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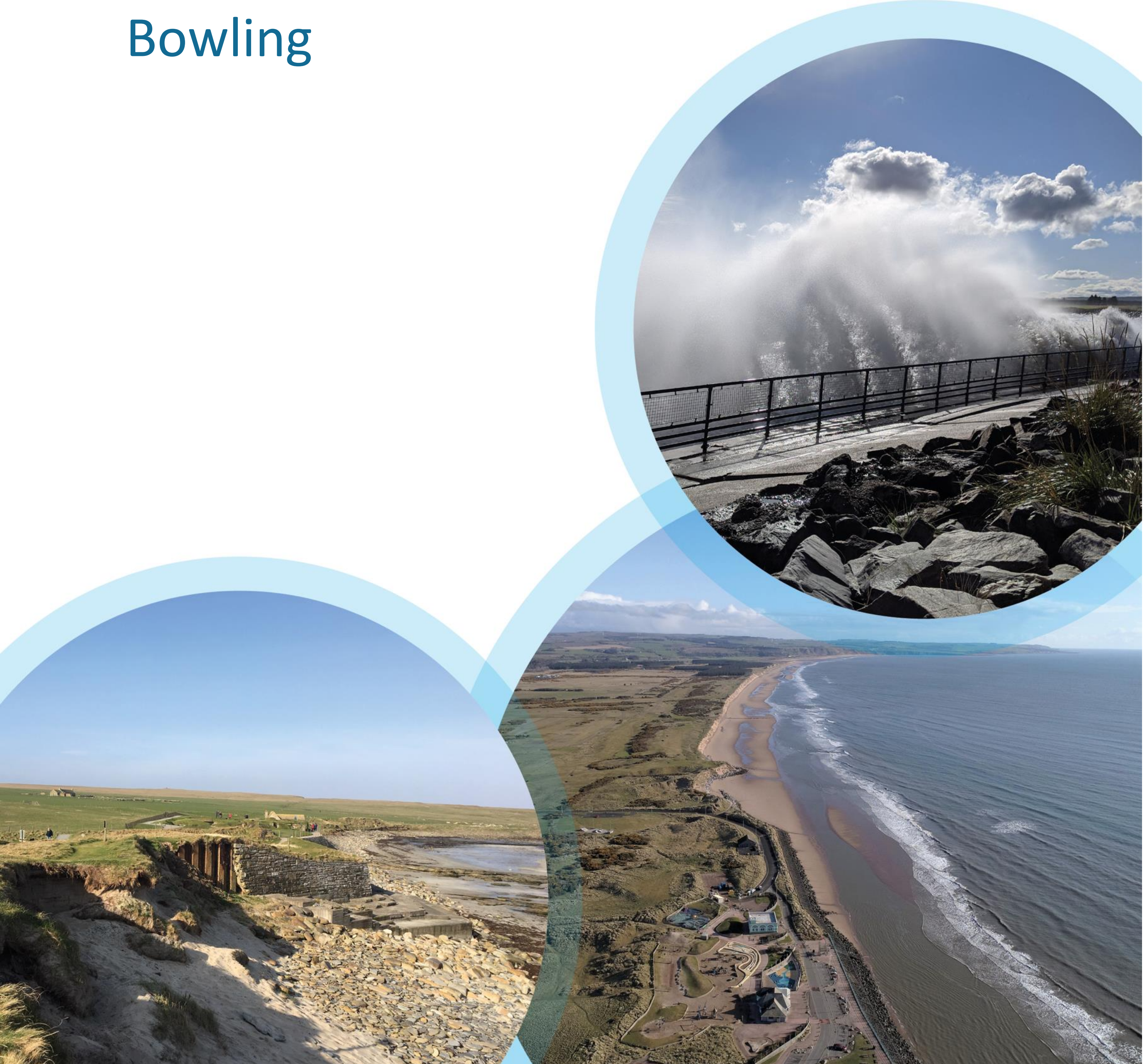
Dynamic Coast

Adaptation and Resilience Options for Dumbarton to Bowling



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Adaptation and Resilience Options for Dumbarton to Bowling

L.A. Naylor, R.A. Dunkley, D. Mitchell, F.M.E. Muir, A.F. Rennie, J.D. Hanson, & M.D. Hurst

CREW CENTRE OF EXPERTISE FOR WATERS

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Authors: L.A. Naylor, R.A. Dunkley, D. Mitchell, F.M.E. Muir, A.F. Rennie, J.D. Hansom, M.D. Hurst

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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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Contents

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 West Dunbartonshire Council (WDC), Scottish Environmental Protection Agency (SEPA), NatureScot and local partners including the Clyde Marine Planning Partnership.

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 at www.DynamicCoast.com.

Acknowledgements

Fiona Mills, Clyde Marine Planning Partnership; Seb Hudson, West Dunbartonshire Council; Nick Everett, NatureScot.

Dumbarton Super Site Summary

Introduction

This report sets out to establish changes to the Dumbarton coast (West Dunbartonshire) and identify adaptation options to enhance its future resilience. Its scope covers the coastal environment of West Dumbarton from Dumbarton Castle, and the mouth of the River Leven, east to Bowling Harbour. This document aims to support key partners in their planning for anticipated increases in coastal erosion and flood risk. The Executive Summary and Technical Annex below are not intended to be precise predictions of a certain future, rather they are scenarios based on a realistic and precautionary interpretation of available evidence. As such the details within should not be interpreted as management decisions in themselves, but supplementary evidence on which government agencies, organizations and landowners may choose to deliver against statutory requirements.

The National Coastal Context

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

The latest research (Dynamic Coast Phase 2) incorporates new tidal surveys and shows that erosion is currently affecting more shores than was the case in 2017 and anticipates that by 2100 accretion will be rare and erosion will dominate much of the soft coast. These projections are based on the high emissions sea level rise scenario and anticipate over 1/3 of Scotland's soft coast will be eroding at greater than 1 m/yr by the end of the century. The increased threat of coastal erosion also increases the risk of coastal flooding; this means that planning ahead for coastal change, both inland and at the shoreline, is both pragmatic and necessary.

Local Coastal Context and Anticipated Change at Dumbarton

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

Notwithstanding the national context of rising sea level and any anticipated acceleration in sea level, the local context of Dumbarton is that of a heavily human modified landscape. These human impacts on the mudflats and saltmarsh of the Dumbarton shore are two-fold: 1) the impact of long-standing maintenance dredging of the River Clyde channel and 2) the equally long-standing legacy of land claim mainly to the rear of the fringing saltmarsh. In some areas such as between Dunglass and Bowling, land claim has moved the now defended shore to the main Clyde navigation channel itself, resulting in wholesale loss of saltmarsh and mudflat along this stretch. These impacts have reduced saltmarsh extents by reducing the supply of sediments from the seaward direction and by land claim encroaching from the landward direction. The measured changes in saltmarsh extent detailed below mainly focus on the seaward extents (human impact 1 above), where the largest amount of change is generally seen along the saltmarsh edge from Dumbarton Bay to Bowling, with much of the MLWS seeing historic recession of greater than 100m in the west, but declining to the east where some accretion has occurred. The situation with MHWS is more variable with the current mean MHWS recession rate at 0.5 m/yr and, localised pockets of lateral accretion of up to 25 m, as well as other areas where accretion is a function of land claim. Recent topographic change analysis shows sediment loss dominates the marsh foreshore, with a total 14,200 m^3 of sediment lost over the last 15 years across both the mudflat and saltmarsh surfaces, with only minor accretion on the upper saltmarsh in the east. In response vegetation edges have fluctuated between erosion and accretion over the last century, with an overall trend of erosion in the west and accretion in the east over the last decade and a mean change rate of +7 cm/yr. It is also worth noting that, with the exception of a short stretch of artificial coastal defence structure at Dumbarton Castle in the west and between Dunglass and Bowling in the east, no formal erosion or flood defence structures exist. At present, the only coastal protection barrier to any future erosion or flooding is the undefended track bed of the Glasgow to Helensburgh/Fort William mainline railway. SEPA identifies much of the land on the estuary side of the railway line between Dumbarton to Bowling to be currently at medium or high flood risk from marine flooding (with a smaller, but still significant area, at risk of river flooding.) The coastal flood risk will increase onto the future with sea level rise. Since coastal erosion and flooding are inextricably linked, then management options to accommodate flooding such as land raising may be untenable since land raising does not address erosion (i.e. the raised land is still at risk of erosion) and it would be difficult to demonstrate no adverse impact on adjacent sections of land due to displaced water volumes. This effectively means that the most resilient option to manage both flood and erosion risks, both now and in the future, is to make space on land for the coast to realign landward. Safeguarding land now (i.e. through strategic planning and/or for existing development planning decisions, using both current and future risks to underpin statutory consultations) will provide the most flexibility and options for climate resilient development pathways.

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. 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 Montrose Bay, 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 (National Overview Report www.DynamicCoast.com/reports.html). For example, in Scotland the emerging Clyde Marine Planning Policy provides an example of best practice at the coast to support transformative forms of adaptation where possible. 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.

Coastal erosion, flooding and erosion-related flooding are considered the key risks impacting the Dumbarton shore now and in the future. Landowners and local authorities have responsibility for, and powers to address, coastal erosion and flooding. Local authorities also have shared powers under the Flood Risk Management (Scotland) Act 2009 and the Climate Change (Scotland) Act 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, Figure 2 and Table 1 sub-divide the Dumbarton shore into management unit areas to identify coastal erosion and flood 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 Dumbarton will have differing impacts on sediment dynamics, beach function and the natural capital that beach, saltmarsh and mudflat 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. For example, other than at Dumbarton Castle in the west and at Dunglass to Bowling in the east, no formal coastal or flood protection structures exist to limit the inland extent of any present or future erosion or flooding. The trackbed of the main Glasgow to Helensburgh main line has not been constructed as a flood or erosion defence. In addition, much of the Dumbarton shore is urban or industrial and at these points and elsewhere, lowering of the mudflat surface and retreat of the saltmarsh edge has weakened the natural capital and natural erosion protection afforded by both saltmarsh and mudflat, and action may be required to help 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 allow time for any physical and policy space needed on land for the shore to realign landwards in the future to be provided. This may include action to offset any negative (erosional) impact on the mudflat sediment budget caused by dredging in the main Clyde channel, perhaps by returning a proportion of the dredged sediment back to the upper mudflat and saltmarsh areas. Retaining dredging volumes that would otherwise be lost to the local system would allow the mudflat and saltmarsh to remain stable for longer, partially offsetting the impact of sea level rise and provide time for other land-based adaptation options to be considered. This approach would also allow the estuary to function more naturally. For example, improved salt marsh function would dissipate storm surge and sea level effects, and thus help protect up-river areas of Glasgow from flooding. In terms of the natural functioning of mudflats and saltmarsh, it is clear that the width of these landforms plays an important role in mitigating the local impact of wave attenuation during storm events. Such landforms are at the 'frontline' of impacts from storms and sea level rise; a consistent sediment supply is needed to help these landforms 'keep up' with sea-level rise. In particular, saltmarsh vegetation plays a key role in wave attenuation: wider saltmarshes reduce wave activity so that a lower and narrower artificial barrier may be needed at the landward limit. This has significant cost savings for coastal protection as well as biodiversity and social amenity benefits. It is currently understood that Peel Ports who dredge the Clyde channel are considering the disposal of some dredged sediment to beneficially recharge some areas of the intertidal, with the mudflat area south of Langdyke, on the south side of the channel opposite the Dunglass basin being a site under consideration. Retaining some or all dredging volumes within the estuary will work with nature and allow the estuary to partially offset the impact of sea level rise; however, a double win-win situation would be achieved if any dredging recycling was placed along the Dumbarton to Bowling side of the river. Dredging recycling thus has the potential to enhance natural estuarine functioning, improve natural coastal protection, and save money in the long run. This is especially valuable when placed in built-up areas at risk of erosion and/or where loss of existing saltmarsh can be mitigated

Additional options inland may include providing space for relocation of at-risk assets to inland risk-free sites, but also allow space for accommodating mudflat and saltmarsh to locate 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. There is thus a need for land-based strategic plans to account for these future risks in today's planning (e.g. Local Development Plans), creating and safeguarding 'windows of opportunity' for future adaptation to occur with minimal societal impact and cost. These concepts are acknowledged within the National Planning Framework 4 and National Land Use Strategy and can be applied as part of local scale statutory development planning as well as multi-scale governance actions such as coordinated, strategic planning to make space on land to adapt essential linear infrastructure of national importance (e.g. rail, road and utility networks) by accommodating erosion.

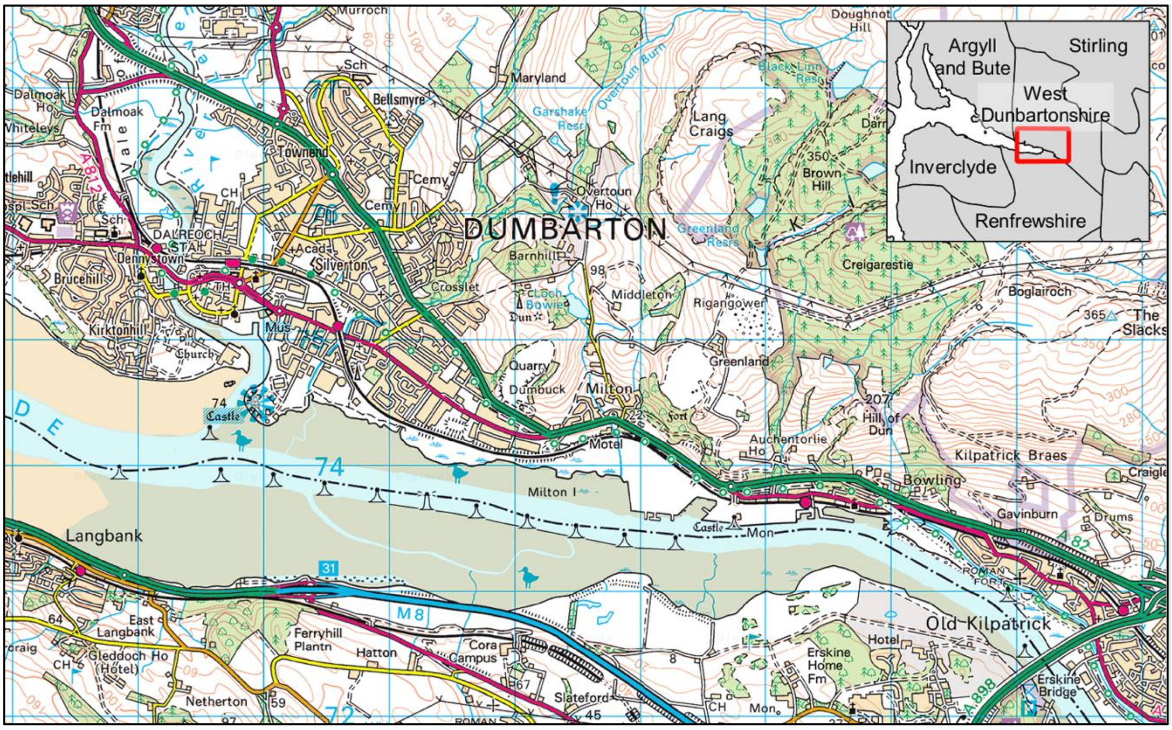

Figure 1 OS Location map of Dumbarton to Bowling. Grid squares are Easting and Northing of size 1 km x 1 km. Crown copyright and database rights OS 2020 100017908.

