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Dynamic Coast

Adaptation and Resilience Options for Golspie and Coul

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Adaptation and Resilience Options for Golspie and Coul

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

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Purpose and Status of this Report

This is a live document to reflect on-going discussions between the Dynamic Coast team (DC), Highland Council (HC), and partners. Its purpose is to collate our evidence and ensure key linkages are made.

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, which includes key results. The report is expected to be viewed alongside online resources at www.DynamicCoast.com.

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Executive Summary

1. The coastal sand dune ridges across Golspie and Coul provide a natural erosion and flood protection role to the interior land behind the dunes. More than 100 Golspie properties lie within 50 m of the current MHWS. Golspie Golf Club's 3rd, 4th and 5th holes and 6th and 7th tees have experienced ongoing, expensive restoration and coastal defense works as a result of coastal erosion and flooding.
2. Several low elevation corridors through both Golspie and Coul's dune ridge provide access for flood waters to travel inland. The dune ridge along Coul Links sits higher than Golspie Links, but a potential breach point exists north of Embo which could be exacerbated by erosion at this channel mouth. At Coul, short dune-capped spits protect low areas behind, but these remain open to tidal access from the north. Whilst currently at medium risk, as sea levels continue to rise the likelihood of future flooding increases (today's 200 yr event, becomes a 75 yr event by 2050 and a 10 yr event by 2080). Unchecked, present maximum coastal erosion rates may increase with sea level rise resulting in ~-330 m retreat by 2100 across Golspie and ~-90 m across Coul.
3. An average of 0.5 m/yr and up to 5 m/yr of erosion along the Vegetation Edge along Golspie and Coul Links has been recorded. Continued monitoring of the health of dune grasses along the Vegetation Edge of each bay is advised, particularly pre- and post-storm activity, as well as ensuring existing land use management continues to respect the vulnerability and value afforded by the low-lying coast ecosystems.
4. Proactive short-term actions addressing coastal flood and erosion risk areas would allow time to develop detailed proposals to accommodate and manage flood and erosion risk over longer-time periods (i.e. develop a Flood and Erosion Risk Management Scheme), ensure consistency with the Shoreline Management Plan (i.e. develop a broader flood and erosion adaptation plan for Golspie and Coul) and support adaptive land-management for managing risks for all coastal assets (e.g. housing, infrastructure, utilities, golf courses).
5. The presently high and quickening rates of erosion at Golspie and Coul, illustrate the present and near-future coastal and land management issues increasingly being grappled-with around the world. The high rates of erosion mean that terrestrial land-use planning must avoid additional development in areas of future risk and safeguard the accommodation space (i.e. the area where the beach system is expected to move inland), maximising future adaptation options for coastal community and planners, to maintain societal resilience as coastal climate change impacts intensify.
6. Considerable change is also anticipated within the low-lying areas of the Loch Fleet National Nature Reserve, which are being/should be considered further by NatureScot. Whilst substantial changes may raise fundamental questions over site management (attempt to maintain existing designated features or anticipate future change) the evidence base herein provides the foundations for dynamic nature conservation into the future, ensuring management is future-smart, if not future-proof.

Golspie and Coul Super Site Summary

Introduction

This report sets out some Resilience and Adaptation Options for the Golspie coast (Highland) between Golspie town, Littleferry at the River Fleet mouth and Coul Links to the town of Embo. The investigations concern the open coast and do not include the Loch Fleet tidal basin coast. The aim is to support key partners in their planning for anticipated increases in the threat of coastal erosion and flooding. The Executive Summary and Technical Summary 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 they 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 may use this report to identify risks and opportunities to improve business 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 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.

Local Coastal Context and Anticipated Change at Golspie and Coul

Between 1904 and 1977, Golspie Links generally saw strong MHWS retreat and Coul Links experienced small pockets of accretion and erosion. Little change was recorded from 1977–2009, except for south Golspie Links by the River Fleet mouth which continued to erode. The pattern of recession in the north and accretion in the south has continued to 2019. The largest amount of change has generally been seen either side of mouth of the Fleet, with the mean recession rate being 2.1 m/yr from 1970–2013 and 7.3 m/yr from 2013–2019.

Recent topographic change analysis shows sediment losses have dominated the lower foreshore and intertidal zone with 100,000 m^3 of sediment loss at Coul from 2016–2019 and 70,000 m^3 loss at northern Golspie from 2013–2019.

However, the north and south banks of the Loch Fleet mouth and adjacent spits show accretion to the east during these same periods, totalling 139,000 m^3 for the north side (Golspie) and 30,000 m^3 for the south side (Coul). Vegetation Edges at Coul have eroded by a maximum rate of 2.2 m/yr and average rate of 0.4 m/yr, and eroded at Golspie by a maximum rate of 5 m/yr and average rate of 1 m/yr at Golspie. Vegetation Edge survey using recent photography (2009–2016) was used as a supplement for recent shoreline change. This identified Vegetation Edge erosion rates of up to 2.3 m/yr in places across central Coul and a generally erosional trend in the south and centre with accretion toward the southern mouth of Loch Fleet.

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 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 Golspie and Coul, 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. 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 (See National Overview Report (www.DynamicCoast.com/reports). 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 Golspie, Coul and elsewhere. Practical implementation mechanisms are also required along with strategic plans and policies, so that adaptation measures such as realigning key infrastructure are ready to be rolled out and implemented when erosion happens. This would shift erosion management from reactive to proactive, and in doing so, enables long-term societal resilience to coastal climate change with the least social and economic costs.

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

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 (www.DynamicCoast.com/reports), but their application in the context of Golspie and Coul 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 such as a sand motor) (see National Overview Report for context). Table 1 outlines the past erosion rates observed at Golspie and Coul and identifies both areas at greatest risk and management and adaptation options. All risk management and adaptation responses require robust appraisal to allow organisations to allow better management of coastal erosion risk and improve societal and ecosystem resilience.

Coastal erosion, flooding and erosion-related flooding are considered the key risks impacting Golspie and Coul now and in the future. Landowners and Local Authorities (LA) have responsibility for, and powers to address, coastal erosion and flooding. LA also have shared powers under the Flood Risk Management (Scotland) Act 2009 and the Climate Change (Scotland) Act 2010, including a statutory duty to report on climate change adaptation progress. Guidance on planning for coastal change can be found here (SNH, 2019, https://www.nature.scot/guidance-planning-ahead-coastal-change). Consistent with a Shoreline Management Plan approach, Figure 2 and Table 1 sub-divide Golspie and Coul into management units to identify coastal erosion risk and management approaches to improve resilience of natural and societal assets in the short-term as well as adaptation options to improve long-term community resilience. Each management option in Golspie and Coul 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. Golspie has urban communities, rural areas and sites of natural and cultural importance which have been subject to ongoing erosion and where traditional, hard engineering erosion-resist management options have increasingly required costly replacement or repair. At these points and elsewhere, beach lowering and retreat has weakened the natural capital afforded by the beach and dunes (such as natural erosion protection); urgent action is required to restore this natural capital.

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 and dunes 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 NPF4 (Consultation documents) and recently revised National Land Use Strategy (Consultation documents).

Resilience and Adaptation Options at Golspie and Coul

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

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

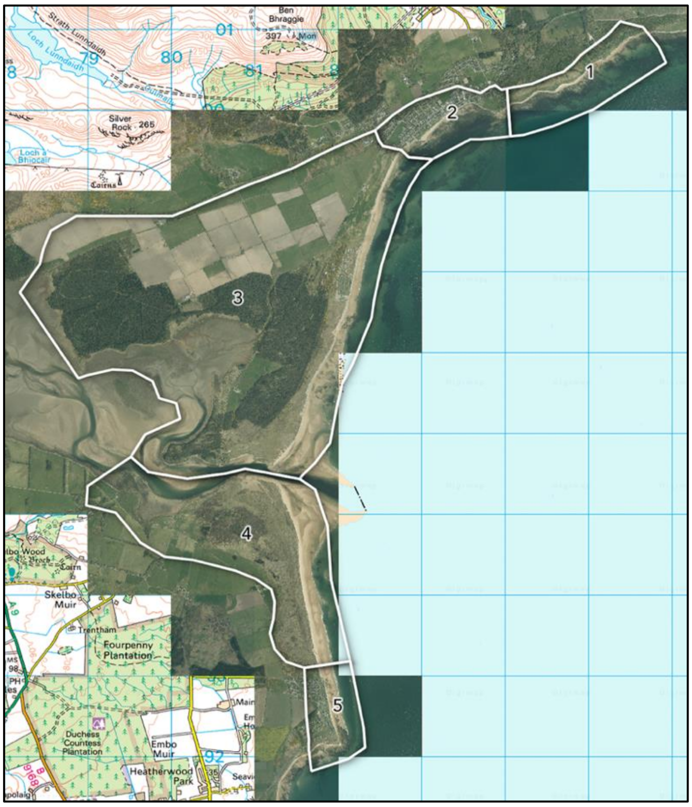

Figure 2 Management unit areas for Resilience and Adaptation Options. Labelling relates to options in Table 1.

Table 1 Risk management, Resilience and Adaptation Options for Golspie and Coul, 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' implications	'Short term' management options to improve short-term resilience	'Long term' adaptation options to improve resilience
Area 1: Dunrobin shore  Natural shingle shore with artificial sections in front of castle estate	Foreshore gravel with sandy shoreface, protected by seawall in parts. Dunrobin Castle estate.	<u>Low Water</u> 1904–1962: +43 m 1970–2019: 0 m <u>High Water</u> 1904–1962: +29 m 1970–2013: -9 m 2013–2019: -3 m <u>Volume</u> N/A <u>Vegetation Edge</u> 2007–2012: -5 m 2012–2016: -4 m	Foreshore lowering, especially on defended shores. Flanking & erosional bites at end. Retreat of soft shorelines 20–60 m loss. Spray & over-wash risk increasing.	<u>**Non-Active Intervention:**</u> 1. **Monitor change/no intervention (now onwards):** Undermining and eventual breach of defences leading to a phased incremental loss of some historic castle grounds, if historic castle buildings are involved then costs to business and affect tourism impact follow. Cost: zero - moderate; Risk: moderate. <u>**Accommodate Erosion**</u> 2. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated / relocated, if or when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 3. Avoid new permanent development in areas of current or future risk. <u>**Erosion Resist:**</u> 4. **Reprofile beach: (0-10 yrs)** Short-term local enhancement of upper beach profile to improve natural resilience of beach by re-organisation of existing beach sediment to maximize natural protection of weak points in sea wall. 5. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences. 6. **Maintain or install new defences (0–20 yrs):** Extend design life of existing or add new defences.	**In addition to deployment of short term options:** <u>**Non-Active Intervention:**</u> 1. **Monitor coastal change/no intervention** (now onwards) alongside **accommodate erosion.** 1. <u>**Accommodate Erosion:**</u> 2. Progress **Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated, if or when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 3. **Realign vulnerable roadways and relocate assets (2050):** avoid future risks and reduce the need for some "erosion resist" options, e.g. relocating formal gardens to behind the castle. 4. <u>**Erosion Resist:**</u> 5. **Combined enhanced defences and beach feed (2050):** Direct defences constructed,fronting beach renourished with sand and gravel to maintain amenity and reduce wave impact on defence structures .
Area 2: Golspie town  Artificial shore with some natural sections	Foreshore with sandy shoreface, sea wall in Golspie town centre and A9 & Fountain Road intersection.	<u>Low Water</u> 1904–1962: +15 m 1970–2013: -2 m 2013–2019: 0 m <u>High Water</u> 1904–1962: +8 m 1970–2013: -2 m 2013–2019: 0 m <u>Volume</u> 2013–2019: 0.6–3.1 m lowering 2013–2019: -4,700 m³ <u>Vegetation Edge</u> 2007–2012: -1 m 2012–2016: -2 m	Foreshore lowering, especially on defended shores. Flanking & erosional bites at end. Retreat of soft shorelines 40 m loss. Spray & over-wash risk increasing. Res. Properties & park	<u>**Non-Active Intervention:**</u> 1. **Monitor change/no intervention (now onwards):** Undermining and eventual breach of defences leading to a phased incremental loss of seaward grounds. Impact on housing assets and related infrastructure (e.g. septic, access roads and utilities). Cost: moderate; Risk: high. <u>**Accommodate Erosion:**</u> 7. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated / relocated, if or when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 8. Avoid new permanent development in areas of current or future risk. <u>**Erosion Resist:**</u> 9. **Reprofile beach: (0–5 yrs):** Short-term local enhancement of upper beach profile to improve natural resilience of beach by re-organisation of existing beach sediment to maximize natural protection of weak points in sea wall. 10. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences. 11. **Maintain or install new defences (0–20 yrs):** Extend design life of existing or add new defences. <u>**Advance:**</u> 2. **Offshore or nearshore breakwater (0-20 yrs):** reinstate historic rubble breakwater along town frontage to reduce storm wave impact.	**In addition to deployment of short term options:** <u>**Non-Active Intervention:**</u> 2. **Monitor coastal change/no intervention** (now onwards) alongside **accommodate erosion.** <u>**Accommodate Erosion:**</u> 6. Progress **Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated, when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 7. **Realign vulnerable roadways and relocate assets (2050):** realignment of existing assets (e.g. housing and infrastructure such as roads, utiltities) to avoid future risks and reduce the need for "erosion resist" options. <u>**Erosion Resist:**</u> 3. **Feed beach (2050):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences. 4. **Combined enhanced defences and beach feed (2050):** <u>**Advance:**</u> 5. **Offshore or nearshore breakwater (2050):** reinstate historic rubble breakwater along town frontage to reduce storm wave impact. 6. **Mega nourishment (2050):** beach & dune reshaping would benefit the entire bay and reduce risk of erosional breach and erosion-related flooding.

