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Dynamic Coast

Adaptation and Resilience Options at the Bay of Skaill

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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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Purpose and Status of this Report

This report reflects on-going discussions between the Dynamic Coast team (DC), Historic Environment Scotland (HES), Orkney Islands Council (OIC) and partners. Its purpose is to collate our evidence and ensure partners are briefed on key aspects.

Structure of Report

This report has been structured to be practitioner focused. It leads with an executive summary and proposed Resilience and Adaptation Options, followed by contextual information and methods within a technical summary, finishing with key results. The report is expected to be viewed alongside online resources via www.DynamicCoast.com.

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Executive Summary

1. The Bay of Skaill is world famous as the location of Skara Brae, the Neolithic Village which is within the Heart of Neolithic Orkney World Heritage Site. Coastal erosion is known to have occurred over millennia in Orkney, indeed the discovery of Skara Brae itself was an outcome of coastal erosion. The current research shows that erosion continues to threaten the site and is set to increase in extent and rate over the coming decades with climate change.
2. Whilst direct coastal flooding is not anticipated to be a major concern, wave-thrown debris and wave spray is currently an issue and is expected to increase in the years to come.
3. The artificial concrete defences at Skara Brae have served to protect much of the archaeological interest of the site over the last 80 years, although current foreshore lowering in front of the site has led to undermining of the toe of the concrete defences, this contributing to cracking of its facia and blow-holes developing on the seaward face, together with flanking erosion at either end of the defences. The erosion risk remains and is set to worsen with climate change.
4. Much of the remainder of the bay is natural (undefended) and beach sediment is free to move along and across shore and in places to roll landwards. In the coming decades this is likely to impact on the adjacent farmland and built assets near the shore.
5. Given the juxtaposition of assets and the anticipated risks, a twin-track approach is proposed where erosion is accommodated through land-based adaptation for the much of the bay, and a combined approach of defence improvements and natural enhancements are deployed at Skara Brae.
6. Close working between landowners, local and national organisations is essential to safeguard internationally and locally important assets from the worsening impacts of climate change. As these approaches are developed, nature-based measures are recommended in strong preference to preferred over traditional engineering approaches, to buy time and plan for adaptation. This study also highlights the importance for adaptational approaches, including support for relocation, for infrastructure and buildings on increasingly mobile shores.

Bay of Skaill Supersite Summary

Introduction

This report sets out the information needed to identify Coastal Resilience and Adaptation Options for the Bay of Skaill (Orkney) and reflects the shared view of Dynamic Coast, Historic Environment Scotland (HES), and Orkney Islands Council (OIC). Its scope covers the area between the rocky headlands bounding the Bay of Skaill and aims to support key partners in their planning for anticipated increases in the threats of coastal erosion and flooding. This report, including the Executive Summary and Technical Annex Summary are not precise predictions of a certain future, rather they are scenarios based on a realistic and precautionary interpretation of available evidence. As such the details within should not be interpreted as management decisions in themselves, but supplementary evidence on which organisations and landowners may choose to act on now and in the future. The information here allows government agencies to improve coastal erosion risk framing within policy and practice, allowing more coastal erosion resilient decisions to be taken and deliver their statutory requirements. Businesses and communities may use this report to identify risks and opportunities to improve continuity.

National Coastal Context

The 2017 Dynamic Coast project published a review of historic, recent and modern maps across Scotland's entire erodible coast (DynamicCoast.com). It showed that the period since the 1970s has seen a 22% fall in the extent of Scotland's shores accreting seawards, a 39% increase in the extent of shores eroding landwards, and a doubling of the average erosion rate to 1 m/yr. This coastal response is consistent with climate change and is expected to quicken as sea levels continue to rise.

The latest research (Dynamic Coast phase 2) incorporates new tidal surveys and shows that erosion is currently affecting more shores than was the case in 2017 and anticipates that by 2100 accretion will be rare and erosion will dominate much of the soft coast. These projections are based on the high emissions sea level rise scenario[1] and anticipate over 1/3 of Scotland's soft coast will be eroding at greater than 1m/yr by the end of the century. The increased threat of coastal erosion also increases the risk of coastal flooding, so that planning ahead for coastal change, both inland and at the shoreline, is both pragmatic and necessary. For Further details see National Overview and Technical Annexes for Work Stream 2 and 2RA (www.DynamicCoast.com/reports).

Local Coastal Context and Anticipated Change at Bay of Skaill

The Bay of Skaill is world famous for its Neolithic village Skara Brae but the archaeological sensitivity of the area extends well beyond the site as excavated and presented to the public, with the area scheduled (SM90276) under the Ancient Monuments and Archaeological Areas Act 1979 extending to Skaill House and Skaill Home Farm to the south and west and down to MHWS to the north and north-west of the Property in Care. In addition, there is a scheduled broch on the north side of the bay (SM1475) and several unscheduled prehistoric burial mounds to the

[1] Calculated change to Mean High Water Springs, based on UKCP18 RCP8.5 (High Emissions Scenario) 95% sea level rise (the 'up to' figure).

east of Mill Croft. The area has been subject to extensive archaeological geophysical survey. Recent finds include the discovery of a cist burial at Skaill Farm, excavated under the HES human remains call-off contract, and a wall and eroding archaeological material at the north end of the Bay, now being monitored by the Archaeology Institute, University of the Highlands and Islands. The current state of knowledge is that Skara Brae was abandoned 4,500 years ago due to large-scale coastal changes and was re-exposed by coastal erosion in a storm in 1850. Pre-industrial sea levels slow rate here, though latest projections expect Orkney to experience some of the quickest sea level rises in Scotland, with levels expected to be up to 1 m higher by 2100[2]. As a result, although past erosion has been modest, erosion is expected to expand to affect more areas and to accelerate over the coming decades.

Historic Environment Scotland are leaders in climate change research and adaptation in the historic environment and have commissioned research into the exposure of Skara Brae. The Heart of Neolithic Orkney World Heritage Site Management Plan 2014-19 (new management plan in preparation) Climate Vulnerability Index and HES risk assessment reports acknowledge the current and anticipated risks to the site and its surrounding archaeology rich areas. Given the genuinely complex, multi-phased development and void spaces within the Neolithic structures, and the extent of unexcavated archaeological deposits, relocation (or perhaps better termed reconstruction) may well prove unrealistic and unattractive. The steady and near complete loss of the Mill, adjacent to Skara Brae, serves as a stark reminder of the high energy storm beach at Skaill.

A valuable evidence base comprising detailed partial and complete bay terrestrial laser scanning (TLS) surveys in 2010, 2014, 2016 & 2018, was commissioned by HES. This data identifies considerable dynamism in the upper beach (around MHWS), with significant erosion around MHWS in 2010 (similar to 1890s position) and significant MHWS accretion noted in 2016 & 2018. The default national approach for Dynamic Coast's shoreline change modelling uses the latest MHWS survey and calibrates future erosion to 2100 using the recent changes between the latest and penultimate survey, for example a 2018 MHWS vs. 2010 (ensuring a >5year time gap). However, given the importance of the World Heritage Site, a more precautionary approach has been adopted within this report, whereby the latest survey (2018) is compared with the 1970s MHWS to average out any short-term fluctuations (presented in the Vegetation Edge and Elevation Change sections) in this report. An even more precautionary approach (worst case) of 2010 vs. 1970s has also been undertaken for the sake of completeness. Nevertheless, whilst MHWS has stabilised and advanced seawards in recent years, currently the base of the seawall is exposed by toe erosion and the vegetation edge is retreating. As such the Neolithic village behind the seawall remains at risk today, and any anticipated MHWS stability in the short-term does not necessarily provide reassurance to managers.

Dynamic Coast research anticipates the beach at Bay of Skaill to retreat between 4–7 m by 2050 and 15–29 m by 2100. However, due to the elevation of the dune interior, direct marine flooding is not expected to impact coastal buildings and infrastructure (despite wave-thrown debris becoming a growing issue). Given the importance of the site locally,

[2] Calculated change to Mean High Water Springs, based on UKCP18 RCP8.5 (High Emissions Scenario) 95% sea level rise (the 'up to' figure).

internationally, in cultural and economic terms, this sober assessment of future risks should assist in the implementation of resilience and adaptation actions within the bay.

Future Resilience and Adaptation Planning

The emerging consensus worldwide is that adapting to climate change sooner will greatly reduce societal risks and costs in the long run. Recent research on climate change adaptation at the coast shows that landward retreat of assets is likely to be required (in all but exceptional cases) to manage long-term risks from sea level rise, regardless of any coastal risk management options taken now (Haasnoot et al 2019). Where the need for coastal adaptation is increasingly urgent (globally and locally), more transformative solutions are needed. Whilst generic aspects of these concepts are explored within the National Overview Report, the following text explores management options at Bay of Skaill within an international context of best practice. To aid users of this report in adopting this approach to adaptation, Dynamic Coast has identified actions that can be taken now, that will provide both physical and policy windows to make space for any adaptation to be implemented. These are highlighted and defined and further explored in the National Overview Report and align with the Intergovernmental Panel on Climate Change (IPCC)'s 2019 report on coastal climate change.

As climate change quickens erosion and increases flood risk, our attention needs to shift from short-term engineering choices at the coast, to dynamic, adaptational land-management inland, to enhance social and economic resilience.

Coastal adaptation to climate change risks, including erosion risk, requires a re-think of the boundary between land and sea, where current land areas will either disappear (due to erosion) or change substantively, due to erosion-induced flooding. This may require transformation of existing communities, policy, planning and infrastructure systems now and over the coming decades (National Overview report www.dynamiccoast.com/reports.html). For example, in Scotland the emerging Clyde Marine Planning Policy provides an exemplar of best practice at the coast, in support of more transformative forms of adaptation that may be applicable to Bay of Skaill and elsewhere. Whilst adaptive and transformative approaches may not be routinely taken forward by local authorities, they will nevertheless be increasingly required across both urban and rural shores when available flood risk management options are ineffective, or where coastal change requires a more flexible approach (including land use changes, avoidance and relocation). Practical implementation mechanisms are also required along with strategic plans and policies, so that adaptation measures such as realigning key infrastructure such as roads are ready to be rolled out and implemented when erosion happens. Similarly, support may also be required to assist with private homeowners, who find themselves at risk. This approach would shift erosion management from reactive to proactive, and in doing so, optimise the long-term societal resilience to coastal climate change with the least social and economic costs.

Dynamic Coast provides the evidence base to assess current and future coastal erosion risks for local government to make risk-informed decisions and policy instruments. The generic coastal risk management and adaptation options can be accessed in the National Overview Report, but their application in the context of Bay of Skaill is listed in Table

1 below. These lie along a spectrum from **doing nothing or non-active intervention**; **accommodate erosion** by adapting development plans and relocating existing assets; **erosion resist** either using traditional engineering structures or nature-based solutions, such as beach feeding; and by **advancing the coast** seawards, perhaps using artificial offshore structures or large-scale beach feeding (e.g. mega nourishment schemes) (see National Overview Report for context). Table 1 outlines the past erosion rates observed at in the Bay of Skaill and identifies both areas at greatest risk and management and adaptation options. All risk management and adaptation responses require robust appraisal to allow organisations better management of coastal erosion risk and improve societal and ecosystem resilience.

Coastal erosion, flooding* and erosion-related flooding* (*mainly via wave and spray, rather than inundation) are considered as the key risks to be investigated at Bay of Skaill now and into the future. Landowners and local authorities have responsibility for, and powers to address, coastal erosion and flooding. Local authorities also have shared powers under the Flood Risk Management (Scotland) Act 2009 and the Climate Change (Scotland) Act 2009, including a statutory duty to report on climate change adaptation progress. Guidance on planning for coastal change can be found in SNH (2019, https://www.nature.scot/guidance-planning-ahead-coastal-change). Figure 2 and Table 1 sub-divide the bay into management units to identify coastal erosion risk and management approaches to a) improve resilience of natural and societal assets in the short-term and b) adaptation options to improve long-term resilience of Bay of Skaill to the same risks. Each management option will have differing impacts on sediment dynamics, beach function and the natural capital that beach-dune systems provide. Importantly, these responses to managing coastal erosion risks involve both the management of activities on land as well as at the coastal edge. Bay of Skaill has sections of traditional, hard engineering, erosion-resist structures that have required costly replacement or repair. At these points and elsewhere, resultant beach lowering and retreat has weakened the natural capital afforded by the beach and dunes (such as natural erosion protection); urgent action is required if this natural capital is to be restored.

This requires strategic development planning decisions to be taken *now*, to provide physical and policy space to accommodate future erosion by adaptation to minimise societal impact and cost.

It is important to note that many of the adaptation options presented in Table 1 and associated text require strategic planning decisions to be taken *now*, to provide the physical and policy space needed for the future. This includes providing space for relocation of assets to inland risk-free sites, but also space for accommodating beach inland of their present position. For example, if planning permission is granted now for assets or infrastructure on land that may be at erosion risk in the future, the opportunity for future landward adaptation to occur is constrained, becomes more expensive, or both. Land-based strategic plans that account for future risks are needed when planning today (e.g. Local Development Plans), to create and safeguard 'windows of opportunity' to accommodate erosion by adaptation with minimal societal impact and cost; concepts acknowledged within the National Planning Framework 4 and recently revised National Land Use Strategy.

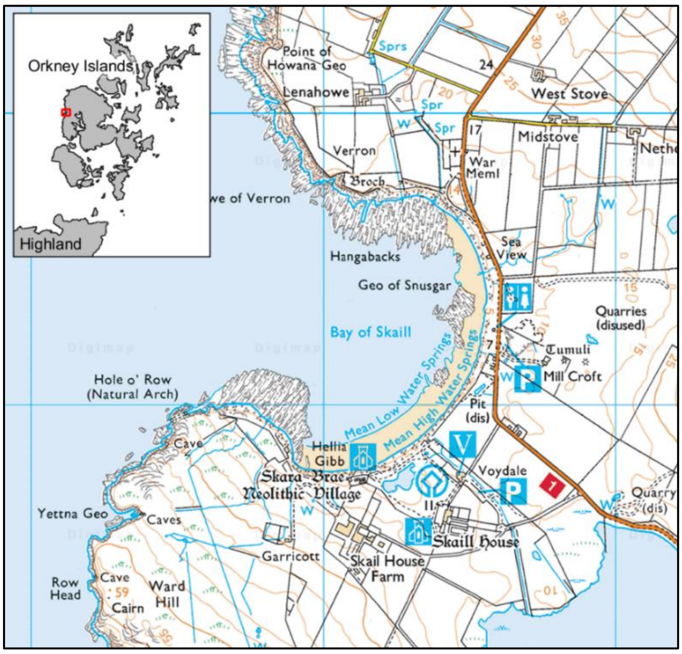

Figure 1 Location map of Bay of Skaill. Grid squares are Easting and Northing of size 1 km x 1 km. Crown copyright and database rights OS 2020 100017908.

Figure 2 Management unit areas for Resilience and Adaptation Options detailed in Table 1.

Resilience and Adaptation Options at Bay of Skaill

Table 1 outlines the management options along the coast which are recommended to be considered alongside dynamic adaptational land-use planning aspects inland.

Table 1 Risk management, Resilience and Adaptation Options for Bay of Skaill. Areas are grouped by management unit, past and anticipated changes alongside 'do nothing' implications. Short and Longer-term options are outlined.

Management Unit Area	Shore Character & Assets	Coastal Changes	'Do nothing' – Likely Implications	'Short Term' Management Options (to improve short-term resilience)	'Long Term' Management Options (to improve long-term resilience)
1. Northern Bay North headland to access road  Natural shore	Gravel upper beach Some areas of foreshore sand. Steep sand cliff. Access road Farmland Unknown and known archaeological remains?	<u>Low Water</u> 1972–2018: +17 m little change <u>High Water</u> 1890–1970: +20 m 1970–2018: -11 m <u>Volume</u> N/A <u>Vegetation Edge</u> 2008–2019: -3 m (-0.3 m/yr)	Access road expected to be undermined (<5 yrs). Continued gravel over-wash landward of beach. Loss of dune & unknown archaeological remains. Beach is 25 m from main road (B9056)	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** Natural sections of beach exposed. Cost: zero; Risk: moderate. **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted/excavated/relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Reroute field boundaries and roadway (0–20 yrs):** Road gives secondary access to church car park (may not justify defence cost). Substantial long-term capital and maintenance savings from re-routing road inland Cost: moderate; Risk: low. **<u>Erosion Resist:</u>** 1. **Reprofile beach: (0–10 yrs):** Short-term local repair to upper beach profile to improve natural resilience of beach. Cost: low; Risk: low 2. **Feed beach: (0–10 yrs):** Short-term local repair to whole beach profile improving natural resilience of the beach. Cost: low; Risk: low	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Natural sections of beach erode. Cost: zero; Risk: moderate **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Realign farm boundaries:** Agricultural land value unlikely to justify defence cost, boundary realignment would avoid future risks and associated maintenance costs. Cost: moderate; Risk: low 3. **Realign roadway:** Road alternative access to church carpark (may not justify defence cost). Long-term capital and maintenance savings from re-routing road inland. Cost: moderate; Risk: low **<u>Erosion Resist:</u>** 1. **Install defences for road:** Cost: high; Risk: high **<u>Advance:</u>** 1. **Mega nourishment (2050)** beach & dune reshaping would benefit the entire bay and reduce erosional risk. Cost: high; Risk: low
2. Northern Bay Junction of access road to beach path  Natural shore with sloped gabions at Seaview	Sandy beach, gravel upper beach Shallow dune ridge Seaview (house) Road (B5096) Farmland Unknown archaeological remains	<u>Low Water</u> 1972–2018: -7 m <u>High Water</u> 1890–1970: +11 m 1970–2018: +12 m <u>Volume</u> N/A <u>Vegetation Edge</u> 2008–2019: +3 m (+0.3 m/yr)	Continued gravel over-wash landward of beach Beach lowering adjacent to defences. Loss of farmland & unknown archaeological remains. Loss of dune. Road threatened by 2060	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** natural sections of beach exposed. Cost: zero; Risk: moderate **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Reroute field boundaries and roadway (0–20 yrs):** Road secondary access to church car park (may not justify defence cost). Long-term capital and maintenance savings from road re-routing. Cost: moderate; Risk: low. **<u>Erosion Resist:</u>** 1. **Defend (0–30 yrs):** Construct defences at road. Cost: moderate; Risk: high 2. **Reprofile beach: (0–10 yrs):** Short-term local repair to upper beach profile to improve natural resilience of beach. Cost: low; Risk: low 3. **Feed beach: (0–10 yrs):** Short-term local repair to whole beach profile improving natural resilience of the beach. Cost: low; Risk: low	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Natural sections of beach exposed. Cost: zero; Risk: moderate **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Realign farm boundaries and roadway:** Agricultural land value unlikely to justify defence cost; Road secondary access to church carpark (may not justify defence cost). Long-term capital and maintenance savings from road re-routing. Cost: moderate; Risk: low **<u>Erosion Resist:</u>** 1. **Defend Road:** Cost: high; Risk: high **<u>Advance:</u>** 2. **Mega nourishment (2050)** beach & dune reshaping would benefit the entire bay and reduce erosional risk. Cost: high; Risk: low
Management Unit Area	**Shore Character & Assets**	**Coastal Changes**	**'Do nothing' – Likely Implications**	**'Short Term' Management Options (to improve short-term resilience)**	**'Long Term' Management Options (to improve long-term resilience)**

