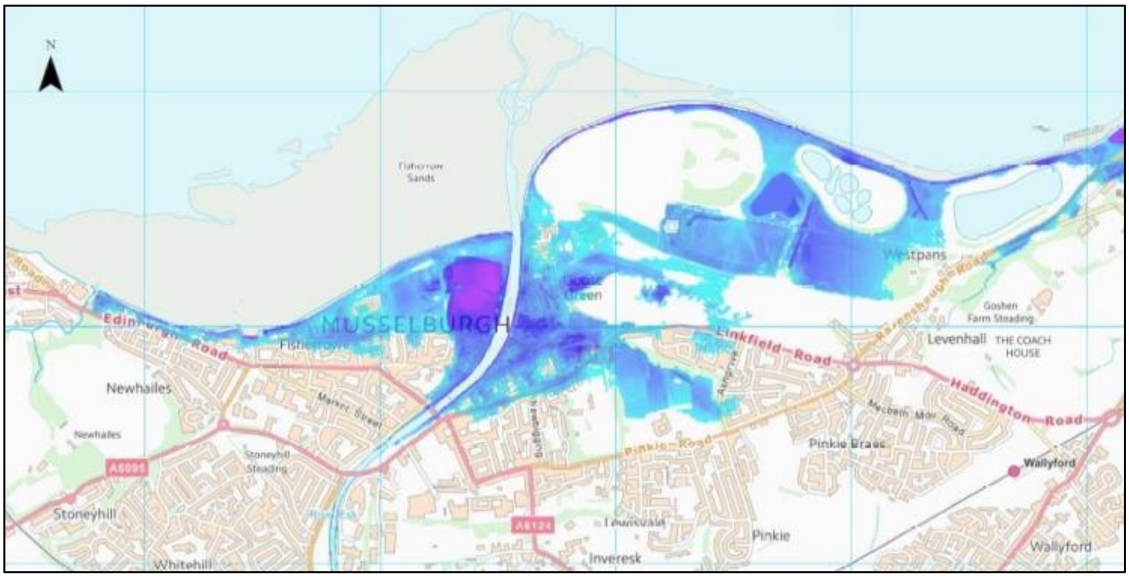

Figure 20: Anticipated coastal flooding (blended approach based Fluvial 50% AEP + CC & Coastal 0.5% AEP). Source: Flood Risk Mapping - Musselburgh Flood Protection

5 Task 3: Identifying Coastal Change Management and Adaptation Options

Task 3 uses historic coastal change (Task 1: Historic Coastal Change Assessment) and anticipated future coastal change (Task 2: Modelling Future Coastal Change Scenarios) to inform potential coastal change management and adaptation approaches. The following suggestions conform with the current Scottish Government coastal change adaptation guidance (Scottish Government, 2023; link - hereafter referred to as 'the Guidance') and acknowledge that a full Coastal Change Adaptation (CCA) Plan is planned for 2024.

Context & Introduction

ELC are planning a Coastal Change Adaptation Plan (CCAP), proposed to commence in 2024. Informed by the Coastal Change Adaptation Guidance (Scottish Government, 2023) and the analysis reported above (Task 1: Historic Coastal Change Assessment and Task 2: Modelling Future Coastal Change Scenarios), we make suggestions below for a monitoring strategy, potential trigger points and potential adaptation actions. Nevertheless, other important aspects to ensure effective future coastal management are also recommended to be addressed, such as community involvement and adopting a Dynamic Adaptive Pathway approach to allow flexibility with future management options and actions.

This section of the report provides the overarching policy context contained in the Guidance and considers the existing Shoreline Management Plan (SMP), before providing some suggestions on the way forward.

Coastal Change Adaptation Planning Guidance

The stated aims of the Guidance are:

1) *Promote the resilience of our natural coastal edge and begin the process of adaptation to climate change;*
2) *Set out a process for a proactive approach to coastal adaptation planning that will maximise opportunities and minimise risk from climate change impacts;*
3) *Ensure our collective coastal adaptation journey starts now; and*
4) *Support local authorities to begin the process.*

Scottish Government (2023) Coastal Change Adaptation Guidance, Pg 4.

The Guidance also identifies that sea levels are anticipated to continue to rise and quicken under all climate scenarios and, as such, our future coastal management approach will need to be radically different from our current approach. Coastal erosion-enhanced flooding is a key risk emphasised by the Committee on Climate Change (CCC) in their Scottish review (Scottish Government, Committee on Climate Change, 2022) with adaptation to both coastal erosion and coastal flooding flagged as essential. The Committee on Climate Change (2022) note ten principles of adaptation, and these should be considered further and in greater depth by ELC in their full CCAP. When applying these principles to the coast, the Guidance makes four recommendations to local authorities preparing CCAPs:

1) *Recognise that alongside mitigation efforts, adaptation planning is essential around the coast.*
2) *Coastal change adaptation plans should be adaptive and sufficiently precautionary to changing risks alongside current and future opportunities.*
3) *Given uncertainties, plans should recognise a range of scenarios of future risks, via levels and thresholds rather than dates. At the time of writing, this guidance recommends trigger points based on using UKCP18 data; however, approaches should adjust as the consensus on the science changes. Plans should include a 'low emissions' future (such as RCP2.6 50%), a 'high' emissions future (such as RCP8.5 95%) alongside a credible maximum scenario (such as H++ scenario which includes a Mean Sea Level rise of 1.9 m above present by 2100), to test adaptive capacity.*
4) *Acknowledge that not all future risks need to be addressed immediately, but flexible approaches should be planned to manage these growing risks if, and when, they occur. This can be achieved by defining and deploying incremental and locally relevant trigger points (based typically on levels and processes rather timescales) which acknowledge lead-in time and locally relevant considerations (coincident risks may include river flooding, tidal range change, extreme events etc). These approaches are a part of a Dynamic Adaptive Pathway. Adaptive approaches which 'jump directly' to address risks not expected until the end of the century may prove more costly*

in the short-term and risk losing community support, however in some cases this may be desirable where, for example, continuity of supply is critical. ***Scottish Government (2023) Coastal Change Adaptation Guidance, Pg 6.***

Furthermore, the Guidance notes that coastal adaptation planning processes should identify areas of the coast where:

a) natural or artificial defences in a fixed or semi-fixed position will be needed in the long term;
b) no active intervention is needed and free coastal change is accepted; and
c) managed re-alignment of the coast would be a more effective strategy in the long-term.

Scottish Government (2023) Coastal Change Adaptation Guidance, Pg 7.

Crucially the Guidance states that:

> *"Development Plans can help safeguard natural features, including those that protect the coast. Where there are risks of erosion and flooding and coastal protection is not feasible, the planning authority may need to consider where infrastructure and assets should be relocated out of harm's way."*

Scottish Government (2023) Coastal Change Adaptation Guidance, Pg 7.

The Guidance goes on to stress the importance of working with natural processes, monitoring change, engaging with communities, working across boundaries and place-based working. Authorities will be required to run place-based coastal change adaptation planning processes that include community engagement activities incorporating co-design concepts. CCAPs should also use technical information from Dynamic Coast, SEPA and consultancy services. For a CCAP with a managed adaptive approach to be successful it will be necessary for local authorities to demonstrate that:

- *It comprises technically feasible and viable options and that the future cost of the options can be accounted for including the potential impacts of these options.*
- *The lead time between the need for an option being triggered and implemented is achievable.*
- *The fullest range of risks has been accounted for using the credible maximum scenario for sea level rise.*

Scottish Government (2023) Coastal Change Adaptation Guidance, Pg 12.

The management suggestions below are made with these policy requirements in mind, and whilst specific to Musselburgh, should help set direction of travel for ELC as they embark upon designing the CCAP for the wider region.

Policy Context to future management options:

The ELC Shoreline Management Plan (2002)

The ELC Shoreline Management Plan (SMP) outlines coastal erosion and flooding issues and management options, as reported in 2002. It remains the current formal policy approach and provides a useful foundation on which to update and advise in line with the Guidance. The SMP outlines key aspects for Management Unit 1 (Musselburgh), outlines the defence locations, land uses, assets, and policy framework. The Key interests note, *"The public also suggested that improvements to flood and coastal defence within MU1 are required (Appendix B), again highlighting the Fisherrow area" (East Lothian Council, 2002, p. 116)*

The Option Evaluation states *(East Lothian Council, 2002, p. 117)*:

> *"The coastline of MU1 is protected with hard defences for 800m of its 2km length and defences extend upstream along the banks of the River Esk. All of the coastal defences protect either commercial/domestic property or roads and the main risk is flooding (Appendix 0). The shoreline is stable or accreting along MU1, thus the erosion risk is low and the main risk to defences would be due to overtopping or structural failure during onerous tidal and storm conditions. As there are no erosion rates for MU1, the cost-benefit analysis method set out in Chapter 8 is not applicable.*
>
> *The No Active Intervention option would result in the eventual failure of some of the coastal and fluvial defences in MU1, particularly as some of the defences are already in poor condition (e.g. defences at the River*

Esk). Failure of the defences would lead to flooding of commercial/domestic property or roads. The monetary value of failure and thus flooding of the hinterland is difficult to quantify and is outwith the scope of the present study. The No Active Intervention option is considered unfeasible.

Part of the shoreline of MU1 is natural with a low dune system separating the sand beach from the road and Fisherrow Links. This part of the shoreline is presently stable or accreting, although it is likely the dunes will undergo some temporary phases of erosion during winter storms. This is a natural coastal process and short-lived phases of erosion should not be considered a problem. Thus, the Hold the line option does not apply for the entire management unit.