Management Unit Area	Shore Character & Assets	Coastal changes	'Do nothing' implications	'Short term' management options to improve short-term resilience	'Long term' adaptation options to improve resilience
Area 3: Golspie Links (Golspie pier to Fleet mouth)  Artificial shore in the north and natural shore in the south	Broad sandy shoreface with boulder revetment in north at Golspie Golf course and gravel beach at caravan park and Go-Kart Circuit. To south into NNR, large gravel/sand spit and marsh parallel to Fleet mouth.	Erosional bite at Caravan park: <u>Low Water</u> 1904–1962: -45 m 1970–2019: -0 m[a] 1970–2019: -15 m[b] <u>High Water</u> 1904–1962: -26 m 1962–2013: -6 m 2013–2014: -4 m 2014–2019: -3 m <u>Volume</u> 2013–2019: 0.5–3.2 m raising (spit), 0.7–3.8 m lowering (north) 2013–2019: +24,000 m^3 <u>Vegetation Edge</u> 2007–2012: -4 m[c] 2009–2012: -13 m 2012–2018: -27 m	Foreshore lowering, especially on defended shores. Flanking & erosional bights at end. Retreat of soft shorelines 100 m loss. Spray & over-wash risk increasing.	<u>Non-Active Intervention:</u> 1. Monitor change/no intervention (now onwards): Undermining and eventual breach of defences leading to a phased incremental loss of seaward grounds at golf course and to the south. Cost: zero - moderate; Risk: moderate. <u>Accommodate Erosion:</u> 2. Develop Dynamic Adaptive Policy Pathway, to enable existing assets to be adaptated / relocated, if or when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 3. Avoid new permanent development in areas of current or future risk. <u>Erosion Resist:</u> 1. Reprofile beach: (0–5 yrs): Short-term local enhancement of upper beach profile to improve natural resilience of beach by re-organisation of existing beach sediment to maximize natural protection of weak or low points. 2. Maintain or extend defences (0-20 yrs): maintain existing boulder revetment and extend south to northern boundary of NNR, noting expectation of erosion being 'past on' to NNR. 3. Feed beach (0–10 yrs): Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences.Maintain or extend defences (0–20 yrs): Existing boulder defences maintained to extend design life and extended south to boundary of NNR	**In addition to deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor coastal change/no intervention** (now onwards) alongside **accommodate erosion.** **<u>Accommodate Erosion:</u>** 2. Progress **Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated, when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded to provide future options. 3. **Realign and relocate vulnerable assets (2050):** Some realignment of existing assets (e.g. golf course and recreation assets included associated infrastructure, e.g. utilities) to avoid future risks and need for "erosion resist" options. **<u>Erosion Resist:</u>** 4. **Feed beach (2050):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences. 5. **Enhanced defences and beach feed (2050):** Direct defences constructed,fronting beach renourished with sand and gravel to maintain amenity and reduce wave impact on defence structures . **<u>Advance:</u>** 6. **Mega nourishment (2050):** beach & dune reshaping to benefit the entire bay and reduce risk of erosional breach and erosion-related flooding.
Area 4: Coul Links (Fleet mouth to Embo)  Natural shore	Broad sand spit parallel to Fleet mouth backed by dune ridge and marsh. Part of Loch Fleet SSSI and SPA. Tracks leading onto northern marsh.	<u>Low Water</u> 1975–2019: +52 m <u>High Water</u> 1904–1977: +42 m (spit), +8 m (south) 1977–2019: +24 m (spit), +19 m (south) 2016–2019: -26 m <u>Volume</u> 2016–2019: 0.2–2.7 m raising (spit), 0.3–2.8 m lowering (south) 2016–2019: -29,000 m^3 <u>Vegetation Edge</u> 2009–2012: +50 m (spit), -3 m (south) 2012–2015: -57 m (spit), -13 m (south) 2015–2019: -39 m (spit), +8 m (south)	Foreshore lowering, retreat of vegetation. Spray & over-wash increasing.	**<u>Non-Active Intervention:</u>** 4. **Monitor change/no intervention (now onwards):** Undermining and eventual breach of defences leading to a phased incremental loss of seaward grounds. Cost: zero - moderate; Risk: moderate. **<u>Accommodate Erosion:</u>** 5. Develop **Dynamic Adaptive Policy Pathway**, for designated nature conservation interests, ensuring the progressive effects of natural coastal change on habitat extent are not viewed as threat or damage. 6. Avoid approval of any new traditional (i.e. permanent) development in areas of current or future risk. **<u>Erosion Resist:</u>** 12. **Reprofile beach: (0–5 yrs):** Short-term local enhancement of upper beach profile to improve natural resilience of beach by re-organisation of existing beach sediment to maximize natural protection of weak or low points. 13. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences. 14. **Install defences (0–20 yrs):** no assets at risk, so unlikely.	**In addition to deployment of short term options:** 1. **Monitor coastal change/no intervention** (now onwards) alongside **accommodate erosion.** **<u>Accommodate Erosion:</u>** 2. Progress **Dynamic Adaptive Policy Pathway (2050):** , for designated nature conservation interests, ensuring the progressive effects of natural coastal change on habitat extent are not viewed as threat or damage. 3. Avoid approval of any new traditional (i.e. permanent) development in areas of current or future risk. 4. **<u>Erosion Resist:</u>** 5. **Feed beach (2050):** no assets at risk, so unlikely 6. **Install defences (2050):** no assets at risk, so unlikely. **<u>Advance:</u>** 7. **Mega nourishment (2050):** beach & dune reshaping to benefit the entire bay and reduce risk of erosional breach and erosion-related flooding.

Management Unit Area	Shore Character & Assets	Coastal changes	'Do nothing' implications	'Short term' management options to improve short-term resilience	'Long term' adaptation options to improve resilience
Area 5: Embo  Partly artificial and natural rockhead shore	Bedrock shore platform and sandy shoreface fronting artificial, protected beach ridge fronting dunes and caravan park. Extent of visible defences 2009 = 95 m, 2019 = 580 m	<u>Low Water</u> 1975–2019: -13 m <u>High Water</u> 2016–2019: -8 m <u>Volume</u> 2016–2019: 0.3–0.7 m lowering 2016–2019: -15,500 m^3 <u>Vegetation Edge</u> 2009–2012: -2 m 2012–2015: -10 m	Loss of sand, further exposure of rock foreshore. Flanking & erosional bight at end of defences. Retreat of soft shorelines 40 m? loss. Spray & over-wash risk increasing.	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** Cost: zero; Risk: moderate. **<u>Accommodate Erosion:</u>** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated / relocated, if or when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Reprofile beach: (0–5 yrs):** Short-term local enhancement of upper beach profile to improve natural resilience of beach by re-organisation of existing beach sediment to maximize natural protection of weak or low points. 3. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences. **<u>Erosion Resist:</u>** 1. **Maintain or install new defences (0–20 yrs):** Extend design life of existing or add new defences.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** **<u>Accommodate Erosion:</u>** 1. Progress **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated / relocated, if or when their present location become exposed to erosion / flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded for options. 2. **Realign roadways and relocate assets (2050):** 3. **Combined enhanced defences and beach feed (2050):** **<u>Erosion Resist:</u>** 1. **Feed beach (2050):** enhancement of whole beach profile to improve natural resilience beach . **<u>Advance:</u>** 2. **Mega nourishment (2050):** beach & dune reshaping to benefit the entire bay and reduce risk of erosional breach and erosion-related flooding.

[a] OS MLWS 1970 & 2019 are identical
[b] Estimate based on Coast X-Ray extracted MLWS
[c] Aerial imagery coverage for 2007only to northing 897000 (Loch Unes)

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

This section briefly expands, by area and management options, on some of the key points emerging from Table 1. If **Non-Active Intervention** (NAI) is the preferred policy option at Golspie and Coul, **then** beach and/or dune cordon erosion or lowering will continue to occur, in both the short and long-term. At Golspie town (**Area 2**) one option is to reinstate the historic boulder barricade (offshore/nearshore breakwater) to reduce the impact of storm waves on the towns existing seawall. Elsewhere at Golspie and Coul, there are no recommended options to **Advance** the current coastal position using such structural **erosion resist** options. However, the use of a large-scale **nature-based erosion resist or advance** 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, depending on the volume of feed and renourishment programme. All the recommended **erosion resist measures** (nature-based or 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 (or regenerated) development of permanent infrastructure, housing or industry in areas forecast 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 permitted in areas at risk. 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.

Land-based adaptation mechanisms are recommended for all areas to accommodate erosion by facilitating landward retreat of natural beach-dune systems and assets on land. For example, in **Area 1 and especially Area 2,** irrespective of the measures adopted at the coastal edge new development should be avoided and land-based policies developed to support adaptation of assets and activities to move away from areas at risk. This also extends to the north section of **Area 3 (**golf course frontage) that is presently protected by a boulder revetement that has failed several times in the recent past. The presence of this revetement has led to beach lowering in front and accelerated recession of the coast to the south, suggesting that a viable alternative option would be to renourish and reprofile the fronting beach, a strategy that would benefit the coast the south into the NNR as well as **Areas 4 and 5** at Coul Links and Embo. Reprofiling the upper beach and frontal dune ridge at the south end of **Area 3** (caravan park and kart track) and local beach feeding would buy time to develop a long term strategy for the entire bay. **Area 5** at Embo is currently partly protected along the caravan site frontage and would benefit from local beach feeding.

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

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 extent and geometry of the foreshore and the low- and high-water marks against previously 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. Between 1904 and 1977, Golspie Links generally saw strong MHWS retreat and Coul Links experienced small pockets of accretion and erosion. Little change was recorded from 1977–2009, except for south Golspie Links by the River Fleet mouth which continued to erode. The pattern of recession in the north and accretion in the south has continued up to 2019. The largest amount of change is generally seen across the edges of the river mouth, with the mean recession rate being 2.1 m/yr from 1970–2013 and 7.3 m/yr from 2013–2019.
2. Recent topographic change analysis shows sediment losses have dominated the lower foreshore and intertidal zone with 100,000 m^3 of sediment being lost across Coul from 2016–2019 and 70,000 m^3 lost across northern Golspie from 2013–2019. However, the north and south banks of the Loch Fleet mouth and adjacent spits show accretion to the east during these same periods, totalling 139,000 m^3 for the north side (Golspie) and 30,000 m^3 for the south side (Coul).
3. Vegetation Edges show a more complex trend with ~400 m long sections of erosion, stability and accretion over the last two decades. Vegetation erosion rates reached 2.2 m/yr along northern Coul, with central Coul showing accretion rates of up to 1.1 m/yr. Pockets in southern Golspie showed vegetation erosion rates of up to 3 m/yr while the area south of the Little Ferry Race Circuit reached up to 5 m/yr erosion, with lesser erosion of 0.5 m/yr across the Golspie Links and town front.
4. Whilst most of the dune cordon provide a good level of flood protection to the low-lying interior, they are essentially narrow with some potential flood corridors where inland streams exit through the dunes and onto the beaches.

The first phase of Dynamic Coast summarised the coastal changes to Golspie and Coul (see pages 30–36 of Cell 3 report) between 1904, 1970/77 and 2014 and a recent Vegetation Edge survey from 2009–2016. The Vegetation Edge across Coul retreated by an average of 3 m/yr from 2009–2016, whilst the MWHS across Golspie has eroded at a rate of between 0.4–2.7 m/yr from 1970–2014.

The second phase of research, outlined below, benefits from Ordnance Survey's aerial survey undertaken in May 2019, 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 at Golspie and Coul

The overall coastal context at Golspie and Coul centres on a series of emerged large gravel spits that have extended south over the past several thousand years from Golspie to partly enclose the low-lying land north of the mouth of the Fleet. The present gravel beach and spit at Golspie sits seaward of the emerged gravel spits. South of the Fleet at Coul, sediments from the north have accumulated and built out, likely as a series of emerged beach ridges with subsequent dune accumulation on top. The mouth of the Fleet itself has short stubby spits extending from either side and recurving landward into the Fleet. Seaward of the mouth a substantial ebb-tide delta has formed fed by sediment exiting from the Fleet and arriving from the north. Both Golspie Links and Coul Links have a similar 3–4 km-long stretches of sand and gravel beach that are pinned at their north (Golspie) and south (Embo) extremities by rock shore platforms. Both Links display extensive areas of sand dune that sit on top of the emerged gravel beach ridges transitioning to coastal heath or forest inland. At an average elevation of 7–9 mOD, with some sections reaching 12 mOD, the frontal dune ridge at Coul Links is higher and wider than along much of Golspie Links; the ridge at north Golspie reaches only 4–5 mOD but much of south Golspie frontal ridge lies below 2 mOD with lower land behind before rising again to 9 mOD. Just north of Embo, a small channel mouth at 2.1 mOD may provide a potential conduit for marine flooding into the low-lying <3 mOD interior behind the frontal dune ridge, a low-lying swale that extends north for almost the entire length of Coul Links. Evidence of dune dynamism can be seen in the ridges inland of each spit that follow the current MHWS morphology. The 7 mOD frontal ridge at north Coul remains open to tidal incursion at its northernmost point, allowing tidal access to the low-lying swales that lie behind and parallel to the frontal ridge, and creating a short tidal corridor behind the dune ridge that has the potential to link with similar low-lying coast-parallel swales to the south.

The nearshore bathymetry is fairly shallow and characterised by low onshore gradients, with sand and gravels that transition to intermittent bedrock in the north and south. Golspie has steeper offshore gradients than Coul, which may allow higher wave activity access to the shoreface.

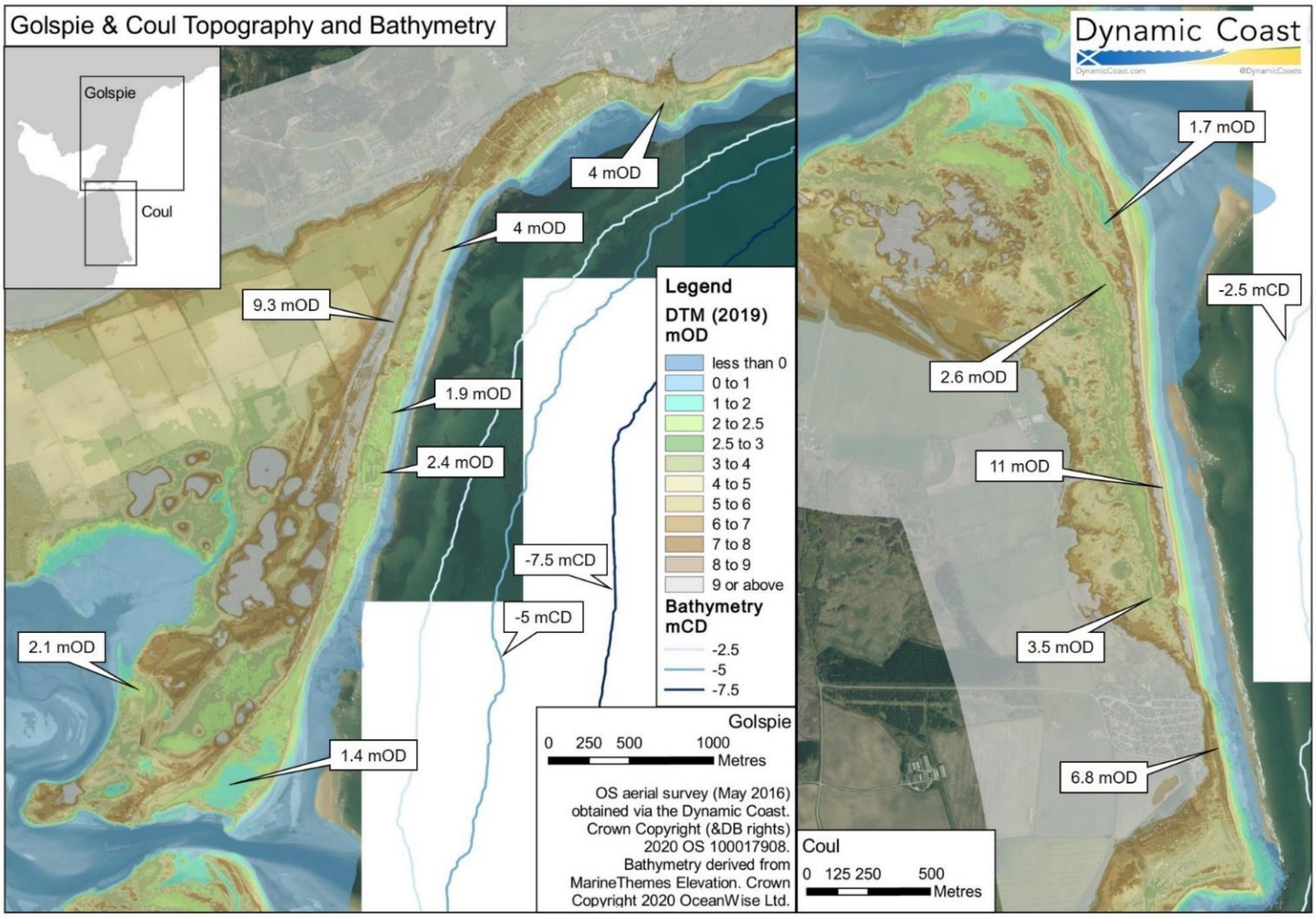

Figure 3 Topography, Bathymetry (mCD) and key flood levels (mOD) at Golspie and Coul (from 2019 OS aerial imagery derived DSM and MarineThemes bathymetry)

