Cyfoeth Naturiol Cymru
Natural Resources Wales

A review of the role of coastal and marine habitats in mitigating coastal flooding and erosion in Wales

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Acronyms, abbreviations & glossary of terms

CCSL: Critical Storm Surge Level

EAD: Expected Annual Damages

FCERM: Flood and Coastal Erosion Risk Management

HAT: Highest Astronomical Tide: the highest water level that can be expected to occur under average meteorological conditions.

Hw_{max}: maximum flood depth

Hs_{max}: maximum wave height

HWL: High Water Level

HTL: Hold the Line SMP policy

LiDAR: Light Detection and Ranging (elevation data)

MHW: Mean High Water: Average height of the daily high waters measured over a 19-year period.

MHWN: Mean High Water Neap: the average of two successive high waters during a period of 24 hours when the range of the tide is at its least.

MHWS: Mean High Water Springs: the average of two successive high waters during a period of 24 hours in each month.

MLWS: Mean Low Water Springs :the average of two successive low waters during a period of 24 hours in each month.

MPA: Marine Protected Area

MR: Managed Realignment SMP policy

MSR: Mean Spring Tidal Range: the difference between the mean high water springs and mean low water springs.

NAI: No Active Intervention SMP policy

OD: Ordnance Datum

RCP scenario: Representative Concentration Pathway scenario

RSLR: Relative Sea Level Rise

SMP: Shoreline Management Plan

SPA : Special Protection Areas

SSSI : Site of Special Scientific Interest

SWEL: Still Water Elevation Level: the average water surface elevation at any instant, excluding variation due to waves and wave set-up but which includes the effects of tides and storm surges.

Crynodeb Gweithredol

Nod yr astudiaeth hon oedd asesu'r ffyrdd y gall cynefinoedd arfordirol ac atebion sy'n seiliedig ar natur helpu i liniaru perygl llifogydd ac erydu ar arfordir Cymru. Cynhaliwyd adolygiad tystiolaeth cyflym o lenyddiaeth academaidd a llenyddiaeth lwyd i asesu'r dystiolaeth ar y prosesau y mae cynefinoedd yn eu defnyddio i liniaru perygl llifogydd ac erydu, ac unrhyw dystiolaeth yn ymwneud â manteision cost defnyddio'r atebion hyn sy'n seiliedig ar natur. Mae'r adolygiad yn canolbwyntio'n bennaf ar y manteision sy'n gysylltiedig â'r risgiau presennol o lifogydd ac erydu, ond mae tystiolaeth ar effeithiau hirdymor posibl newid yn yr hinsawdd wedi'i chynnwys pan fydd ar gael.

Aseswyd chwe math eang o gynefin gwahanol fel rhan o'r adolygiad, gan gynnwys y canlynol:

- Morfa heli
- Llaid a thywod rhynglanw
- Dolydd morwellt
- Twyni tywod
- Systemau traeth (gan gynnwys tywod a cherrig mân)
- Riffau biogenig

Mae datrysiadau seiliedig ar natur a thechnegau rheoli llifogydd naturiol yn cael eu cydnabod yn gynyddol fel cyfle i fynd i'r afael â pherygl llifogydd mewn ffordd fwy cynaliadwy, ond hyd yma, mae eu defnydd mewn prosiectau a rhaglenni rheoli llifogydd wedi bod yn gyfyngedig. Felly, mae'r adolygiad yn bwriadu codi ymwybyddiaeth o rôl y cynefinoedd hyn a'r atebion i liniaru perygl llifogydd ac erydu arfordirol. Gall hyn hysbysu ymarferwyr am y cyfleoedd sydd ar gael i ystyried ac integreiddio eu defnydd o fewn yr achosion busnes ar gyfer rhaglenni rheoli perygl llifogydd ac erydu arfordirol yn y dyfodol, a phrosiectau ehangach.

Mae'r adolygiad yn amlygu y gall y cynefinoedd uchod ddarparu swyddogaethau sylweddol o ran gwarchod yr arfordir, ond mae'r graddau'n amrywio rhwng y mathau o gynefinoedd, a gallant ddibynnu ar amrediad o nodweddion safle-benodol.

