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A.F. Rennie, J.D. Hansom, M.D. Hurst, F.M.E Muir, L.A. Naylor, R.A. Dunkley,
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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 to organisations with responsibility for coastal erosion and flood risk management, including Angus Council (AC), Scottish Environmental Protection Agency (SEPA), NatureScot and local partners Montrose Golf Links Limited (MGLL) and Montrose Port Authority (MPA).

Structure of Report

The 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 designed to be viewed alongside the National Overview and online resources available at www.DynamicCoast.com.

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Executive Summary

1. The coastal sand dune ridges within Montrose Bay provide a natural erosion and flood protection role to the interior land behind the dunes. However, the dunes at Montrose Links (adjacent to the golf course) and the dunes and the beach elsewhere are now eroding at faster rates than they have in the past.
2. Whilst much of the southern part of the Montrose Links dune ridge is high, several lower corridors through it provide access to the interior to flood waters. Whilst these areas are at low risk currently, as sea levels continue to rise the likelihood of flooding increases in the future (today's 200 yr event, becomes a 75 yr event by 2050 and a 10 yr event by 2080). Unchecked, present coastal erosion is expected to access two additional flood corridors within 2-3 years and a fourth within 6 years.
3. The Dynamic Coast team and Angus Council (who have responsibility for managing coastal erosion) have devised a three-fold strategy to manage these increasing threats. Firstly, urgent works aimed at raising the internal elevation along these southern flood corridors would enhance the short-term flood protection provided by the dunes. This allows, secondly, the development of detailed proposals to manage flood risk over longer-time periods (i.e. develop a Flood and Erosion Risk Protection Scheme); and lastly develop broader adaptive approaches defined within the SMP2 (i.e. develop a broader adaptation plan for Montrose and Montrose Links to support sustainable development). In parallel with these adaptive approaches, alternative 'mega-nourishment' schemes may also be explored as an alternative future long-term strategy.
4. The presently high and quickening rates of erosion at Montrose Links, provide a spotlight on future coastal management issues increasingly being grappled-with around the world. In the absence of (or until a mega-nourishment scheme is implemented), the high rates of erosion mean that terrestrial land-use planning must safeguard the accommodation space (area in beach system is expected to move) to ensure future coastal planners' options are unconstrained, whilst businesses and society are supported.
5. Within the coming decades, considerable change is also anticipated within the low-lying areas of St Cyrus 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.

Montrose Links Super Site Summary

Introduction

This report sets out some Resilience and Adaptation Options for Montrose Bay (Angus and Aberdeenshire, Figure 1) and reflects the shared view of Dynamic Coast, Angus Council and NatureScot, for the area between the rocky headlands of Milton Ness in the north to Scurdie Ness in the south, including St Cyrus National Nature Reserve (northern third of the bay). The investigations concern the open coast, and do not include the Montrose Basin coast. The report aims to support key partners in their planning for anticipated increases in the threats 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[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 Montrose Bay

As de-facto landowners of Montrose Links and authors of the Shoreline Management Plan 2, Angus Council are empowered under the Coast Protection Act 1949 and Flood Risk Management (Scotland) Act 2009. Given their

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

overarching interests, Angus Council are working closely with the Dynamic Coast team to integrate data and advice provided, alongside others, to better inform broader and longer-term aspects. The second focus area within the super site is the National Nature Reserve (NNR) that extends northwards from the mouth of the River North Esk and, as landowners of the NNR, NatureScot are in close liaison with Dynamic Coast and Angus Council.

Coastal erosion has occurred within sections of Montrose Bay over at least the last 130 years, with erosion dominating in the south, and accretion in the north, parts of the bay. The changes have been monitored and strategies outlined within Angus Council's Shoreline Management Plans (2004 and 2017). Dynamic Coast's detailed assessments (below) show erosion is quickening across parts of the beach. Pre-industrial sea levels were stable here, though latest projections expect Montrose to experience up to 0.9 m of sea level rise by 2100 (RCP8.5 95% figure). Sea level changes, alongside other factors, suggest erosion will expand to affect most areas and quicken in rate over the coming decades. Dynamic Coast research anticipates the beach at Montrose to retreat up to 85 m in the next 30 years and up to 250 m by 2100, assuming the absence of resilient substrates to curtail erosion. At the northern end of the bay, St Cyrus is expected to retreat up to 5 m over the next 30 years and up to 50 m by 2100. In addition to the land-losses associated with erosion, direct coastal flooding is expected to impact low lying areas of the dunes in the coming years (through wave overtopping via low-lying gaps in the dune cordon). As the dunes continue to erode, both erosion and erosion-induced flooding risks and impacts increase. For example, existing buildings, such as those immediately adjacent to the golf course and on the north side of Traill Drive are likely to be affected by erosion-related flooding (Table 1).

Future Resilience and Adaptation Planning

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 Montrose 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 (sand motor) (see National Overview Report for context). Table 1 outlines the past erosion rates observed at Montrose Bay, 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 Montrose Bay now and in the future. Whilst responsibility for coastal erosion lies with landowners, 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). Consistent with a Shoreline Management Plan approach (and the Angus SMP2), Figure 2 and Table 1 sub-divide Montrose Bay into management unit areas 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 Montrose 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. Montrose has both urban communities and rural areas 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.

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.

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 National Planning Framework 4 and recently revised National Land Use Strategy.

Figure 1 Location map of Montrose Bay. Grid squares are Easting and Northing of size 1 km x 1 km. Crown copyright and database rights OS 2021 100017908.

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

Resilience and Adaptation Options at Montrose Bay

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

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

Management Unit Area	Shore Character & Assets	Coastal Changes*	'Do nothing' – Likely Implications**	'Short term' management options (to improve short-term resilience)	'Long term' management options (to improve long-term resilience)
Area 1: Montrose Port to Traill Drive  Artificial shore	A) Rock armour and seawall fronted by narrow sandy intertidal B) Harbour, GSK plant, Caravan Park, Roadway, Splash playpark	<u>For both A and B:</u> <u>Low Water</u> 1882–1982: 40 to 270 m loss 1970–2018: 75 to 360 m loss <u>High Water</u> 1890–1970: 40 m gain 1970–2018: 20 to 50 m loss <u>Height change</u> Foreshore 2009–2018: 0.5-1.5m lower <u>Vegetation Edge</u> 1900–1970: <40 m loss 1970–2019:stable	For both A and B: Increased sediment flux into navigation channel with further depletion of Annat Bank (served in the past as a sediment sink/partial barrier to sediment flux to channel). Continued foreshore lowering and steepening, landward retreat of MLWS and increasing wave overtopping risks, increasing erosion and flood risks. Reduction of amenity beach and access points.	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Squeeze, beach lowering & loss of natural sections of amenity beach. **<u>Accommodate Erosion</u>:** **2.** Develop **Dynamic Adaptive Policy Pathway**, to 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. **<u>Erosion Resist:</u>** 3. **Enhance defences (0–20 yrs):** Direct defences constructed, set back from quay wall at both the Northern and Ferryden Harbours to protect low lying properties from coastal flooding. 4. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting defences and Traill Drive. 5. **Reprofile beach (0–5 yrs):** Short-term local enhancement of upper beach profile to improve natural resilience of beach fronting access at Traill Drive.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** **1. Monitor change/no intervention:** Squeeze, beach lowering & loss of natural sections of amenity beach. **<u>Accommodate Erosion</u>:** **2. Realign vulnerable assets (2050):** to avoid future risks and reduce the need for some "erosion resist" options, e.g. non-key parts, or more flood vulnerable assets, within the Port, GSK site (on-site relocation of more vulnerable assets (offices) to safer areas). **3. Realign vulnerable assets (2050):** Non-strategic assets (Caravan Park, recreation area & road) relocated to lower or risk free sites; defences removed to allow dune to revert to natural (dynamic blue/green edge rather than sea wall). 4. **Develop Dynamic Adaptive Policy Pathway (0-2050):** 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. **<u>Erosion Resist:</u>** **5. Combined enhanced defences and beach feed (2050):** Direct defences set back from quay wall at Northern and Ferryden Harbours, fronting beach nourished with sand and gravel to maintain amenity and reduce wave impact on existing structures. **6. Enhance defences (2050):** Port requires marine quayside access so if port is to remain viable repair and raising of quay-side assets is inevitable. GSK site is of strategic importance and costly/impractical to relocate. Continued operation of GSK requires enhancements of existing defences to manage growing risks.
Area 2: Montrose Golf Links  Natural shore, apart from armoured path onto beach	Dune ridge fronted by wide intertidal sand beach. Rock armour at path to beach in south fronted by wide sandy intertidal. Golf Links, Residential and Non-Residential Property. Former Airfield, potential development	<u>Low Water</u> 1882–1982: ~70 m loss 1970–2018: ~70 m loss <u>High Water</u> 1902–1982: 20 m loss 1970–2013: 20 to 50 m loss 2013–2018: 12 m loss <u>Volume</u> Foreshore 2009–2018: 0.5-1.5m lower <u>Vegetation Edge</u> 2010–2015: 15 m loss 2015–2019: 8.4 m loss	Ongoing but reduced southward sediment flux to navigation channel with further depletion of Annat Bank (served in the past as a sediment sink). Continued foreshore lowering and steepening, retreat of MLWS and increasing wave overtopping risks. Reduction of amenity beach and access points. Foreshore & beach lowering, dune recession, short-term (5 years) erosion-related flood risk via corridors through dunes (especially in south).	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Retreat of natural sections of amenity beach, retreat may lead to access issues. **<u>Accommodate Erosion</u>:** 2. Develop **Dynamic Adaptive Policy Pathway**, to 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. **<u>Erosion Resist:</u>** 3. **Dune cordon repairs (NOW–5 yrs): Urgent need to** maintain protection provided by the seaward dune cordon at key low points to reduce the short term risk of a breach giving flood access to dune corridors and interior. Immediate remodeling of dune cordon needed to match adjacent dune topography. 4. **Extend defences (0–20 yrs):** Direct defences (e.g. boulder revetment) extended north from Traill Drive and Splash Playpark to protect dune cordon and corridors from ongoing erosion. 5. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting the dune cordon. **6. Reprofile upper beach (0–5 yrs):** Short-term local enhancement of upper beach profile to improve natural resilience of beach fronting the dune cordon.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** **1. Monitor change/no intervention:** Retreat of natural sections of amenity beach and dune cordon, retreat may lead to access issues. **<u>Accommodate Erosion</u>:** **2. Relocate golf course assets (2050):** consistent with SMPs, already initiated on loss of tees. Relocation inland as accomodation space needed to cope with future erosion, flood risks: golf courses are not fixed assets and could be relocated to risk free sites. Potential erosion-related flood risk remains via dune corridors into golf course. Any modification of dune may require partial relocation of the course. **3. Set-back flood defences along inland route of Traill Drive (2050):** Elevate Triall Drive to provide flood barrier for town for flooding via golf course, which may also provide direct link from the Port to airfiled development. **4. Feed beach (2050):** Long-term local to mega-scale beach nourishment programme to enhance beach profile and dune cordon to maintain natural protection over the long term, reduce risk of breaching and erosion-related flooding. Feed may range in scope from 'on beach' feeding to larger 'whole bay"' scale mega nourishment program (akin to Sand Engines used in the Netherlands). **5. Develop Dynamic Adaptive Policy Pathway (0-2050):** Support existing and future assets to anticipate future relocation, requires mechanisms created to facilitate transition, along with other legislative/policy mechanisms that promote (Local Development Plan prioritising adaptive businesses etc). Other policies may also need support (Protected Habitats, etc). Public and stakeholder engagement to prepare for coastal change. **<u>Erosion Resist:</u>** **6. Extend defences (2050):** Direct defences extended north from Triall Drive and Splash Playpark to protect dune cordon and corridors from ongoing erosion. **<u>Advance:</u>** **7. 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' – Likely Implications**	'Short term' management options (to improve short-term resilience)	'Long term' management options (to improve long-term resilience)
Area 3: Kinnaber Links to North Esk  Natural shore	Forestry and Agriculture Some disused buildings within dunes, Golf Links, Residential and Non-Residential Property. Former Airfield and potential development sites.	<u>Low Water</u> 1882–1982: 36 m gains 1970–2018: ~70 m loss <u>High Water</u> 1890–1970: ~7 m gain 1970–2018: <11 m loss <u>Volume</u> Foreshore 2009–2018: 0.5-1.5m lower <u>Vegetation Edge</u> 2013–2019: <3.5 m loss	Foreshore & beach lowering, dune recession, short-term (5 years) erosion-related flood risk via corridors through dunes (esp in south). Retreat of amenity beach.	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Retreat of natural sections of amenity beach and dune cordon, retreat may lead to access issues & exposure of built assets. **<u>Accommodate Erosion</u>:** 2. Develop **Dynamic Adaptive Policy Pathway** to support existing and future assets anticipate future relocation as per **Area 2**. **<u>Erosion Resist:</u>** 3. **Extend defences (0–20 yrs):** Extend defences (e.g. boulder revetment) north from Traill Drive to arrest further dune erosion, North Esk structure end problematic flanking and changing channel. 4. **Feed beach (0–10 yrs):** Short-term local enhancement of beach profile to improve natural resilience of fronting beach. 5. **Dune cordon repairs (0–5 yrs):** Maintain protection of dune cordon to reduce short term risk of breach in frontal dune to give flood access to dune corridors. Remodel dune cordon to match adjacent. 6. **Reprofile upper beach (0–5 yrs):** Enhancement of upper beach profile improves the natural resilience of the fronting beach.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Retreat of natural sections of amenity beach and dune cordon, retreat may lead to access issues and exposure of built assets as beach is narrower and landward of earlier position. **<u>Accommodate Erosion</u>:** 2. **Set-back flood defences (2050):** Provide barrier to overland flow across dune interior towards assets during extreme events. To be deployed alonside NAI (above). 3. **Development of Dynamic Adaptive Policy Pathway (0-2050):** to support existing and future assets anticipated? future relocation. Currently agri-forestry, this area may provide accomodation and relocation space for adjacent areas, but any development plans here should be aware of potential increased erosion risk and resilience loss. **<u>Erosion Resist:</u>** 4. **Extend defences (2050):** defences extended north from Triall Drive and Golf links to protect dune cordon and Kinnaber Links from ongoing erosion. Defence structure end at North Esk exit will be problematic due to changing channel and flanking. **<u>Advance:</u>** 5. **Mega nourishment (2050):** beach & dune reshaping would benefit the entire bay and reduce risk of erosional breach and erosion-related flooding.
Area 4: St Cyrus (North Esk to Milton Ness)  Natural shore	NNR Visitor centre and walkway Old fishing huts within dunes. Forestry and Agriculture Some disused buildings.	<u>Low Water</u> 1882–1982: ~20 m loss 1970–2018: ~20 m loss <u>High Water</u> 1901–1974: <12 m gain 1974–2018: <50 m gain <u>Volume</u> Foreshore 2009–2018: 0.4-0.7m lower <u>Vegetation Edge</u> 1900–1970: <40 m loss 1970–2018: Gains 2018–2019: Stable/erosional	Foreshore & beach lowering, switch from beach accretion to beach and dune recession, short-term erosion-related flood risk to NNR via former North Esk channel route. Loss of amenity dunes and beach. Foreshore & beach lowering, dune recession, short-term erosion-related flood risk via corridors through dunes. Loss of amenity beach.	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Retreat of natural sections of amenity beach and dune cordon, retreat may lead to access issues & exposure of built assets. 2. **Proactive forward planning of habitat management:** Provide accomodation space for key habitats, and proactive relocation of built assets within NNR (bridge). **<u>Accommodate Erosion</u>:** 3. Develop **Dynamic Adaptive Policy Pathway** to support existing and future assets anticipate future relocation as per **Area 2**. **<u>Erosion Resist:</u>** 4. **Dune cordon repairs (0–5 yrs):** Maintain the protection provided by the dune cordon to reduce any short term risk of a breach in seaward dune. Remodel dune cordon to match adjacent. 5. **Reprofile upper beach (0–5 yrs):** Short-term local enhancement of upper beach profile to improve natural resilience of beach fronting the dune cordon. 6. **Feed beach (0–10 yrs):** Short-term local enhancement of whole beach profile to improve natural resilience of the beach fronting the dune cordon. 7. **Build flood barrier (0–20 yrs):** New flood bund constructed across south end of NNR to isolate old channel of North Esk to separate NNR wetland & dunescape from marine flood access via North Esk. 8. **Insert new defences (0–20 yrs):** Direct defences (e.g. boulder revetment) extend south to North Esk exit. Defence structure end at North Esk exit problematic with changing channel pathway and flanking).	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Retreat of natural sections of amenity beach and dune cordon, retreat may lead to access issues & exposure of built assets. 2. **Proactive forward planning of habitat managemen**t **(0-2050)**: Provide accomodation space for key habitats, and proactive relocation of built assets within NNR . **<u>Accommodate Erosion</u>:** 3. **Set back flood defences (2050):** Provide barrier to overland flow adjacent to property (NNR visitor centre) to interrupt flood waters during extreme events. 4. Proactive **development of a Dynamic Adaptive Policy Pathway (0-2050)** to support existing and future assets anticipate future relocation. Whilst this area is currently NNR and agricultural it may play provide accomodation space for adjacent (recreational and other) activities, however any plans or repairs to existing assets in their current location should be cognisant of increased erosion risk and resilience actions. **<u>Erosion Resist:</u>** 5. **Insert new defences (0–20 yrs):** Direct defences (e.g. boulder revetment) extend south to North Esk exit. Defence structure end at North Esk exit problematic with changing channel pathway and flanking. 6. **Enhance flood barrier (2050):** Flood bund constructed across south end of NNR to isolate old channel of North Esk and separate NNR wetland and dunescape from marine and fluvial flood access via North Esk. 7. **Combination of beach feed and enhanced flood barrier (2050):** Options 6 and 7 above combined to isolate North Esk old channel flood access and enhance St Cyrus beach sediment budget. **<u>Advance:</u>** 8. **Mega nourishment (2050):** beach & dune reshaping would benefit the entire bay and reduce risk of erosional breach and erosion-related flooding.