3. Central bay Beach path to Mill  Natural shore	Sandy beach, gravel upper beach Low dune cliff, inland negative gradient Toilet block & parking, Skerravoe (house), farmland, unknown and known archaeological remains	Low Water 1972–2018: -23 m High Water 1890–1970: +15 m 1970–2018: +24 m Volume N/A Vegetation Edge 2008–2019: +5 m (toilets) -2 m (south)	Foreshore & beach lowering, gravel over-wash accelerating. Road threatened by 2050 Public toilets threatened by 2040 Skerravoe threatened by 2060	**Non-Active Intervention:** 1. **Monitor change/no intervention (now onwards):** Natural sections of beach exposed. Cost: zero; Risk: moderate **Accommodate Erosion:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. **Erosion Resist:** 1. **Defend (0–30 yrs):** Construct defences at house and road. Cost: moderate; Risk: high 2. **Re-profile beach (0–20 yrs):** Short-term local repair to upper beach profile to improve natural resilience of beach to Toilet Block & house Cost: low; Risk: low 3. **Feed beach (0–20 yrs):** Offers short-term local repair to eroded beach profile, improving the natural resilience of the beach adjacent to Toilet Block & Skerravoe. Cost: low; Risk: low	**In addition to continued deployment of short term options:** **Non-Active Intervention:** 1. **Monitor change/no intervention:** Natural sections of beach exposed. Cost: zero; Risk: moderate **Accommodate Erosion:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Relocate (2050):** Public Toilets & car park, Identify and relocate any built and/or archaeological assets **Erosion Resist:** 1. **Defend Road and house:** Cost: high; Risk: high 2. **Feed beach (2050):** Longer-term repair to eroded beach profile, improving the natural resilience of the beach adjacent to Toilet Block & Skerravoe. Cost: low; Risk: low **Advance:** 1. **Mega nourishment (2050)** beach & dune reshaping would benefit the entire bay and reduce erosional risk. Cost: high; Risk: low
4. Mill to Skara Brae  Natural shore	Sandy beach, gravel upper beach Low dune cliff, inland negative gradient to former winter loch. Footpath to Skara Brae Farmland Scheduled monument Unknown archaeological remains	Low Water 1972–2018: -29 m High Water 1902–1972: +14 m 1972–2010: -12 m 2010–2018: +12 m Volume 2010–2014: -560 m³ (shore) -180 m³ (veg edge) 2014–2018: +1,800 m³ (shore) -180 m³ (veg edge) Vegetation Edge 1902–1972: -6 m loss (-0.1 m/yr) 1972–2008: -4 m loss (-0.1 m/yr) 2008–2015: -2.5 m loss (-0.4 m/yr) 2015–2019: -1 m loss (-0.25 m/yr)	VE retreat continues and accelerates. LW & HM retreat dominates. Increasing flood risk to Mill burn & visitor centre area Mill eroded completely by 2035 {check extents of orig building} Path eroded by 2050	**Non-Active Intervention:** 1. **Monitor change/no intervention (now onwards):** Natural sections of beach exposed. Prospect of unknown archaeological remains being exposed. Cost: zero; Risk: moderate **Accommodate Erosion:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. **Erosion Resist** 1. **Defend (0–10 yrs):** Extend defences from existing at Skara Brae to protect access path to site. Cost: moderate; Risk: moderate 2. **Re-profile beach (0–20 yrs):** Offers short-term local repair to beach erosion, improving the natural resilience of the beach adjacent path. Cost: low; Risk: low 3. **Feed beach (0–20 yrs):** Offers short-term local repair to eroded beach profile, improving the natural resilience of the beach adjacent to path. Cost: low; Risk: low	**In addition to continued deployment of short term options:** **Non-Active Intervention:** 1. **Monitor change/no intervention:** Natural sections of beach exposed. Prospect of unknown archaeological remains being exposed. Cost: zero; Risk: moderate **Accommodate Erosion:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Identify and relocate archaeological assets inland:** Removes assets from coastal erosion risk. Requires major archaeological excavation and is partially destructive. Relocation problematic given unexcavated land landward is part of a larger archaeological site. Cost: high; Risk: low. **Erosion Resist:** 1. **Defend (by 2050 onwards):** Extend defences to protect path to Skara Brae. Cost: moderate; Risk: moderate. 2. **Re-profile beach (2050 onwards):** Longer-term repair to eroded beach profile improving the natural resilience of the beach adjacent path. Cost: low; Risk: low 3. **Feed beach (2050 onwards):** Longer-term repair to eroded beach profile, improving the natural resilience of the beach adjacent to path. Cost: low; Risk: low **Advance:** 1. **Mega nourishment (2050)** beach & dune reshaping would benefit the entire bay and reduce risk of erosional breach and erosion-related flooding. Cost: high; Risk: low
Management Unit Area	**Shore Character & Assets**	**Coastal Changes**	**'Do nothing' – Likely Implications**	**'Short Term' Management Options (to improve short-term resilience)**	**'Long Term' Management Options (to improve long-term resilience)**

5. Skara Brae  Artificially defended shore	Veneer of sand atop rock platform Upper beach and dune bluff defended by concrete sea wall Skara Brae & structures Scheduled monument	<u>Low Water</u> 1972–2018: -50 m <u>High Water</u> 1902–1972: +6 m 1972–2010: -8 m 2010–2018: +20 m <u>Volume</u> 2010–2014: +100 m³ (shore) +20 m³ (veg edge) 2014–2018: +3,500 m³ (shore) +4 m³ (veg edge) <u>Vegetation Edge</u> 2008–2019: no change	Foreshore lowering (0.7 m by 2050, 1.6 m by 2100), toe exposure & seawall undermined Increased wave energy and risk of seawall failure	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** Natural sections of beach exposed. Cost: zero; Risk: high **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. **<u>Erosion Resist:</u>** 1. **Enhanced defences (now onwards)**: Ongoing repairs at sea wall toe to avoid undermining, dune face blowouts, flanking; anticipate need to raise parapet, insert flanking wall and enhanced toe protection. Cost: high; Risk: moderate 2. **Re-profile beach (0–20 yrs):** Offers short-term local repair to beach erosion, improving the natural resilience of the beach adjacent path. Cost: low; Risk: low 3. **Feed beach (0–20 yrs):** Offers short-term local repair to eroded beach profile, improving the natural resilience of the beach adjacent to path. Cost: low; Risk: low	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Natural sections of beach exposed. Cost: zero; Risk: high **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Identify and relocate archaeological assets inland:** Removes assets from coastal erosion risk. Requires major archaeological excavation and is partially destructive. Relocation problematic given unexcavated land landward is part of a larger archaeological site. Cost: high; Risk: low. 3. **<u>Erosion Resist:</u>** 1. **Feed beach:** Longer-term repair to eroded beach profile, improving the natural resilience of the beach adjacent to defences. Cost: moderate; Risk: moderate 2. **Local Offshore breakwater (2050):** Reducing approaching wave energy to reduce storm impacts. Cost: high; Risk: moderate **<u>Advance:</u>** 1. **Mega nourishment (2050)** Beach & dune reshaping would benefit the entire bay and reduce risk of erosional breach and erosion-related flooding. Cost: high; Risk: low
6. West of Skara Brae  Natural shore	Sandy beach & till-capped rock platform Raised bluff composed of soft glacier tills and sand Farmland Scheduled monument Unknown archaeology?	<u>Low Water</u> 1970–2018: -50 m <u>High Water</u> 1902–1972: +6 m 1972–2018: +8 m <u>Volume:</u> 2010–2014: +900 m³ (shore) -80 m³ (veg edge) 2014–2018: +1,200 m³ (shore) +50 m³ (veg edge) <u>Vegetation Edge</u> 2015–2019 -5 m	Slow episodic cliff collapse. Loss of farmland and archaeology	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** Natural sections of beach exposed. Prospect for at-risk archaeology. Cost: zero; Risk: moderate **<u>Accommodate Erosion</u>:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. **<u>Erosion Resist:</u>** 1. **Re-profile beach (0–20 yrs):** Offers short-term local repair to beach erosion, improving the natural resilience of the beach adjacent path. Cost: low; Risk: low 2. **Feed beach (0–20 yrs):** Offers short-term local repair to eroded beach profile, improving the natural resilience of the beach adjacent to path. Cost: low; Risk: low	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adapted / relocated, if or when their present location becomes untenable due to erosion risk. Choice of timing depends on local trigger points, space on land needs safeguarded for options. 2. **Monitor change/no intervention:** Natural sections of beach exposed. Prospect for at-risk archaeology. Cost: zero; Risk: moderate **<u>Accommodate Erosion</u>:** 1. **Re-profile beach (now onwards):** Short-term local repair to beach erosion, improving the natural resilience of the beach adjacent to defences. Cost: low; Risk: moderate 2. **Feed beach (now onwards):** Longer-term repair to eroded beach, improving the natural resilience of the beach adjacent to defences. Cost: low; Risk: moderate **<u>Erosion Resist:</u>** **<u>Advance:</u>** 1. **Mega nourishment (2050)** Beach & dune reshaping would benefit the entire bay and reduce risk of erosional breach and erosion-related flooding. Cost: high; Risk: low

* LW = Low Water, HW = High Water, VE = Vegetation Edge; negative values are changes in a landward direction (lost to sea)

The section below briefly expands, by area and management option, some of the key points emerging from Table 1.

The greatest societal resilience and lowest costs for Bay of Skaill will occur when coastal risk management decisions are made alongside adapting land-based policies now to accommodate future erosion.

For example, if **Non-Active Intervention** (NAI) is the preferred policy option at Bay of Skaill, then beach and/or dune cordon erosion or lowering will continue to occur, in both the short and long-term and the existing Skara Brae seawall will continue to be undermined and place archaeology at enhanced risk. At Bay of Skaill, there are no recommended options to **Advance** the current coastal position using **erosion resist** options (i.e. onshore or offshore traditional engineering structures such as seawalls or breakwaters). However, use of a large-scale **nature-based erosion resist** option, such as a mega nourishment programme (or sand engine), would benefit the entire bay and enable the current beach-dune position to be advanced seaward and protection offered to the existing seawall. Depending on the volume of feed and renourishment programme, this would provide an engineered but nature-based solution to erosion for the entire bay into the longer term. All other recommended **erosion resist measures** (nature-based and traditional engineering) would be applied to specific areas of the bay as detailed in Table 1 and summarised below. Importantly, in all areas where any NAI, advance or any type of **erosion resist** measures are implemented in the short and longer-term, it is recommended that land-based policies are adapted now to **accommodate erosion** by restricting future new development in areas anticipated to be eroded by 2100. This makes space for beach-dune systems to respond naturally and dynamically to coastal climate change impact, such as sea level rise, and avoids societal 'lock-ins' by minimising the amount of permanent development (i.e. conventional brick and mortar) permitted in areas at risk. However, short-term economic benefits in these areas can potentially occur through innovative measures such as permitted temporary development, such as assets that are demountable and/or can be relocated inland as landward erosion expands and quickens.

The risks and management options are broadly similar across all of the Bay of Skaill areas with the exception of the existing seawall at Skara Brae. Coastal flooding (although groundwater flooding is highlighted in the HES CCRA) is not an issue so all the available options below focus on managing coastal erosion.

Proposed Approach

Land-based adaptation is recommended for all the bay, apart from Skara Brae, to accommodate erosion by allowing landward retreat of natural beach-dune systems and facilitating landward relocation of assets further inland. However, Area 5 (Skara Brae) may well be an area where erosion resist is the only viable option due to the unique characteristics of the Neolithic village, at least in the short to medium term. In all other areas, short term options focus on re-profiling the upper beach and or local beach feeding with sediment (actions which buy time), in association with land-based adaptation and relocation of assets inland to risk-free sites. However, over the longer term a whole bay and nature-based option would be a mega-nourishment programme to enhance the beach and allow a shift seaward. This would also obviate any need to remove the existing artificial defences at Skara Brae itself, since at that point a substantial protective beach would lie to seaward.

In the current absence of enhanced resilience options, the present and growing risk to the site remains. As such the necessary planning for an emergency relocation of the remains of Skara Brae should be planned for, in response to a breach of the sea wall. Urgent repairs to the sea wall and enhancement of the beach in front of Skara Brae should be prioritised. This grey-green approach (a mix of traditional and Nature-Based solutions) should buy time for a longer-term strategy to manage Skara Brae, but also to draw up adaptation actions with landowners to provide climate-smart strategies to manage growing future risks, these should include the relocation of at-risk assets (buildings and infrastructure).

It should be acknowledged that sea level rise doesn't act in isolation and that other climate variables (temperature, humidity and rainfall) also present risks to the assets within the Bay of Skaill, other non-climate variables are also changing. For example, the ability of society and the scientific community to respond to challenges is increasing. As such we should ensure future managers are as unconstrained as possible. Such a dynamic adaptive approach informed by up-to-date monitoring and risk assessments should allow future manager to move between strategies as required.

Technical Summary

Methods

Identification of Flood Protection Features

High resolution Digital Elevation Models (DEMs) were automatically analysed to identify the extent of the coastal barriers protecting low-lying areas of flood risk. Regular shore-normal profiles were extracted at 10 m intervals along the DEM and analysed to identify the width of barrier and volumes of sediment above key flood elevations. These allowed potential breach points to be identified alongside SEPA's anticipated coastal flood extents. A second set of profiles were then extended along the low points of potential flood corridors to enable detailed topography to be compared with anticipated flood levels.

Anticipated Shoreline Recession due to Relative Sea Level Rise: Modified Brunn Rule

Relative sea level rise is expected to exacerbate rates of erosion of coastal barriers, with knock-on effects for any extant flood risks identified. Past rates of coastal erosion in the face of known rates of relative sea level change were used to modify and train an equilibrium model (the Bruun Rule) for shoreline change prediction (Dean and Houston, 2016). Shoreline change was then modelled to 2100 under low to high Representative Concentration Pathway (RCP) scenarios within UKCP18, encompassing predicted changes in relative sea level.

Modelling Past and Future Erosion: CoSMoS-COAST

The Coastal One-line Assimilated Simulation Tool (CoSMoS-COAST, Vitousek et al., 2017) was adapted to simulate coastal evolution under the climate change scenarios presented by UK Climate Projections 2018 (UKCP18). The model uses a process-based approach to simulate shoreline change via wave-driven alongshore and cross-shore sediment transport processes, as well as long-term shoreline migration driven by relative sea level rise (RSLR). The model is forced using local records of relative sea level change and wave hindcast data, as well as Ensemble Kalman Filtering which assimilates the modelled shoreline to historic positions of Mean High Water Springs over the 20th century. The forecast model was validated with recent shoreline position observations derived from high-resolution topographic surveys, satellite imagery and aerial photography. Shoreline change was then modelled to 2100 under low to high Representative Concentration Pathway (RCP) scenarios within UKCP18, encompassing factors such as anticipated changes in sea level rise and wave action.

Vegetation Edge Analysis

The retreating vegetation edge is a clearly identifiable feature within remotely sensed imagery, high resolution DEMs and via ground survey. Its position can be extracted manually or semi-automatically allowing time-lapse comparisons from data from different time-periods. Multiple sets of aerial imagery over the last few decades have been compared with comparable resolution ground survey to produce time-series vegetation edge retreat positions.

Updating the Extent of the Intertidal: Coast X-Ray

Dynamic Coast developed a tool (Coast X-Ray) to analyse the back catalogue of Sentinel 2 satellite imagery, using a Normalised Difference Water Index, to demarcate areas which are always water (sea), always non-water (land) and areas which are intermittently water and land (the intertidal zone). This water occurrence index is converted into a percentage figure, but the number of images used in the analysis and the median NDWI value are also available. Results show that Coast X-Ray can be used to inform potential changes to the extent and geometry of the foreshore and the low- and high-water marks against previously published tide lines.

Mapping Coastal Erosion Disadvantage

An assessment was additionally carried out to quantify the Coastal Erosion Disadvantage (ie social vulnerability of Scotland's communities to coastal erosion), using Dynamic Coast erosion data from the recent past (1970s) through to 2050. Mapping of social vulnerability in relation to coastal erosion was carried out using Scotland's Census data from 2011 and the latest data from the Scottish Index of Multiple Deprivation (2016 & 2020). Building upon previous considerations of social vulnerability related to coastal erosion and flooding, the Social Vulnerability Classification Index is a derivative of that developed by Fitton (2015). It includes existing academic and policy literature concerning coastal erosion and flooding vulnerability and identifies key indicators of social vulnerability to coastal erosion and flooding. It seeks also to extend SEPA's (2011) early approach to identifying "Potentially Vulnerable Areas" and Sayers et al (2018) flood risk vulnerability assessment, which does not consider coastal erosion.

Results

The following section provides the research results on coastal change (erosion/accretion), flood risk and coastal erosion enhanced flooding.

