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Dynamic Coast

Future Coastal Change

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Future Coastal Erosion

M.D. Hurst, F.M.E Muir, A.F. Rennie & J.D. Hansom

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The cover image shows: (Top) Storm waves reflecting and undermining artificial defences at Golspie, Highland. Copyright: A. MacDonald (2020). (Bottom left) coastal erosion of the beach crest adjacent to the World Heritage Site at Skara Brae, Bay of Skaill in Orkney. Copyright: A Rennie / NatureScot (2019). (Bottom right) an oblique aerial image of the Splash play park at Montrose looking north. In the 1980s the play park was set-back within the dune, due to the subsequent coastal erosion, now it is in a more exposed position relying on artificial coastal defences. Copyright: F. McCaw (2021).

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WS2 Future Coastal Change (Technical Annex)

Context

The 2012 UK Climate Change Committee Risk Assessment (Scotland) identified a series of evidence gaps for assessing the impacts of future climate change on the coast and its assets: 'maps of past erosion, current state and future erosion conditions are required' as well as an appreciation of 'Major coastal flood/reconfiguration (including coastal erosion)'. The Dynamic Coast project published the first national assessment in 2017 (Hansom et. al., 2017) which analysed the changes in Mean High Water Spring (MHWS) between the 1890s, 1970s and modern shorelines, as depicted by the most recent national data from detailed Ordnance Survey mapping, updated by aerial photography and LiDAR where available. Where significant, the established modern rates of change were extrapolated landwards to identify assets at risk by 2050 and 2100 under these same current erosion rates. This initial assessment of the future path of coastal erosion deliberately assumed that the present shoreline retreat rates (1970s to modern) would continue unchanged for the remainder of the century. Published prior to the availability of the UKCP18 climate projections (UKCP18) (with its anticipated quickening of relative sea level rise (RSLR)), the 2017 extrapolated MHWS results were acknowledged to underestimate the likely extent and complexities of shoreline retreat. Addressing such a limitation is a key aim of this second phase of Dynamic Coast research; to incorporate the effects of projected RSLR from the UKCP18 climate projections (UKCP18) on any anticipated future erosion rates. Several scenarios of future RSLR provided by UKCP18 were tested, referred to as representative concentration pathways (RCP) in accordance with the Intergovernmental Panel on Climate Change (IPCC) pathways for greenhouse gas concentrations in Earth's atmosphere (IPCC, 2014). Future predictions of shoreline change on the Scottish coast have been made for RCP2.6, 4.5 and 8.5 (Figure 1). Globally, greenhouse gas emissions are currently tracking to the most extreme RCP8.5 emissions scenario (Schwalm et al., 2020).

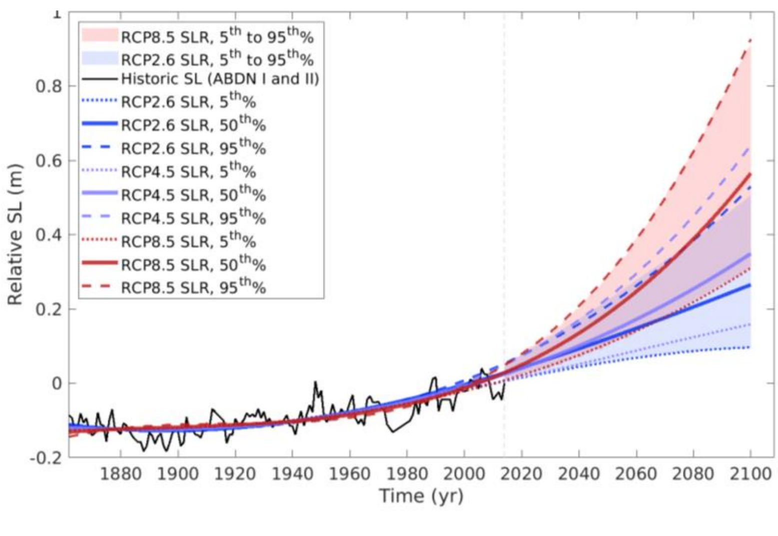


Figure 1 Relative sea level rise scenarios from UKCP18 under three representative concentration pathways used during the project, projected forward to 2100 for the representative site of Aberdeen (with Permanent Service for Mean Sea Level record plotted in black).