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

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

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 **Areas 1 and 2** the natural capital is retained, and loss of amenity beach reduced; in **Areas 3 and 4** the future relocation of any new development is avoided for areas of erosion risk. The recommendation is that land-based policies are developed to support adaptation of assets and activities away from areas inland of coastal stretches identified for NAI – a twin-track approach where adaptation is planned simultaneously with a NAI coastal risk management approach.

Areas 1 and 2 have substantial existing assets and it is recommended that planning is required to reduce erosion and erosion-related flood risk to existing infrastructure. Landowners, along with local to national government, action is needed to identify policy and funding mechanisms to facilitate landward relocation of existing assets (e.g. promenade and playpark in Area 1 and golf course holes in Area 2). Flood risk alleviation measures need undertaken where existing infrastructure is at risk of erosion-related flooding, such as moving or land-raising those assets (e.g. relocating or raising offices and plant to reduce flood risk on the GSK site). To manage erosion risks, **Area 1** has existing hard erosion structures and weak current natural capital, with few short and long-term sediment and nature-based **erosion resist** options. In this area it is recommended that a combination of sediment and/or nature-based approaches to managing erosion risks and land-based accommodate erosion policies are used to reduce the use of additional hard erosion resist options. Where hard erosion resist measures are necessary, these should be combined with natural and nature-based erosion resist and land-based adaptation measures. This may offset the high cost of structural erosion resist techniques and the known risks and adverse impacts of using these methods in isolation.

Area 2 has many similarities to Area 1 but presents more opportunity for sediment and nature-based erosion resist options, such as beach feeding, the relative scale of which would strengthen short and medium-term natural capital and resilience. This would 'buy time' to relocate non-essential assets inland (e.g. access roads and golf course holes) of Area 2 while land-based adaptation plans can be agreed and implemented before more direct erosion of these assets occurs. This would improve business continuity for important golf and tourism assets and safeguard currently available landward space.

Areas 3 and 4 have the largest range of potential risk management and adaptation options, owing to the fewest number of built assets at the coast, or inland. There is thus physical space on land behind the existing coastal edge to accommodate erosion and erosion-related flooding now and in the future. The key recommendation is to safeguard this space and coasts to accommodate future erosion with the least societal impacts, through proactive adaptation planning now to limit future development and agree arrangements to move 'at risk' assets landward as part of development and asset maintenance planning (e.g. the Nature Reserve Visitor Centre in **Area 4**, if it became threatened by erosion or flooding). Planning for this now/in advance of the retreat will improve business continuity and reduce future costs, and also provide adaptation space for assets that may require future relocation from **Areas 1 and 2**. Nature-based erosion resist measures can be used in parallel in the short and long-term, such as for nature conservation purposes. If erosion resist is chosen as the preferred option, then risks of erosion elsewhere in the bay from this decision would need careful, detailed study to assess the consequential risks prior to approval.

Proposed approach

Angus Council SMP2 remains the formal policy approach for the Bay, however in support of the southern section of Montrose Links (Area 2 in Table 1 and Figure 2) the Dynamic Coast team and Angus Council (who have responsibility for managing coastal erosion) have devised a three-fold strategy to manage these increasing threats. **Firstly, urgent works aimed at raising the internal elevation along these southern flood corridors** would enhance the short-term flood protection provided by the dunes. This allows, **secondly, the development of detailed proposals to manage flood risk** over longer-time periods (i.e. develop a Flood and Erosion Risk Protection Scheme); and **lastly develop broader adaptive approaches defined within the SMP2** (i.e. develop a broader adaptation plan for Montrose and Montrose Links to support sustainable development). In parallel with these adaptive approaches, alternative 'mega-nourishment' projects may also be explored as an alternative future long-term strategy, which may form part of the operations in developing a Flood and Erosion Risk Protection Scheme.

Technical Summary

Methods

Identification of Flood Protection Features

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

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

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

Modelling Past and Future Erosion: CoSMOS-COAST

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

Vegetation Edge Analysis

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

Updating the Extent of the Intertidal: Coast X-Ray

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

Mapping Coastal Erosion Disadvantage

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

Results

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

Coastal Change

Summary

1. Beach lowering and dune face erosion at Montrose is ongoing and rapid, especially in the south. Between 2009 and 2018 the beach surface has generally lowered by around 0.6 m, with upper beach typically lowering by around 0.9 m. The landward recession of the Vegetation Edge in the south has fluctuated between 3.4–5.9 m/yr over the last decade.
2. Whilst the eroding dune cordon at Montrose currently protects the low-lying dune interior from marine flooding, several weak points within the cordon are at risk of breaching in the short-term (within 3–5 years at present rates).
3. The lowest of the dune breach points (4 mOD) are currently at risk from wave erosion depending on combinations of tide, surge and waves. As mean sea level rises into the future, waves approaching 5 mOD are expected to be more frequent with RCP8.5 sea level rise of up to 0.29 m by 2050 and up to 0.92 m by 2100.
4. The potential flood corridors connect to low-lying areas identified by SEPA to be at Low Probability[2] Coastal Flood Risk within the golf course. SEPA's anticipated flood envelopes do not extend to reach built assets.
5. Whilst partners consider resilience and adaptation plans, Angus Council has requested Dynamic Coast support for emergency intervention, to provide time to develop broader plans.
6. These broader plans may involve dune enhancement, similar to beach recycling and reprofiling (e.g. Summary 5, SNH 2000) but within the dune cordon, as a rapid and cost effective approach to increasing flood protection.
7. Other options include beach nourishment, initially using sand won from dredging in Montrose Harbour, but with the progressive addition of sediment sourced from elsewhere.
8. Over time, erosion has been commonplace in the south of the bay. However, historical and recent accretion in the northern part of the bay, at St Cyrus NNR, now appears to be replaced by erosion, presenting management issues.

The first phase of Dynamic Coast summarised the coastal changes to the southern section of Montrose Bay (see page 20 of Cell 2 report) between 1903, 1984 and 2013. The southern sections of the dunes have retreated by around 50 m between 1982 and 2013, whilst the northern part of the bay has advanced approximately 45 m over the same period.

[2] SEPA define Low probability as 1:1,000 year event or an annual exceedance (return period) of 0.1%.

The second Dynamic Coast phase, outlined below, benefits from Ordnance Survey's aerial survey undertaken in May 2018, and updated by multiple vegetation edge surveys. Whilst these are discussed in turn below, various interactive tools are available within www.DynamicCoast.com for the user/reader to interrogate the results.

Existing Topography and Flood Levels within Montrose Bay

The natural dune ridge in Montrose Bay is approximately 100 m wide in the south and narrows northwards to a point at the mouth of the River North Esk. The defended section of the bay (Area 1, south from Traill Drive) has a high level of protection, afforded by the presence of coastal defences that extend to the harbour and mouth of the River South Esk (Figure 3).

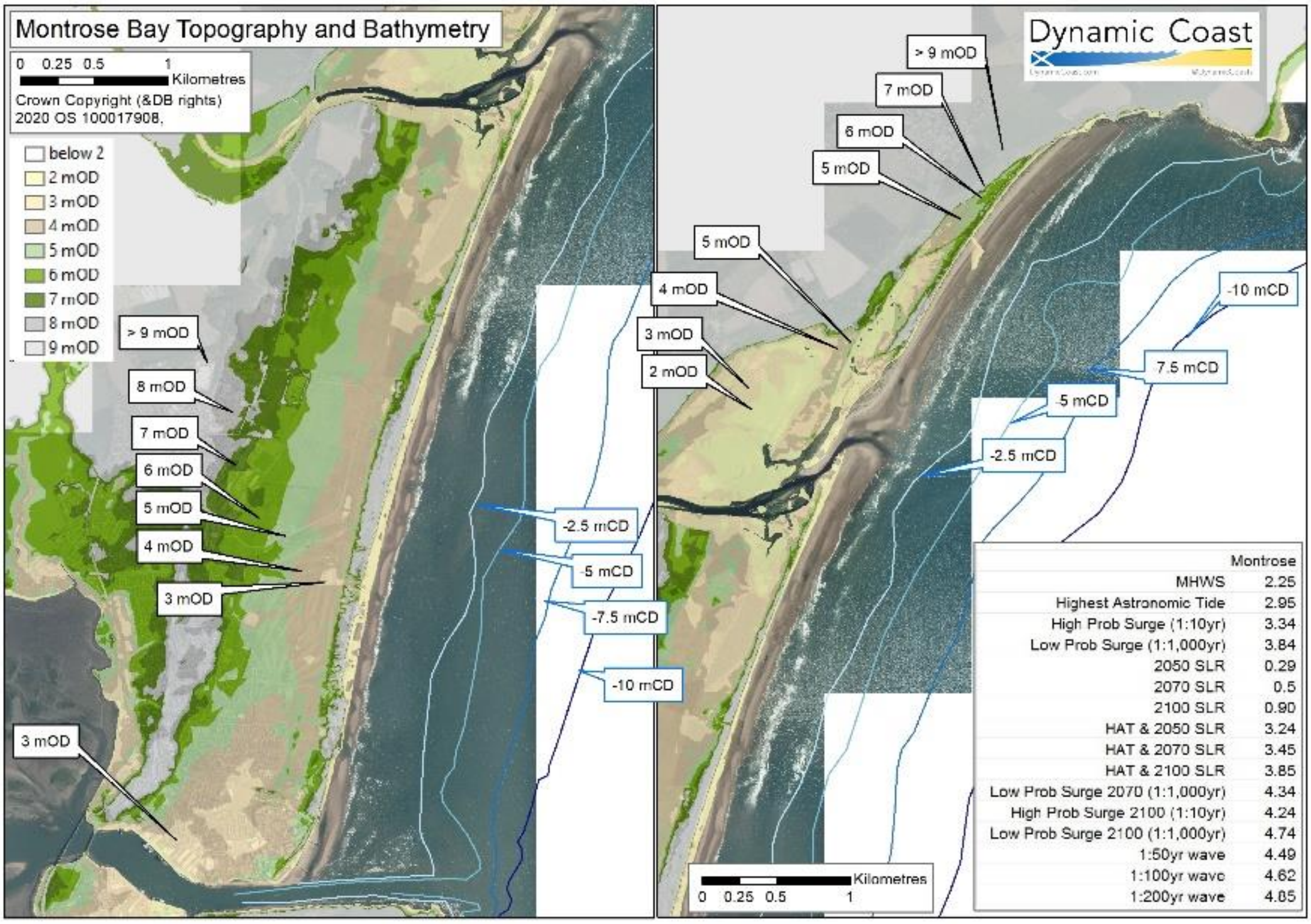


Figure 3 Topography, Bathymetry and key flood levels (mOD) within Montrose Bay.

Natural Coastal Flood Protection Features within Montrose Bay

An automated terrain analysis has been carried out with the OS 2018 DEM being analysed at 10 m intervals with key attributes noted in Figure 4. These include the extent of ridge features (identified from topographic high points), potential flood corridors (from 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, this being the elevation of likely future flood levels combined with wave heights and explored within the Flooding section of this report.

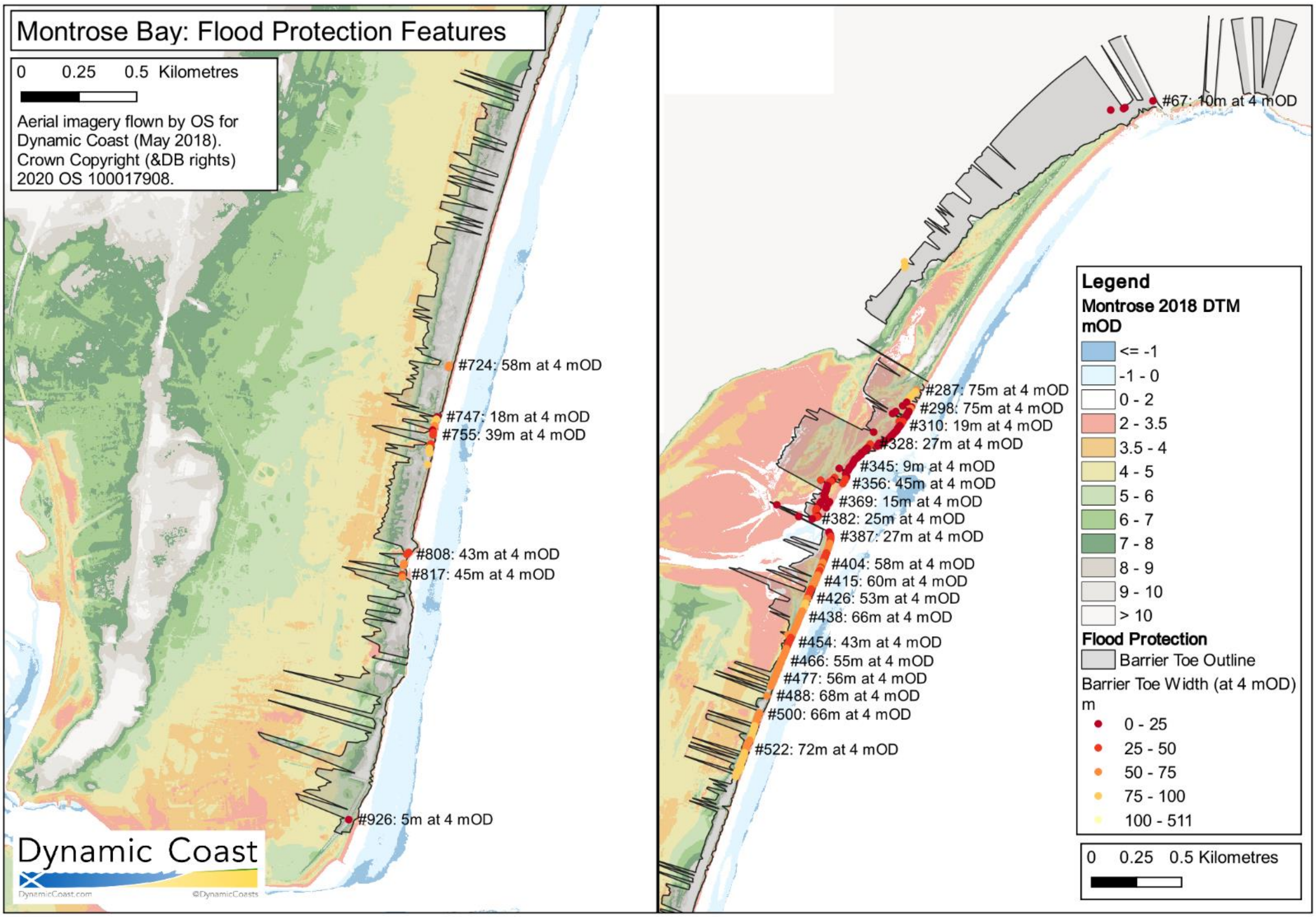


Figure 4 Flood protection features at Montrose, showing the extent of the barrier toe (grey box) and the front points of barriers symbolised by the width of each barrier at 4 mOD. Barrier toe width of narrowest barriers is annotated alongside transect number.

