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Dynamic Coast

Adaptation and Resilience Options for St Andrews Links

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Adaptation and Resilience Options for St Andrews Links

A.F. Rennie, J.D. Hansom, M.D. Hurst, F.M.E Muir, L.A. Naylor, R.A. Dunkley, & C.J. MacDonell

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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 aims to provide Resilience and Adaptation Options for organisations with coastal erosion and flood risk management responsibility including St Andrews Links Trust (SALT), Fife Council (FC), Scottish Environment Protection Agency (SEPA), and NatureScot.

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. See the link below for an interactive web-map of the results:

Browser link
www.dynamiccoast.com/webmaps.html

Acknowledgements

Euan Loudon, Sandy Reid and Gordon Moir (St Andrews Links Trust); West Sands Partnership, Ranald Strachan (Countryside Ranger, Fife Coast and Countryside Trust), Dr Clare Maynard (GreenShores project, University of St Andrews) and the community volunteers who have invested in their links, providing the sound foundations for further necessary resilience and adaptation actions to maintain the links for the rest of the century.

Executive Summary

1. St Andrews Links, as the international Home of Golf, comprises six golf courses supporting 230,000 rounds of golf annually. The coastal sand dune cordon at St Andrews provides natural erosion and flood protection to the golf courses and other infrastructure within the low-lying interior. Historically, the dunes have grown east and northwards towards the sea, although this has slowed over recent decades with some erosion now occurring at several locations.
2. Since 2010, St Andrews Links Trust together with the West Sands Partnership have worked to enhance the natural protection of the dune ridges and salt marshes within the Eden estuary, to reduce the flood risk to the lower-lying links areas.
3. Updated aerial surveys have identified erosion affecting much of the upper beach on the West Sands, and under a 'do nothing scenario' even currently stable areas are expected to retreat in the next 30 years. The Jubilee 8th to 10th holes may be threatened in the next twenty years, along with the access road, returning the peninsula towards is 18th century extent. Under the same scenario, the Swilcan dunes are expected to retreat increasing the erosion and flood risks to the Club House car park during the second half of the century.
4. Recent analysis shows much of the dunes to be flood resilient, but there remains a current flood risk at the Swilcan Burn and at several low points in the east-facing West Sands dunes and on the southern Eden Estuary shore. As sea levels continue to rise, fair-weather flooding (i.e. tidal inundation without storms) is anticipated from 2070. Rainfall-related waterlogging is already being noticed, and is likely to worsen within low-lying areas.
5. St Andrews Links Trust, and the West Sands Partnership have shown commendable leadership by successfully deploying building with nature approaches which enhance the present links natural flood protection function. However rising sea level (alongside other factors) is likely to increase the extent and rate of erosion. Thus, existing efforts will need to be scaled up to maintain the dune cordon's protective function to the links within.
6. Proactive short-term actions addressing the above flood risk areas, alongside targeted dune resilience measures would allow time to develop detailed proposals to manage flood risk over longer-time periods. Such an approach within a flood risk management plan consistent with the adaptive approaches defined within the Fife Council Shoreline Management Plan 2, could provide a flexible adaptive approach for managing threatened assets within the links. Whilst erosion risks can be mitigated, as sea levels continue to rise the low ground levels (particularly on the Eden & Strathtyrum Courses) are the main points of weakness which will likely prompt the need for adaptation within parts of the links.
7. Close cooperation between St Andrews Links Trust, West Sands Partnership & community volunteers, has been crucial in the success of resilience and biodiversity improvements; and is vital going forward.

St Andrews Super Site Summary

Introduction

This report sets out resilience and adaptation options for St Andrews Links (Fife) and reflects the shared view of Dynamic Coast and St Andrews Links Trust (SALT). Its scope covers the links area north of St Andrews town, including part of the south side of the Eden Estuary (Figure 1). The report aims to support key partners in their planning for anticipated increases in the threat of coastal erosion and flooding. The Executive Summary and technical annex below are not intended to be 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 in the coming decades.

The 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 St Andrews Links

Substantial coastal change has occurred within the St Andrews Links (Figure 1) over the last 130 years, with accretion dominating much of the peninsula that extends north into the Eden estuary (Dynamic Coast 2017). Detailed assessments in the Technical Summary below identify that conditions are now changing and erosion and flood risk are real and growing threats to the St Andrews Links and the assets within and around them. Pre-industrial relative sea levels were falling slowly here (1 mm/yr fall), due to the land benefiting from isostatic uplift. However, latest projections expect St Andrews to experience sea level rise of up to 0.9 m by 2100, at a rate of up to 14 mm/yr[2]. As a

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

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

result, past accretion and recent stability is expected to be replaced by erosion, which is likely to quicken in rate over the coming decades.

Dynamic Coast research anticipates, under High Emissions Scenario and a "do nothing" coastal management strategy, that the Out Head section of West Sands at St Andrews will retreat into the links by up to 240 m in the next 30 years and up to ~750 m by 2100. Direct flooding from the sea is also a growing risk to the golf course and some assets. Potential routes for flooding have been identified at the Swilcan Burn, Eden and West Sands shores. The threat of erosion enhanced flooding is anticipated in the coming decades, unless the current nature based solutions are expanded. The Technical Summary contains more detailed summary of research outcomes.

Shoreline Management Planning context

Fife Council Shoreline Management Plan 2 (LINK coming) outlines the Council's policy approach (as voted by Fife Council Committee). The range of options varies from No Active Intervention (NAI), Managed Realignment (MR), Hold the Line (HTL) and Advance the Line (ATL). The Council's stated policy is outlined below (Fife SMP2):

- St Andrews — by 2030s, 2060s and 2100 'Hold the Line'
- St Andrews golf links — by 2030s, 2060s and 2100 'Hold the Line'
- St Andrews Golf links to Guard Bridge — by 2030 Manage Realignment, 2060 & 2100 Hold the Line

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 and relocation of assets is likely to be required to manage long-term risks from sea level rise, regardless of any coastal risk management options taken now (Haasnook et al 2019). Where the need for coastal adaptation is increasingly urgent (globally and locally), more transformative solutions may be needed. Whilst the generic aspects of these concepts are explored within the National Overview Report (www.DynamicCoast.com/reports). This document explores management options at St Andrews Links, within the context of international best practice. To facilitate adopting an adaptation approach 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, which aim to reduce long-term costs of maintaining defences. These align with the Intergovernmental Panel on Climate Change (IPCC)'s 2019 report on coastal climate change. 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 in the coming decades. The Fife Council SMP, published in 2011, considers the risks posed by climate change from flooding. However, given the coastal change method for estimating future erosion was based on historic rates, the SMP does not reflect the anticipated increasing amount of erosion and erosion-enhanced flooding that sea level rise might bring. Whilst the SMP retains value, the absence of these factors mean that policy makers currently assume a more static shoreline than is anticipated There are more recent planning approaches that adopt the need for flexibility and adaptation. For example, in Scotland the emerging Clyde Regional Marine Plan provides an exemplar of coastal policy, in support of more transformative forms of adaptation that may be applicable.

Dynamic Coast provides the evidence base to assess current and future coastal erosion risks for landowners and local government to take risk-informed decisions. The generic coastal risk management and adaptation options lie along a spectrum that aligns closely with the standard policy options in Shoreline Management Planning - from **no-active intervention (doing nothing)**; **accommodate erosion** by adapting strategic plans and relocating existing assets or land uses; **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 (see National Overview Report for context). Table 1 outlines the past erosion rates observed at St Andrews, identifies the areas at greatest risk and suggests management and adaptation options. All risk management and adaptation actions require robust appraisal to allow organisations to better manage coastal erosion risk and improve societal and ecosystem resilience.

Coastal erosion, flooding and erosion-related flooding are considered as the key risks impacting St Andrews now and in the future. Whilst the responsibility for coastal erosion consequences rests with landowners; local authorities (LA), in this case Fife Council, have powers to address coastal erosion under the Coast Protection Act 1949. Fife Council also has shared powers under the Flood Risk Management (Scotland) Act 2009 and produce a local flood risk management plan under the flood act. The Climate Change (Scotland) Act 2010 includes a statutory duty to report on climate change adaptation progress. Guidance on planning for coastal change can be found here (SNH, 2019, http://www.dynamiccoast.com/links.html), though supplementary guidance from the Scottish Government is called for within our recommendation.

The St Andrews peninsula is sub-divided here into management unit areas (which are smaller than the Policy Units in the Fife Shoreline Management Plan 2.), Considering these in turn from south to north (Figure 2, Table 1), each has specific adaptation and resilience recommendations. These options address the risks of **beach and dune erosion on the Swilcan Burn and West Sands (Area 1 & 2)**, **salt marsh and dune erosion on the Eden shore (Areas 3–4)**, **flooding via Swilcan Burn (Area 1)** and **breach-points in the West Sands and Eden shore (Areas 2–4)**. Whilst flooding is a present and growing issue, the direct risks from erosion in the coming thirty years is increasing. As a result, the next few decades present opportunities to enhance the natural beach and dune protection of the links shore and saltmarshes along the links Eden shore. Beyond 2070 flood risks increase further and will increasingly present routine and periodic issues. Each management option will have differing effectseffects on sediment dynamics, beach function and the natural capital that coastal systems provide. Importantly, these responses to managing coastal erosion risk must involve both the management of activities on land as well as at the coastal edge. It follows that adaptation of the at-risk components of golf courses by shifting inland and away from the zone of most risk, is encouraged to ensure a flexible adaptive strategy to allow world class golf still to be played here into the 22nd Century.

Identifying and securing adaptation space now, gives future decision makers more flexibility and choice, when climate change impacts are greater.

It is important to note that many of the adaptation options presented here require **strategic planning decisions to be taken *now*, to provide physical and policy space for future adaptation action** to be possible. For example, if planning permission is granted now for assets or infrastructure on land that may be at 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. These concepts are acknowledged within the National Planning Framework 4 and National Land Use Strategy.

Resilience and Adaptation Options at St Andrews Links

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

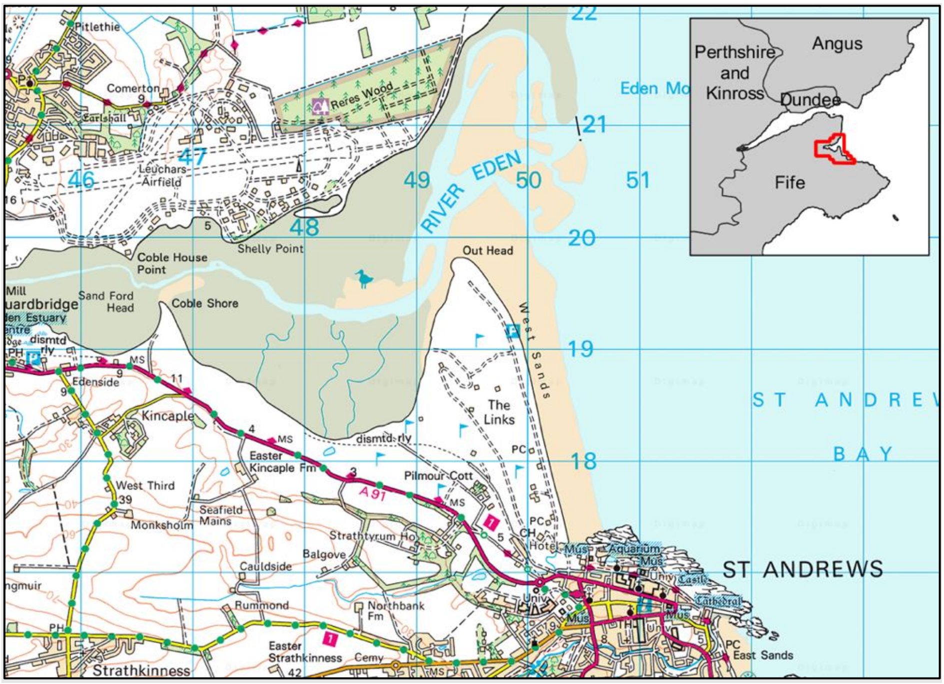


Figure 1 Location map of St Andrews Links. Grid squares are Easting and Northing of size 1 km x 1 km. Crown copyright and database rights OS 2020 100017908.

Figure 2 Management unit areas for Resilience and Adaptation Options at St Andrews Links. Labelling relates to Table 1

Table 1 Potential Resilience and Adaptation Options for St Andrews Links. Sections grouped by management unit area, past and anticipated changes alongside 'do nothing' implications. Short and Longer-term options are outlined. Consultation and costs benefit appraisal would proceed any implementation.

Area	Shore Character and Assets	Coastal changes* Gain = seaward movement. Loss = landward movement	"Do nothing" Implications	Future – 'Short term' options (0–5 yrs): (see description at bottom of table) {options ordered from avoidance to resist} Note Risks are explained in table footer.	Future – 'Medium (5–10 yrs): and Long term (10–30 yrs): options
1: Swilcan Burn Mouth Artificial planting & sand-fed dunes (Note these interventions have influenced the changes reported) 	Sea wall (east) and fed dunes (west), fronted by wide sandy intertidal. Golf courses, road, SALT buildings Utilities etc.	<u>Low Water</u> 1981–2018: 45 m loss <u>High Water</u> 1893–1993: 130 m gain 1993–2009: 4 to 20 m gain 2009–2018: 12 to 16 m loss <u>Surface change</u> 2013–2018: Foreshore -0.3 to +0.5 m Dune face +0.6 m <u>Vegetation Edge:</u> 1850–2007: 50 to 120 m gain 2007–2018: 8m gain	HW erosion by 2050 28 m lost / 2050–80 39 m lost / 2080–2100 86 m lost Foreshore lowering and steepening, retreat of MLWS. Dune erosion is anticipated from 2030 (<1 m/yr). Greater changes to Swilcan Burn mouth and associated incr. wave overtopping risks. Reduction in amenity beach and access points.	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Loss of natural sections of amenity beach. Cost: zero; Risk: high. **<u>Accommodate Erosion</u>:** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Managed Realignment:** Phased re-location of at risk assets to resilient and sustainable locations inland. Cost: high; Risk: moderate. **<u>Erosion Resist:</u>** 1. **Enhance defences (0–10 yrs):** Direct hard defences constructed at toe of dunes. Cost: high; Risk: high. 2. **Feed beach & dune (0–10 yrs):** Short-term local repair to beach and dune profile to improve natural resilience of the beach at Swilcan Burn mouth. Cost: low; Risk: moderate. 3. **Reprofile upper beach (0–5 yrs):** Short-term local repair to upper beach profile to improve natural resilience of beach at Swilcan dunes (as done in 2010). Cost: low; Risk: moderate. 4. **Low cost flood protection measures on Swilcan (0–5 yrs):** Consider subtle land-raising adjacent to Clubhouse and Old course to enhance natural protection features. Cost: low; Risk: moderate. 5. **Moderate cost flood protection measures on Swilcan (0–5 yrs):** Local repair and re-profile on dune toe; Swilcan burn edge linked with sluice flap system (weak point in 2010 surge event). Water controls applied to the Swilcan to manage flow to prevent flood but also beach erosion from excess outfall. Cost: high; Risk: moderate.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Loss of natural sections of amenity beach. Cost: zero; Risk: high. **<u>Accommodate Erosion</u>:** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependent on locally defined trigger points, space on land needs to be safeguarded for option. 2. **Realign roadways and relocate assets:** Coach car park (by 2050) and road (by 2060) at risk, some realignment within existing car park would avoid risks up to 2060. After this little accommodation space without impinging on golf course. Cost: moderate; Risk: low **<u>Erosion Resist:</u>** 1. **Feed beach:** On-going repair to upper beach profile to improve natural resilience of beach at Swilcan dunes (as done in 2010). Cost: low; Risk: moderate. 2. **Combined beach feed & enhanced Swilcan defences (2050):** fronting beach nourished with sand maintain amenity and reduce wave impact on existing structures which are allowed to remain in place. In combination with further land-raising adjacent to Clubhouse & Old course, or flood protection measures on Swilcan. Cost: high; Risk: low **<u>Advance:</u>** **Mega nourishment (2050)** beach & dune reshaping could benefit the entire bay and reduce risk of erosional breach and erosion-related flooding. Cost: high; Risk: low
2: West Sands to Out Head Natural sand dune with a wide low-angled beach. Occasional pockets of dune rehabilitation (Note these interventions influence changes reported) 	Golf courses, road, SALT buildings Utilities etc.	<u>Low Water</u> 1981–2018: 90 to 130 m loss <u>High Water</u> 1893–1993: 160 to 250 m gain 1993–2013: 15 to 100 m gain 2013–2018: 12 to 35 m loss <u>Volume</u> 2013–2018: Foreshore -1.2 to +0.3 m Dune face +0.9 m <u>Vegetation Edge:</u> 1850–2007: 190 to 420 m gain 2007–2018: 5 m loss to 25 m gain	Foreshore lowering and steepening, retreat of MLWS. Dune erosion is anticipated from 2030 (<1 m/yr). Landfill at immediate risk of exposure. By 2050 turning circle at risk By 2070 Course, Coach park & West Sands Road at risk from retreating Veg Edge. Reduction in amenity beach and access points.	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Loss of natural sections of amenity beach and dune cordon. Exposure of landfill. Cost: zero; Risk: high. **<u>Accommodate Erosion</u> :** **1. Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for options 1. **Managed Realignment (now onwards):** Support West Sands Partnership to realign public access routes through dunes. Using low-cost dune profiling, boardwalks where appropriate and sand nourished 'clavicular gate' system on beach side. Ongoing since 2017, continue. Cost: moderate; Risk: moderate. 2. **Pro-active management strategy (0–20 yrs):** Annual West Sands Partnership meeting to define actions, secure licence and consent. Cost: low; Risk: low. 3. **Building with Nature (0–20 yrs):** Encourage and implement dune health recovery via biodiversity support projects such as dune-grass planting.Cost: low; Risk: low. **<u>Erosion Resist:</u>** 1. **Feed beach (0–10 yrs):** Short-term local repair to whole beach profile to improve natural resilience of the beach fronting the dune cordon. Cost: low; Risk: low. 2. **Dune cordon repairs (0–5 yrs):** Maintain the protection provided by the dune cordon in to reduce the short term risk of a breach in seaward dune to give flood access to dune corridors. Cost: low; Risk: low. 3. **Reprofile upper beach (0–5 yrs):** Short-term local repair to upper beach profile to improve natural resilience of beach fronting the dune cordon. Initially at Landfill Cost: low; Risk: low. 4. **Emergency response protocol (0–5 yrs):** Using free beach sand prior to predicted surge events, dozer beach side access points and flood channel areas. Re-profile once surge threat subsides. Cost: moderate; Risk: moderate.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Loss of natural sections of amenity beach and dune cordon. Cost: zero; Risk: high. **<u>Accommodate Erosion</u> :** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for option 2. **Managed Realignment (2040 onwards):** Phased re-location of at risk assets (West Sands Road (2040) & Jubilee holes) to sustainable locations. Phased & reduced use of grass parking areas to allow dune roll-back and maintain width & resilience of dunes. Potential for residual erosion-related flood risk remains (2070–2100), with risks to assets, Club House & Green Keepers building (2090). Cost: high; Risk: high 3. **Set back flood embankments within links interior (2050):** Provide barrier to overland flow from the golf course links overtopping during extreme events. Cost: low; Risk: moderate. **<u>Erosion Resist:</u>** 1. **Feed beach (2040 onwards):** Long-term beach nourishment programme to maintain beach & dune profile to enhance protection provided by dune cordon over the long term and reduce risk of breach and erosion-related flood. Cost: moderate; Risk: low. 3. **Extend defences (2040 onwards):** Direct defences (e.g. boulder revetment) install along West Sands to protect dune toe & adjacent cordon and corridors from ongoing erosion. Risk of foreshore lowering and beach loss reduces likely lifespan of defences and recreational value of beach to residents and visitors Cost: very high; Risk: moderate to high. 4. **Combined beach feed & defences (2050):** fronting beach nourished with sand maintain amenity and reduce wave impact on existing structures which are allowed to remain in place. In combination with direct defences and other land-raising adjacent to low points in dunes. Cost: high; Risk: moderate to high **<u>Advance:</u>** **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