Methods

Rising sea levels increase the elevation of waterlines, moving them landward on sloped coastlines. These changes allow waves, which provide the energy to mobilise sediment and drive erosion, to reach further inshore before their energy is dissipated. Thus, shoreline retreat is expected to be exacerbated by RSLR. We project future shoreline change using a modified Bruun Rule approach that is trained by analysis of past shoreline change, and accounts for projections of future RSLR. The Bruun Rule (Bruun, 1954) predicts shoreline response to RSLR, for soft (sandy beach) shorelines. The model assumes that the nearshore topography maintains a constant elevation profile that is raised and translated landward through time (Figure 2). Material eroded from the nearshore is assumed to be transported offshore to the lower profile to maintain the form of the elevation profile. The change in shoreline position over some time period is proportional to the rate of change in relative sea level, and inversely proportional to the average gradient of the shoreface.

There is empirical support for the application of the Bruun Rule to observed coastal change under conditions of known sea level rise (Zhang et al., 2004), particularly where other sediment transport processes that result in a long-term surplus or deficit of coastal sediment (relative to the predictions of the Bruun Rule) are of negligible importance or can be otherwise accounted for (Passeri et al., 2014). Several modifications to the Bruun Rule have attempted to account for these additional sources, sinks and fluxes of sediment (Rosati et al., 2013; Dean and Houston, 2016). In the absence of sediment budgets, or quantified fluxes, these can be grouped into an unknown volumetric flux term (Vousdoukas et al., 2020) representing the magnitude of the sediment gains or losses. However, where historical shoreline position changes and relative sea level changes are known, the volumetric deficit or surplus can be estimated from observed shoreline changes. This effectively identifies and quantifies the net effect of volumetric sediment fluxes that are not explicitly accounted for by the Bruun Rule, such as due to gradients in alongshore sediment transport. Under the assumption that areas of surplus sedimentary fluxes will continue to receive similar surplus (e.g. near to river mouths where sediment is delivered to the coast), or areas of deficit will continue to lose sediment (e.g. areas particularly affected by aeolian losses), future projections of sea level rise can then be used to produce estimates of future shoreline positions according to this modified Bruun Rule (Dean and Houston, 2016; Vousoukas et al., 2020).

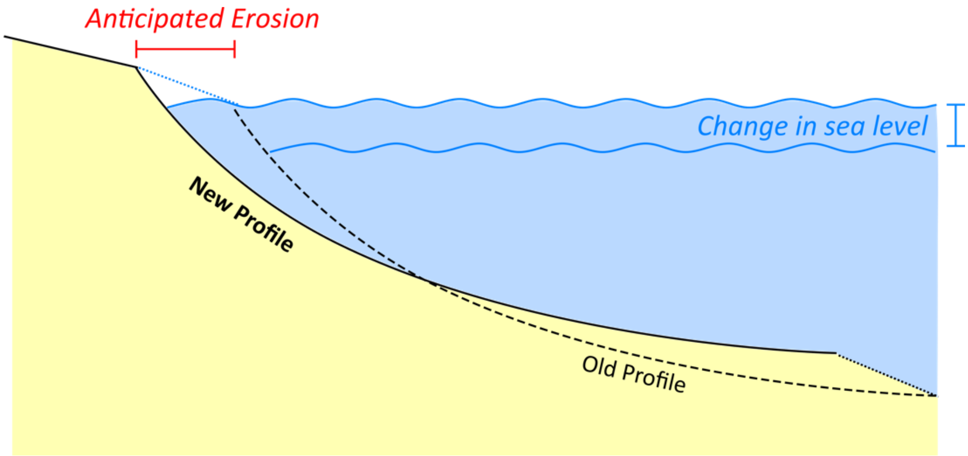


Figure 2 Schematic diagram showing the expected shoreline response to a change in relative sea level according to the Bruun Rule method deployed here. Anticipated erosion results from landward shore profile migration with relative sea level rise.