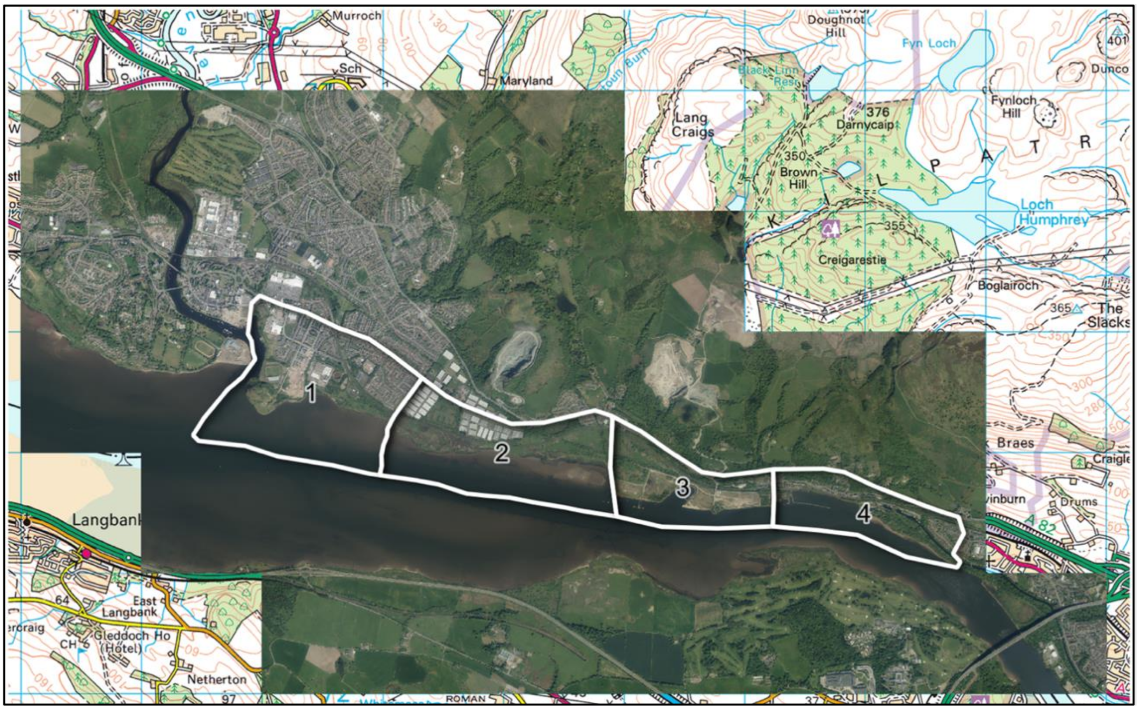

Figure 2 Management unit areas for Resilience and Adaptation Options. Labelling relates to options in Table 2.

Resilience and Adaptation Options at Dumbarton

Table 1 outlines the management options recommended, alongside dynamic adaptational land-use planning aspects inland.

Table 1 Risk management, Resilience and Adaptation Options for Dumbarton to Bowling. Sections are grouped by management unit area, past and anticipated changes alongside 'do nothing' implications. Short and Longer-term options are outlined.

Area	Shore Character & Assets	Coastal Changes*	'Do nothing' – Likely Implications**	'Short term' management options (to improve short-term resilience)	'Long term' management options (to improve long-term resilience)
1. Dumbarton Castle and town 	Dumbarton Castle rock framed by estuary mudflats and saltmarsh. Seawall along eastern Castlegate Gardens, rising made ground landward with industrial estate, gas and sewage works, housing and rail embankment (not seawall) A814runs coast parallel inland.	<u>Low Water</u> 1896-1994: -105 m 1994-2016: 14 m <u>High Water</u> 1896-1994: -72 m 1994-2003: 45 m 2003-2018: -33 m <u>Volume</u> Landward marsh 2003–2018: 0.6 m raising Seaward sediment 2003–2018: 1.0 m lowering <u>Vegetation Edge</u> 2010-2018: -11 m	Foreshore lowering, retreat of soft shorelines. Marshland vegetation retreat/erosion and flooding of low-lying land. Potential saline intrusion into wastewater treatment works.	<u>**Non-Active Intervention:**</u> 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leads to incremental loss of land. Impact on essential infrastructure (gas/sewers, railway line) and built assets (housing, warehouses). Cost: moderate; Risk: high. <u>**Accommodate Erosion**</u>**:** 2. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing defendant on locally defined trigger points, safeguard space on land for options. 3. **Avoid new permanent development** in areas of current or future risk (avoid replacing warehouses with housing: land raising only alleviates flooding not erosion). 4. **Proactive habitat management planning**: Provide accommodation space on current land areas for key marine (e.g. SPA) habitats. <u>**Erosion Resist:**</u> 5. **Saltmarsh restoration:** nature-based approaches to improve the resilience of existing saltmarshes, eg recycling dredge material on mudflat would assist saltmarsh resilience. 6. **Enhance /extend defences (0–20 yrs):** Structural defences (boulder revetement) extended to alleviate erosion and erosion-related flood risk. 7. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used, potential use of recycled dredge sediment.	**In addition to continued deployment of short-term options:** <u>**Non-Active Intervention:**</u> 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leads to incremental loss of land. Impact on essential infrastructure (gas/sewers, railway line) and built assets (housing, warehouses). Cost: moderate; Risk: high. <u>**Accommodate Erosion**</u>**:** 2. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing defendant on locally defined trigger points, safeguard space on land for options 3. **Avoid new permanent development** in areas of current or future risk (avoid replacing warehouses with housing: land raising only alleviates flooding not erosion). 4. **Proactive habitat management planning**: Provide accommodation space on current land areas for key marine (e.g. SPA) habitats. <u>**Erosion Resist:**</u> 5. **Saltmarsh restoration:** nature-based approaches to improve the resilience of existing saltmarshes, eg recycling dredge material on mudflat would assist saltmarsh resilience. 6. **Enhance /extend defences (2050): Structural** defences (seawall, boulder revetement) extended to arrest erosion and erosion-related flood risk. 7. **New defences (20-50 yrs):** Structural defences (seawall, boulder revetement) extended to arrest erosion and erosion-related flood risk to defend key infrastructure. 8. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used, potential use of recycled dredge sediment.

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)
2. Milton Bay area 	Mudflats and saltmarsh edge fronting low-lying grassland. Industrial estate, rail line on raised ground, A82 and A814 running along back edge.	<u>Low Water</u> 1896-1994: -136 m 1994-2016: 6 m <u>High Water</u> 1896-1994: 115 m 1994-2003: 80 m 2003-2018: -7 m <u>Volume</u> Landward marsh 2003–2018: 1.1 m raising Seaward sediment 2003–2018: 0.7 m lowering <u>Vegetation Edge</u> 2010-2018: 8 m	Foreshore lowering, retreat of soft shorelines from erosion. Marshland vegetation retreat, and flooding of low-lying land and landward encroachment of saline conditions (e.g. saltmarsh plants already growing on the landward side of the raised railway line).	<u>**Non-Active Intervention:**</u> <u>**Non-Active Intervention:**</u> 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leads to incremental loss of land. Impact on essential infrastructure (gas/sewers, railway line) and built assets (housing, warehouses). Cost: moderate; Risk: high. <u>**Accommodate Erosion**</u>**:** 2. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing defendant on locally defined trigger points, safeguard space on land for options 3. **Avoid new permanent development** in areas of current or future risk (avoid replacing warehouses with housing: land raising only alleviates flooding not erosion). 4. **Proactive habitat management planning**: Provide accommodation space on current land areas for key marine (e.g. SPA) habitats. <u>**Erosion Resist:**</u> 5. **Saltmarsh restoration:** nature-based approaches to improve the resilience of existing saltmarshes , eg recycling dredge material on mudflat would assist saltmarsh resilience. 6. **New defences (0-20 yrs):** Structural defences (boulder revetment, seawall) for key infrastructure that are not currently protected (railway), increase standard of erosion and erosion-related flood risk. 7. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used, potential use of recycled dredge sediment.	**In addition to continued deployment of short-term options:** <u>**Non-Active Intervention:**</u> 1. **Monitor change/no intervention (now onwards):** Undermine and eventual breach of defences leading to a phased incremental loss of reclaimed land. Impact on assets and related infrastructure (warehouses. railway). Cost: moderate; Risk: high. <u>**Accommodate Erosion**</u>**:** 2. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing defendant on locally defined trigger points, safeguard space on land for options 3. **Avoid new permanent development** in areas of current or future risk (avoid replacing warehouses with housing: land raising only alleviates flooding not erosion). 4. **Proactive habitat management planning**: Provide accommodation space on current land areas for key marine (e.g. SPA) habitats. <u>**Erosion Resist:**</u> 5. **Saltmarsh restoration:** nature-based approaches to improve the resilience of existing saltmarshes, eg recycling dredge material on mudflat would assist saltmarsh resilience. 6. **New defences (2050):** Structural defences (boulder revetment, seawall) for key infrastructure that are not currently protected (railway), increase standard of erosion and erosion-related flood risk. 7. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used, potential use of recycled dredge sediment.

Area	Shore Character & Assets	Coastal Changes*	'Do nothing' – Likely Implications**	'Short term' management options (to improve short-term resilience)	'Long term' management options (to improve long-term resilience)
3. Dunglass Basin and Castle 	Concrete harbour front created around made ground of previous petrochemical site, now barren with some trees, and meadow with cycle path behind. Railway line and A82 frame back edge.	Low Water 1896-1994: -53 m 1994-2016: - 48 m High Water 1896-1994: +300 m (made ground) 1994-2003: -10 m 2003-2018: -22 m Volume N/A Vegetation Edge 2010-2018: 0 m	Foreshore lowering on defended shore. Defences weakened and undermined. Increase in flood and spray risk	**Non-Active Intervention:** 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leads to incremental loss of land, some potentially contaminated. Impact on essential infrastructure (gas/sewers, railway line) and built assets (housing, warehouses). Cost: moderate; Risk: high. **Accommodate Erosion:** 2. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing defendant on locally defined trigger points, safeguard space on land for options 3. **Avoid new permanent development** in areas of current or future risk. For example, avoid placing permanent assets in areas at risk of erosion and flooding (planned for the Esso Site and Scott's Yard). 4. **Proactive habitat management planning**: Provide accommodation space on current land areas for key marine (e.g. SPA) habitats. **Erosion Resist:** 5. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used. 6. **Enhance /extend defences (0–20 yrs):** Direct defences (. sea walls) extended to alleviate erosion, flooding and erosion-related flood risks. **Advance:** 7. **Basin infill:** infilling basins, possibly using dredge material to move erosion resist line to the main channel. If proceeds, only temporary/demountable development on claimed land should be permitted.	**In addition to continued deployment of short-term options:** **Non-Active Intervention:** 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leads to incremental loss of land, some potentially contaminated. Impact on essential infrastructure (gas/sewers, railway line) and built assets (housing, warehouses). Cost: moderate; Risk: high. **Accommodate Erosion:** 2. **Develop Dynamic Adaptive Policy Pathway:** Enable existing assets to be adapted / relocated if present location is exposed to erosion/flood risk. Timing defendant on locally defined trigger points, safeguard space on land for options 3. **Avoid new permanent development** in areas of current or future risk. For example, avoid placing permanent assets in areas at risk of erosion and flooding (planned for the Esso Site and Scott's Yard). 4. **Proactive habitat management planning**: Provide accommodation space on current land areas for key marine (e.g. SPA) habitats. **Erosion Resist:** 5. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used. 6. **Enhance /extend defences (0–20 yrs):** Direct defences (. sea walls) extended to alleviate erosion, flooding and erosion-related flood risks. **Advance:** 7. **Basin infill:** infilling basins, possibly using dredge material to move erosion resist line to the main channel. If proceeds, only temporary/demountable development on claimed land should be permitted.
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)**

4. Bowling Harbour area 	Some mudflats within intertidal of Bowling Harbour, enclosed by Frisky Wharf. Canal runs ENW-ESE with a sandy shore and woodland on the south side. A82, A814 and railway run closely together.	<u>Low Water</u> 1896-1994: 3 m 1994-2016: 48 m <u>High Water</u> 1896-1994: -44 m 1994-2003: -22 m 2003-2018: -10 m <u>Volume</u> N/A <u>Vegetation Edge</u> 2010-2018: -6 m	Foreshore lowering, retreat of soft shorelines and vegetation. Defences weak along railway line (not erosion sea wall)	**<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leading to incremental loss of land. Assets and related infrastructure impacts (e.g. warehouses, rail track). Cost: moderate; Risk: high. **<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 dependent on locally defined trigger points, safeguard space on land for increased options 3. **Avoid new permanent development** in areas of current or future risk (e.g. avoid replacing warehouses with housing, as land raising will not alleviate erosion, it only helps accommodate flooding). 4. **Proactive habitat management planning**: Provide accommodation space for key marine (e.g. SPA) habitats. **<u>Erosion Resist:</u>** 5. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used. 6. **Enhance /extend defences (0–20 yrs):** Direct defences (sea walls) extended to alleviate erosion, flooding and erosion-related flood risk. **<u>Advance:</u>** 7. **Basin infill:** infilling basins, possibly using dredge material to move erosion resist line to the main channel. If proceeds, only temporary/demountable development on claimed land should be permitted.	**In addition to continued deployment of short-term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention (now onwards):** Undermine and breach of defences leading to incremental loss of land. Assets and related infrastructure impacts (e.g. warehouses, rail track). Cost: moderate; Risk: high. **<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 dependent on locally defined trigger points, safeguard space on land for increased options 3. **Avoid new permanent development** in areas of current or future risk (e.g. avoid replacing warehouses with housing, as land raising will not alleviate erosion, it only helps accommodate flooding). 4. **Proactive habitat management planning**: Provide accommodation space for key marine (e.g. SPA) habitats. **<u>Erosion Resist:</u>** 5. **Nature-based erosion resist options preferable,** hybrid or green grey options recommended (ecological benefits) where conventional engineering is used. 6. **Enhance /extend defences (0–20 yrs):** Direct defences (sea walls) extended to alleviate erosion, flooding and erosion-related flood risks **<u>Advance:</u>** **Basin infill:** infilling basins, possibly using dredge material to move erosion resist line to the main channel. If proceeds, only temporary/demountable development on claimed land should be permitted.