National Coastal Flood Protection Features across Golspie and Coul

Automated terrain analysis was carried out on Golspie and Coul's soft coast, to systematically identify natural flood protection features (i.e. dunes and cliffs) shown in Figure 4. These features include the extent of ridge features (identified from topographic high points), potential flood corridors (identified from topographic low points), the presence of cliff features and the extent and volume of continuously elevated ground (i.e. barriers) at location-specific flood levels. For Golspie and Coul, the protection function of the dune cordons can best be summarised by the dune width at 3.5 mOD, this being the elevation of likely future flood levels combined with wave heights and explored in the flooding section of this report. The dune cordon characteristics in Figure 4 can be compared with the elevation changes in Figure 7 and Figure 10 to highlight sections of potential flood risk in Areas 2 and 3, where current rates of erosion may compromise the already narrow dune front to expose the low-lying backdune to flooding. In Areas 4 and 5 at Coul, the barrier front toe points show a wider and therefore more protective dune front, but this barrier feature extraction further supports the breach points for flood corridors expanded on in the Existing Topography at Golspie and Coul section. This process also calculates the sediment volumes within each barrier feature, allowing for both an understanding of protective capacity as well as an order of magnitude for possible future dune infilling.

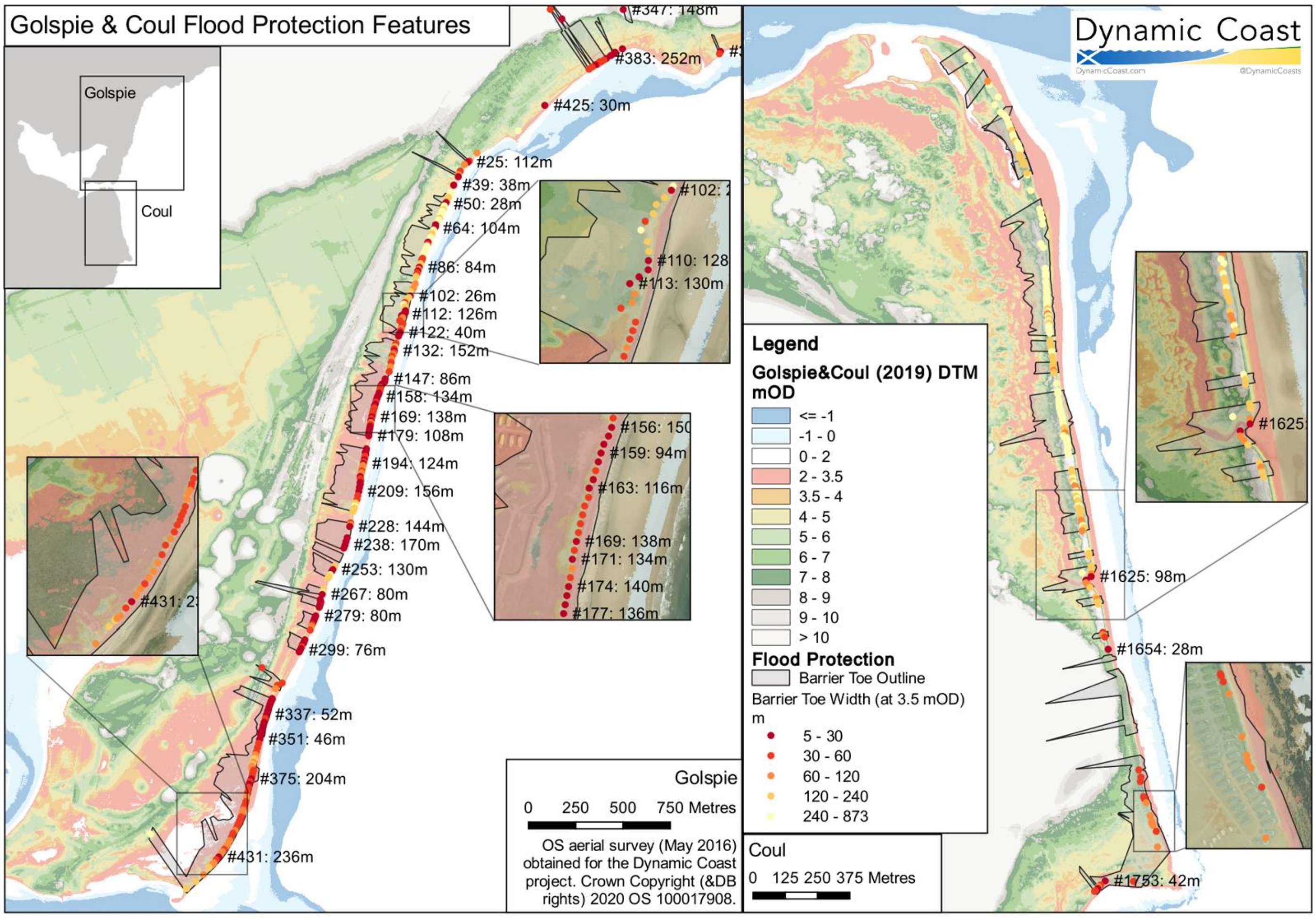

Figure 4 Flood protection features at Golspie and Coul, showing the extent of the barrier toe (grey box) and points at front of barrier symbolised by the barrier width at 3.5 mOD. Barrier toe width is annotated alongside transect number.

Changes to Low Water at Golspie and Coul

Figure 5 shows planimetric changes to MLWS between the 1975-2019 OS surveys and the 2016–2018 MLWS from Coast X-Ray using the Sentinel-2 satellite data. In general, the period 1975–2019 saw erosion along the south Golspie shore of up to 160 m at the most dynamic section of the spit, and accretion along northern Coul of up to 180 m along what was previously a N-S sand bar that has since shifted in position. The sections along northern Golspie and southern Coul show surprisingly little change to the MLWS position considering its likely dynamism. The Coast X-Ray MLWS line, (albeit defined by the position at which >80% of Sentinel-2 images in the stack analysed are classified as containing water) deviates from the 2019 OS MLWS position and plots consistently landward of the 2019 line by up to ~700 m at the Fleet mouth and by 20–60 m elsewhere. However, it should be noted that the Coast X-Ray line derives from only 2 years of images that may not fully capture the full tidal extent at low water. In general, and apart from the mouth of Loch Fleet, it appears that MHWS has moved landward overall along much of the Golspie to Coul coastline.

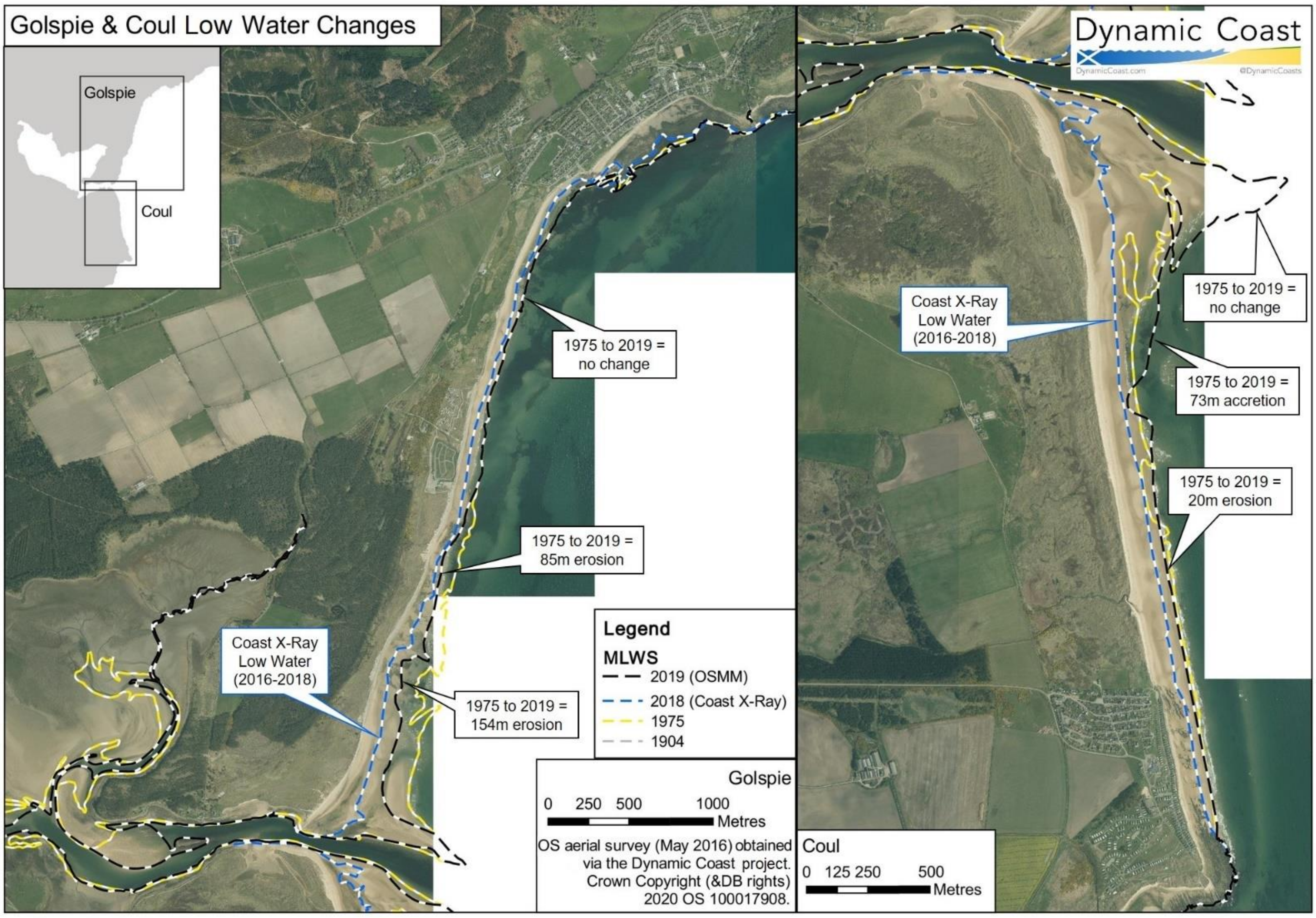

Figure 5 Changes to each lower beach – comparison of various MLWS surveys and Low water (80% water occurrence) from Coast X-Ray

Changes to High Water at Golspie and Coul

Figure 6 shows change in the upper beaches of Golspie and Coul as depicted by the position of MHWS. In general, the period 1904–1977 was characterised by erosion along the north spit of the River Fleet mouth, and a smaller amount of accretion on the southern spit. 1977–2009 saw no change between OS MHWS lines; this due to lack of updated OS measurements rather than no real-world lateral change in MHWS. 2009–2019 saw a continuation of these trends with an increased erosion rate in the north (0.7 m/yr from 1904–1970, 2.2 m/yr from 1970–2013, and 2.6 m/yr from 2013–2019). The northernmost point of the Coul spit along the River Fleet mouth has fluctuated significantly since 1904, with the seaward side accreting and the N-S marsh channel behind progressing south with each survey. The 1904 MHWS is more complicated compared to modern measurements but, overall, the trend in high water change from 1977–2013 and 2013–2019 is accretionary, at an average rate of ~3 m/yr. In general, Figures 5 and 6 demonstrate that over the period of 1975–2019, Golspie has migrated consistently landward and Coul has undergone phases of accretion and erosion, with accretion in the north and south (at Embo) and erosion in the centre. However, the Coast X-Ray MLWS positions suggest the shorefaces of both Golspie and Coul have exhibited foreshore beach steepening in recent periods.