*The existing defences protect the urban area and roads from flooding, therefore it is recommended these defences be maintained for the duration of the SMP. Thus, **Selectively Hold the Line** is a feasible option for MU1. The structural condition of the defences at the mouth of the River Esk is poor and capital works will be required within the next 10 years (Appendix D). The level of the defences at the mouth of Fisherrow harbour and Fisherrow promenade is relatively low approximately 4.3mOD) and may have to be raised over the next 50 years to cope with the predicted sea level rise and increase in storminess.*

Sediment transport in MU1 is from west to east, although the volumes of sediment transported are relatively low. It is anticipated that the Selectively Hold the Line option in MU1 would have negligible impact on the shorelines of adjacent units. The status quo is maintained, and, as no new coastal defences are proposed, the impact on existing coastal processes in the process unit will be negligible.

***Advance the Line** is not considered a feasible option for MU1, as this will create an artificial line of defence further seaward that the current MHWS and would upset the natural operation of coastal processes, which may have implications for the adjacent shoreline. As the immediate hinterland of the defences in MU1 is urban, removal of the defences would result in considerable flooding and damage to assets. Thus, there are no suitable areas of MU1 where Retreat the line, via removal of the existing defences, is considered a feasible option.*

The preferred strategic option for coastal defence in MU1 is to Selectively Hold the Line. This involved the maintenance of existing defences only. No new constructions of coastal defences is recommended, although capital works may be required at the mouth of the River Esk, Fisherrow Harbour and Fisherrow promenade" (East Lothian Council, 2002, p. 117).

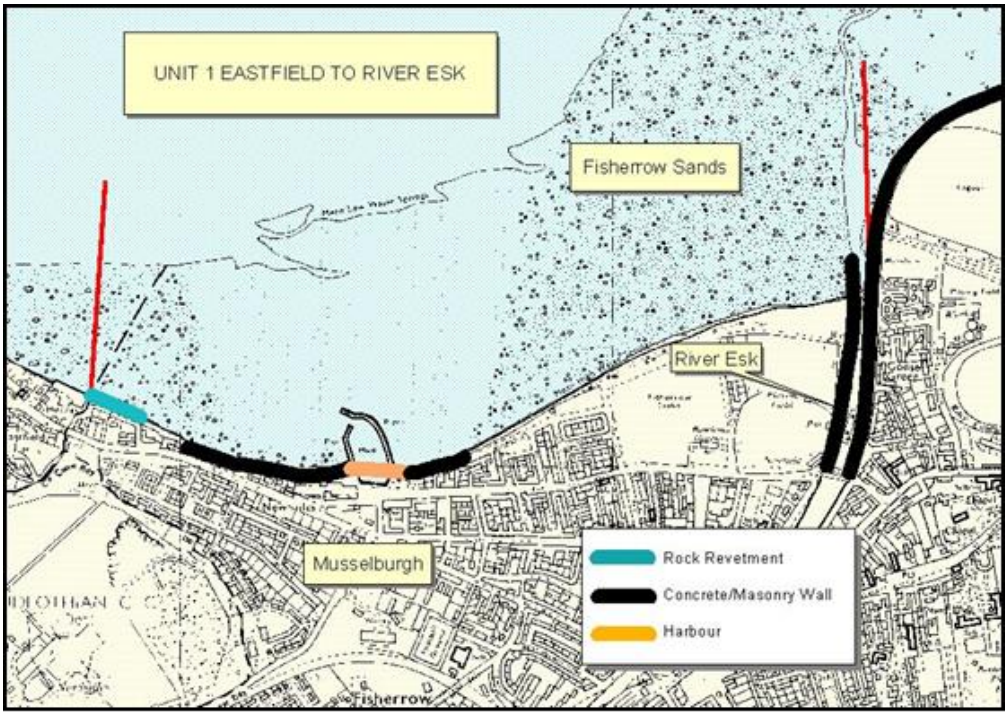

Figure 21: Extract from ELC SMP (2002), Management Unit 1 (i.e. Musselburgh) noting the extent of artificial defences and thus the extent of 'Selectively Hold the Line'.

Reflections on ELC SMP Policy for MU1.

The SMP is clear on the current policy but mute regarding any changes to the current management approach in the longer-term: there have been no alterations to the position within the SMP since its publication. The close proximity of buildings, assets, and erosion/flood structures to the coast, does lend continued support to the view within the SMP that Managed Realignment is neither desirable nor practical, particularly in the short-term. Whilst the playing fields at Fisherrow Links may imply space between built assets and the coast, wastewater infrastructure is present close to the footpath. These assets effectively constrain the options within the grassed areas, making any short-term managed realignment options impractical. Interestingly, when earlier map evidence is reviewed (1980s & 1890s County Series, and 1940s aerial imagery, Side by side georeferenced maps viewer - National Library of Scotland (nls.uk)) the bulk of the coastal development can be seen to have been in place for at least 80 years. Such historic planning decisions within Musselburgh's coastal zone mean that current Council planners and engineering options are constrained by previous management decisions with long-lasting consequences.

However, since the SMP was first published and enshrined into policy, rates of sea level rise have been increasing with nearly a three-fold increase in rates of sea level rise over the period of 2006-2018, to 3.7 mm/year compared to the rate between 1901-1990 (1.35 mm/year). As shown in Figure 1, the Met Office UK climate projections predict sea level rise under all future climate scenarios, including if net zero were to be achieved in the future. Since "*there is also a [time] lag between CO_2 and temperature rises in the atmosphere, and its effect on sea level, future sea level rise will continue, from past emissions, even if net zero is achieved tomorrow,*" (Naylor, 2023). Thus, there has been a substantial change in the environmental context since the production of the SMP that calls for re-evaluation of the management of coastal change.

CCAP Stage 1: The Policy Approach CCAP Stage 1: The Policy Approach

The Guidance states that:

> "*Where a Shoreline Management Plan already exists, it would not normally be necessary to start again. In these cases, the existing Plan should be reviewed and updated in line with this guidance. In general, any plan should be driven by coastal processes and the interconnected nature of coastal communities and not by Local Authority or other administrative boundaries.*".
>
> ***Scottish Government (2023) Coastal Change Adaptation Guidance, Pg 13.***

Whilst the DEFRA 2006 guidance (Department for Environment, Food and Rural Affairs, 2006) is noted, the CCAP process is encouraged to include the coastal hinterland and allow planning space for adaptation by relocation of coastal assets.

ELC have confirmed that the current policy approach for MU1 remains unchanged and is to **Selectively Hold the Line for defended shores, whilst managing flood risks more widely**. ELC have also confirmed that there have been no alterations to the position within the SMP since its publication. Officers have confirmed that it is proposed that a Coastal Change Adaptation Plan for East Lothian Council will be undertaken in 2024-25 and it will take cognisance of the CCA Guidance (Scottish Government, 2023).

The continuing function of the existing and proposed new flood structures are required and must be resilient to coastal change. Alternatively (or additionally), the coast must be managed in a way that coastal erosion does not undermine existing and new defences. Analysis of historic and future coastal change above (Task 1: Historic Coastal Change Assessment and Task 2: Modelling Future Coastal Change Scenarios) shows that under a range of futures (ranging from best case to worse case emissions scenarios) the existing and proposed flood management structures are expected to be at risk from coastal erosion. Further, this report identifies two locations where the juxtaposition of structures and low beach resilience are currently a concern (Figure 22 and Figure 23). The following section (CCAP Stage 2) explores the range of adaptation actions that may address these risks and support the SMP policy of Hold the Line.

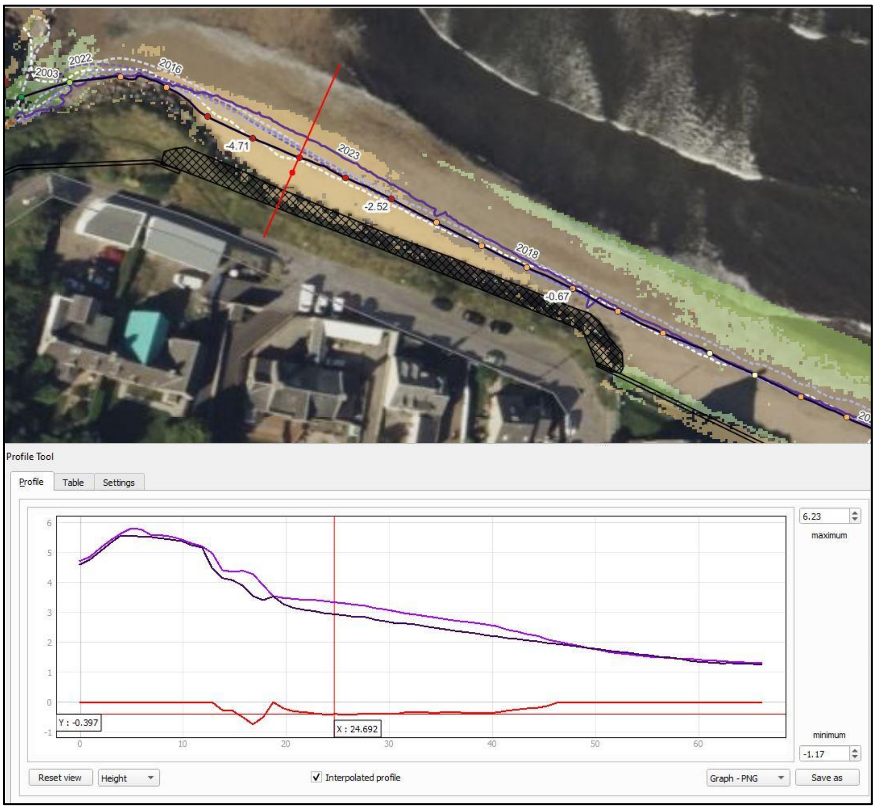

Figure 22: Pre- and post-Storm Babet height and MHWS changes at the proposed westerly rock revetment structure (hatched black; adjacent to Edinburgh Road cul-de-sac), showing two surface elevations in cross-section (pink pre-Babet, purple post-Babet, nett vertical change in red). The red dot on the map along the red cross-section line between the structure (hatched) and the various MHWS lines indicates the position (at 24.692m from start of cross-section) on the cross-section diagram.