This section briefly expands the key points for each area and management option in Table 1. If **Non-Active Intervention** (NAI) is the preferred policy option along the Dumbarton Coast, then saltmarsh erosion or foreshore lowering will continue to occur, as well as undermining and eventual breach of defences, leading to an incremental loss of (claimed) land and impacts on existing assets and related infrastructure (e.g. warehouses. railway) as well as on any planned new assets. No areas within the Dumbarton Coast area have short-term options to **Advance** the current coastal position (i.e. offshore traditional engineering structures); such short-term measures are unsuitable for an estuarine and navigable river. Some **erosion resist** measures (nature-based and conventional engineering) may be appropriate for specific areas (Table 1) and are summarised below. Erosion risks for the Dumbarton Coast were derived from a combination of DC2 data and modelling outputs as well as scenarios generated by the Urban Coastal Erosion Susceptibility Model (U-CESM) (Fitton et al (2015) A national coastal erosion susceptibility model for Scotland, link). However, the Dumbarton Coast differs from other Dynamic Coast Adaptation and Resilience Plan reports since it is largely composed of artificial made ground (23 hectares historically claimed from the sea) and now occupied by industrial and urban land use protected by hard structures. Wherever possible, nature-based **erosion resist** options (e.g. saltmarsh restoration) are preferable and where conventional engineering is used, hybrid or green grey options are recommended to improve ecological and multifunctional benefits (Naylor, et al., 2017). The positioning of any new or enhanced **erosion resist** defences may have long-term impacts on the resilience of the internationally designated saltmarshes in front; this natural capital also currently provides flood and erosion risk alleviation to the railway and other assets behind it. We recommend that impacts on natural capital that arise from new or replacement **Erosion Resist** measures are carefully considered in line with the forthcoming Statutory Marine Plan. Where **Erosion Resist** options are used to protect future planned assets, such protection will need to be maintained and improved indefinitely to cope with quickening landward erosion and sea level change.

Importantly, in all areas where NAI or **erosion resist** measures are implemented in the short and long-term, it is recommended that land-based policies are adapted now to **accommodate erosion** by restricting future new development in areas anticipated to be at risk from erosion and or erosion-induced flooding by 2100 (e.g. permanent infrastructure, rerouting of key roads, housing or industry/commercial development, development planned for the old ExxonMobil site). Such a proactive accommodate erosion approach to land-based strategic planning and investment avoids societal ‘lock-ins’ by minimising the amount of permanent development in areas of current and future risk. In areas at risk of erosion, it allows policy development to provide ‘accommodation space’ for landward relocation of key infrastructure such as roads and utilities, although short-term economic benefit might come from permitting temporary and demountable development in at risk areas. It also allows space and time for the saltmarsh-mudflat ecosystems to respond naturally to sea level rise and provide added protection to the land (Barbier, et al., 2011).

The Dumbarton shore is primarily a naturally low-lying, soft sediment estuarine coast with a large area (23 hectares) of artificial made ground. As a result, the risks and management options are broadly similar across **Areas 1–4, although Areas 1, 2 and 4** have the greatest amount of existing housing, commercial space or utility (e.g. sewage and gas works) assets at risk. Proactive planning, finance mechanisms and community engagement are key to enable landward realignment of assets in advance of costly repairs and/or replacement of erosion resist measures. However, in all areas, and in locations anticipated to be at risk of future erosion, LA regeneration plans are currently under consideration by the LA. Given the footprint overlap between areas anticipated to be at future risk and current development plans, we suggest that revisions to development plans should be revisited in light of the data presented here and the Glasgow City Region's Climate Change Adaptation Plan, both aimed at securing the resilience of key infrastructure assets, housing and economic regeneration for the Dumbarton coast corridor.

In **Areas 1–4**, safeguarding space for potential future realignment of nationally important assets (E.g. railway line) through climate resilient, future-smart, intergenerational dynamic adaptation pathway planning now, increases the range of options for future generations to manage erosion and flood risks. For example, using land raising to allow development will offset flood risk but does not remove erosion risk. Two **Accommodate Erosion** scenarios have been developed (Figures 17-19) to identify zones where an adaptation approach would be beneficial as well as saving money with reduced compulsory purchase and relocation of assets. To buy time whilst **accommodate erosion** measures are being identified and implemented, nature-based **erosion resist** measures are recommended in **Areas 1–4** (see Table 2 for details of the areas).

Area-specific Recommendations

Area 1 Dumbarton Castle and town (along with **Area 4, Bowling Harbour area**) is at risk of continued foreshore lowering and landward retreat of soft sediment coastal habitats (internationally designated mudflats and saltmarshes), leading to vegetation retreat, flooding of low-lying land and landward encroachment of saline conditions. It is the most heavily developed of the Dumbarton coast with a combination of housing and critical local infrastructure (e.g. utility installations (sewage, water, electricity, roads) and national infrastructure (mainline railway and gas network). Area 1 has also been subject to recent land raising for housing to accommodate flood risk, but bot erosion risk. Urgent **accommodate erosion** policies are recommended in Area 1 to allow realignment of critical infrastructure. Use of recycled dredge sediments may profitably be used to replenish mudflat and saltmarsh in this area.

Area 2 (Milton Bay Area) has similar erosion risks and adaptation recommendations to **Area 1** but with large warehouse areas and fewer houses. However, the mainline railway, A82 and A814 lie along at the landward edge of Area 2. Area 2 has a mix of artificial made ground and natural ground that would allow more space to accommodate erosion and natural coastal realignment along the mainline railway on sea level rise. Saltmarsh species are already present landward of the railway line, indicating saltwater ingress inland of the railway at present. If relocation of the mainline railway line does not occur then conventional or hybrid erosion resist measures will be required immediately seaward of the at-risk assets. Use of recycled dredge sediments may profitably be used to replenish mudflat and saltmarsh in this area.

Area 3 Dunglass Basin and Castle is at risk of foreshore lowering and erosion-related flood risk along the currently defended shore. **Area 3** has few current developments but is subject to advanced regeneration plans (including with City Deal regeneration funding) that will increase the numbers of assets. If these plans proceed then an 'avoidable lock-in' occurs that will require **erosion resist** measures to be maintained into the future. We recommend these plans are revisited as part of COVID-19 Green Recovery planning to consider alternative, climate resilient regeneration options. These might include avoiding placing permanent assets in areas at risk of erosion and flooding (those planned for the ExxonMobil site and Scott's Yard) and instead consider more innovative, and future-smart flexible solutions such as temporary/demountable alternatives or recreation spaces. Climate resilient alternatives for such land can be seen at Edinburgh's Granton Waterfront Park, an example of accommodating erosion and flooding whilst meeting housing and regeneration needs. The proposed realignment to create nature reserve north and west of the ExxonMobil site is a good example of a future smart **accommodate erosion** option. Any erosion resist strategy may consider the recycling of recycled dredge sediments for basin infill in this area.

Area 4 Bowling Harbour area has similar risks to that of **Area 3** and other existing developments at risk of erosion. The main railway line will be under risk of erosion and flood in the future, but currently benefits from protection from Bowling Harbour outer wall acting as an erosion buffer. Future erosion risk management in this area rests on how Bowling Harbour outer wall is managed. It is possible that the marine basins in **Areas 3 and 4** could be infilled as part of an **erosion resist option in order** to minimise the length of protection required along this already partly canalised part of the Clyde channel. However, if this approach is adopted then development is likely to follow. Again, any development lock-ins in this area serves to constrain the future use of this and adjacent land for other, more adaptive purposes. Any erosion resist strategy may consider the recycling of recycled dredge sediments for basin infill in this area.

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.

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.

Adaptation Scenarios: Hard Infrastructure on an Estuarine Coast

The Dumbarton to Bowling site exerts limitations on the open-coast modelling exercises of this phase of Dynamic Coast (anticipated shoreline change using Modified Bruun Rule and CoSMoS-COAST MHWS modelling) due to the estuarine environment with a majority of artificial coastline and large sections of made-ground. This report has therefore been supplemented with a semi-quantitative analysis of adaptation scenarios which create boundary lines of adaptation based on existing infrastructure and elevation, erodability, projected SLR and SEPA flood likelihoods.

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. Final sections consider options, caveats and how adaptation planning might be implemented.

Coastal Change

Summary

1. The low water mark across Dumbarton to Bowling has generally seen recession from 1896–1994 of up to 141 m, with some recent accretion in places. This retreat coupled with MHWS erosion has led to an overall beach lowering and steepening due to the faster rates of MLWS retreat. MHWS retreat across Dumbarton has reached up to 0.5 m/yr with localised accretion at Milton of 0.8 m/yr. Bowling Sands has experienced MHWS retreat of up to 0.3 m/yr, with the Milton to Bowling section less variable overall due to hard infrastructure and the upstream position.
2. Recent topographic change analysis shows sediment losses have dominated the foreshore and estuarine sediment with ~14,200 m^3 being lost over 15 years. Stability with some elevation increase has dominated the vegetation and inland marsh, with a height increase rate of 4–7 cm/yr from 2003–2018. Out across the foreshore of Management Units 1 and 2, the rate of elevation loss has ranged from 5–8 cm/yr.
3. The low topography of the marshland means that across some sections from Dumbarton to Milton, the infrastructure is unprotected from flooding through small corridors and culverts. The railway is the primary line of defence against flooding in most sections due to it being artificially elevated.
4. Vegetation edges have fluctuated between erosion and accretion from 2004–2018, with an overall trend of salt marsh erosion at Dumbarton of 0.3–0.6 m/yr and vegetation accretion across much of Milton at a rate of 1.0 m/yr. The soft sands and vegetation across Bowling have experienced vegetation edge erosion at a rate of up to 0.6 m/yr.
5. The primary risk across the site is the erosion of sensitive salt marsh and resultant increased flood risk to the vastly low-lying business parks and residential properties. Main floodwater access would be along culverts and streams flowing out through the marshland, providing an access point for water behind dilapidated defences.
6. Milton Island has been identified has largely made-ground and the previous location of a marsh pond. This low-lying land is now the subject of development plans after remediation work to clean the decommissioned Esso fuel storage site has taken place.

The first phase of Dynamic Coast summarized the coastal changes to Dumbarton Castle Bay (see page 22 of Cell 6 report) between 1896, 1963 and 2013. The shore has undergone variable change of up to 80 m retreat in one section between 1896 and 1963, with a further 20 m retreat between 1963 and 2013 in scattered sections often seen along variable salt marsh shores.

The second phase of research, outlined below, benefits from Ordnance Survey 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 from Dumbarton to Bowling

The topography of Dumbarton is controlled by the underlying geology of sandstones across the shores and under the town of Dumbarton, backed by a younger complex of hard igneous rock that makes up the larger hills and quarry running alongside the A82 and Dumbarton Rock itself (Figure 3). The shore in front of Dumbarton to Milton is dominated by low-lying mudflats and saltmarsh of up to 50 cm height, which then transitions through the MHWS edge at 2 mOD to reeds and grasses behind, before reaching the elevated railway line and woodland behind this. Sections of the land under the Dumbuck Warehouses east of Dumbarton only reaches 2.5 mOD fronted only by the elevated railway line at 4.5 mOD. A steadily sloping section of grasses and sparse woodland lies south of Milton, which a portion of the National Cycle Network path runs through. This contains a 2.5 ha pocket of land below 3 mOD, which drops to 1.8 mOD in some parts directly behind the wedge of made ground adjacent to Dunglass Basin. This wedge was raised from below MHWS in the early 20th century and now sits between 2–6 mOD behind a vertical concrete and iron sea wall. East of this the Bowling coast remains armoured by harbour walls from 4–5 mOD with intermittent low-lying jetties. East of Bowling canal, the coast then transitions to low-lying sand with a relatively sharp slope up to woodland >6 mOD.

The nearshore bathymetry shows a fairly continuous shelf edge where the nearshore environment at 1 mCD drops off into the River Clyde to a depth of 8 mCD. The estuarine environment of Dumbarton to Bowling is displayed in the contrasting bathymetry of the relatively deep river channel and the broad shallow mudflats of the intertidal zone.

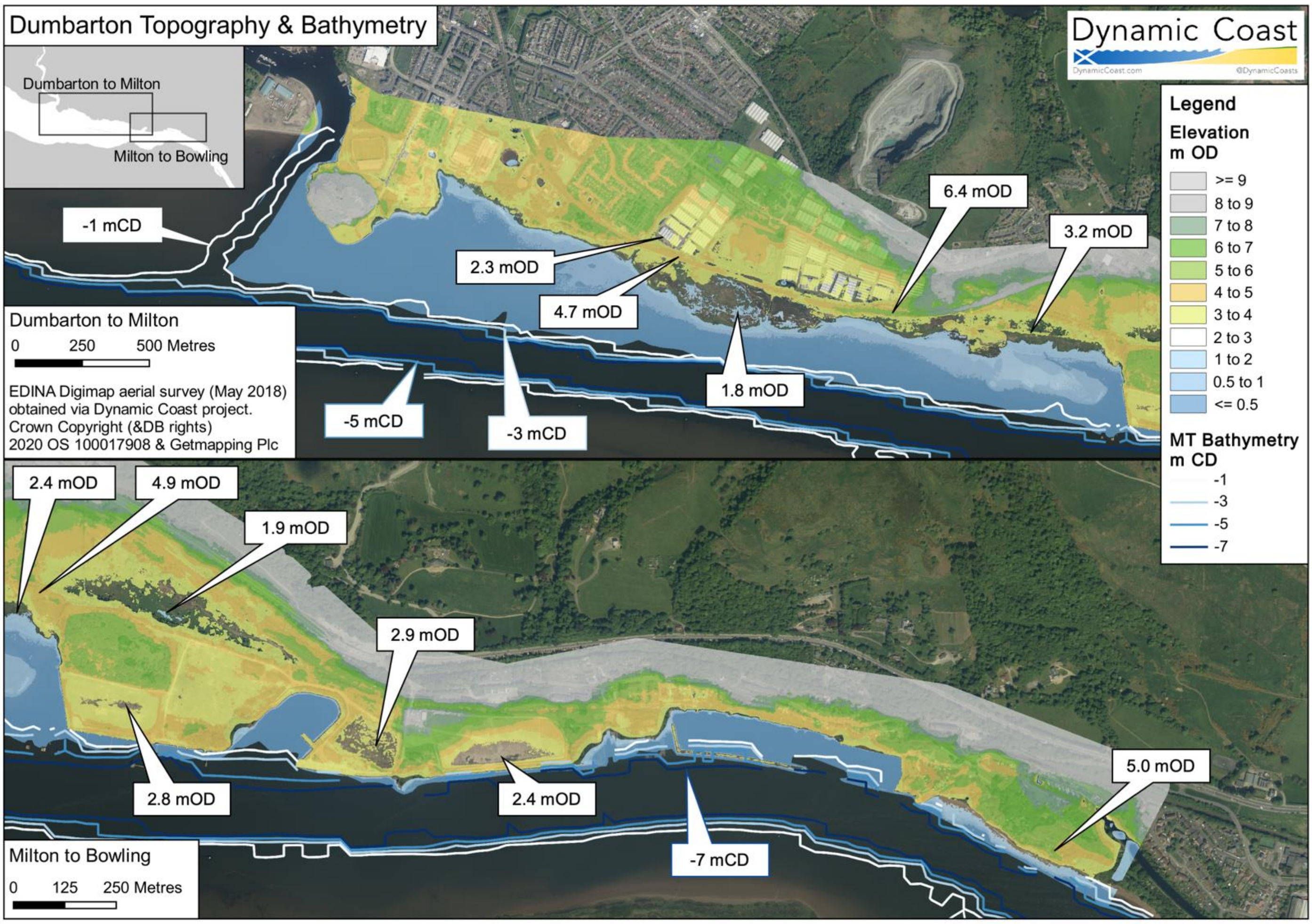

Figure 3 Topography, Bathymetry (mCD) and key flood levels (mOD) across Dumbarton (from September 2018 OS aerial imagery derived DSM and MarineThemes bathymetry)

National Coastal Flood Protection Features from Dumbarton to Bowling

An automated terrain analysis has been carried out with the OS 2018 DEM being analysed at 5 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 soft coast is perhaps best summarised by the barrier width at 3.5 mOD, this being the elevation of likely future sea levels explored within the Coastal Flooding section. The automatic barrier extraction was not run on the armoured coast of Dumbarton to Bowling, but it is important to note the barrier features surrounding this as the morphologies extracted may highlight potential floodwater entry points that would further be exacerbated by any erosion or saltmarsh retreat. It also should be noted that the railway embankment acts as the first point at which a barrier feature is identified, suggesting no natural flood protection exists for the land in front of this.