Changes to Low Water in Montrose Bay

Figure 5 shows the observed changes in the position of Mean Low Water Springs from Ordnance Survey mapping in 1882, 1988 and 2018, compared with the average low water position 2016–2018 derived from the Sentinel satellite Coast X-Ray method. Coast X-Ray aligns well with the elevation-derived OS MLWS of 2018, confirming foreshore lowering and landward retreat of low water between the North and South Esk mouths. Figure 5 identifies a much-reduced Annat Bank, the intertidal spit on the north side of the dredged navigation channel of Montrose Port Authority. Low water retreat has occurred at Area 1, with the level of flood and erosion protection offered by the artificial structures reducing over time due to associated shore-face lowering. To the north of Traill Drive (Area 2) low water has retreated 70 m from 1882–1988 (0.6 m/yr retreat) and 70 m from 1988–2018 (2.3 m/yr retreat). Adjustments to the intertidal area at the mouth of the North Esk is complicated by the ever-changing tidal bars, however further northwards (Area 4) there is a general slow retreat of low water, typically 20 m landward retreat between both 1882–1988 and 1988–2018. Coast X-Ray is evaluated further in Technical Annex WS7 – Coastal X-Ray (www.DynamicCoast.com/reports).

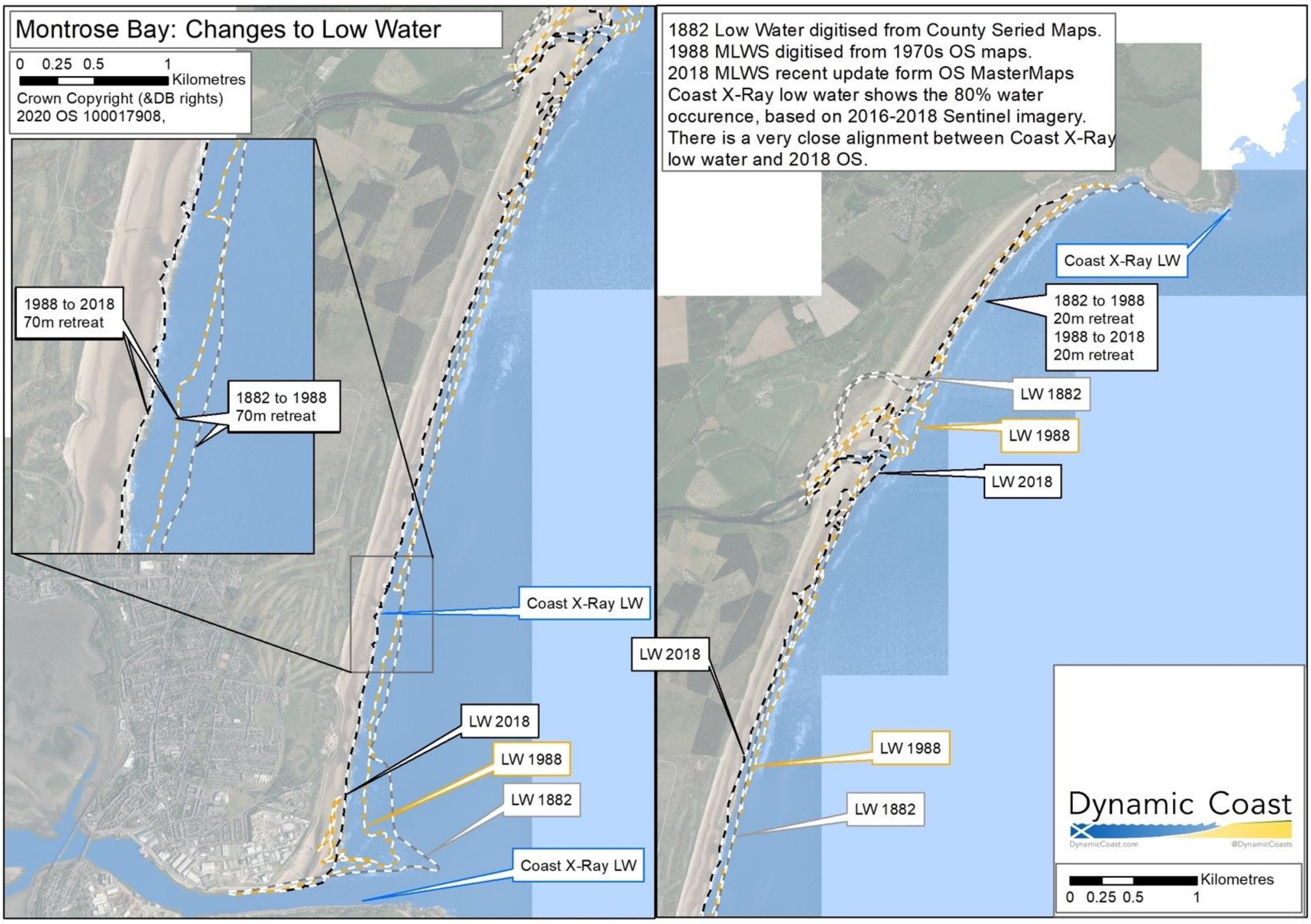


Figure 5 Change to the lower beach – comparison of various MLWS surveys (1882, 1988 & 2018) and Low water (80% water occurrence) from Coast X-ray

Changes to High Water in Montrose Bay

Figure 6 shows the observed changes in planimetric position of Mean High Water Springs from OS mapping in 1902, 1988, a GPS ground survey DSM 2013 and OS photogrammetric DSM from 2018. The DSM changes show losses and gains to the upper beach identified by changes in surface topography. In Area 1, coastal defence structures have arrested the landward progress of MHWS. However, to the north in Area 2 modest retreat occurred between 1901 and 1982 (20 m), however between 1982 and 2013 there was between 30–65 m of erosion in places (1–2 m/yr). Between 2013 and 2018 a further 12–25 m was lost (2.4–5 m/yr). Historic, recent and current erosion rates reduce northwards towards Kinnaber Links. The changes around the mouth of the North Esk are more complex (due to the additional sediment supply and river flows). Whilst much of St Cyrus (Area 4) has experienced an influx of sediment over recent centuries, a comparison between the 2013 and 2018 High Water lines suggests a northerly moving erosional trend which would reverse past accretion. Such clear-cut characterisations are likely to oversimplify the complex interactions at work, but at a future date a switch like this is likely, given rising sea levels and stagnating sediment supplies.

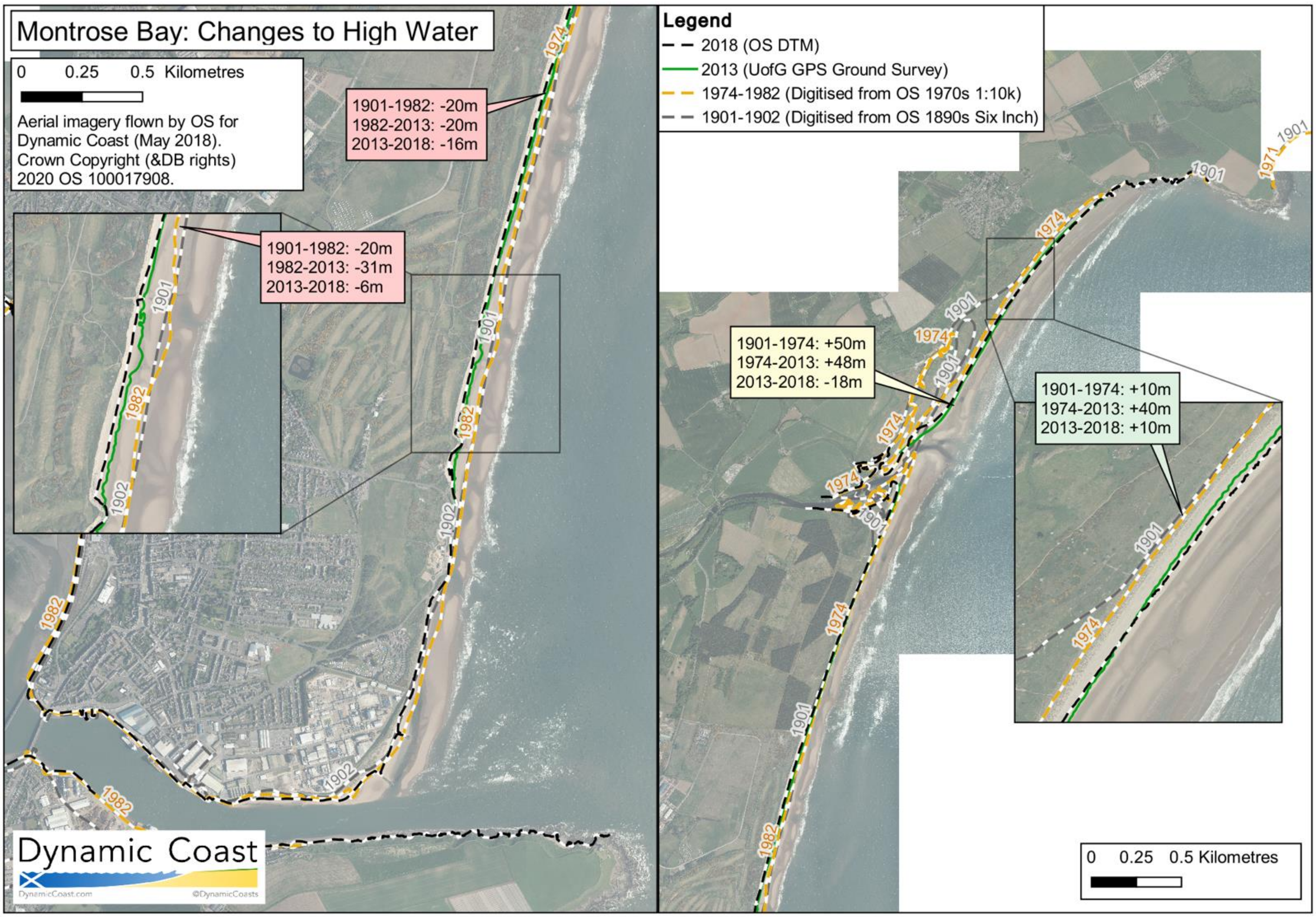


Figure 6 Change to upper beach – comparison of MHWS (dates)

Comparison of the 2013 and 2018 DSMs allows quantification of surface losses on the intertidal foreshore (typically between 0.5 and 1.5 m, and 8 m at the retreating dune toe). At the south end of the Bay, at the harbour mouth the intertidal Annat Bank shows limited recent (2013–2018) change (Figures 5 and 7), its 1882 volume and extent having been already greatly diminished. Since the energy of storm waves at breaking point is depth dependent then foreshore lowering will lead to an increase in wave energy at the upper beach. Where dunes are high then wave energy is both absorbed and reflected and may lead to ongoing erosion and further beach lowering. Where dunes are low and potential breach points exist then the risk of overwash into the dune interior and landward areas progressively increases as the decreasing footprint of the fronting dunes becomes increasingly compromised.

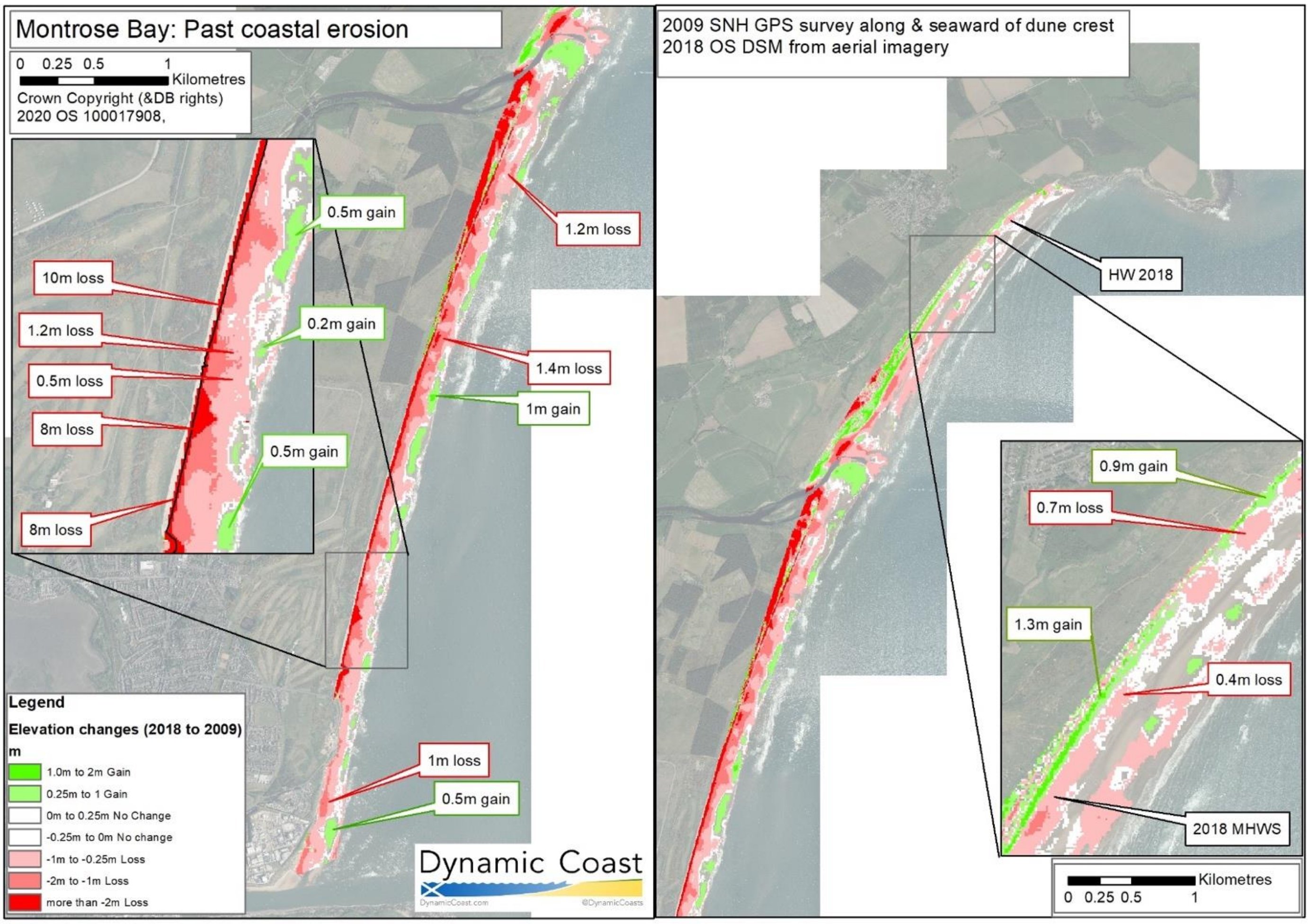


Figure 7 Changes in foreshore elevation from 2009 (SNH GPS survey seaward of dune crest) to 2018 (OS DSM from aerial imagery).

Dune Vegetation Edge Changes

Figure 8 shows time-series observed changes in Vegetation Edge position within Montrose Bay, based on recent aerial and ground survey data. The vegetation edge at the southern section of the Bay shows consistent erosion, which is typically associated with undercutting of the dune toe due to incident wave action, particularly when superimposed on a high spring tide. When the wind or swell waves are not from the east sector (i.e. between south-east and north-east), or if the tidal level is lower, then observed erosion is more limited (*pers. com.* John Adams, Montrose Golf Links). For reasons of consistency, the most recent aerial survey data is used as a baseline for quantification and modelling (below), with Figure 9 showing ground survey from mid-January 2020 that captured erosion of the Vegetation Edge caused by a single storm, Storm Brendan.