Mae morfeydd heli yn gweithredu fel llain glustogi yn erbyn grym tonnau a stormydd a llifau cerrynt. Maent yn amddiffyn yr arfordir trwy dri phrif ddull, sef gwanhau tonnau, sefydlogi traethlin a dal dŵr llifogydd. Mae gwanhau tonnau o fewn morfeydd heli yn bennaf yn swyddogaeth o effeithiau bathymetreg a dyfnder dŵr, a nodweddion llystyfiant ar wyneb y gors, sy'n cynhyrchu effeithiau ffrithiannol ar donnau. Mae amrediad o werthoedd wedi'u cofnodi ar gyfer eu gallu i wanhau tonnau, gyda rhai astudiaethau'n awgrymu y gallant leihau uchder tonnau 72% ar gyfartaledd ar draws arwyneb cyfan y gors (Narayan, Beck, Reguero, Losada, Van Wesenbeeck, et al., 2016).

Mae presenoldeb llystyfiant yn cael effaith gadarnhaol sylweddol ar wanhau tonnau (Shepard, Crain a Beck, 2011) o gymharu ag arwynebau heb lystyfiant, ond mae astudiaethau hefyd yn awgrymu y gall nodweddion planhigion a math o rywogaethau hefyd effeithio ar raddau'r gwanhau. Fodd bynnag, mae astudiaethau efelychu diweddar wedi canfod bod hyd at 95% o ostyngiad cyffredinol yng ngrym tonnau cyn ised â 50% o orchudd llystyfiant morfa heli (Castagno et al., 2022).

Yn ogystal, gall morfeydd heli wasgaru lefelau dŵr uchel a grym tonnau yn effeithiol o dan amodau storm a lefel dŵr eithafol, ond mae sawl ffactor allweddol yn dylanwadu ar hyn, gan gynnwys nodweddion ecosystem y gors, y storm a'r dirwedd ar raddfa fwy. Fodd bynnag, nid yw'r canfyddiadau hyn yn berthnasol yn gyffredinol ar gyfer safleoedd adlinio rheoledig. Mae'r dystiolaeth hefyd yn awgrymu efallai na fydd safleoedd adlinio rheoledig yn darparu'r un lefel o wasanaethau perygl llifogydd â chorsydd naturiol oherwydd yr amser y mae'n ei gymryd i aeddfedu a datblygu cymhlethdod morffolegol tebyg i gorsydd yn eu cyflwr naturiol. Mae nifer o astudiaethau diweddar wedi ceisio amcangyfrif gwerth economaidd amddiffyn yr arfordir a lliniaru perygl llifogydd a ddarperir gan forfeydd heli, gyda rhai amcangyfrifon, er enghraifft, dros £105,000 yr hectar o forfeydd heli mewn costau amddiffyn a osgoir (Thornton, G. Luisetti, et al., 2019).

Gall dolydd morwellt ddarparu amddiffyniad arfordirol trwy leddfu grym ac uchder tonnau a achosir gan effeithiau ffrithiannol wrth i donnau basio trwy lystyfiant yn y golofn ddŵr. Gall morwellt hefyd fod yn effeithiol wrth wanhau llif a chyflymder cerrynt. Mae amgylcheddau dŵr bas a nerth tonnau isel yn fwy tebygol o ddarparu'r amodau gorau posibl i forwellt ddarparu amddiffyniad o'i gymharu â dyfroedd dyfnach. Mae rhai astudiaethau'n awgrymu y gallai dolydd morwellt arwain at ostyngiad o 36% yn uchder tonnau ar gyfartaledd (Narayan, Beck, Reguero, Losada, Van Wesenbeeck, et al., 2016). Fodd bynnag, mae gallu morwellt i leihau perygl llifogydd ac erydu yn fwy cyfyngedig na chynefinoedd eraill, megis morfa heli, oherwydd ffactorau megis hyblygrwydd uwch y llystyfiant. Mae effeithiolrwydd dolydd morwellt yn dibynnu ar lystyfiant a math o rywogaethau, biomas, natur dymhorol ac ansawdd dŵr. Ni all morwellt warchod traethlinau ym mhob lleoliad a/neu senario, ac mae rhai astudiaethau'n awgrymu y gallai atebion hybrid, lle caiff plannu morwellt ei gyfuno â maeth y traeth neu ei osod o flaen twyni, ddarparu dull mwy effeithiol o ddefnyddio morwellt i amddiffyn yr arfordir.