Coastal Change

Summary

1. The current state of knowledge is that the Neolithic village of Skara Brae was abandoned 4,500 years ago due to large-scale coastal changes and was re-exposed for at least the second time by coastal erosion in a storm in 1850. It has been a focal point of environmental and archaeological research since. Coastal erosion and associated instability and sand blow in the coastal dunes that formerly fronted the village is thought to have led to progressive inundation of the village by blown sand that led to its eventual abandonment. Following its abandonment, the village lay below a veneer of sand until frontal erosion, progressing landward revealed built structures on the seaward face of the dunes. In 1925 and 1926 a seawall was constructed by HM Office of Works (OoW) when it was first taken into state care to defend the site from further erosion. The structure has been added to by OoW and subsequent responsible state bodies, with toe protection and repairs over the years since. The existence of the seawall, and the survival of the site, is the direct consequence of sustained state intervention over a period of 100 years. However, erosion has continued in other parts of the bay, particularly adjacent to the seawall, although some limited areas have recently experienced relative stability.
2. Recent analysis (shown below) confirms changes to the lower beach, upper beach and vegetated edge, which are of concern and present a risk to assets.
3. Low Water (LW) has progressively retreated across much of the bay, over time. High Water (HW) has undergone periodic fluctuation reflecting its high energy setting, whilst the Vegetation Edge has progressively retreated landwards over recent decades.
4. Some of these threats are well known (e.g. undermining of the artificial defences fronting Skara Brae), others less so. Nevertheless, separate research methods independently suggest erosion to become widespread and quicken, as sea levels continue to rise, for the remainder of the present century and beyond.

The first phase of Dynamic Coast summarised the coastal changes to Bay of Skaill (see page 9 of Cell 10 report) between 1900, 1972 and 2014. The upper beach in front of the Skara Brae seawall defences show stability from 1972 to 2014, but further east and north shows instability with a landward migration of MHWS and Vegetation Edge over recent decades.

The second phase of Dynamic Coast, outlined below, benefits from both Terrestrial Laser Scanning (TLS) of Skara Brae and aerial LiDAR surveys by HES in 2018, and updated by multiple Vegetation Edge surveys. Whilst these are discussed in turn below, various interactive tools are available within www.DynamicCoast.com for the user/reader to interrogate the results.

Existing Topography and Flood Levels within Bay of Skaill

The natural coastal sand dune ridge and gravel beach at the Bay of Skaill serves to protect the interior dunes and adjacent farmland and built assets whilst the artificial sea wall protects the site of Skara Brae. The interior elevation of the dune ridge is generally above 7 mOD, rising inland to 8 m and 9 mOD and although some areas close to the shore lie at 6 mOD, these are encircled by 7 mOD contours. This means that the dunes are above current high magnitude flood levels (see insert on Figure 3) and likely to remain so for decades to come. Nevertheless, spray and wave thrown beach sediments present a current issue at the Bay of Skaill, including Skara Brae itself, in common with other high energy shores in Orkney.

Given the topography (Figure 3) the flood risk at the Bay of Skaill is regarded to be limited since the frontal dunes are backed by gradients that rise inland. However, a restricted corridor along the present course of the stream outlet from the Loch of Skaill, may be an issue for future fluvial flooding, but not for coastal flooding given the surrounding ground exceeds 7 mOD and, with the outlet currently self-sealing with coastal sediment, this unlikely to change substantially in the future.

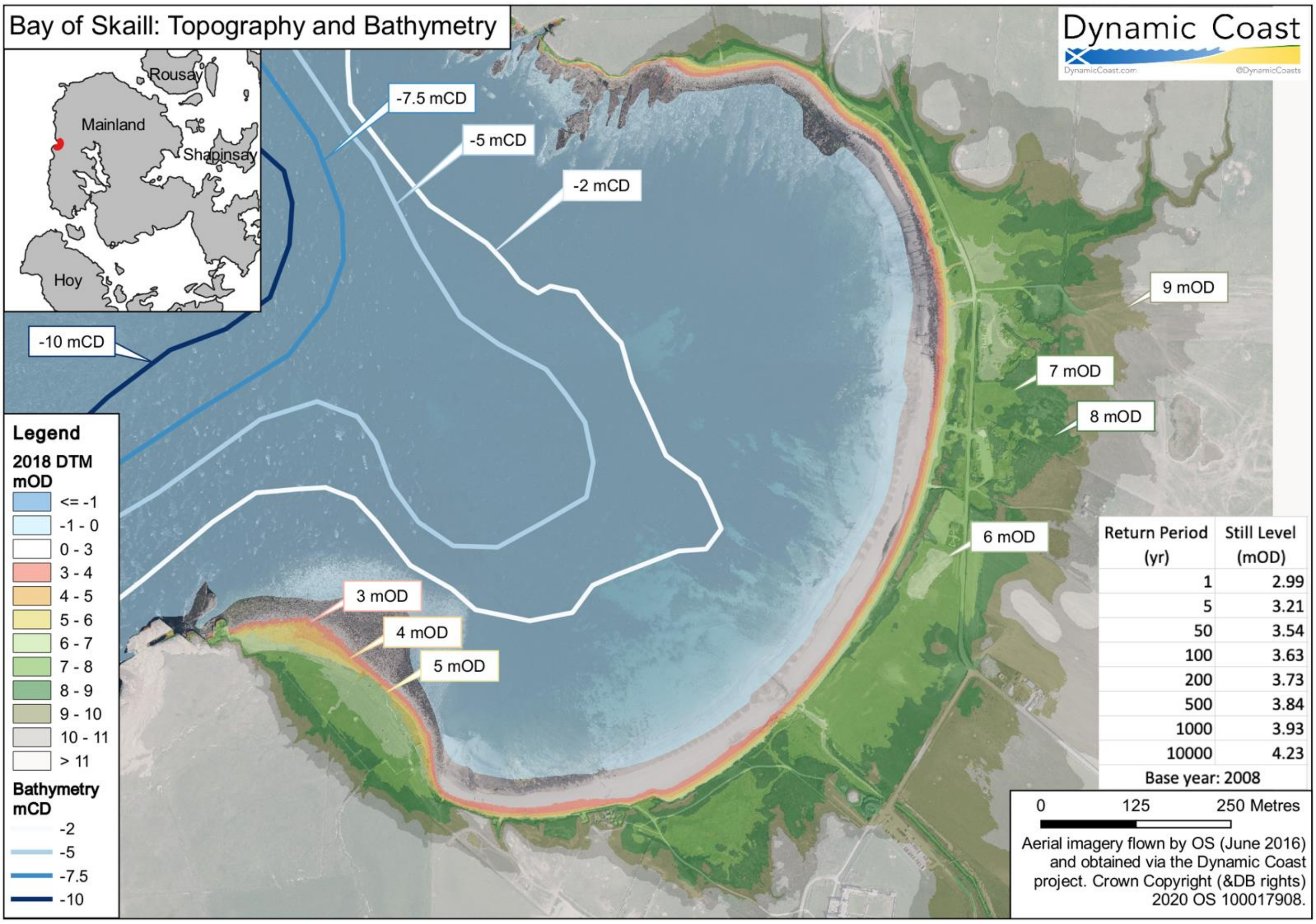

Figure 3 Topography, bathymetry and key flood levels for Bay of Skaill

Natural Coastal Flood Protection Features within Bay of Skaill

Automated terrain analysis has been carried out on the Skaill DSM to identify the extent of barrier features and identify their overlap with areas at potential flood risk. However, the rising ground levels inland at Bay of Skaill beyond the dune face mean that the interior is not at risk from coastal flooding, even under the anticipated 1 m of RSLR by 2100. The extent of the coastal flood protection features is depicted in Figure 4, with natural barrier front points symbolised with barrier widths. To be noted is the lack of barrier features which lie at at-risk flood elevations, due to the high cliff dune morphology; some barriers may be narrower than others but very few are at flood risk because of their width.

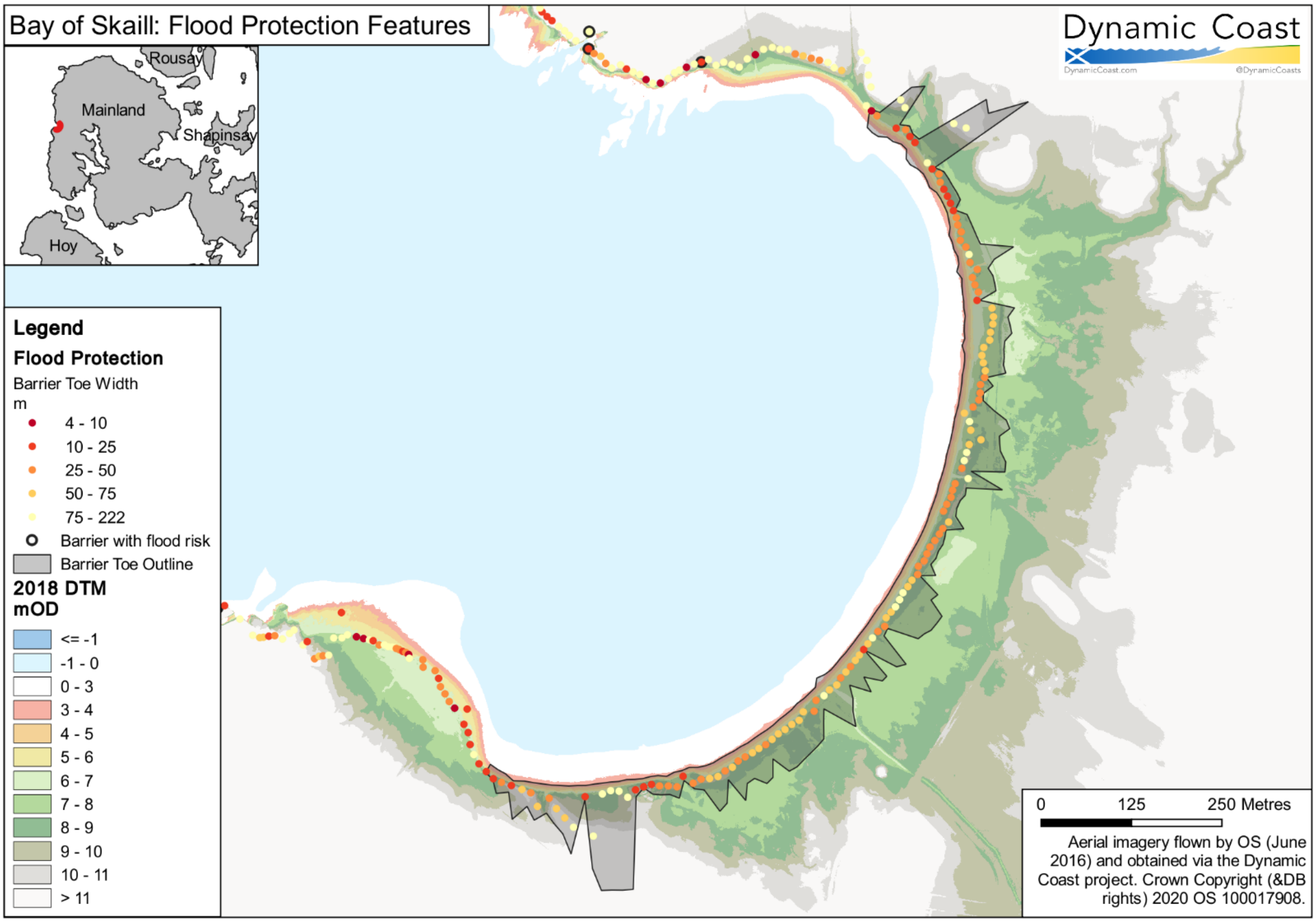

Figure 4 Extent of natural flood protection features at Bay of Skaill: The positions of the dune ridge barrier toes seaward and landward are derived from LiDAR automatic terrain analysis (toe of seawall at Skara Brae also shown). The barrier widths are presented as front toe points, however due to the morphology of the cliff dune system, the protective capacity of these dunes at key flood elevations is very high (as shown by the lack of barriers at risk of flooding (black rings around points).

Changes to Low Water at Bay of Skaill

Figure 5 shows the observed changes to low water by comparing the Ordnance Survey Mean Low Water Spring (MLWS) line surveyed in 1972, with a low water line derived from the Coast X-Ray method. The Coast X-Ray approach infers a foreshore lowering adjacent to the Skara Brae site which has resulted in the position of low water retreating landwards ~55m from 1900–2018. Given that the energy of storm waves at breaking point is depth dependent, foreshore lowering will lead to a reduction in wave attenuation and an increase in wave energy at the beach. On low shores this would normally increase the risk of coastal flooding due to wave setup and overtopping, but the mean 7–8 mOD height and width of the dune cordon at Bay of Skaill beach suggests this to be unlikely.

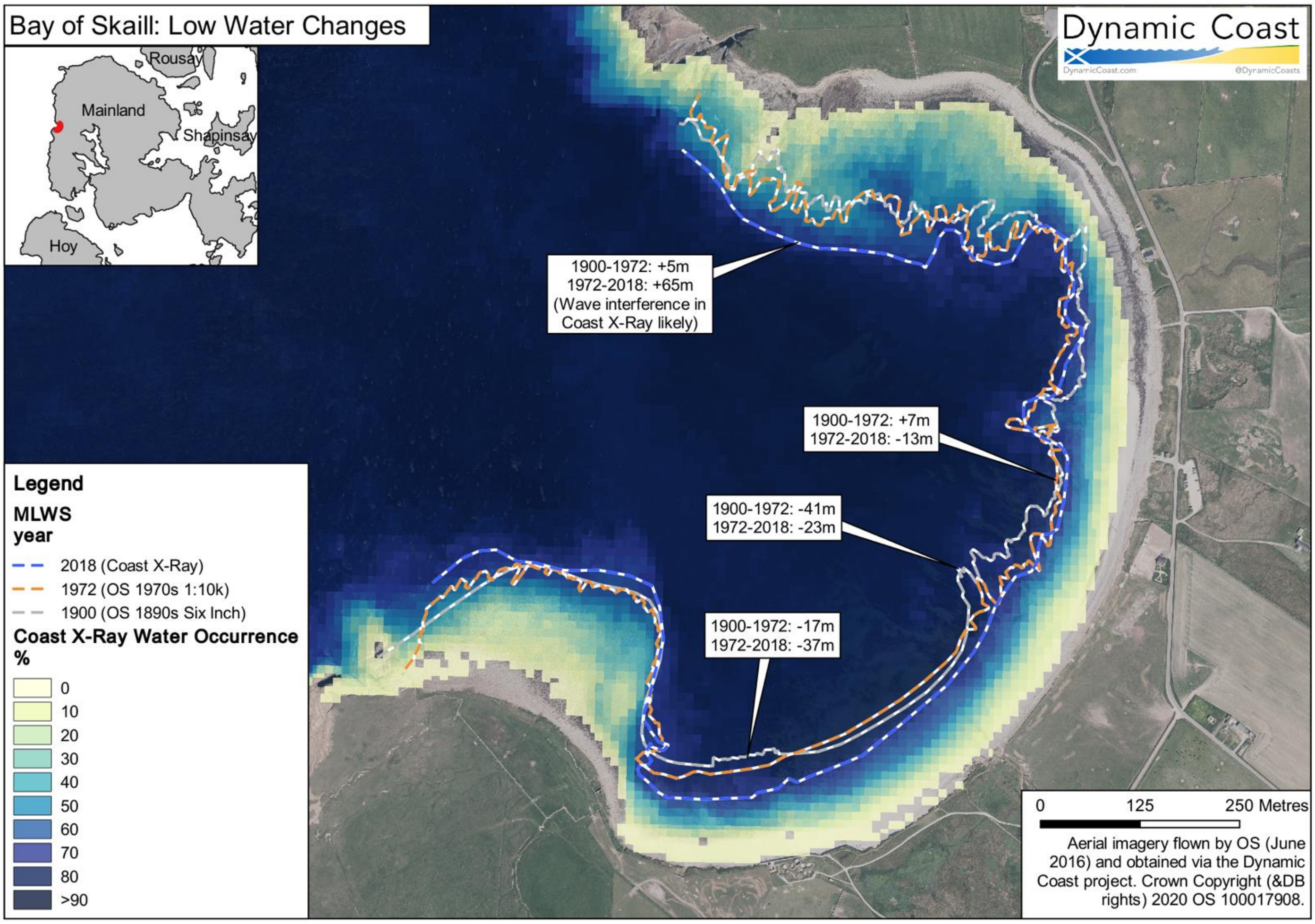

Figure 5 Comparison between the latest OS Mean Low Water Springs line (surveyed in 1972) and Low Water (80% water occurrence) from Coast X-Ray

Changes to High Water at Bay of Skaill

Figure 6 depicts changes in the position of MHWS between 1900 and 2018 in the Bay of Skaill (Skara Brae HW has been artificially fixed in position since the 1920s by a seawall), showing maximum shifts of 27–44 m in the central bay and smaller shifts of 6–14 m in both the north and south of the bay. Figure 7 details the shifts in MHWS in the southern part of the Bay of Skaill and shows recent build-up of upper beach sediment between 1972 and 2017/2018. This suggests the geometry of the upper beach is highly variable with both phases of landward retreat and seaward gains, yet over the same time period MLWS shows progressive landward retreat leading to shoreface steepening (sediment loss at MLWS may result in gain at MHWS).