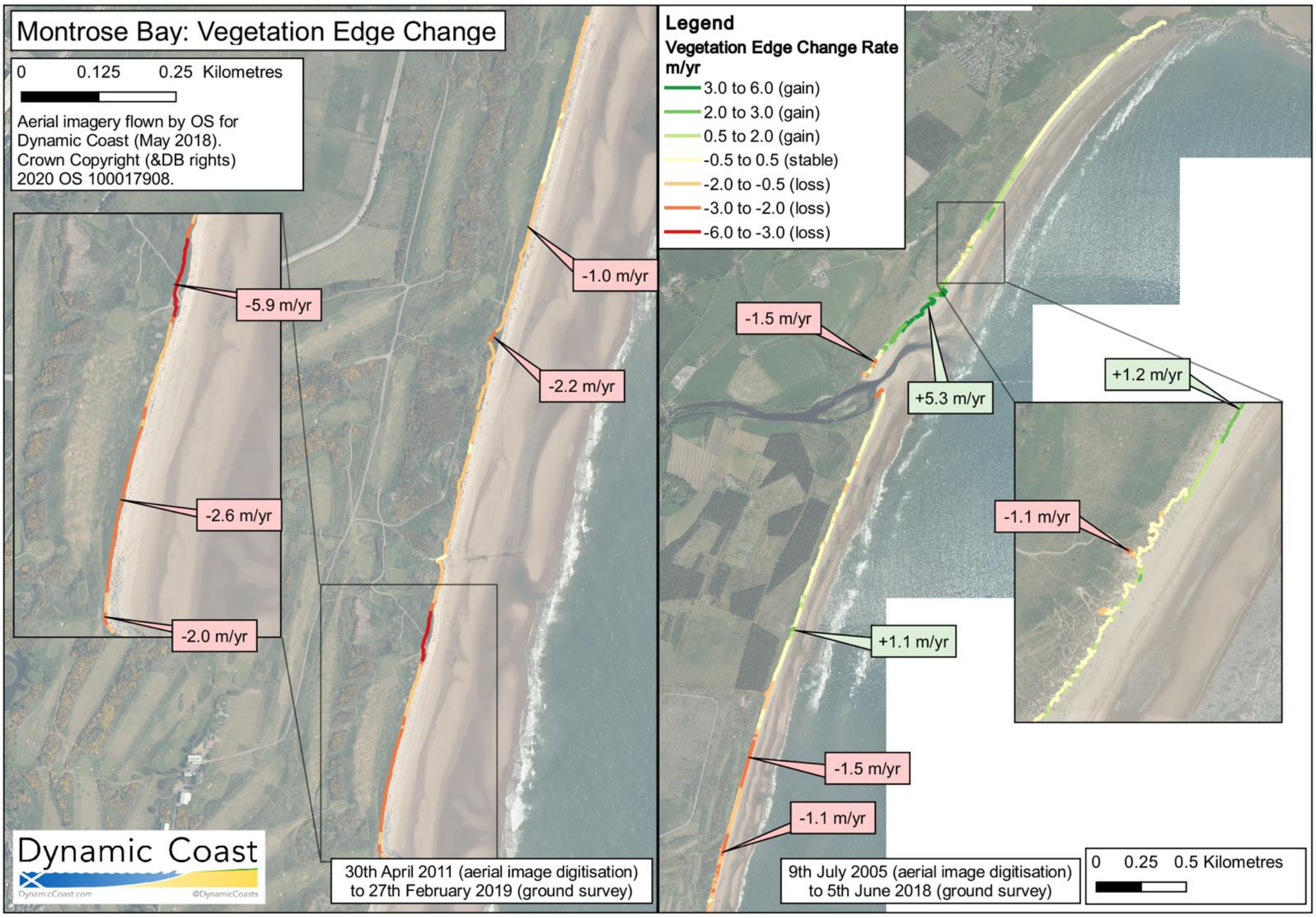


Figure 8 Vegetation edge change at Montrose Bay (2011 to 2019 and 2005 to 2018). Note the -5.9 m retreat which reflects the retreat of the vegetation edge following the removal of the rock armour at this location.

Figure 10 shows rates of change of the Vegetation Edge, High Water and Low Water lines for representative transects near the southern section of dunes. Whilst this shows variability in the rate of Vegetation Edge erosion (e.g. 2013–2015 and 2015–2018) and masks MHWS and MLWS variability due to the lack of data for intervening years, the overall erosional trend of Vegetation Edge and MHWS is clear. Landward movement of MLWS has slowed over the two periods shown, perhaps due to gain of sediment eroded from the upper beach and dunes. Despite this, the overall trend is for erosion of all three indices and attendant foreshore lowering.

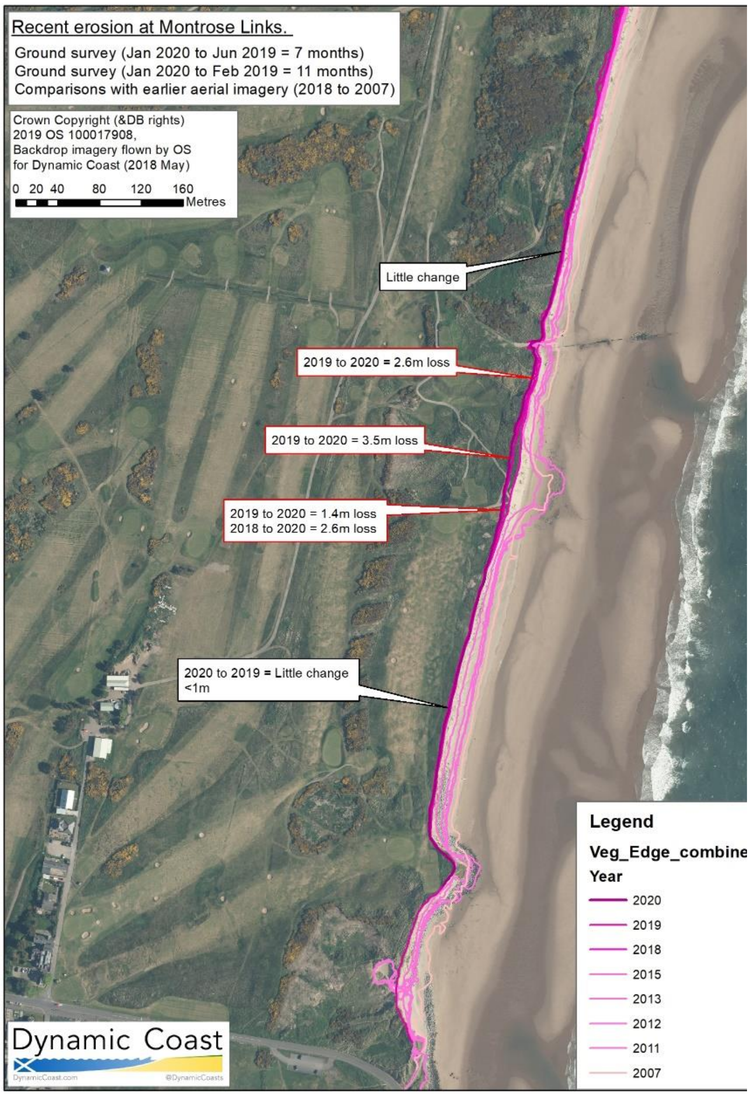


Figure 9 Detailed vegetation edge change following Storm Brendan (ca. 12th to 14th January 2020) compared with recent ground survey and aerial photography analysis.

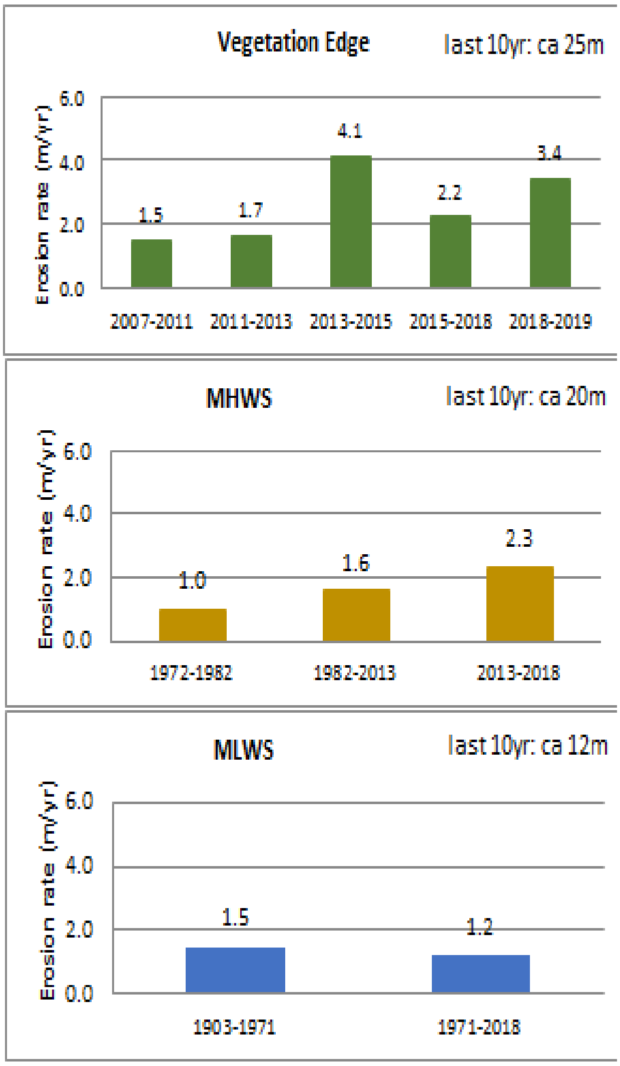


Figure 10 Comparison of rates of change – Vegetation Edge, Mean High Water Springs and Mean Low Water Springs.

Volumetric Changes within Montrose Bay

The elevation changes captured by the data depicted in Figure 7 above allow annual volumetric change rates to be calculated for the period between 2009, 2013 and 2018 in each of the four management units in Figure 11. The overall pattern is for erosion to be concentrated in the upper beach and dune face areas with the lower intertidal areas showing lesser volumes of loss as well as some areas of gain, particularly at St Cyrus. The aggregated annual change within each management unit is shown in Table 2 with the main units showing sediment loss over the period 2009-2013 and 2013-2018, except gains mainly in the north in Area 4 and a negligible amount in Area 1 2009-2013.

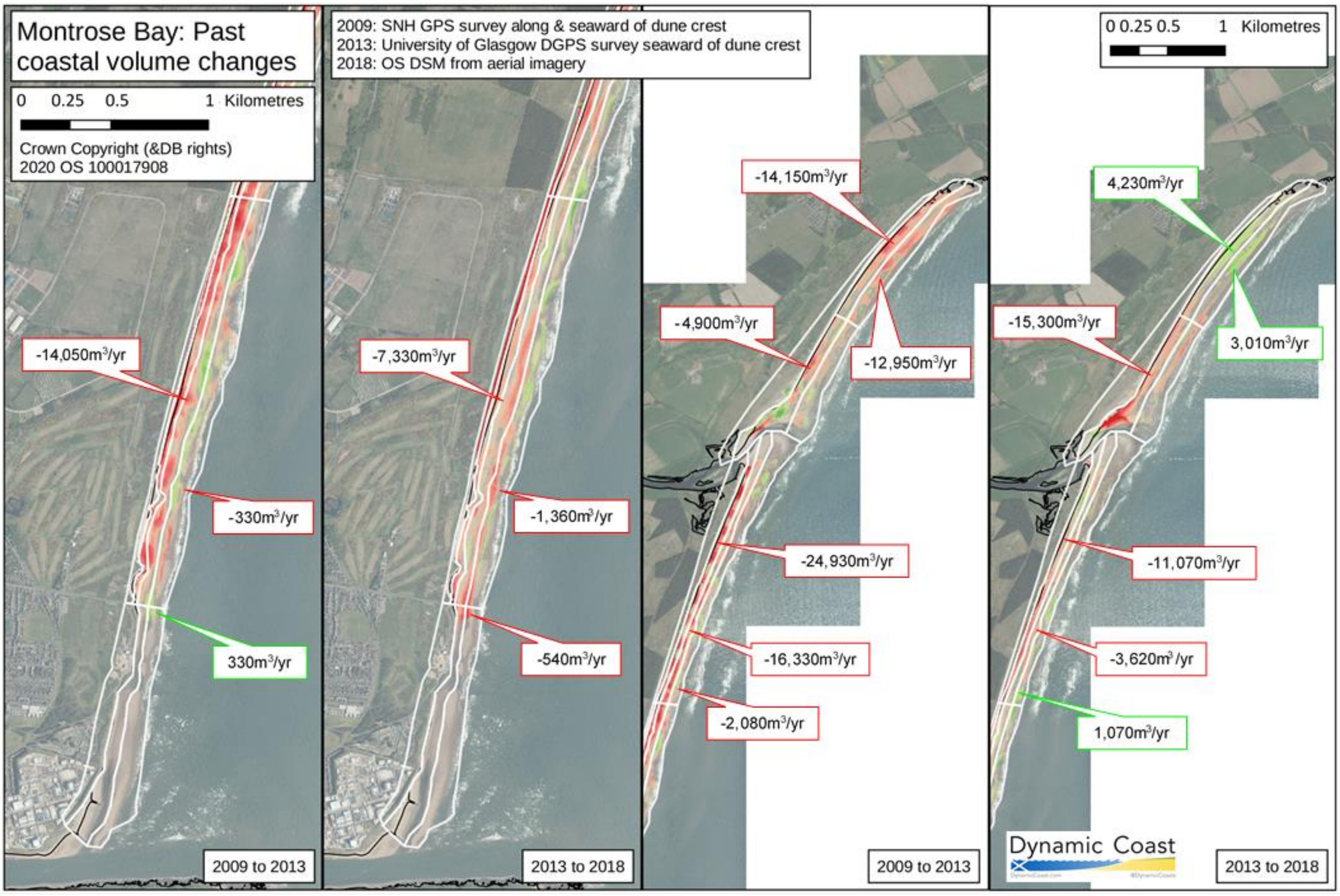


Figure 11 Comparison of rates of volume change across each geomorphic section outlined in white, from 2009 to 2013 and 2013 to 2018

Table 2 The annual volume change for each of the four management units

Management Unit	2009–2013		2013–2018	
	Area (m2)	Change (m3/yr)	Area (m2)	Change (m3/yr)
1 - Port-Traill Drive	1,603	+400	8,173	-1,400
2 - Golf Links	224,400	-56,100	344,000	-36,200
3 - Kinnaber Links	196,600	-49,200	365,120	-22,900
4 - St Cyrus	135,418	-33,900	416,262	10,600

It should be noted that the volumetric changes within the intertidal and beach face (Figure 11 and Table 2) do not capture changes within the nearshore and subtidal part of the beach and, in the absence of time series bathymetric surveys, an alternative approach helps cast light on the broader nearshore sediment budget that has a role in wave absorption and coastal stability. For example, the sediment flux (volume of material moving past a vertical plane) from the southern 1 km section of dunes can be estimated using the amount of change along the entire active face (i.e. from dune crest to the nearshore wave closure depth at -10 mCD). This 'rule of thumb' method is used by a number of coastal scientists to provide a first order calculation from a typical dune crest down to the wave closure depth, the alongshore width and the retreat rate per year. This identifies sediment loss from a discrete section of coast to provide an approximation of the annual sediment change over the foreshore, intertidal and subtidal. The approach assumes uniform cross-shore retreat and provides an order of magnitude minimum supplementary volume needed to maintain a stable shoreline position. Using such a calculation, Table 3 estimates that the 1 km of dune and beach north of Traill Drive losses are ~74,000 m^3/yr. This approach assumes uniform cross-shore retreat, yet the Vegetation Edge retreats more quickly than MHWS or MLWS and a nominal average erosion rate of 3.4 m/yr. Together, these assumptions indicate the volumes lost are likely to be a conservative measure of the annual sediment loss.

Table 3 Sediment loss from southern section of Montrose Golf Course Links, using an 'active face' approach. CD=chart datum/OD=Ordnance datum

Dimension	Measurement	Amount	Unit
Length	Dune height (nominal)	9	mOD
	Wave closure depth (nominal)	10	mCD
	CD to OD conversion	+2.7	m
	Active face height (9+10+2.7)	21.7	m
Breadth	Erosion rate (min)	1.5	m/yr
	Erosion rate (mean)	2.6	m/yr
	Erosion rate (max)	4.1	m/yr
	Erosion rate (nominal)	3.4	m/yr
Height	Southern golf course	1,000	m
Volume	**Active face sediment loss (nominal)**	**73,780**	**m^3/yr**
Calculation: 21.7 x 3.4 x 1,000 =73,780			

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 95^{th}% estimate, given the precautionary principle. The coastal change incorporates shoreface 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 of many possible scenarios to inform the possible scale of change. Figure 12 and the Dynamic Coast web-maps (www.dynamiccoast.com/webmaps.html) show the anticipated future positions of MHWS in 2050 and 2100 estimated using a Modified Bruun Rule calculation for a future relative sea level rise of 0.92 m at 2100 (UKCP18 RCP8.5 95^{th}%). The amount of landward retreat reaches 85 m by 2050 and 255 m by 2100 and excludes the artificially defended shores along Traill Drive and the north St Cyrus rock cliffs which are assumed to remain static.