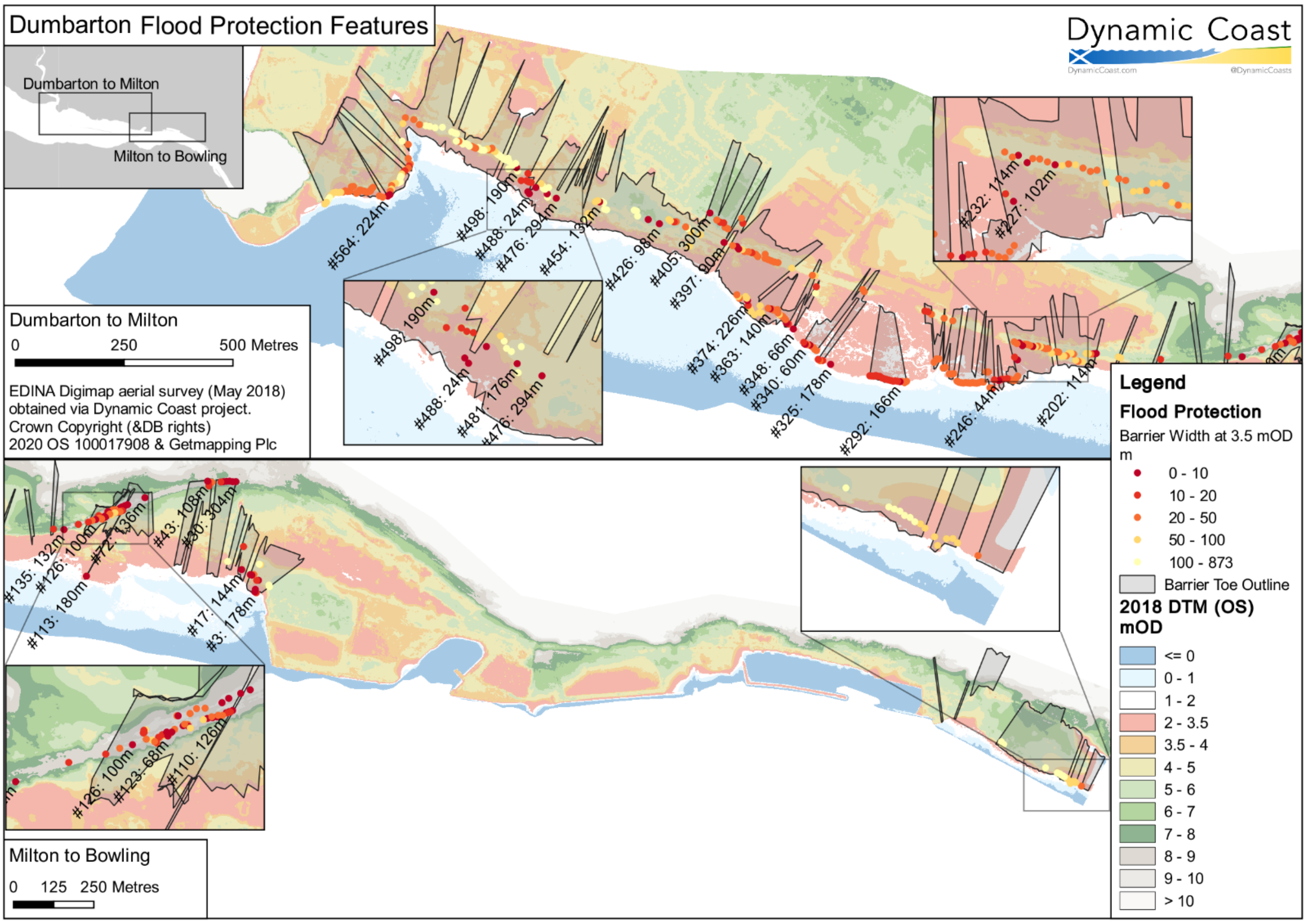

Figure 4 Flood protection features across Dumbarton, showing the extent of the barrier toe and the front points of the barrier symbolised by the barrier width at 3.5 mOD, and labelled with total barrier toe width.

Changes to High and Low Water from Dumbarton to Bowling

Figure 5 shows the planimetric change to MLWS over the course of the last century. The general trend in MLWS change from 1896 to 1994 is widespread retreat from Dumbarton to Milton, with the MLWS mark having retreated inland by as much as 140 m. This trend is less pronounced but still present from Milton to Bowling; the significantly lower retreat rates here are most likely due to a combination of the narrower, deeper river-dominated geomorphology and of the greater amount of hard coastal infrastructure and human interaction with the coastal edge. From 1994 to 2018, very little change in the MLWS can be seen across all four management units, suggesting either that few edits have been made to the original 1994 line, or that little change has taken place across the lower intertidal zone. The latter is unlikely, considering the Coast X-Ray MLWS shows fluctuations in the smaller channel mouth positions and morphologies, which would be expected over this timeframe. From the 1994 MLWS to the Coast X-Ray period between 2016–2018, there has been further beach shortening as the MLWS has proceeded inland at a greater rate than the MHWS, retreating in places from Dumbarton to Milton by up to 31 m. At Dunglass Castle, the accuracy of the Coast X-Ray MLWS mark is less reliable as the other MLWS lines run close to the deep water edge of the harbour wall, whereas the Coast X-Ray MLWS is up to 50 m seaward of this. However, further east at Bowling sands, the 1994 and 2018 OS MLWS lines remain in a very similar position to the 1896 MLWS which ran straight along a harbour wall. This wall has subsequently been removed, suggesting some inaccuracy to the 2018 MLWS line compared with the Coast X-Ray line for this section up to 46 m seaward.

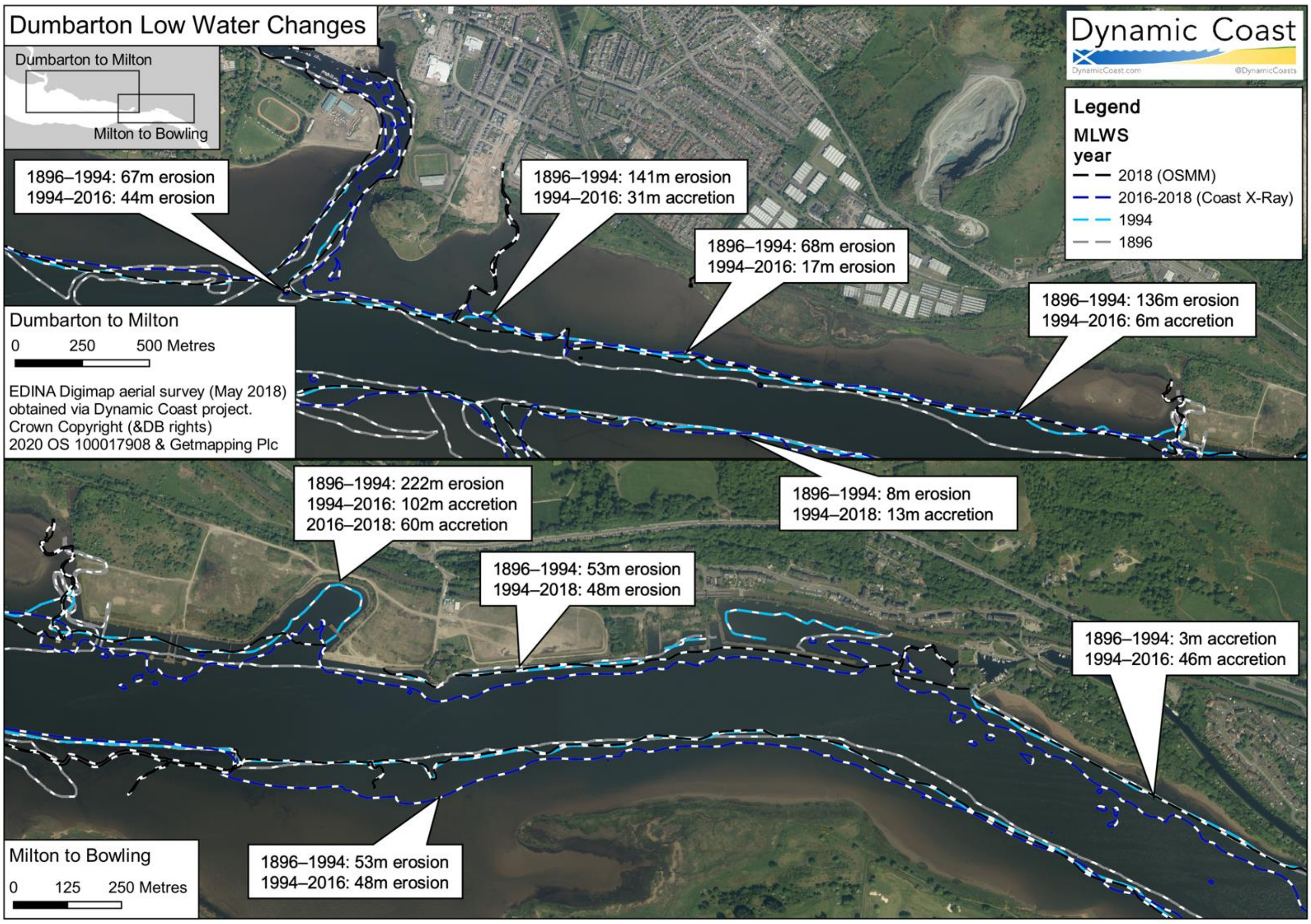

Figure 5 Changes to each lower beach – comparison of various MLWS surveys and Low water (80% water occurrence) from Coast X-Ray

Figure 6 shows the changes to the upper shore of Dumbarton as depicted by the positions of MHWS. The most notable changes across high water from Dumbarton to Milton are seen in the fluctuating saltmarsh edge. Adjacent to Dumbarton Rock, the saltmarsh accreted by up to 66 m between 1896 and 1994, before progressively eroding back to close to the 1896 line by 2018. However, during the same period but further to the east, the saltmarsh edge eroded by as much as 72 m before accreting by 15 m and remaining in a steady location since 2003. Further to the east in front of the Dumbuck Warehouse estate, the MHWS accreted by up to 117 m from 1896–1994 where it remained fairly stable before receding laterally up into the marsh channels by 96 m from 2014–2018. Due south of Milton, a section of sensitive saltmarsh experienced 94 m accretion from 1994–2003, which was followed by an erosional period up to 2014 where the MHWS receded back to its 1994 position, before accreting forward again by 98 m by 2018.

Milton to Bowling shows less fluctuation due to its history of made-ground creation and harbour construction displayed on historical maps from the last century. From 1896, a harbour wall running parallel to the Clyde was in place, which by 1920 had developed into an additional dock with jetties running northeast. West of this, the current-day prism of raised land southeast of Milton was still mud and saltmarsh, but by 1958 this 14 ha area had been filled in behind an extension of the eastern harbour wall and large storage tanks were installed. The infrastructure atop these made-ground sections have now been cleared and both sections are undergoing remediation before consideration for new development. These changes are captured in the MHWS observations through time. The greatest natural MHWS change along this stretch has been at the small sandy beach east of Bowling Harbour in Management Unit 4, where the MHWS has steadily been eroding at a rate of 0.3 m/yr since 1896.