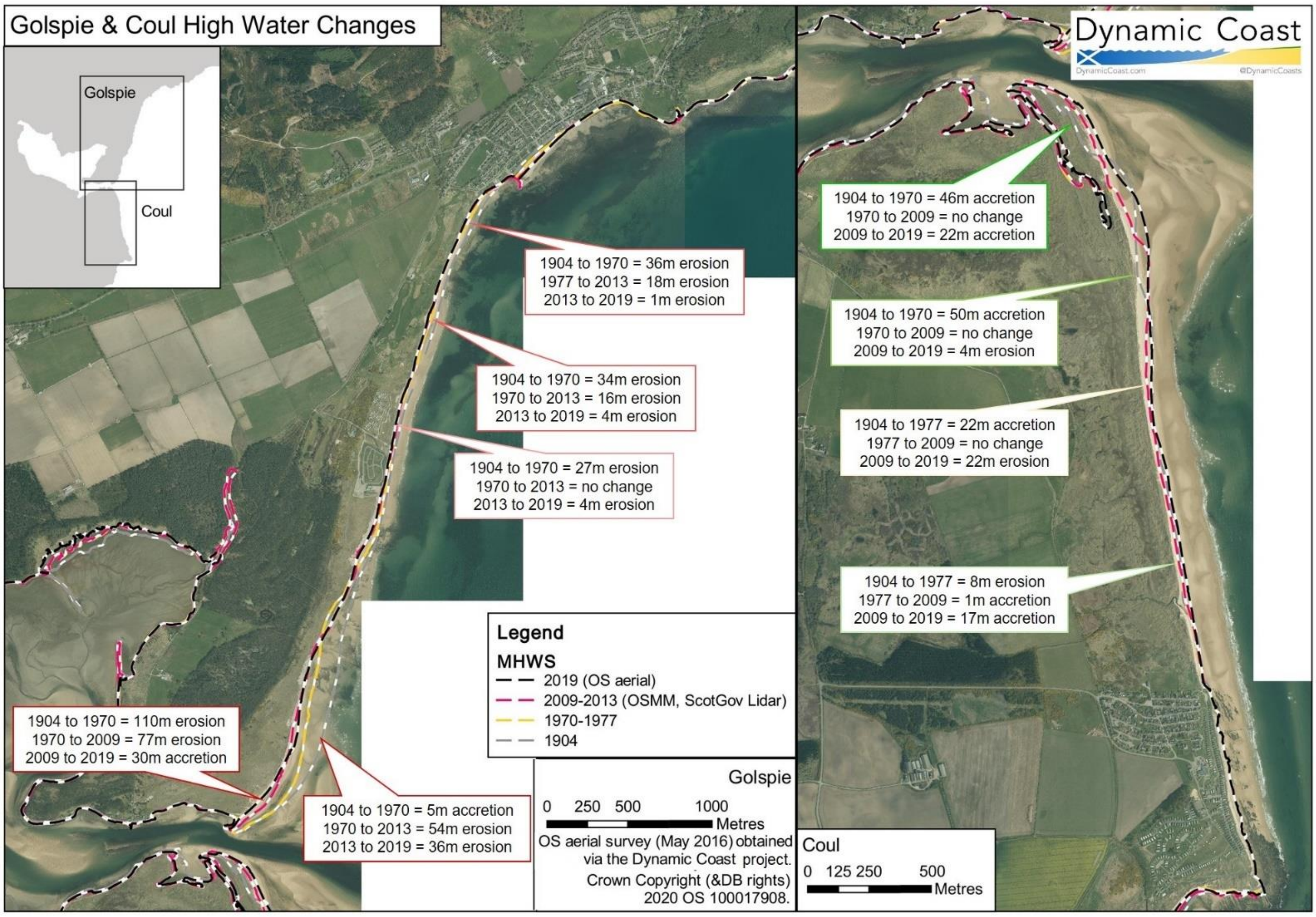

Figure 6 Changes to each upper beach – comparison of MHWS surveys dated 1904, 1970/77, 2009 (OS map series), 2013 (ScotGov lidar survey) and 2019 (OS aerial imagery DSM)

Using the most recent vertical change data derived from DSMs, Figure 7 demonstrates the net effect of changes in the positions of MLWS and MHWS and show the recent losses depicted in red/pink (2013–2019 at Golspie and 2016–2019 at Coul) experienced on the lower parts of the beach. The exceptions are parts of the lower beach of south Golspie and at both sides of the Fleet mouth where accretion occurred across this period. At Golspie, erosion dominated between 2016–2019, this being reflected in the Vegetation Edge dropping by as much as 2.7m in the south and 2.6 m in the central section, with lower beach dropping by 2.3m. However, pockets of erosion and accretion occur at both spits with the north side rising by up to 3.1 m at MLWS. Coul has broadly experienced accretion (wind-blown) across the central section with the Vegetation Edge showing an average gain of 1 m between 2013–2019, but elevation losses dominate the lower intertidal.

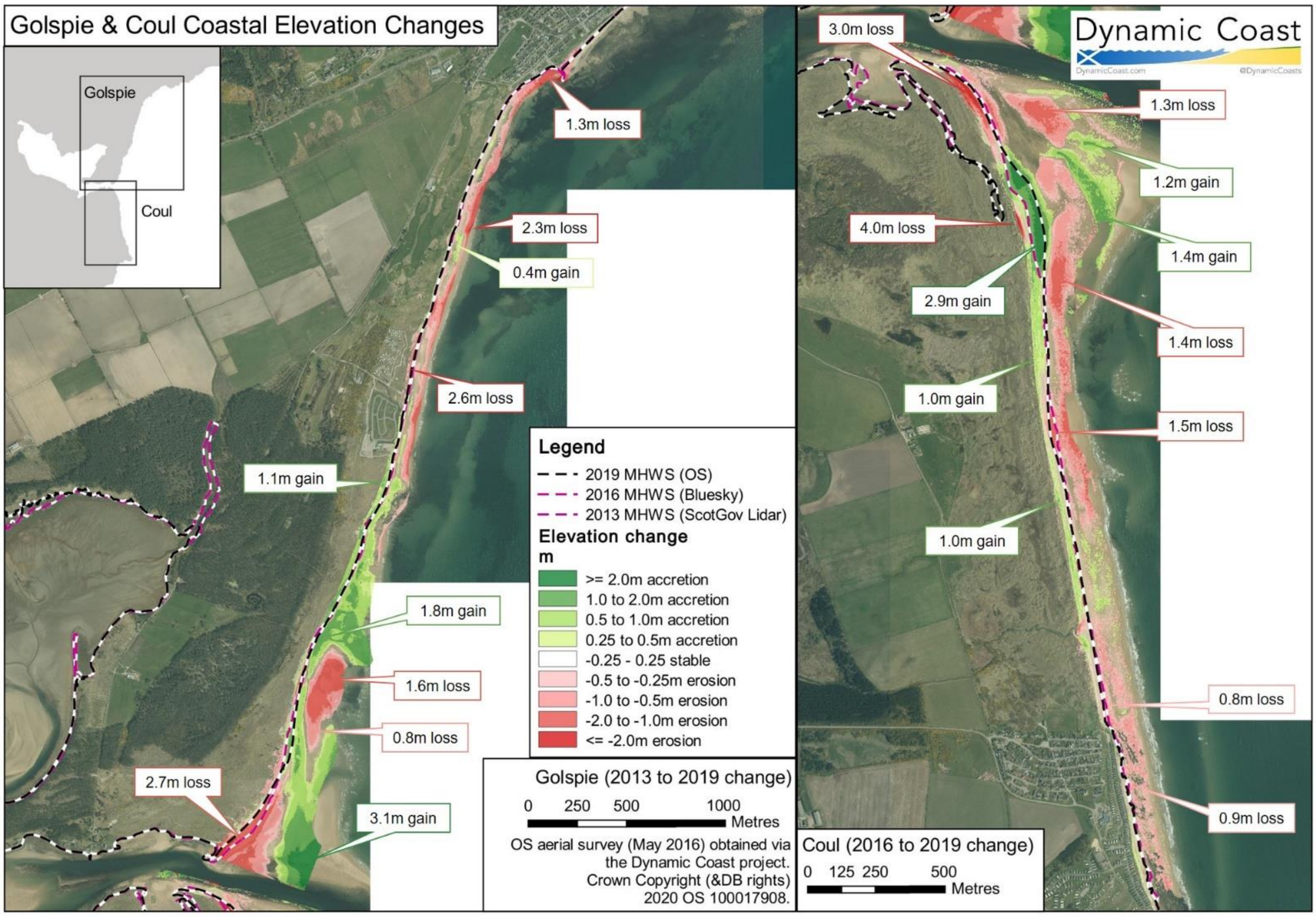

Figure 7 Changes to the foreshore - comparison of the difference in beach elevation from 2013 (SNH aerial DSM) to 2019 (OS aerial DSM) at Golspie and 2016 (Bluesky aerial DSM) to 2019 (OS aerial DSM) at Coul

Dune Vegetation Edge Change at Golspie and Coul

Figure 8 details change in the vegetation edge position, with Figure 9 depicting the rates of change produced. Unsurprisingly, the most significant lateral changes in Vegetation Edge occurred across either side of the Loch Fleet mouth, where sediment transport processes at the spits result in more dynamism than elsewhere. 2007/2009–2012 saw widespread vegetation edge stability at Dunrobin and north Golspie, but with localised erosion and accretion of -6 m to +6 m respectively. Along the middle and south Golspie sections, more widespread and consistent erosion of the Vegetation Edge occurred with up to 5 m loss along the caravan park frontage; 7 m at the southern end of the go-kart track; and up to 14 m retreat in the NNR to the south of the go-kart track. Between 2009–2012, several overwash areas and aeolian blowouts of the frontal dune ridge along the south Golspie Links resulted in vegetation retreat of up to 22 m. At north Coul Links, accretion occurred between 2009-2012 resulting in up to 50 m seaward shift in the Vegetation Edge. Further south at Coul there was only localised retreat of 4–7 m.

More recently the period 2012–2015/16 displayed widespread vegetation retreat across southern Coul Links, removing the accretion of the previous period in the north by an equal 50 m and a mean retreat across the entire southern Coul Links of 15 m. In the north of Golspie, Vegetation Edge stability persisted between 2012–2016, but dune defence works over the front of the golf course frontage masks areas where the dune face had shifted inland. In the undefended sections to the south, overwash events during this period along the caravan park and go-kart track frontage resulting in Vegetation Edge retreat of 7 m to 13 m respectively, rising to 57 m loss in the NNR to the south of the track boundary. At the south end of Golspie Links, some 16 m of landward shift occurred in the vegetation edge position. Along the Coul Links frontage, more widespread Vegetation Edge retreat of 13 m to 54 m occurred over the 2012–2016 period, with the protected stretch of the Embo caravan park frontage retreating by a maximum of 5 m. Nevertheless, the vegetation edge came within 3 m of some of the caravans and may pose a future erosion risk for the infrastructure and buildings close to the dune ridge.

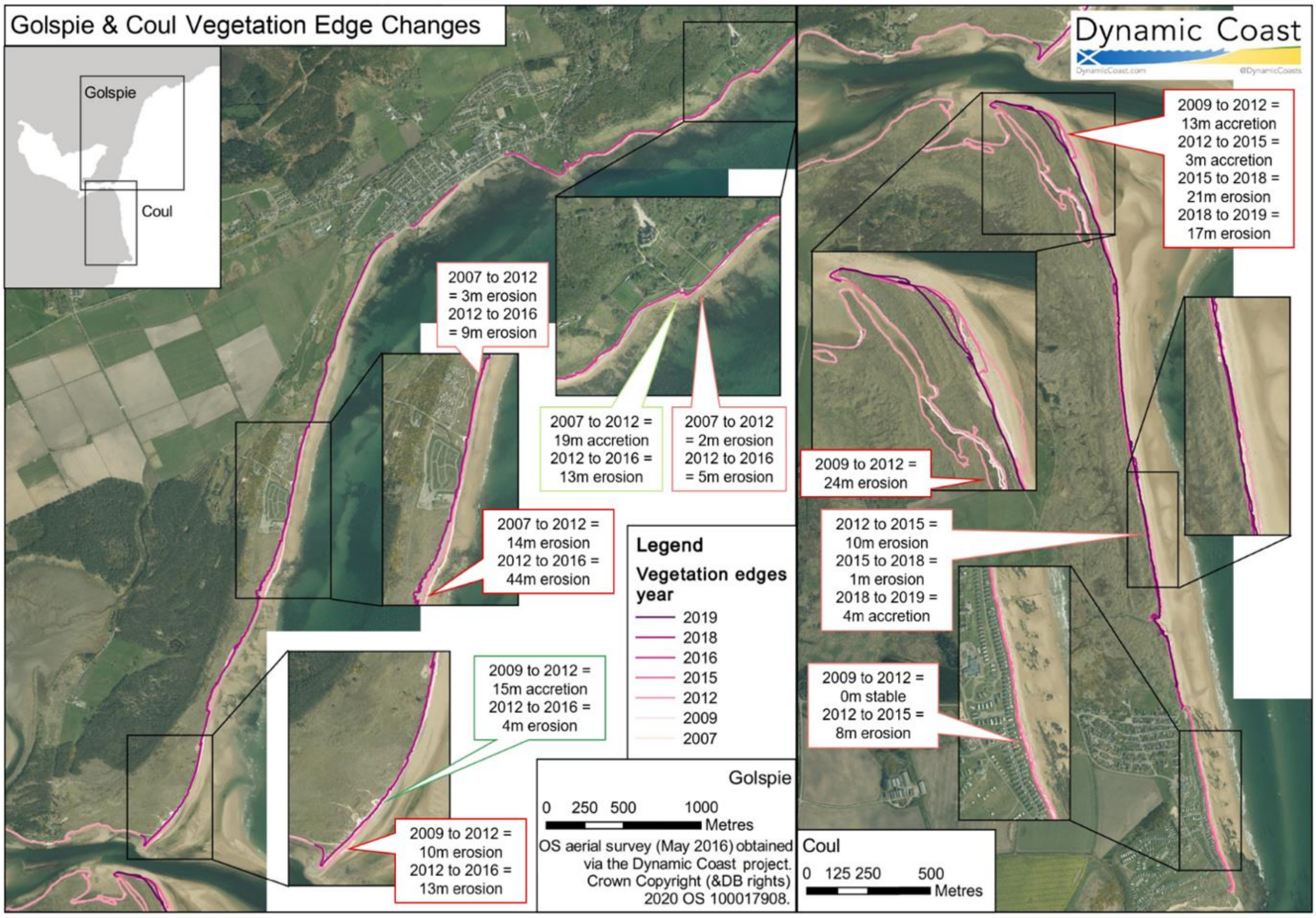

Figure 8 Vegetation Edge position changes at Golspie and Coul from aerial images taken in 2007, 2009, 2012, 2015, 2016, and ground surveys from 2018 and 2019

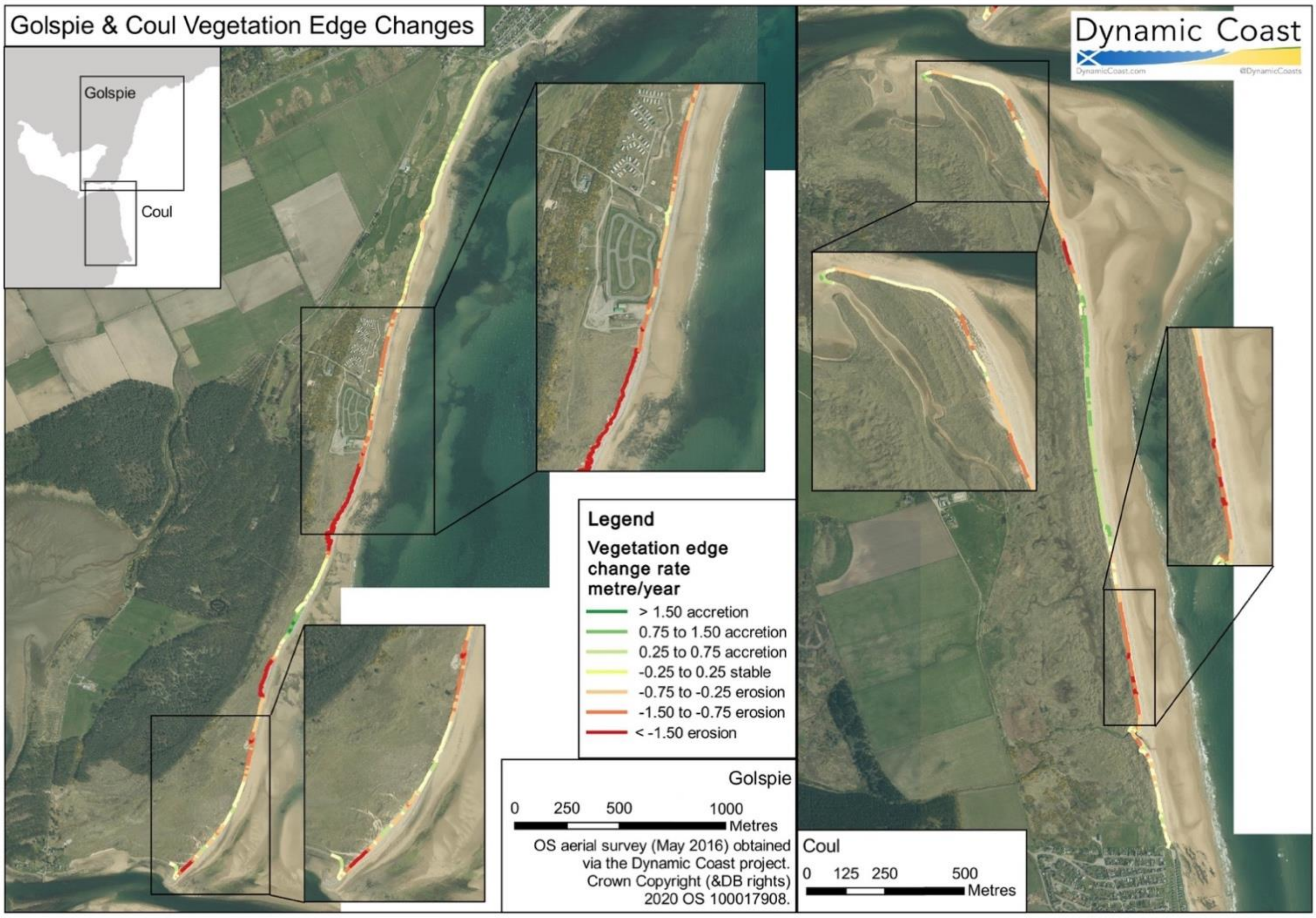

Figure 9 Recent Vegetation Edge rates of change at Golspie (2007–2018) and Coul (2009–2018)