Such an approach has been applied widely and was recently implemented in a global scale analysis of shoreline change (Vousdoukas et al., 2020). However, the modified Bruun Rule suffers some acknowledged limitations (Cooper et al., 2020) that we have sought to mitigate in our analysis. Firstly, it is implicit that the hinterland topography is readily erodible (i.e. there is accommodation space for the beach to retreat into); we limit the extent of shoreline retreat into erodible material using an underlying physical susceptibility model (the UPSM of Fitton et al., 2017; which limits erosion when bedrock is encountered) and we halt retreat where artificial coastal defences (also mapped during the project) are encountered. Secondly, where hinterland topography is low-lying the magnitude of shoreline change is expected to scale to the average gradient of the inland topography, rather than the shoreface, when considering RSLR (Wolinsky and Murray, 2009). We sample the OSTerrain5 (Ordnance Survey, 2021) topographic dataset immediately inland from the coast to allow RSLR to be proportional to the lowest mean gradient out of either the foreshore or the hinterland. Thirdly, it is important to note that shoreline retreat does not necessarily imply that beaches themselves will be lost to erosion, but rather that they may migrate landward through time. Despite the known shortcomings in the Bruun Rule approach, and in the absence of an internationally accepted alternative, the modifications used here are an appropriate first-order method to provide indicative predictions of decadal shoreline change across regional/national space scales.