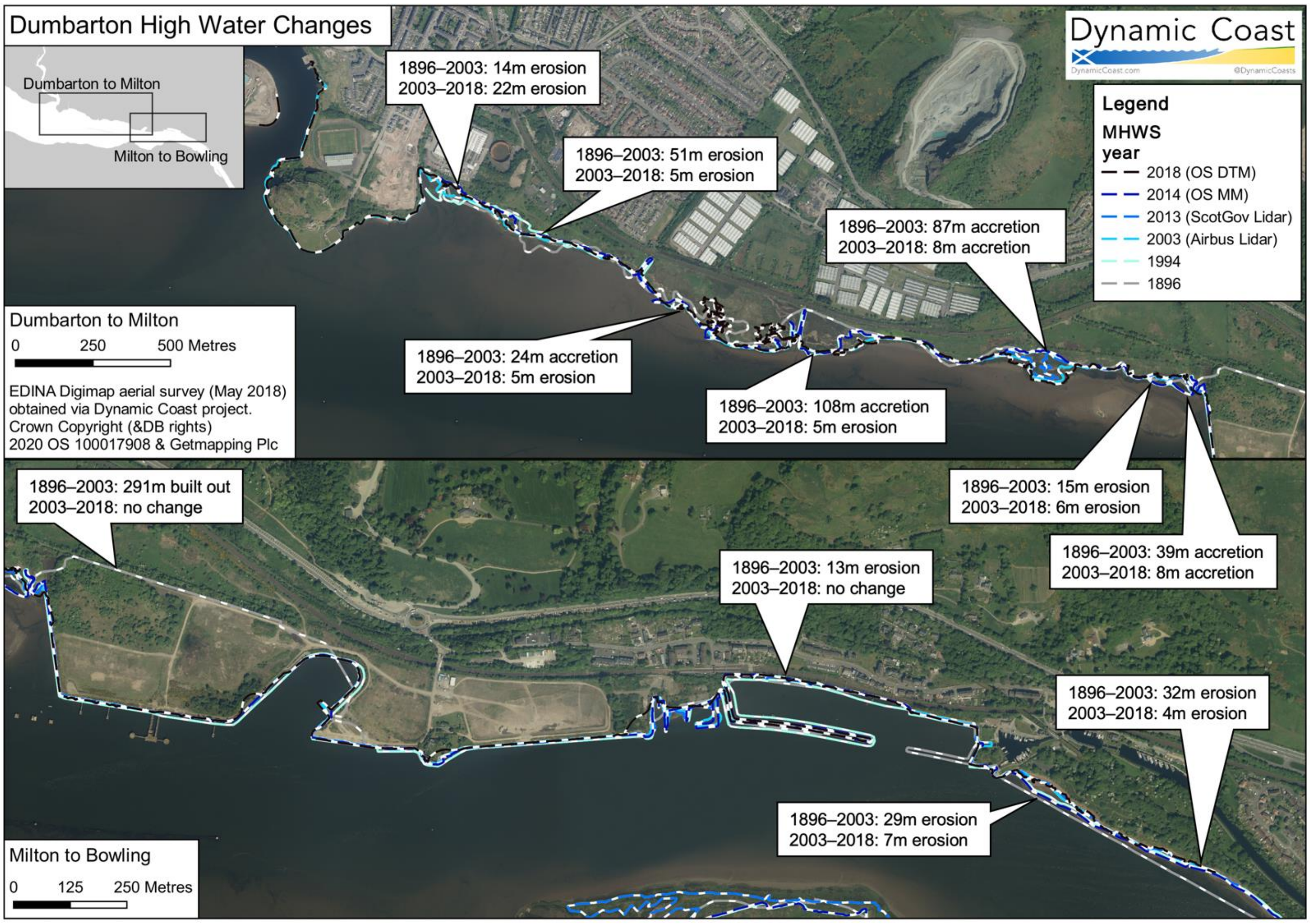

Figure 6 Changes to the upper shore – comparison of MHWS surveys dated 1896, 1994 (OS map series), 2003 (Airbus Lidar), 2013 (ScotGov lidar survey), 2014 (OS MasterMap) and 2018 (OS aerial imagery DTM)

Intertidal Changes from Dumbarton to Bowling

Figure 7 demonstrates the net effect of changes in the positions of MHWS and the Vegetation Edge as expressed in the vertical changes across the beaches as derived from DTMs captured by Airbus in 2003 and OS in 2018. The coverage of the both high-resolution surfaces used in the elevation change analysis is only from the southwest side of Dumbarton Rock to Milton Island just west of the Milton to Bowling remediation site. The elevation difference between the two periods shows widespread minor lowering of the mudflats with pockets of more pronounced sediment loss at the east and west of the surface extent. It is probable that much of the elevation gain recorded further inland from the MHWS is an artefact caused by a combination of a difference in season and vegetation coverage between the two DTMs used and a difference in the elevation data capture and surface smoothing methods (Airbus aerial lidar vs. OS aerial photogrammetry). However, the region along the MHWS shows concentrated sections of both elevation increase and decrease over time which is ratified in many cases by the change in the lateral Vegetation Edge position for a similar period, as shown in Figure 8. Sections of this saltmarsh loss can be seen in the east, south of

Dumbarton, whereas saltmarsh and reed edge growth can be seen along the vegetation south and southeast of the Dumbuck Warehouses. The most prominent elevation changes along the swath of MHWS are annotated with their magnitudes in Figure 7.

Figure 7 Changes to the foreshore - comparison of the difference in beach elevation from 2003 (Airbus aerial lidar) to 2018 (OS aerial DTM)

Dune Vegetation Edge Changes from Dumbarton to Bowling

Figure 8 and Figure 9 demonstrate the change in Vegetation Edges across different survey methods and with a range of survey years from 2004 to 2018. The insets across the figure show close-up views of the greater changes in the Vegetation Edge position both landward and seaward. A lateral change trend is not as apparent along the entire shore region, but there is slightly more loss of vegetation adjacent to Dumbarton Rock and across the sandy beach west of Bowling Harbour. There is also a focused section of Vegetation Edge advance across the shore south of Dumbuck, as shown in Figure 9. In the areas highlighted in the insets in Figures 8 and 9, where the elevation change is supported by a strong lateral change in Vegetation Edge in the same time period, the underlying vegetation is primarily saltmarsh and short reeds, with some more grass-dominated vegetation towards the Gruggies Burn mouth in the east and Bowling Harbour sand beach in the west.

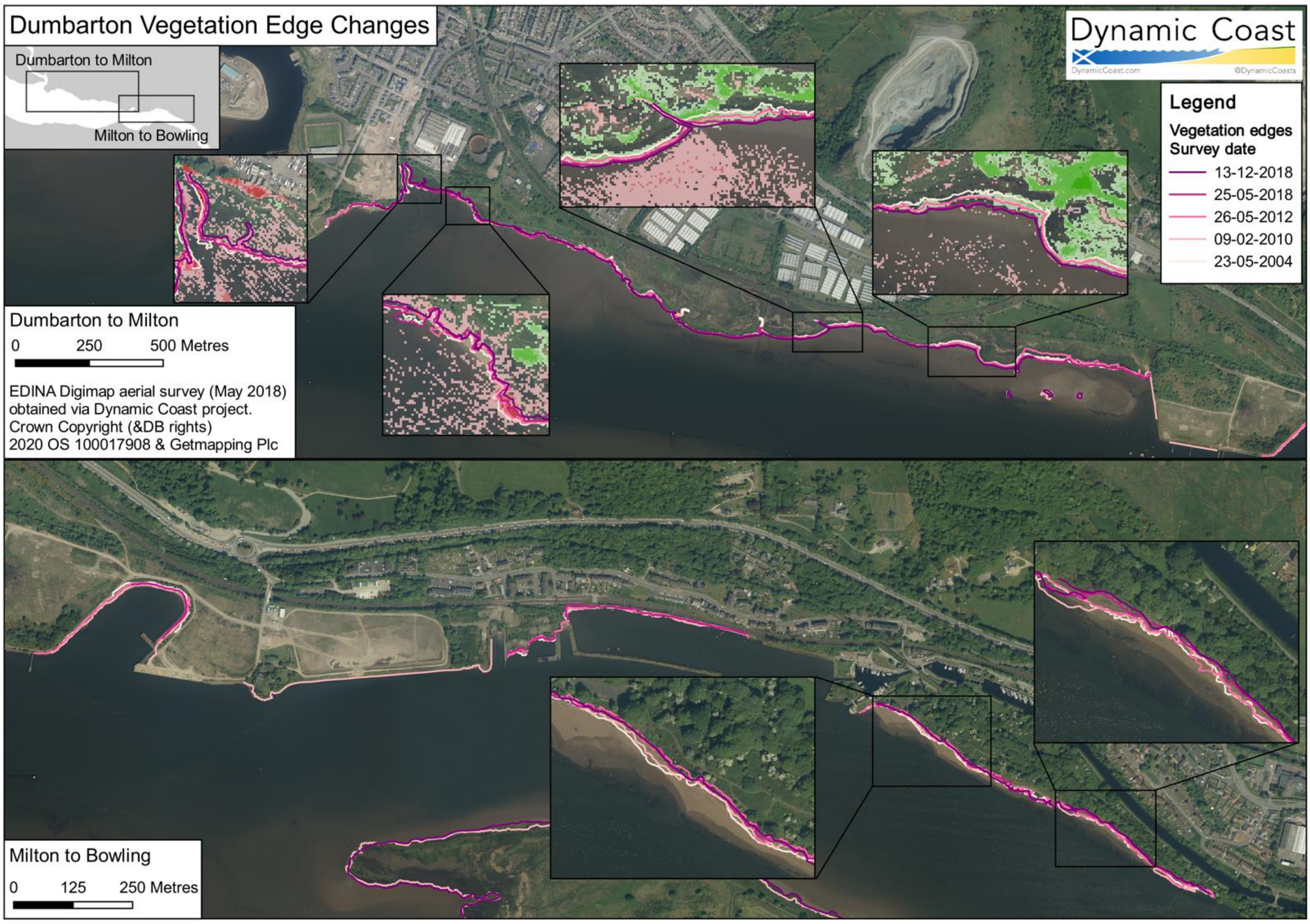

Figure 8 Detailed Vegetation Edge changes across Dumbarton comparing aerial image-digitised (2004, 2010, 2012) and ground-surveyed (2018) edges

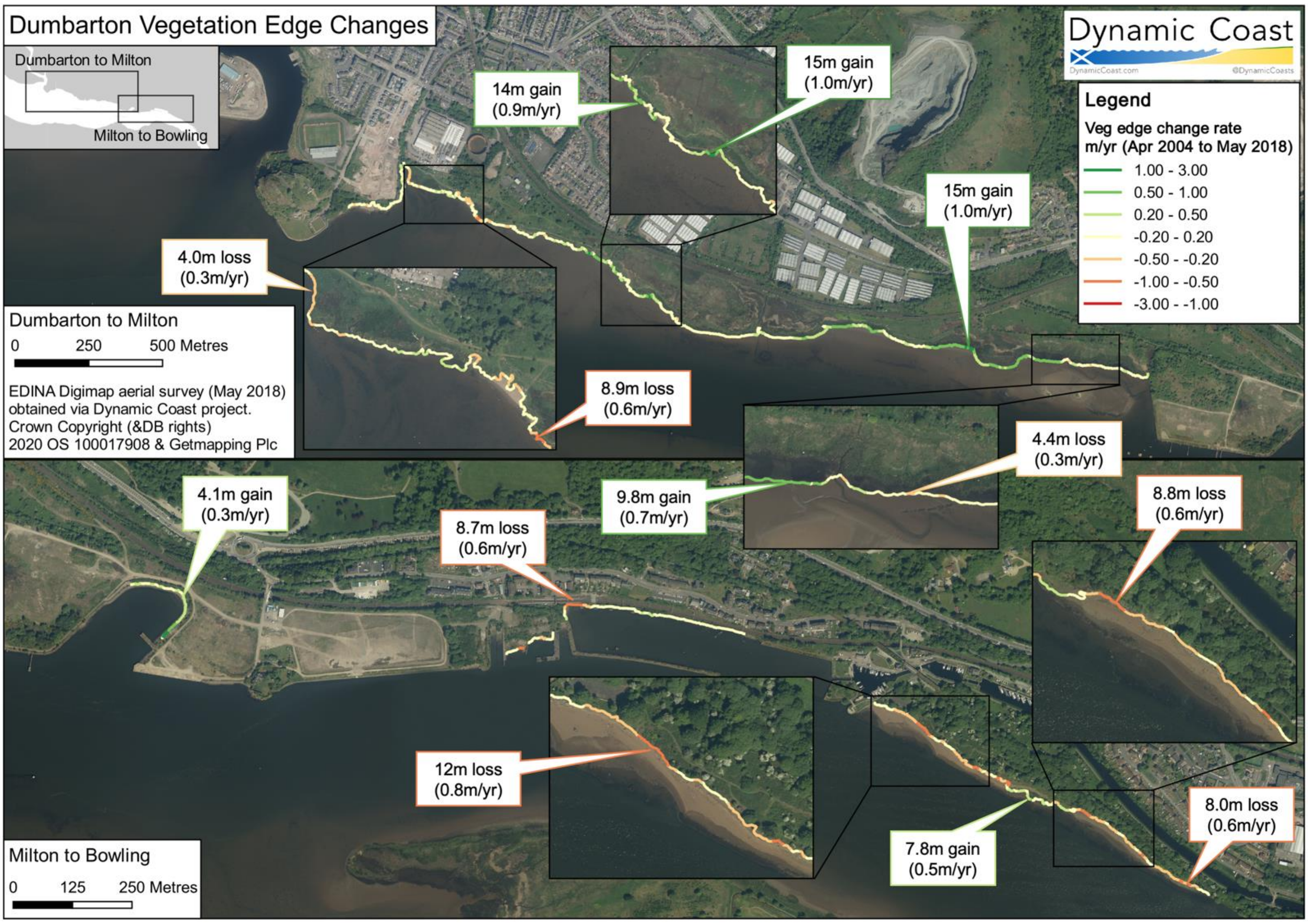

Figure 9 Recent Vegetation Edge change across Dumbarton bays from April 2004 to May 2018 (both captured via aerial image digitisation)

Volumetric Changes from Dumbarton to Bowling

The volume changes across Dumbarton shore have been calculated using the values stored in the elevation change surface (Figure 10). Each cell in the regularly gridded change surface has an area of 4 m^2 which is then multiplied with the elevation change for that cell to get a cubic volume of gain or loss (by height increase or decrease). Volume change per cell is then summed across each of the geomorphic sections displayed in Figure 10. The volume change values for the two management units covering the elevation change surface are presented as a summary in Table 2 and in full in the Appendix.

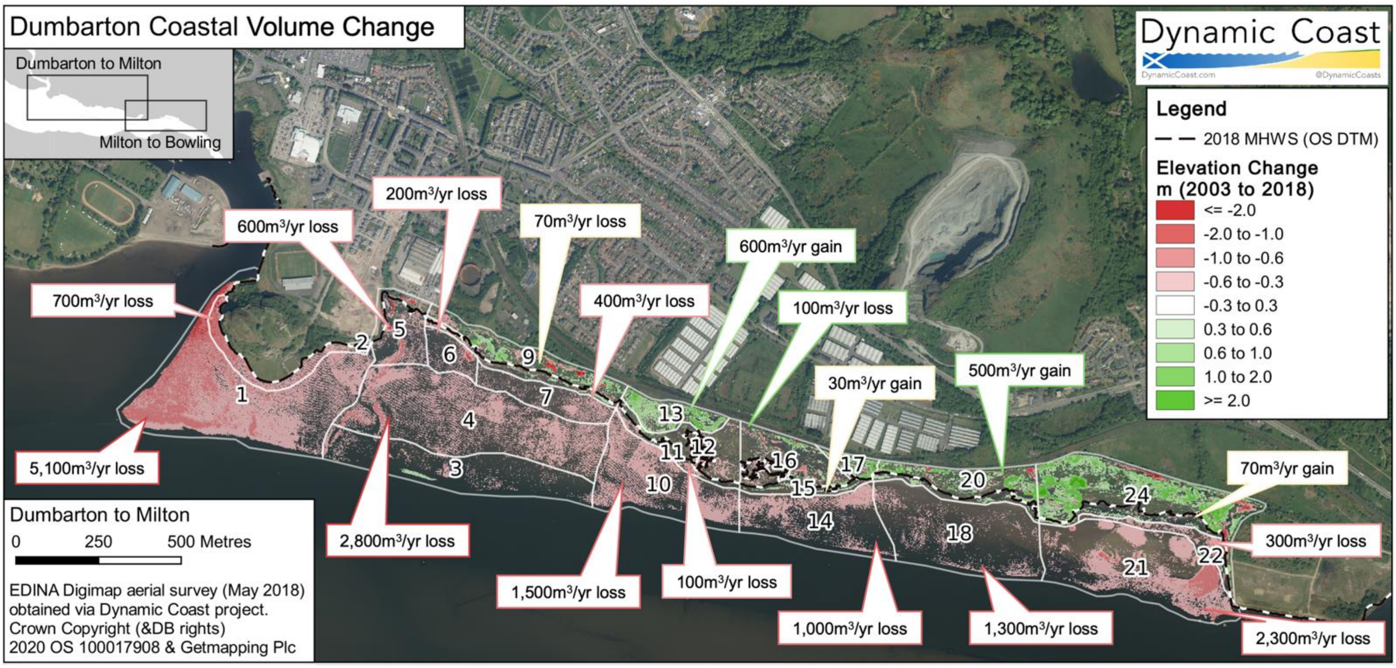

Figure 10 Comparison of rates of volume change across each geomorphic section outlined in white, from 2003 (Airbus aerial lidar) to 2018 (OS aerial DTM)

Table 2 Summarised volume changes from 2003 (Airbus aerial lidar) to 2018 (OS aerial DTM) across the western two management units

MGMT Unit	Change area (m^2)	Volume change (m^3)	Volume change rate (m^3/yr)
1 (Dumbarton)	523,300	-161,200	-10,700
2 (Milton)	633,100	-53,000	-3,500

Social Vulnerability Classification Index

Communities within the Dumbarton and Bowling supersite emerges from the SVCI analysis as being highly vulnerable to coastal-erosion related flooding events. The high levels of vulnerability indicated by the SVCI for the areas of Dumbarton to Bowling align closely to the levels of deprivation identified by the SIMD (2020).