Volumetric Changes at Golspie and Coul

The elevation changes captured by DSMs depicted in Figure 7 above allow annual volumetric change rates to be calculated for the period for the period 2013–2019 at Golspie and 2016–2019 at Coul. These are shown in Figure 10 where the overall trend is a bias toward erosional loss across the lower foreshore and intertidal zone of both coasts, with the northern part of Golspie showing consistent losses of up to 4,600 m^3/yr. Maximum erosion rates for Golspie reach 13,100 m^3/yr close to the Fleet mouth due to local dynamism but pockets of loss also occur on the south side of the mouth at Coul (5,100 m^3/yr loss and 12,000 m^3/yr loss). Pockets of gain also occur on the north side (23,200 m^3/yr) and south (10,200 m^3/yr). Overall, the aggregated annual change within each management unit shown in Table 2 reflects a net loss of sediment at Golspie town from 2013–2019 of more than 4,700 m^3/yr; a net loss of -15,900 m^3/yr in the northern part of Golspie Links; 20,000 m^3/yr net gain in the southern part of Golspie Links; net losses of 29,200 m^3/yr at Coul and 15,500 m^3/yr at Embo.

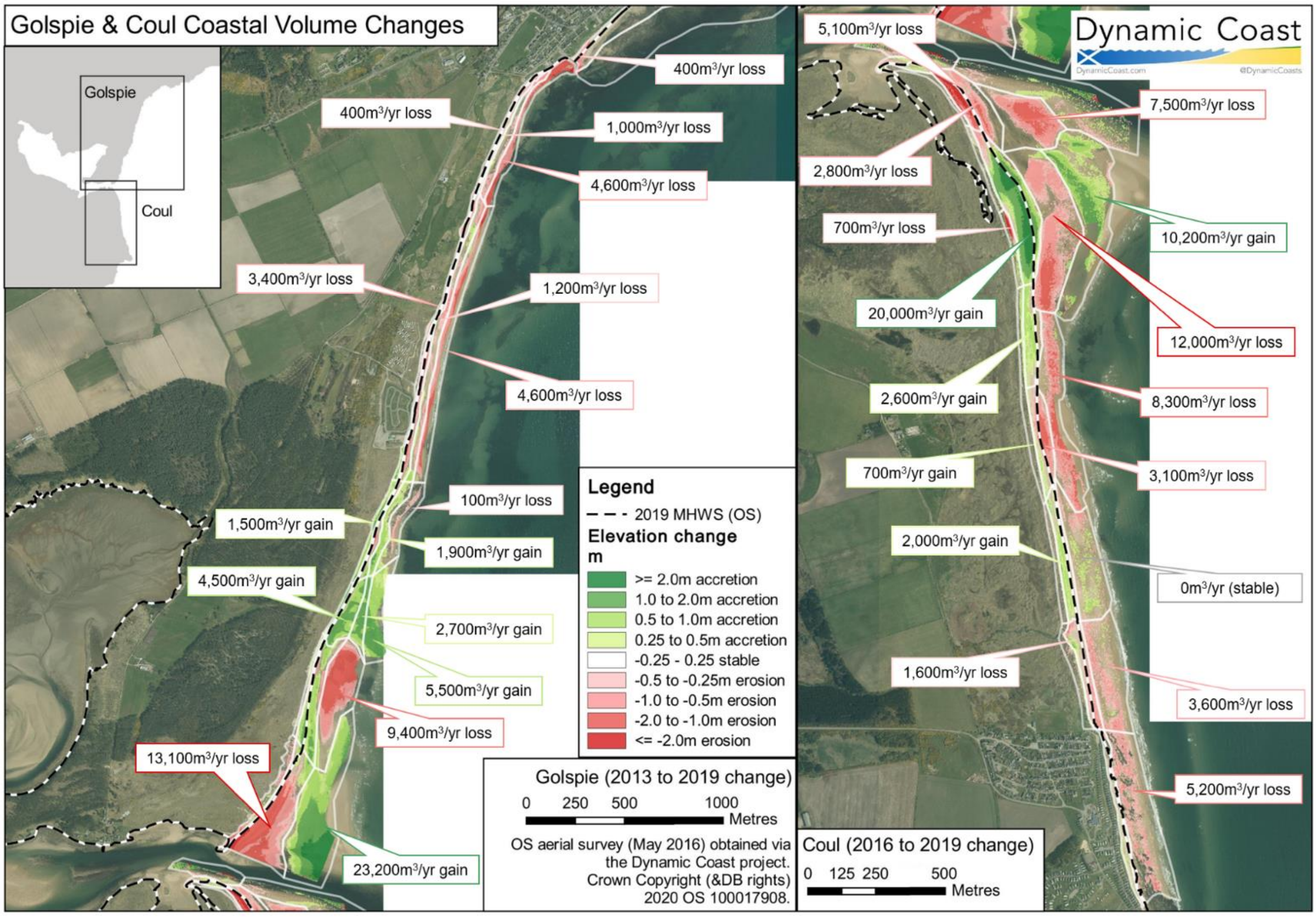

Figure 10 Comparison of rates of volume change across each geomorphic section outlined in white, from 2013 (SNH aerial DSM) to 2019 (OS aerial DSM)

Table 2 Summarised volume changes from 2013 (SNH aerial DSM) and/or 2016 (Bluesky aerial DSM) to 2019 (OS aerial DSM) across the five management units

	2013–2019			2016–2019		
MGMT Unit	Change area (m^2)	Volume change (m^3)	Change rate (m^3/yr)	Change area (m^2)	Volume change (m^3)	Change rate (m^3/yr)
1 – Dunrobin	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
2 – Golspie town	5,400	-4,700	-800	*N/A*	*N/A*	*N/A*
3 – Golspie Links North	214,600	-95,500	-15,900	*N/A*	*N/A*	*N/A*
3 – Golspie Links South	530,900	119,700	20,000	*N/A*	*N/A*	*N/A*
4 – Coul Links	100	0	0	631,100	-29,200	-9,700
5 - Embo	*N/A*	*N/A*	*N/A*	69,300	-15,500	-5,200

Future Shoreline Projections

Future projections are based on the Modified Bruun Rule (see methods above) which are projected forward based on UKCP18 Representative Concentration Pathway 8.5 (UKCP18 RCP8.5) using the 95th% estimate, given the precautionary principle. The coastal change incorporates shore face gradient and is calibrated with recent coastal change data (which reflects/assumes continued sediment supply from the immediate hinterland). These anticipated shorelines are not intended to be reliable detailed predictions, but a precautionary future scenario to inform the possible scale of change.

Figure 11 shows the anticipated future positions of MHWS every decade up to the year 2100, estimated using a Modified Bruun Rule calculation for a future relative sea level rise of 0.95 m at 2100 (UKCP18 RCP8.5 95th%). The rate of landward retreat increases with each decadal prediction, with the Golspie shore retreating at an average of -0.3 m/yr by 2050 and by -0.7 m/yr by 2100, and Coul retreating an at average of -0.1 m/yr by 2050 and -1.1 m/yr by 2100. The maximum retreat at Golspie is seen close to the Loch Fleet spit (-330 m from 2019–2100) where dynamism has been highest in the past and where the backdune gradient is lowest. It is also worth highlighting the impact of the -193 m retreat which may fully cover the caravan park by 2100, and the -37 m retreat that will erode through several properties' boundaries in Golspie town by 2100. Coul shows less retreat projected due to its less volatile MHWS change history, however the consistent MHWS retreat of ~-90 m by 2100 will cause the entire dune face to migrate backwards, with a greater potential for short-term storm events to breach the current dunes causing inundation.

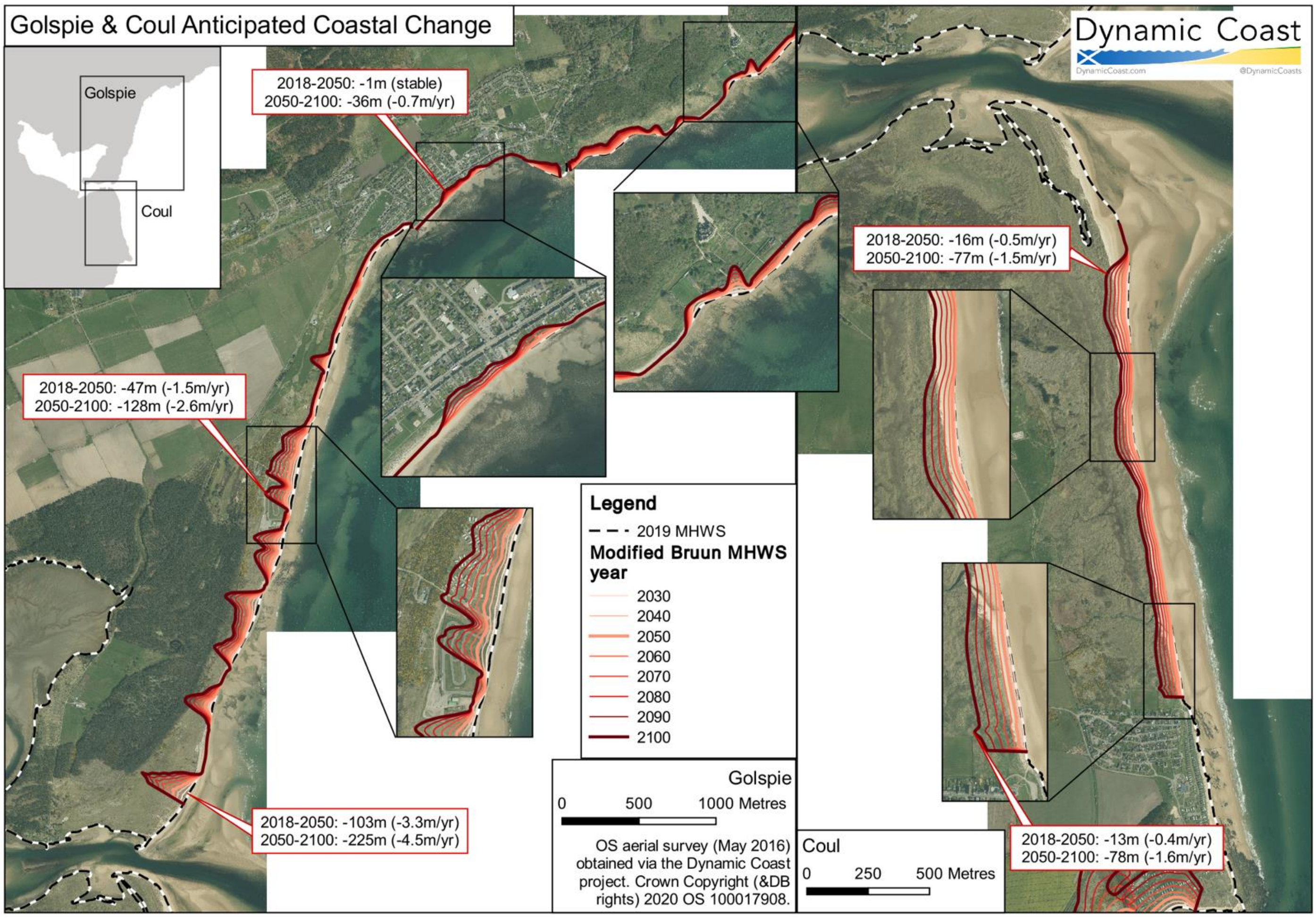

Figure 11 Anticipated shoreline change using modified Bruun rule.

The arrival of a retreating MHWS on the beach is normally preceded by the undercutting of vegetation at the coastal edge, especially where any dune machair cover (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 20 m between MHWS and the vegetation edge for each bay, and this is 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. There is a mean lateral offset of 20 m between MHWS and the Vegetation Edge for Golspie Links and 30 m for Coul Links, which is used to project the Modified Bruun MHWS predictions inland and provide a clearer perspective on the timings of when the un-vegetated and dynamic beach will arrive at the position of landward assets. A detailed view of decadal MHWS predictions using this method can be seen on the interactive web-map associated with this document (www.dynamiccoast.com/webmaps.html). This visualisation shows that encroachment of the vegetation edge could come to the golf links as soon as 2030 and the caravan park as soon as 2050.