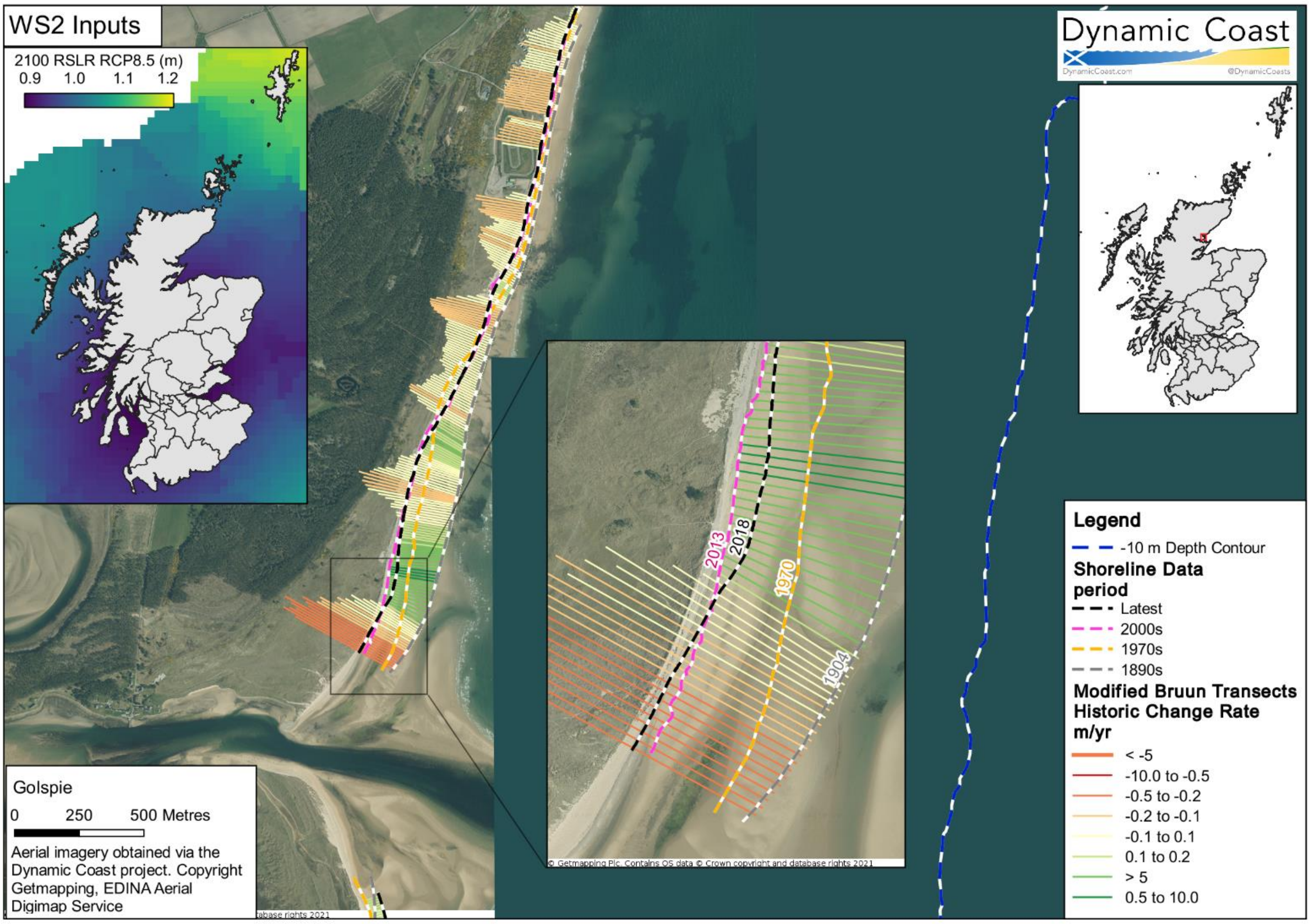


Figure 3 Input datasets used in the modified Bruun Rule calculations around the soft coast of Scotland. Calculations are mode on shore normal transects, coloured according to the magnitude of historic shoreline change. Inset maps show the location of the example site presented here (top left), and the national datasets of historic RSLR (left) and UKCP18 future RSLR at 2100 under the RCP8.5 scenario (right).

Dynamic Coast Phase 2 has applied this modified Bruun Rule approach to all areas of soft coast around Scotland. Shore-normal transects were built from a smoothed modern shoreline to intersect with mapped MHWS shoreline positions derived from historical and modern OS maps, and coastal LiDAR topographic datasets (Scottish Remote Sensing Portal) (Figure 3). The average shoreface slope was calculated using the distance from the -10 m depth contour to the modern MHWS position on the open coast and, on sections of inner coast where bathymetric contours do not reach -10 m, the horizontal and vertical differences between MHWS and Mean Low Water Springs (MLWS) were used. The unknown volumetric sediment flux term was estimated from the most recent shoreline position change with a time difference greater than 5 years (most recent mapped shoreline position minus the penultimate shoreline position that was >5 years younger) together with the historical RSLR rates derived from the glacio-isostatic adjustment model of Bradley et al., 2011 (Figure 3).

Future scenarios of RSLR based on UKCP18 projections for the coast of Scotland were used within our calibrated, modified Bruun Rule to predict future shoreline positions. We modelled three scenarios of relative sea level rise based on the UKCP18 RCP8.5 (95th percentile) scenario (often referred to as 'high emissions' or a 4.3°C global temperature rise by 2100), the RCP4.5 (50^{th} percentile) ('intermediate emissions' or a 2.4°C global temperature rise by 2100) scenario and the RCP2.6 scenario ('low emissions' or a 1.6°C global warming by 2100) (Figure 1). The 'high emissions' RCP8.5 scenario seems to define the current global climate trajectory (Schwalm et al., 2020). Future shoreline retreat was only allowed to project landward of soft coasts where land was identified as 'erodible' (as depicted within the Underlying Physical Susceptibility Model (UPSM), (Fitton et al., 2017). Where land is not thought to be erodible, shoreline retreat is allowed to occur up to an arbitrary maximum distance of 25 m in order to indicate a propensity for erosion. Similarly, where coastal defences are known to occur, different management scenarios can be explored. For example, a cautious approach assumes that artificial (and natural) defences are unmaintained and coastal erosion extends landward of the defences. An optimistic approach assumes that shorelines can retreat up to, but not beyond, artificial coastal defence positions. It is acknowledged that for the purposes of a national-scale assessment of shoreline change, these simplifications of complex situations are designed to give a reasonable indication of where and by how much these types of shorelines may change.