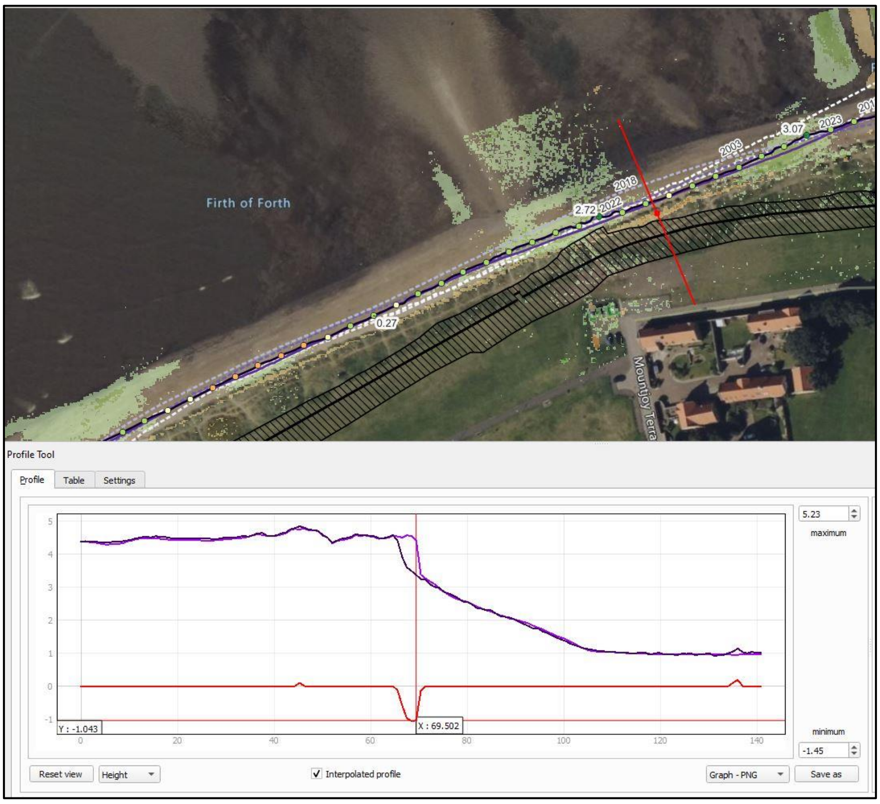

Figure 23: Pre- and post-Storm Babet height and MHWS changes at the proposed easterly hybrid defence structure (hatched black), showing two surface elevations in cross-section (pink pre-Babet, purple post-Babet, nett vertical change in red). The red dot on the map along the red cross-section line between the structure (hatched) and the various MHWS lines indicates the position (at 69.502m from start of cross-section) on the cross-section diagram.

ELC's current coastal management policy and the proposed position of the flood management structures mean that short-term coastal management options focus on maintaining the current configuration, and thus alternative approaches (e.g. managed realignment and/or adaptation by relocating assets) may not have been fully considered since SMP publication. Nevertheless, ELC's coastal management policy doesn't explicitly consider how 'Hold the Line' will change, as climate risks increase. This represents a discord with the Guidance meriting its reconsideration within a wider review (Scottish Government, 2023, p. 16; Table 1). A 'health check' of the existing SMP is needed as the CCAP is developed. Such work should reappraise the assets at risk, including flood risk aspects as well as the demographics, development considerations, and economics of each area. This should aim to ensure all long-term sustainable, climate-resilient options are explored, and growing risks are managed iteratively and adaptively. Such a review might seek to define strategic trigger points where a change in policy or management direction is needed in response to particular circumstances, such as when a sea wall fails or reaches the end of its practical life.

For practical purposes the short-term policy of 'Hold the Existing Line' of existing and proposed defences is carried forward in this report. Therefore, sub-policies include 'Maintain/replace', 'New Defences' or 'Temporary Intervention'. The analysis in Task 1: Historic Coastal Change Assessment and Task 2: Modelling Future Coastal Change Scenarios highlights that erosion risks are growing and thus so too are adaptation requirements. Nature-based approaches would be included within 'Temporary Interventions' and include beach feeding/nourishment schemes where the natural coastal defences (i.e. beach and dunes) are enhanced with additional natural material (and where appropriate, dune planting and other control measures) in order to increase the resilience of the flood management structures as provided by the beach and dunes. Such adaptation actions may be modest in the short-term but are likely to become larger and more expensive in the future, the rate and extent of which will depend on the trajectory of future emissions, sea level rise and any associated increases in storm impact. Recent Environment Agency work anticipates 90% increase in repair costs for coastal assets due to climate change (Environment Agency 2020).

To provide a context for the Step 2 Adaptation Plan, a range of options briefly explored below and aims to provide a springboard for ELC CCAP considerations.

A future based on a 'do nothing' coastal management strategy

All management options need to be compared against a 'do nothing' coastal management baseline. This ensures that existing coastal management is not taken for granted. Such a situation for a high emissions future is shown in Figure 13 (bottom). In this instance the existing known coastal protection structures provide protection to an arbitrary distance of 25m inland. Whilst this is shown as a simple 25m buffer, in reality, the impacts from, for example, a sea wall failing are unlikely to be linear. Figure 13 shows erosion is allowed to propagate inland where the shoreline is natural (i.e. free from artificial coastal defences), and the underlying geology is thought to be readily erodible.

Under this situation where the existing defences are present, but not maintained, then a range of assets are expected to be at risk under a high emissions scenario, including up to 19 residential properties, up to five non-residential properties, up to 95m of road and a range of water-related infrastructure (see Table 3). Under a low emissions scenario, and in the absence of coastal management, the anticipated erosion still occurs, but at a later date and across a more limited frontage. Fewer assets are expected to be impacted, as outlined in Table 3.

A future based on constructing the proposed new artificial flood management structures alongside a 'do nothing' coastal management strategy

This option includes the construction of new coastal flood management structures, but with no coastal erosion management (i.e. 'do nothing') such as beach nourishment. Such a situation is shown in Figure 13; bottom image) for a high emissions scenario. In this instance the existing known coastal protection structures provide protection beyond an arbitrary 25m distance inland. Whilst this is shown as a simple 25m buffer, in reality impacts from, for example, a sea wall failing are unlikely to be linear, but may include localised undermining. Note that the proposed coastal flood management structures are neither designed nor certified for any coastal erosion protection function. However, they may have limited coastal protection functions (e.g. reducing the impact of waves on the land behind them) and therefore have been modelled here to allow the same nominal 25m of erosion. Figure 13 to Figure 16 shows that erosion is allowed to propagate inland where the coast is natural (i.e. free from artificial coastal defences), and the underlying geology is thought to be readily erodible

Under this scenario, anticipated beach erosion and lowering is expected to negatively impact the existing and proposed flood management structures (see Table 2), initially within limited sections by 2040 but across the majority of the shore front in later decades. Such a situation presents a risk to the performance of the proposed flood management structures, as they are not designed to withstand marine undermining or storm wave overtopping. The initial human impacts of this lowered risk management performance are most likely to be experienced in the vicinity of Mountjoy Terrace (to the east of the harbour) and opposite Newhailes playing field to the west of the harbour. Such a situation presents a risk to the performance of the proposed flood management structures, as they are not designed to withstand marine undermining or storm wave overtopping. For this reason, coastal monitoring and coastal erosion resilience measures are expected to be necessary, in the coming years / decades, if the planned flood performance is to be maintained. Under a low emissions scenario the wider impacts are expected to be experienced later across much of the shore, nevertheless the close proximity of the proposed flood risk management structures to present MHWS means it is advisable to consider the potential for impacts of erosion over the next two decades regardless.

A future based on beach nourishment ensuring separation of erosion risk from new flood management structures in the short to medium term

Under this scenario the proposed ELC flood structures are constructed as planned, however the anticipated erosion rates are used to estimate future volumetric sediment losses from the beach and dunes. These anticipated losses form the basis for indicative feed volumes to offset expected erosion, ensuring that the proposed flood management structures are not undermined by beach lowering and retain their design function (i.e. for longer than the previous scenario without the beach nourishment) in the face of climate change, at least in the short to medium term. To inform this, two methods are available, the first is a transect-based approach that takes the anticipated erosion rates multiplied by the area of the 'active beach face' (top of shore platform to dune crest) to inform the anticipated volumetric losses within the beach. The second approach takes the net eroded volumes within each section (based on the volumetric change analysis) and uses these to estimate the necessary feed volumes. Both options are outlined below and serve to guide order of magnitude estimates. A more rigorous monitoring strategy needs to be established to more accurately assess coastal zone changes and inform desired management approaches. In the future, hydrodynamic modelling of sediment transport rates and patterns will be essential to explore the sediment residence time on the fed beach and, coupled with a modelling strategy, establish the tigger point for refeeding as required.

A future based on erosion resilient flood management structures.

Under this scenario the proposed ELC would be required to withstand marine undermining whilst providing a flood management function. Essentially, this is a 'hard' civil engineering solution, where a more resilient structure is designed and built, whose physical integrity and performance continues even when adjacent beach levels drop. Further advice from Jacobs (as ELC's consultant engineers) can be sought to inform the costs and implications. Such an approach is anticipated to result in retreat, narrowing and lowering of the beach. In time this results in reduction in the protective function of the natural beach, reduction, and eventual loss of recreational and amenity value of the beach and reduction in the habitat functionality of any designated intertidal and supratidal habitats. In an unmanaged situation where beach levels continue to drop over decades, wave overtopping risks increase and threats to any structures and coastal assets become increasingly severe. A possible end point is complete loss of the beach itself. A similar situation to this is already occurring in Scotland where the beach face adjacent to the hard defences of Traill Drive at Montrose, where Angus Council's efforts to repair defences following storms are being severely hampered by extremely low beach levels.