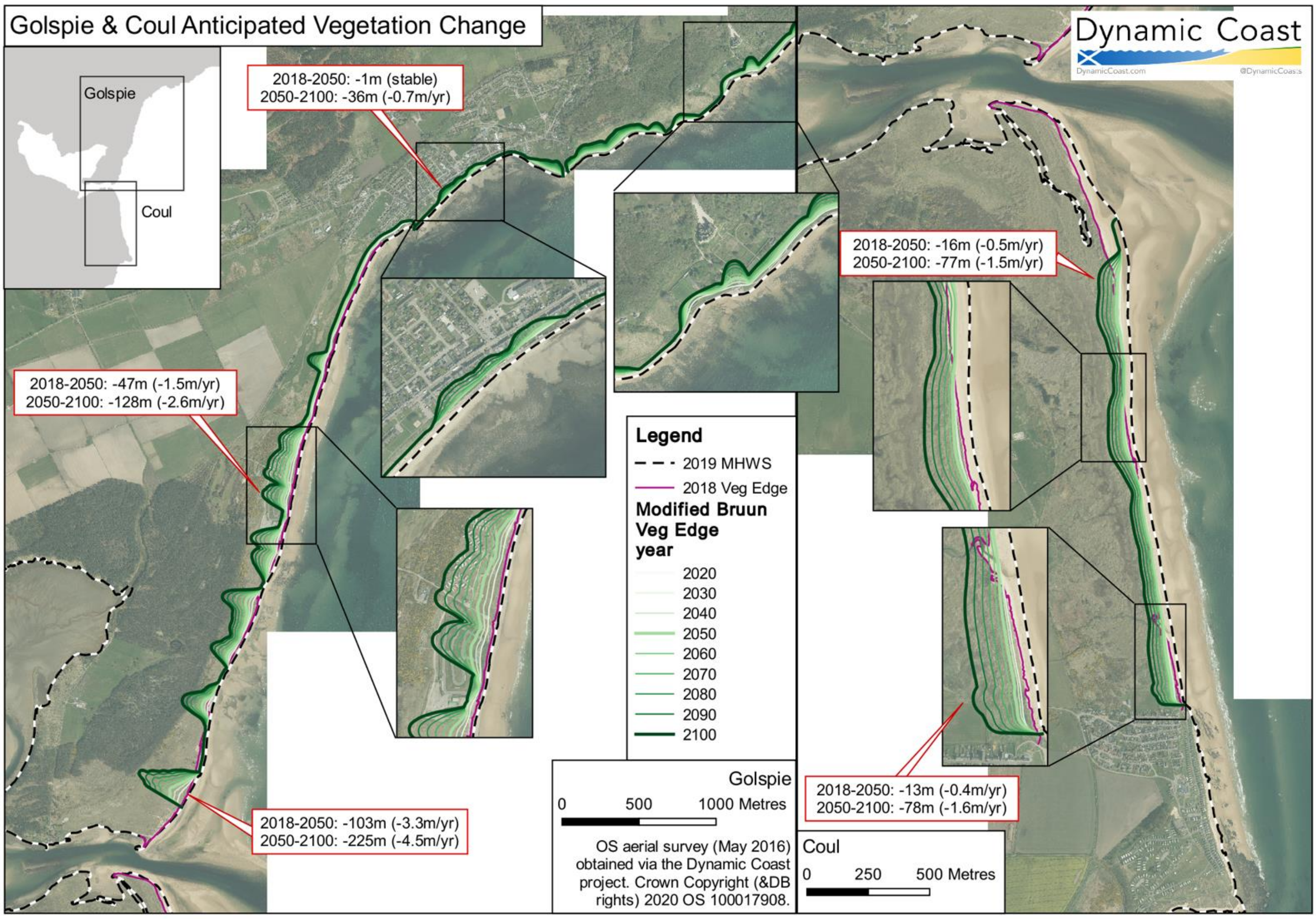

Figure 12 Anticipated shoreline change using modified Bruun rule for Vegetation Edge.

Figure 13 depicts the anticipated erosion and coastal evolution of Golspie and Coul 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 95^{th}% 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 amount of sediment transport and therefore erosion and MHWS retreat simulated by this model is highly dependent on the coastal type; there is generally more retreat predicted across soft undefended coast than gravel and hard armouring such as directly in front of the kart track and Golspie town. There is a maximum 60 m of MHWS advance from present–2100 along south Golspie and 71 m MHWS retreat along north Coul, suggesting a S–N longshore transport of sediment simulated. 10 m retreat is predicted south of the kart track and a maximum 40 m in front of Golspie town north of the pier. The retreat in front of Dunrobin Castle is 16 m, which does not take into account the presence of the vertical sea walls but nonetheless lies beyond them, suggesting the elevation of these sea walls will become more important with aggressive SLR in the future. The average retreat across Coul Links is 20 m, but is 11 m across the front of Embo (possibly due to the shingle armouring along the Vegetation Edge and rock platform further offshore).

Figure 13 also includes the Dynamic Coast (2017) linear projection of recent MHWS recession rates. CoSMoS-COAST predicts different change than the linear projection of current erosion rates because CoSMoS-COAST includes long- and cross-shore sediment transport (not included in the first phase of Dynamic Coast (2017)). CoSMoS-COAST also adjusts its parameters to regular inputs of historic MHWS observations in order to more accurately simulate future MHWS change. However, the irregular time gaps of shorelines from Dynamic Coast phase 1 (1890s to 1970s and 1970s to Modern) mean CoSMoS-COAST can make only limited adjustments to its modelled erosion rates and only partly capture the actual rates observed over the last decade. The result produces an agreement with anticipated direction and trends in and Dynamic Coast (2017), but with an overall underprediction of known recession.

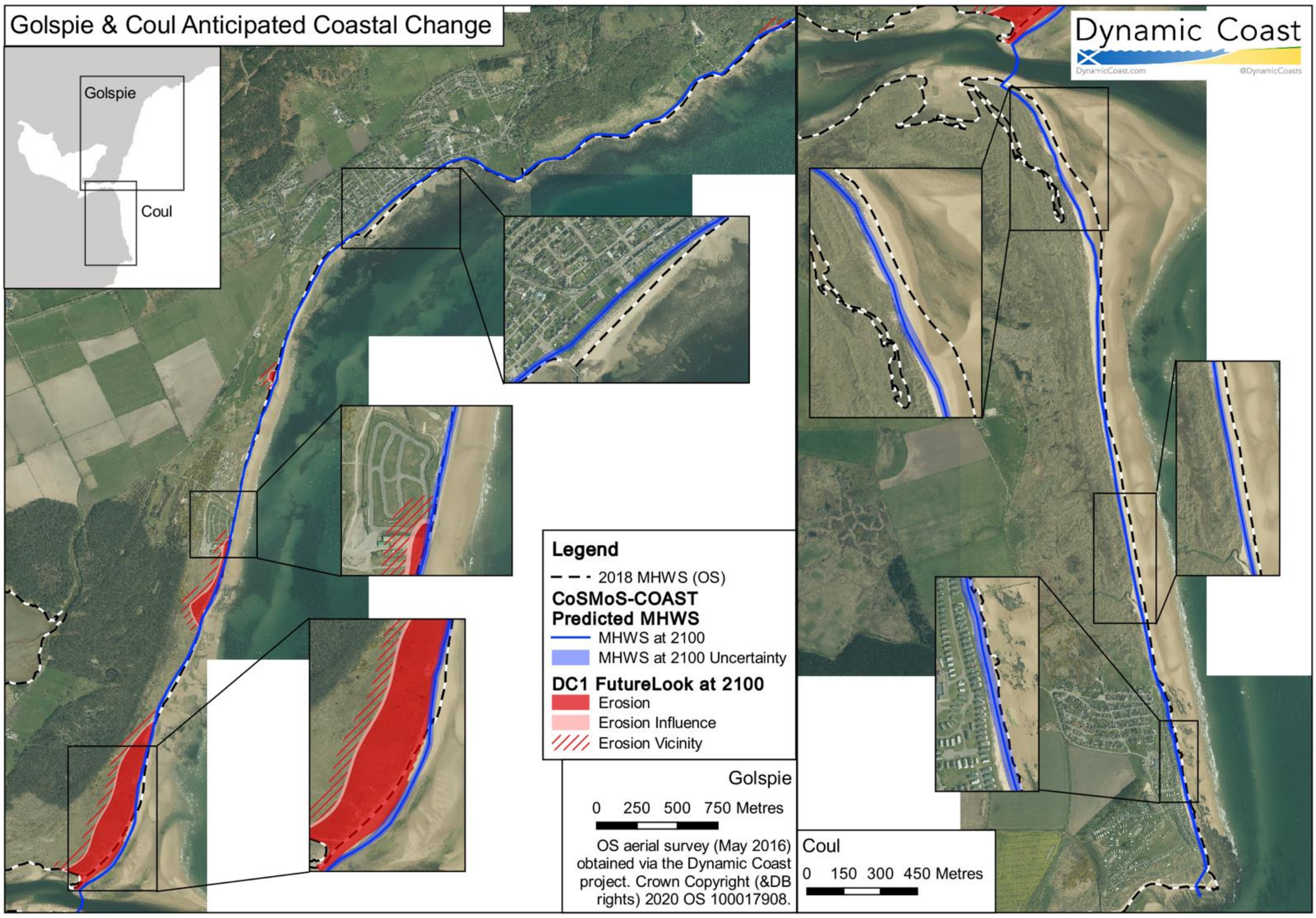

Figure 13 Anticipated shoreline change using CoSMoS-COAST modelling

Figure 14 shows the same CoSMoS-COAST MHWS projections, but compared against the Modified Bruun MHWS projections. The effect that the irregular time gaps of shorelines from Dynamic Coast phase 1 have on the amount of erosion able to be simulated is also apparent here; the overall trend is also of widespread erosion, but with some sections in disagreement over the amount of erosion simulated. In order to constrain uncertainty in the CoSMoS-COAST sediment movement calculations, the latest MHWS lines are used as validation and not as actual calibration for the simulated MHWS to shift to. Therefore this modelled shoreline can be thought of as a future best-case scenario where erosion has not been currently present.

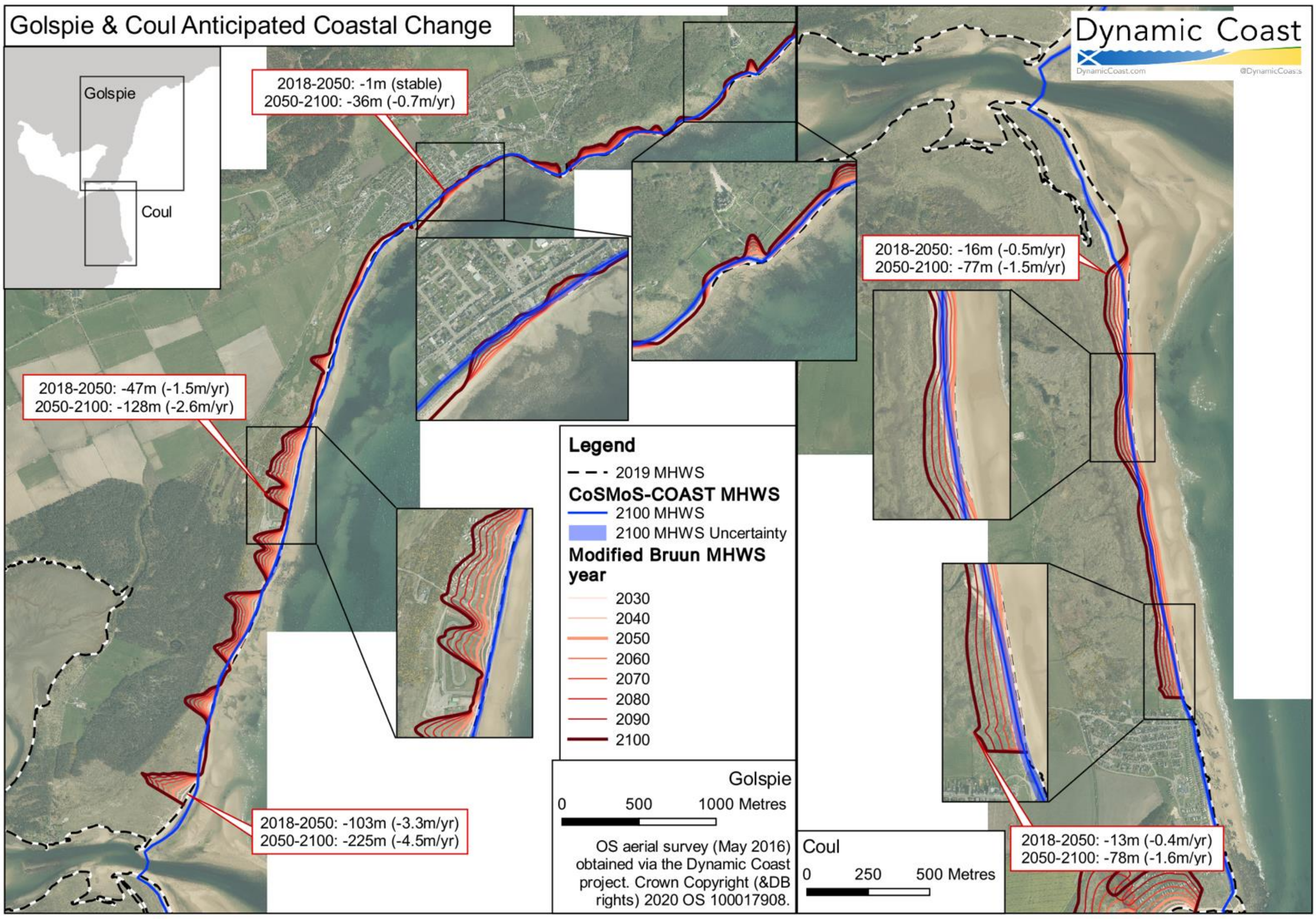

Figure 14 Anticipated shoreline change using CoSMoS-COAST modelling with Modified Bruun Rule MHWS predictions for comparison

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). The Golspie and Coul supersite emerges from within the SCVI as being "slightly resilient" in terms of social vulnerability to coastal change (Figure 15). The slight resilience of the communities residing within the Golspie and Coul super-site appears to be based upon communities emerging from within the SCVI analysis as having slight levels of resilience, particularly, in relation to the domains of population and sustainable communities.

Golspie and Coul emerges from amongst all the super-sites within the study as the most resilient within the domain of populations and 'sustainable. However, contributing factors to Golspie and Coul's vulnerability as a super-site include lower results within the field of "skills, education and training" and social vulnerability related to economic prosperity.

The communities within the Golspie and Coul super-site area also emerged as displaying social-vulnerability in relation to "physical and mental Health and Wellbeing" aspects. It is therefore understood that the population residing in the areas of the Golspie and Coul areas have higher levels of individuals living with activity limiting health problems or disabilities and therefore the community emerges from the CEVI analysis as displaying less resilience in this domain, than in comparison to domains such as population and sustainability communities where they are stronger.