Area	Shore Character and Assets	Coastal changes* Gain = seaward movement. Loss = landward movement	"Do nothing" Implications	Future – 'Short term' options (0–5 yrs): (see description at bottom of table) {options ordered from avoidance to resist} Note Risks are explained in table footer.	Future – 'Medium (5–10 yrs): and Long term (10–30 yrs): options
3: Eden Estuary (north) Natural and fed dunes, sloped and vertical gabions, fronted by narrow beach merging with natural and enhanced salt marsh. Dune ridge high, apart from southern section. 	Golf courses	Low Water 1981–2018: 190 m loss High Water 1893–1981: 54 m loss 1981–2013: 20 m loss 2013–2018: 40 m gain to 5 m loss Volume 2013–2018: Foreshore -0.1 to +1.3 m Dune face -3.0 to +2.5 m Vegetation Edge: 1850–2007: 52 m loss 2007–2018: stable	Foreshore & beach lowering, dune recession. Potential undermining of existing dunes, fed-dunes and defences (2030 onwards). Erosion risk to Jubilee 8th hole (2030 onwards?) Residual flood risk generally low (due to high ground levels), but higher at south. Loss of amenity beach.	**Non-Active Intervention:** 1. **Monitor change/no intervention:** Loss of natural sections of amenity beach, dune toe and fed beach. Exposure & undermining of defences. Loss of Jubilee 8th hole. Cost: zero; Risk: high. **Accommodate Erosion:** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Managed Realignment (now onwards):** Phased re-location of at risk assets (Jubilee 8th hole) to sustainable locations. Cost: moderate; Risk: moderate. 3. **Land-raising on coastal edge (0–20 yrs):** modest raising of coastal edge (southern section only) would reduce flood overtopping risk. Cost: low; Risk: low. 4. **Feed beach & dune (0–10 yrs):** Short-term local repair to whole beach profile (as in 2000 and 2015) to improve natural resilience of the beach fronting the dune cordon and defences. Cost: low; Risk: low. 5. **Dune cordon repairs (0–5 yrs):** Maintain the protection provided by the dune cordon to reduce the short term risk of a breach in seaward dune to give flood access to dune corridors. Interior land-levels are mostly high so residual risks are low. Cost: low; Risk: low 6. **Reprofile upper beach (0–5 yrs):** Short-term local repair to upper beach profile to improve natural resilience of beach fronting the dune cordon and defences. Consider lowering dune heights at dunes adjacent to Jubilee 8th hole to reduce wind scour of beach. Cost: low; Risk: low. **Erosion Resist:** 1. **Extend defences (0–20 yrs):** Direct defences (e.g. sloped gabion baskets / boulder revetment) extended from existing Eden defences. Risk of foreshore lowering and flanking. Cost: high; Risk: moderate. **Advance:** 1. **Saltmarsh creation (2050)** would benefit the entire Eden and reduce risk of erosional breach and erosion-related flooding.	**In addition to continued deployment of short term options:** **Non-Active Intervention:** 1. **Monitor change/no intervention:** Loss of natural sections of amenity beach, dune toe and fed beach. Exposure & undermining of defences. Loss of New 9th hole, Eden 4th & 7th holes. Monitor change/no intervention. Cost: zero; Risk: high. **Accommodate Erosion:** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Dune cordon repairs (2040 onwards):** Maintain the protection provided by the dune cordon to reduce the short term risk of a breach in seaward dune to give flood access to dune corridors. Interior land-levels are mostly high so residual risks are low. Cost: low; Risk: low 3. **Reprofile upper beach (2040 onwards):** Short-term local repair to upper beach profile to improve natural resilience of beach fronting the dune cordon & defences. Cost: low; Risk: low. 4. **Feed beach & dune (2040 onwards):** Short-term local repair to whole beach profile (as before) to improve natural resilience of the beach fronting the dune cordon and defences. Cost: low; Risk: low. **Erosion Resist:** 1. **Extend defences (2040 onwards):** Direct defences (e.g. sloped gabion baskets / boulder revetment) extended from existing Eden defences. Risk of foreshore lowering and flanking. Cost: high; Risk: moderate. 2. **Land-raising on coastal edge (2040 onwards):** modest raising of coastal edge (southern section only) would minimise overtopping risk. Cost: low; Risk: low. **Advance:** **Saltmarsh creation (2050)** would benefit the entire Eden and reduce risk of erosional breach and erosion-related flooding.
4: Eden Estuary (south) Salt marsh (partially enhanced) in front of narrow embankment, low lying interior 	Golf course, low-lying land with farmland and A91 arterial route into St Andrews from the west.	Low Water 1981–2018: stable High Water 1893–1981: 8 to 52 m gain 1981–2013: 34 m loss 2013–2018: 25 m gain Volume 2013–2018: Foreshore +0.2 m Dune face +0.5 m Vegetation Edge: 1850–2007: 16 to 25 m loss 2007–2018: 7m gain	Foreshore & beach lowering, Potential undermining of existing dunes and defences (2030 onwards). Erosion & flooding risk to Eden course (2030 onwards) Residual flood risk high (due to low ground levels). Increased water-logging (from 2030) Fair weather flooding (from 2050) Loss of amenity beach.	**Non-Active Intervention:** 1. **Monitor change/no intervention:** Loss of natural sections of salt marsh. Exposure & undermining of defences. Periodic flooding to golf holes (**Eden,** (13th–15th, 6th winter) and Strathtyrum (3rd–5th & 11th–14th) Cost: zero; Risk: high. **Accommodate Erosion:** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Managed realignment of field & enhanced salt marsh farming (from now):** Investigate breach of historical embankment plus new embankment on SE side to reduce flood risk to golf assets. Design to encourage salt marsh growth, as part of wider salt marsh expansion within the Eden Estuary & C-sequestration plan. Cost: moderate; Risk: moderate. **Erosion Resist:** 1. **Extend defences (0–20 yrs):** Direct defences (e.g. sloped gabion baskets/boulder revetment) extended from existing Eden defences. Risk of foreshore lowering and out-flanking by erosion. Cost: high; Risk: moderate. 2. **Land-raising on coastal edge (0–20 yrs):** embankment enhancements (targeted widening & raising) to minimise overtopping risk. Cost: low; Risk: low. 3. **Enhanced salt marsh (0–10 yrs):** Short-term expansion of salt marsh enhancements to increase extent, roughness and consequential flood protection function. Cost: low; Risk: low.	**In addition to continued deployment of short term options:** **Non-Active Intervention:** 1. **Monitor change/no intervention:** Loss of natural sections of salt marsh. Exposure & undermining of defences. Periodic flooding to golf holes (**Eden,** (13th–15th, 6th winter) and Strathtyrum (3rd–5th & 11th–14th). Cost: zero; Risk: high. **Accommodate Erosion:** 1. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Internal reorganisation of golf assets (2040 onwards): Re-configure at risk holes on Eden,** (13th–15th, 6th winter) and Strathtyrum (3rd–5th & 11th–14th) within existing Balgove course and adjacent areas. Careful consideration of drainage & flood implications. Land raising may be an option for flood control but ineffective for erosion. Cost: medium; Risk: low. 3. **Managed Realignment (2050 onwards):** Phased re-location of at-risk golf assets (Eden 13th–15th, 6th winter. Strathtyrum 3rd–5th & 11th–14th) to sustainable locations inland. Land raising may be an option for flood control but ineffective for erosion. Careful consideration of drainage & flood implications Cost: high; Risk: moderate. **Erosion Resist:** 1. **Investigate further enhance drain capacity (2040 onwards):** to address waterlogging & fair-weather flooding on lower sections of course. Adjacent land could provide flood amelioration. Cost: moderate; Risk: low. 2. **Extend defences (2040 onwards):** Direct defences (e.g. sloped gabion baskets / boulder revetment) extended from existing Eden defences. Risk of foreshore lowering and out-flanking by erosion. Cost: high; Risk: moderate. 3. **Land-raising on coastal edge and A91 (2050):** modest raising along embankment to minimise overtopping risk **and** set-back embankment for increased flood protection to A91. Cost: moderate; Risk: moderate. **Advance:** 4. **Saltmarsh creation (2050)** would benefit the entire Eden and reduce risk of erosional breach and erosion-related flooding.

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

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

This section briefly expands, by area and management option, some of the key points emerging from Table 1. For example, if **No Active Intervention** (NAI) is to be the preferred policy option at St Andrews, then beach and/or dune cordon erosion or lowering will continue to occur, in both the short and long-term. At St Andrews, there are no recommended options to **Advance** the current coastal position using **erosion resist** options (i.e. offshore traditional engineering structures) such as breakwaters on grounds of cost and environmental impact on the adjacent coast. However, use of a large-scale **nature-based erosion resist** option, such as a mega nourishment programme, shouldn't be excluded in the longer-term. All other recommended **erosion resist measures** (nature-based and traditional engineering) could be applied to specific areas of the bay as detailed in Table 1. Importantly, in all areas where any NAI or any type of **erosion resist** measures are implemented in the short term, it is recommended that land-based policies are adopted now to **accommodate erosion** in future by restricting new (or regenerated) development of permanent infrastructure 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 also avoids societal 'lock-ins' by minimising the amount of permanent development that is permitted in areas at risk. Thus, the Dynamic Adaptive Pathways approach allows short-term economic benefits in these areas can potentially be realised through innovative measures such as permitted temporary development, assets that are demountable and/or can be relocated inland as landward erosion expands and quickens.

Proposed approach

Scaling-up Building with Nature techniques in the dunes and marsh buys time to develop flexible adaptation strategies for at-risk areas.

Whilst erosion risks are anticipated on the West Sands and Eden shores, the flood corridors have been identified and shown in Figure 3a, alongside indicative areas interventions in Figure 3b. We recommend that SALT consider the future management of St Andrews Links under a four-phased approach comprising consideration of the following measures (1 to 3 are shown alongside the associated **flood** corridors in Figure 3):

1. **flood management options both at the Swilcan Burn,** and along the Eden Estuary (**expanding salt marsh planting** and embankment works);
2. deploy **more dune enhancement works** to maintain the integrity of the dune cordon as a protective landform;
3. **beach nourishment to enhance the beach sediment budget and reduce dune-toe erosion over the longer-term;**

4. **explore course redesign, repositioning assets to risk-free locations** to ensure golf can sustainably be played at St Andrews beyond 2100.

It is important to note that while all the above measures address the combined risks from erosion and marine flooding, measure 4 also addresses risks of waterlogging of the low-lying interior due to increased seasonal rainfall and/or higher water tables.

For all areas detailed below, St Andrews Links Trust as landowner, alongside support from local to national government, must identify practical steps and associated policy and funding mechanisms to facilitate longer-term landward relocation of at-risk assets such as carparks, roads and sections of golf courses. In parallel, short-term flood risk alleviation measures (such as moving or land-raising assets) need to be undertaken where existing infrastructure is at risk of erosion-related flooding.

Taking each of these areas in turn adaptational and resilience options are explored below. **Area 1** (fronted by the Swilcan Dunes) is close to the town of St Andrews and supports infrastructure assets such as car parks and the main road within St Andrews which are at risk of erosion and erosion-related flooding. In the future, flooding from Swilcan Burn may become a daily challenge, restricting use of these key assets and areas of surrounding golf courses. In this area, short-term (0–5 year) nature-based erosion resist measures such as beach feeding, dune reprofiling and subtle land raising to alleviate risk are needed to improve the resilience of these assets.

In **Areas 2–4** (West Sands and Eden coast of the Links), the golf courses (mid-section of the Jubilee Course, in particular) are the main assets at risk of erosion and erosion-related flooding, together with saltmarsh and dune erosion on the Eden shore. In this area it is recommended that a combination of sediment feeding and/or nature-based approaches to managing erosion risks are implemented to strengthen short and medium-term resilience provided by the beach-dune and saltmarsh systems. Further investment in this natural capital would 'buy time' to explore necessary and detailed adaptational options to re-design and relocate those threatened and less important golf course assets inland. Land-based adaptation plans will need to be designed, agreed and implemented before erosion and fair-weather flooding of these assets occurs. Taking a long view, agricultural land south of the A91 (if available for coastal adaptation), provides useful accommodation space for relocating at risk assets. This can be achieved through proactive adaptation planning now to limit future development of this land, to ensure it can be used when needed. By planning ahead, these measures will help manage both erosion and erosion-related flood risk with less disruption to the business continuity of a key economic asset for St. Andrews. St. Andrews Links Trust, would be choosing its future

Investing more in nature based solutions provides the time for the Links Trust to invest in adaptation strategies.

This way, we can choose our future by design, not by disaster.

by design, not disaster. Close coordination between business, local and national government is recommended to enable relocation plans to be designed, agreed and implemented in a dynamic and flexible manner.