A future based on adapt by avoidance.

The above options present scenarios of a variety of possible management futures, but most of these centre on the concept of the coast position remaining approximately in its present position into the future, in other words a 'Hold the Line' approach. 'Holding the Line' may locally be highly desirable, operationally convenient and a feasible strategy in the short term. However, in coming decades 'Holding the Line' is expected to become increasingly untenable in the face of anticipated coastal erosion and associated coastal flood risk increases as a result of rising sea levels and increased storm intensity (see Figure 1).

As acknowledged by the Committee on Climate Change (Scottish Government, Committee on Climate Change, 2022) *"it is unrealistic to promote a hold the line policy for much of the coastline (i.e. employing hard or soft engineering to prevent further erosion), and realistic plans to adapt to change are needed."* Given the importance of the community assets along the coastal frontage at Musselburgh, it is recommended that careful consideration of longer-term risks occur by ELC establishing a CCAP using a Dynamic Adaptive Pathways approach.

The concept of moving community and assets away from the current shorefront may seem foreign and unnecessary to today's residents. However, increasing numbers of communities around Scotland and elsewhere are realising that the way they have used their coastal areas in the past may not be realistic in the future. Musselburgh will not be alone in this regard. But if climate change and associated rising sea levels remain unaddressed, coastal erosion will quicken and beach levels will lower (as discussed above), and the risk to shore front community assets will be substantial, and very different to those experienced by today's residents and communities. Adaptation by avoidance is a key planning approach that should be considered in the forthcoming Coastal Change Adaptation Plan. This is being done elsewhere in Scotland where the creation of coastal buffers aims to accommodate future coastal change and reduce risk to assets (e.g. Edinburgh City Plan 2023, Granton Waterfront Development and other CCAPs). Experience from other locations, including Fairbourne in Wales and the East Coast of England demonstrates that, if these adaptation approaches become necessary, then they are best developed with full community involvement, rather than being imposed from above.

Coastal Change Adaptation Plan Stage 2: The Adaptation Plan

Context

ELC are directed toward the Stage 2 section of the Guidance (Scottish Government, 2023) and encouraged to consider other CCAPs which are in development, including the Moray CCAP. Based on this it is acknowledged that ELC would be at Phase 0 (i.e. the start of the adaptation process), and as such the range of future management options need to be appraised locally for each Coastal Change Management Area, and trigger points considered. We acknowledge that the partial 'Hold the Line' policy remains, and that initially this may extend across the full Musselburgh coastal edge. However, future management approaches may, or indeed need to, differ as conditions change. For example, the current expectation is that the existing beach levels offer reasonable protection and require only local enhancements. However, within only a few decades, depending on the progression of erosion, the rate of sea level and the frequency and intensity of future storms, the requirements for beach nourishment and renourishment will increase. Trigger points should be defined to consider when and where beach feeding or alternative actions should occur. Such trigger points could be thresholds in the position of a shoreline indicator, such as MHWS, a threshold in volumetric beach losses, or a threshold in beach gradient. Additionally, if land-use changes occur (e.g. facilities are moved, such as the water treatment works) then there may be less imperative to maintain natural and artificial defences. At this trigger point, alternative options may be considered to transition towards a Managed Realignment approach, where other assets are moved to more inherently resilient land.

To take this forward, we encourage ELC to work with communities and adaptation specialists to define what their vision of long-term adaptation looks like and outline the range of possible management approaches required to deliver this adaptation to support the desired outcomes. Adaptation is realised through a series of looped questions requiring ongoing monitoring in the context of defined trigger points, outlined via the example below (Figure 24). The approach is likely to be different for each stretch of coast and there may be more or fewer steps to secure longer-term adaptation. Early feedback from Moray Council noted that the council may remain in the initial part of the loop (monitor, trigger not actioned, continue to monitor) for some time before any strategic shift in approach is required, but this may not be the case in other locations.

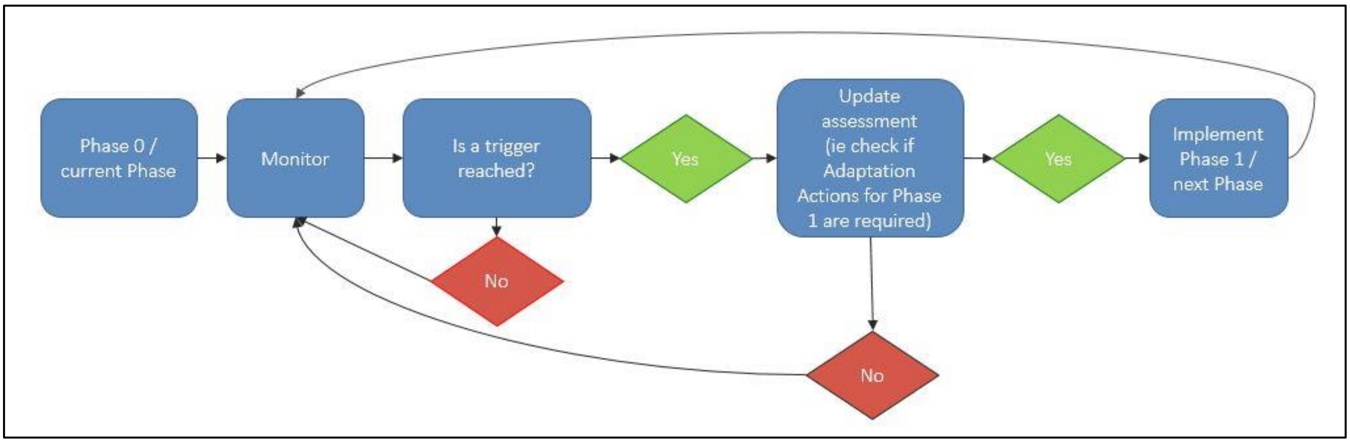

Figure 24: Flow chart showing the monitoring / adaptation loop (amended from a Moray Council CCAP consultation materials)

Coastal management options

Coastal Change Management Areas (CCMAs) should be defined, based on contiguous areas behind a single type of defence or shoreline type, and their landward extent includes areas of anticipated coastal change and / or coastal flood risk. We have suggested four CCMAs as defined within Figure 25, including:

1. West of Harbour,
2. Harbour,
3. Promenade and
4. Park.

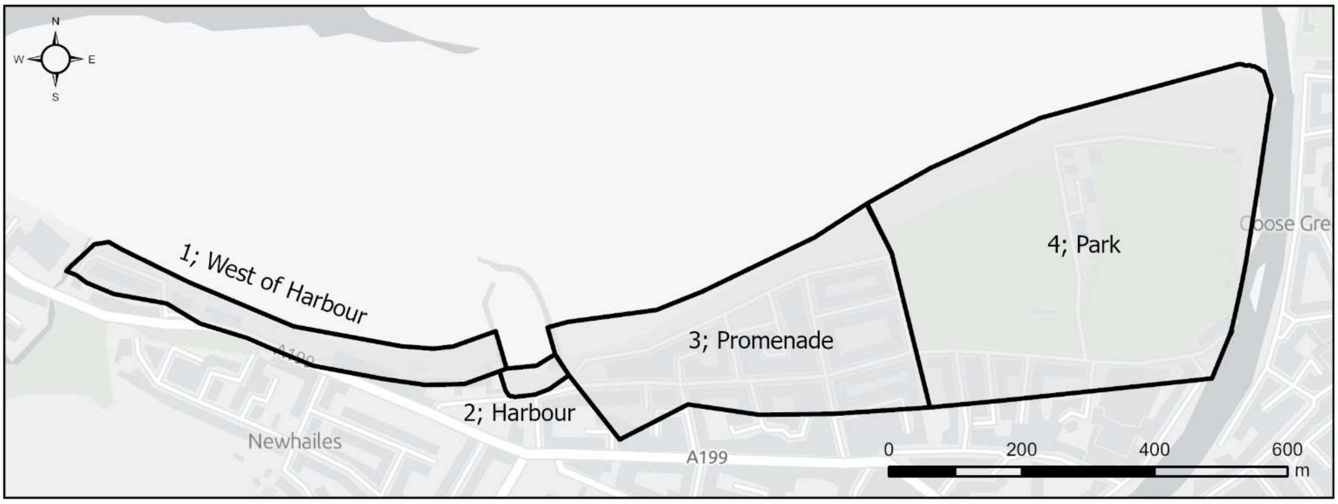

Figure 25: Map showing suggested Coastal Change Management Areas for the Musselburgh coastal area. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Introduction to Dynamic Adaptive Pathways & Triggers

The Dynamic Adaptive Pathway approach has been developed to manage uncertainty and prepare for a range of possible management approaches that can be navigated between when required (as defined by identified triggers). Such an approach removes arbitrary policy periods (e.g. short-term policy is operational now, but when do we switch to a long-term strategy?) but instead uses locally relevant triggers to initiate a review. We recommend that ELC's full CCAP explore these fully, including implementation of the necessary supportive steps to assist anticipated future relocation and avoid adding new assets at future risk (e.g. the black pathway in Figure 26 requires pre-planning for relocation). We recommend there is also merit in exploring nature-based approaches, informed by our research here, recognising these may be a subset of the possible adaptation options.