Where soft shorelines are comprised of saltmarsh the approach outlined above is problematic, since the modified Bruun method used here is based on wave processes impacting unconsolidated material such as beach sand. Whilst salt marshes are certainly influenced by waves, their morphological development is principally driven by tidal dominated processes acting on consolidated silts and muds. Because of this, using the MHWS position as a simple 'shoreline delimiter' may not be representative, and the seaward vegetation edge of the marsh may provide a more recognisable and robust position as recorded by ground survey and plotted on maps. In addition, where sedimentation rates remain high, salt marshes can keep pace with sea level rise (e.g. Kirwan et al., 2016 & Teasdale et al., 2011) and so two-dimensional approaches are likely to over-simplify complex three-dimensional changes in the saltmarsh surface. Where detailed time-series LiDAR (or equivalent) surveys are available, they provide data that is better suited to inform recent saltmarsh changes, and any potential future adjustments with rising sea level.

Figure 4 Example of shoreline changes anticipated up to 2100 under RCP 8.5 95th percentile scenario according the modified Bruun rule. Limits are placed on the amount of shore retreat that could occur due to its underlying physical susceptibility to erosion, such as encountering outcropping bedrock.

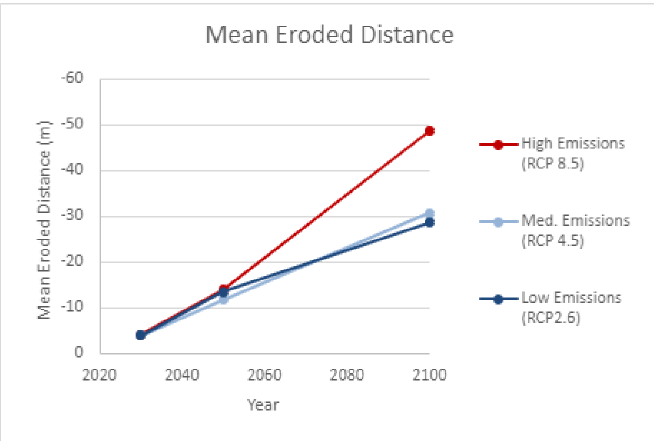
The approach outlined here reflects both methodological and input data improvements over Dynamic Coast in 2017 (Hansom et al., 2017). For example, since 2017, and as a direct result of Dynamic Coast, OS have undertaken a widescale update of MHWS tidelines in Scotland, expanding this to the rest of the UK. They also have improved the attribution associated with each tide line segment to better reflect the actual survey date that is entered into the OS data archive. The Scottish Government's Phases 1-4 LiDAR has also been incorporated together with additional updates from the OS and other Dynamic Coast partners.

The implications of the projected future erosion are assessed using a similar approach to the 2017 Future Look assessment, namely that the areas between the current MHWS and the 2050 and 2100 projected MHWS lines are filled to create 'eroded area' features which then intersect against mapped assets (roads & buildings), along with a 10 m 'erosion influence' buffer and a further 50 m 'erosion vicinity' buffer around the eroded areas. More detailed timing of erosion intersection with mapped assets are provided by decadal steps in the anticipated movements of MHWS lines between 2020 and 2100.

For the avoidance of doubt, the approach adopted here aims to provide first order constraints on future shoreline retreat rates in areas of soft coast around the Scottish coast, calibrated by historical shoreline change rate. To be applicable at national scale, the approach is necessarily generalised and simple; any more detailed analysis requires detailed site-specific information much of which is unavailable at a national level. However, our first order estimates of retreat are broadly supported by the application of a more rigorous process-based numerical model (Vitousek et al., 2017) at selected coastal sites around Scotland. The Vitousek numerical model CoSMoS-COAST was used in four (Super Site) locations to simulate coastal evolution under the same UKCP18 climate change scenarios used with the modified Bruun Rule approach, but additionally and explicitly considering wave-driven alongshore and cross-shore sediment transport processes, as well as long-term shoreline migration driven by RSLR (which otherwise follows a Bruun rule approach). CoSMoS-COAST is forced using local records of relative sea level change and wave hindcast data, with past simulation of shoreline position starting at 1900 and matched to known historic positions of MHWS observations (sourced from Dynamic Coast Phases 1 and 2). Shoreline position is therefore modelled into the future by CoSMoS-COAST with a level of complexity missing from the modified Bruun Rule approach. This Super Site site-focused and limited validation process produces results that are broadly in tune with the modified Bruun approach and delivers outputs of anticipated shoreline change through to 2100.