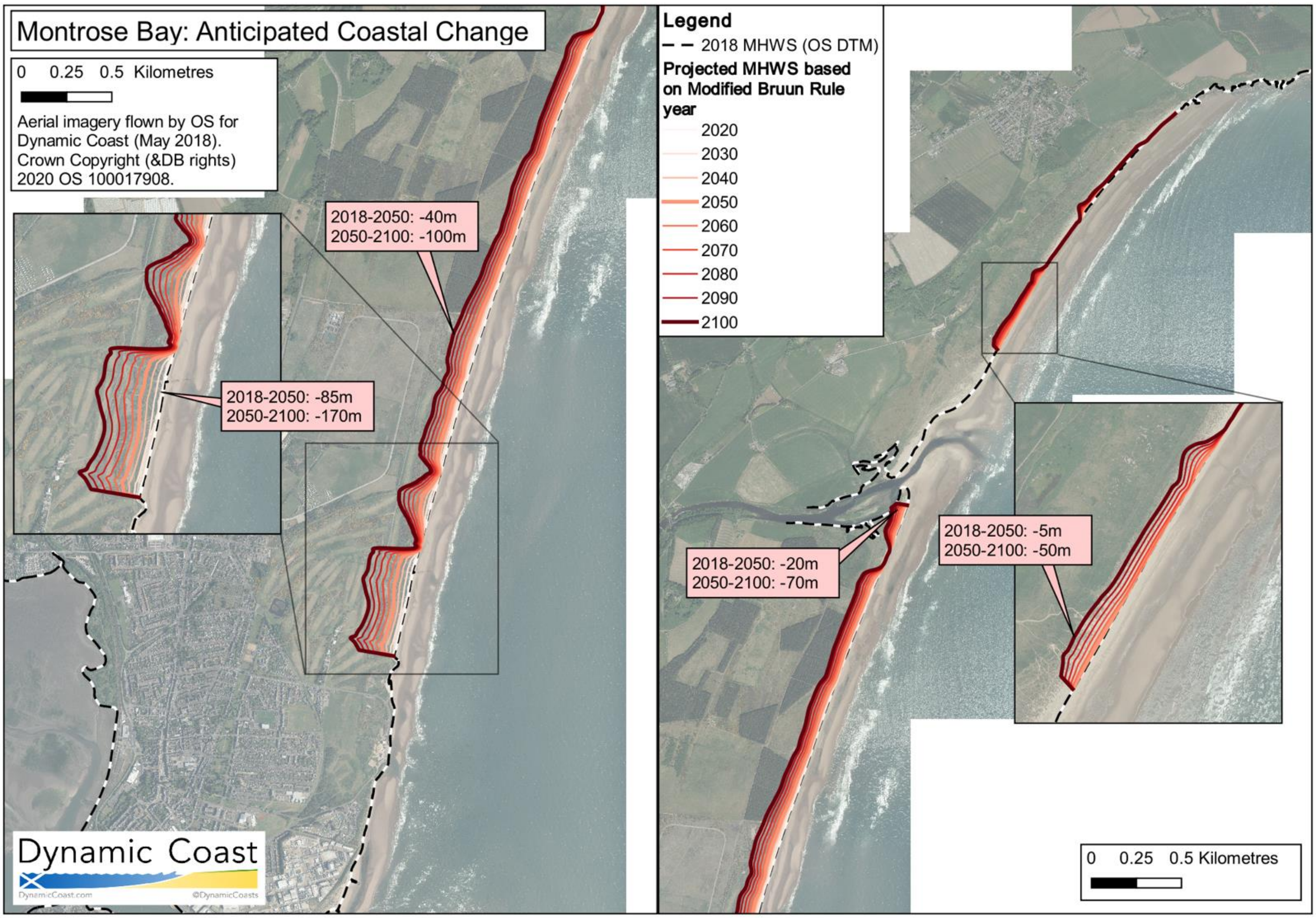


Figure 12 Anticipated coastal change – Modified Bruun Rule MHWS

The arrival of a retreating MHWS on the beach of each bay is normally preceded by the undercutting of vegetation at the coastal edge, especially where any dune or 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, at Montrose there is a mean lateral distance of 20 m between MHWS and the Vegetation Edge which is used to project the Modified Bruun MHWS predictions inland, in order 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 to arrive at a given point inland in advance of that predicted by the Modified Bruun Rule on its own. A detailed view of each decadal Vegetation Edge prediction using this method can be seen on Figure 13. The progress of beach and dune landward movement and vegetation offset is curtailed by the presence of rock and cliff in the north at St Cyrus.

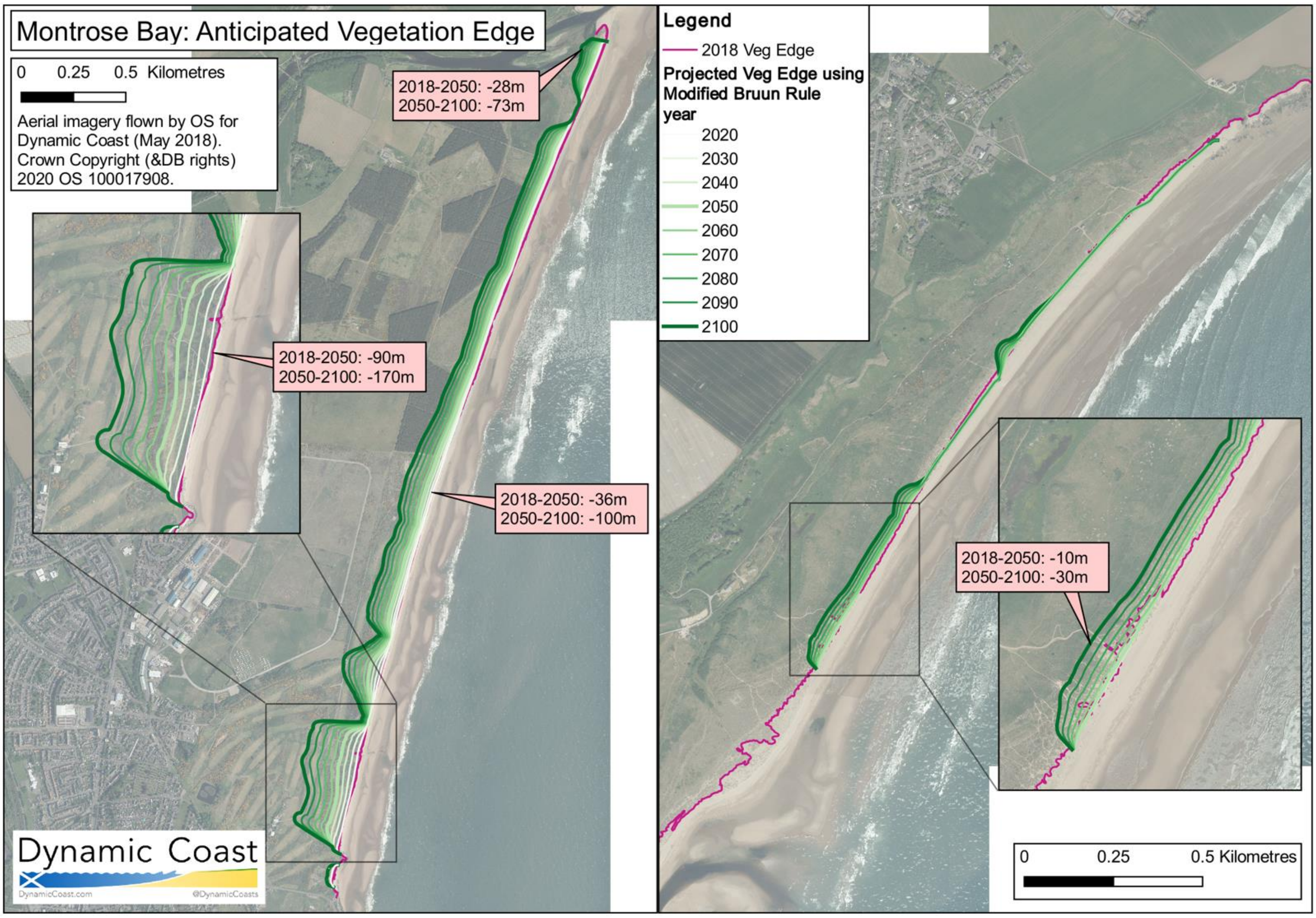


Figure 13 Anticipated coastal change – Modified Bruun Rule Vegetation Edge

Figure 14 depicts the anticipated erosion and coastal evolution of Montrose Bay using a different model: the Coastal One-line Assimilated Simulation Tool (CoSMoS-COAST, Vitousek et al., 2017). CoSMoS-COAST is forced by the RCP8.5 95th% sea level change scenarios within UK Climate Projections 2018 (UKCP18) and models long-term shoreline migration due to sea level rise and includes wave-driven alongshore and cross-shore sediment transport processes. Validated with recent shoreline position observations from Dynamic Coast, shoreline change is then modelled to 2050 and 2100. In Montrose Bay this shows an anticipated landward migration of the shore in the south of 3–11 m by 2050 and 8–24 m by 2100 and in the north at St Cyrus by 14–30 m by 2050 and 36–51 m by 2100 (excluding the artificially defended shores along Traill Drive in the south and the rock cliffs at northern St Cyrus).

Figure 14 also includes the Dynamic Coast (2017) linear projection of recent MHWS recession rates. The CoSMoS-COAST predicts less erosion than the linear projection of current erosion rates because CoSMoS-COAST includes along and cross-shore sediment transport as well as accretion from elsewhere in Montrose Bay (not included in the first phase of Dynamic Coast (2017)). CoSMoS-COAST also adjusts its parameters to regular input of MHWS measurements. However, the irregular time gaps of shorelines in Montrose Bay (1890s to 1970s and 1970s to modern) mean CoSMoS-COAST can make only limited adjustments to its modelled erosion rates and only partly captures the actual rates observed over the last decade. The result produces agreement with the anticipated direction and trends in Figure 12 and Dynamic Coast (2017), but underpredicts known recent recession. CoSMoS-COAST assumes the present sediment budget to remain more or less the same into the future.

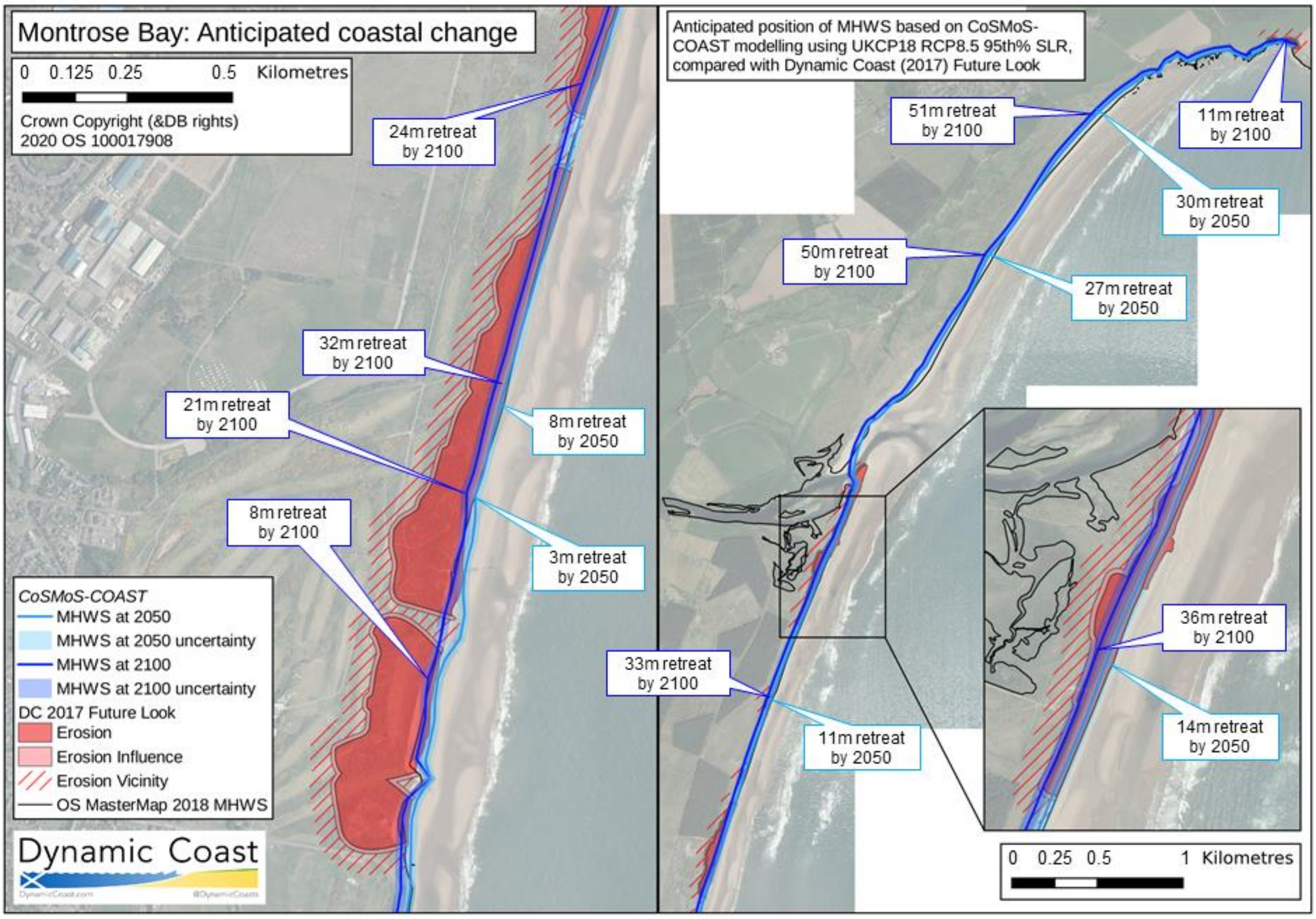


Figure 14 Anticipated future coastal change – CoSMoS-COAST MHWS and Dynamic Coast (2017) Future Look.

Figure 15 compares the CoSMoS-COAST results with the Modified Bruun Rule approach from Figure 12. This shows a similar underprediction in the future MHWS position by the CoSMoS-COAST model, and greater correlation between the DC 2017 linear erosion rate projection and the Modified Bruun Rule, when Figure 12 and Figure 14 are compared. However, this comparison also supports the prediction that sea level rise projections of 0.92 m by 2100 will bring widespread erosion to the Bay, even across sections that were previously experiencing accretion.