The trigger points for implementing adaptation actions should be informed by appropriate monitoring (both coastal but also golf course, including for waterlogging issues). We recommend a ‘Dynamic Adaptive Approach’ be developed by SALT and partners, where multiple future management paths are planned, and future managers decide when the time is right to, for example, phase out resistance measures and initiate adaptation actions (including relocating at risk assets). The favoured options above, minimise aesthetic and recreational impacts. Enhancements to the Eden embankment (now protected by a wider energy-absorbing marsh) are as important as dune enhancements on the West Sands. Whilst the land-raising at the clubhouse and Old Course are modest, repairing the six dune blow-outs within the West Sands Dunes in the coming years would greatly enhance the protection provided by the dunes. Detailed consideration of placement of the land-raised areas would be required, not only to maximise flood protection (and egress / return of flood waters) but also from an aesthetic and golf-playability perspective. Given the anticipated increased erosion rates, partner discussions regarding sediment husbandry and licenced re-use are necessary to maximise the natural resilience offered by the dunes. International experience shows that Building with Nature techniques allows future flexibility to enact broader adjustments (Interreg BwN 2020). Significant gains in the width of dune vegetation at West Sands have been identified since 2015, attributable largely to the intervention of the West Sands Partnership in fencing, feeding and dune planting, and switch from mechanical beach cleaning (which removed beneficial seaweed as well as sand) to merely manual litter removal, since 2014. The sustainability of building with nature options is moderate to high in the face of sea level rise, representing a moderate cost option over the medium to long-term.

Such an adaptive approach builds on past successes and aims to secure the medium-term resilience of the dune cordons and marshes, whilst allowing longer-term strategies to be developed. Over the last few decades, the use of sediment sourced (under licensed terms) from Out Head has greatly enhanced the natural resilience of the dunes alongside salt marsh enhancement schemes. Consideration of the sustainable use of these local sediments is essential and continued liaison with partners is necessary. Whilst the immediate threats are modest, the St Andrews Links Trust recognise they have a window of opportunity to further develop and implement short and longer-term strategies. These approaches are outlined within Figure 3.

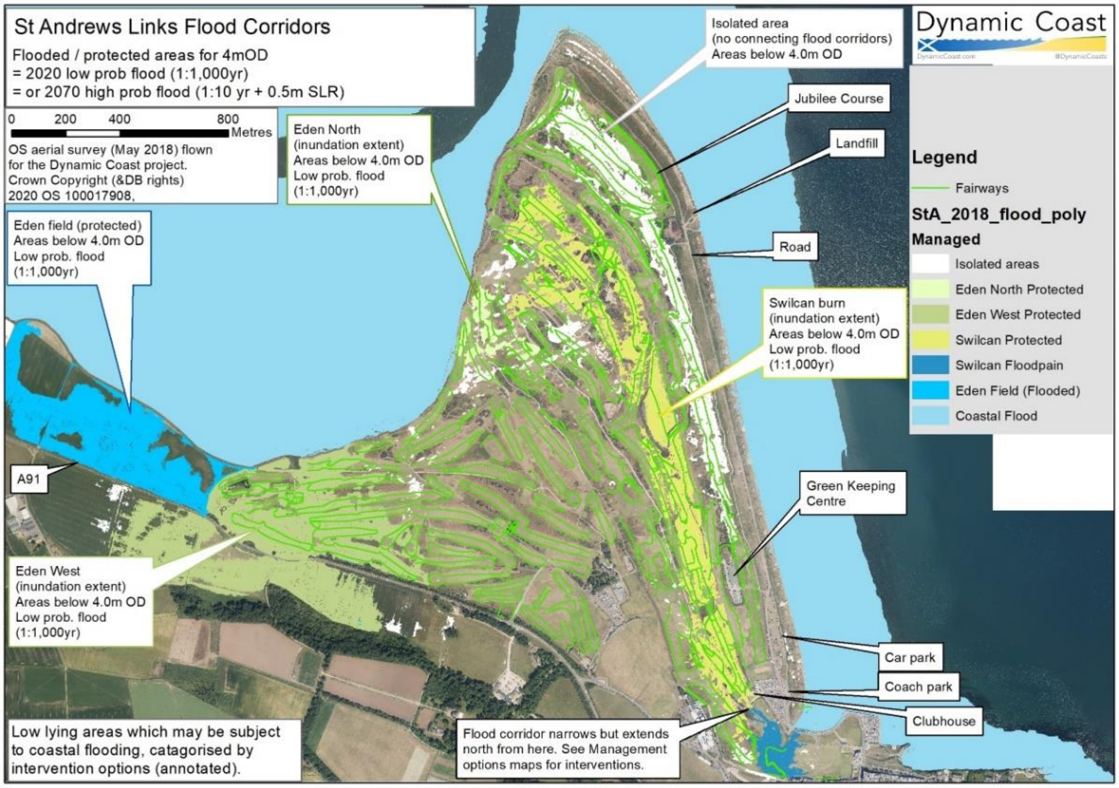


Figure 3A Identified flood corridors across St Andrews Links

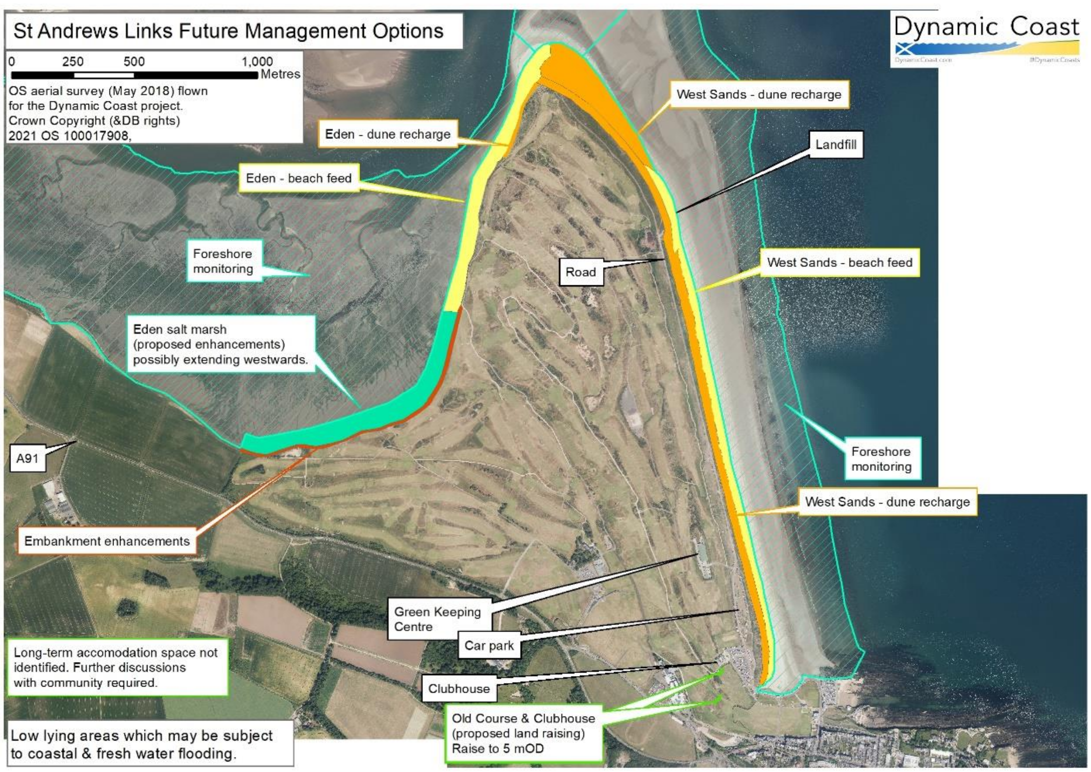


Figure 3B Proposed resilience and adaptation measures.

Technical Summary

Governance

St Andrews Links Trust, is the body, formed by an Act of Parliament in 1974 to be responsible for the management and maintenance of the historic Links at St Andrews. As the landowners they have worked closely through the West Sands Partnership to successfully enhance the resilience of the dunes to erosion and flooding. West Sands Partnership was formed by St Andrews Links Trust (SALT), Fife Coast and Countryside Trust (FCCT) and Fife Council (FC), advised and guided by SNH (now NatureScot). The Partnership has been vital in co-ordinating and driving local coastal enhancements. FC are empowered under the Coast Protection Act 1949 and Flood Risk Management (Scotland) Act (2009) to manage flooding and erosion and have published the Shoreline Management Plan 2 and delivered a major dune enhancement project in 2010. SALT are the primary land managers and carry out all coastal operations to date; FCCT are the supporting land managers and co-ordinate, advocate, advise and hold licence and consent for dune operations. FCCT are also tasked with co-ordinating dune restoration using community and public volunteer involvement, and the ranger service support (under service agreement with SALT) provides project advice, on-site daily management, education and protection for coastal issues. FCCT also manage the Eden Estuary Local Nature Reserve and as such work closely with SALT, Dr Clare Maynard (St Andrews University) and NatureScot on coastal and shoreline projects. This linked approach assists greatly in delivery of dune and saltmarsh enhancements for multiple and mutual benefits. Given the close working of SALT and FC, the Dynamic Coast research aims to appraise the past approaches, consider future risks and inform longer-term planning.

Current Strategies

Importance should be placed upon support projects and management, highlighting public support. Since 2010, over 1500 individual volunteers with thousands of hours of manpower have committed to remove invasive non-native plants and restore and transplant dune vegetation along the whole system. Using mini support projects such as the ‘Christmas Trees – New Dunes for Old Trees’ project, ecological support projects such as Out Head conservation grazing of Hebridean sheep and the repurposing of 12 acres from municipal parking to grazed and managed coastal grassland since 2014. Additionally, West Sands has a Code of Conduct for all beach visitors to define expected behaviour to protect the site. A new ranger service aims to educate the public, carry out monthly manual beach cleans to replace mechanical cleaning and form a Coastal Volunteer Group to assist maintaining the coastal fringe and dunes, are all long-term management objectives. Ratified and consented by FC, the Eden Estuary LNR Management Plan has led NatureScot to adopt the Saltmarsh Programme as part of the recognised long-term management of the site; this supports joined-up coastal management as well as shoreline planning and conservation objectives for the site.

What is clear from the above, is that a virtuous feedback has been created and is invested in between the landowners, partners, and community groups, who share and invest in a natural and sporting asset. Such collaboration and investment is vital in the coming years as the challenges posed by climate change increases.

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 model and the CoSMoS-COAST model

Relative sea level rise is expected to exacerbate rates of erosion of coastal barriers, with knock-on effects for any existing 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. The advantage of the Modified Bruun approach at a national level is that it requires the use of a restricted dataset, such as was available for the whole soft Scottish coast. In some locations a more complete dataset is available that allows a more detailed and nuanced modelling to be done at these sites, for example including wave data and shore parallel (alongshore) sediment transfer, both absent from the Bruun approach. Accordingly, for some sites with good data availability, we adapted the Coastal One-line Assimilated Simulation Tool (CoSMoS-COAST, Vitousek et al., 2017) 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 worldwide, extent and geometry of the foreshore and the low- and high-water marks but used in Dynamic Coast for comparisons with published Ordnance Survey 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 links at St Andrews have seen substantial eastward growth over the last few centuries. Map analysis shows that since about 1900, new dunes have built up to allow construction of 11 golf holes. More recently however, areas of accumulation have become less common, and erosion is now affecting more areas than in the past.
2. Whilst most of the dune cordon provides a good level of flood protection to the low-lying interior, potential flood corridors remain at the Swilcan Burn, at several low points in the east-facing dunes and along the Eden Estuary Shore. Recent dune works undertaken in the last few decades mainly along the West Sands have been very effective in the short term, with marsh enhancements along the Eden Estuary Shore showing moderate success, although longer-term risks remain mainly related to the potential risk to the low-lying areas of links and rising sea level.
3. Under a "do nothing" scenario, coastal erosion is anticipated to effect up to 120 m of the West Sands, 150 m of Out Head? and progressively effect salt marsh extent within the Eden Estuary as well as potentially flooding parts of the links by 2100.

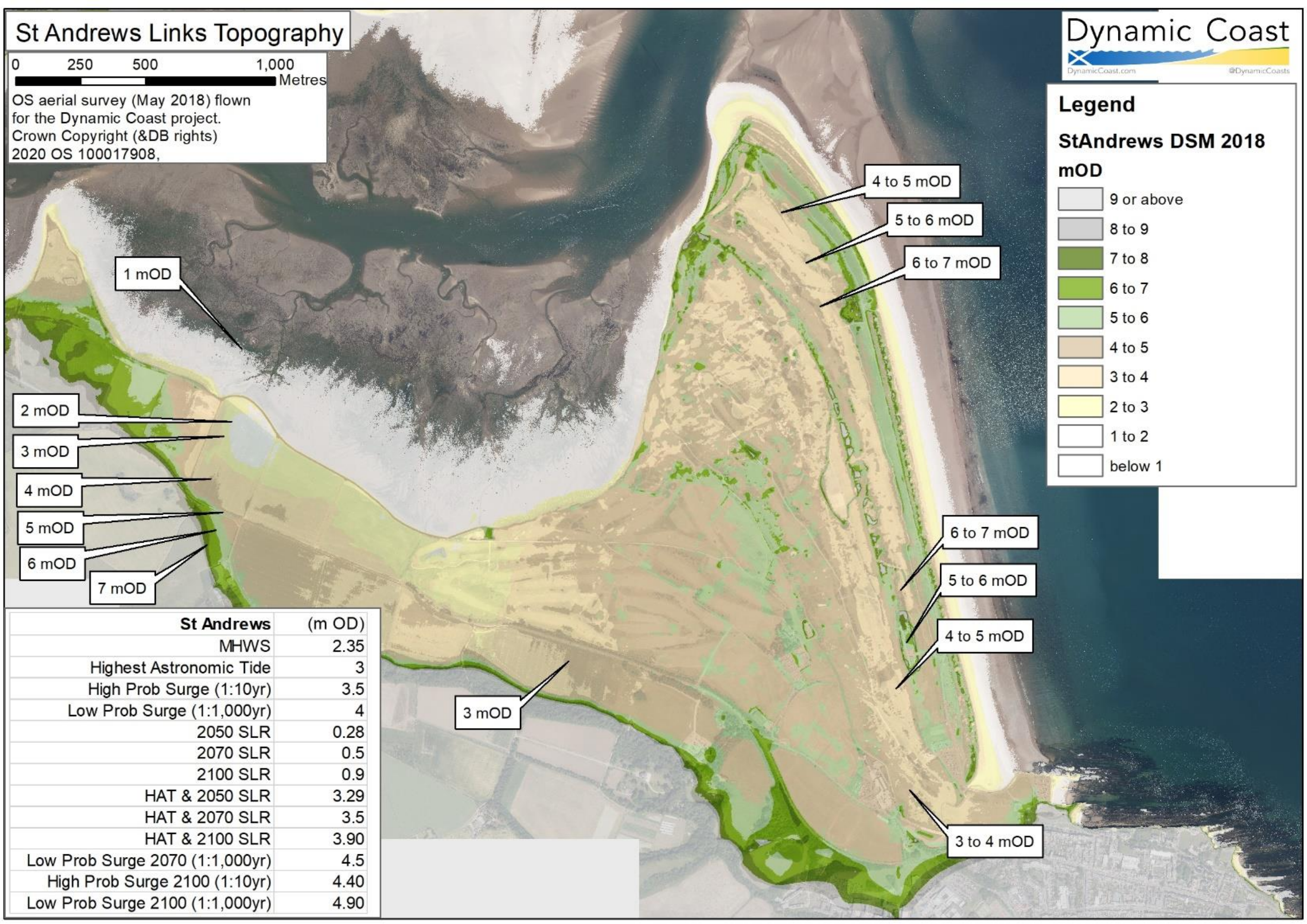
The first phase of Dynamic Coast summarized the coastal changes to St Andrews Links (see page 9 of Cell 2 report) between 1896, 1982, 1994 and 2013. For example, the southern sections of the dunes retreated around 50 m between 1982 and 2013, whilst over the same period the northern part of the bay advanced approximately 45 m.

The second phase of Dynamic Coast, outlined below, benefits from Ordnance Survey aerial survey undertaken in May 2018 and augmented with vegetation edge surveys from Satellite (see Dynamic Coast WS3 Veg edge), air photography and ground survey. Whilst these are discussed in turn below, various interactive tools are available within www.DynamicCoast.com for users to interrogate.

Existing Topography and Flood Levels at St Andrews Links

The cordon of coastal sand dune ridges at St Andrews provide natural erosion and flood protection for the interior links land and golf courses behind the dunes. Historically the dunes on the east-facing beach have moved seaward although this has slowed over recent decades with some erosion now occurring toward Out Head.