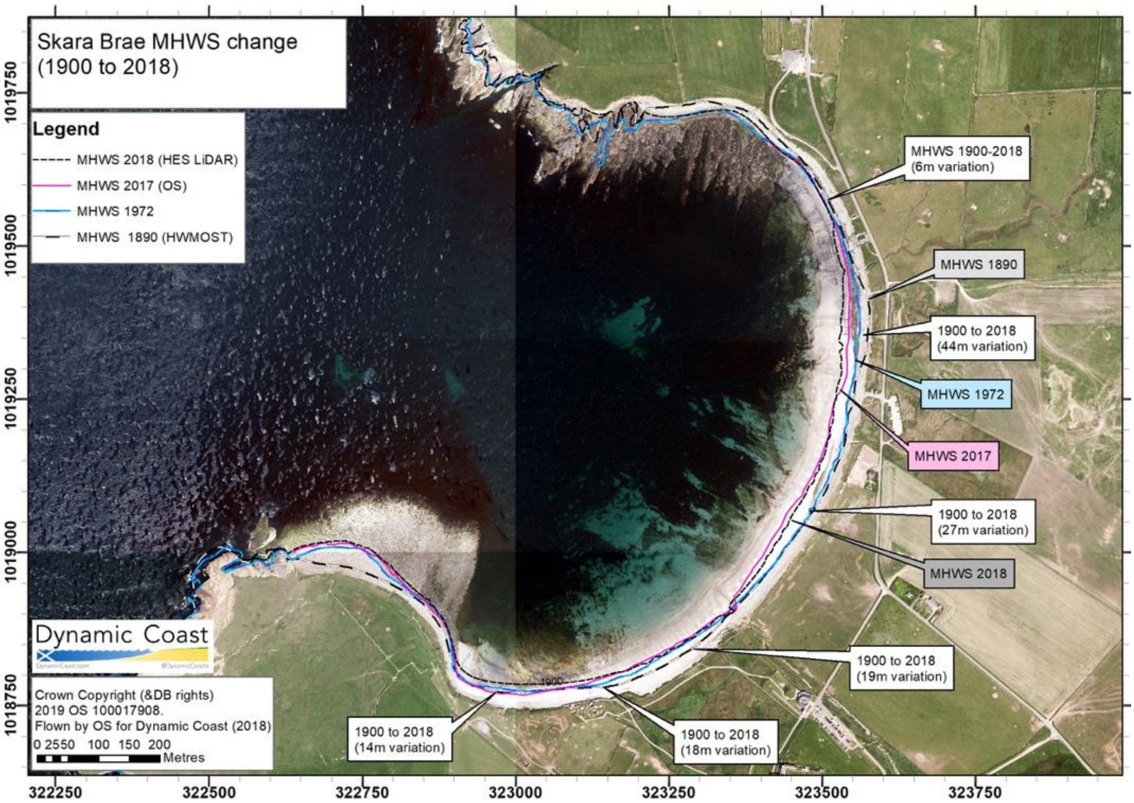

Figure 6 MHWS position changes between 1900 and 2018 at Bay of Skaill with total distance variations from 1900 position.

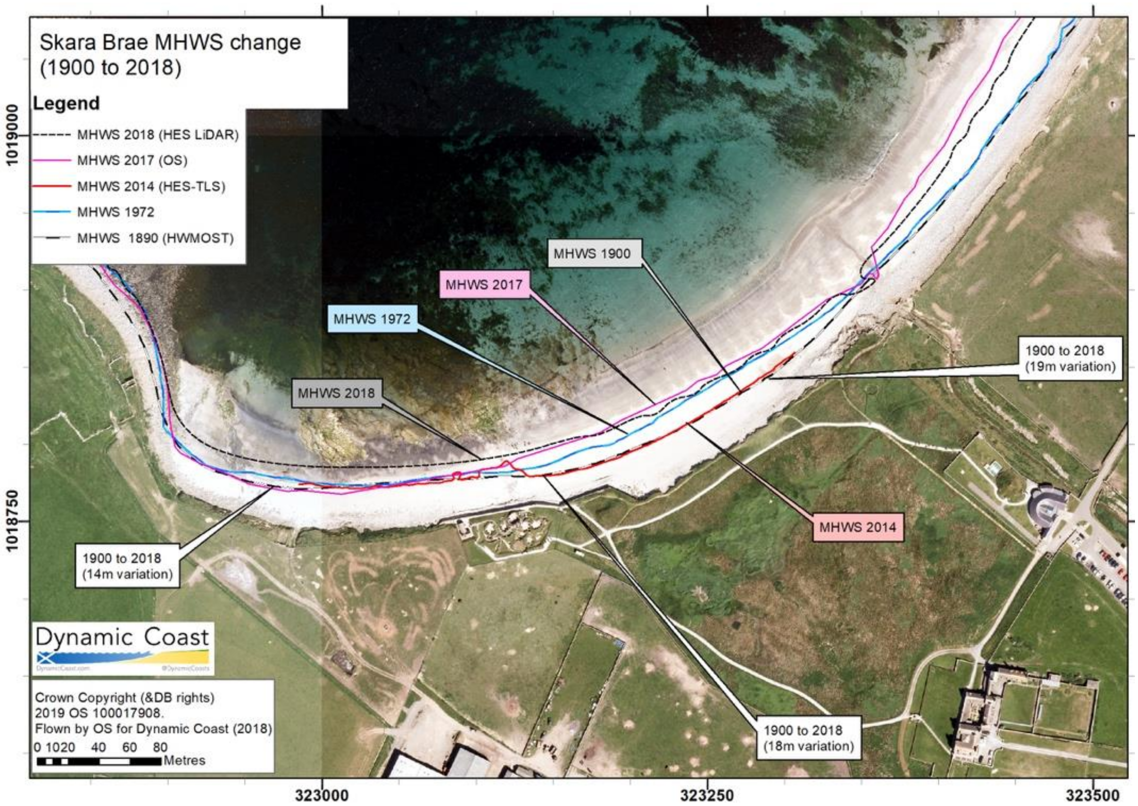

Figure 7 MHWS position changes between 1900 & 2018 at Skara Brae. Inserts show total variation distances from 1900 position.

A number of high resolution Digital Elevation Models (DEMs) exist for Skara Brae due to the ongoing monitoring work by HES to ensure the valuable cultural asset is being adequately protected and maintained. Part of this maintenance also involves assessing sediment movement surrounding the hard sea wall fronting the Skara Brae site. Figure 8 shows the changes in elevation from 2010–2014 and 2014–2018 across Skara Brae, highlighting the trends of foreshore accretion and dune front erosion, as well as the magnitude and rate of retreat along the vegetation edge east of the site and to a lesser extent at the base of the defence wall. The short time span of 4 years between each elevation surface also emphasises the dynamism of sediment across this relatively small scale, with the foreshore switching between erosional and accretionary in under a decade.

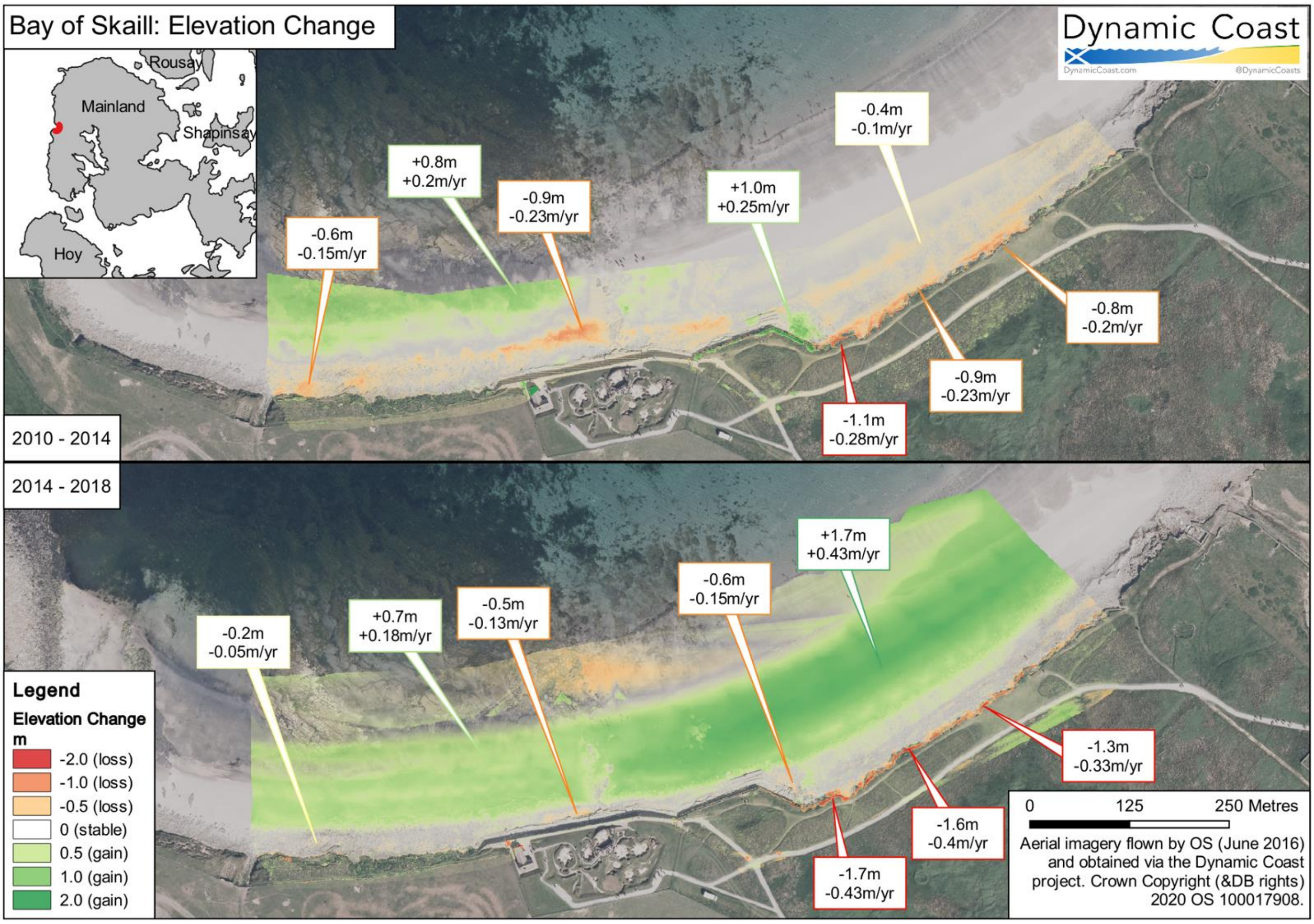

Figure 8 Changes in foreshore elevation over the last decade across Skara Brae, from 2010 (Lidar DTM) to 2014 (Terrestrial Laser Scan) and 2014 to 2018 (Terrestrial Laser Scan).

In 2018, two high quality Digital Surface Models (DSMs) of the Skara Brae foreshore area were collected, allowing a check of data quality as well as an assessment of short-term upper beach variability (Figure 8). These demonstrate internal consistency and indicate that substantial vertical change can occur in the upper beach within one year. Low beach gradients at MHWS elevations as seen here can produce substantial lateral change in MHWS positions over a short period of time as the beach height fluctuates.

Vegetation Edge Change across Bay of Skaill

Figure 9 shows the Vegetation Edge monitoring from various sources: historic maps (1902 and 1972), recent aerial imagery (2008 and 2015/6) and field survey (April 2019). The position of the Vegetation Edge is a useful additional indicator of coastal erosion since it defines the point at which landward assets become directly impacted by wave erosion (e.g. by undermining of the coastal bluff), as opposed to simply being at heightened risk due to the approach of another indicator such as MHWS. MHWS is used within Dynamic Coast as a key coastal position indicator because of its nationally time-series availability from the Ordnance Survey. The Vegetation Edge is now being collected semi-automatically within Dynamic Coast as an added layer of data to complement MHWS as an indicator of cumulative erosion that is relatively free from the short-term noise and fluctuation that affects MHWS. Additionally, the rates of change as well as distance changes can be calculated to gain a clearer understanding and more normalised view of the change in Vegetation Edge (Figure 10).

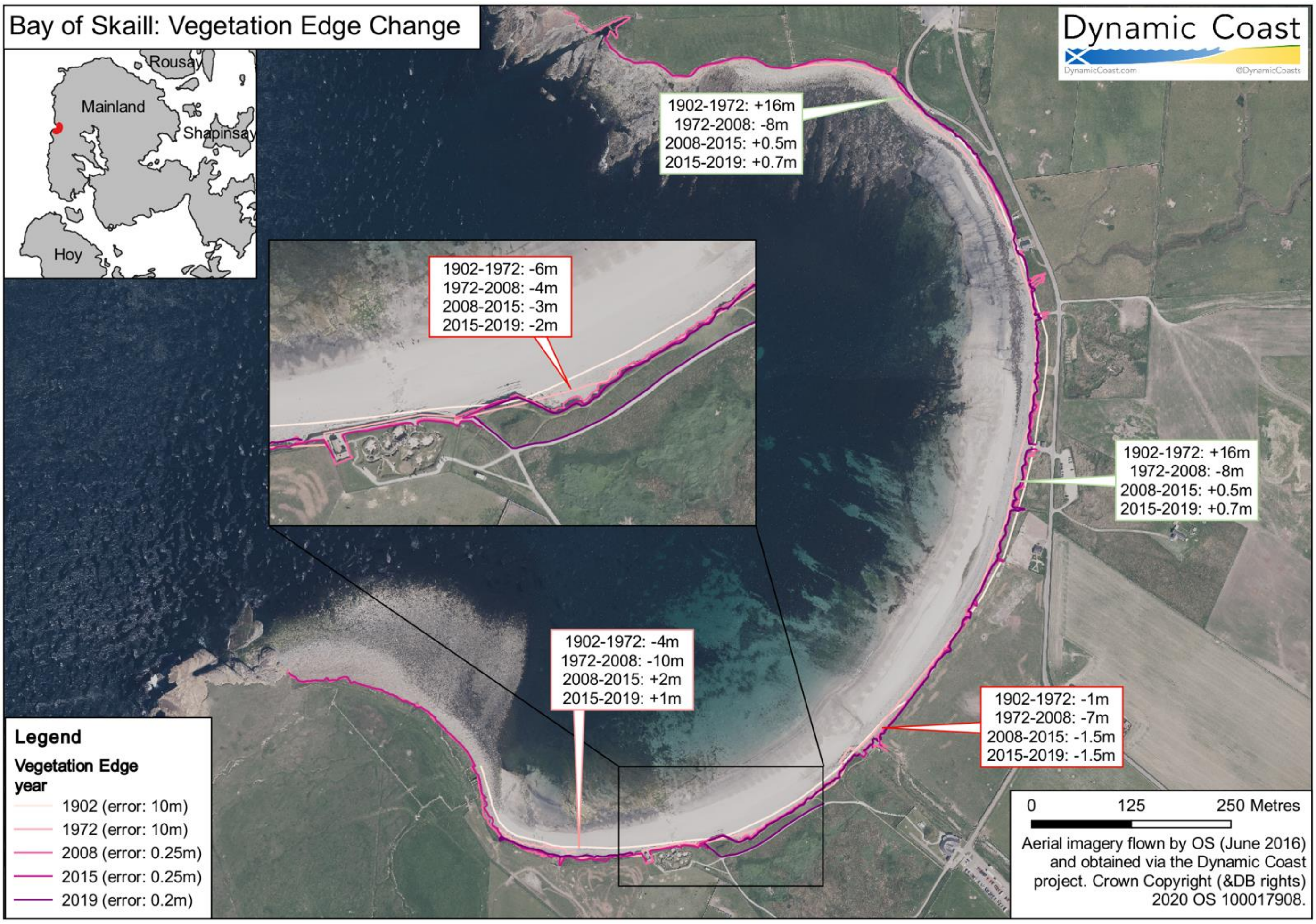

Figure 9 Vegetation Edge lines from 1902, 1972 (OS map digitisation), 2008, 2015 (aerial image digitisation) and 2019 (ground survey) for Bay of Skaill with focus on Skara Brae.

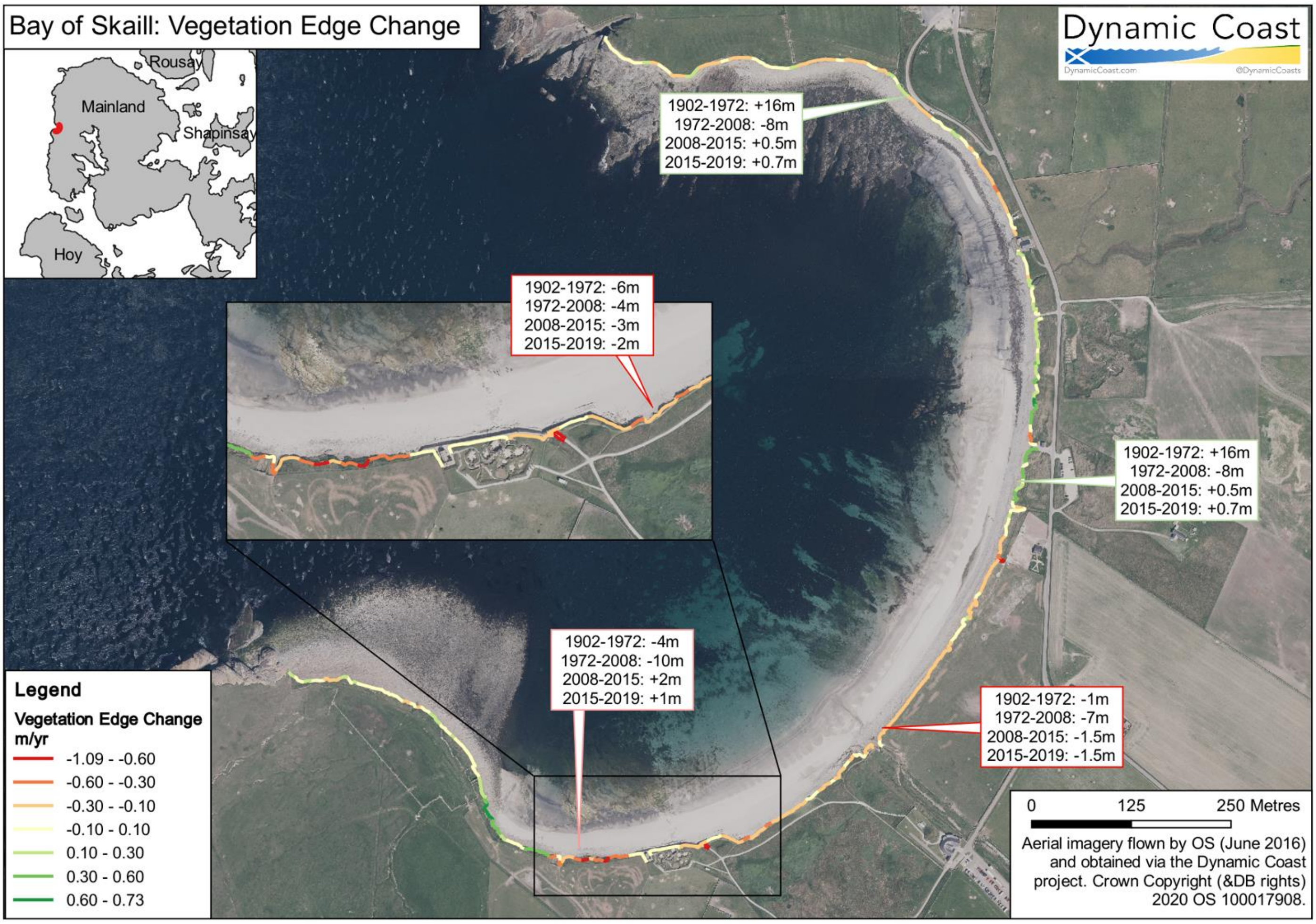

Figure 10 Vegetation Edge change across the Bay of Skaill measured between 2008–2015

The past time-series Vegetation Edge change at Bay of Skaill can be converted into a rate (m/yr0 and projected forward to 2050 and 2100 as a way of visualising coastal edge change based on present conditions. This method is similar to the geometric shore retreat projections presented in the first phase of Dynamic Coast. Figure 11 shows progressive landward shifts of the Vegetation Edge across much of the Bay of Skaill, although the rate is variable. Relatively rapid rates occur in the south and adjacent to the end of the seawall at Skara Brae, but less change occurs toward the centre of the bay. Projecting the past rates forward to 2050 and 2100 shows some areas to undergo 19 m of retreat by 2050 and 50 m by 2100 whilst others appear relatively stable (Figure 11). However, erosion at specific points is known to negatively impact on adjacent coastal edges and so the position of the future eroded Vegetation Edge is more likely than not to become more uniformly distributed landward.