Gall systemau traeth a thwyni tywod chwarae rhan sylweddol mewn lliniaru amddiffynfeydd rhag llifogydd ac erydu arfordirol trwy weithredu fel clustogfeydd i effeithiau tonnau a llifogydd arfordirol. Maent yn systemau deinamig sy'n golygu y gallant fynd trwy newidiadau cyflym ac anrhagweladwy. Fodd bynnag, mae eu heffeithiolrwydd wrth ddarparu amddiffyniad arfordirol yn dibynnu ar allu'r system i weithredu mewn cyflwr naturiol, e.e. trwy brosesau naturiol cludo gwaddod, a lle nad yw symudiad a mudo'r cynefinoedd yn cael eu cyfyngu gan ddatblygiadau arfordirol neu strwythurau amddiffyn. Yn ystod y blynyddoedd diwethaf mae gwaith wedi'i wneud i wella'r ddealltwriaeth o ymatebion systemau traeth (cerrig mân a graean) i stormydd er mwyn helpu i wella rhagfynegiadau o'u hymateb morffolegol i ddigwyddiadau o'r fath. Fodd bynnag, prin yw'r enghreifftiau ac astudiaethau achos, yn enwedig yng Nghymru, o ddefnydd ac effeithiolrwydd systemau traethau a thwyni tywod ar gyfer amddiffyn yr arfordir, a manteision cost defnyddio technegau rheoli sy'n gysylltiedig â'r systemau hyn. Mae angen gwneud mwy o waith i fynd i'r afael â'r bwlch hwn yn y dystiolaeth er mwyn asesu eu defnyddioldeb o safbwynt amddiffyniad arfordirol ac o gymharu ag atebion eraill sy'n seiliedig ar natur.

Mae systemau riffau biogenig yn cynnwys riffau o wystrys, cregyn gleision, a riffau Sabellaria (llyngyr diliau). Mae eu gallu i warchod yr arfordir yn bennaf yn dibynnu ar osgled llanw lleol a maint yr ecosystem, ond mae cynefinoedd yn y parthau isaf o'r amrediad rhynglanwol yn tueddu i fod yn llai effeithiol na'r rhai uchel yn y parth rhynglanwol ar gyfer gwanhau tonnau oherwydd dyfnder llifogydd tonnau uchaf uwch. Fodd bynnag, gall riffau chwarae rhan anuniongyrchol bwysig wrth sefydlogi'r is-haen a'r gwely gwaddod, a thrwy hynny amddiffyn ecosystemau sy'n uwch yn yr amrediad llanw, yn enwedig gwastadeddau rhynglanwol, rhag ynni hydrodynamig, a thrwy hynny eu hamddiffyn rhag erydu a helpu i gynyddu mewnbynnau gwaddod i wastadeddau rhynglanwol.

Mae trefniadau llanw hefyd yn cael effaith nodedig ar y graddau y gall gwahanol gynefinoedd ddarparu gwarchodaeth arfordirol effeithiol i gynefinoedd i ddarparu gwarchodaeth arfordirol. Mae cyfran fawr o forlin Cymru yn profi trefniadau llanw macro (>4m o amrediad llanw'r gwanwyn) neu lanw mega (>8m o amrediad llanw'r gwanwyn) (Horrillo-Caraballo et al., 2021). Mae'r berthynas eang rhwng amrediad llanw ac uchafswm dyfnder llifogydd ac uchder tonnau uchaf felly yn awgrymu, os edrychir arnynt ar eu pen eu hunain, y gallai cynefinoedd sydd i'w cael yn uwch yn y parth rhynglanwol, megis morfeydd heli, twyni tywod a systemau traethau, fod yn fwy effeithiol wrth glustogi'r cynnydd yn nyfnder dŵr a llifogydd sy'n gysylltiedig â chynnydd mewn amrediad llanw (Bouma et al., 2014).