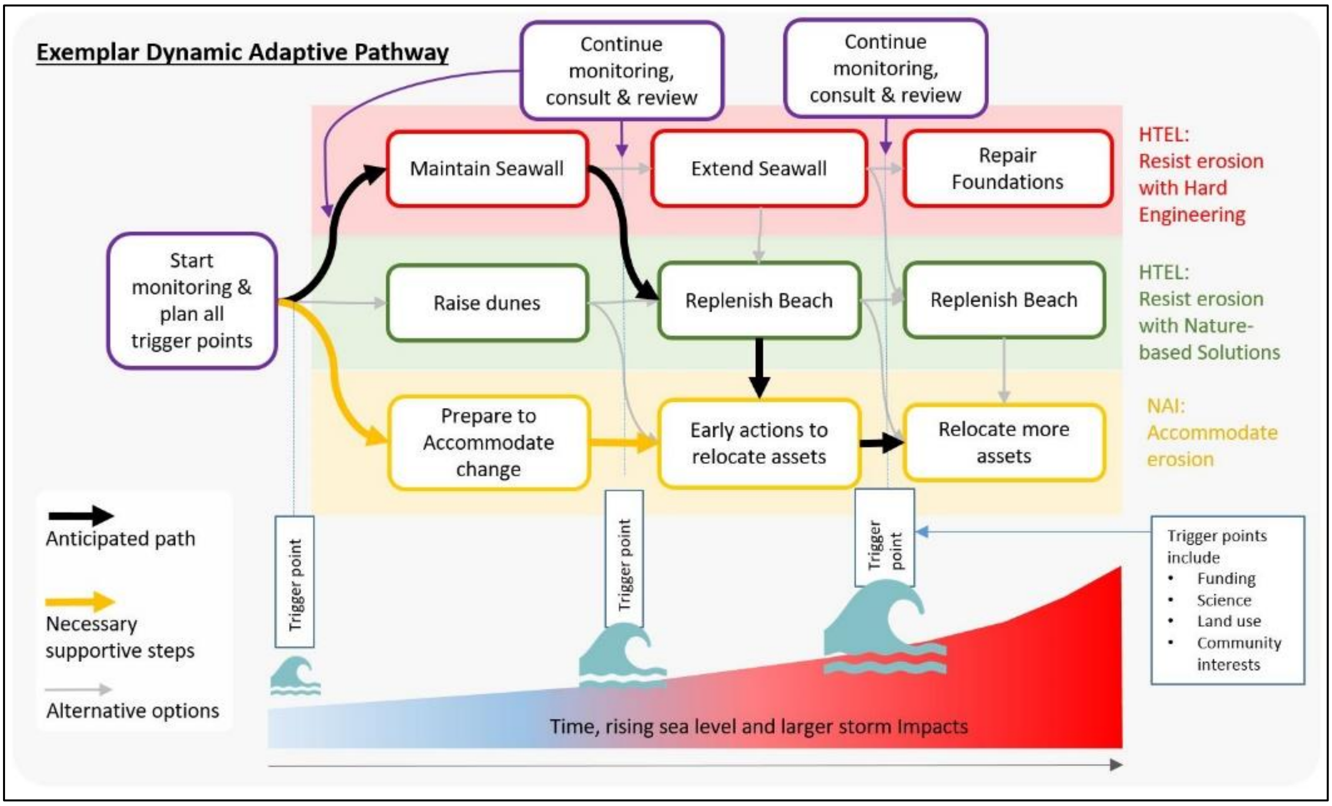

Figure 26: Diagram from the Guidance, depicting a Dynamic Adaptive Pathway, where multiple coastal management options are planned for and navigated between as trigger points are crossed.

Monitoring coastal change to inform Triggers

ELC need to consider the range of coastal monitoring techniques available to them and consider how best to use these to define trigger points. Whilst monitoring can be informed through various traditional methods (e.g. topographic ground survey) improvements in drone-based surveying techniques now allow greater efficiency and areal accuracy. Earth Observation techniques, as outlined in Figure 8 can inform changes without the need to visit the shore, but with compromises in accuracy. More basic techniques also have their place, for example ground survey that measures the distance from a known point to either the dune edge, cliff or the strand line left following a spring tide.

Whilst it is for ELC to define their own monitoring strategy, we recommend a minimum of six-monthly topographic surveys of the available intertidal area, preferably at MLWS. We also recommend continuing to explore the potential for using remote sensing techniques as part of an automated early warning or trigger system. Liaison with other local authorities, Dynamic Coast, the Scottish Government, and the university sector is strongly encouraged, as this is a key area which authorities can learn from each other and benefit from collaboration. Further information is available on the Coastal Change Adaptation pages of the Dynamic Coast website (Dynamic Coast - Coastal Change Adaptation), including some monitoring case studies.

Triggers for Adaptation to Flooding

Various trigger points or thresholds can be defined that may warrant a change of management strategy or action. For example, a representative elevation for roads or property is identified, and then used alongside a tide gauge (recording the observed flood levels) to consider the exceedance frequency. Such an approach was used within the Moray CCAP. An alternative could use the frequency of waves overtopping flood defences.

Triggers for Adaptation to Erosional change

For coastal erosion, triggers can include the distance between an asset (e.g. building, path or sea wall) to either MHWS, vegetation edge or, a nominated elevation contour, or to a tangible ground observation (e.g. does a spring high tide strand line reach within a certain distance from a path/wall). Alternatively, a trigger can be based on change to a coastal indicator (e.g. MHWS) i.e. has the coast eroded above a nominated rate or distance? These triggers can be phased so that when a lower threshold is crossed the monitoring frequency/accuracy is increased. If a further threshold is reached then further action is triggered. Likewise different triggers can be developed for different asset types, matched to their acceptable level of risk/impact. We suggest these should be developed by ELC and consulted on to ensure they are both locally acceptable and appropriate. Whilst there is a wide range of community and public assets along the Musselburgh shore, it is logical to develop triggers based on the position of these assets relative to the position of the proposed flood structures and their importance for flood protection.

A simple example of an erosion trigger is shown in Figure 27 and Figure 28, where two lines are created 10 m and 20 m from the proposed flood structures. Whilst MHWS requires surveying equipment, a simple proxy can also be used (for example: a strand line following a high spring tide). If this occurs within 20 m of the nominated structure, then increased monitoring is undertaken. If the second threshold is passed (i.e. 10 m) then more substantive action is undertaken, for example inspection by ELC flood team to assess the competence / performance of the structure.

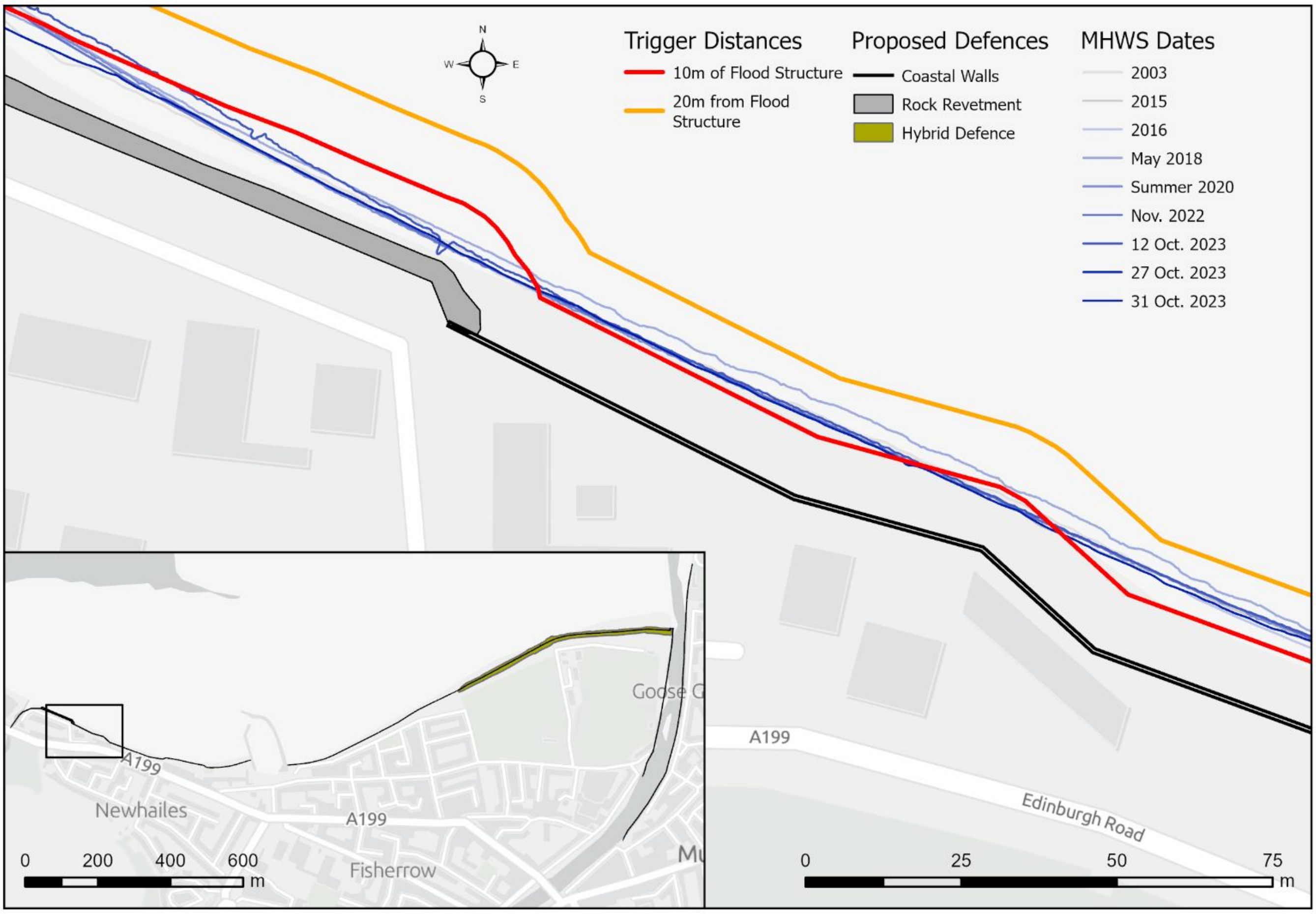

Figure 27: Map of the proposed flood structures within CCMA1 (West of Harbour) and the associated buffers for 10 and 20m. The recent position of MHWS (blue lines) are also shown for context, the darkest is the 2023 MHWS line. The parallel black lines are the proposed coastal wall and the grey area the renewed rock revetment. The trigger distance buffers are created from the seaward edge of the proposed structures . Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