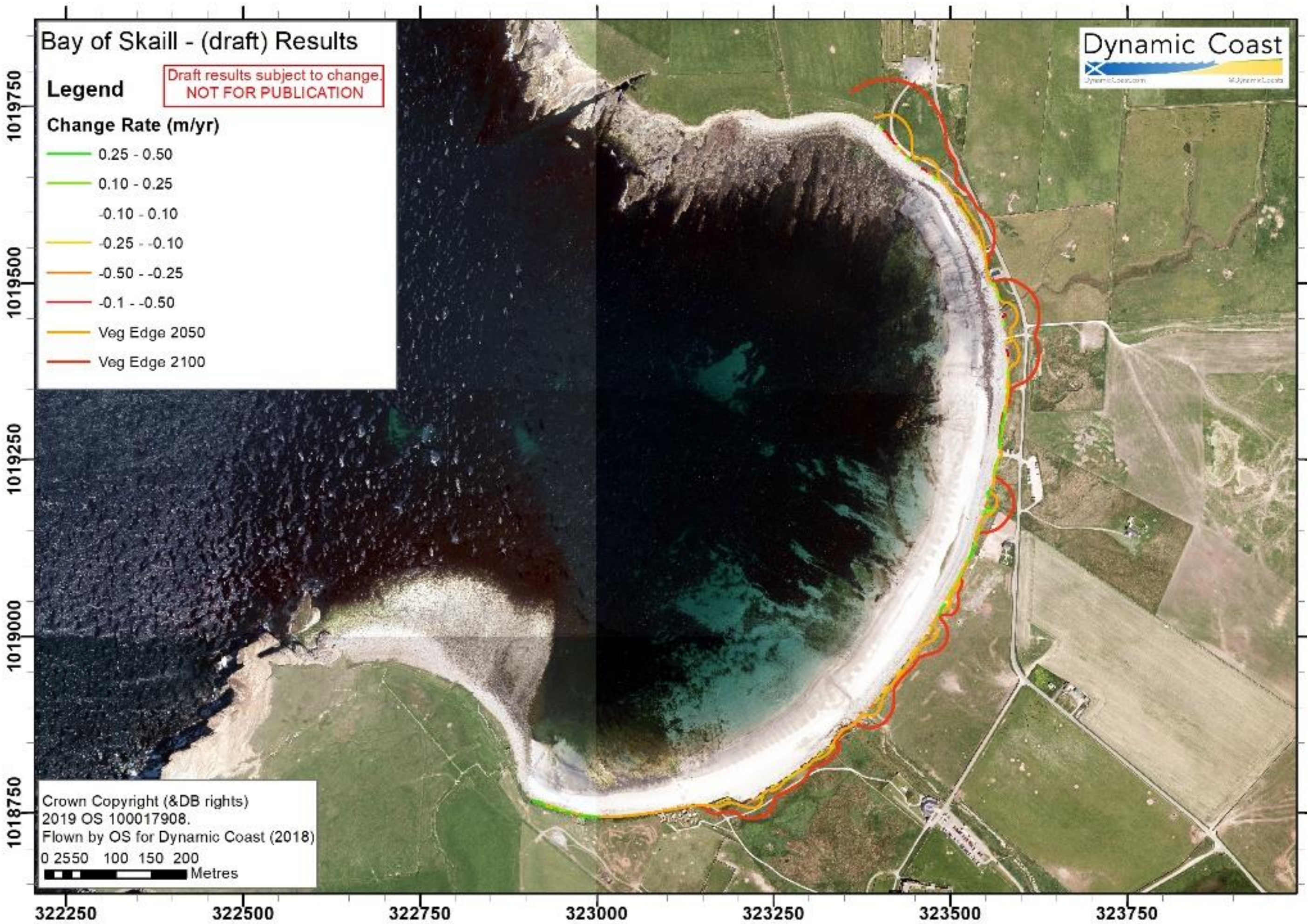

Figure 11 Anticipated recent veg edge retreat rates by 2050 and 2100. The position of the eroded lines depends on a linear extrapolation of past rates, no impact of eroded areas on stable adjacent areas (unlikely), and no artificial intervention.

Volumetric Changes within Bay of Skaill

The elevation changes captured by the datasets depicted in Figure 8 allow annual volumetric change rates to be calculated for the period between 2010–2014 and 2014–2018 across the Skara Brae site. The marking of these zones gives areas to sum elevation change across, thereby giving volumes for these specific zones. This volumetric quantification shows that the rate of loss in sediment volume has been steady across the vegetation edge and sea wall base, with an influx of sediment across the shoreface in more recent years. The limited coverage of the elevation surfaces means that a full assessment of sediment movement in and out of the entire bay system cannot be made, but it is likely that due to the curved nature of the 'pocket' bay, there is a limited supply of sediment into the system and the primary sediment being mobilised is from other parts of beach and the vegetation edge clipping back. This is further supported by the seaward-pointing arch shapes seen in the sand aerial imagery of Figure 12, representing erosional 'cusp' shapes at the wave breaking zone.

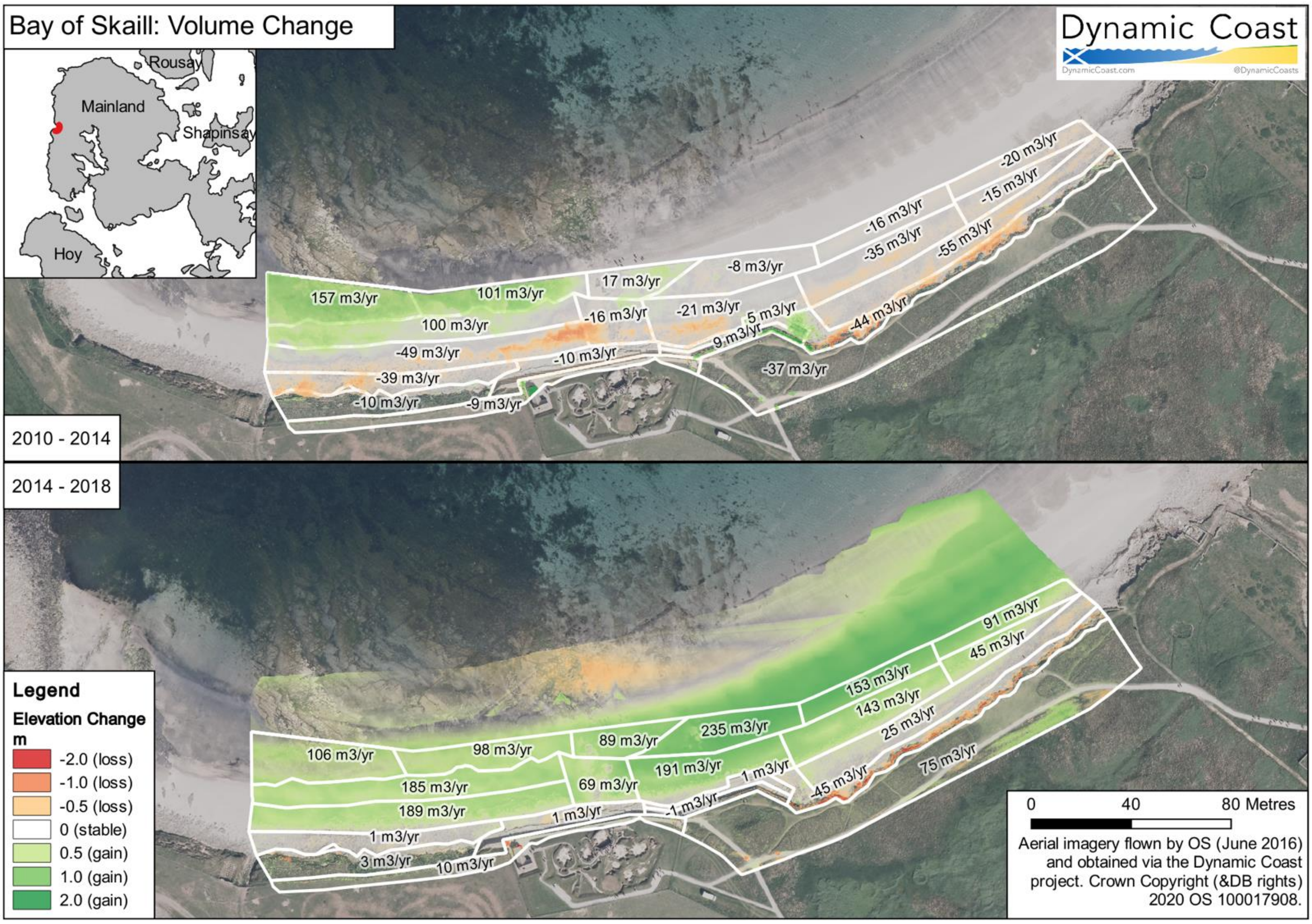

Figure 12 Comparison of rates of volume change across each geomorphic section outline in white, from 2010–2014 (top) and 2014–2018 (bottom).

Future Shoreline Projections

Future projections are based on the Modified Bruun Rule which are projected forward based on UKCP18 Representative Concentration Pathway 8.5 (RCP8.5) using the 95th percentile estimate, given the precautionary principle. The coastal change incorporates shore face gradient and is calibrated with recent coastal change data. These anticipated shorelines are not intended to be reliable detailed predictions, but a precautionary future scenario of many possible scenarios to inform the possible scale of change. Figure 13 shows the anticipated future positions of MHWS each decade through to 2100 estimated using a Modified Bruun Rule calculation for a future relative sea level rise of 1.02 m at Bay of Skaill (UKCP18 RCP8.5 95 percentile). In the southern half of the bay, the amount of landward retreat (erosion) reaches -7 m by 2050 and -28 m by 2100, with a maximum switch in historic erosion rate at one transect from stable/no change (1972–2018) to -0.5 m/yr (2050–2100). The amount of landward retreat is anticipated to be up to -29 m by 2100 in the northern part with erosion rates of between -0.4 to -0.8 m/yr by 2100.

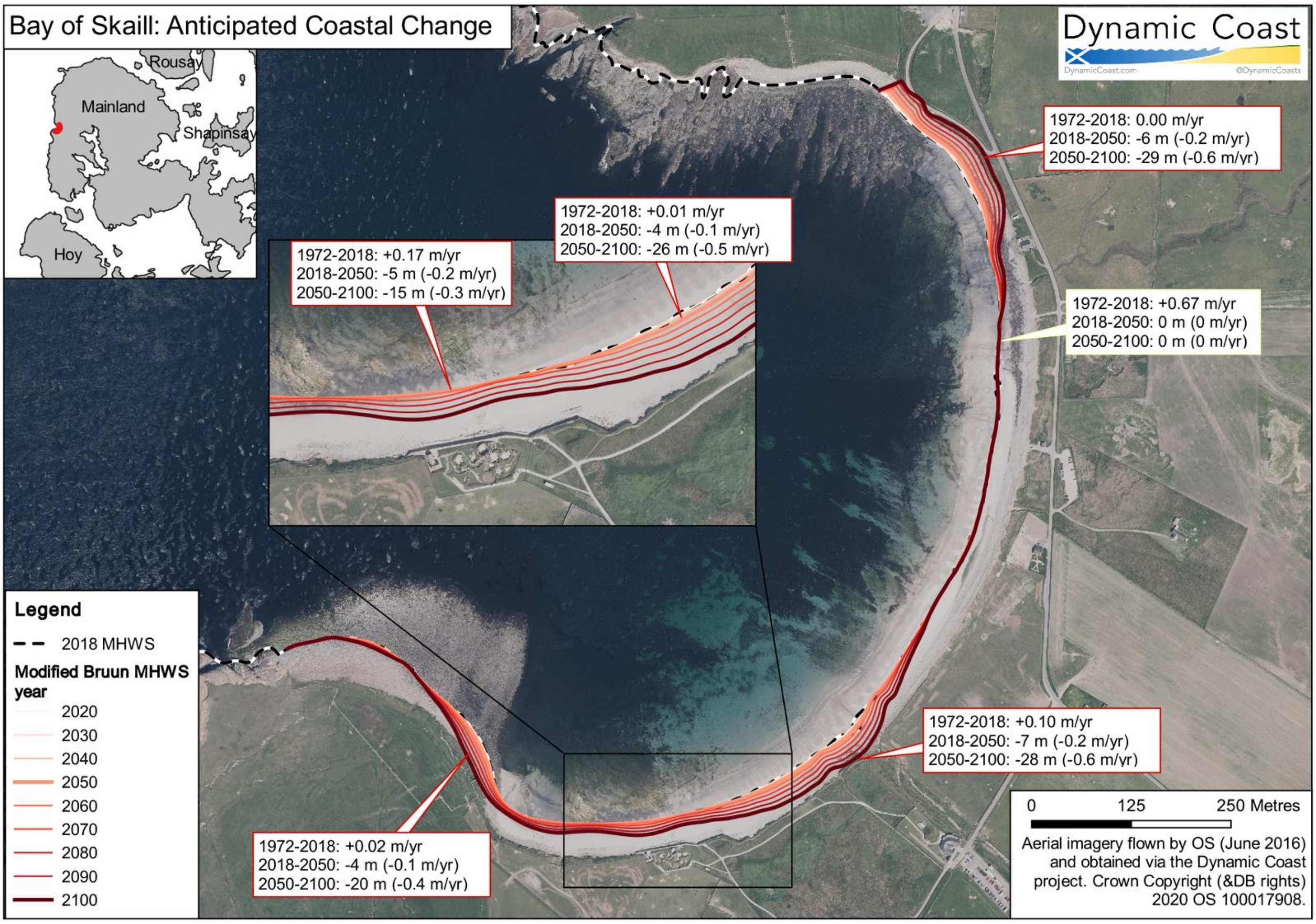

Figure 13 Future MHWS from Modified Bruun Rule (using the precautionary MHWS change from 1972–2018 as calibration), excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

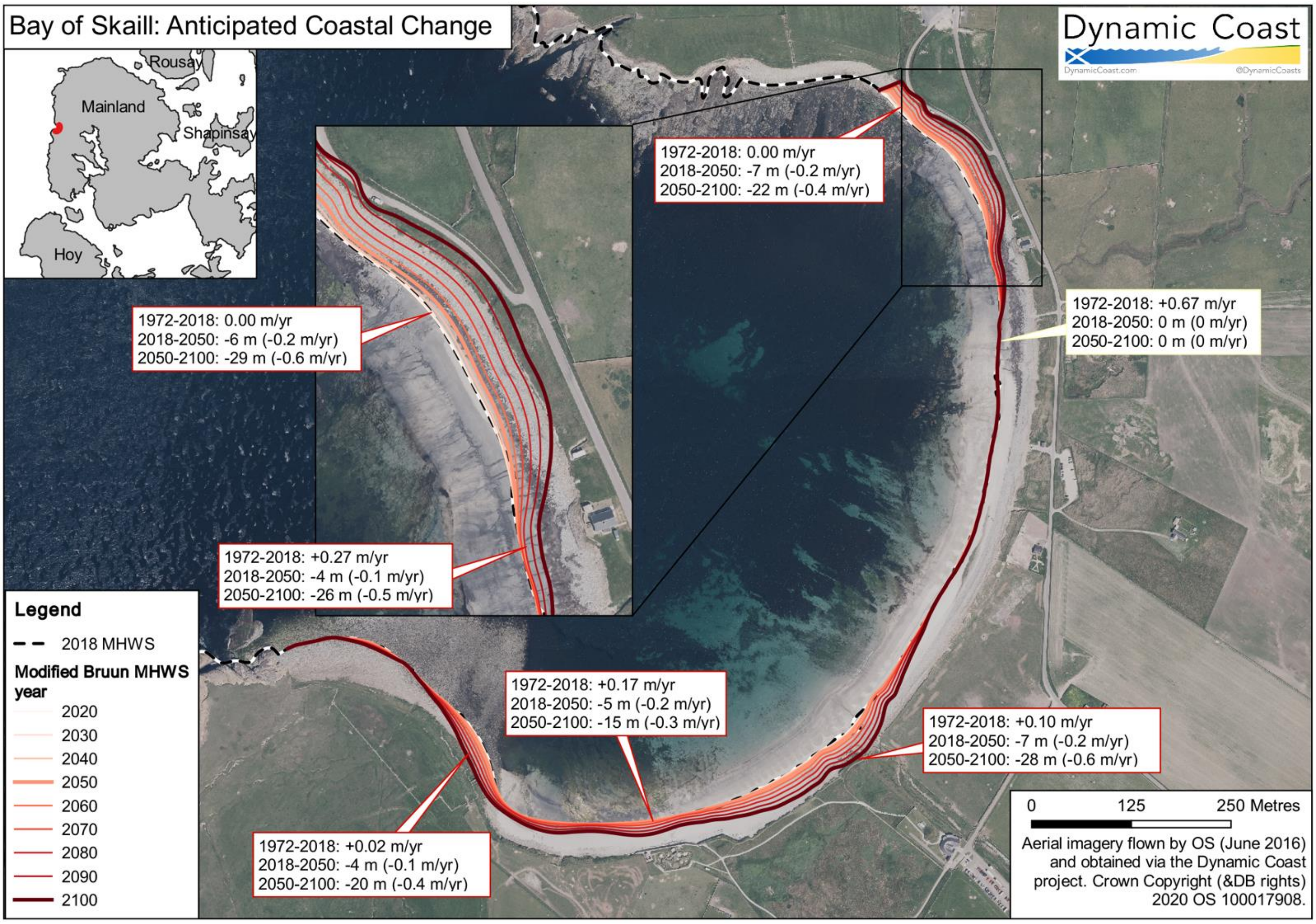

Figure 14 Future MHWS from Modified Bruun Rule (using the precautionary MHWS change from 1972–2018 as calibration), excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

The retreat rates, as explained, are based on both the rate of sea level rise expected in the future and the rates of retreat recorded in the past and present, with a maximum erosion limit set by the erodability of a backdune area. As shown in the sections on MHWS, Vegetation Edge and elevation change, short-term changes can reflect a large amount of dynamism in the Bay of Skaill system. Therefore, the Modified Bruun Rule retreat for Bay of Skaill can be calculated based on short-term (2010–2018) MHWS change which is moderate and accretionary in places with only partial coverage across the front of Skara Brae (Figure 15), and on a more representative and precautionary longer-term (1972–2018) erosional trend in MHWS change (Figure 13, Figure 14).