Mae'r adolygiad yn dangos pwysigrwydd y cynefinoedd morol ac arfordirol o ran darparu mesurau lliniaru yn erbyn risgiau llifogydd ac erydu. Mae hyn yn amlygu pwysigrwydd gwarchod a rheoli cynefinoedd yr arfordir yng Nghymru i gynnal a/neu wella eu cyflwr a sicrhau eu bod yn gallu gwrthsefyll amryfal bwysau fel newid yn yr hinsawdd, datblygu a gwasgfa arfordirol i sicrhau y gallant ddarparu'r gwasanaethau diogelu'r arfordir hyn a buddion ehangach. Yn ogystal, mae'r canfyddiadau'n tynnu sylw at rôl bosibl adfer a chreu cynefinoedd wrth ddarparu atebion seiliedig ar natur sy'n cefnogi rheoli llifogydd mewn lleoliadau priodol ar hyd arfordir Cymru.

Erys tystiolaeth gyfyngedig ar fanteision perygl llifogydd ac erydu, a manteision cost rhai cynefinoedd yr arfordir. Mae hyn yn arbennig o wir ar gyfer systemau traeth, twyni tywod a riffau biogenig lle byddai tystiolaeth bellach yn helpu i gefnogi'r dadansoddiad o'u heffeithiolrwydd wrth liniaru perygl llifogydd ac erydu.

Executive summary

The aim of this study was to assess the ways in which coastal habitats and nature-based solutions can help to mitigate flood and erosion risk at the coast in Wales. A rapid evidence review of academic and grey literature was undertaken to assess the evidence on the processes by which habitats provides flood risk and erosion mitigation and any evidence related to the cost-benefits of using these nature-based solutions. The review principally focusses on the benefits associated with current flood and erosion risks, but evidence on potential long-term impacts from climate change is included where available.

6 different broad habitat types were assessed as part of the review, including:

- Saltmarsh
- Intertidal muds and sands
- Seagrass meadows
- Sand dunes
- Beach systems (including sand and shingle), and
- Biogenic reefs

Nature-based solutions and natural flood management techniques are increasingly recognised as an opportunity to address flood risk in a more sustainable way, but to date, their use in flood management projects and programmes has been limited. The review therefore intends to raise awareness of the role of these habitats and solutions in mitigating flood and coastal erosion risk. This can inform practitioners of available opportunities to consider and integrate their use within the business cases for future flood and coastal erosion risk management programmes and wider projects.

The review highlights that the above habitats can provide significant coastal protection functions, but the degree varies between habitat type(s) and can depend on a range of site-specific characteristics.

Saltmarshes act as a buffer against wave and storm energy and current flows. They provide coastal protection through three primary mechanisms, namely, wave attenuation, shoreline stabilisation and floodwater retention. Wave attenuation within saltmarshes is largely a function of the effects of bathymetry and water depth and the characteristics of vegetation on the marsh surface which produce frictional effects on waves. A range of values have been recorded for their wave attenuation capacity, with some studies suggesting they can reduce wave heights by an average of 72% across the whole marsh surface (Narayan, Beck, Reguero, Losada, Van Wesenbeeck, *et al.*, 2016).

The presence of vegetation has a significant positive effect on wave attenuation (Shepard, Crain and Beck, 2011) compared to unvegetated surfaces but studies also suggest that plant characteristics and species type can also impact on the degree of attenuation. However, recent simulation studies have found that up to a 95% overall reduction in wave energy was found at as low as 50% saltmarsh vegetation cover (Castagno et al., 2022).

In addition, saltmarshes can effectively dissipate high-water levels and wave energy under storm and extreme water level conditions, but several key factors influence this, including the characteristics of the marsh ecosystem, storm events and larger-scale landscape. However, these findings do not generally hold for managed realignment sites. The evidence also suggest that managed realignment sites may not provide the same level of flood risk services as natural marshes due to the time that it takes to mature and develop a morphological complexity similar to marshes in their natural states. A number of recent studies have attempted to estimate the economic value of coastal protection and flood risk mitigation provided by saltmarshes, with, for example, some estimates at over £105,000 per ha of saltmarsh in avoided defence costs (Thornton, G. Luisetti, *et al.*, 2019).