At the Swilcan Burn, the southern end of the east-facing beach at St Andrews Links has benefitted from successful dune reconstruction in 2010, but the land behind remains low and subject to flood risk. Along the Eden estuary side of Out Head, the dunes and land behind is high and, although now protected by gabion baskets to combat erosion, artificial feeding of the beach has resulted in local increases in dune height to 8 mOD. However, to the west the dunes are absent along much of the Eden estuary shore and, since the land is low (3–4 mOD), flood protection to the low-lying land behind is provided by earthen embankments. These embankments have failed in the recent past and have been reinstated in situ. On the West Sands (the east-facing beach), the fronting dune ridge is 5–9 mOD, although several lower areas occur within the dune ridge that represent potential flood risk corridors (Figure 4).

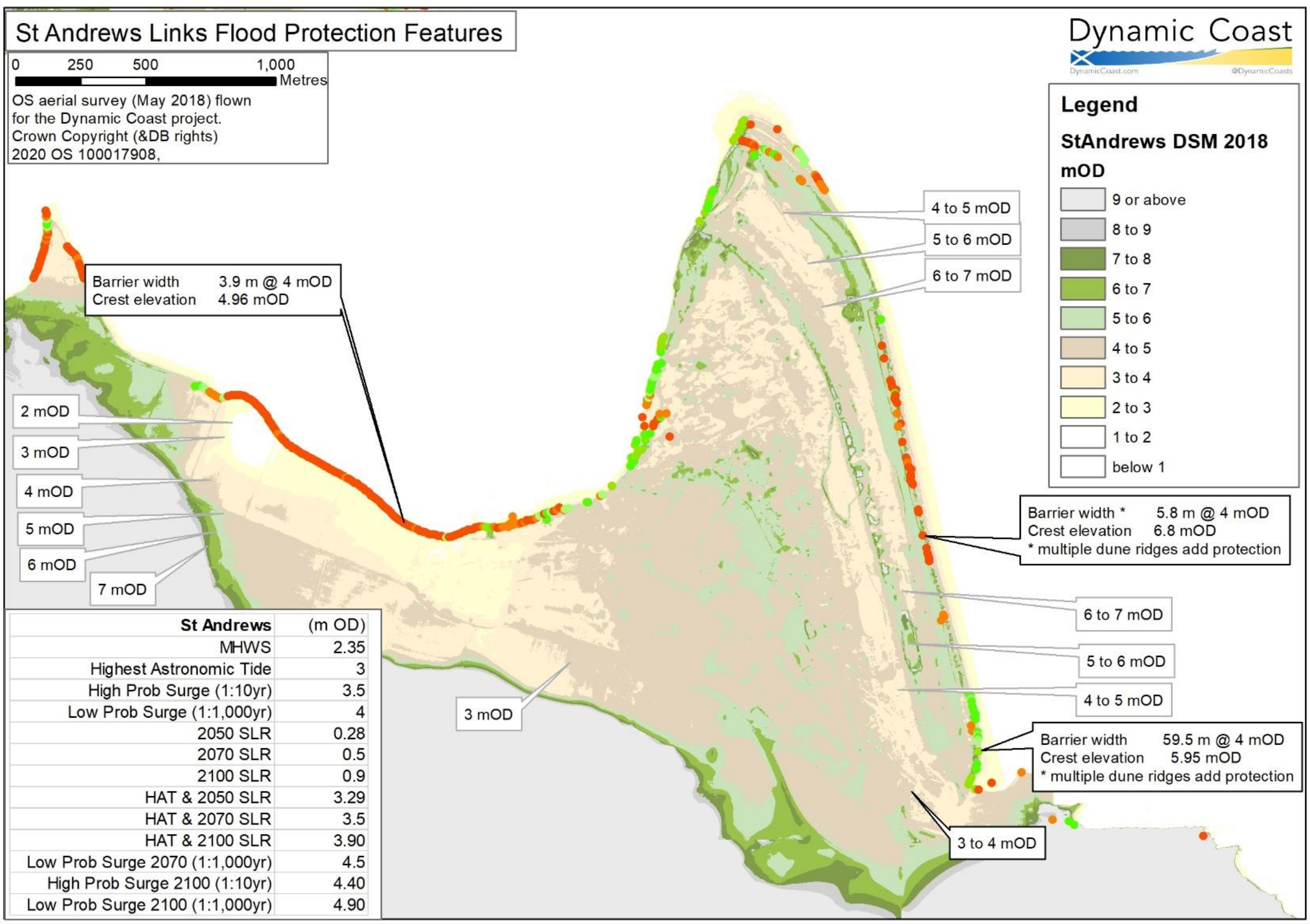


St Andrews	(m OD)
MHWS	2.35
Highest Astronomic Tide	3
High Prob Surge (1:10yr)	3.5
Low Prob Surge (1:1,000yr)	4
2050 SLR	0.28
2070 SLR	0.5
2100 SLR	0.9
HAT & 2050 SLR	3.29
HAT & 2070 SLR	3.5
HAT & 2100 SLR	3.90
Low Prob Surge 2070 (1:1,000yr)	4.5
High Prob Surge 2100 (1:10yr)	4.40
Low Prob Surge 2100 (1:1,000yr)	4.90

Figure 4 Topography, Bathymetry and key flood levels (mOD) at St Andrews Links.

Natural Coastal Flood Protection Features at St Andrews

Automated terrain analysis using the OS 2018 DEM and analysed at 10 m intervals with key attributes noted is shown in Figure 5. These include the extent of dune ridges (topographic high points), potential flood corridors (topographic low points), the presence or absence of cliff features and the extent and volume of barrier features at specific flood levels. Whilst a range of key heights are available, the overall relative protective function of the dune cordon is perhaps best summarised by the dune width at 4 mOD. The importance of the 4 mOD elevation is related to likely future flood levels combined with wave heights and is further explored within the flooding section below (Figure 5). Within the West Sands the broader dune cordon includes multiple dune ridges (green shading above) complement the flood protection features. So, whilst there are relative weak points notes (orange and red dots) the actual protection is higher.



St Andrews	(m OD)
MHWS	2.35
Highest Astronomic Tide	3
High Prob Surge (1:10yr)	3.5
Low Prob Surge (1:1,000yr)	4
2050 SLR	0.28
2070 SLR	0.5
2100 SLR	0.9
HAT & 2050 SLR	3.29
HAT & 2070 SLR	3.5
HAT & 2100 SLR	3.90
Low Prob Surge 2070 (1:1,000yr)	4.5
High Prob Surge 2100 (1:10yr)	4.40
Low Prob Surge 2100 (1:1,000yr)	4.90

Figure 5 Altitudes of flood protection features at St Andrews Links, showing the extent of the dune cordon (or barrier) (shown by 4 mOD contour). Colour dots identify transects within narrow sections of the dunes or embankments (green dots wide, red dots narrow).

Past Intertidal Changes at St Andrews

Figure 6 shows the observed changes in position of Mean Low Water Springs from Ordnance Survey mapping in 1883, 1981 and 2018, compared with the average low water position 2016–2018 derived from Coast X-Ray (Sentinel satellite method). Coast X-Ray aligns well with the elevation-derived OS MLWS, confirming foreshore lowering and landward retreat of low water along the West Sands. Good agreement is also seen along the current Eden channel in the north, but the Eden mouth is more complicated with changing positions of ephemeral flood and ebb channel tidal bars. Coast X-Ray is evaluated further in Technical Annex Work Stream 7 Coastal X-Ray (www.DynamicCoast.com/reports).

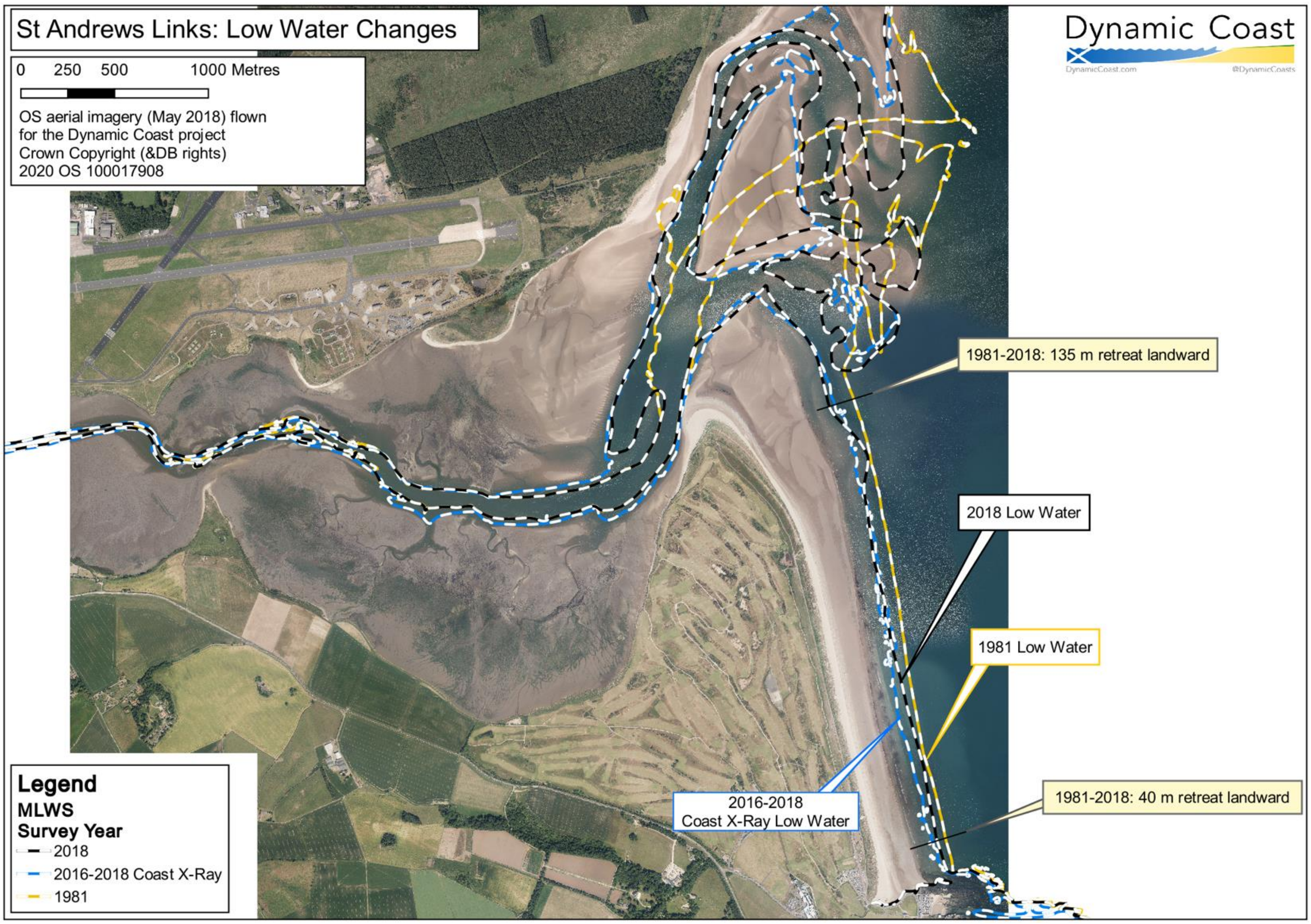


Figure 6 Change to the lower beach – comparison of various MLWS surveys (1882, 1988 & 2018) and Low water (80% water occurrence) from Coast X-Ray.

Changes to High Water at St Andrews

Observed changes in the position of Mean High Water Springs derived from OS mapping in 1893, and the OS photogrammetric DSM in 2018 is shown in Figure 7. Summarising the changes using the two transects on Figure 7 shows seaward advance over 1893–1981 along the entire West Sands shoreface, with a 228 m seaward shift in the north (average 2.6m/y) and less in the south; though to what extent this is wholly natural or enhanced by human interference, such as dune infilling, is unknown. The period 1981–2018 shows a different story with advances being dramatically reduced to only 21 m in the north (average 0.6m/y) and 8 m in the south. Along the Eden estuary shoreface, part of which is protected by gabions, shows much less variation in position. Further contextual changes for the St Andrews Links can be found in the Dynamic Coast Cell 2 Report (www.DynamicCoast.com/outputs.html)

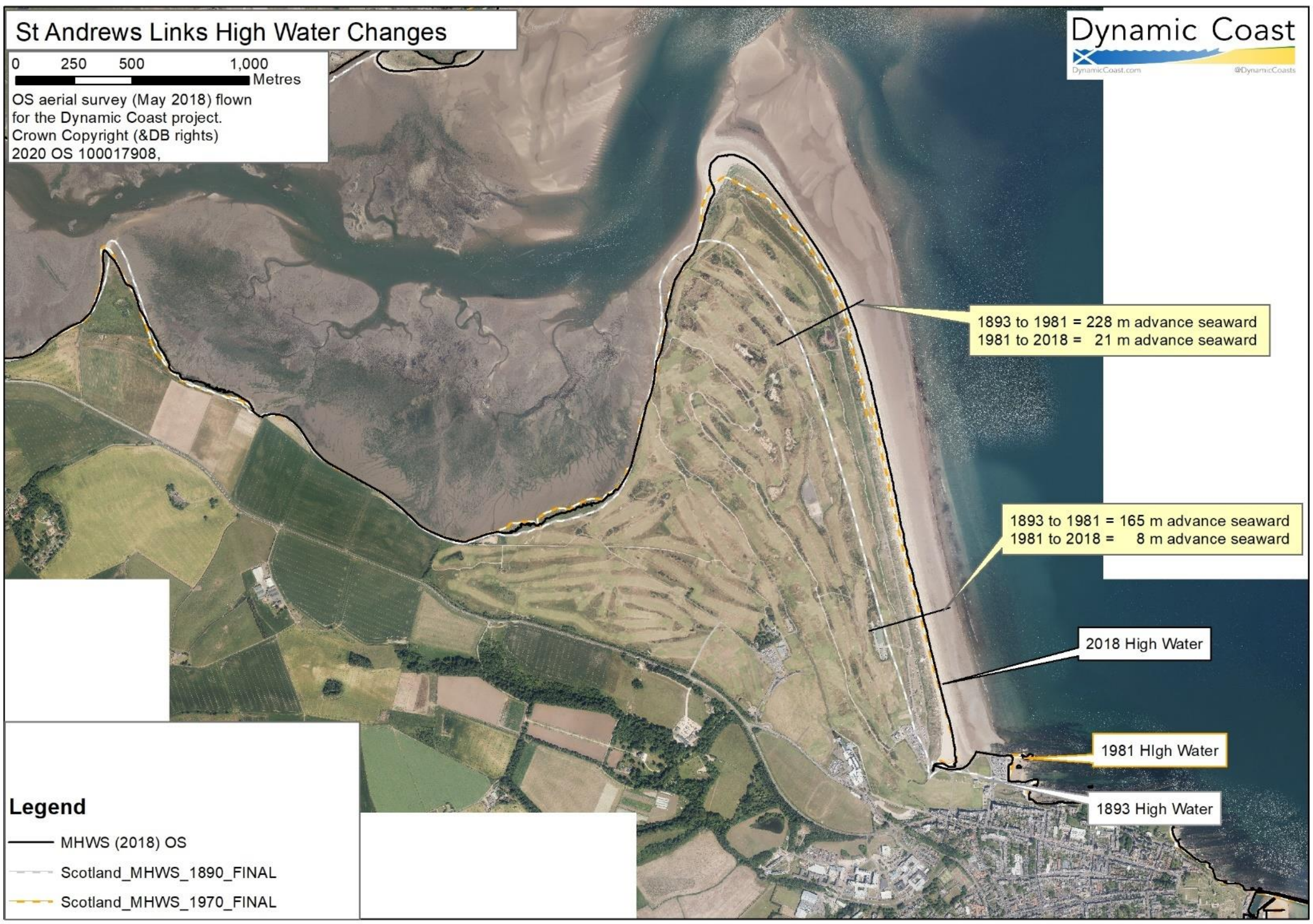


Figure 7 Change to upper beach – comparison of MHWS (1893, 1981, 2018)

Figure 8 shows the DSM height change between 2013 and 2018 that allows quantification of surfaces losses of the first coastal dune ridge and intertidal foreshore. These show changes along the West Sands where increase in heights, typically of about 0.7 m, are found along the first dune ridge. This gives way, within a few hundred metres of Out Head (the northern tip of the peninsula), to erosion of the dune and the upper beach that amounts to 1.3 m lowering. The mid intertidal of

West Sands gained about 0.4 m but the entire length of low water sands between St Andrews and the intertidal sand banks north of Out Head lost 0.6 m in height. Despite the upper beach gains and management, foreshore steepening (vertical losses particularly at low water) is of concern, as the foreshore (MHWS to MLWS) and nearshore (MLWS to wave base typically 10mCD) appears to be narrowing. These areas provide a crucial role in absorbing storm wave energy and if further depleted or lost a greater proportion of wave energy is focussed on the upper beach, with increasing risks to land-based assets, and so strategies that enhance the local supply of sediment to the beach are likely to benefit the entire foreshore. Within the Eden Estuary, gains were seen between 2013 and 2018 of up to 1.7 m at Out Head and 1.4 m along the Eden Estuary east section, as well as increases of about 0.25 m on the fronting salt marsh that spans the Eden East and Eden West sections. Beyond this into the Eden West, few changes in height were noted as this shore is artificially fixed with an earthen embankment, but the saltmarsh shows height increases are likely related to saltmarsh reinstatement work.