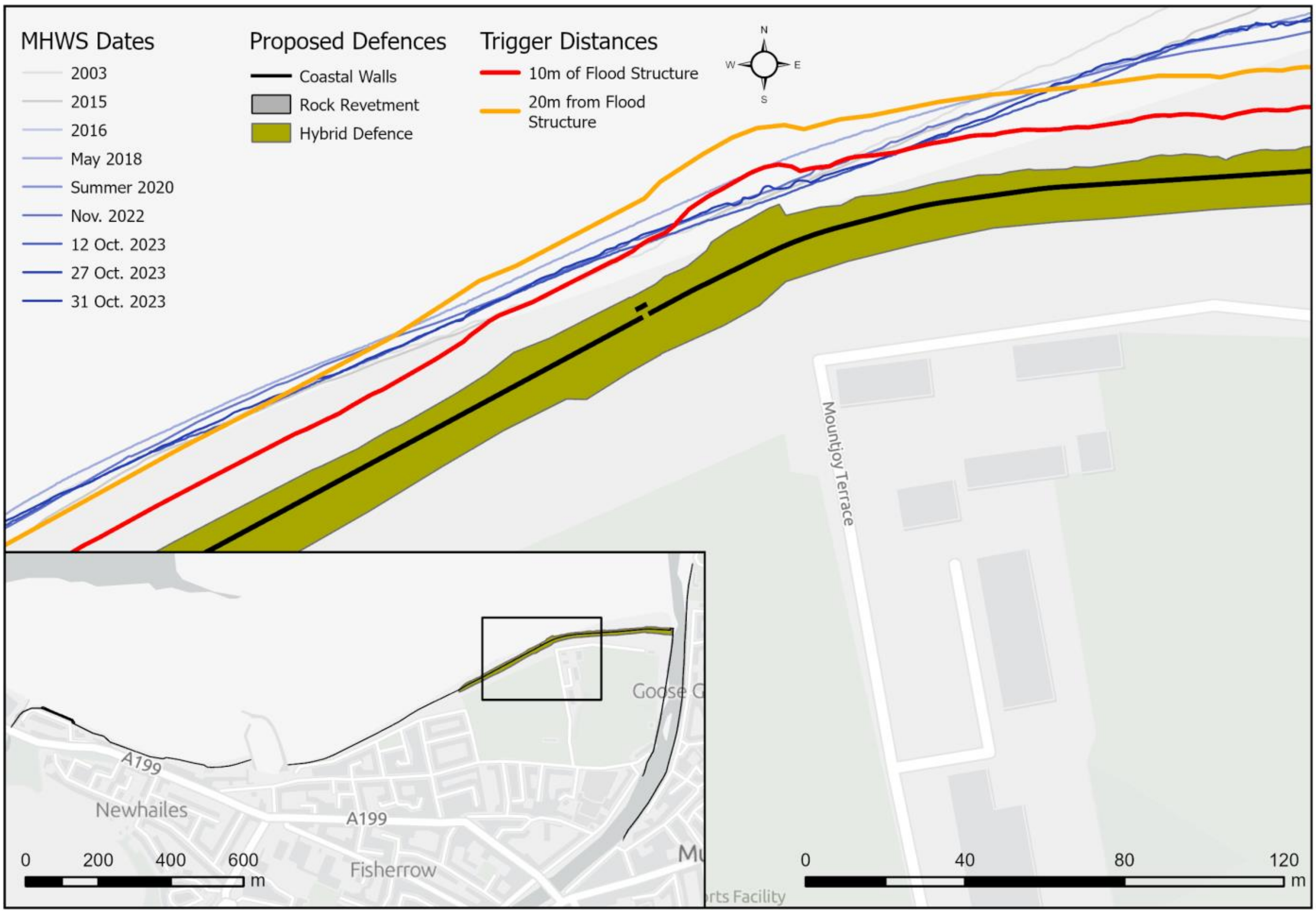

Figure 28: Map of the proposed flood structures within CCAM4 (Park) and the associated buffers for 10 and 20m. The recent position of MHWS (blue lines) are also shown for context, the darkest is the 2023 MHWS line. The green area is the proposed hybrid defence, from the seaward edge of which the trigger distance buffers are created. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Resilience and Adaptation Actions

For each individual trigger within each CCMA, adaptation actions should also be defined. These should include further basic monitoring (e.g. a site inspection), advanced monitoring (e.g. targeted survey & analysis at increased frequency or accuracy), or practical activities to enhance the resilience at necessary locations. Such works should consider both enhancement of natural features (e.g. nourishing the beach or raising the dunes) or works on the built defence assets (e.g. maintain defences, sustain defences, or improve defences). Whilst these examples would be relevant for repairs and improvements in protection, the DAP may also define actions which include preparing for relocation. It is important that triggers reflect the necessary lead-in time for deployment. For example, if beach nourishment is proposed, are the necessary permissions and licenses secured and if not, what are realistic time periods for this? If relocation of assets is proposed as a future option, then can suitable land be zoned for such relocation, and if not, what are the costs and timescales and planning lead-times associated with acquiring or designating new land uses? As with monitoring efforts, it is recommended that adaptation options and their implementation (such as planning timescales needed to create coastal buffers and processes to support relocation) are carried out by working closely with and sharing practice with other local authorities, government agencies involved in adaptation planning with their communities. It is also recommended to collaborate with and draw on the expertise in wider professional practice (e.g. universities, the third sector and consultancies).

Preliminary estimates of beach nourishment volumes.

If beach nourishment is used as a nature-based option, then it is possible to produce an "order of magnitude" estimate of the minimum nourishment required to maintain a protective beach. Using a *transect approach* and the key elevations and distances the anticipated flood structure crest is expected to be 5.9 mOD and, standing between 1.45 and 1.8 m above current ground levels (Jacobs) (Price & Baxter, 2021, p. 55). Erosional transects are considered within each of the CCMAs. Within CCAM1 (West of Harbour) there are 23 erosional transects with 10 m spacing and an average erosion rate of –0.32 m/yr anticipated over the next decade. Thus, the anticipated loss per year is estimated to be around 220 m^3/yr ((5.9 - 0.3 for the toe elevation) x 120 x 0.32 = 215 m^3). CCMA2 is the harbour and is discounted, and CCMA3 is the Promenade and MHWS is not expected to erode significantly by 2030 under this scenario (although ongoing monitoring and triggers are required here). CCMA4 (the Park) has 45 erosional transects by 2023, with an average erosion rate of –0.82m/yr. Thus, the anticipated loss per year is estimated to be around 2,000 m^3/yr ((5.9 - 0.55 for the toe elevation) x 450 x 0.82 = 1,974 m^3/yr).

An alternative approach for indicative nourishment volumes uses the *observed losses from sections of the beach* (based on the volumetric analysis 2018-2023). The losses within each of the CCMAs are listed below. It is interesting that the longer-term losses are more modest in the order of 1,500 m^3/yr, compared with losses of ca. 4,000 m^3 experienced during storm Babet. This is perhaps indicative that recovery of beach material occurs in calmer conditions in the aftermath of a storm event. Nevertheless, this analysis confirms that the recent losses are relatively modest even during recent storm conditions.

Table 5: Estimated net volumetric losses in m^3 from CCMAs, used to inform minimum anticipated annual feed.

Analysis Period	Area	Beach sediment losses (m^3)		
		CCMA1 (West of Harbour)	CCMA3 (Promenade)	CCMA4 (Park)
2018 - 2023	Lower beach losses	-1,246	-95	-1,425
	Middle beach losses	-271	-	-4,399
	Upper beach losses	-40	-	-
	Totals (2018-23)	*-1,557*	*-95*	*-5,824*
	Totals per year	*-311*	*-19*	*-1,165*
Storm Babet	Lower beach losses	-316	-	-180
	Middle beach losses	-2,218	-976	-58
	Upper beach losses	-213	-104	-10
	Totals	*-2,747*	*-1,080*	*-248*

Further considerations may be necessary such as, however, including beach feed design (fill geometry) to maximise erosion management (noting nominal westerly movement of sediment etc), consideration of sand retention measures (e.g. groins) and opportunities to minimise impacts to recreational facilitates and designated interests. Whist these fill volumes may be initially modest, there will be broader benefits in undertaking several years' worth of fill, to secure efficiencies of scale, and potential enhancements in erosion protection, habitat, and recreational provision.

Consideration of where to source the sand should be considered early and explored with key partners.

Whilst the nourishment estimates are offered as an initial estimate (based on current rates of change), ELC and the community should be aware that as sea levels rise more rapidly towards the second half of the century, erosion is likely to quicken and expand into currently stable areas (e.g. Figure 13). As such, it is highly likely that nourishment volumes would need to increase to offset this future erosion. These are essentially sacrificial activities which buy time for wider and bolder adaptation approaches such as asset relocation that may be required in the longer-term. It is essential that these are explored within the council's forthcoming CCAP.