Seagrass meadows can provide coastal protection through the dampening of wave energy and height that is caused by frictional effects as waves pass through vegetation in the water column. Seagrass can also be effective at attenuating current flow and velocity. Shallow water and low wave energy environments are more likely to provide optimal conditions for seagrass to provide protection compared to deeper waters. Some studies suggest that seagrass meadows could lead to a reduction of wave heights by an average of 36% (Narayan, Beck, Reguero, Losada, Van Wesenbeeck, *et al.*, 2016). However, the capacity of seagrass to reduce flood and erosion risk is more limited than other habitats such as saltmarsh, due to factors such as the higher flexibility of the vegetation. The effectiveness of seagrass meadows depends on vegetation and species type, biomass, seasonality, and water quality. Seagrass cannot protect shorelines in every location and/or scenario and some studies suggest that hybrid solutions, where seagrass planting is combined with beach nourishment or placed in front of dunes, could provide more effective means of using seagrass for coastal defence.

Beach systems and sand dunes can play a significant function in mitigating coastal flood and erosion defence by acting as buffer zones to the effects of coastal waves and flooding. They are dynamic systems which means that they can undergo rapid and unpredictable changes. However, their effectiveness in providing coastal protection depends on the capacity of the system to act in a natural state e.g through natural processes of sediment transport and where the movement and migration of the habitats are not restricted by coastal developments or defence structures. In recent years work has been done to improve the understanding of the responses of beach systems (shingle and gravel) to storm events in order to help improve predictions of their morphological response to such events. However, there are limited examples and case studies, particularly in Wales, of the use and effectiveness of beach systems and sand dunes for coastal protection and the cost benefits of using management techniques associated with these systems. More work is needed to address this evidence gap to assess their utility from a coastal defence perspective and in comparison to other nature-based solutions.

Biogenic reef systems include oyster reefs, mussels, and Sabellaria (honey comb worm) reefs. Their ability to provide coastal protection mainly depends on the local tidal amplitude and size of the ecosystem but habitats in the lower zones of the intertidal range tend to be less effective than those high in the intertidal zone for wave attenuation due to higher maximum wave flooding depth. However, reefs can play an important indirect role in stabilising substrate and the sediment bed and thereby protect ecosystems higher in the tidal range- particularly intertidal flats- from hydrodynamic energy, thereby protecting them from erosion and helping to increase sediment inputs to intertidal flats.

Tidal regimes also have a notable impact on the degree to which different habitats can provide effective coastal protection effectiveness of habitats to provide coastal protection. A large proportion of the Welsh coastline experiences macro (>4m spring tidal range) or mega tidal regimes (>8m spring tidal range) (Horrillo-Caraballo *et al.*, 2021). The broad relationship between tidal range and maximum flood depth (hw_{max}) and maximum wave height (Hs_{max}) therefore suggests that if viewing them in isolation, that habitats that are found higher in the intertidal zone, such as saltmarsh, sand dunes and beach systems, may be more effective in buffering the increases in water depth and flooding associated with increases in tidal range (Bouma *et al.*, 2014).

The review demonstrates the importance of the marine and coastal habitats in providing mitigation against flood and erosion risks. This highlights the significance of protecting and managing coastal habitats in Wales to maintain and/or improve their condition and ensure their resilience against multiple pressures such as climate change, development and coastal squeeze to ensure that they can provide these coastal protection services and wider benefits. In addition, the findings highlight the potential role of habitat restoration and creation in providing nature-based solutions that support flood management at appropriate locations along the Welsh coast.

There remains limited evidence on the flood and erosion risk benefits and cost benefits of certain coastal habitats. This is particularly the case for beach systems, sand dunes and biogenic reefs where further evidence would help to support the analysis of their effectiveness in mitigating flood and erosion risk.

Introduction

Background

Climate change will have profound implications for coastal communities, increasing the frequency and magnitude of extreme water levels around the UK coastline. Over 70,000 properties in Wales and roughly 191,000 people are currently at risk of flooding from the sea alone (Natural Resources Wales, 2023). With future climate change, coastal areas will be at increased risk of coastal flood and erosion events, driven predominantly by an increase in mean sea-level rise which is projected in the UK under all emission scenarios (Met Office, 2019). This will have significant impacts for communities who live and work in coastal areas. For example, estimates suggest that an additional 33,000 properties and 95,000 people will be at risk from flooding by the sea by 2120 (ibid.). In addition, these effects will impact on some of Wales' most important natural habitats and heritage sites which are located along our coastline.