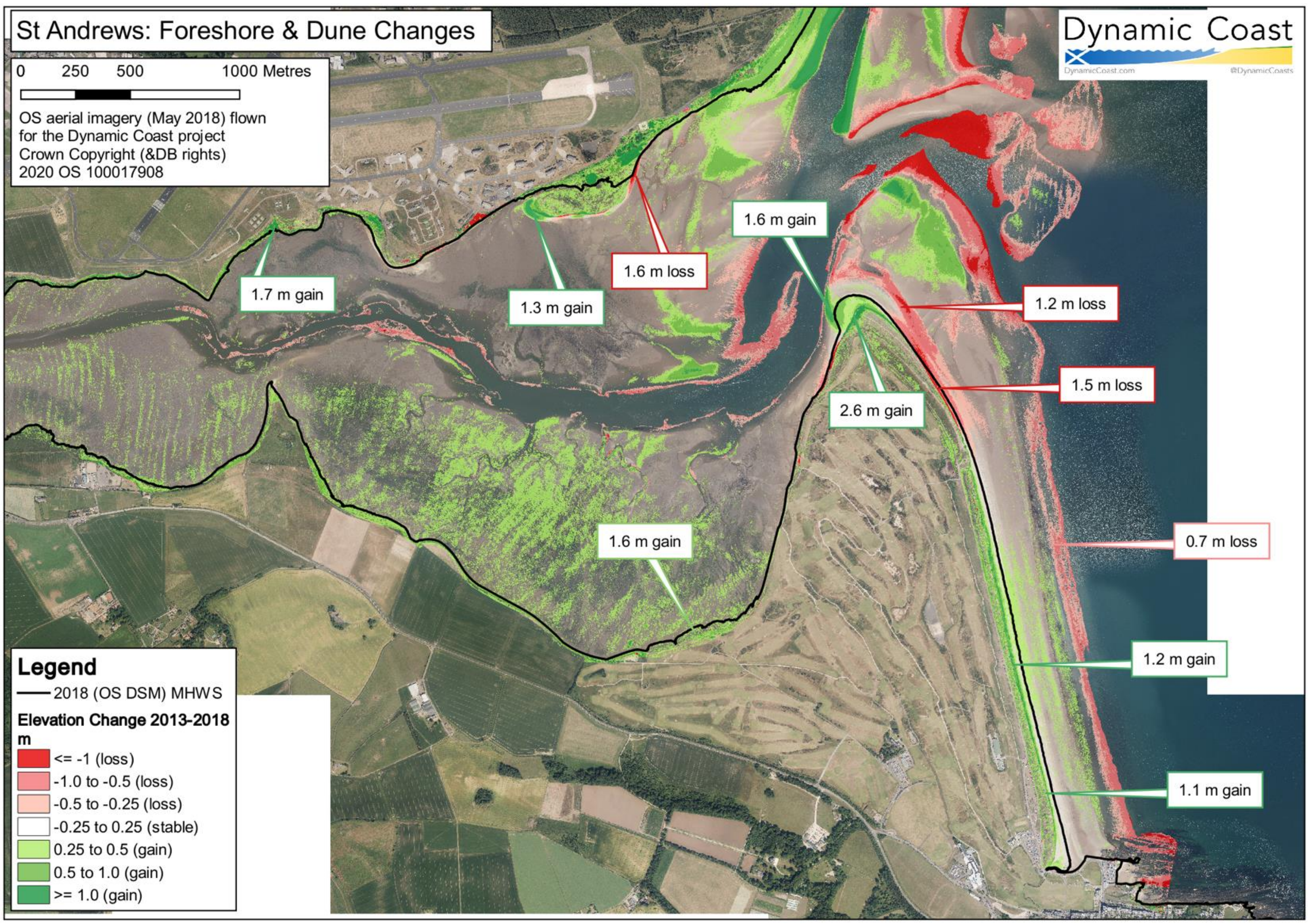


Figure 8 Changes to foreshore elevation - comparison of the difference in beach elevation from 2013 (Scottish Government Phase 2 Lidar) to 2018 (OS DSM from aerial imagery).

Dune Vegetation Edge Changes in St Andrews

Figure 9 shows time-series observed changes in Vegetation Edge positions between 1850 and 2018 at St Andrews Links, based on early mapping updated with recent aerial photography and ground survey. The trends shown largely mirror the changes in MHWS positions and shows gain along the West Sands shore (apart from recession of the vegetation edge south of Out Head), gain at Out Head and relative stability along the Eden Shore. These planimetric changes, showing gains and losses of MLWS, MHWS and vegetation edge, help inform the volumetric changes in the intertidal and dunes in Figure 8.

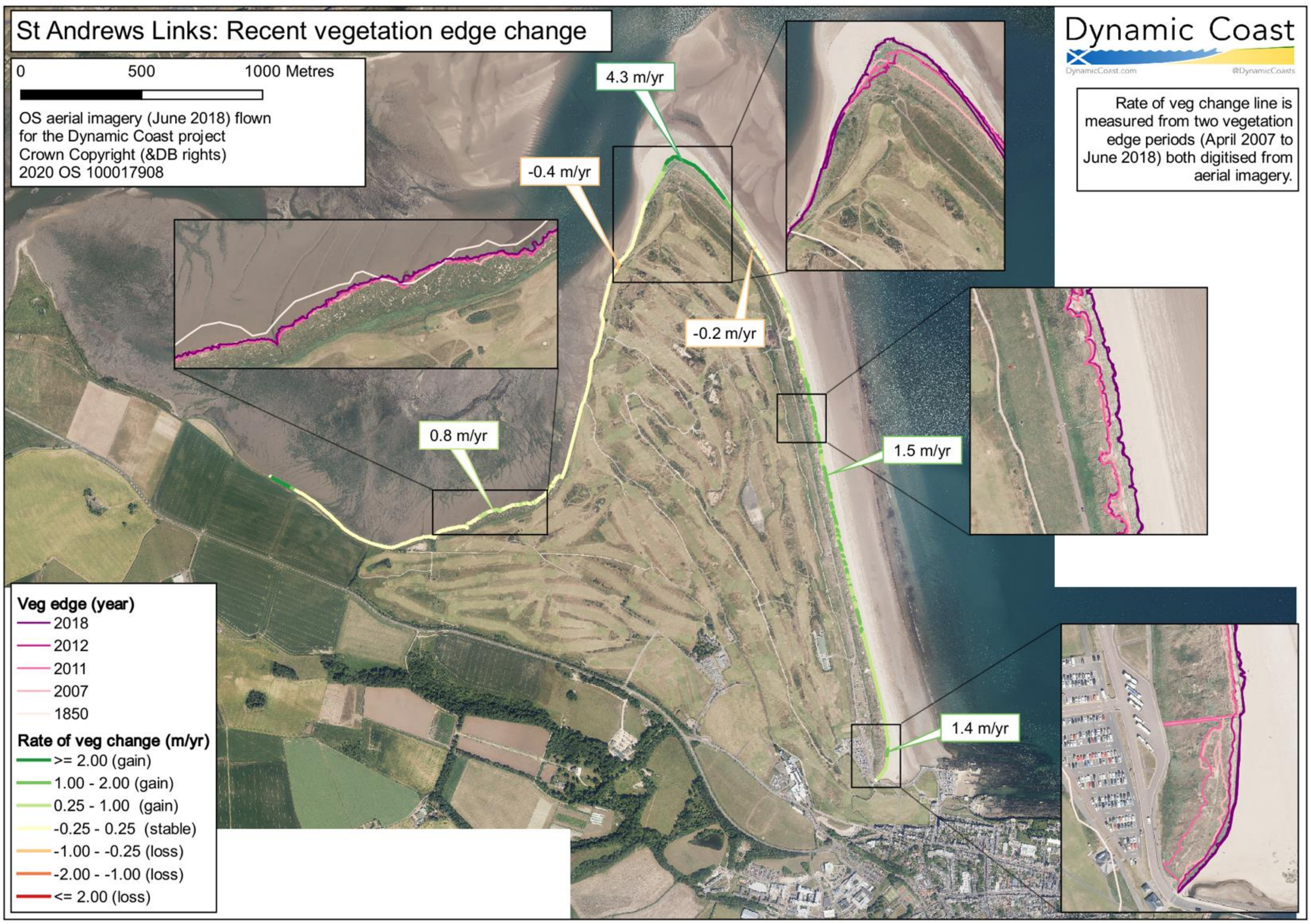


Figure 9 Vegetation edge change maps of St Andrews Links showing observed edges from 1850, 2007, 2011, 2012, and 2018 and the rate of change of distance between 2007 and 2018. Dune infilling accounts for some of this change.

Volumetric Changes across St Andrews

The elevation changes captured by DSMs depicted in Figure 8 above allow average annual volumetric change rates to be calculated for the period 2013–2018. Figure 10 demonstrates gains in volume experienced by the upper beach and dunes along most of the West Sands frontage, with the exception of a small area of erosion south of Out Head. The volumes relate to different landform units within the management units indicated on the figure. Nevertheless, the losses experienced along the lower foreshore are clear enough as is the gain of sediment at the Eden side of Out Head as well as the gains within the Eden intertidal area that is saltmarsh dominated.

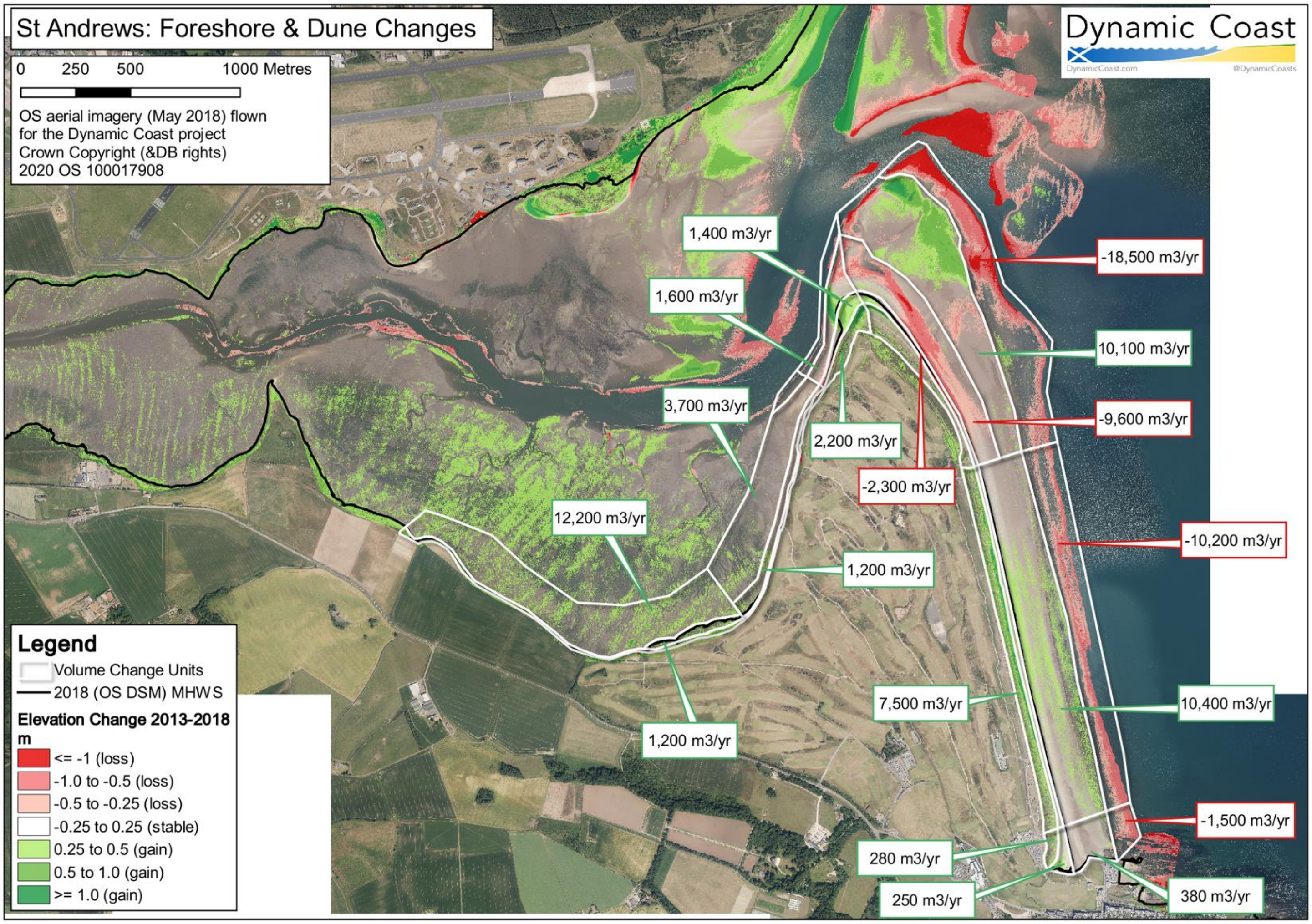
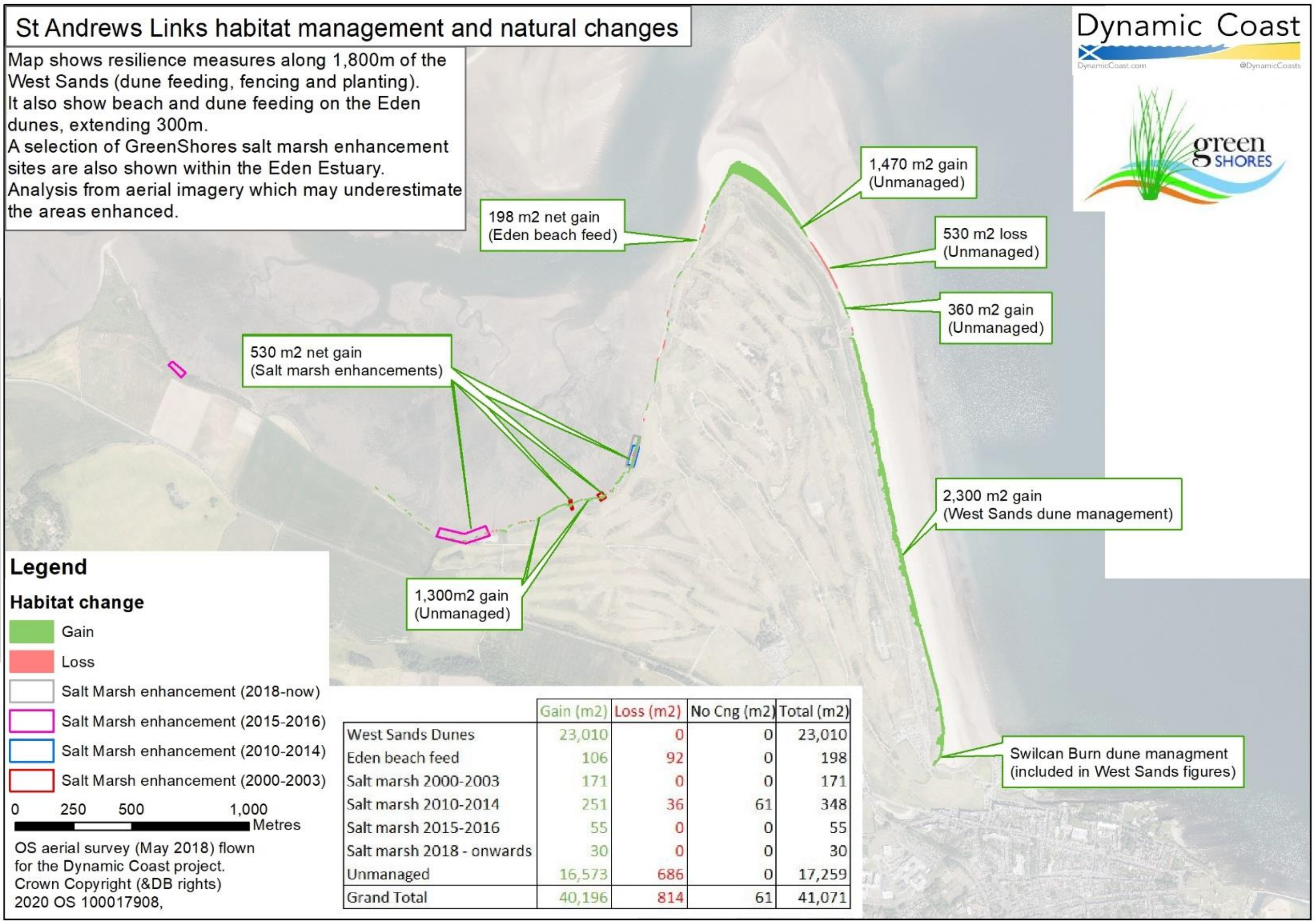


Figure 10 Comparison of rates of volume change 2013–2018 by landform unit within each management unit, both outlined in white. Erosion depicted in red and gain in green (see Appendix Table A).