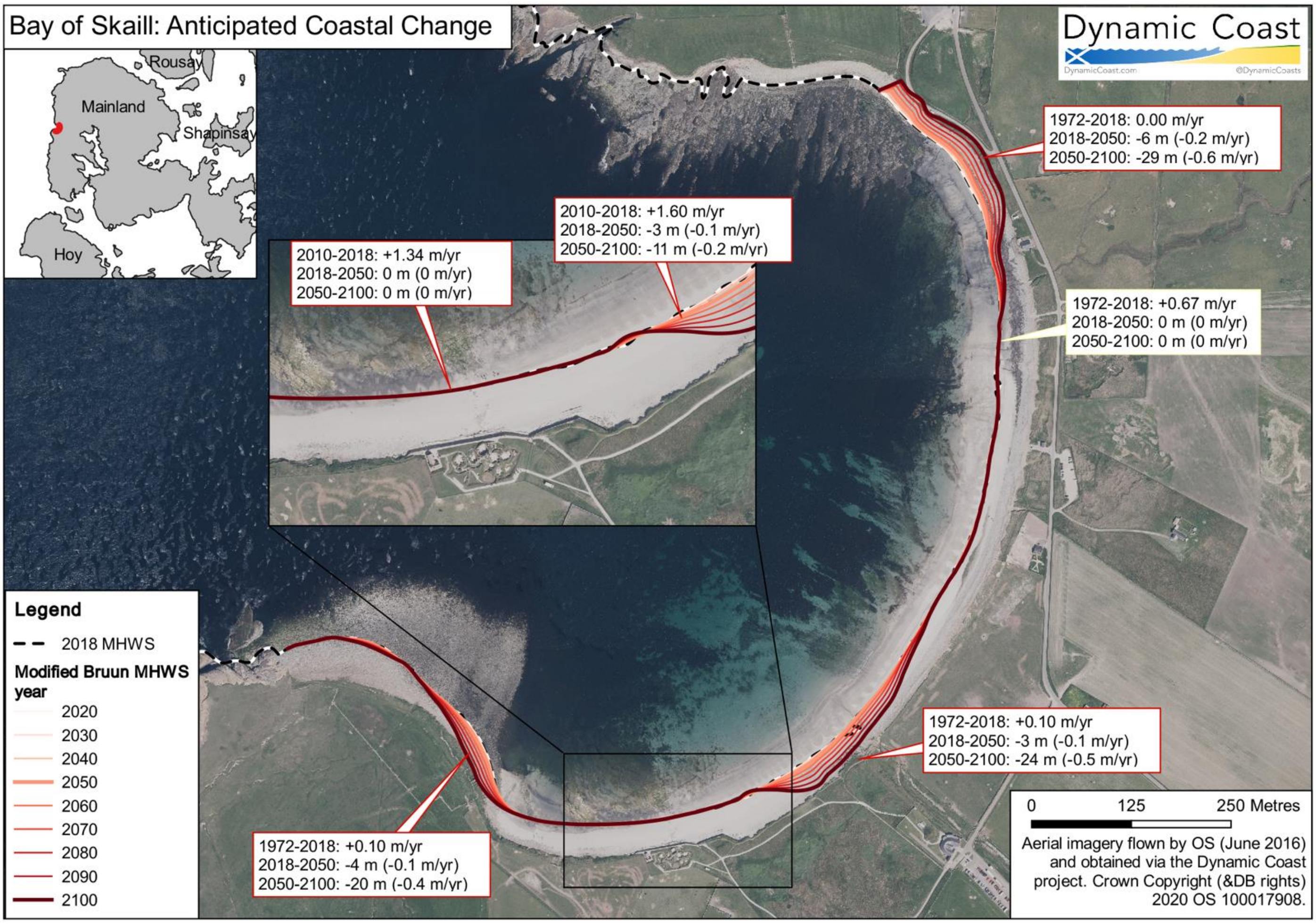

Figure 15 Future MHWS from Modified Bruun Rule using (using the short-term MHWS change from 2010–2018 as calibration, i.e. national run), excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

Figure 16 incorporates the horizontal offset between MHWS and the Vegetation Edge. This provides a clearer perspective on the timings of when the (un-vegetated) beach will coincide with assets. The small road to the east of B9056 at the north of Figure 16, is at immediate threat. Seaview (the northern house) house is expected to become increasingly exposed as the edge of the vegetation retreats landwards; arguably this has already started with -8 m of retreat between 1972 and 2018, averaging -17 cm/yr. Adjacent to the northern house, anticipated Vegetation Edge retreat based on Modified Bruun MHWS retreat coincides with the B9056 between 2040 and 2050. The path from the Skara Brae visitor centre to the site could be impacted by 2070. While this is by no means an exact projection of Vegetation Edge retreat, applying the ~40 m offset between the current MHWS and Vegetation Edge to the future MHWS projections helps to visualise timings of when the un-vegetated beach and dune face will impact on land-based assets. This generalisation also does not mean that the Vegetation Edge across the central-southern section of the bay is fixed in place, as seen by recent retreat in Figure 10.

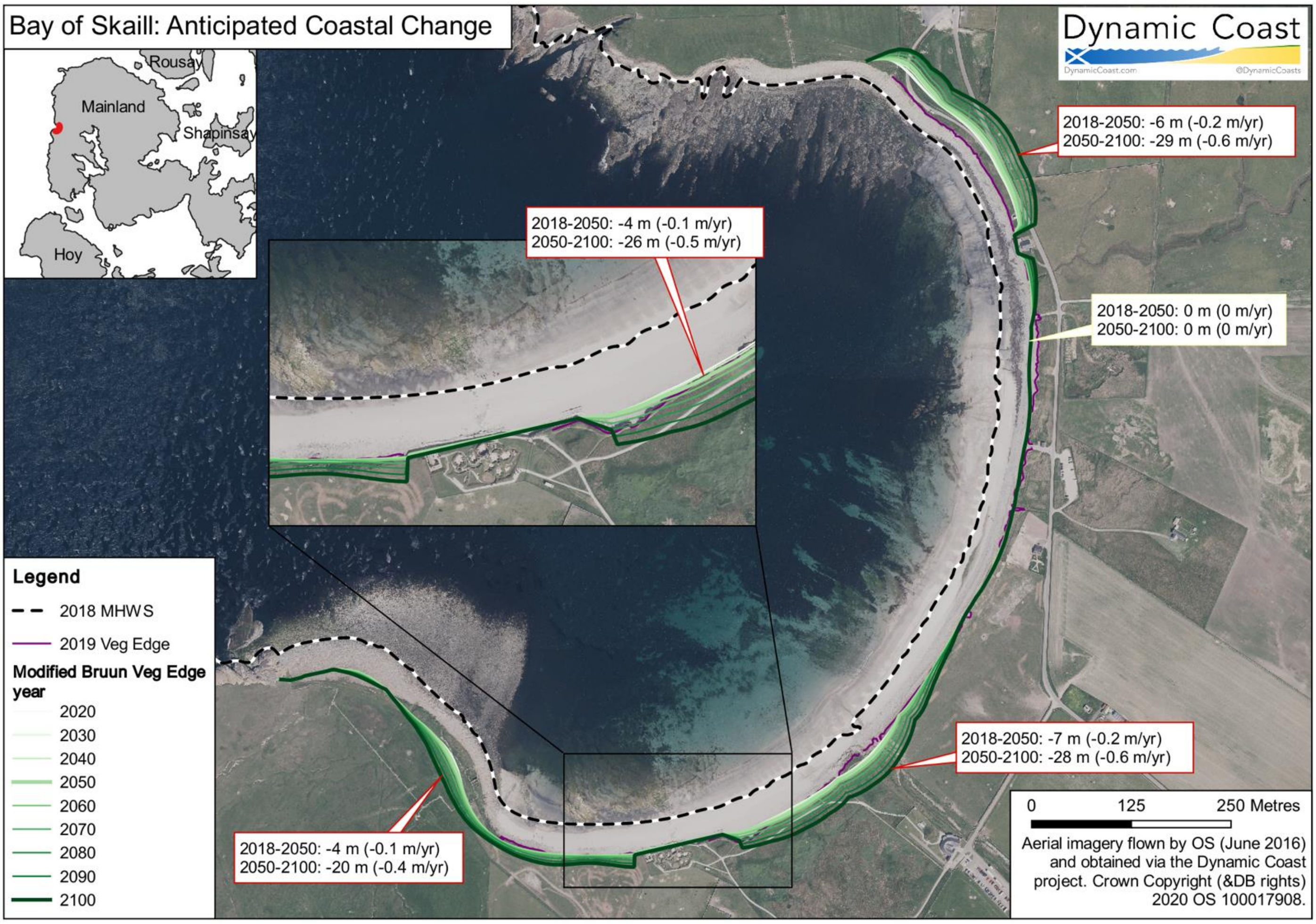

Figure 16 Future Vegetation Edge positions under the Modified Bruun Rule, excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

A useful way of depicting the effect of these planimetric changes is to construct cross sections normal to the coast. Figure 17 depicts two cross sections: one taken through the mid-point of the Skara Brae seawall, the other taken through the dunes immediately to the east of the sea wall (at the marker post shown in the bottom scene of Figure 18). These cross sections show that, without the seawall, ~17 m of retreat at the dune crest would have occurred up to the present day, with approximately half of Skara Brae lost. If the seawall were breached or removed, then the orange line is an approximate guide to the anticipated position of the equilibrium shoreline and provides justification for the continued maintenance of the seawall. The two further cross sections show the position of any future undefended shore, the light red line with a 2 m horizontal offset to the equilibrium profile (undefended shore) to reflect the shoreface retreat anticipated by the Modified Bruun Rule by 2050 (Figure 19). Left undefended, most of the Skara Brae monument (up to the 7th House) would be lost over the next thirty years. The dark red line incorporates 23 m (2 m by 2050 and additional 21 m by 2100) of horizontal retreat anticipated by the Modified Bruun Rule by 2100.

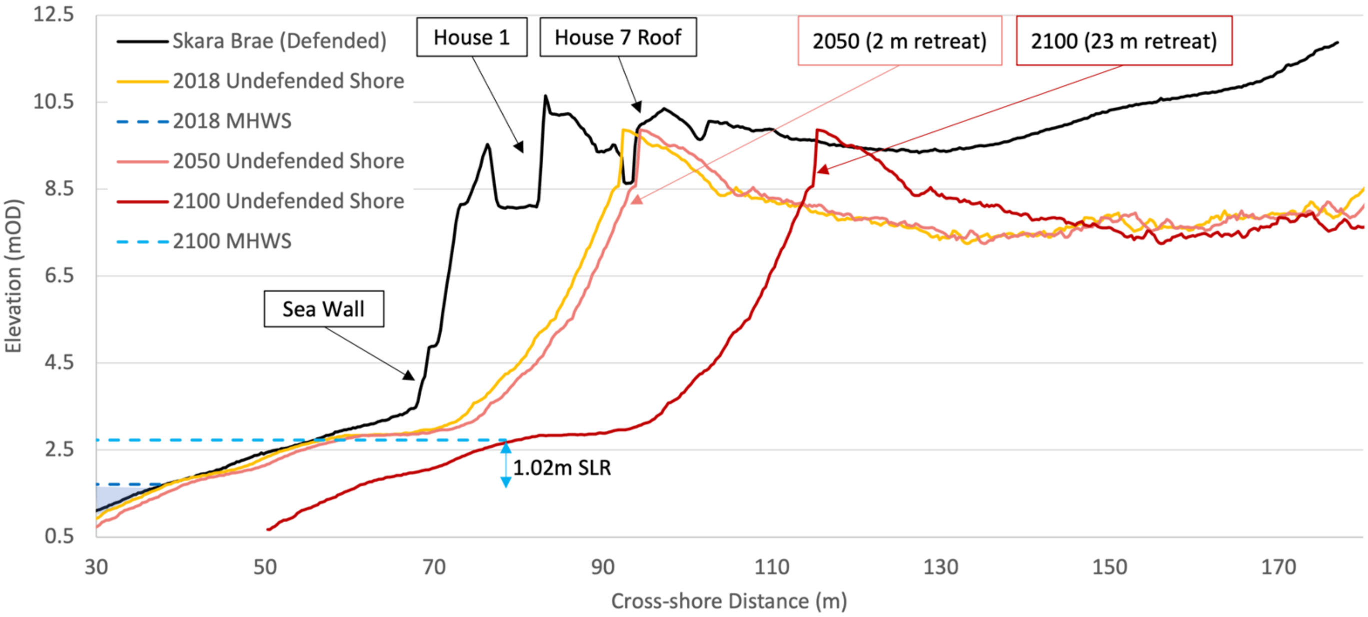

Figure 17 Representative cross sections through Skara Brae (black) and dune adjacent to Skara Brae (orange). 2 m (2050, pink) and 23 m (2100, red) horizontal offsets are applied to the undefended shore based on Modified Bruun MHWS projections under UKCP18 RCP8.5 95th%.

Whilst Figure 17 depicts a scenario where Skara Brae remains undefended, or has its defences breached, it also provides an insight on how isolated and exposed the protected village may become under a ‘do nothing scenario’, as the surrounding shores retreat landwards. Whilst seawalls are effective in protecting assets immediately landward, they often result in beach lowering in front and accelerated erosion of adjacent land and beaches, with flanking of the seawall. This typically leads to a cycle of exposure, repair and extension of defences *ad infinitum,* and serve to produce a defended promontory that is more exposed than before. Engineering defences that extend the entire length of the eroding edge is one of several options, but an alternative approach is to consider a more holistic bay-wide approach with wave energy absorption structures in the intertidal or nearshore, either engineered or nature-based, such as beach nourishment. An alternative approach in the longer term is to consider relocating the assets to a location that is inherently more resilient; however given the unique characteristics of the Neolithic village, this is not practical given current technologies.

Figure 18 Skara Brae sea wall showing latest phase of undermining of toe concrete to expose friable bedrock beneath. Bottom scene shows seawall end flanking and erosional bight resulting from ~0.4 m/yr retreat of Vegetation Edge, which now lies 20 m landward from the seawall.