Typically, the standard approach towards providing coastal protection has relied on the use of hard infrastructure such as seawalls, groynes, levees and breakwaters. However, these types of defences also tend to cause unintended outcomes for the natural environment in terms of reducing natural diversity along coastlines and can lead to, 'coastal squeeze' where habitats are eroded or diminished due to being prevented from naturally migrating inland. In addition, the costs associated with storm surges and rising sea-levels have been increasing in low lying coastal areas in recent years and these are likely to increase further in the future with the predicted increase in the frequency of coastal flooding and extreme weather events with climate change (Hynes *et al.*, 2022). This will mean that it will become increasingly unviable to prevent flooding in every location both now and in the future through the use of traditional hard defence and flood measures (Natural Resources Wales, 2023) (Sayers, P.B et al. in (Haigh *et al.*, 2022)).

Whilst these types of defence will still be needed in certain locations to protect properties and infrastructure, there is an increasing recognition that natural flood management techniques, or nature-based solutions can provide an alternative or complementary form of coastal protection and adaptation. The Welsh Government's National Strategy for Flood and Coastal Erosion Risk Management (Welsh Government, 2020) recognises the role that nature-based solutions and natural habitats can provide in delivering cost-effective solutions to reduce flood risk and supporting coastal zone management and adaptation. It references a range of actions, including safeguarding and managing threatened habitats, and habitat restoration as part of strategic direction for the management of the coast over the next century through the Shoreline Management Plans (SMP). As well as their role in mitigating flood risks, they can provide a range of other benefits, including creating habitats for wildlife and improving biodiversity, storing carbon, attracting tourism to boost local economies and providing recreational opportunities that can support individual health and well-being.

Marine and coastal habitats such as saltmarshes, shingle and sand dunes play an important role in helping to mitigate coastal flood risk and support climate change adaptation. At the coast, there are opportunities to restore habitats and ecosystems as well as deploy management techniques such as beach and shingle nourishment or hybrid solutions that can help to support more natural coastal processes and mitigate flood and erosion risks. Nature-based solutions may however not be suitable for all types of coastal defence and setting. Their effectiveness will vary depending on the nature and magnitude of coastal and tidal floods and storms, they can also have long lag-times in terms of their establishment and there may be trade-offs between different goals and beneficiaries at certain locations (Smith, A and Chausson, A, 2021).

However, coastal margin environments have experienced declines and significant losses in their extent, condition, and connectivity of habitats over several decades (Natural Resources Wales, 2020). Major changes in saltmarsh extent have occurred due to historical land claim and roughly 30% of the original sand dune area in Wales has been lost to development and erosion since 1900 (ibid.). Mean sea-level rise with climate change and the effects of coastal squeeze will also likely lead to continued declines in the extent of ecosystems over the next century and beyond. For example, up to 21-25% of saltmarsh features in marine protected areas (MPAs) in Wales is predicted to be lost through the effects of coastal squeeze by 2155 (Oaten, Finch and Frost, 2024a). Climate change is also predicted to lead to the loss in extent and fragmentation of ecosystems from increased storminess leading to higher rates of erosion, and increased flooding and storm damage without appropriate intervention or management activities (Haigh *et al.*, 2022).

Much work has been done to understand the opportunities and relevant processes and mechanisms to create and deploy solutions in the field (Kenneth Pye, Blott and Guthrie, 2017) (Pye and Blott, 2018) (McCue, Pye and Wareing, 2010). However, less work has been done on exploring and summarising the processes and benefits they provide in relation to reducing flood and erosion risk at the coast risk relative to using more traditional defence approaches, particularly on cost-benefits. McKinley *et al.* (2020), focussing principally on saltmarshes, have also highlighted how there is limited public awareness and high degrees of uncertainty regarding the benefits that are provided by coastal habitats.

In order to maximise the opportunities for management, restoration and project activities that can utilise such solutions, there is a need to foster and enhance knowledge and awareness of the evidence of the benefits provided by them and with reference to specific localities in Wales and the impacts of particular interventions on flood risk (Bennett *et al.*, 2023).