Since 2010, the West Sands Partnership have embarked on a campaign of dune repair and resilience works that has both maintained and improved visitor access. This has involved fencing off areas of dunes for replanting and partially infilling and replanting low areas and dune blow-outs. Undertaken in discrete phases, the works together mark the largest known dune rehabilitation program in Scotland with over 1.8 km of dune enhancement involving 23,000 m^2 of dune creation to date (2018), with sand mainly sourced from the licenced extraction site at Out Head. The West Sands dunes have acculులated over 7,000 m3 between 2013 and 2018 largely on acount of this intervention. Within the Eden Estuary, saltmarsh planting works have resulted in over 500 m^2 of new saltmarsh within the enhancement sites, joined by a further unmanaged gains of 1,300 m2 on adjacent shores (Figure 11), which may at least be partly a secondary benefit of the sucessful planting on adjacent shores (via local attnuation of waves and currents). These areas are based on aerial photography and represent an underestimate of the enhancement extent.



	Gain (m2)	Loss (m2)	No Cng (m2)	Total (m2)
West Sands Dunes	23,010	0	0	23,010
Eden beach feed	106	92	0	198
Salt marsh 2000-2003	171	0	0	171
Salt marsh 2010-2014	251	36	61	348
Salt marsh 2015-2016	55	0	0	55
Salt marsh 2018 - onwards	30	0	0	30
Unmanaged	16,573	686	0	17,259
Grand Total	40,196	814	61	41,071

Figure 11 Habitat management and natural changes within and adjacent to the St Andrews Links

Future Shoreline Projections

Future projections nationally are based on the Modified Bruun Rule with the CoSMoS-COAST model used for data-rich sites (see methods above) and projected forward based on UKCP18 Representative Concentration Pathway 8.5 (UKCP18 RCP8.5) using the 95th% estimate,. The coastal changes incorporate shore face gradients and calibrated with recent coastal change data (which reflects/assumes continued sediment supply from the immediate hinterland and alongshore). These anticipated shorelines are not intended to be reliable detailed predictions, but a precautionary future scenario to inform the possible scale of change.

Using the modified Bruun method, Figure 12 shows an estimate of the anticipated future positions of MHWS at St Andrews in 2050 and 2100. This calculation shows that relative sea level rise of 0.92m by 2100 (UKCP18 RCP8.5 95th%) is likely to result in ~760 m landward retreat (erosion) near Out Head by the end of the century. The intervening rates and amount of erosional loss is also shown by time stamps in Figure 12. Under a 'do nothing scenario' the erosion at Out Head would return the peninsula towards its 18th century extent, with extensive losses to the mid-section of the Jubilee Course. Under the same scenario erosion issues are anticipated on the southern sections of the West Sands close to the Swilcan Burn mouth. The national modelling undertaken focusses on the open and inner shores at St Andrews Links, as such salt marsh shores have not been included. This is not because salt marshes aren't dynamic, nor important as they are both, but because there are very no rapidly deployable simple methods for salt marsh evolution to account for sea level. As such erosion may be possible within shores which haven't been modelled. In addition, abrupt changes in coast orientation occur then model overprediction produces odd contour returns, e.g. contours at the tip of Out Head is merely a model artefact.

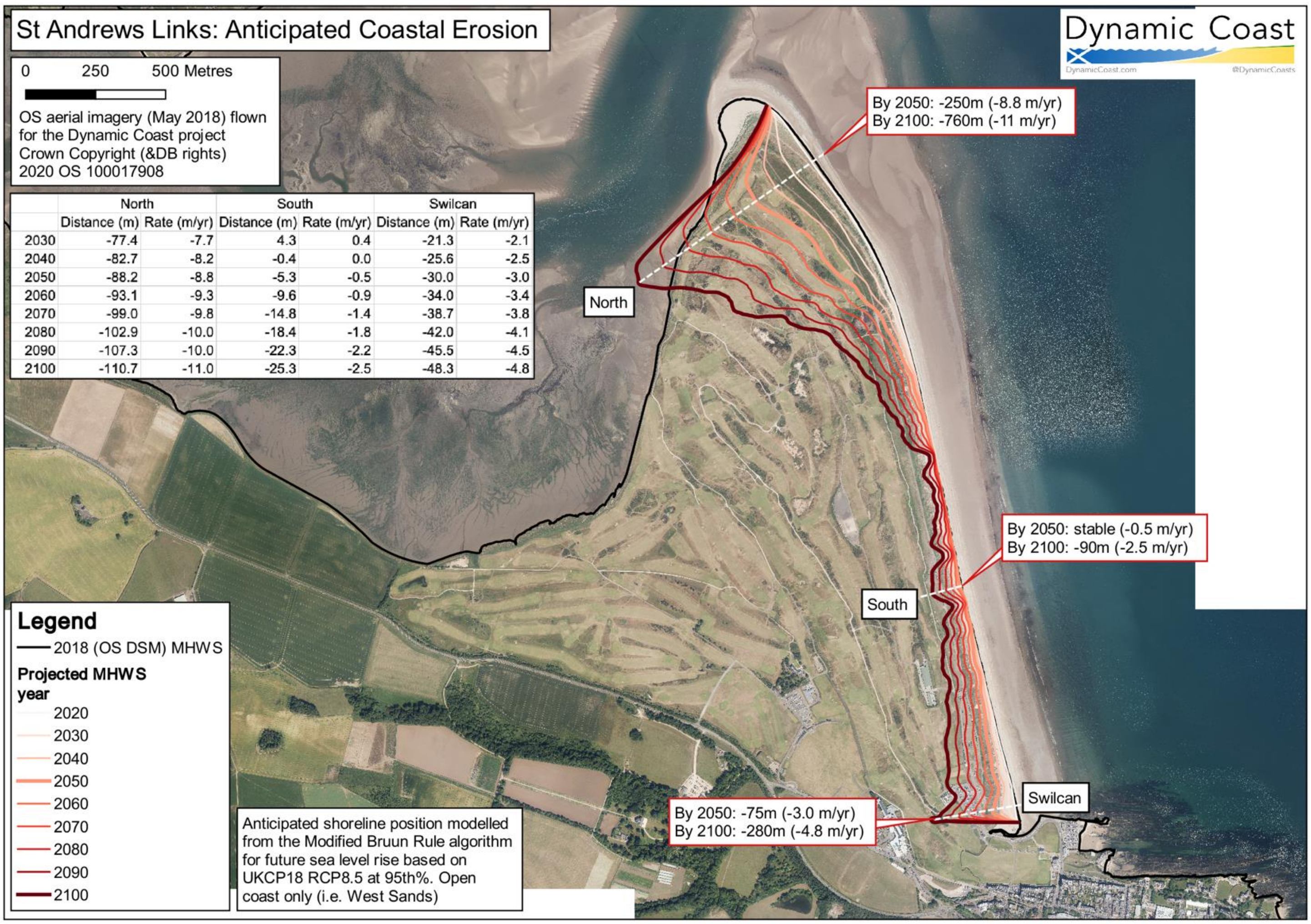


Figure 12 Anticipated coastal change – Modified Bruun Rule MHWS

The retreat of MHWS on the beach is normally accompanied by the undercutting of vegetation at the coastal edge, especially where any dune vegetation (or saltmarsh vegetation where present) is damaged. This vegetation edge essentially marks the common perception of erosion of the land and its assets, due to landward retreat of MHWS.

However, there is a mean lateral offset of 30 m between MHWS and the vegetation edge at St Andrews, and the latter can be used to project the modified Bruun MHWS predictions inland to provide insight on the timing when the un-vegetated and dynamic beach is anticipated to arrive at the position of any landward asset. Overall, this adjustment anticipates recession at a given time to be further inland than that predicted by the modified Brunn Rule on its own. A detailed view of each decade vegetation edge prediction using this method can be seen on Figure 13. Figure 13 shows the anticipated position of the vegetation edge modelled from the modified Bruun rule and projected forward to 2100 (thick green line). It is clear in Figure 13 that within the next 50 years the coach park and road along the links are at risk of coastal erosion, under a “do nothing” scenario.

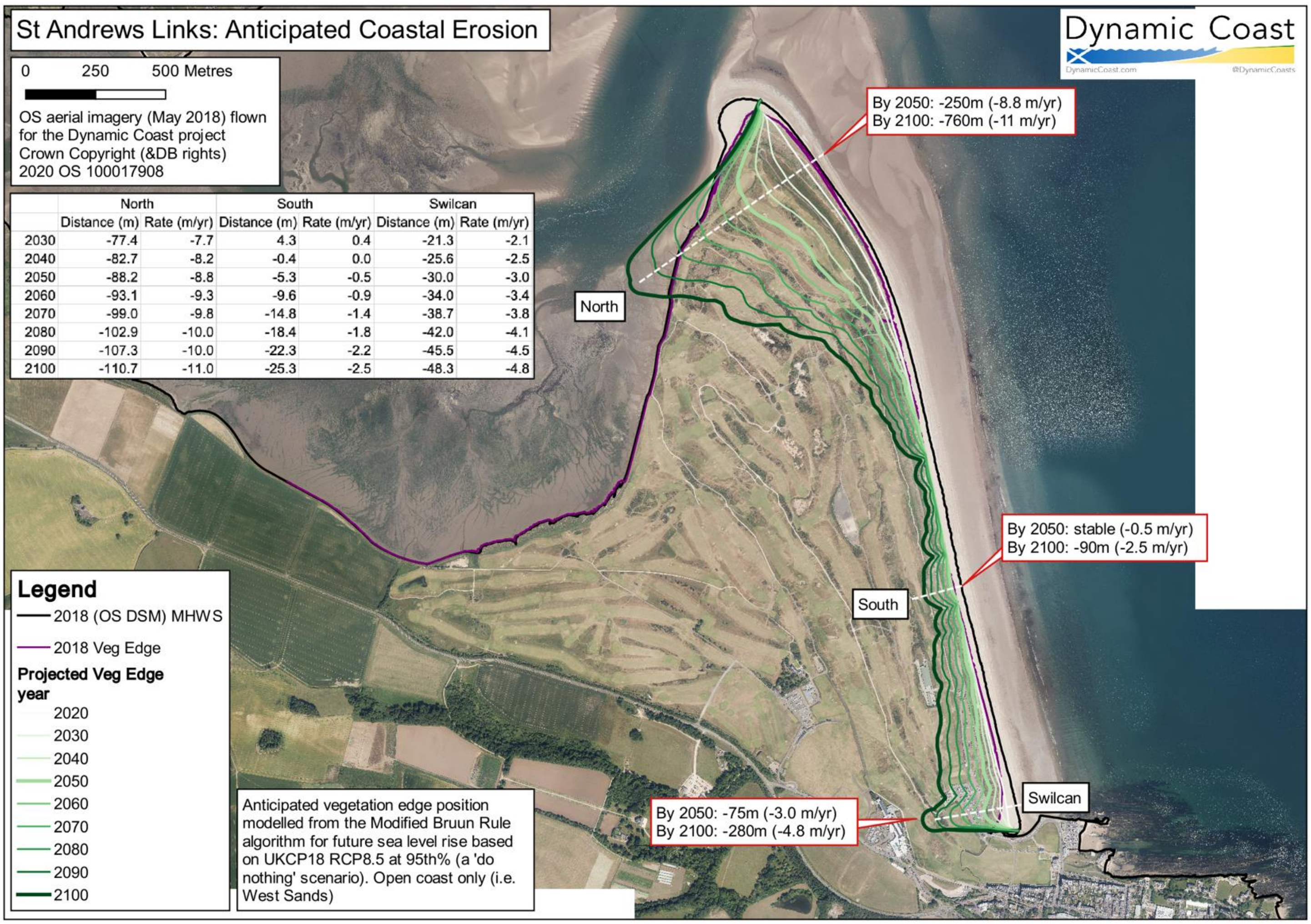
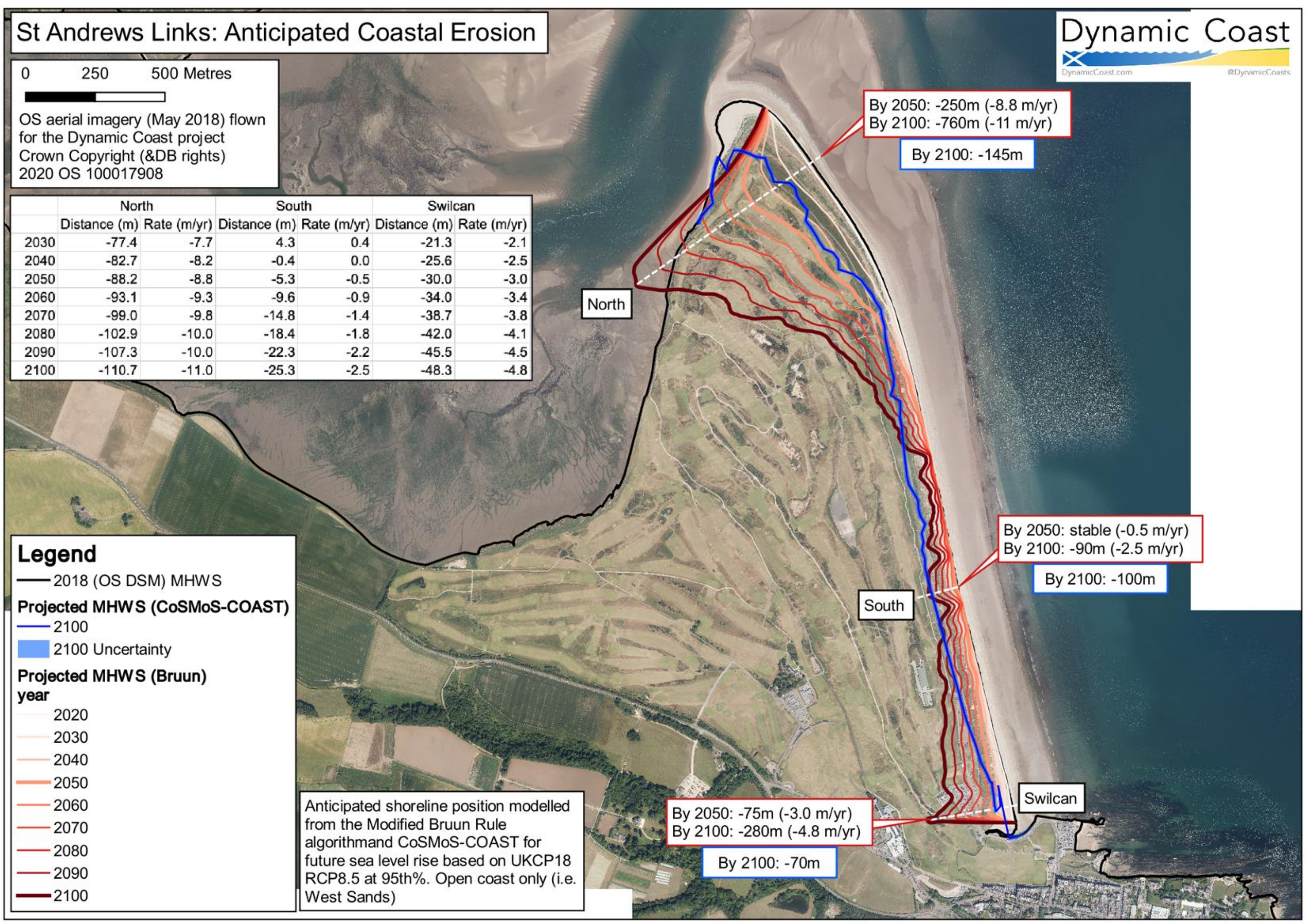


Figure 13 Anticipated coastal change – Modified Bruun Rule Vegetation Edge. Rates shown are the same as Figure 12, the vegetation edge here is offset from MHWS and assumed to retreat at the same rate.