6 Recommendations

1. **We recommend that ELC consider establishing a beach monitoring programme** to provide the data to underpin and inform both the trigger points and any consequential short-term resilience and long-term adaptation actions.
2. **We recommend ELC consider developing adaptation measures** initially for areas where the resilience of natural shores is low (including nature-based approaches) but broaden these to become a 'whole beach' approach. Local beach feeding of the most vulnerable areas will lead to swift redistribution of sediments, so the council may find it wise to invest efforts to rapidly upscale to a 'whole beach' approach to effectively manage any change at the appropriate scale. We suggest that the evidence means that the council consider this as an urgent task, and we recommend that no time should be wasted in developing these resilience and adaptation actions.
3. **We recommend ELC undertake a CCAP for its entire shore frontage, but to prioritise the Musselburgh section to ensure alignment with the planned FRM works**. As part of this CCAP, we recommend the short-term measures suggested here be thoroughly investigated alongside several longer-term adaptation options aimed at enhancing both the resilience of the coast and keeping the community safe as climate change progressively impacts both them and their assets. Such an approach has substantial benefits beyond the proposed flood scheme and is in support of ELC's planning and climate change duties.

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8 Technical Annex

Glossary

3D: Three dimensional; in the context of this report, usually referring to the addition of vertical data (e.g. elevation models) for analysis

Accretion: the build-up of coastal sediment typically by wave, tide, or wind processes, which leads to the seaward movement of contours such as MHWS lines

Beach nourishment: the artificial addition of appropriate sediment to a beach to ameliorate coastal erosion.

CCC: The UK Committee on Climate Change, which provides independent review to UK Governments

CCAF: the Scottish Government's Coastal Change Adaptation Fund. See www.DynamicCoast.com/cca

CCAP: Coastal Change Adaptation Plans, these are new plans which replace SMPs (see below)

DEM/DSM: Digital Elevation Model (or Digital Surface Model), a regular gridded image raster with each cell containing a height for the given location

Earth Observation: refers to the use of remote sensing technologies to monitor land, marine (seas, rivers, lakes) and atmosphere. Satellite-based EO relies on the use of satellite-mounted sensors to gather data about the Earth's characteristics. The images are then processed and analysed in order to extract different types of information that can serve a very wide range of applications and industries.

ELC: East Lothian Council

Erosion: the removal of coastal sediment typically by wave, tide, or wind processes, which leads to the landward movement of contours such as MHWS lines.

Groyne: an artificial structure which acts as a barrier to sediment moving along the coast

LiDAR: Light Detection And Ranging; a laser scanning device for accurate measurement of heights & distances.

Macrotidal: areas where the tidal range is greater than 4 m

MU1: Management Unit 1, an area defined within a SMP

MHWS: Mean High Water Springs, the upper coastal line used to define the beach

MLWS: Mean Low Water Springs, the lower coastal line used to define the beach

Precautionary Principle: where there is uncertainty a precautionary approach should be undertaken

Raster: a pixel-based spatial dataset, for example an image or Digital Elevation Model

RCP: Representative Concentration Pathways including 2.6 (often referred to as a Low Emissions Scenario, in line with the Paris Agreement, 4.5 (Medium Emissions Scenario) and 8.5 (High Emissions Scenario).

RCP8.5 95%: the percentage figure refers to the 95th percentile of a range of projected sea levels (Figure 1)

SMP: Shoreline Management Plan

OD: Ordnance Datum; standard height datum used in Great Britain for the measurement of mean sea level as defined by the Ordnance Survey using a tide gauge at Newlyn.

OS: Ordnance Survey; the national mapping agency for Great Britain.

Transect: a line extending perpendicular to the shoreline, which measurements are made along

UAV: Unoccupied Aerial Vehicle, colloquially known as a Drone

UoG: University of Glasgow

VE: Vegetation Edge, the edge of terrestrial vegetation adjacent to beach sediments often used for coastal change assessments

Task 1: Methods for assessing historic shoreline change

Coastal change indicators from Coast X-Ray

The Coast X-Ray method was developed by Dynamic Coast to investigate intertidal elevations derived water line positions in satellite images obtained at known tide elevations (Fitton, et al., 2021). The position of the water line is compared from images captured when the tide was at the 70th percentile of the tidal range to calculate rates of change in the period 2016 to 2021. The position of Mean Low Water Springs (MLWS) was also derived from a 2021 satellite image and compared to mapped MLWS from Ordnance Survey 1850 map.

Satellite-derived coastal change indicators

The position of Mean High Water Springs (MHWS) has previously been used as a principal coastal change indicator by Dynamic Coast (Hurst, et al., 2021). Previous analysis has been based on sparse observations based on few available topographic surveys. Recent developments in the deployment of software to automate analysis of satellite imagery allows for a richer time series of shoreline observations to be generated, albeit at coarser resolution with larger uncertainties than ground surveys and observations. We have deployed the CoastSat software (Vos, et al., 2019) to extract time series of water edges for satellite images that coincide with tide elevations above 0.85mOD, tidally corrected for beach slope (measured from LiDAR topographic survey) to equivalent MHWS elevation of 2.66 mOD. The resultant shoreline positions have been obtained from Sentinel-2 and Planet Labs satellite imagery.

The seaward edge of terrestrial vegetation marks what is commonly perceived to be the coastal edge, any movement of which is usually interpreted as coastal erosion. The vegetation edge then can also be used as a proxy for coastal change, particularly informing upper beach change. Best used alongside other coastal metrics to inform local understanding, it serves as a visible metric that can be appreciated without specialist survey equipment. Recent research at the University of Glasgow has developed new approaches to automating the mapping of vegetation edges from satellite observations (Muir, et al., 2023), extending the capabilities of CoastSat (Vos, et al., 2019). We therefore derive a timeseries of vegetation edge positions at the coast from the same Sentinel-2 and Planet Labs satellite imagery as used for water edge above (Figure 29) and derive average rates of shoreline change by regression analysis of shoreline position through time.

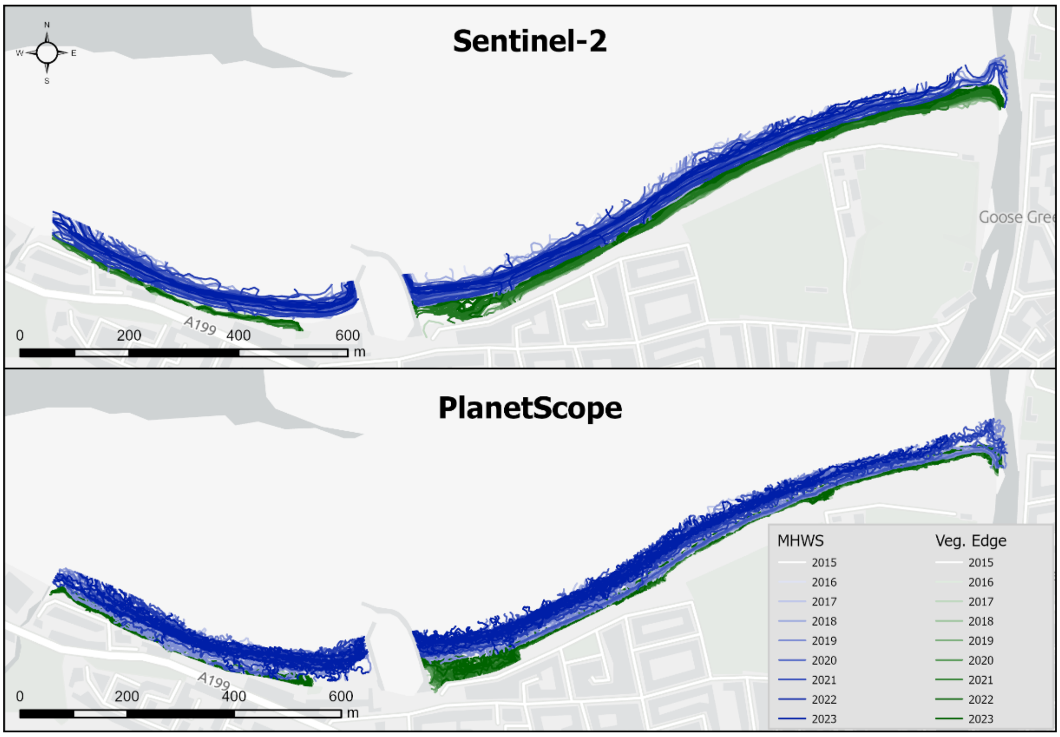

Figure 29: Map of satellite-derived MHWS and VE colour-coded by date. Basemap: OS Light Grey via ArcGIS Pro; contains OS data © Crown Copyright and database right 2023. Contains data from OS Zoomstack.

Topographic survey derived coastal change indicators

ELC provided a Digital Terrain Model from 2018 (Fugro LiDAR), and a topographic survey from 2022 (L&M via Jacobs). The L&M / Jacobs topographic survey was initially processed as a Triangulated Irregular Network (TIN) and then interpolated to a raster. Rasters derived from both surveys were contoured to extract the appropriate Mean High Water Springs (MHWS) elevation of 2.66 mOD. In addition, Scottish Phase 5 LiDAR is also available, but the coverage only partially covers the area of interest (no usable data east of the harbour). All available LiDAR was nevertheless downloaded and processed to extract a partial MHWS contour line at the same elevation to the west of the harbour. These new MHWS lines were then compared with pre-existing data from previous Dynamic Coast projects (2017 & 2021).

Using Digital Terrain Models (DTMs), a preliminary Geomorphic Change Detection (GCD) analysis (Wheaton et al., 2010) has been undertaken. The following data has been used; ELC commissioned Fugro LiDAR (2018), and Jacobs and both University of Glasgow unpiloted aerial vehicle (UAV) topographic surveys (2023). Additional datasets such as L&M / Jacobs topographic survey (2022), and Scottish Government LiDAR products (Phase 3 and Phase 5) were also available and processed by not fully analysed. However, neither of the Scottish Government LiDAR datasets have full coverage over the site (mostly available west of harbour), and with DTM quality often being noticeably poorer towards the edges of the surveys, further reducing the usable extent.