This aim of this review is to summarise the physical (flood risk reduction) benefits of coastal habitats. The key objectives are to:

- Understand the effectiveness of different types of coastal habitat to help mitigate flood and erosion risk, and against different magnitudes of flood and erosion risk.
- Describe the processes and key factors involved in the delivery of the flood risk and erosion protection and
- Understand any evidence related to the economic and cost-benefits of using natural flood management techniques at the coast relative to traditional defence structures.

It focusses specifically on the evidence related to current flood and erosion risks and does not aim to assess the ability of coastal habitats and NbS to provide protection against future climate risks. However, where relevant evidence does exist this has been included for reference.

Methodology

A Rapid Evidence Review was undertaken to complete the assessment following guidance specified by Defra and the Natural Environment Research Council (NERC) (Collins, A et.al, 2015). This method was selected based on the approximate time length available to complete the review (6-8 months) and the inclusion of a critical appraisal of the evidence, without the comprehensiveness required by a full Systematic Review.

The first step of the review entailed the production of a Review Protocol as detailed in the guidance which specified the core primary and secondary research questions, scope, inclusion and exclusion criteria and search methods.

The next step of the review entailed the assessment of the evidence base to answer the primary research question of what flood risk benefits were provided by coastal habitats. This largely entailed an assessment of academic peer-reviewed literature, but also included relevant grey-literature sources from institutions and environmental regulators. Details of the primary and secondary research questions inclusion and exclusion criteria and subsequent search strings can be found in the Appendix.

The review focusses on the following types of coastal habitat that are of most relevance to those found along the Welsh coastline:

- Saltmarsh,
- Intertidal mud and sands
- Seagrass meadows
- Sand dunes
- Beach systems (including sand and shingle), and
- Biogenic reef systems

The review does not assess the evidence in relation to green-grey infrastructure except for those cases which assess the use of hybrid systems where for example a coastal habitat or beach nourishment approach is used in conjunction with traditional defence structures. A previous guidance report (Natural Resources Wales, 2022) is available which provides details on the opportunities to use ecological enhancement features in coastal defence schemes.

An initial earliest search date of 2008 was selected to collate the most recent evidence on the coastal protection benefits of nature-based solutions. During the analysis some articles that were found from other articles and published prior to this date were included where they were of relevance to the evidence base. Additional relevant articles that were found through these journals and not found in the original search were included in the analysis.

Saltmarsh

Saltmarshes are coastal wetlands that are usually found in intertidal settings in sheltered environments between marine and the terrestrial boundaries of estuaries. The terrestrial borders of saltmarshes are defined by the highest astronomical tide (HAT) and at their sea-facing side, saltmarshes will typically be connected to mudflats. Saltmarshes in the UK are typically comprised of three broad zones along the vegetated platform of the marsh profile as shown in Figure 1 These are a lower marsh, which is located between the sea-facing platform, and Mean High Water Neap (MHWN) tidal levels (flooded twice daily). A middle marsh area extends from MHWN to Mean High Water Spring tidal level (MHWS) and an upper marsh between MHWS and HAT (Bennett *et al.*, 2023).