Figure 14 compares the shorelines in Figure 13 depicts the anticipated erosion and coastal evolution of St Andrews using a different model: the Coastal One-line Assimilated Simulation Tool of 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, but also includes wave-driven along- and cross-shore sediment transport whose accumulation has the potential to offset at least some erosion. Like the Modified Bruun Rule, the model makes use of MHWS observations from the first phase of Dynamic Coast in calibrating the past predictions of shoreline position, to more accurately predict future changes with sea level rise through to 2100. The pattern of MHWS at the southern transect along West Sands is similar to the Modified Bruun Rule modelling, with ~100 m of MHWS retreat, but there is only 145 m retreat at Out HeadFigure 14. The irregular time gaps of shoreline observations in St Andrews (1890s to 1970s and 1970s to modern) serve to limit the ability of CoSMoS-COAST to tune its modelled erosion rates and can only partly capture the actual rates over the last decade that are needed to project into the future. In St Andrews, the model offers a higher level of complexity in some aspects of sediment movement in the long- and cross-shore, but is likely to under predict in comparison to the Modified Bruun Rule due to its limitations in simulating sediment sources and sinks from outside the system (i.e. Eden Estuary sediment and tidal activity). Both models are however in overall agreement on the anticipated direction of travel of coastal change.



	North		South		Swilcan	
	Distance (m)	Rate (m/yr)	Distance (m)	Rate (m/yr)	Distance (m)	Rate (m/yr)
2030	-77.4	-7.7	4.3	0.4	-21.3	-2.1
2040	-82.7	-8.2	-0.4	0.0	-25.6	-2.5
2050	-88.2	-8.8	-5.3	-0.5	-30.0	-3.0
2060	-93.1	-9.3	-9.6	-0.9	-34.0	-3.4
2070	-99.0	-9.8	-14.8	-1.4	-38.7	-3.8
2080	-102.9	-10.0	-18.4	-1.8	-42.0	-4.1
2090	-107.3	-10.0	-22.3	-2.2	-45.5	-4.5
2100	-110.7	-11.0	-25.3	-2.5	-48.3	-4.8

Figure 14 Anticipated coastal change – Modified Bruun Rule MHWS with CoSMoS-COAST MHWS projection for 2100.

Social Vulnerability Classification Index

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). Given the extent of anticipated coastal erosion (shown above) is located in areas away from residential property, there is a limited exposure to resident within St Andrews. The average Social Vulnerability Classification Index (SVCI) produces weighted indicators of socio-economic vulnerability that rate most of St Andrews as highly and moderately vulnerable, although some areas emerged from the recent SIMD (2020) study as predominantly the least deprived (bottom 10%) in terms of social deprivation. The areas of North Haigh and Strathkinness and Craigton emerge as occupying the top two categories of social vulnerability in the SVCI where some parts of the University of St Andrews student accommodation is based. North Haugh also has a higher proportion of older residents and a relatively high level of long-term unemployment which may contribute to the demonstration of higher level of social vulnerability in these locales. However, any anticipated erosional change at St Andrews largely affects the West Sands beach, dunes and golf courses and has a very limited overlap with North Haugh. Figure 1 shows the heavy red line of the 2100 anticipated coast to have limited penetration into North Haugh and so there appears very limited socio-economic vulnerability to coastal erosion at St Andrews.

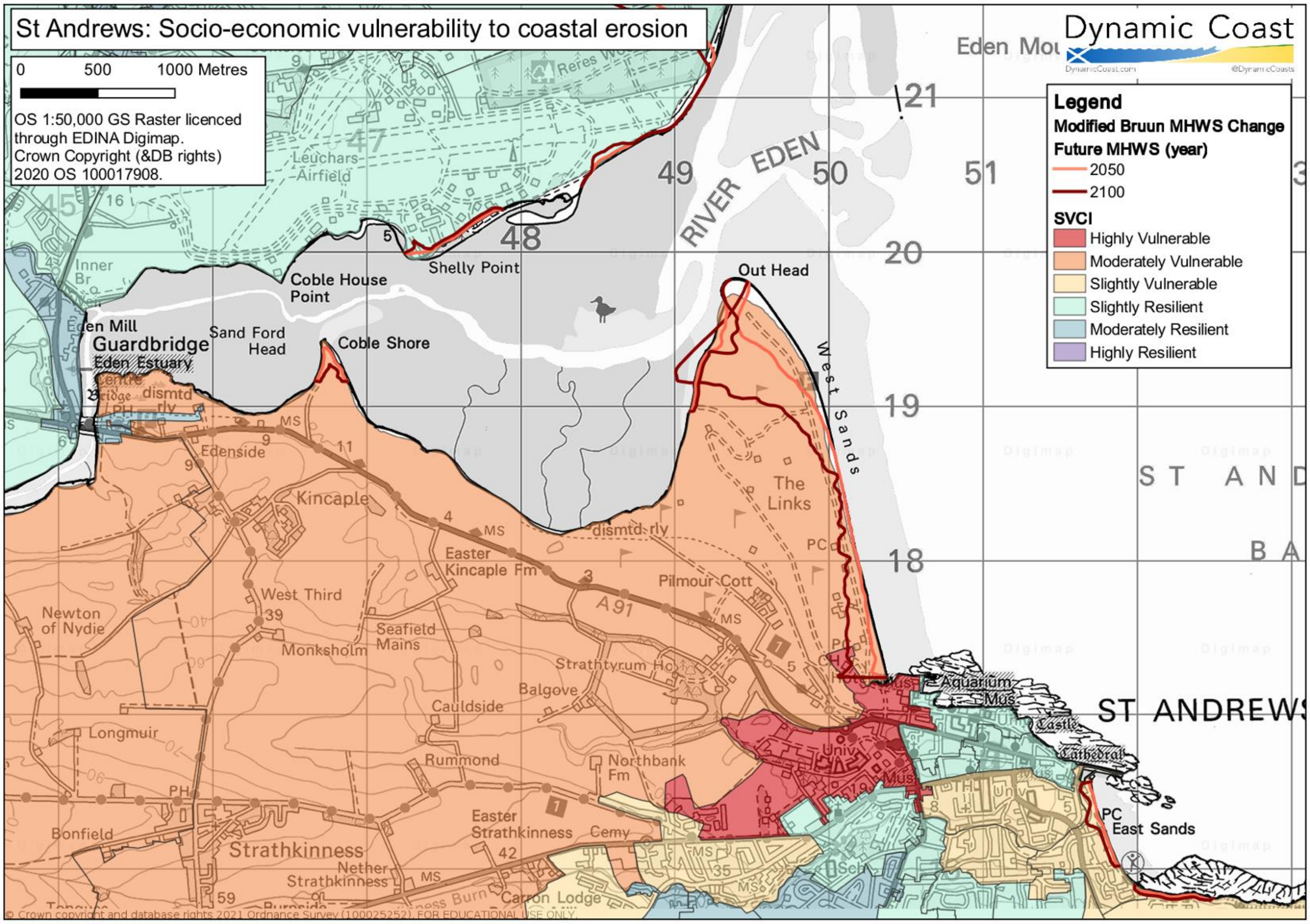


Figure 15 SVCI classifications per data zone with anticipated coastal change using the Modified Bruun Rule shown in red shade seawards on a heavy red line.

Flooding

Coastal Flood Boundary

The Coastal Flood Boundary (CFB) dataset was published by Department for Environment Food and Rural Affairs in 2018 (link) is reported in Table 2. It displays the anticipated still water surface level of surge events at various frequencies across St Andrews. 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 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 (2018) update deviates from the last version, there is a negligible increase (1 cm) at St Andrews.

Table 2 Tidal and flood levels for St Andrews

Description	Level (mOD)	Description	Level (mOD)
MHWS	2.35	1 yr (100% AEP)	3.26
HAT	2.95	10 yr (10% AEP) SEPA High prob. event	3.5
Base year	2008	100 yr (1% AEP)	3.74
FID		200 yr (0.5% AEP) SEPA Med. prob. event	3.83
Fitton method cross-checked with CFB (2019) at Tay Bar		1,000 yr (0.1% AEP) SEPA Low prob. event	4.03

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 16 shows the present-day high probability and low probability coastal flood extents, in greater detail than SEPA's flood maps as it benefits from a recent digital surface model (2018) and is more likely to accurately represent actual current land levels. Figure 16 demonstrates the linear nature of the flood risk as it follows the swales that lie between the dune ridges. However, it also highlights the current high probability flood risk along the low-lying agricultural land behind the Eden Estuary that also affects the arterial road into St Andrews (A91).

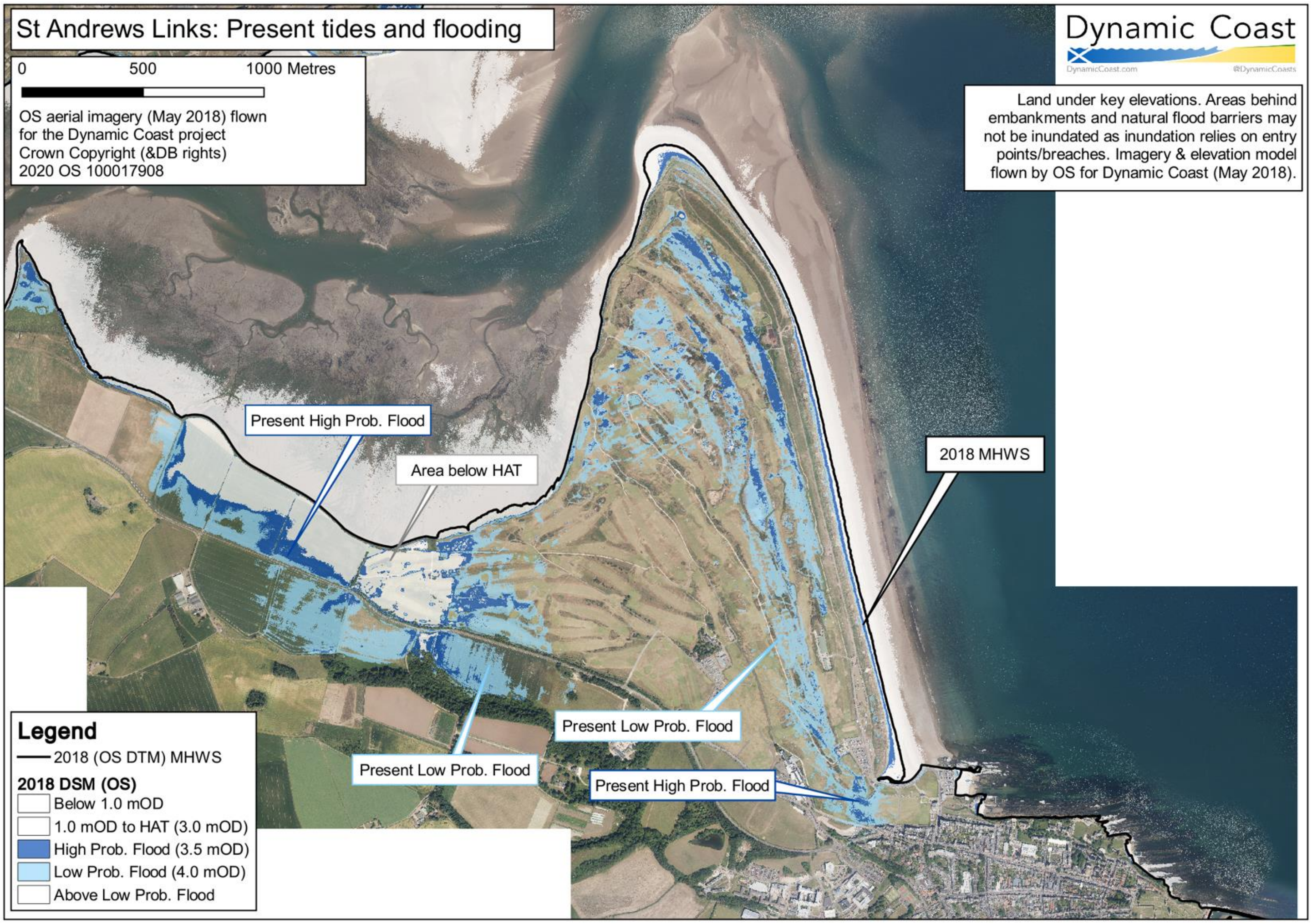


Figure 16 Summary of areas below present-day high probability flood levels (1:10 yr 3.5 mOD) and low probability (1:1,000 yr 4.0 mOD) flood levels at St Andrews Links.

Relative Sea Level Rise

The UK Climate Projections data (2018) has been used to anticipate increases in mean sea level at St Andrews. 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 Pathways 8.5. For context a 2°C future, corresponds to the RCP4.5 50th% at 2085. 4°C corresponds to RCP8.5 50th% by 2085 and the 5.5°C future corresponds to the 95th% by 2085.

The anticipated increases in mean sea level at St Andrews are summarised below. Thus by 2050 mean sea level is likely to increase between 0.1 m and 0.28 m; and are as likely as not to be more than 0.18 m above average levels seen between 1980 and 2000. Rates of sea level rise by 2050 are expected to be between 3 mm/yr and 8 mm/yr and as likely as not above 6 mm/yr. For context, the long-term pre-industrial relative sea level trend at St Andrews is -0.99 mm/yr (I.e. slightly falling; Bradley et al 2019). It should be noted that the UKCP18 Climate Projections could not rule out sea level rises above those noted within the RCP8.5 scenario.

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

Table 3 Existing and future tidal extents based on UKCP18 RCP8.5 for St Andrews. Shaded row highlights the worked example in the text above

Year	MSL increase (m above 1980–2000 levels)		
	5%	50%	95%
2010	0.0	0.02	0.03
2020	0.02	0.05	0.08
2030	0.04	0.08	0.13
2040	0.07	0.13	0.2
2050	0.10	0.18	0.28
2060	0.13	0.24	0.38
2070	0.17	0.31	0.50
2080	0.21	0.39	0.62
2090	0.26	0.47	0.76
2100	0.30	0.54	0.89
2300	0.70	1.71	3.48

Period	Rate of increase (mm/yr)		
	5%	50%	95%
2000–2010	0.0	2.0	3.0
2010–2020	2.0	3.0	5.0
2020–2030	2.0	3.0	5.0
2030–2040	3.0	5.0	7.0
2040–2050	3.0	5.0	8.0
2050–2060	3.0	6.0	10.0
2060–2070	4.0	7.0	12.0
2070–2080	4.0	8.0	12.0
2080–2090	5.0	8.0	14.0
2090–2100	4.0	7.0	13.0
2100–2300	2.0	5.9	13.0

The existing tidal inundation extents and increases anticipated by 2100 are shown in Figure 17 where the extent of land at the elevation of Highest Astronomic Tide (HAT) by 2070 covers the same areas presently at risk to High Probability flooding (1:10 yr), and the land at HAT by 2100 covers the same areas presently at risk to Low Probability flooding (1:1,000 yr). Total sea levels range between 2.35–3 mOD, which then increase to 3.25–3.9 mOD by 2100 with 0.9 m of sea level rise. Such an image is helpful in informing the growing risk of so called 'fair weather flooding' where flooding may increasingly occur in the absence of storms as the tide reaches higher and further inland due to increased mean sea level.