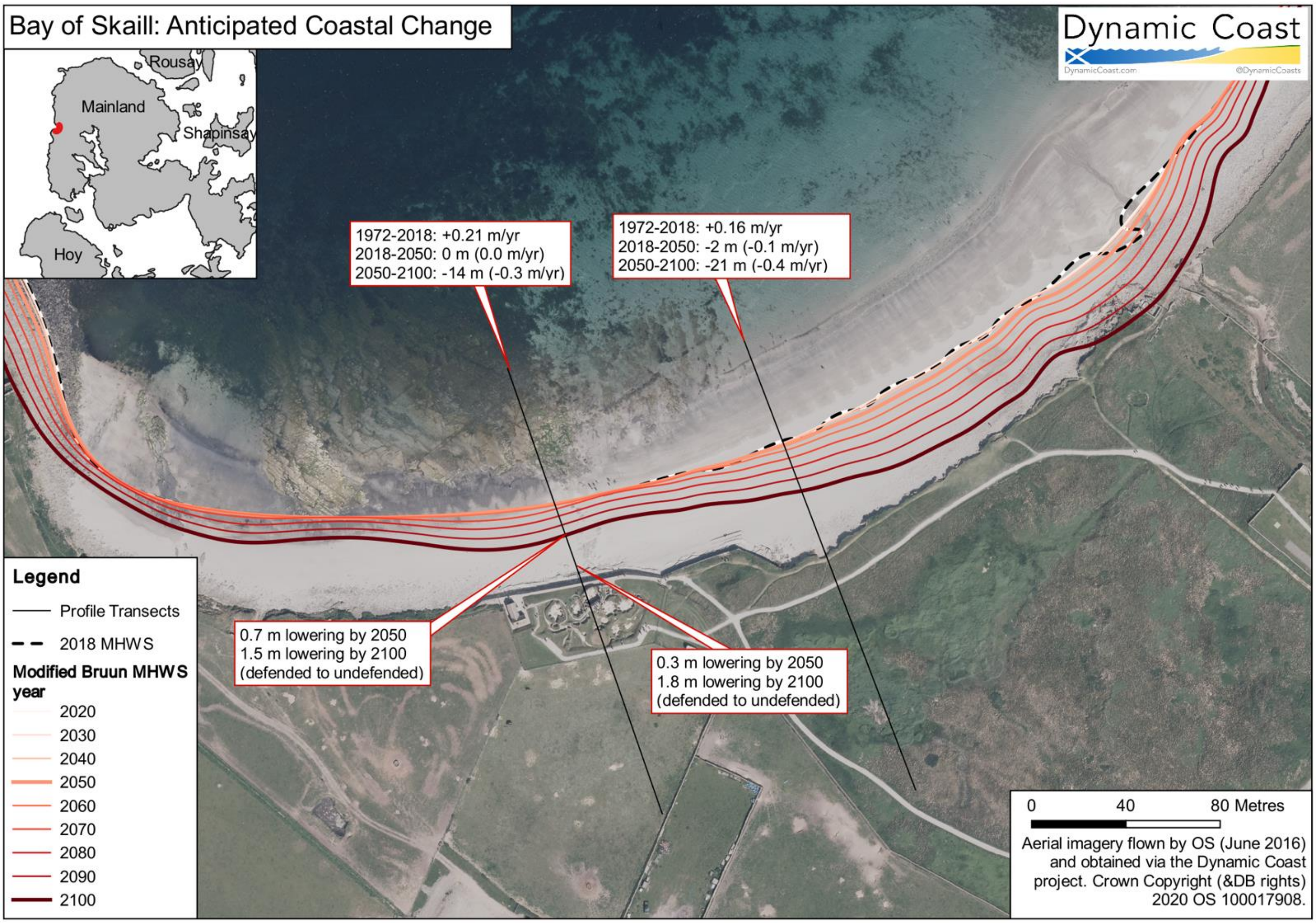

Figure 19 Anticipated beach lowering at sea wall toe: 0.3 m by 2050 and 1.8 m by 2100 {0.9 m by 2050 and 1.6 m by 2100}, excluding the artificially defended shore at Skara Brae

Figure 20 depicts the anticipated erosion and coastal evolution of the Bay of Skaill using a different model: the Coastal One-line Assimilated Simulation Tool (CoSMoS-COAST, Vitousek et al., 2017). CoSMoS-COAST is forced by the RCP8.5 95th% sea level change scenarios within UK Climate Projections 2018 (UKCP18) and models long-term shoreline migration due to sea level rise and includes wave-driven alongshore and cross-shore sediment transport processes. Validated with recent shoreline position observations from Dynamic Coast, shoreline change is then modelled to 2050 and 2100. The smaller-scale, more complex model shows an anticipated landward migration of the shore of 8–32 m by 2050 and a further -45 m by 2050, excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

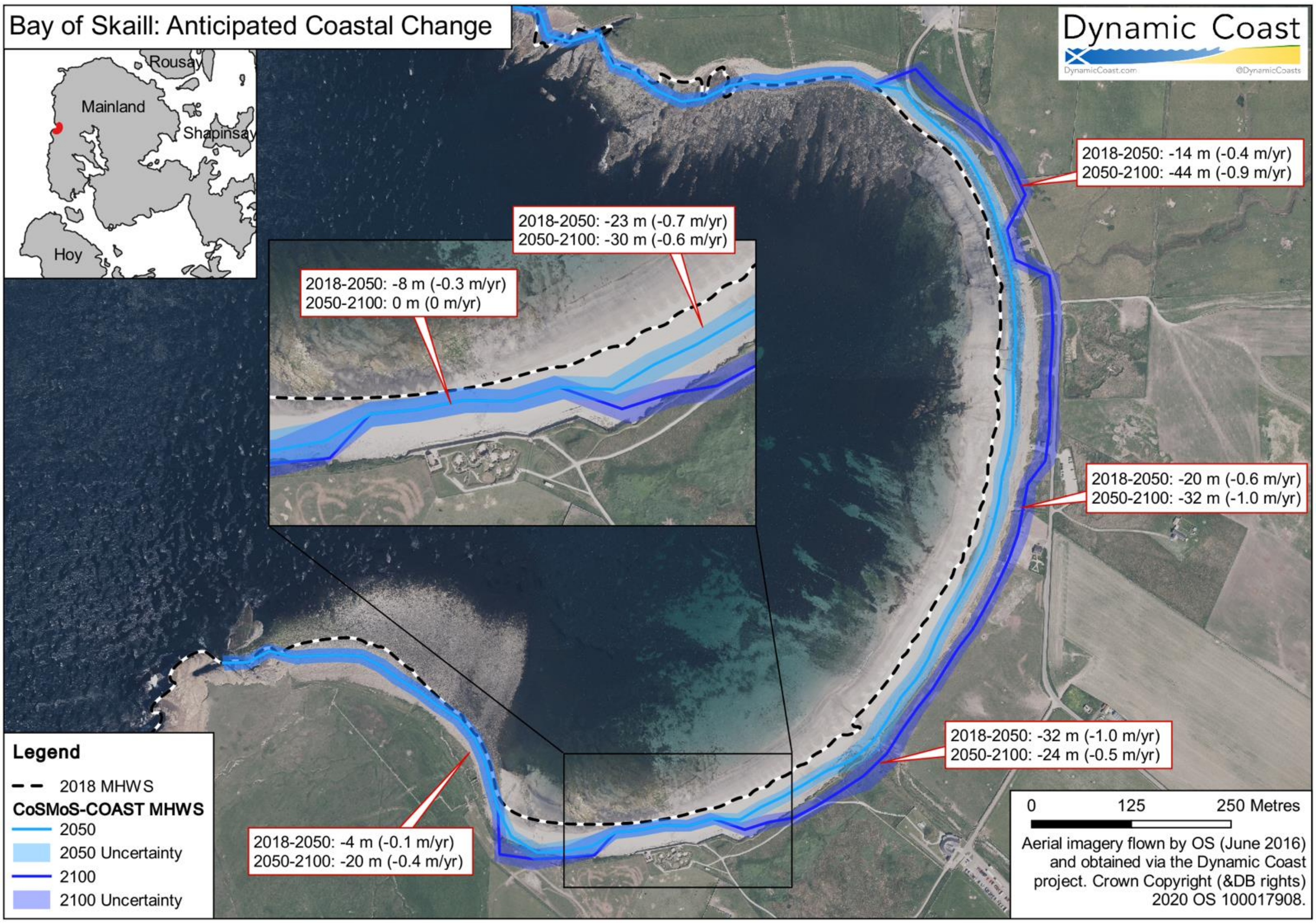

Figure 20 CoSMoS-COAST results for the RCP8.5 95th% sea level rise scenario (annotated with vector change from 2018 MHWS), excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

CoSMoS-COAST also adjusts its parameters to regular input of MHWS measurements, in the same way that the Modified Bruun Rule MHWS projections do (Figure 21). However, the irregular time gaps of shorelines in Montrose Bay (1890s to 1970s and 1970s to Modern) mean CoSMoS-COAST can make only limited adjustments to its modelled erosion rates and only partly captures the actual rates observed over the last decade. The long-term trend of erosion captured from 1972–2018 is magnified by the CoSMoS-COAST simulation with future SLR, and with close-to zero longshore sediment transport being modelled within the bay (due to the dominant cross-shore transport system), the rising sea level has a much greater impact on the bay than modelled using the Modified Bruun Rule. Additionally, the sharp and protective cliff dune morphology is not accounted for in the model in the same way as it is in the Modified Bruun Rule, so the potential for MHWS recession is greater. However, both models do predict extensive erosion by 2100 with a difference in position of 10–25 m for 2050 and 10–65 m for 2100 (mainly along the centre of the bay where CoSMoS-COAST has not limited recession using the past accretionary trend in MHWS as much as Modified Bruun), so CoSMoS-COAST can be viewed as a worst-case scenario.

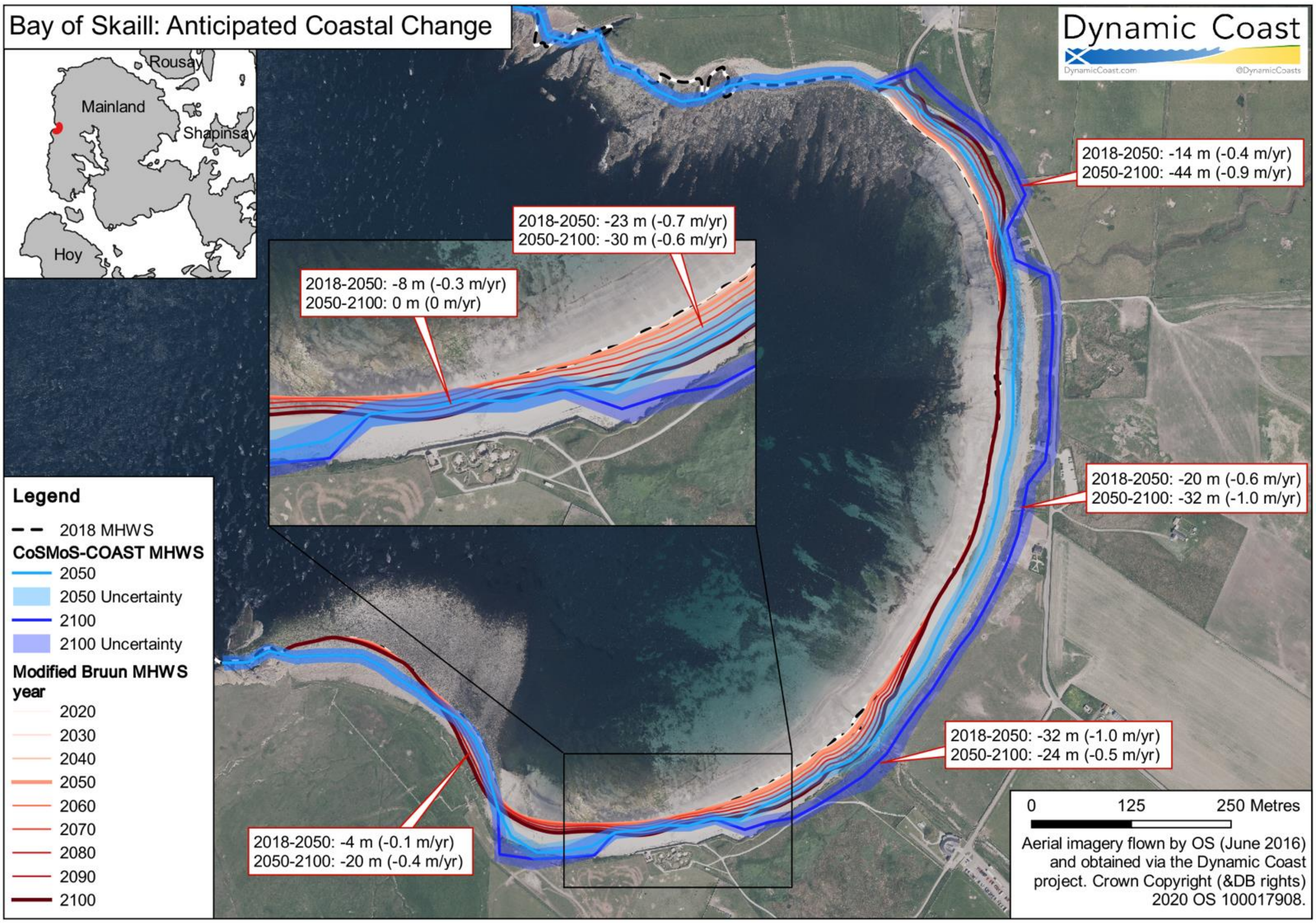

Figure 21 CoSMoS-COAST and Modified Bruun Rule approach comparison, excluding the artificially defended shores at both Skara Brae and a property (Seaview) in the north of the bay.

The anticipated erosion results assume that the hinterland is erodible but the presence of rockhead (the upper surface of bed rock) will serve to constrain the progress of erosion inland at any one location. Dynamic Coast research (2017) incorporated national datasets for rockhead altitude to curtail future erosion. These national-scale datasets are coarse (50 m pixel), but provide some impression of the proximity and altitude of rock exposures. Figure 22 suggests that the intertidal exposure of rock extends landwards and increases in altitude within the vicinity of Skara Brae (green pixels). However, the same cannot be said for the centre of the bay which has lower altitude rockhead (red pixels). Further investigations are recommended, to verify and appreciate the implications of local bedrock on future erosion.

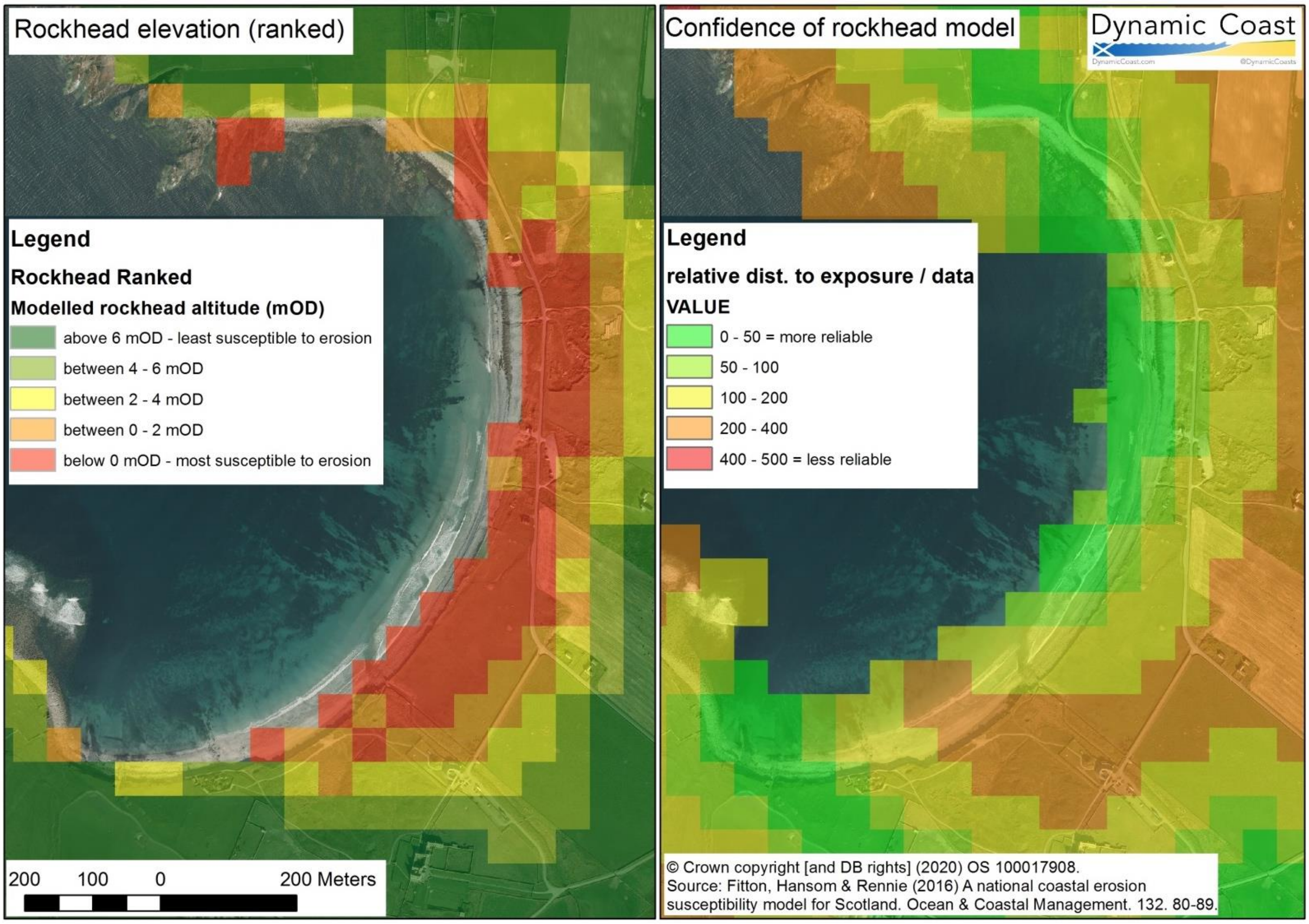

Figure 22 showing the modelled rockhead altitude within the Bay of Skaill (left), showing that surrounding Skara Brae rockhead is at altitudes which may curtail coastal erosion, unlike the centre of the bay. The confidence of the model is shown on the right image.

Mapping Coastal Erosion Disadvantage

For detailed methods and reporting on the approach taken below, the reader is directed to the Technical Annex Work Stream 6 –Mapping Coastal Erosion Disadvantage (www.dynamiccoast.com/reports). The Bay of Skaill super-site emerges from within the Social Vulnerability Classification Index as being “slightly resilient”. A slight resilience of the community residing within the Bay of Skaill area appears to be based upon these communities emerging from within the SVCI analysis as having slight levels of resilience, particularly, in three domains.

These domains include “physical and mental Health and Wellbeing”. It is therefore understood that the population residing in the areas of the Bay of Skaill have lower levels of individuals living with activity limiting health problems or disabilities and therefore the community emerges from the SVCI analysis as being more resilient. The second domain that contributes strongly to the Bay of Skaill’s moderate level of resilience is that of “Cohesive and Connected Communities”, which indicates that there were lower levels of social isolation, higher numbers of individuals able to utilise information and higher levels of social cohesion, which is the result, for example, of lower crime rates and fewer individuals living in single-person households. In considering evidence shows that factors within this second subdomain play a prominent role in community resilience to extreme events (Kazmierczak et al, 2015; Lindley et al 2011b; Sayers et al, 2018). The third most significant area that contributes to the resilience of communities within the Bay of Skaill Supersite region was that of economic prosperity, given that there were relatively fewer individuals identified as being employment deprived in the vicinity of the supersite. The relative economic prosperity of an area has been noted as playing a significant role in the resilience of communities to flooding events (Fitton et al, 2018; Lindley et al 2011b; Wade et al, 2005).