Of all the supersites, Dumbarton and Bowling has the highest level of physical and mental health-related vulnerabilities. Of note are high rates of limited daily activity due to health issues and recorded cases of depression, a SVCI indicator of mental wellbeing. Dumbarton and Bowling also emerged as exhibiting a high level of social vulnerability within the 'Population' domain (Table 1). The Dumbarton and Bowling super-site scored highly within this category of social vulnerability because of high numbers of children under four-years of age, as well as an elderly population. Levels of economic prosperity were also recorded as low within Dumbarton and Bowling, although rather than this being due to high rates of long-term unemployment, the score for Dumbarton and Bowling was influenced by a high number of households with dependent children where there was no employed adult.

A high level of vulnerability was also recorded within the 'Sustainable Communities' domain of the SVCI for Dumbarton and Bowling. This was resultant from high building density; high levels of social housing and to a lesser, but still significant, extent of private-rented housing. The presence of these combined factors would affect the ability of communities to display resilience when facing the impacts of a costal erosion related flooding event.

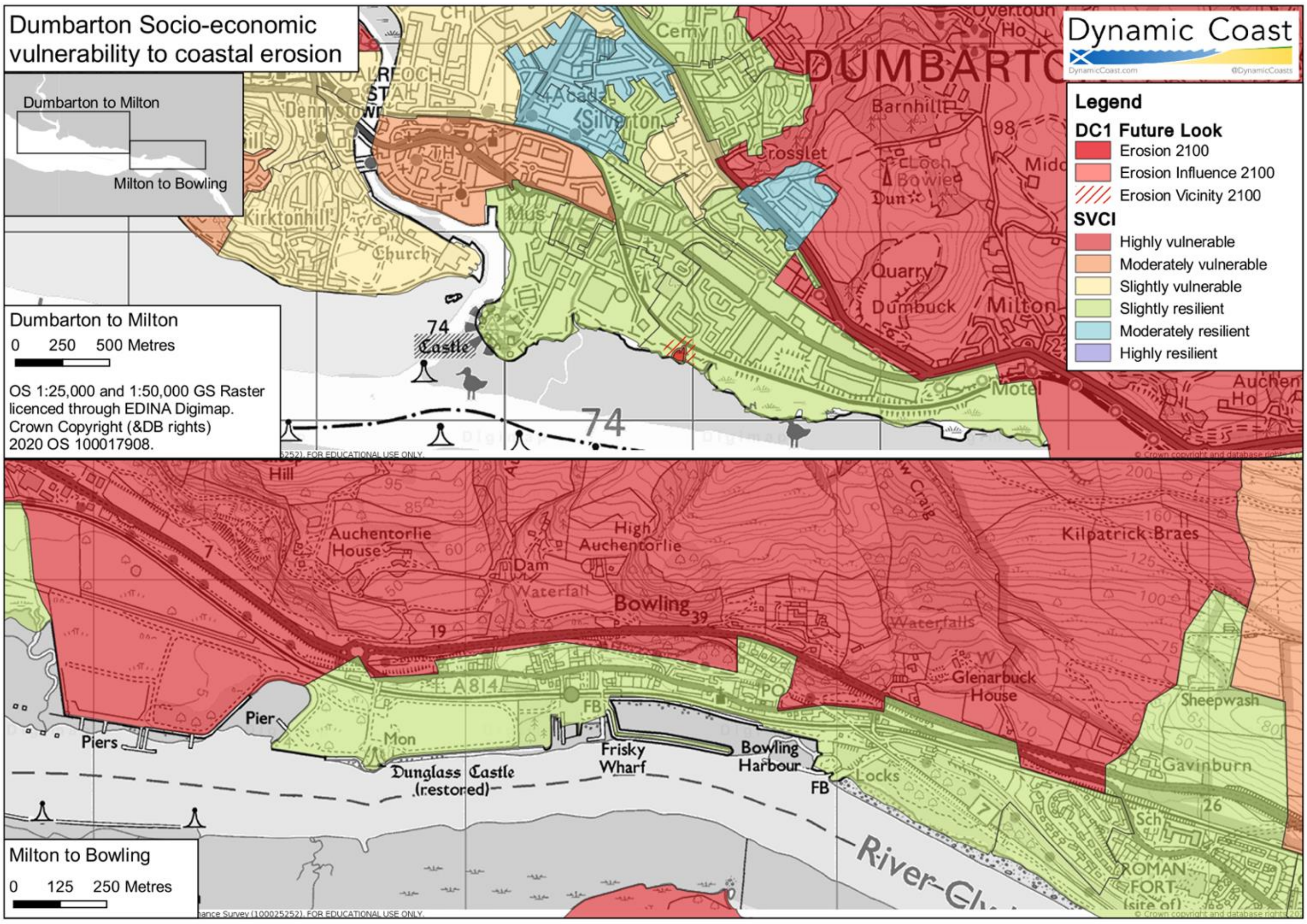

Figure 11 SVCI classifications per data zone with anticipated coastal change using the Future Look from Phase 1 of Dynamic Coast

Coastal Flooding

Coastal Flood Boundary

The Coastal Flood Boundary (CFB) dataset, published by DEFRA in 2018 (link), is reported in Table 3. It displays the anticipated still water surface level of surge events at various frequencies. Still water level calculations such as these superimpose the surge level on top of the highest astronomic tide level; and as such they exclude other dynamic hydrodynamic effects such as wave run-up etc; which would need to be considered to gain a realistic impression of worst-case storm impacts. Whilst in some parts of Scotland the recent update deviates from the last version, there is a negligible increase (1 cm) from Dumbarton to Bowling.

Table 3 Tidal and flood levels for Dumbarton

Description	Level (mOD)		Description	Level (mOD)
MHWS	1.99		1 yr (100% AEP)	3.51
HAT	2.59		10 yr (10% AEP) SEPA's High prob. event	4.03
Base year	2017		100 yr (1% AEP)	4.46
FID	1806		200 yr (0.5% AEP) SEPA's Med. prob. event	4.54
			1,000 yr (0.1% AEP) SEPA's Low prob. event	4.73

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 3) 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 12 shows the present-day high probability and low probability coastal flood extents, in greater detail than SEPA's Flood Risk Maps as it benefits from a recent digital surface model (2018) and is more likely to accurately represent current land levels. Figure 12 demonstrates the potential inundation of the saltmarsh and industrial and residential areas closest to the water's edge. It should be noted that the embankment that the train line lies upon may act as a barrier for this potential inundation, and flooding will only occur if a corridor exists making a conduit for water to enter the backshore area.

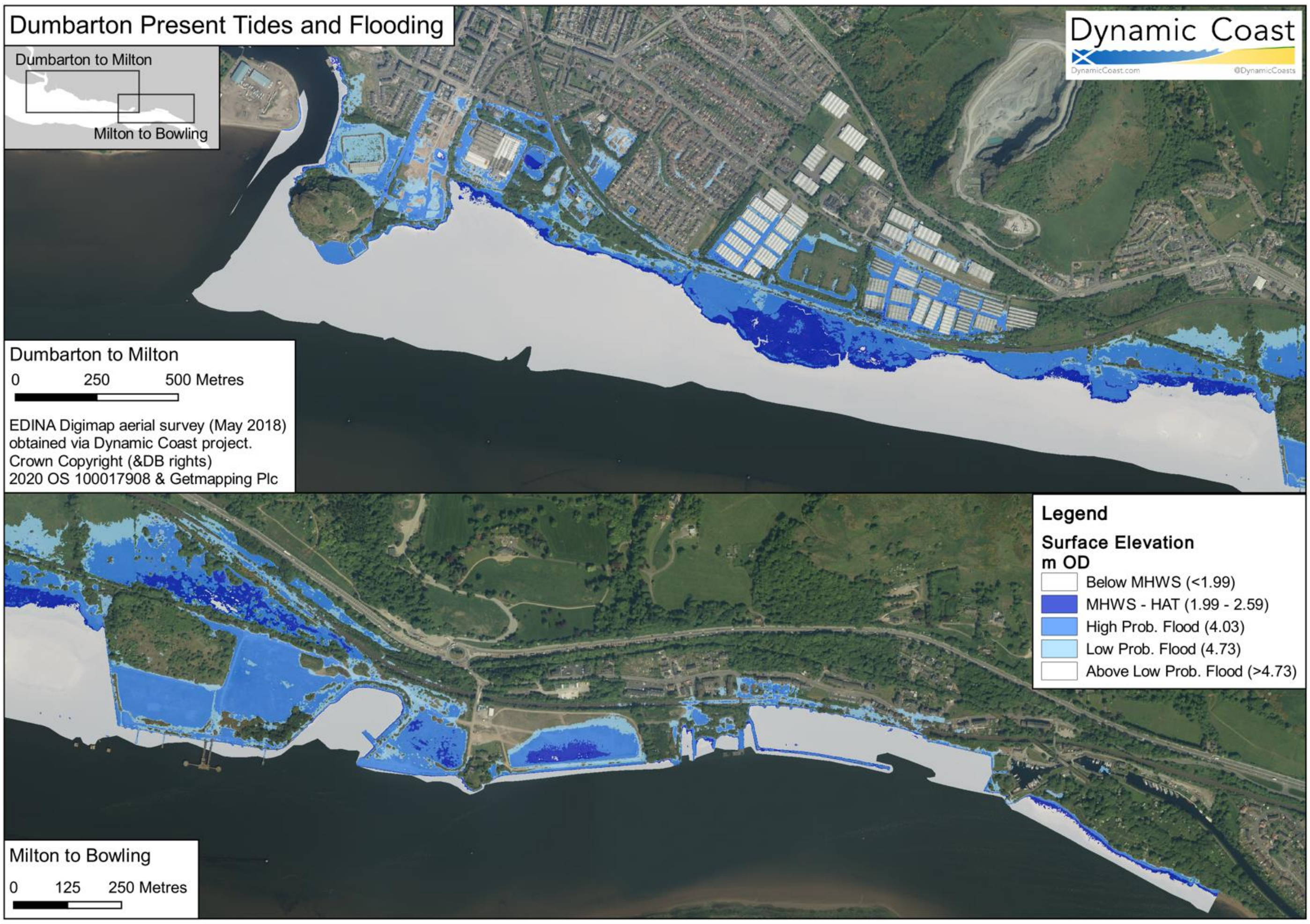

Figure 12 Summary of present-day tides and high probability (1:10 yr, 4.03 mOD) to low probability (1:1,000 yr, 4.73 mOD) flood levels from Dumbarton to Bowling

Relative Sea Level Rise

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

The anticipated increases in mean sea level from Dumbarton to Bowling are summarised below. By 2050 mean sea level is likely to have increased between 0.09 m and 0.28 m; and are as likely as not to be above 0.17 m above average levels seen between 1981–2000. Rates of sea level rise from 2040–2050 are expected to be between 2.9 mm/yr and 8.3 mm/yr and as likely as not above 5.2 mm/yr. For context, the long-term pre-industrial relative sea level trend at Dumbarton 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 mean sea levels based on UKCP18 RCP8.5 for Dumbarton. Values in shaded row are used in example above

Year	MSL increase (m above 1981-2000 level)		
	5th%	50th%	95th%
2010	0.00	0.02	0.03
2020	0.02	0.05	0.07
2030	0.04	0.08	0.13
2040	0.06	0.12	0.19
2050	0.09	0.17	0.28
2060	0.13	0.23	0.38
2070	0.16	0.30	0.49
2080	0.21	0.38	0.62
2090	0.25	0.46	0.75
2100	0.29	0.54	0.90
2300	0.65	1.67	3.44

Period	Rate of increase mm/yr		
	5th%	50th%	95th%
2000–2010	0.0	2.0	3.0
2010–2020	2.0	3.0	4.0
2020–2030	2.0	3.0	6.0
2030–2040	2.0	4.0	6.0
2040–2050	3.0	5.0	9.0
2050–2060	4.0	6.0	10.0
2060–2070	3.0	7.0	11.0
2070–2080	5.0	8.0	13.0
2080–2090	4.0	8.0	13.0
2090–2100	4.0	8.0	15.0
2100–2300	1.8	5.7	12.7

The existing tidal inundation extents and increases by 2100 are shown in Figure 13. Such a figure is helpful in informing 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 future SLR are close to present high probability flood levels (2100 HAT at 3.49 mOD vs. high prob. flood at 4.03 mOD). Figure 14 shows the key present day and anticipated flood elevations for Dumbarton by 2100, which reflect the increased impact of storm events, when 0.9 m is added to flood extents.