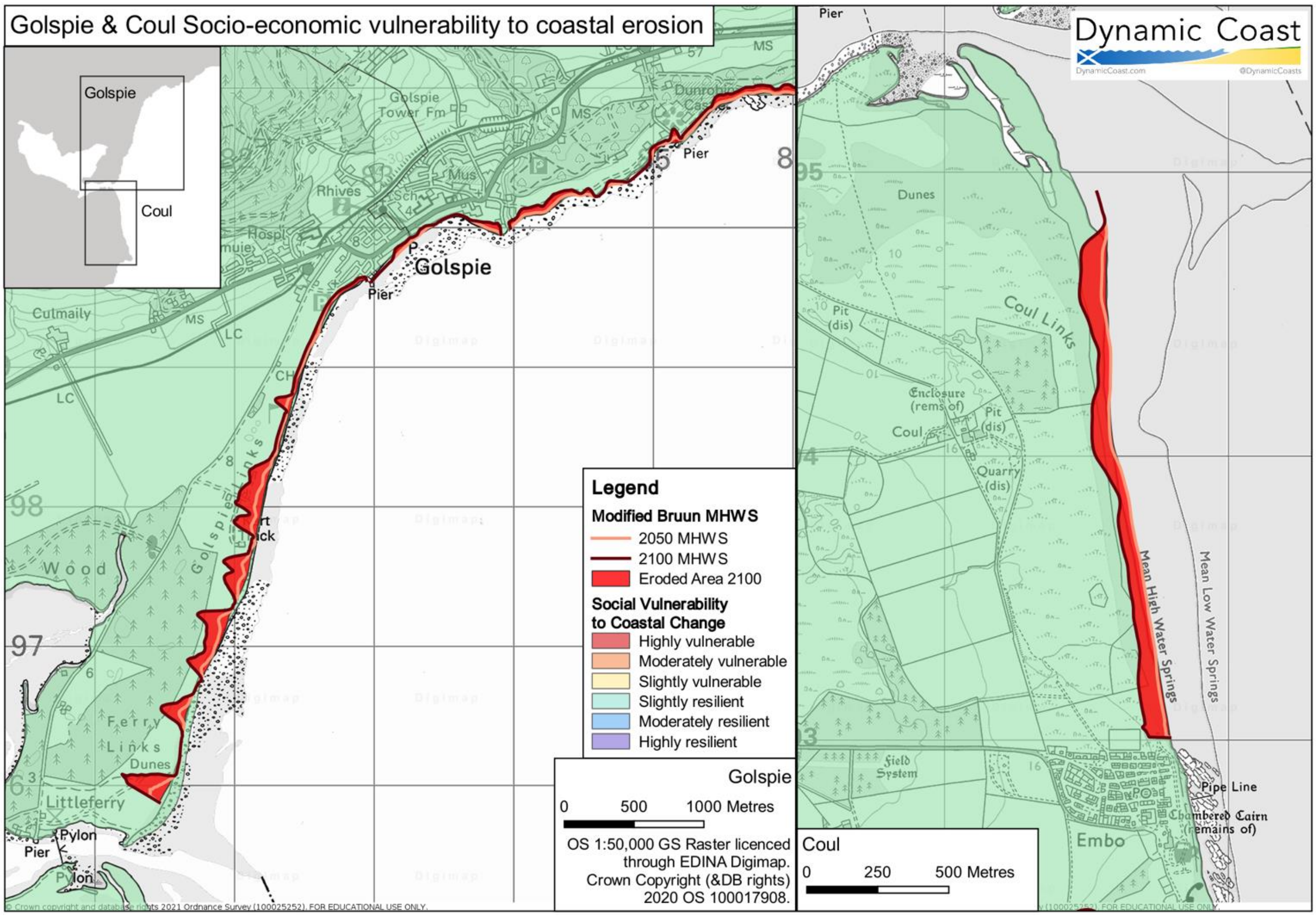

Figure 15 CEVI classifications per data zone with anticipated coastal change using the Modified Bruun Rule

Coastal Flooding

Coastal Flood Boundary

The Coastal Flood Boundary (CFB) dataset published by DEFRA in 2018 (link) displays the anticipated still water surface level of surge events at various frequencies. Still water level calculations such as these superimpose any surge level during storms to be in addition to the highest astronomic tide level. As such they exclude other hydrodynamic effects such as wave run-up etc that would need to be considered to gain an estimate of worst-case storm impact.

Present day Mean High Water Springs reaches 1.97 mOD and, excluding weather effects, the highest astronomic tide (HAT) reaches 2.45 mOD. SEPA anticipate the High Probability flood level to have a still water level of 3.02 mOD with a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 3.42 mOD, with a 0.1% annual exceedance frequency.

SEPA's Flood Risk Maps

The current version of SEPA's published flood risk map takes the anticipated still water surface levels from the CFB analysis (above) and intersect these with detailed topographic mapping to identify areas which would be inundated under high (10 yr return period), medium (200 yr return period) and low (1,000 yr return period) probabilities. 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 Risk Map for Golspie and Coul's coastal flooding as it benefits from a recent digital surface model (2019) and is more likely to accurately represent actual current land and water levels. Figure 16 demonstrates the linear nature of the flood risk as it follows the swales that lie between the dune ridges, particularly with entry points along the low-lying land north of Coul and south of Golspie. This also demonstrates the potential flood risk that already exists across the caravan park and racetrack at Golspie Links.

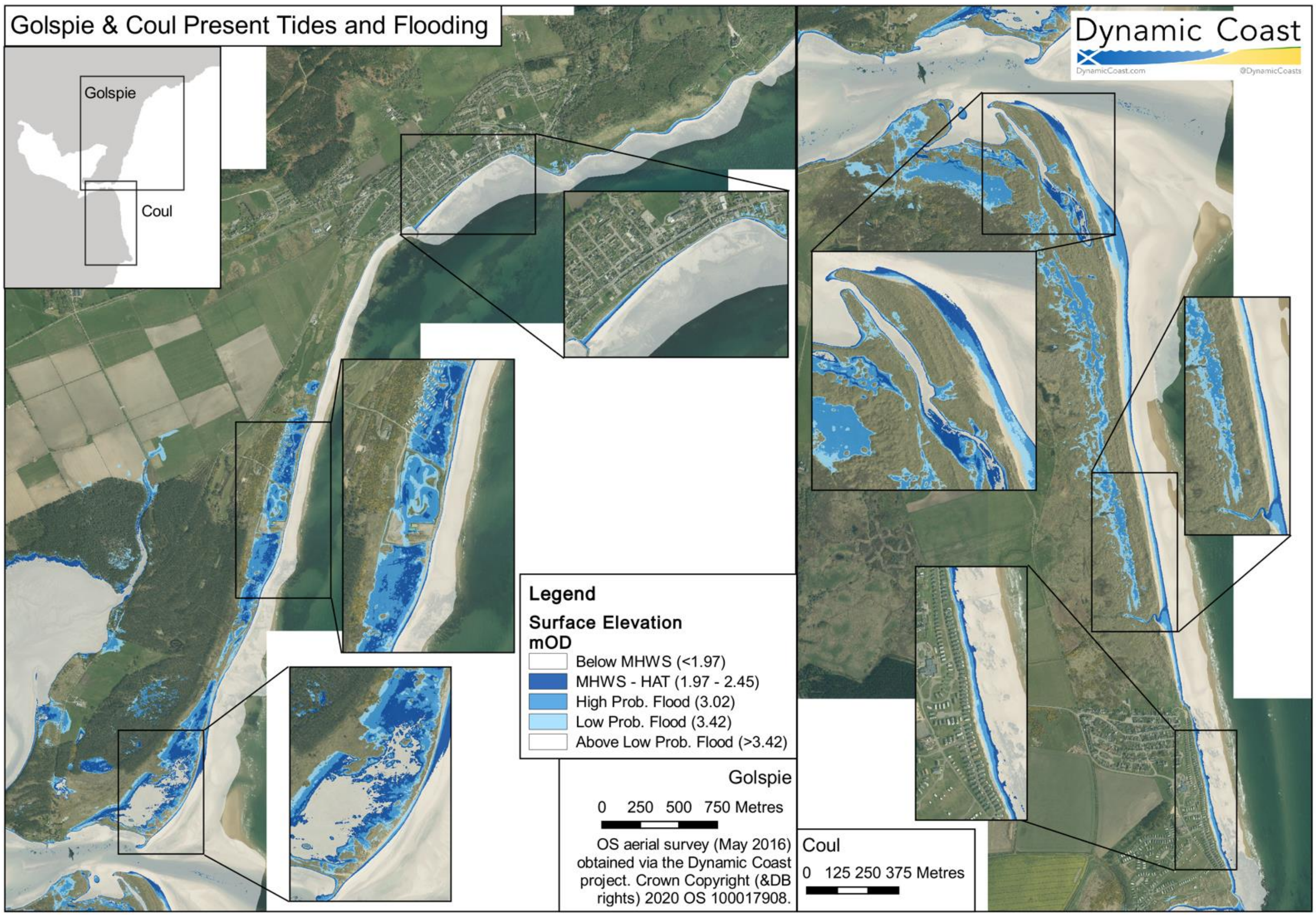

Figure 16 Summary of present-day tides and high probability (1:10 yr, 3.02 mOD) to low probability (1:1,000 yr, 3.42 mOD) flood levels across Golspie and Coul.

Relative Sea Level Rise

The UK Climate Projections data (2018) has been used to anticipate increases in mean sea level across the Golspie and Coul coast. 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 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 Golspie and Coul are summarised below. By 2050 mean sea level is likely to increase between 0.12–0.31 m and, as likely as not, to be more than 0.21 m above the average levels of 1980–2000. Rates of sea level rise by 2050 are expected to be between 3.4 mm/yr and 8.8 mm/yr and, as likely as not, above 5.7 mm/yr. For context, the long-term pre-industrial relative sea level trend at Golspie is -0.6 mm/yr (Bradley et al 2019).

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 Golspie

Year	MSL increase (m above 1981–2000 levels)		
	5th%	50th%	95th%
2010	0.01	0.03	0.04
2020	0.04	0.06	0.09
2030	0.06	0.10	0.15
2040	0.09	0.15	0.22
2050	0.12	0.21	0.31
2060	0.16	0.27	0.41
2070	0.21	0.34	0.53
2080	0.25	0.42	0.66
2090	0.30	0.50	0.80
2100	0.34	0.59	0.95
2300	0.75	1.76	3.54

Period	Rate of increase (mm/yr)		
	5th%	50th%	95th%
2000–2010	1.0	3.0	4.0
2010–2020	3.0	3.0	5.0
2020–2030	2.0	4.0	6.0
2030–2040	3.0	5.0	7.0
2040–2050	3.0	6.0	9.0
2050–2060	4.0	6.0	10.0
2060–2070	5.0	7.0	12.0
2070–2080	4.0	8.0	13.0
2080–2090	5.0	8.0	14.0
2090–2100	4.0	9.0	15.0
2100–2300	2.1	5.9	13.0

The existing tidal inundation extents and increases by 2100 are shown in Figure 17 which aims to inform the growing risk of so called 'fair weather flooding' where flooding may increasingly occur in the absence of storms as a result of increasing reach of the tide due to increased mean sea level. The levels presented here affected by SLR are very similar to the present flood levels.

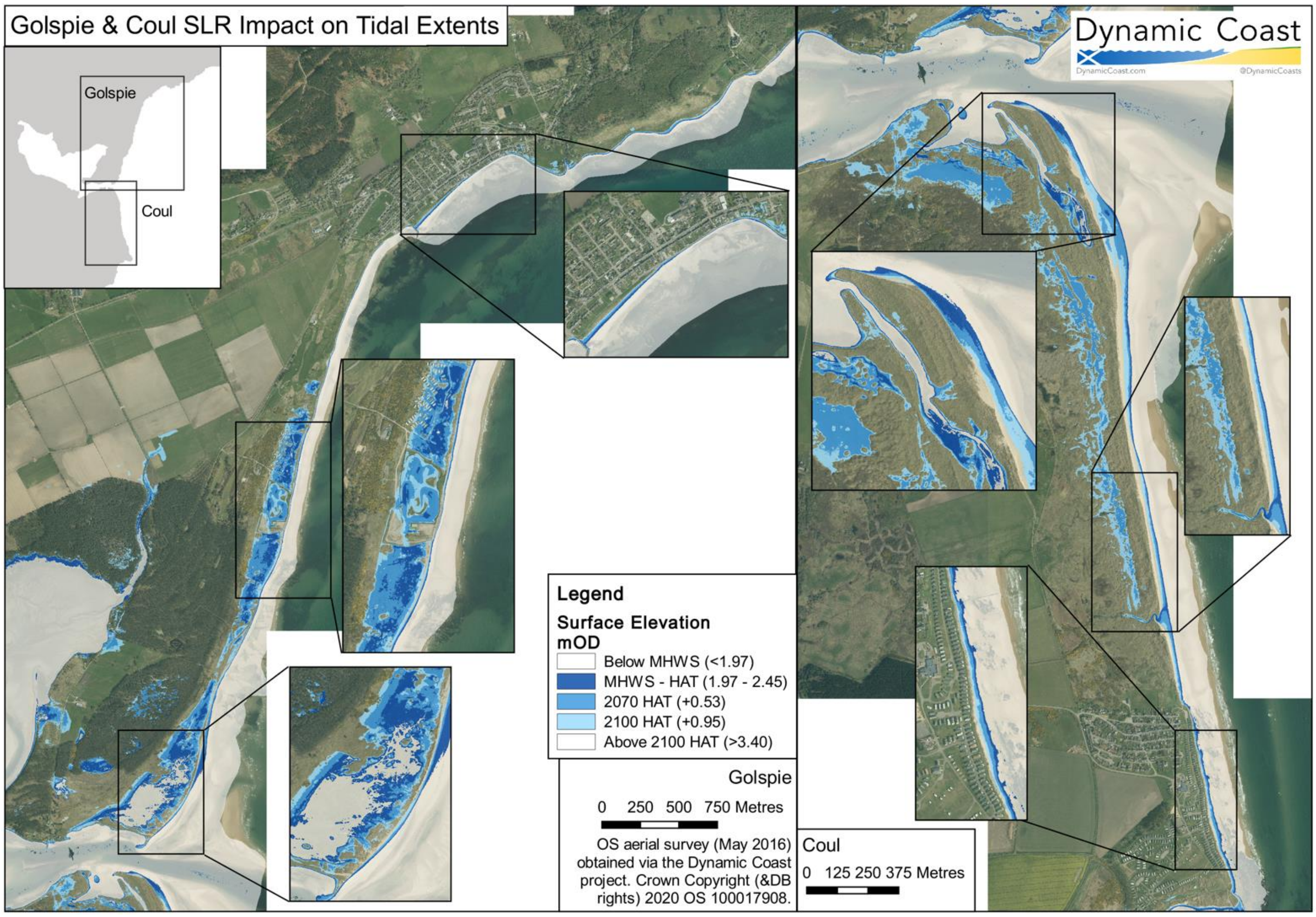

Figure 17 Present day extent of the Highest Astronomic Tide and the future anticipated under UKCP18 RCP8.5 95% sea level rise by 2070 & 2100.

Figure 18 shows the key present day and anticipated flood elevations for Golspie and Coul by 2070 and 2100, which reflect the increased impact of storm events, when 0.95 m is added to flood extents. These elevations hold much greater risk of inundation to towns and property as well as a much greater coverage across the dune ecosystem.