Areas wherein the Bay of Skaill supersite communities emerged as less-resilient within the SVCI analysis, included in the domains of physical assets, population and sustainable communities. Moreover, despite slight levels of resilience displayed by the community residing within Bay of Skaill, the SVCI results should be treated with caution given the context of the remote locale of the Orkney Islands, the remoteness of the community would present unique and complex challenges to both the immediate and long-term response to any coastal-erosion related flooding event. The isolated nature of the Orkney Islands necessitates consideration of the magnitude of impact of a potential coastal-erosion event on key and/or limited resources and infrastructure of the island and the island community as a whole. This may relate specifically to the maintenance of key transport nodes to, for example, provide essential supplies and lifeline routes onto the island. Resultantly, any coastal-related flooding event could severely compromise the resilience that the community appear to exhibit at present and may affect the long-term sustainability of the community.

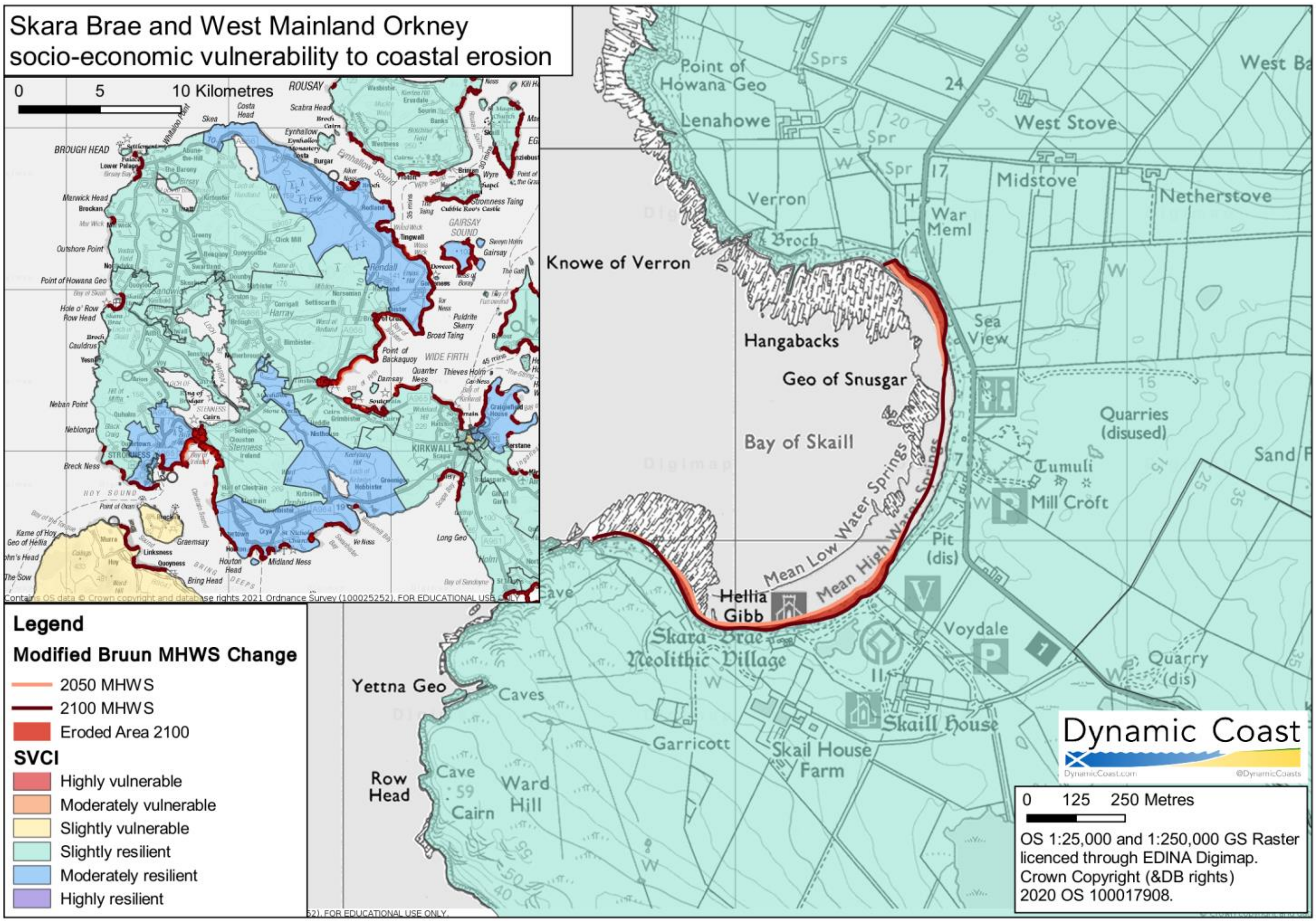

Figure 23 SVCI classifications per data zone with anticipated coastal change using the Modified Bruun Rule.

Flooding

Whilst sea levels are expected to quicken above past long-term averages, the land adjacent to the Bay of Skaill is sufficiently high to avoid being at risk of direct flooding for the foreseeable future. HES staff confirm that wave undermining and flanking of the seawall and wave thrown debris and spray is an ongoing issue at Skara Brae. With foreshore lowering the frequency and intensity of these processes is likely to increase in the coming decades.

Coastal Flood Boundary

The Coastal Flood Boundary (CFB) dataset published by DEFRA in 2018 (link) is reported in Table 2. It displays the anticipated still water surface level of surge events at various frequencies. Still water level calculations such as these superimpose the surge level on top of the highest astronomic tide level; and as such they exclude other dynamic hydrodynamic effects such as wave run-up etc; which would need to be considered to gain a realistic impression of worst-case storm impacts. Whilst in some parts of Scotland the recent update deviates from the last version, there is a negligible increase (1 cm) at Bay of Skaill. The current version of SEPA's published flood risk maps intersect the anticipated still water surface levels from the CFB analysis (above) with detailed topographic mapping to identify areas inundated under high (10 yr return period), medium (200 yr return period) and low (1,000 yr return period) probabilities. These extents exclude the wave run up and other hydrodynamic effects, considered below.

Table 2 Tidal and flood levels for Bay of Skaill

Description	Level (mOD)	Description	Level (mOD)
MHWS	1.79	1 yr (100% AEP)	2.99
HAT	2.3	10 yr (10% AEP) SEPA's High prob. event	3.31
Base year	2017	100 yr (1% AEP)	3.63
FID	1349	200 yr (0.5% AEP) SEPA's Med. prob. event	3.73
		1,000 yr (0.1% AEP) SEPA's Low prob. event	3.93

SEPA's Flood Risk Maps

The current version of SEPA's published flood risk maps show the high (10 yr return period), medium (200 yr return period) and low (1,000 yr return period) likelihood flood extents for coastal flooding, river flooding and surface water flooding. The coastal flood events are the anticipated still water surface levels from the CFB analysis (Table 2) intersected with detailed topographic mapping to identify areas which would be inundated, though these extents do not include the wave run up and other hydrodynamic effects, considered below.

Figure 24 shows the present-day high probability and low probability coastal flood extents, in greater detail than SEPA's Flood Risk Maps for Bay of Skaill's coastal flooding, as it benefits from a more recent digital surface model (2018) and is therefore more likely to represent actual current land and water levels. Figure 24 demonstrates the lack of entry points for coastal floodwater to inundate the backdune, highlighting the protective nature of the existing dunes.

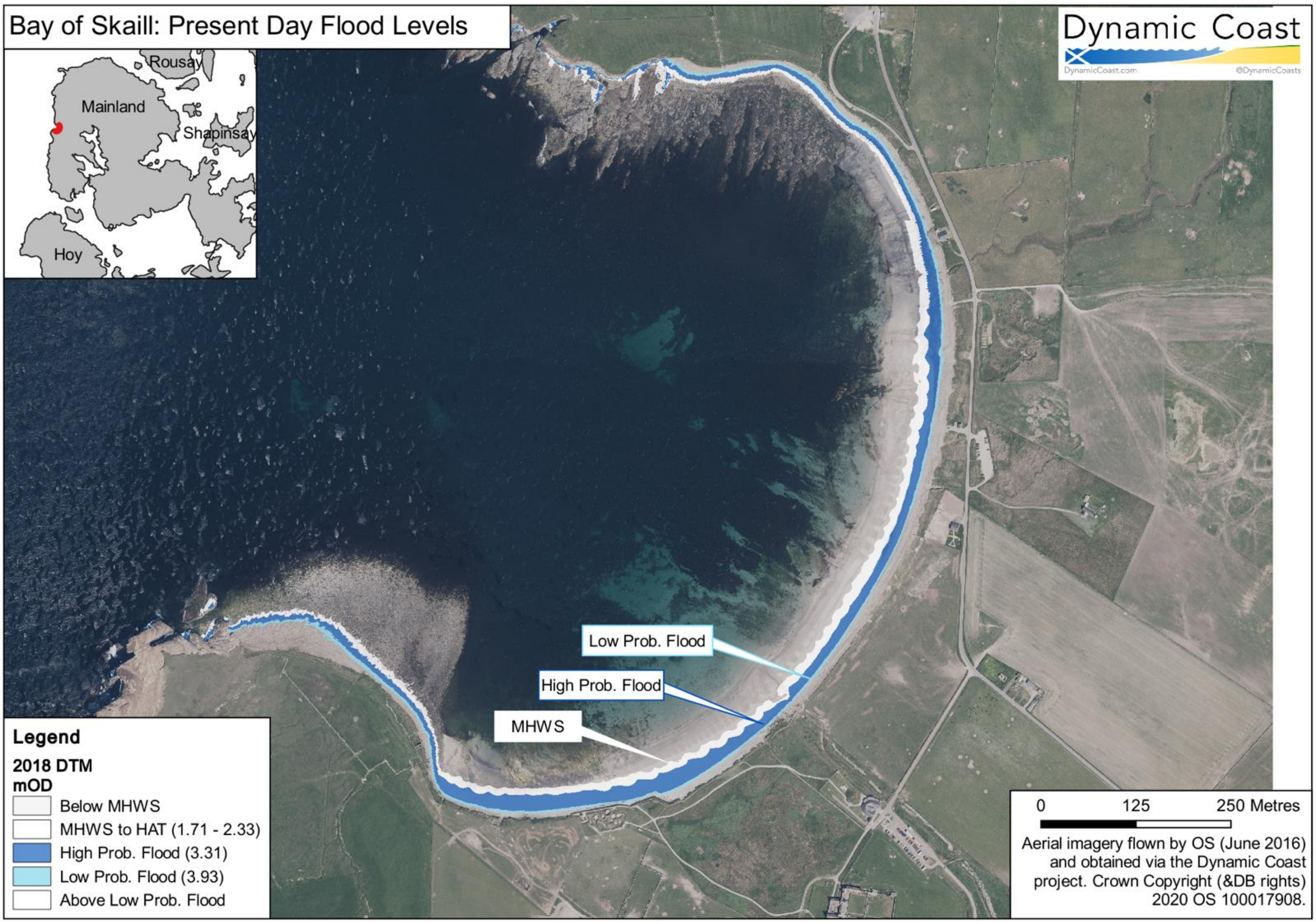

Figure 24 Summary of present day high probability (1:10 yr 3.34 mOD) and low probability (1:1,000 yr 3.84 mOD) flood levels at Bay of Skaill

Future Flood Risk

Sea level rise is expected to quicken above long-term averages, however the land adjacent to the Bay of Skaill is sufficiently high to avoid being at risk of direct flooding for the foreseeable future. Nevertheless, HES staff confirm that wave-thrown debris and spray is an issue at Skara Brae, given foreshore lowering the frequency and intensity is likely to increase in the coming decades. Figure 25 shows the key present day and anticipated flood elevations for Bay of Skaill. Highest Astronomic Tide is estimated to be at 2.33 mOD within the Bay of Skaill. Considering DEFRA's CFB elevations a high probability flood level of 3.31 mOD has a 1 in 10-year likelihood (ie 10% chance in any 1 year). Rising mean sea levels will result in tidal levels reaching levels previously only reached through storm events; thus by 2100 the level reached by the present day 1:10 year storm (3.31 mOD) will occur on the highest tides of the years (HAT & 2100 SLR = 3.35 mOD). See Figure 25 for a comparison of key present and future flood events.

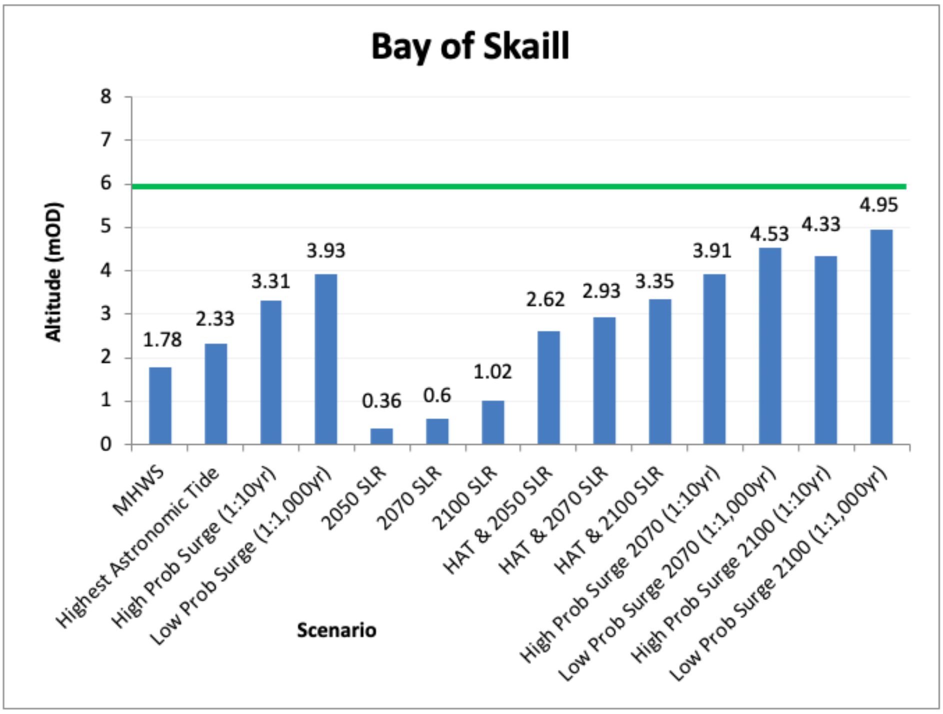

Figure 25 Summary of present and future key flood levels at Bay of Skaill. The green line identifies the altitude of adjacent low-lying areas at Bay of Skaill (~6 mOD).

Wave Run-up and Other Dynamic Components

Detailed consideration of wave run-up and overtopping potential has not been undertaken at Bay of Skaill and is outwith the scope of this study. Nevertheless, this is an aspect that merits further consideration in the future to determine its impact on the trajectory of the results presented here. The transformed wave data used within the CoSMoS-COAST model provide an indication of wave heights within the bay. Once transformed to the nearshore environment using the bay's morphology, the average wave heights for the period of 1980–2018 are 1.7 m across the centre of the bay, 0.5 m across the front of Skara Brae, and 0.8 m and 0.3 m at the north and south corners of the bay respectively.

Relative Sea Level Rise

The long-term (last 1 kyr) sea level trend at Bay of Skaill using glacio-isostatic adjustment modelling is a relative sea level rise of 0.4 mm/yr (Bradley, pers. Com. BRITICE_CHRONO project). These figures do not include changes to tidal variation but these are of smaller magnitude than increases in mean sea level.

The UKCP18 SLR data has been used to anticipate future increases in mean sea level at the Bay of Skaill (Table 3). Whilst there are considerable domestic and international efforts to cut greenhouse gas emissions, the recent global trends remain aligned with the High Emissions Scenario also known as Representative Concentration Pathway 8.5. For context, a 2°C future warming by 2100 corresponds to the RCP4.5 50% at 2085. 4°C corresponds to RCP8.5 50% by 2085 and the 5.5°C future corresponds to the 95% by 2085.

The anticipated increases in mean sea level at Bay of Skaill by 2050 is likely to be between 0.18 m and 0.36 m above the average levels seen between 1980–2000 (as likely as not to be above 0.26 m). Rates of sea level rise by 2050 are expected to be between 5 mm/yr and 10 mm/yr (as likely as not to be above 7 mm/yr). By 2100 the anticipated increase in mean sea level at Bay of Skaill is likely to be between 0.43 m and 1.02 m above the average levels seen between 1980–2000 (as likely as not to be above 0.67 m). Rates of sea level rise by 2100 are expected to be between 6 mm/yr and 16 mm/yr (as likely as not to be above 10 mm/yr).

Give the precautionary principle the 95% figures of the RCP8.5 are used throughout this assessment.

Table 3 Existing and future mean sea levels based on UKCP18 RCP8.5 for Dumbarton. Values in shaded row are used in example above

Year	MSL increase (m above 1981–2000 levels)			Period	Rate of increase (mm/yr)		
	5%	50%	95%		5%	50%	95%
2010	0.03	0.05	0.06	2000–2010	3.0	5.0	6.0
2020	0.06	0.09	0.12	2010–2020	3.0	4.0	6.0
2030	0.10	0.14	0.18	2020–2030	4.0	5.0	6.0
2040	0.13	0.19	0.26	2030–2040	3.0	5.0	8.0
2050	0.18	0.26	0.36	2040–2050	5.0	7.0	10.0
2060	0.22	0.33	0.47	2050–2060	4.0	7.0	11.0
2070	0.27	0.41	0.60	2060–2070	5.0	8.0	13.0
2080	0.33	0.50	0.73	2070–2080	6.0	9.0	13.0
2090	0.38	0.58	0.88	2080–2090	5.0	8.0	15.0
2100	0.43	0.67	1.02	2090–2100	5.0	9.0	14.0
2300	0.97	1.99	3.77	2100–2300	2.7	6.6	13.8

References

Day JC, Heron SF, Markham A, Downes J, Gibson J, Hyslop E, Jones RH, Lyall A (2019) Climate Risk Assessment for Heart of Neolithic Orkney World Heritage property: An application of the Climate Vulnerability Index. Historic Environment Scotland, Edinburgh. HES download page here.

Haasnoot et al (2019) Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. Environ. Res. Commun. 1 071006