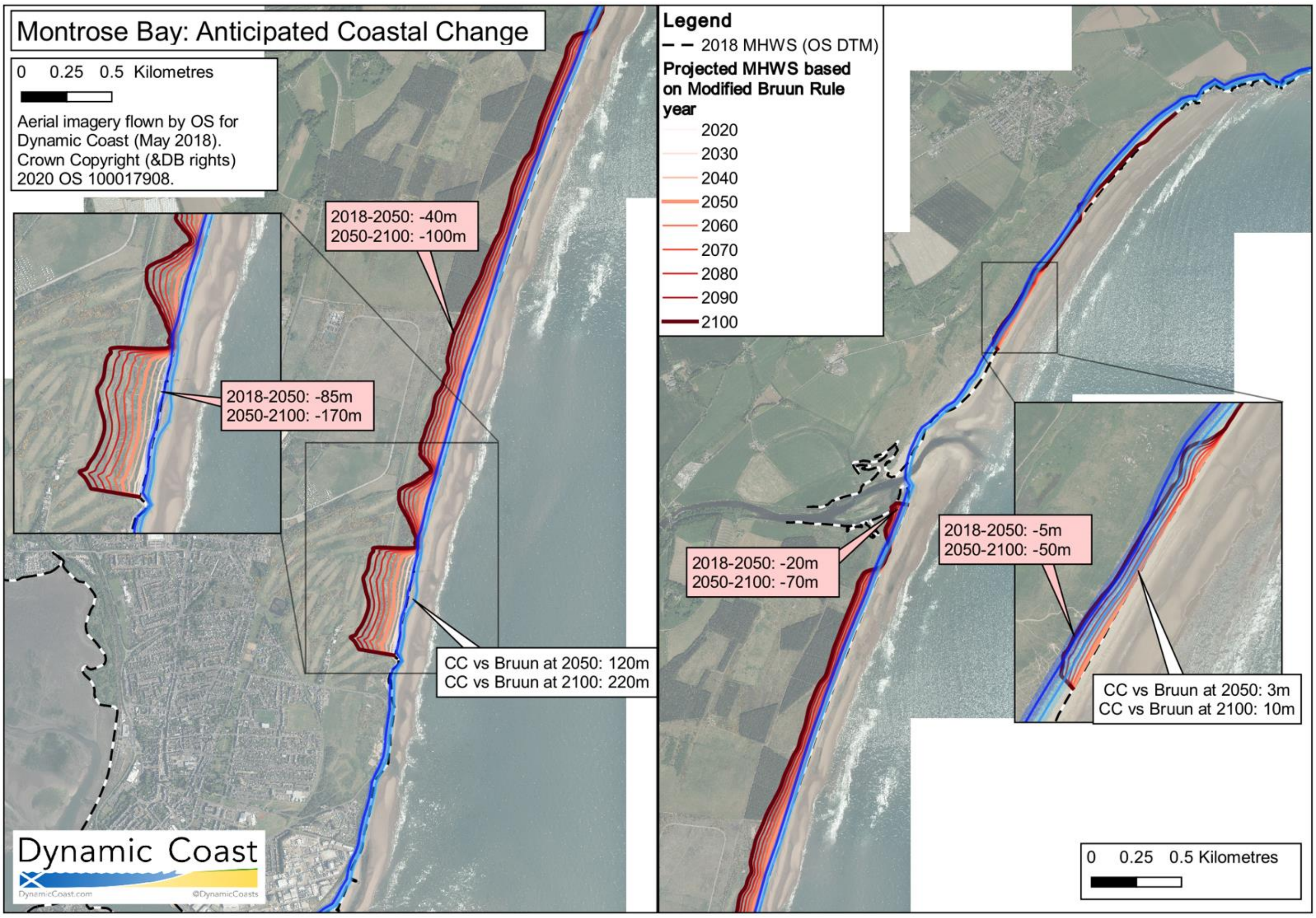


Figure 15 Anticipated coastal change – CoSMoS-COAST and Modified Bruun MHWS results.

Social Vulnerability Classification Index

The average Social Vulnerability Classification Index (SVCI) for Montrose, upon calculation of weighted indicators of socio-economic vulnerability, is of rating 4 which corresponds to a classification of Slightly Resilient. However, some areas of Montrose Bay were within the second most vulnerable category within the SVCI. A high level of vulnerability arose within the category of community cohesion; this could be accounted for by high crime rates and a large proportion of single person households within these areas. Moreover, there appears to be a higher level of vulnerability within the Montrose area that can be attributed to the "Education" category assessed within the SVCI and this is likely to be due to a high proportion of residents reporting having left school with no qualifications. In terms of its score within the "physical assets" category, overcrowding has influenced the SVCI outcome. The vulnerable areas of Montrose identified within the SVCI had the highest rates of physical and mental health-related vulnerability within the SVCI. This is due to a high proportion of people reporting limitations on physical activities due to health-related issues. Areas of Montrose exhibiting higher levels of social vulnerability also score relatively high in the population category, with the highest number of children under four-years old and a relatively high proportion of older people. Social vulnerability related to economic prosperity within Montrose emerged from the SVCI analysis as resultant largely of employment deprivation and long-term unemployment rates. Those living within Montrose emerge as being those who need to travel the greatest distances to reach their workplaces, contributing to an assessment of the 'sustainable communities' domain.

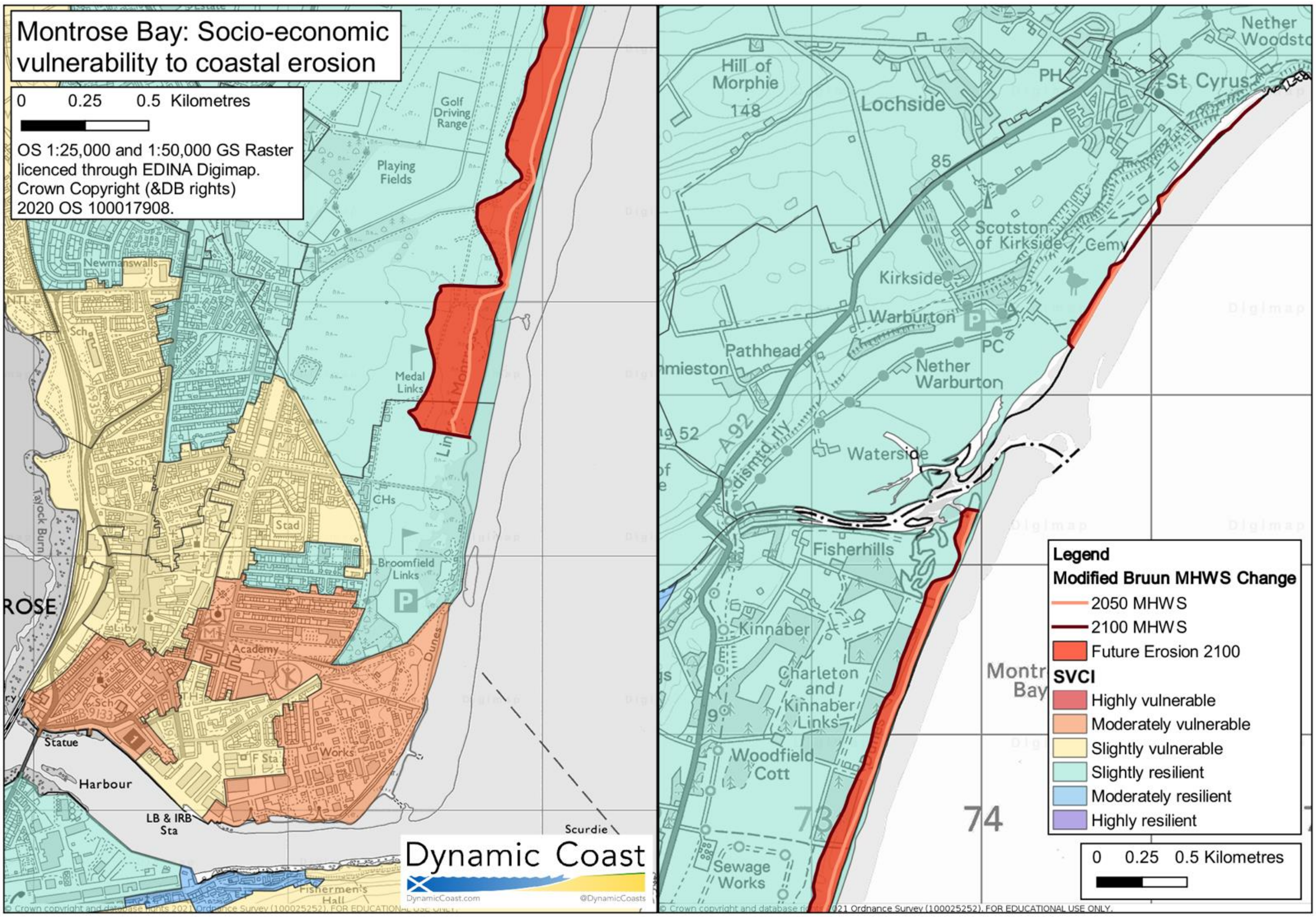


Figure 16 SVCI classifications per data zone with anticipated coastal change using the Modified Bruun Rule

Flooding

Coastal Flood Boundary

The Coastal Flood Boundary (CFB) dataset published by DEFRA in 2018 (link) is reported below. It displays the anticipated still water surface level of surge events at various frequencies, across Montrose Bay. Still water level calculations such as these can superimpose the surge level on top of the highest astronomic tide level to gain a realistic impression of worst-case storm impacts; however they exclude other hydrodynamic effects, such as wave run-up which would need to be considered. Whilst in some parts of Scotland the recent update deviates from the last version, there is a negligible increase (1 cm) at Montrose.

Table 4 Tidal and flood levels for Montrose sort table grids

Description	Level (mOD)	Description	Level (mOD)	Description	Level (mOD)
MHWS	2.25	1 yr (100% AEP)	3.09	C1 1 yr (100% AEP)	3.08
HAT	2.96	10 yr (10% AEP)	3.34	C1 10 yr (10% AEP)	3.31
Base year	2017	100 yr (1% AEP)	3.59	C1 100 yr (1% AEP)	3.52
FID	2063	200 yr (0.5% AEP)	3.66	C1 200 yr (0.5% AEP)	3.57
		1,000 yr (0.1% AEP)	3.84	C1 1,000 yr (0.1% AEP)	3.7

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 4) 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 17 shows the present-day high probability and low probability coastal flood extents, in greater detail than SEPA's Flood Risk Maps for flooding in Montrose, as it benefits from a more recent digital surface model (2018) and is therefore more likely to represent actual current land and water levels. Figure 17 demonstrates potential entry points for flood water that exist at present at the mouth of the rivers and the increase in extent of flooding south across the backdunes in a low probability event.

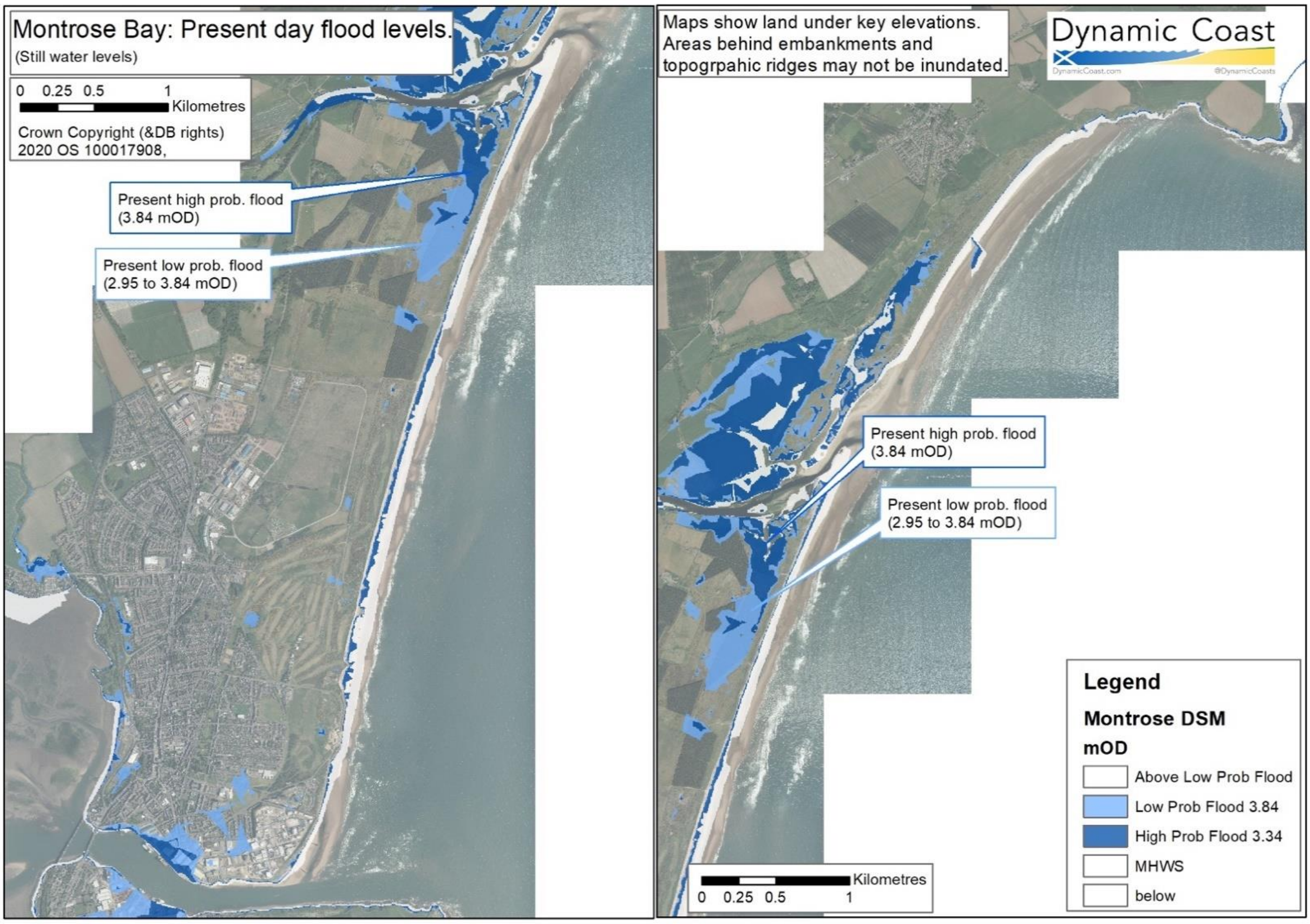


Figure 17 Summary of present day high probability (1:10 yr 3.34 mOD) and low probability (1:1,000 yr 3.84 mOD) flood levels at Montrose Bay.

Relative Sea Level Rise

The UK Climate Projections data (2018) has been used to anticipate increases in mean sea level in Montrose Bay. Whilst there are considerable domestic and international efforts to cut greenhouse gas emissions, the recent global trends remain aligned with the High Emissions Scenario (or Representative Concentration Pathways 8.5). For context, a 2°C future, corresponds to the RCP4.5 50^{th}% at 2085; 4°C corresponds to RCP8.5 50^{th}% by 2085; and the 5.5°C future corresponds to the 95^{th}% by 2085.

The anticipated increases in mean sea level at Montrose are summarised in Table 5; by 2050 mean sea level is likely to increase between 0.1 m and 0.29 m above the average levels seen between 1980 and 2000, and are as likely as not to be above 0.19 m. Rates of sea level rise by 2050 are expected to be between 3 mm/yr and 9 mm/yr and as likely as not to be above 6 mm/yr. When considering future sea level rise, it is helpful to appreciate that the long-term pre-industrial relative sea level trend at Montrose was -0.82 mm/yr (Bradley et al 2019).

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

Table 5 Existing and future tidal extents based on UKCP18 RCP8.5 for Montrose

Year	MSL increase (m above 1980–2000 levels)		
	5th%	50th%	95th%
2010	0.01	0.02	0.04
2020	0.02	0.05	0.08
2030	0.04	0.09	0.13
2040	0.07	0.13	0.20
2050	0.10	0.19	0.29
2060	0.14	0.25	0.39
2070	0.18	0.32	0.50
2080	0.22	0.39	0.63
2090	0.27	0.47	0.77
2100	0.31	0.56	0.92
2300	0.72	1.73	3.50

Period	Rate of increase (mm/yr)		
	5th%	50th%	95th%
2000–2010	1.0	2.0	4.0
2010–2020	1.0	3.0	4.0
2020–2030	2.0	4.0	5.0
2030–2040	3.0	4.0	7.0
2040–2050	3.0	6.0	9.0
2050–2060	4.0	6.0	10.0
2060–2070	4.0	7.0	11.0
2070–2080	4.0	7.0	13.0
2080–2090	5.0	8.0	14.0
2090–2100	4.0	9.0	15.0
2100–2300	2.1	5.9	12.9

The existing tidal inundation extents and the increases in extents by 2100 are shown in Figure 18 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 RSLR are very similar to present high and low probability flood levels.