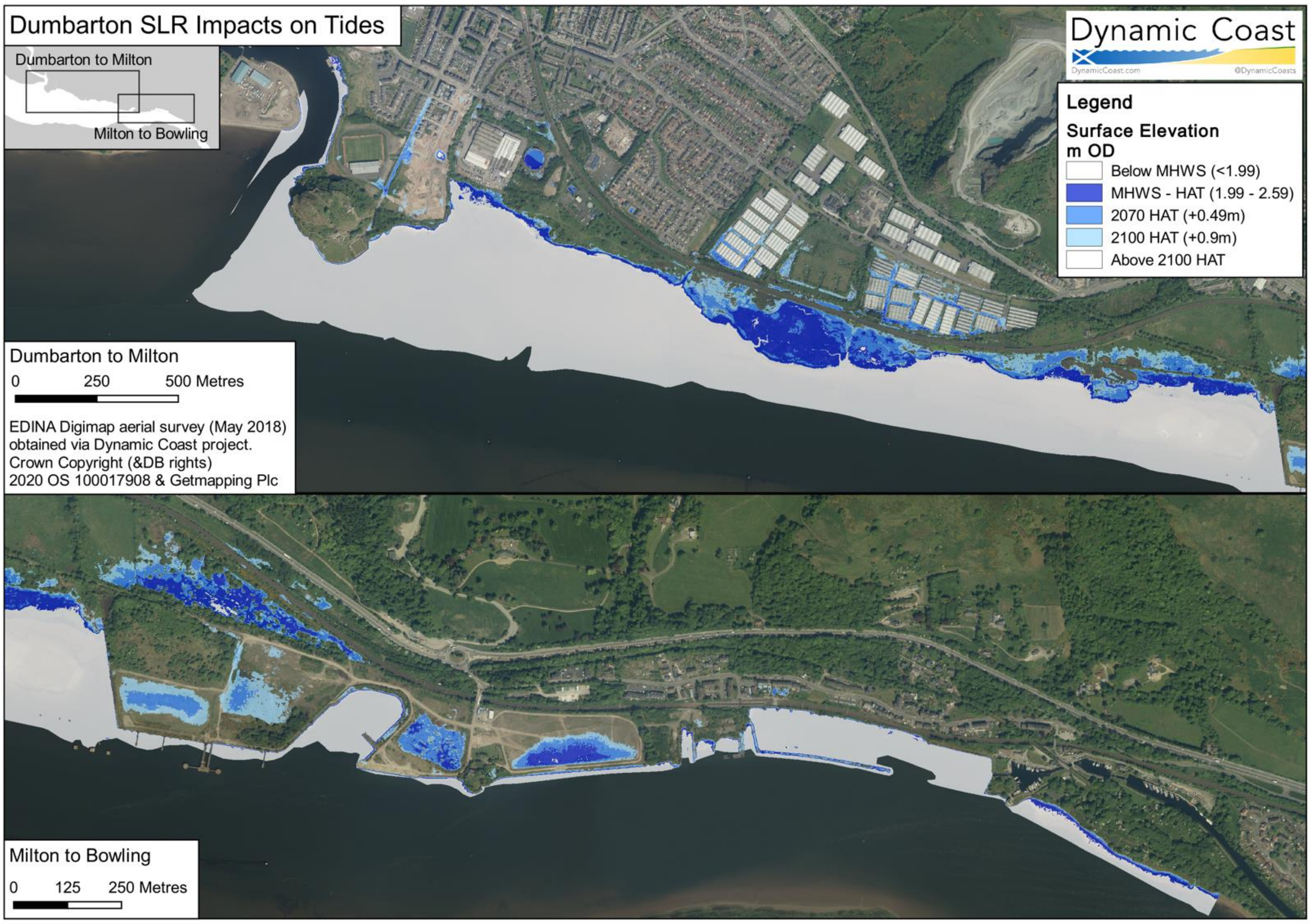

Figure 13 Present day extent of the Highest Astronomic Tide and the future anticipated under UKCP18 RCP8.5 95% sea level rise by 2070 & 2100.

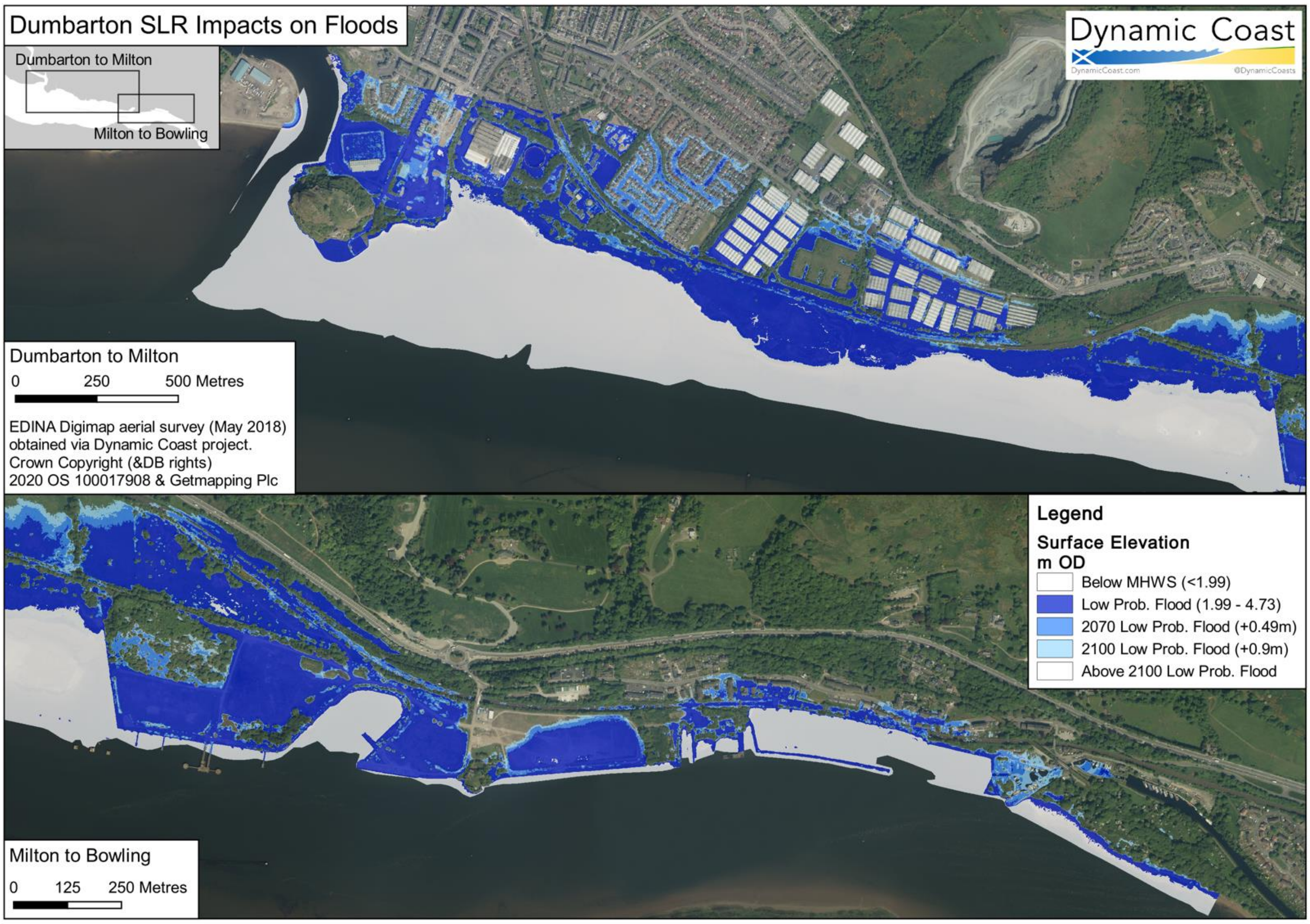

Figure 14 Present day and future flood events anticipated under UKCP18 RCP8.5 95th% sea level rise by 2070 & 2100.

Figure 15 plots the key present day and anticipated flood elevations for Dumbarton. MHWS reaches 1.99 mOD and if weather effects are excluded the highest astronomic tide reaches 2.59 mOD. SEPA anticipate the High Probability flood level to have a still water level of 4.03 mOD, this has a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 4.73 mOD, this has a 0.1% annual exceedance frequency. 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 4.54 mOD and the Low Probability flood level will have a still water level of 5.24 mOD by 2070; by 2100 these event levels rise to 4.96 mOD and 5.66 mOD respectively, 2.97 m and 3.67 m above the current-day MHWS.

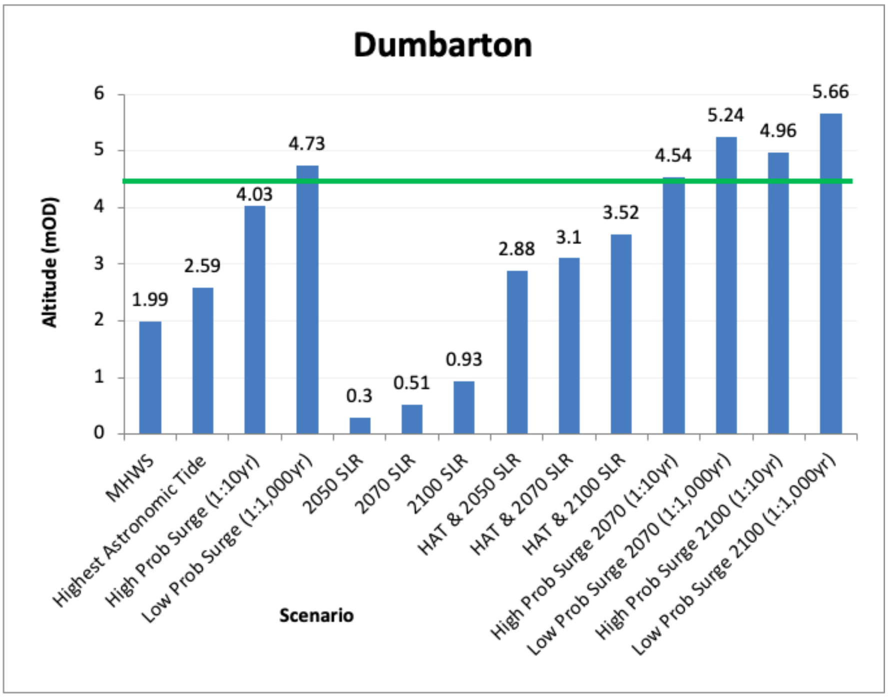

Figure 15 Summary of present and future key tide and flood levels at Dumbarton

Informed Adaptation at the Coast

Fairly heavily populated and the site of residential properties, business parks and primary links for transport infrastructure, Dumbarton to Bowling has a restricted selection of options for adaptation and resilience to coastal change. In making predictions for the future of its shore, Dumbarton to Bowling is a unique supersite in that several of the methods for more traditional soft coast management are not relevant for this defended, artificial estuarine location. However, this site is also the subject of discussions on development plans for the future, and so past and future coastal change should play a role in the decisions made on how the shore is managed. This section seeks to present some alternative scenarios about how we might adapt our land-based decisions to reflect the risks posed by coastal erosion in a changing climate, whilst also meeting the need to build sustainable, resilient and positive places for people to live and work.

Adaptation Scenarios for Urban Shores

Dumbarton to Bowling is currently defended by natural (salt marsh) and hard-engineered (harbour walls) solutions. This semi-quantitative analysis looks at how the following factors, compiled by reviewing data on existing coastal protection assets (Table 4), relate to these assets and future development plans. It aims to identify opportunities and barriers for realignment of the coast in order to minimise future risk and maximise ecological value in a more transformative way.

Table 4 Datasets used to form adaptation scenarios

Dataset	Category	Source	URL
Underlying Physical Susceptibility Model (UPSM)	Spatial	Fitton, Hansom and Rennie, 2016	Ocean & Coastal Management, 132
SEPA Flood Maps (Coastal, High (1:10yr) likelihood)	Spatial	Scottish Environmental Protection Agency (SEPA)	SEPA Flood Maps
1:50,000 bedrock geology maps	Spatial	British Geological Survey	BGS Digital Maps
High resolution aerial imagery	Spatial	Getmapping Plc. and EDINA Digimap	EDINA Digimap Aerial
1:50,000 and 1:25,000 colour raster maps	Spatial	Ordnance Survey (OS) and EDINA Digimap	EDINA Digimap OS
National current MHWS mark	Spatial	Dynamic Coast (Phase 1) and OS	SNH Gateway: NCCA - Dynamic Coast
Land ownership	Spatial	West Dunbartonshire Council	
Local development plan, 2018 (revised)	Published document	West Dunbartonshire Council	Local Development Plan 2: Proposed Plan

A series of scenario 'lines' were developed using a number of risk thresholds shown in Table 5. These thresholds and scenario lines were developed in close coordination with a cross-sector team (strategy, resilience, housing, coastal flood protection, climate change and landscape) to ensure that they were co-produced and of the most value to urban coastal managers. The lines were then used to articulate adaption scenarios in which development options might be encouraged or discouraged to minimise long-term coastal risk. The adaptation scenarios are named to align with

Tables 1 and 2 in this document in order to retain consistency in how coastal adaptation options are communicated. An example of the underlying datasets associated with the scenario lines is shown in Figure 17.

Table 5 Comparison of scenario development approach and data inputs in Edinburgh and Dumbarton case studies.

Scenario	Associated measures	Description	Method used to create the scenarios
Erosion Resist	Hold The Line, IPCC Protection	Erosion risks are actively managed with a range of engineering measures, some of which may also include the co-use of nature-based solutions.	First land-based structure (building, railway, sewage works, etc.) including the current line of conventional defences where these exist (e.g. sea wall)
Accommodate Erosion	Adaptation on land to reduce the effects of erosion, IPCC Retreat	Changes to land management made to move existing assets out of harm's way, avoiding adding any new additional assets (including via redevelopment) that may heighten risk.	A) Landward of areas of highest UPSM, or the next major infrastructure asset (e.g. railway), where the highest UPSM extended a long distance inland. B) As above, but with culverting added to allow flooding of the landward side of the railway.
Transformative	N/A	Further changes to land management made to move existing assets out of harm's way, avoiding adding any new additional assets that may heighten flooding *and* erosion risk.	As above, but landward of moderate areas of UPSM (60-100), SEPA coastal flooding data (High likelihood; 1:10yr event) and areas of made ground (determined by BGS 50k mapping).