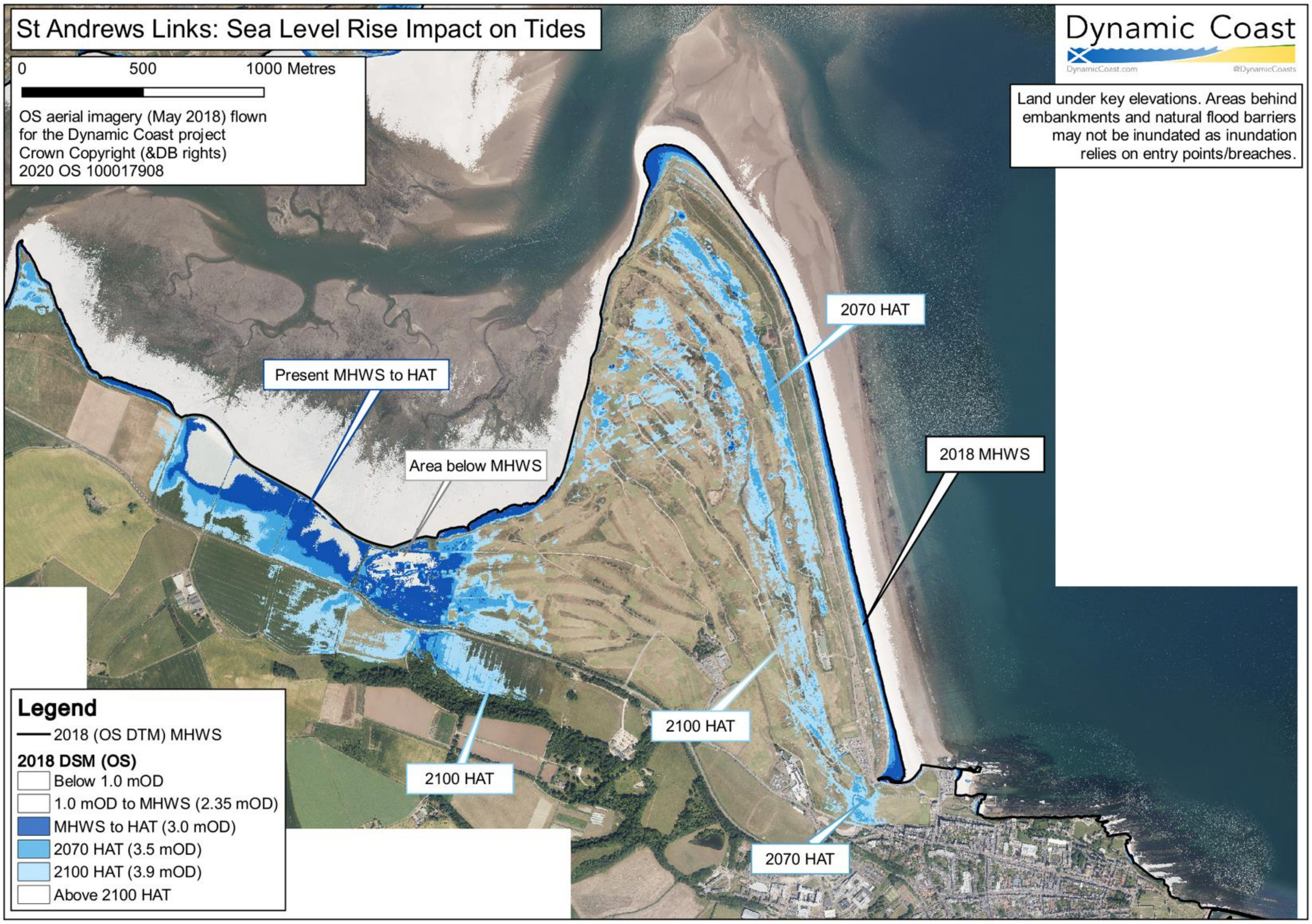


Figure 17 shows present day extent of the Highest Astronomic Tide and the future anticipated under UKCP18 RCP8.5 95% sea level rise by 2070 & 2100.

Figure 18 shows the key present day and anticipated flood elevations for St Andrews by 2070 and 2100 under RCP8.5 95th% sea level rise, which reflects the increased impact of storms and inundation events when 0.9 m is added to the current flood extents. These elevations hold a much greater risk of inundation to towns and property as well as a much greater coverage across the dune ecosystem. Having said this, it is worth highlighting that the dune front at West Sands (as it stands currently) acts as a natural barrier to this potential flooding, with the main entry points for flood corridors into the backdune entering from Out Head and south via the Swilcan Burn. The efforts of West Sands Partnership in managing the visitor pressure, whilst maintaining dune altitudes is particularly important.

Both figures show extensive inundation potential across Management Unit 4 (Eden Estuary) and a significant reduction of foreshore extent at West Sands and Out Head. If any part of the protective dune barriers become breached in the future then flood corridors would be created.

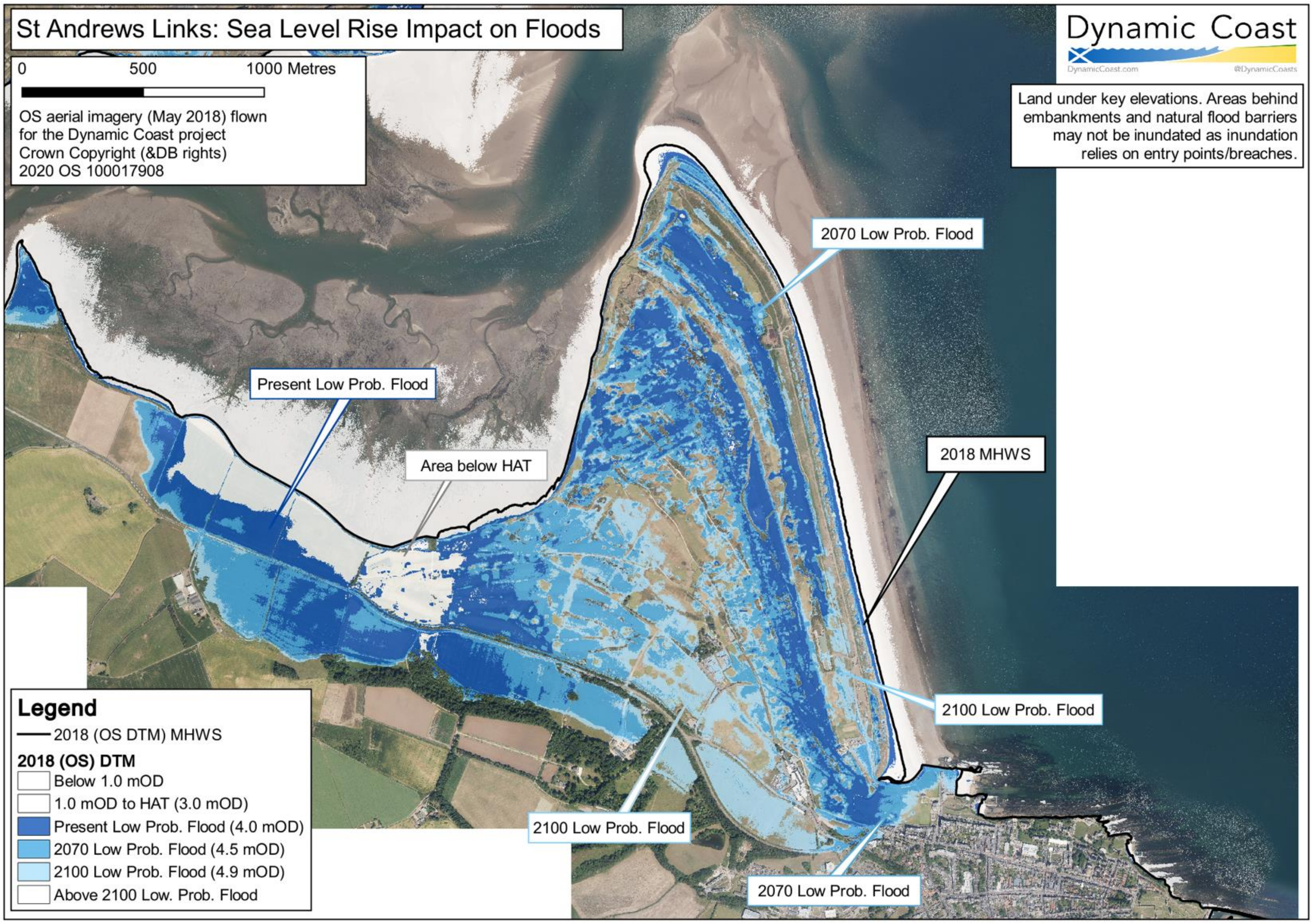


Figure 18 shows present day flood extents, together with future flood extents anticipated by 2100, under UKCP18 RCP8.5 95% sea level rise

Figure 19 plots the key present day and anticipated water elevations for St Andrews. Mean High Water Springs reaches 2.25 mOD and the highest astronomic tide (which excludes weather effects) is expected to reach 2.95 mOD. SEPA anticipate the High Probability flood level to have a still water level of 3.5 mOD and a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 4.03 mOD, this has a 0.1% annual exceedance frequency as shown on Table 3.

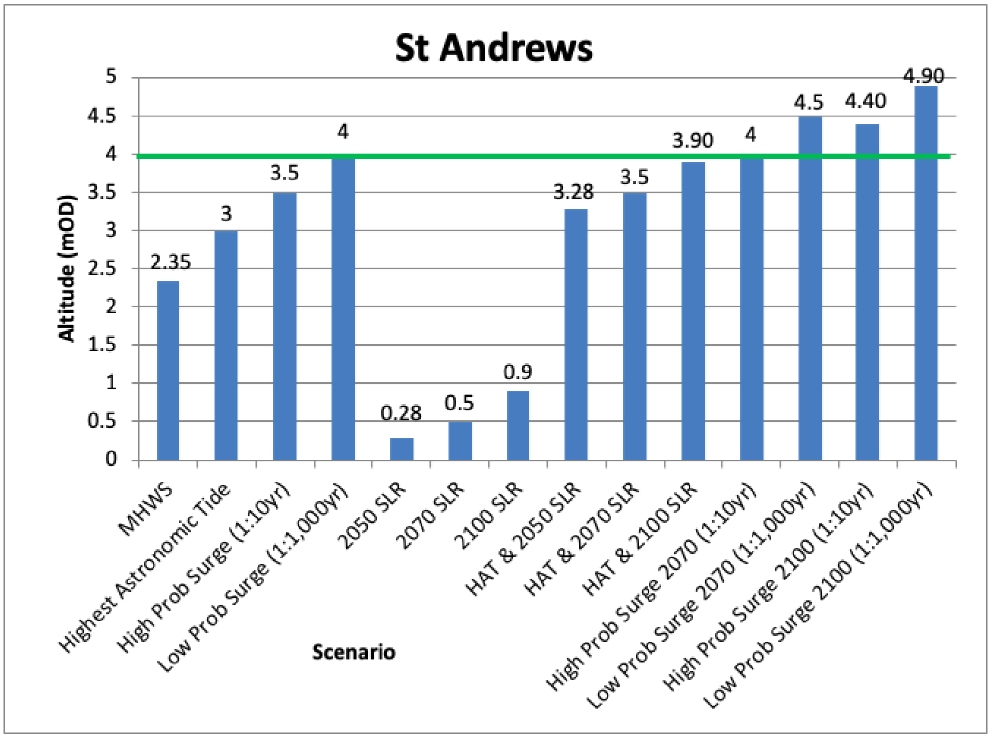


Figure 19 Summary of present and future key tide and flood levels at St Andrews. There are substantial areas of the dune links interior below 4 mOD (annotated with green line) although the dune crest and embankments are higher.

Flood Protection Features

Whilst Figure 5 provides a summary map of the protective function the dunes and embankments play in protecting the links interior, the following section contrasts three transects: West Sands, Swilcan burn and Eden estuary shore. The typical height of the dunes on the West Sands is above 5 mOD with isolated dune crests reaching up to 9 mOD. Whilst there are several locally low points within the West Sands dune cordon, these are separated from the interior links by older internal dune ridges (Figure 20). The exception to this on the West Sands is the Swilcan burn, whose banks reach 3.2 mOD in places (Figure 21).

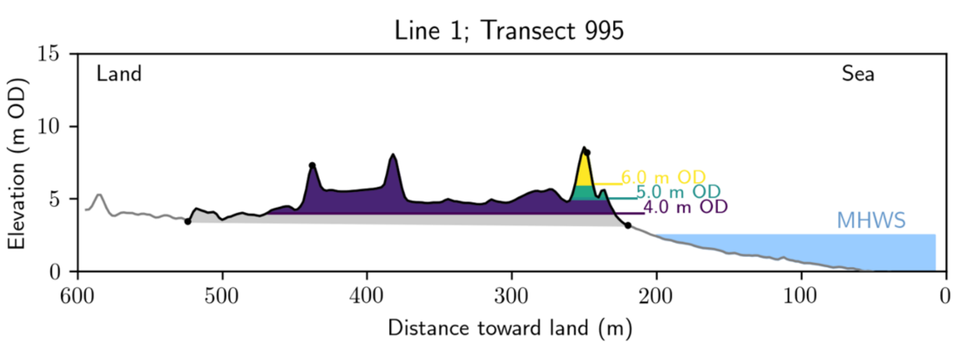


Figure 20 Exemplar transect through the West Sands dune cordon of multiple dune ridges, each providing a flood protection function. These ridges are shown as green areas in Figure 5. Key attributes are annotated along with the volume above certain elevations (a proxy for resilience).

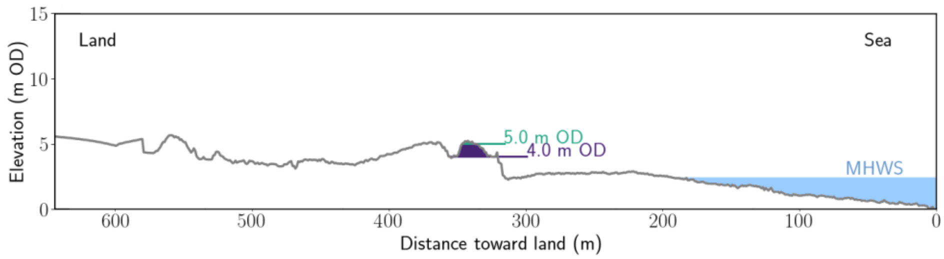


Figure 21 Exemplar transect through the Swilcan Burn area showing the narrow ridge (with the road, highlighted). The lower interior is connected to the sea via the Swilcan burn. The 18th green of the Old Course lies at 400–500 m on this transect.

The western-facing Eden estuary shore is typically lower where some crest levels are around 4 mOD. However, on the northern-facing estuary shore there is only a narrow embankment where levels approach 5 mOD (Figure 22). However, between the 13th and 6th west green of the Eden golf course there is almost no protective crest, and levels are typically below 5 mOD.

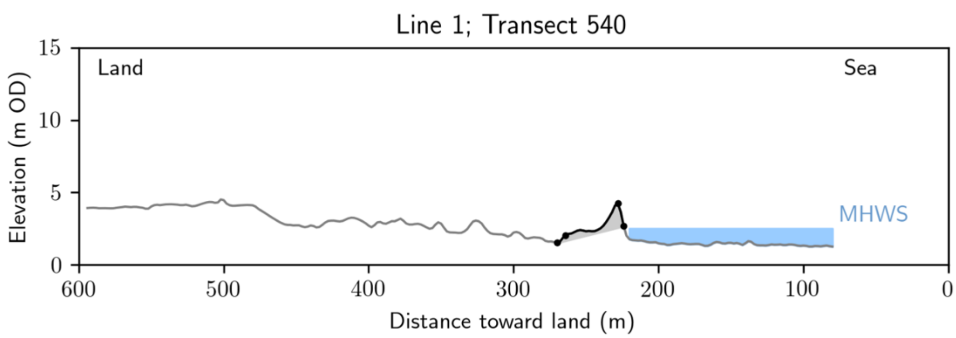


Figure 22 Exemplar transect through the Eden Estuary shore showing the narrow embankment protecting low-lying land at great risk from flooding.

Dynamic Coast data can be interrogated via the above tightly spaced transects (online maps are to be published on www.DynamicCoast.com) allowing any weak points along the coast to be identified and prioritised for management or enhancement. This type of dune reinstatement (raising the height of low-lying flood corridors and planting them with marram) has been successfully deployed by SALT over the last two decades. Such approaches address the short term flood risk but should be considered alongside beach-face erosion control measures to ensure the broader resilience of the entire dune cordon and links.

Consideration of Wave Run-up and Other Dynamic Components

Although the analysis of flooding in this study has not included wave run-up, wave climate was used as a direct input for the CoSMoS-COAST model to simulate wave-driven sediment processes in order to more accurately predict MHWS change in the future. The offshore wave climate at each supersite was considered in the form of Cefas Wave Hindcast wave conditions modelled from WaveWatch III data for the period of 1980–2018. At St Andrews, the offshore wave conditions are modelled as a mean height of 0.7 m and mean direction of 80° from north across the entire series, and then transformed to a nearshore a mean height of 0.49 m and a mean ENE approach direction (75° from north).

Combined Erosion and Flooding

Whilst recent erosion has been modest and localised (Figure 8), the anticipated erosion fuelled by sea level rise is potentially far more extensive (Figure 12). Similarly, whilst the present risk from tidal inundation (not flooding) is modest (i.e. yellow and white areas below 3 mOD in Figure 4 and white areas in Figure 16), any future sea level rise serves to increase the areas at risk from 'fair weather flooding' (where tidal inundation occurs without storms, Figure 17 and Figure 18). Under a "do nothing" coastal management strategy (where natural and artificial defences are not maintained into the future) the flood protection function of the dune cordon is likely to reduce due to frontal erosion and access along any low-lying corridors, resulting in the loss of parts of the links and increasing the risks to assets within the interior of the links.

Assets Potentially at Risk

Further more detailed assessments can be undertaken to inform assets at risk from flooding or erosion enhanced flooding.

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West Sands Partnership

END