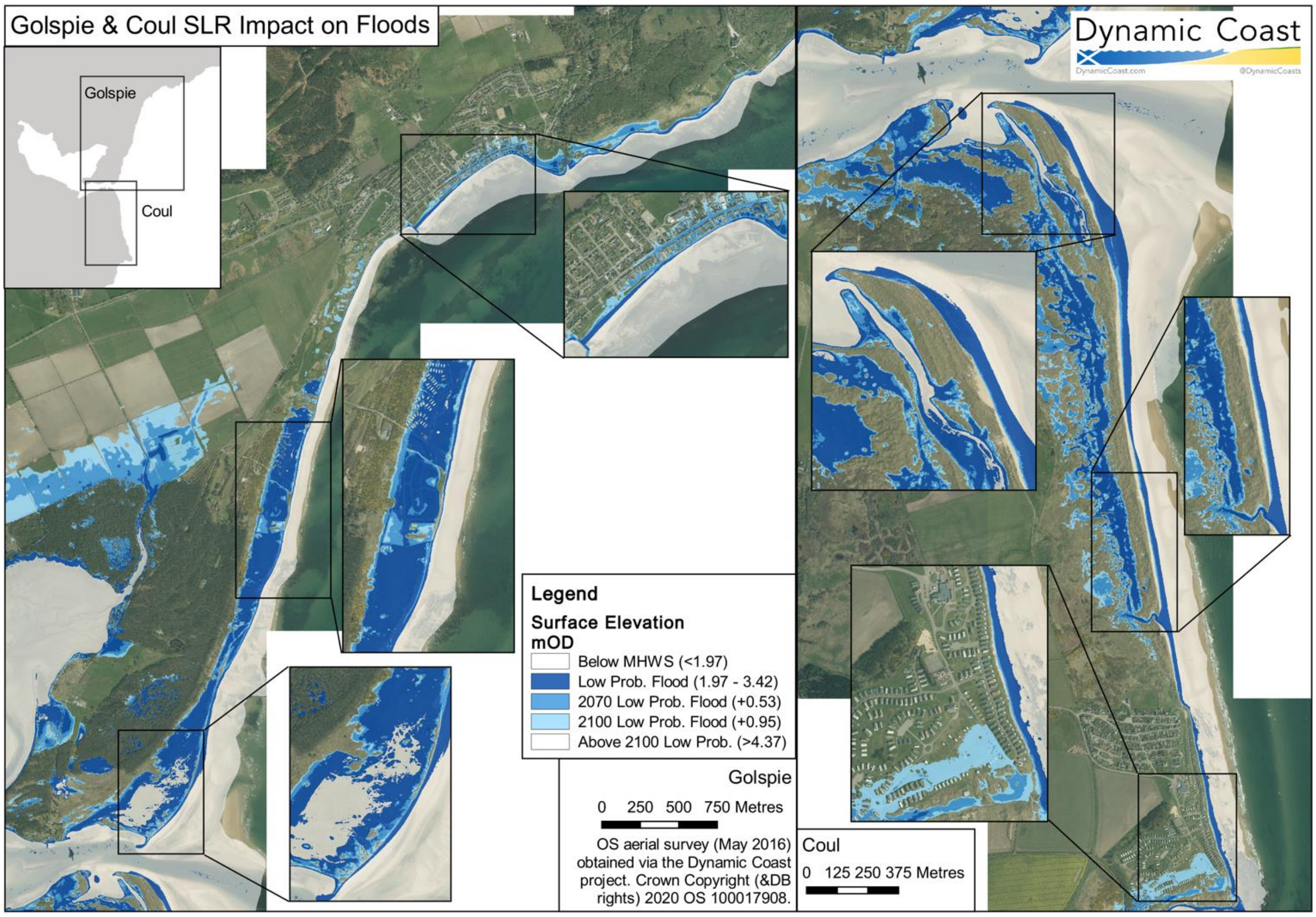

Figure 18 Present day and future flood events anticipated under UKCP18 RCP8.5 95th% sea level rise by 2070 & 2100

Figure 19 plots the key present day and anticipated flood elevations for Golspie and Coul. Mean High Water Springs reaches 1.97 mOD and if weather effects are excluded the highest astronomic tide is expected to reach 2.45 mOD. SEPA anticipate the High Probability flood level to have a still water level of 3.02 mOD, this has a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 3.42 mOD, this has a 0.1% annual exceedance frequency as shown on Table 2. If the effects of SLR under RCP8.5 are applied to these levels, the High Probability flood level will have a still water level of 3.55 mOD and the Low Probability flood level will have a still water level of 3.95 mOD by 2070; by 2100 these event levels rise to 3.97 mOD and 4.37 mOD respectively, 2 m and 2.4 m above the current-day MHWS.

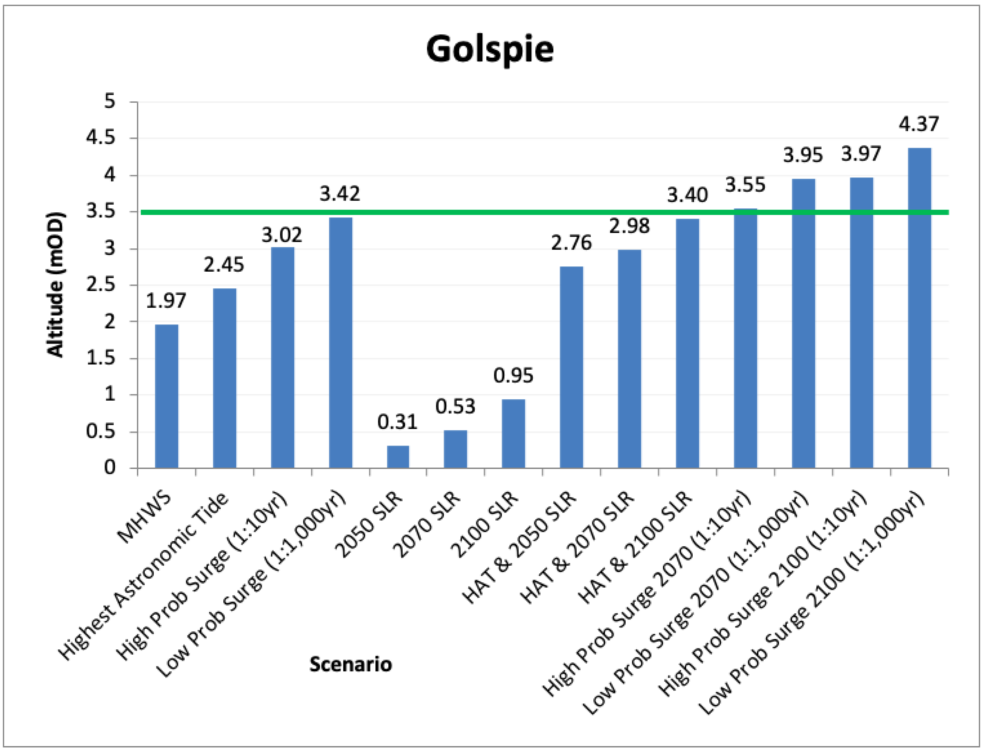

Figure 19 Summary of present and future key tide and flood levels at St Andrews. There are substantial areas of the dune links interior below 3.5 mOD (annotated with green line) although the dune crest and embankments are higher.

Combined Erosion and Flooding

The automated terrain analysis (Figure 4, Figure 20) has identified key metrics which reflect the geometry of the dune ridge (i.e. the flood protection feature). The typical height of the Coul dune crest is 7–9 mOD, with some sections reaching 12 mOD; the ridge at Golspie is much lower, reaching only 4–5 mOD with the south Golspie Links dune front lying below 2 mOD. Given these elevations and the current flood heights, the present dune ridge at Coul provides an essential flood protection function to the low-lying interior of the dunes, but with key weak points that could act as flood corridors if eroded. The dune ridge at Golspie however has little in the way of a pronounced barrier and has already been the subject of storm-related dune blowouts which have compromised the flood protection of the dunes. Key locations that may be impacted by an erosional breach in the dune front are inset in Figure 20 with the corresponding extracted barrier features attached. While some transects show an elevated interior which will not be as affected by coastal inundation of lower water levels, most have important assets close behind the initial barrier feature, and/or offer an entry point for water to travel north and south in behind the dunes. The Modified Bruun MHWS projections for 2050 and 2100 mapped against these barrier features show the potential for MHWS retreat through the current barrier positions.

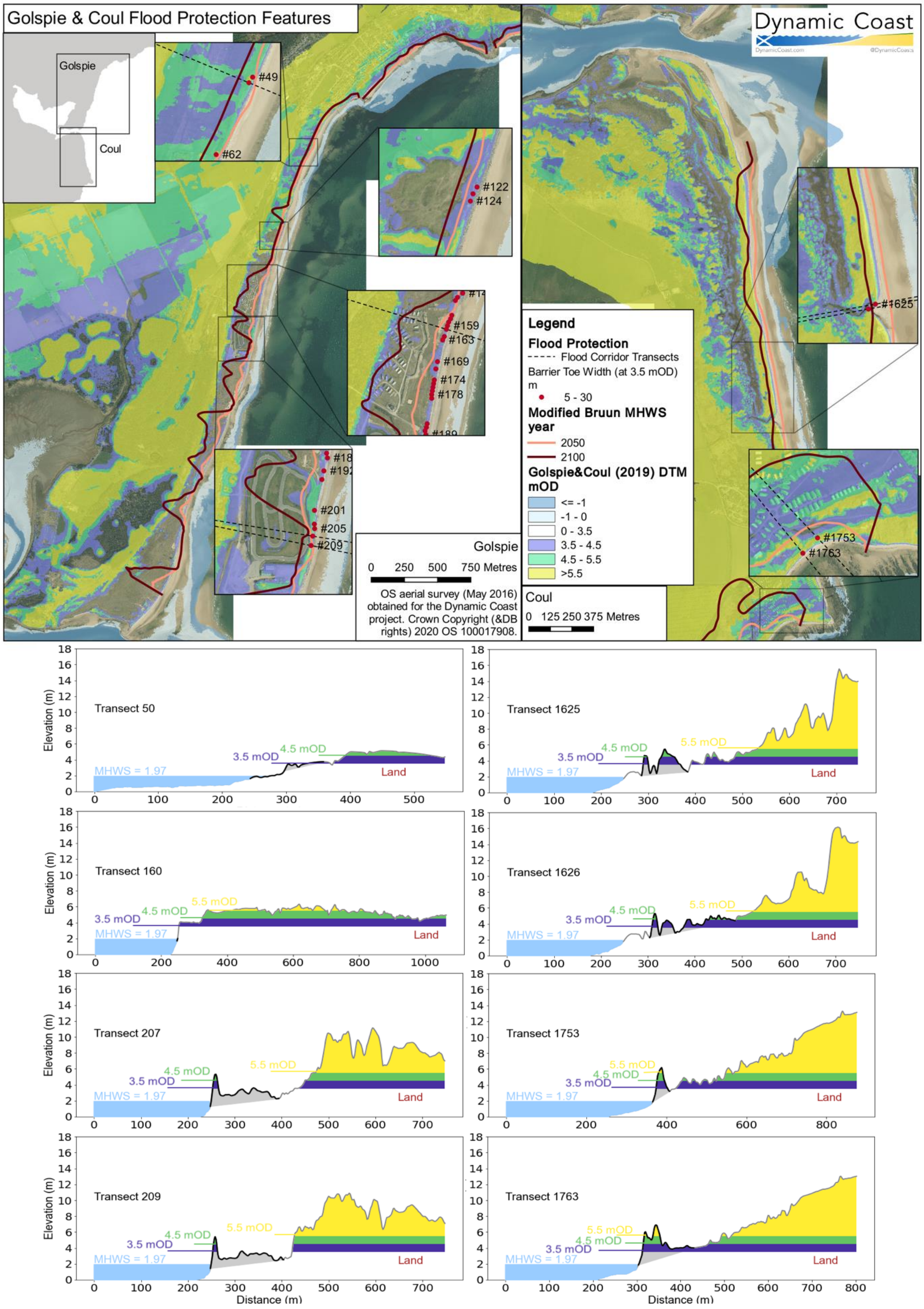

Figure 20 Identification of flood corridors within the southern section of dunes. The top figure shows locations of key potential flood corridors, and the bottom figures are the automatically extracted barrier features across the transects in the top figure.

Appendix

Table 3 Volume changes per management unit and sub-section, defined by geomorphic type

MU	Section	Geomorphic description	2013–2019 change area (m²)	Volume change 2013–2019 (m³)	Volume change rate 2013–2019 (m³/yr)	2016–2019 change area (m²)	Volume change 2016–2019 (m³)	Volume change rate 2016–2019 (m³/yr)
1	1	Rocky foreshore	2,814	-2,383	-397			
	2	Rocky intertidal	323	-847	-141			
	3	Veg edge	2,209	-1,391	-232			
2	4	Sandy foreshore	25,946	-27,716	-4,619			
	5	Sandy intertidal	38,738	-27,432	-4,572			
	6	Sandy intertidal	22,529	-659	-110			
	7	Sandy foreshore	24,129	-5,721	-954			
	8	Sandy foreshore	51,800	-7,355	-1,226			
	9	Sandy foreshore	21,523	11,343	1,891			
	10	Sandy backshore	10,960	-2,780	-463			
	11	Sandy backshore	33,009	-20,162	-3,360			
	12	Sandy backshore	15,529	-920	-153			
	13	Veg edge	9,539	-3,424	-571			
	14	Veg edge	20,485	-161	-27			
	15	Veg edge	12,025	9,240	1,540			
	16	Sandy intertidal	35,766	32,945	5,491			
	17	Sandy foreshore	17,004	16,164	2,694			
	18	Sandy backshore	29,156	26,979	4,497			
	19	Veg edge	4,039	4,907	818			
	20	Sandy foreshore	77,214	-56,423	-9,404			
	21	Sandy backshore	49,737	21,059	3,510			
	22	Veg edge	7,883	423	71			
	23	Sandy foreshore	119,176	139,342	23,224			
	24	Sandy backshore	98,824	-78,319	-13,053			
	25	Veg edge	20,418	-5,608	-935			
3	26	Veg edge				5,512	-433	-144
	27	Sandy backshore				6,964	454	151
	28	Sandy backshore				10,056	-15,378	-5,126
	29	Veg edge				6,220	496	165
	30	Sandy backshore				52,056	59,848	19,949
	31	Sandy foreshore				20,620	-8,308	-2,769
	32	Veg edge				7,180	-2,050	-683
	33	Veg edge				16,928	1,990	663
	34	Sandy backshore				19,916	7,830	2,610
	35	Sandy backshore				23,052	-9,203	-3,068

	36	Veg edge				9,092	-622	-207
	37	Sandy backshore				20,388	5,921	1,974
	40	Sandy intertidal				44,052	-22,593	-7,531
	41	Sandy foreshore				79,812	-35,913	-11,971
	42	Sandy foreshore				43,772	-24,853	-8,284
	43	Sandy foreshore				45,648	63	21
	45	Sandy intertidal				66,208	30,460	10,153
	46	Sandy intertidal				67,096	187	62
	47	Sandy foreshore				16,328	-918	-306
4	38	Veg edge				11,332	-508	-169
	39	Sandy backshore				18,460	-4,748	-1,583
	44	Sandy foreshore				40,432	-10,875	-3,625
	48	Rocky foreshore				54,876	-15,496	-5,165
	49	Rocky backshore				14,456	26	9

End.