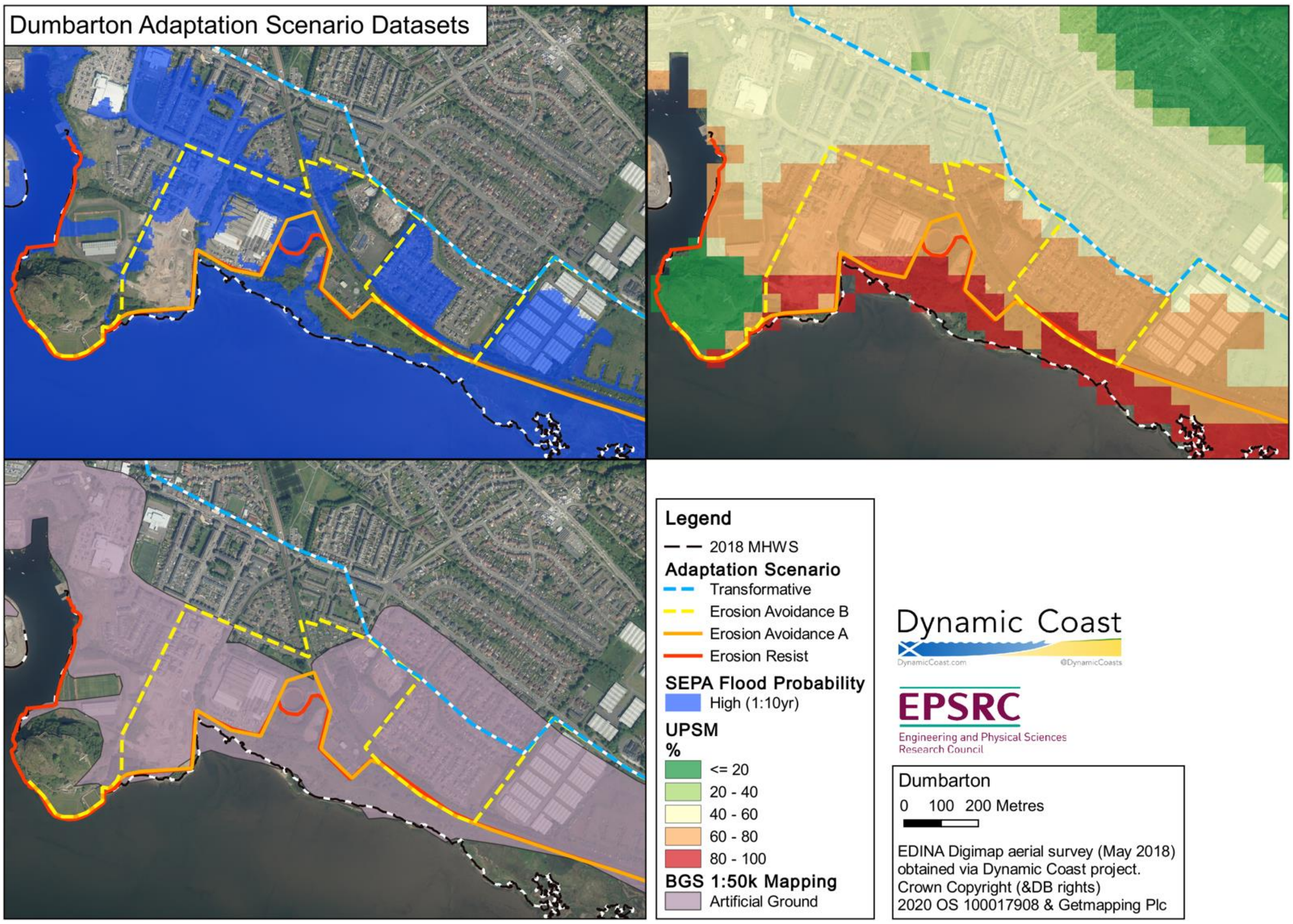

Figure 16 Zoomed example of the underlying datasets whose thresholds guided the adaptation scenario boundary lines

The analysis proposes a two-part **Accommodate Erosion** scenario that considers natural habitat loss as well as existing assets. Figure 17 and Figure 18 show the **Accommodate Erosion** by adaptation scenario lines based on the threshold data extents decided upon for visualising boundaries of adaptation. The **Erosion Resist** scenario assumes the railway will continue to be protected in its current position, which could have long-term impacts on the resilience of the saltmarshes fronting it; this natural capital currently provides nature conservation and flood and erosion risk alleviation to the railway and other industrial and housing assets behind it. The **Accommodate Erosion** A scenario excludes the land recently elevated for the Mary Fisher Crescent housing estate (performed to alleviate flood risk but not future erosion risks). The **Accommodate Erosion** B scenario includes this land as it could erode in the future. The **Transformative** scenario acknowledges both erosion and the River Leven flood risk, offering the potential to repurpose greenspace to relieve flood risk downstream.

Figure 17 Dumbarton to Milton adaptation scenarios.

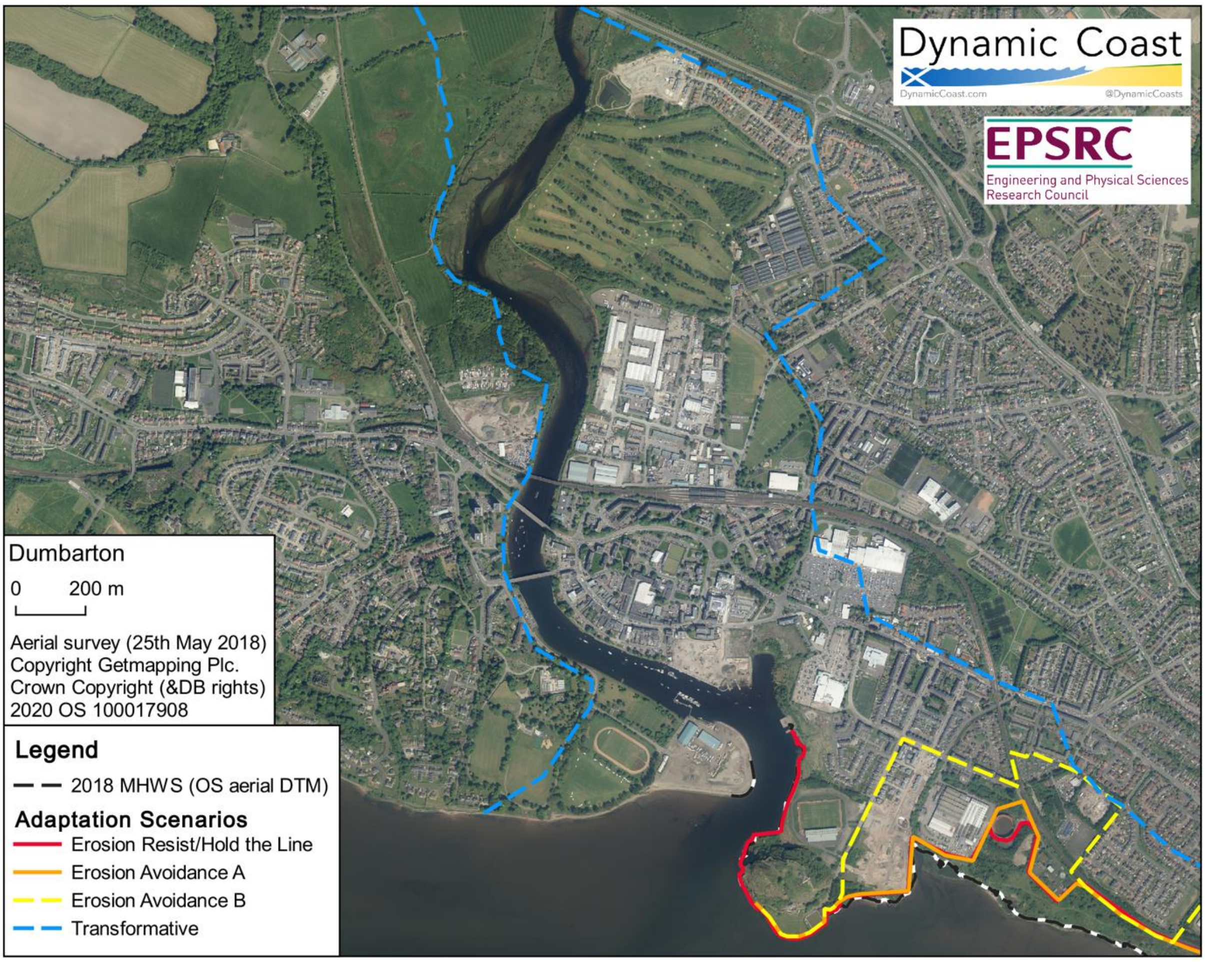

Figure 18 North Dumbarton adaptation scenarios, with the extension of the Transformative line to account for coastal flooding.

The **Erosion Resist** scenario in Figure 19 is defined by the hard estuary defences. The **Accommodate Erosion** A and B scenarios both discourage re-development or new development across made-ground. The **Transformative** scenario runs along the natural boundary created by the increase in elevation, with less extreme habitat loss than the Dumbarton to Milton section.

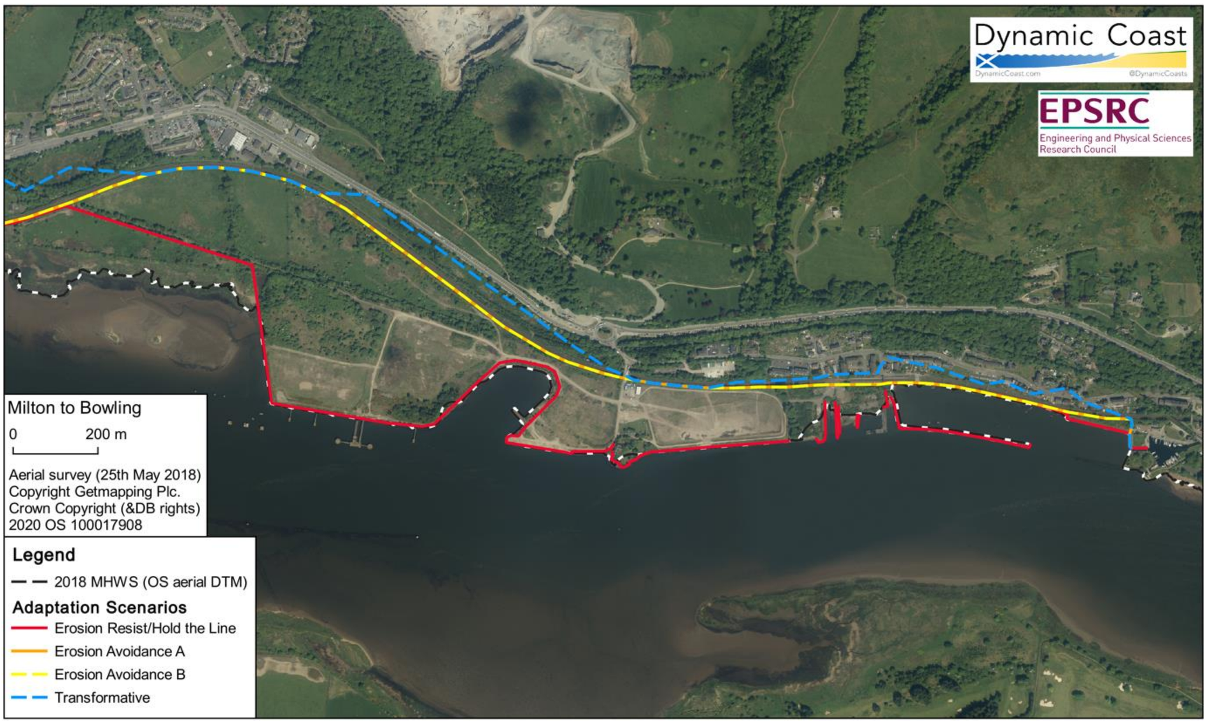

Figure 19 Milton to Bowling adaptation scenarios

Development Policies (From LDP2 Report of Examination April 2020)

Woodland Trust Scotland would like to see urban native trees included as part of the development, with appropriate native trees selected to provide benefits and be best adapted in the urban environment, as part of the enhancement of the existing green infrastructure.

Network Rail state that early engagement with them is essential to ensure that their rail assets are protected and train service delivery is not compromised.

SNH state that despite a lack of clarity (in west Esso Bowling being marked as Green Belt on the Proposals Map and Green Network Enhancement on the Strategy Map), they welcome the proposal for Open Space/Green Belt and Green Network Enhancement within west of the site. Although SNH are disappointed that this Open Space does not extend through the site to the east (including linking to Scott's Yard), which would follow the SPA and enable landscape enhancement and recreational access along the shore.

From LDP2 Report of Examination April 2020:

"SEPA (PLDP/676/4) state that are generally supportive of the proposed development uses of all of the key sites, but strongly emphasise that in circumstances, such as Scott's Yard/Esso Bowling, where a more vulnerable residential use is being proposed, the recommendations of the Flood Risk Assessment will be critical to the viability of the site. This will be particularly relevant, as new data emerges on flood risk and climate change which could further restrict sustainability of residential development at this location."

"With regard to the RSPB's request to reintroduce a section of the 2016 Proposed Plan strategy for the west of the site in relation to coastal realignment, climate change and migration of habitats, the Council would point out that the

project has been adjusted due to further technical work taken between the Proposed Plan (2016) (CD 13) and Local Development Plan 2 and these adjustments have resulted in the area of land previously allocated within the Proposed Plan (2016) (CD 13) being removed within this Plan. The Council would point out that wider area of green network enhancement has been provided to the immediate west of the land the RSPB are commenting upon. As SNH have not raised any issues with the change in strategy, no modifications to the Plan are required in this regard."

Influencing Future Climate Change Resilience with Decisions Made Now

The current local development plan for Esso Bowling and Scott's Yard shows a combination of:

- Erosion Resist where a wall is proposed, with large numbers of new businesses being proposed which creates a lock-in that could be avoided;
- Erosion Avoidance where areas are being proposed to allow flooding and accommodation space for habitats to adapt to climate change.

In this plan, it is proposed that the road will be aligned seaward of its current location, in an area with underlying natural erosion susceptibility. Based on this work, the following questions need to be considered by councils and politicians:

- Can we afford to maintain Erosion Resist management approaches into the future?
- Are assets we build now placed in sites requiring continued capital and maintenance costs to manage flood and erosion risk? Ad Infinitum?
- Can we afford such costs for the design life of the new assets?
- What long-term multiple benefits do Erosion Avoidance options provide (lower cost/greater wellbeing/ habitats)?
- How can we make planning decisions on land that support natural processes to increase our natural resilience to coastal climate change?
- How can the planning (and other) tools you have now be used to safeguard space on land for future adaptation?

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Appendix

Table 6 Volume changes per management unit and sub-section, defined by geomorphic type

MGMT Unit	Section ID	Geomorphic description	Area covered (m^2)	Volume change 2003-2018 (m^3)	Volume change rate 2003-2018 (m^3/yr)
1	1	Muddy intertidal	151,500	-76,800	-5,100
	2	Muddy foreshore	21,400	-11,100	-700
	3	Intertidal	74,300	-9,700	-600
	4	Nearshore	153,100	-42,500	-2,800
	5	Foreshore	29,700	-8,400	-600
	6	Foreshore	16,500	-3,700	-200
	7	Foreshore	30,700	-7,100	-500
	8	Veg edge	14,400	-1,200	-80
	9	Backshore	31,900	-700	-40
2	10	Intertidal	72,900	-22,700	-1,500
	11	Veg edge	9,800	-2,000	-100
	12	Backshore	32,000	-5,000	-300
	13	Backshore	21,200	8,600	600
	14	Intertidal	63,800	-15,400	-1,000
	15	Veg edge	10,400	500	30
	16	Backshore	41,500	-1,900	-100
	17	Backshore	7,800	2,800	200
	18	Intertidal	101,500	-20,000	-1,300
	19	Veg edge	11,500	900	60
	20	Backshore	31,400	7,100	500
	21	Intertidal	111,300	-35,000	-2,300
	22	Foreshore	16,200	-4,000	-300
	23	Veg edge	16,500	1,000	70
	24	Backshore	85,300	31,900	2,100

End.