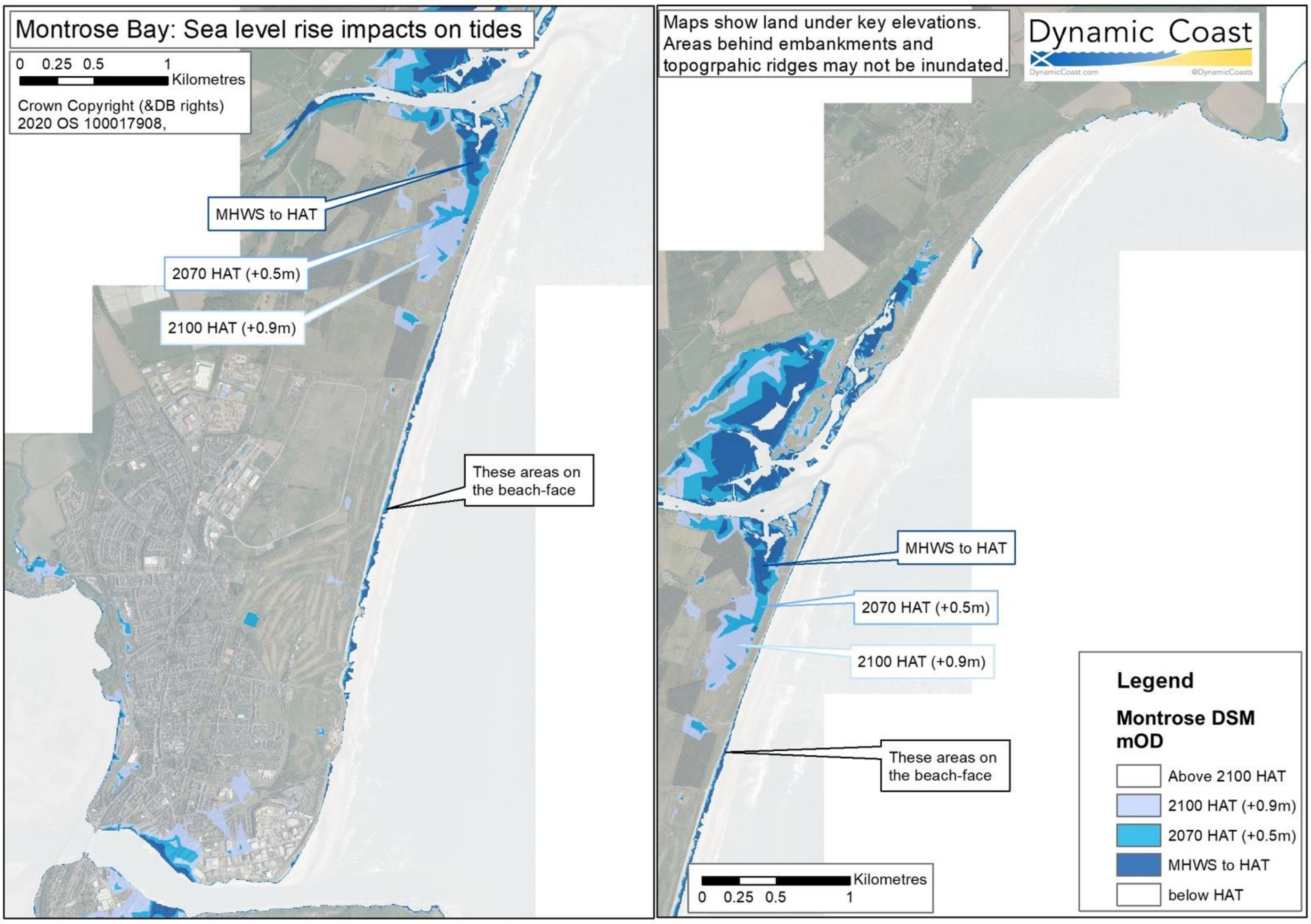


Figure 18 Present day tidal extents and the future tidal extents anticipated under UKCP18 RCP8.5 95% sea level rise by 2070 and 2100.

Figure 19 shows the key present day and anticipated flood elevations for Montrose by 2070 and 2100 under RCP8.5 95th% sea level rise, which reflect the increased impact of storms and inundation events when 0.92m 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 Montrose Links (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 the North Esk river mouth and south via Montrose Harbour.

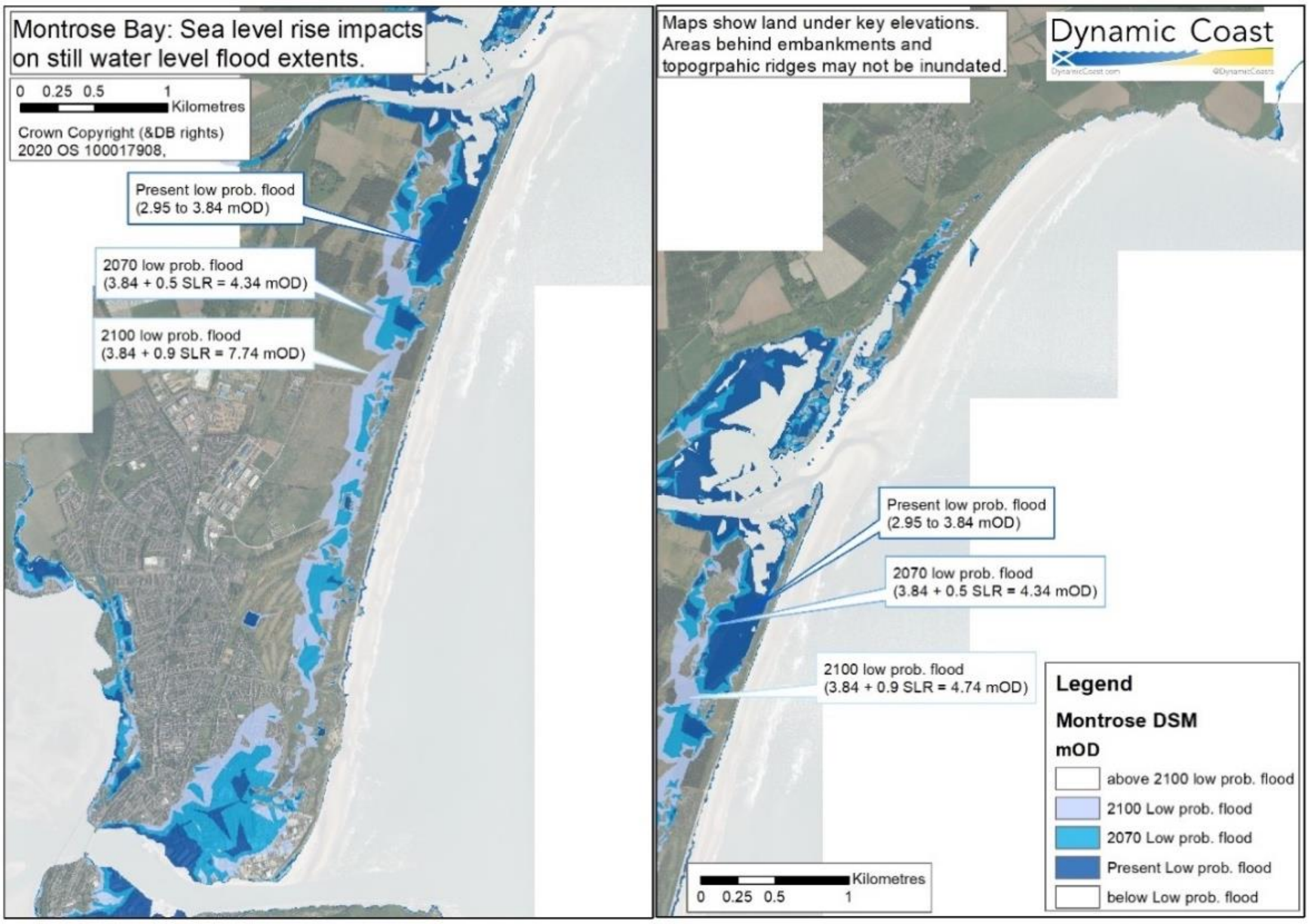


Figure 19 Present day flood extents and the future flood extents anticipated under UKCP18 RCP8.5 95% sea level rise by 2100

Figure 20 plots the key present day and anticipated water elevations for Montrose Bay. Mean High Water Springs reaches 2.25 mOD and if weather effects are excluded the highest astronomic tide (HAT) is expected to reach 2.95 mOD. SEPA anticipate the High Probability flood level to have a still water level of 3.34 mOD, this has a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 3.84 mOD, this has a 0.1% annual exceedance frequency, which is shown on Figure 17. If the effects of RSLR under RCP8.5 are applied to these levels, the High Probability flood still water level will increase to 4.24 mOD by 2100 and the Low Probability flood will increase to 4.74 mOD; respectively bringing them to 1.99 m and 2.49 m above the current MHWS level.

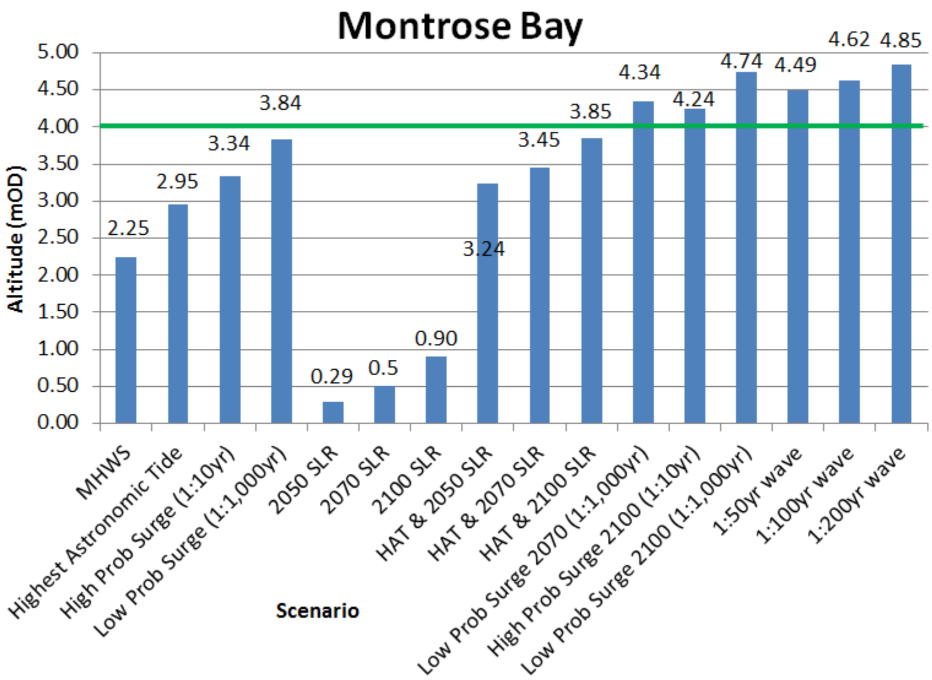


Figure 20 Summary of future key tide and flood levels at Montrose Bay. There are substantial areas of the dune interior across the bay below 4 mOD (annotated with green line)

Consideration of Wave Run-up and Other Dynamic Components

Dynamic Coast team liaised with SEPA and JBA (Dr D. Pender) to explore the extreme wave run-up calculations for Montrose. The Stockdon (2006) approach was used to consider the wave characteristics under three scenarios: present day, 2050s and 2080s. Three representative beach slope values were used resulting in the following levels.

Dynamic Coast and JBA conclude from Table 6 that 5 mOD represents an appropriate elevation that the highest waves may reach (2% of waves). Although the likelihood of this occurring at the present day is low, this will increase toward the end of the century. 5 mOD is used here as a time-averaged representative level where wave overtopping is possible for dune heights close to this value. If this occurs the areas of inundation are represented by the still water level (CFB) method used in SEPA's maps, discussed above.

The offshore wave climate at each super site was considered in the form of Cefas Wave Hindcast wave conditions modelled from WaveWatch III data for the period of 1980–2018. This time series was used at each super site as a direct input for the CoSMoS-COAST model to simulate wave-driven sediment processes and more accurately predict MHWS change in the future. At Montrose, the offshore wave conditions are modelled as a mean height of 0.59 m and mean direction of 90° from north across the entire series, which is transformed to nearshore conditions of a mean height of 0.40 m and a mean direction of coming from ENE (80° from north).

Table 6 Wave run up calculations for Montrose (Source: JBA)

Table A-1: Total Sea Level Results (including runup)

Return Period	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4
	Total Sea Level (mAOD)				R2% Values			
	Present Day				Present Day			
1yr	3.706	3.706	3.708	3.823	1.285	1.285	1.285	1.359
10yr	4.037	4.037	4.040	4.195	1.518	1.518	1.518	1.635
30yr	4.173	4.173	4.176	4.357	1.610	1.610	1.610	1.754
75yr	4.294	4.294	4.297	4.474	1.676	1.676	1.676	1.879
100yr	4.335	4.335	4.337	4.521	1.698	1.698	1.698	1.926
200yr	4.437	4.437	4.440	4.639	1.729	1.729	1.736	2.022
1000yr	4.654	4.654	4.654	4.905	1.815	1.815	1.816	2.243
	2050				2050			
1yr	3.921	3.921	3.923	4.038	1.294	1.294	1.294	1.368
10yr	4.253	4.253	4.255	4.412	1.528	1.528	1.529	1.644
30yr	4.390	4.390	4.393	4.576	1.621	1.621	1.622	1.769
75yr	4.510	4.510	4.517	4.699	1.686	1.686	1.686	1.893
100yr	4.550	4.550	4.554	4.741	1.708	1.708	1.709	1.935
200yr	4.653	4.653	4.653	4.859	1.746	1.746	1.747	2.039
1000yr	4.868	4.868	4.868	5.126	1.828	1.828	1.829	2.257
	2080				2080			
1yr	4.169	4.169	4.170	4.286	1.302	1.302	1.303	1.377
10yr	4.502	4.502	4.504	4.663	1.539	1.539	1.539	1.653
30yr	4.641	4.641	4.643	4.827	1.633	1.633	1.634	1.776
75yr	4.759	4.759	4.764	4.948	1.697	1.697	1.699	1.901
100yr	4.800	4.800	4.802	4.991	1.721	1.721	1.721	1.943
200yr	4.906	4.906	4.906	5.104	1.760	1.760	1.761	2.039
1000yr	5.114	5.114	5.114	5.381	1.841	1.841	1.843	2.273

Combined Erosion and Flooding

The automated terrain analysis (Figure 4, Figure 21) has identified key metrics which reflect the geometry of the dune ridge (i.e. the flood protection feature). The typical height of the southern part of the dune crest is ~9 mOD, rising to 14 mOD about 1.5 km north of Traill Drive. The interior of the dunes is lower with typical elevations between 4 mOD (occupied by the lower parts of Montrose Golf courses, Figure 3). Some of the former blow-outs (narrow corridors through the dunes) have minimum elevations below 4 mOD and may reflect the effect of the ground water table at these points (Figure 21). For the avoidance of doubt, given these elevations and the current flood heights, the present dune ridge at Montrose continues to provide an essential flood protection function to the low-lying interior of the dunes. It follows that if coastal erosion removes the low-lying entrances to any, or all, of these corridors then potentially large areas behind become accessed by marine flooding during storms.

Within the southern section of Montrose Bay, there are several former blow-out corridors that bisect the 100 m wide sand dune ridge and increase the potential for coastal flooding within the SEPA Potentially Vulnerable Area for flooding. The four northernmost blow-out corridors lie behind the rapidly retreating unprotected section of dunes in Area 2 shown in Figure 21. In the left-hand figure the low-lying dune interior is shown in red, orange and yellow (2–5 mOD), whilst areas above 5 mOD are shown in greens and greys. The potential flood corridors are shown on the right-hand side of Figure 21 as transect lines annotated with IDs and symbolised using the elevations from the left figure. The inset shows the dune profiles along these transects with areas of natural barrier features at 4–5 mOD in purple, 5–6 mOD in green, and areas above 6 mOD in yellow (i.e. low, medium and high flood elevations). If storm wave runup reaches 5mOD then overwash may allow marine water to access the dune hinterland and simultaneously may enlarge and lower the elevation accessed by waves. It also follows that ongoing coastal erosion progressively reduces the volume and height of the frontal dunes that serve to plug the low entrances to the corridors and, over the short-term, will allow marine access at progressively lower storm wave run-ups.