Indicative Results

Based on the latest survey data for those areas investigated (the majority of the soft coast, with the exception of salt marsh shores) 46% of the soft coast is currently experiencing coastal erosion. This compares with the earlier results, resampled from Dynamic Coast (2017) where an average of 38% was estimated to be erosional. The present rate of erosion and anticipated changes under different emissions scenarios is explored within Figure 5. Nationally, under a Low Emission Scenario the proportion of eroding shores rises from 46% in 2020 to 57% by 2030, 58% by 2050 and falls to 56% by 2100. The late-century slight-fall reflects that on a proportion of shores, erosion is curtailed by the shore encountering bedrock as it transits landward. Under a Medium Emissions Scenario the proportion of shoreline increases then settles above 60% as bedrock is met. Under a High Emissions Scenario the percentage of shorelines expected to be erosional rises from 46% in 2020, to 63% in 2030, 73% by 2050 and 84% by 2100. Figure 6 explores the average anticipated amount of erosion since 2020. There is little difference in the average distance eroded between the Emission Scenarios up to 2050; although more shorelines are affected under the Medium and High Emissions Scenarios (initially with low rates of erosion), which results in a lower average eroded distance than the Low Emissions scenario. Towards the end of the century the average eroded distances increase to an average of 48m lost under the High Emissions Scenario with the Medium and Low Emissions Scenarios producing averages of 30 & 29m of erosion, respectively).



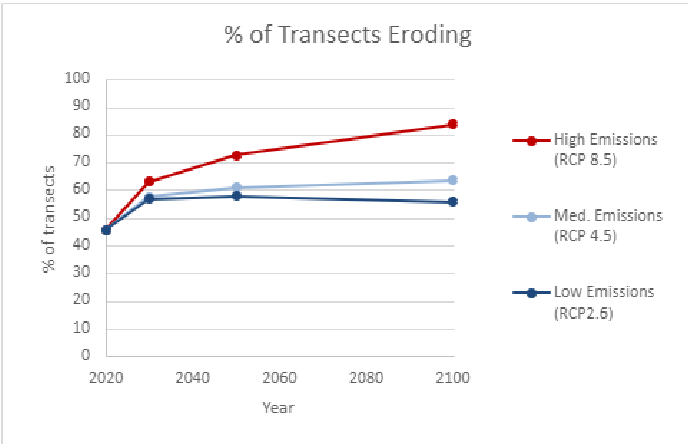


Figure 5 shows the percentage of transects which are erosional, presently (2020) and in the future under differing climate emissions scenarios.

Figure 6 The mean eroded distance by year, under differing climate emissions scenarios. (* measured from the anticipated 2020 shoreline)*

Figure 7 shows indicative outputs for the modified Bruun Rule shoreline change in the form of transects, future MHWS lines, and erosion polygons. The pop-up box refers to the different measurements (stored on each transect) of past MHWS change and future distances and rates of change, projected using these past trends as well as the sea level rise projected for that particular area. Each transect holds this granularity of information so that the modified Bruun calculation can be performed to give a distance that the MHWS may retreat cross-shore along that transect axis.