Quantifying rates of change

Two approaches to measuring and reporting shoreline change (either MHWS or vegetation edge) have been used here. The approach based on survey data involves reporting end-point rates, the difference in position of a shoreline indicator, divided by the time period elapsed between the surveys. This approach has been used for comparing MLWS positions, and all MHWS contours derived from LiDAR and topographic surveys. Where richer timeseries are available (i.e. where MHWS and vegetation edge were derived from satellite images), average rates of shoreline change were calculated by regression analysis of shoreline position through time (Figure 30).

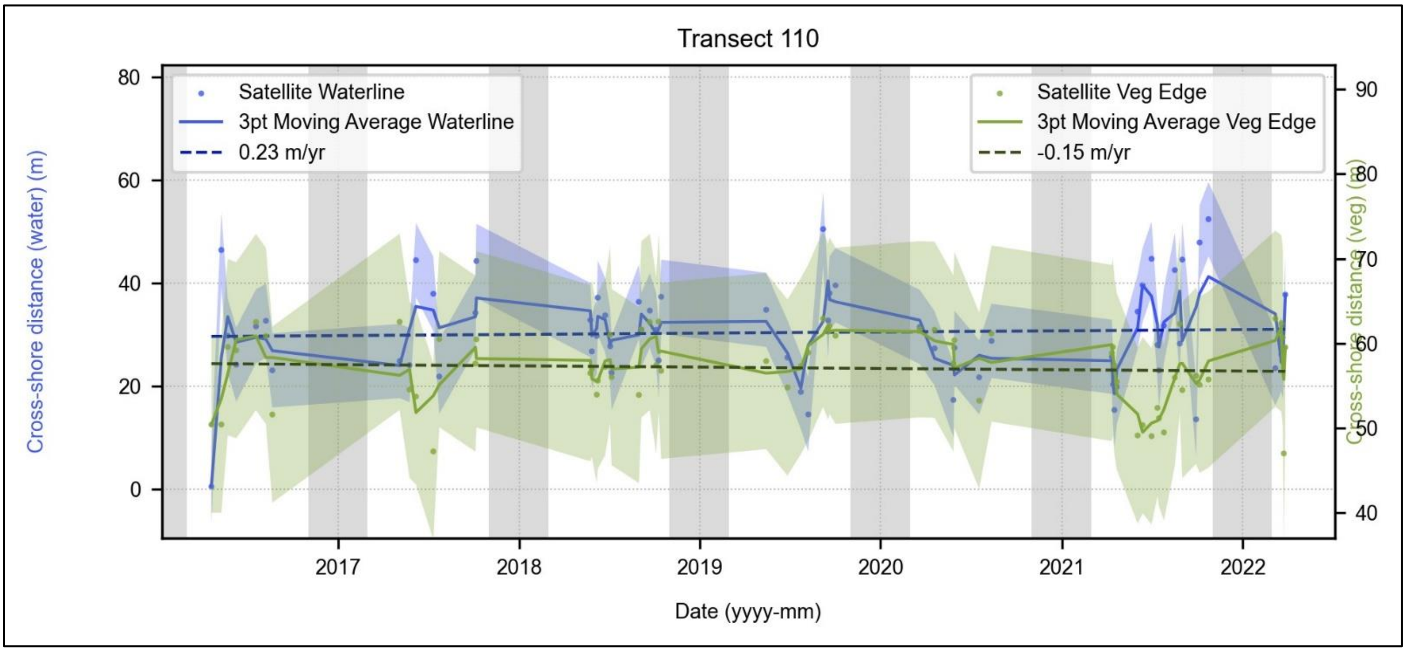

Figure 30: An example plot of a timeseries of MHWS and VE positions derived from satellite images (Sentinel-2), with regression line plotted and equation displayed to show average rate of change for both coastal change indicators. For reference Transect 153 is approximately adjacent to Beach Lane.

Volumetric Change Assessment & vertical uncertainty

The key feature of the Geomorphic Change Detection methodology (Wheaton, et al., 2010) is determining "real change" as opposed to any change attributable to the inherent uncertainty in each of the surveys used. As such, surveys with detailed survey quality reporting (and surveys of sufficient quality) are therefore essential when undertaking this analysis.

Along with Ground Control Points (GCPs) that were measured during the University of Glasgow topographic surveys and other documented accuracies, a careful assessment of elevation accuracy checks has been undertaken using areas immediately landward of the beach that would be expected to have minimal to no real elevation change between each survey (MacDonell, 2020). Sample points spaced 1 metre apart (n = 3,938 points; hard surfaces = 1,910 points, grass = 2,028 points) were established and values from the raw GCD result (simple raster differencing, without any uncertainty masking) extracted at these points. Table 6 shows the results of data quality assurance tests for the data that was analysed and presented. Differences in elevation at locations that should not have experienced any significant topographic change (hard surfaces & short grass) are on average less than 3 cm, which are of an acceptable standard.

Table 6: Data quality checks of Geomorphic Change Detection analysis in areas of expected minimal/no change (hard surfaces & short grass).

GCD analysis	Surface Type	Mean (m)	Median (m)	Std. Dev. (m)
Long-term (2018 – 2023, exc. Storm Babet)	**Hard**	-0.029	-0.033	0.181
	Grass	-0.006	-0.014	0.112
	Both surface types	*-0.017*	*-0.023*	*0.150*
Storm Babet (October 2023)	**Hard**	-0.011	-0.013	0.224
	Grass	0.012	-0.011	0.158
	Both surface types	*0.000*	*-0.012*	*0.193*

Horizontal uncertainty assessment

Given these surveys have also been used for establishing MHWS positions it would be pertinent to understand what an uncertainty in elevation would be propagated like in the horizontal, assuming an average beach slope for Musselburgh of 0.1 (1 m in every 10 m). Based on the result of the GCP checks on the two University of Glasgow topographic surveys, a vertical uncertainty of the magnitude seen in them (3cm) would yield a horizontal uncertainty of ± 30 cm. However, this also needs to be considered alongside the inherent uncertainty in the horizontal position as well, which is usually slightly smaller than the corresponding vertical value. In the case of the two University of Glasgow topographic surveys this was around 2 cm. Therefore, to visualise this, a given MHWS line (at 2.66 mOD) would have a 2 cm buffer around it, plus an additional 30 cm buffer around the initial buffer. MHWS could statistically be located anywhere with this overall uncertainty buffer zone. It is also worth remembering that this will vary for each survey (as a snapshot in time, and with varying uncertainties even for the same data collection/processing methodologies), and also vary spatially with respect to differences in beach slope (i.e. as the beach steepens uncertainty related to vertical changes reduces).

Task 2: Methods for modelling future shoreline change scenarios

Approach

The updates shoreline datasets were further processed using the Dynamic Coast's Coastal Mapping Tools (CMT) (Hurst, et al., 2021) to explore possible future coastal changes.

Future coastal change is predicted based on historic observations of coastal change, which have been updated according to Task 1: Historic Coastal Change Assessment. Observations of the position of MHWS from recent surveys inform the historic perspective with rates of change in MHWS extrapolated forward in time and modified based on the expected effects of sea level change. Historic shoreline change varies through time, and is dependent on the timescale of observation, with storm related erosion (e.g. during Storm Babet) and post-storm recovery of the beach superimposed on the longer-term multi-annual trajectory of change. In order to make prediction at decadal timescales into the future, the most recent rates of observed change available that spanned a time period of at least four years were used. Thus, the period 2018-2023 based on recent beach surveys was used as the calibration period from which future shoreline change is extrapolated. Superimposed on these rates, the effects of sea level change are accounted for following a modified Bruun Rule approach (Bruun, 1954; Rosati et al., 2013; Vousdoukas et al., 2020; Hurst et al., 2021). This approach assumes that the influence of sea level rise will be that beach geometry will be translated landward through time at a rate that is proportional to the product of the rate of sea level rise and the gradient of the shoreface. The effect of sea level rise is in addition to the ongoing historic trajectory of shoreline change due to gains and losses of sediment. This approach has been deployed globally (Vousdoukas, et al., 2020) and applied by Dynamic Coast in Scotland, with some key limitations mitigated (Hurst, et al., 2021).

Of particular note for Musselburgh is that where the hinterland topography is very low gradient, it is the gradient of the hinterland that is expected to control the response to sea level rise (Wolinsky and Murray, 2009), and as such Musselburgh is a site that is particularly sensitive to the expected effects of sea level rise due to its low-lying nature. Furthermore, much of the Musselburgh beach is backed by coastal defences, where the amount of erosion that can be forecast is limited to 25 m landward of these defences. This somewhat arbitrary 25 m buffer exists to acknowledge that failure of the defences would result in erosion impacts landward of their current position, but any impacts on defences is unlikely to be linear.

Future climate scenarios

The future sea level rise scenarios considered here are identical to those considered by Dynamic Coast 2 (Rennie, et al., 2021). Three representative concentration pathways (RCP) have been considered, referring to anticipated concentrations of greenhouse gas concentration in the atmosphere, aligned with the UK Climate Projections 2018 provided by the Met Office (UKCP18) (see Figure 1). RCP 2.5 represents a scenario in which Net Zero greenhouse gas emissions were to be achieved globally, instantaneously, and is thus considered a best case (but unlikely scenario). RCP 8.5 is the worst-case future climate scenario but remains our current global trajectory (Schwalm, et al., 2020), and thus the 95th percentile has been used as the most precautionary approach.

Best- and worst-case erosion scenarios

Further to exploring a range of future climate scenarios that cover best- and worst-case, the most benign and maligned rates of coastal change from the 21st century survey observations of MHWS position (considered most accurate and reliable) have been superimposed to explore best- and worst-case scenarios relating to the variability in observed shoreline change (e.g. Figure 15).

Task 3: Methods for assessing coastal change adaptation options

Given that the Coastal Change Adaptation Guidance provides important policy context for the assessment of coastal change adaptation options, details of the required approach have been provided in the main text.