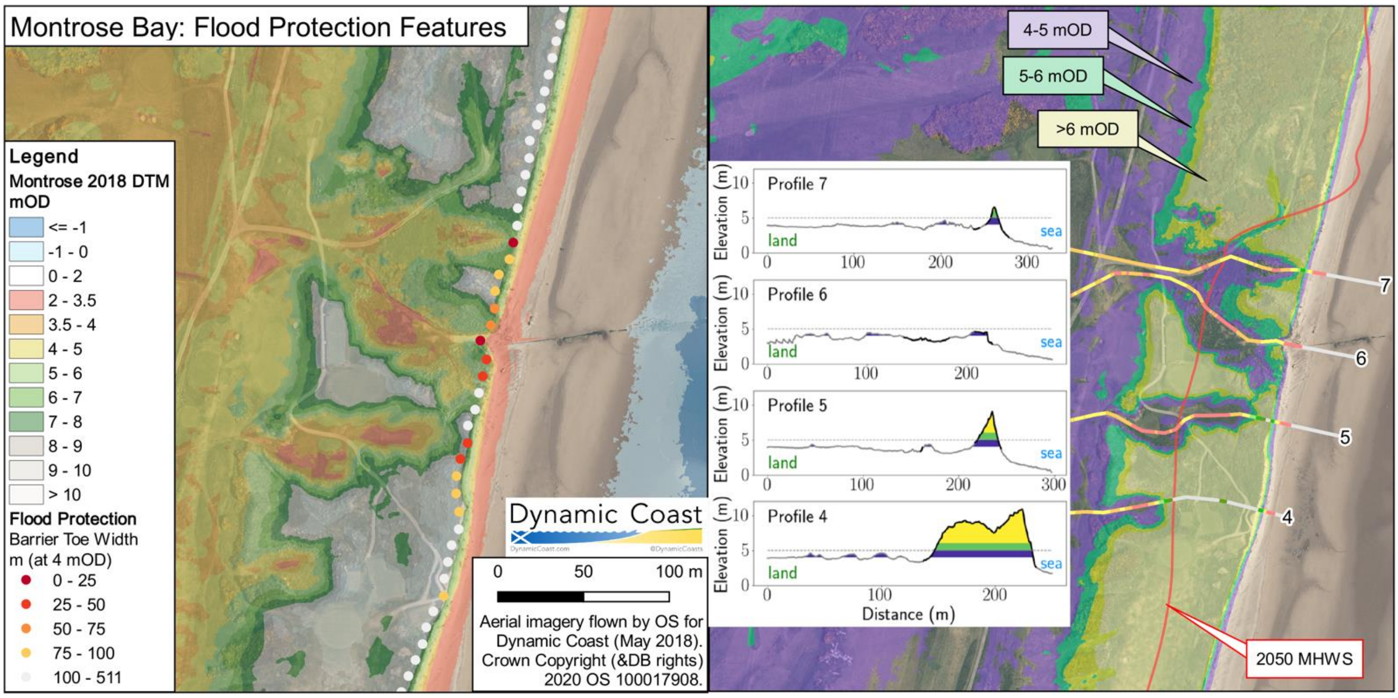


Figure 21 Identification of flood corridors within the southern section of dunes.

Figure 22 forms the basis for short-term management measures aimed at raising the dune crest levels above critical flood levels and corridor infilling, both of which avoid the risk of impacting on adjacent coastal processes, a key drawback with structural interventions. Figure 22 depicts a three-phase approach to such topographic infill of the dune cordon: short term infill of the frontal dune ridge requires only 4,370 m3 but may last only a few years, medium term infill requires about 10,980 m3 lasting longer, whilst a longer-term infill of the entire corridor areas requires 37,810 m3 and will last as long as the rest of the dune cordon. This last option reinstates the full dune cordon topography but will continue to be subject to erosion as before. However, it buys time to develop other adaptational approaches. The availability of suitable infill material is a risk to this approach, which in the short-term may necessitate using sand from the back-dunes in the north of Area 2 or in Area 3 where these provide a higher and wider dune ridge.

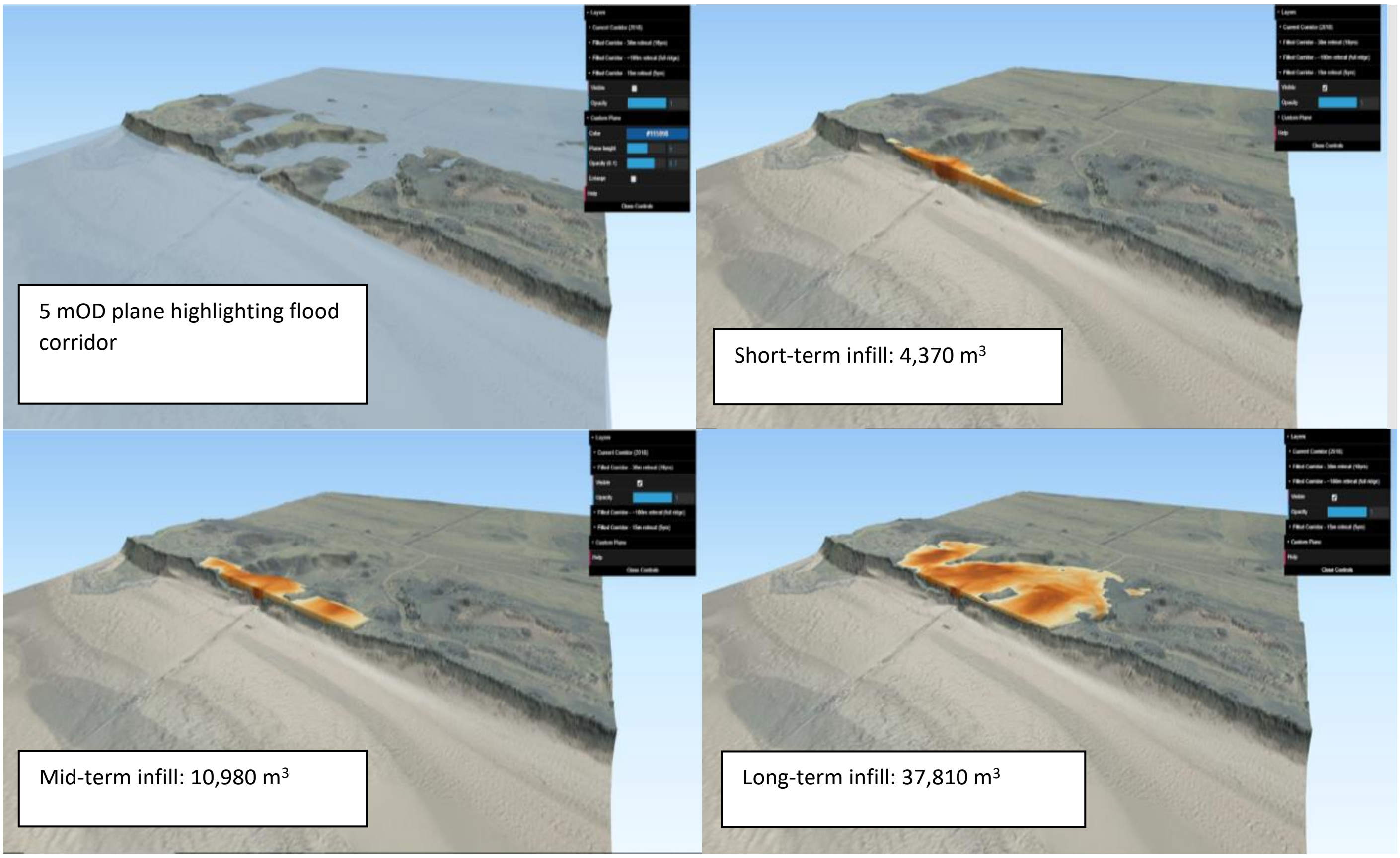


Figure 22 Sediment infill and dune reprofiling options within the southern section of Montrose dunes (NOTE: short, mid and long term options could be enacted immediately).

Table 7 provides a guideline on 'life expectancies' for the plotted blow-out corridors using Vegetation Edge retreat rates. Vegetation Edge retreat rates vary both spatially and temporally across Montrose (Figure 8, Figure 9). This can be demonstrated using a locally representative cross section, although in other areas the rates of change may be slightly slower. As a result, Table 7 should be regarded with caution and is presented here to provide an order of magnitude of 'life expectancy' for sections of the dune cordon; but it suggests it may be as limited as ca. 2047. This compares with a comparable figure of ca. 2060 based on a comparison of the anticipated Vegetation Edge (

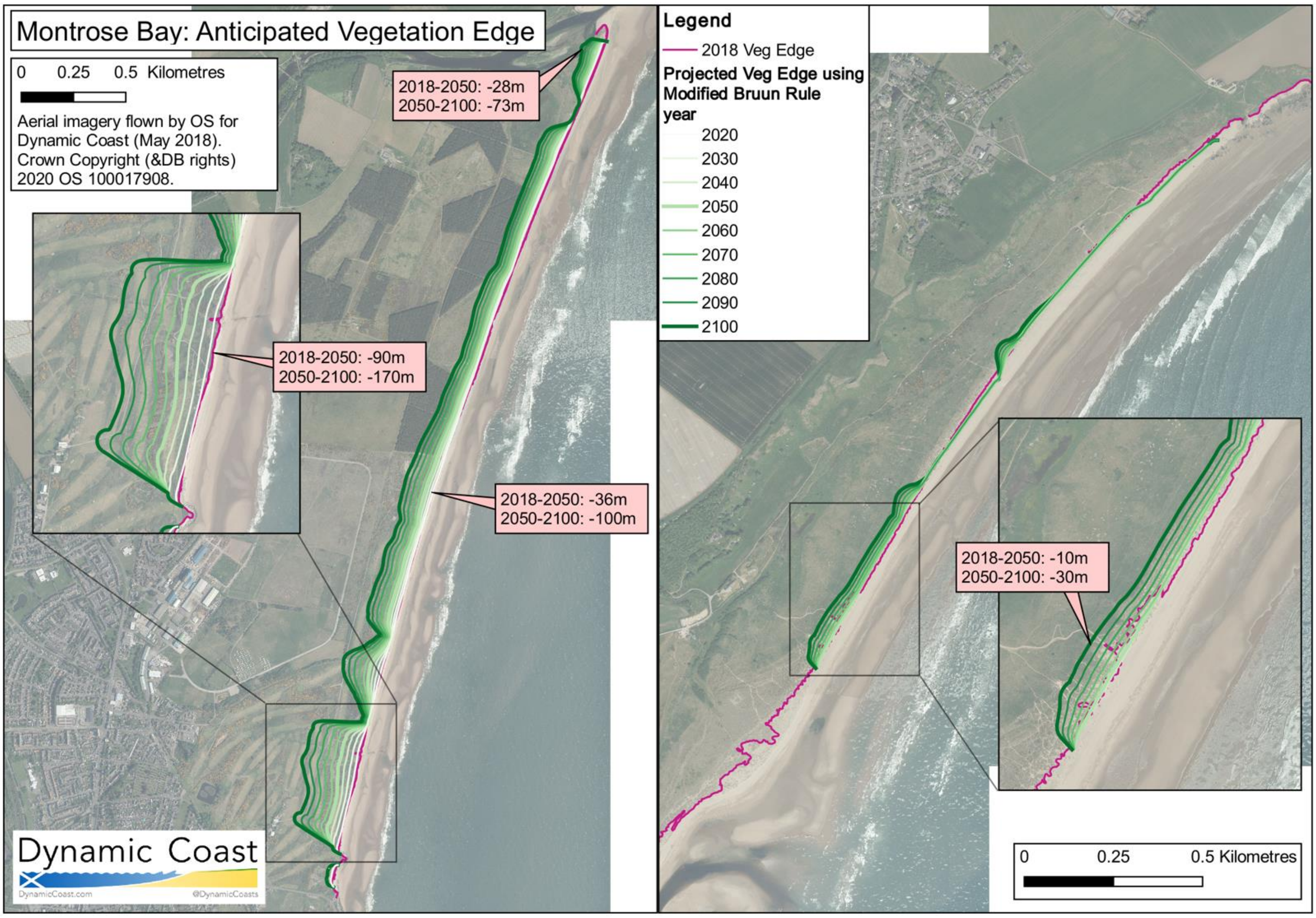
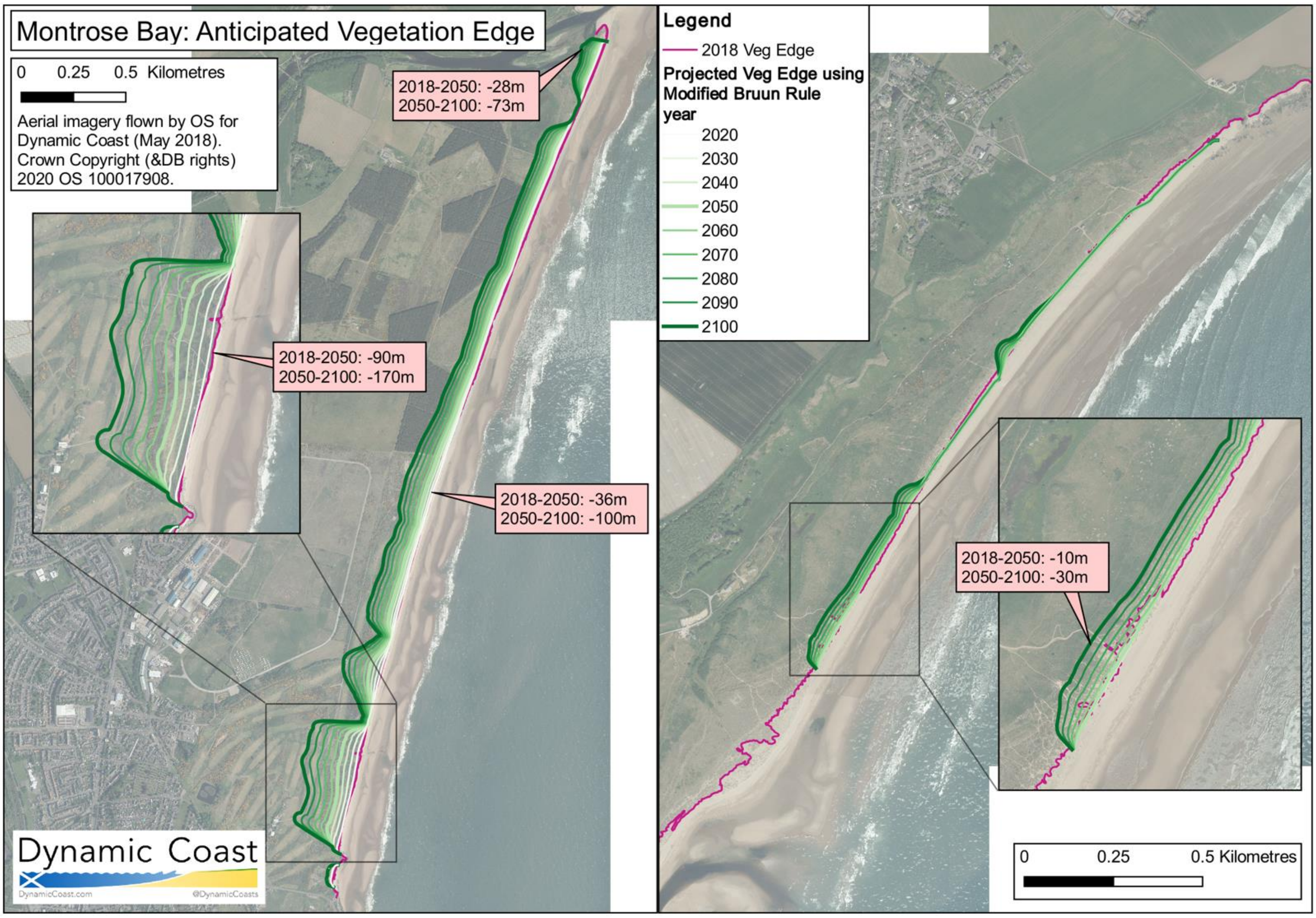


Figure 13) compared with the topography (Figure 22). Thus, a continuance of existing rates or modelled erosion suggests that large sections of the dune ridge will be breached within three or four decades is a realistic future, based on a 'do nothing scenario'.



Repeated here for ease of reading: Figure 13 Anticipated coastal change – Modified Bruun Rule Vegetation Edge

	Nominal cross section in south		Average rate in southern section	
	Rate or retreat (m/yr)	'Life expectancy' (yrs after 2019)	Rate or retreat (m/yr)	'Life expectancy' (yrs after 2019)
Minimum	1.5	75	1	110
Average	2.6	43	1.5	71
Maximum	4.1	27	2.5	44

Table 7 Nominal vegetation edge retreat rate within southern section of bay with estimated 'life expectancy' based on dune width.

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