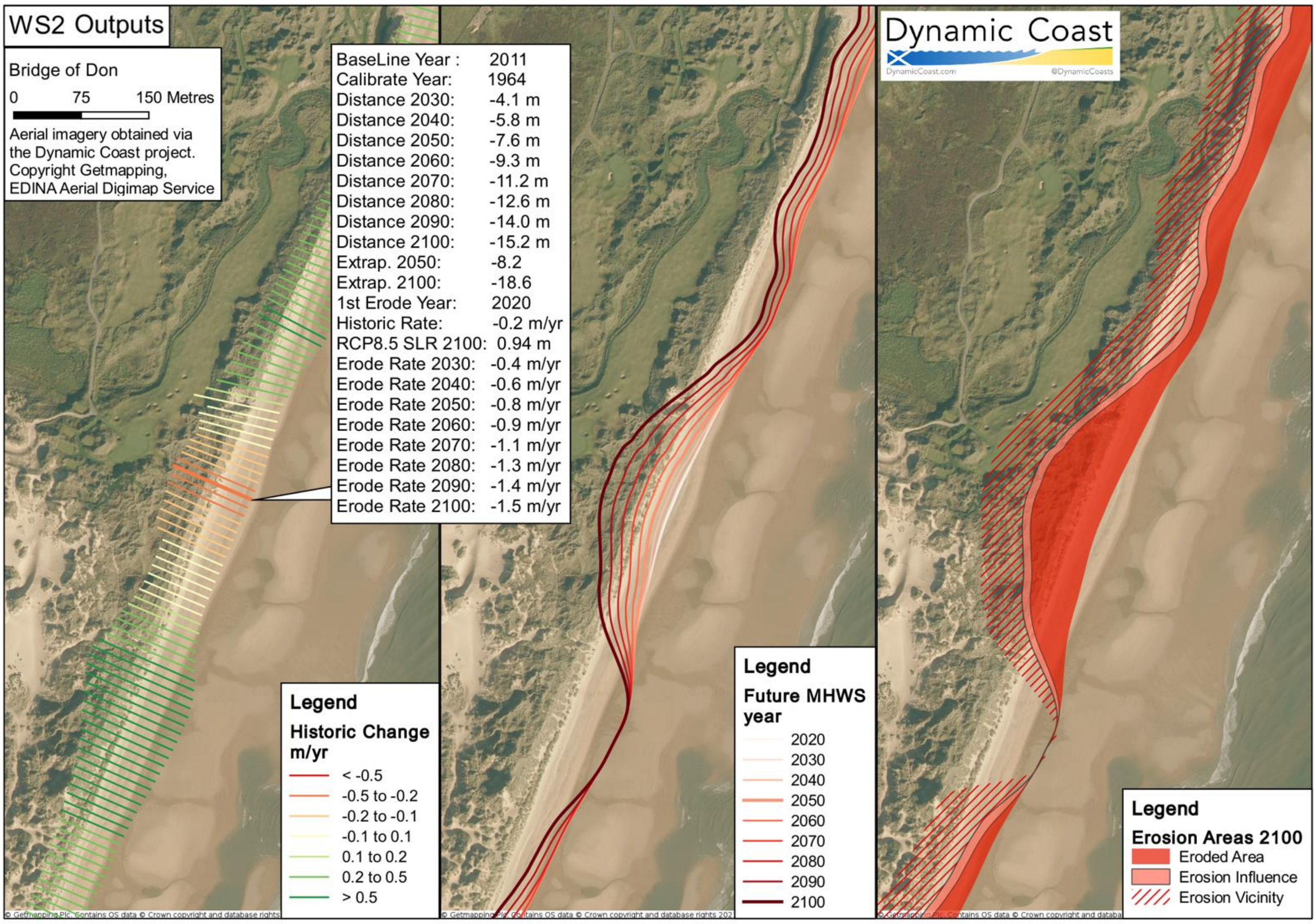


Figure 7 Outputs produced for the modified Bruun Rule MHWS change. The first panel shows transects at regular 10m spacing perpendicular to the coast, intersected with historic shorelines and used as the axis on which to shift the MHWS back by the Bruun-calculated amount. The second panel shows the future MHWS lines at decadal intervals. The third panel shows the erosion polygons for 2100, extracted from the filled area between the 2020 and 2100 MHWS lines, and buffered landward with an additional 10 m (Erosion Influence) and 50 m (Erosion Vicinity).

The eroded areas, as mentioned, allow for investigation into the implications of the MHWS retreats; these polygons are used in an asset intersection exercise which extracts statistics of counts, lengths and areas as well as number of features of different national assets. The full results of this asset intersection can be found in the National Overview report, but for illustrative purposes Figure 8 shows some of these assets and how they are intersected and counted to give a greater understanding of the extent and types of erosion risk to Scotland's assets and communities.

NB: It should be noted that the above models of anticipated change are based on shoreline data which is unable to reflect small-scale local level changes. For this reason, the Dynamic Coast outputs should not be used for assessment at the property level.

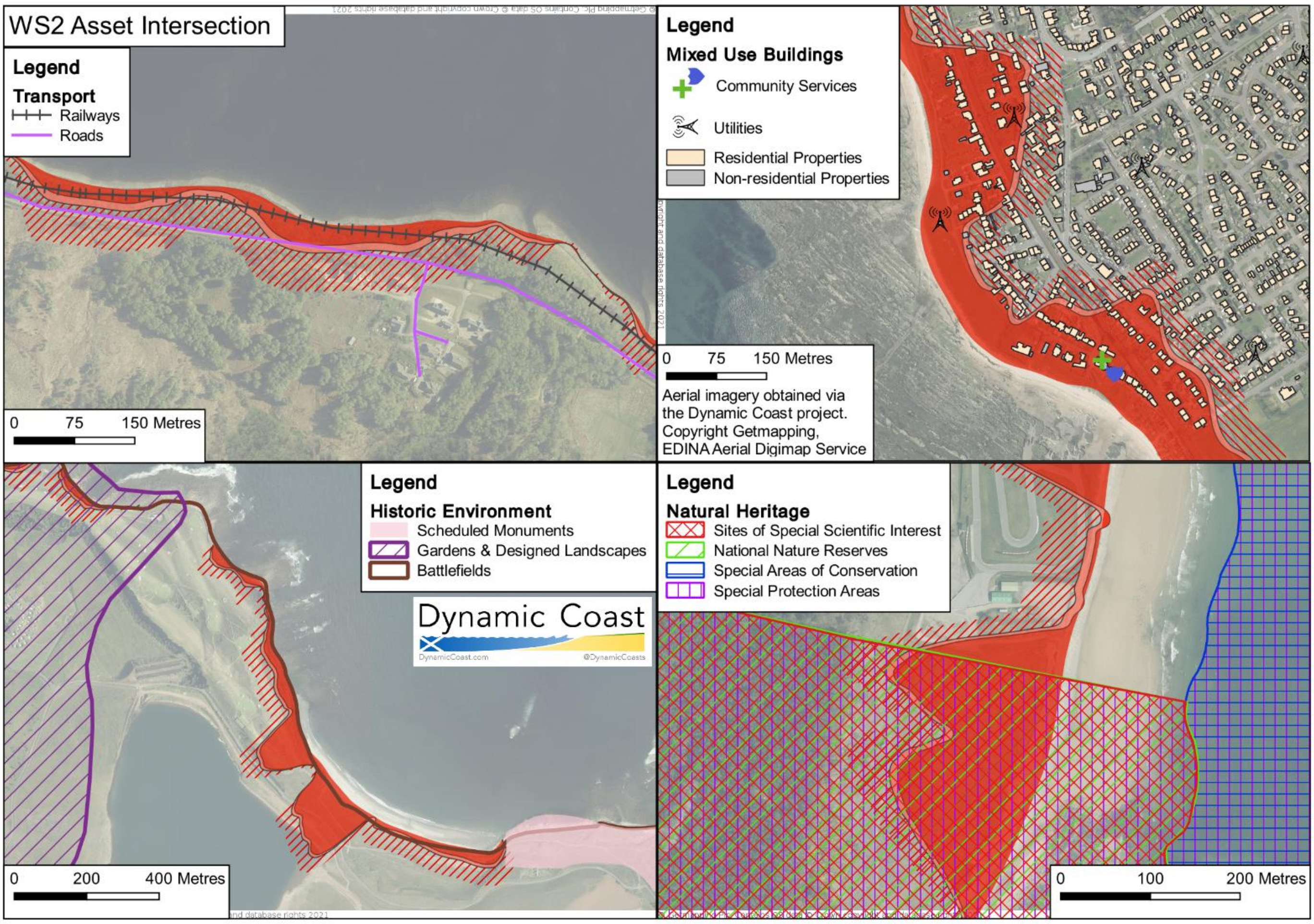


Figure 8 Example collections of assets used to intersect with the erosion areas of WS2, to quantify the impact of erosion on different sectors and land uses (e.g. transport, mixed use buildings, and natural and cultural heritage).

See the link below for an interactive web-map of the results. The data index also provides a guide to the published data, including plain English explanation of the data and the individual layers.

Interactive map	Data Index
www.dynamiccoast.com/webmaps.html	http://www.dynamiccoast.com/downloads.html

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