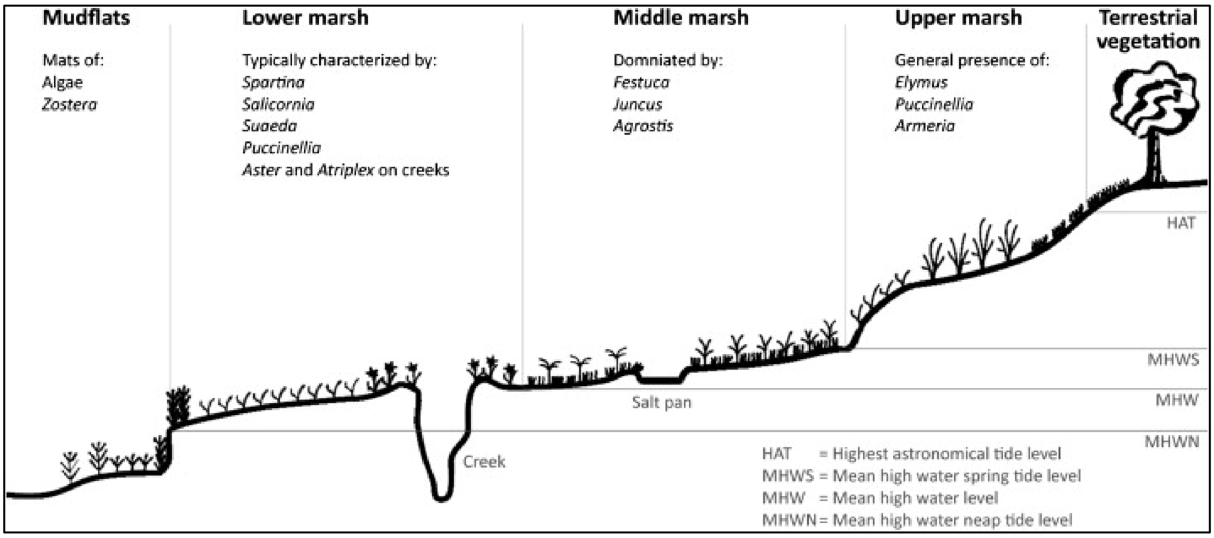

Figure 1: A typical general profile of saltmarsh systems in the UK. Source: Foster *et al.* (2013).

Saltmarshes can act as a buffer against wave and storm energy and current flows through both direct and indirect mechanisms. They can help to reduce flood risk by three primary mechanisms, namely, wave attenuation, shoreline stabilisation and floodwater attenuation.

Wave attenuation

Waves approaching shorelines are either generated locally through the action of wind waves or by the action of offshore winds (swell waves). The latter are generated over much longer distances and periods and therefore tend to have more power than those generated locally and wave run-up and overtopping are also usually greater in swell waves than in wind waves of equivalent height (Forbes, Ball and McLay, 2015).

Wave attenuation by coastal habitats (or saltmarshes) refers to the process by which saltmarshes reduce the energy of waves and/or wave heights. This is achieved either through the frictional drag produced by vegetation on a marsh surface (Jordan and Fröhle, 2022) and topographic variations over the marsh surface (Leonardi *et al.*, 2018) or the build-up of peat and soil on a marsh which alters their bathymetry and therefore the shape and depth of the underwater and near-water surfaces which interact with waves (Jordan, P

& Fröhle, P, ibid.). This physically constrains wave formation and results in wave dampening or a reduction in wave heights. Reductions in wave height and energy also depend on habitat and site-specific ecological and geophysical factors that influence the dynamics of incoming waves (Narayan, Beck, Reguero, Losada, van Wesenbeeck, *et al.*, 2016).

Narayan *et al.* (2016) undertook a meta-analysis of 69 studies which looked at the effectiveness of coastal habitats in reducing wave attenuation and found, that on average, saltmarshes were one of the most effective habitats in terms of wave reduction, on average reducing wave heights by 72% (95% CI 62-79%).

Broadly, tidal amplitude will play a role in the effectiveness of wave attenuation by different coastal habitats. The maximum flood depth (hw_{max}) and maximum wave height (Hs_{max}) that intertidal ecosystems encounter increase with tidal range. Bouma *et al.*, (2014) suggest that the effectiveness of wave attenuation decreases with maximum flood depth which means that the size of an intertidal habitat that is needed to provide wave attenuation values increases with tidal range as demonstrated in Figure 2 below.

The implications of this are that ecosystems that are high in the intertidal zone such as saltmarshes will generally be more effective at wave attenuation than those lower in the intertidal zone such as seagrass and biogenic reefs due to the lower maximum flooding depth (ibid.). However, the location of the ecosystem/habitat relative to the tidal range will also affect the wave attenuation and where wave attenuation in the tidal cycle will be optimal. Therefore, wave attenuation, particularly in those ecosystems occurring relatively low in the intertidal will be most beneficial in micro and meso-tidal ecosystems (such as mussel and oyster beds) because the maximum wave inundation will be relatively small and the time during which waves are exposed to the habitat longest.

This has potential implications for the effectiveness of different coastal habitats in Wales to provide coastal protection. There is a large geographical variation in tidal characteristics around the Welsh coastline but broadly, the South and North Wales coastlines are largely mega-tidal (tidal range exceeding 8m) and flood-dominant, whilst the West coast is predominantly macro-tidal (tidal range exceeding 4m) and ebb dominant (Horrillo-Caraballo, 2021). Estuaries and semi-enclosed nearshore areas within Wales also experience significant tidal amplification.

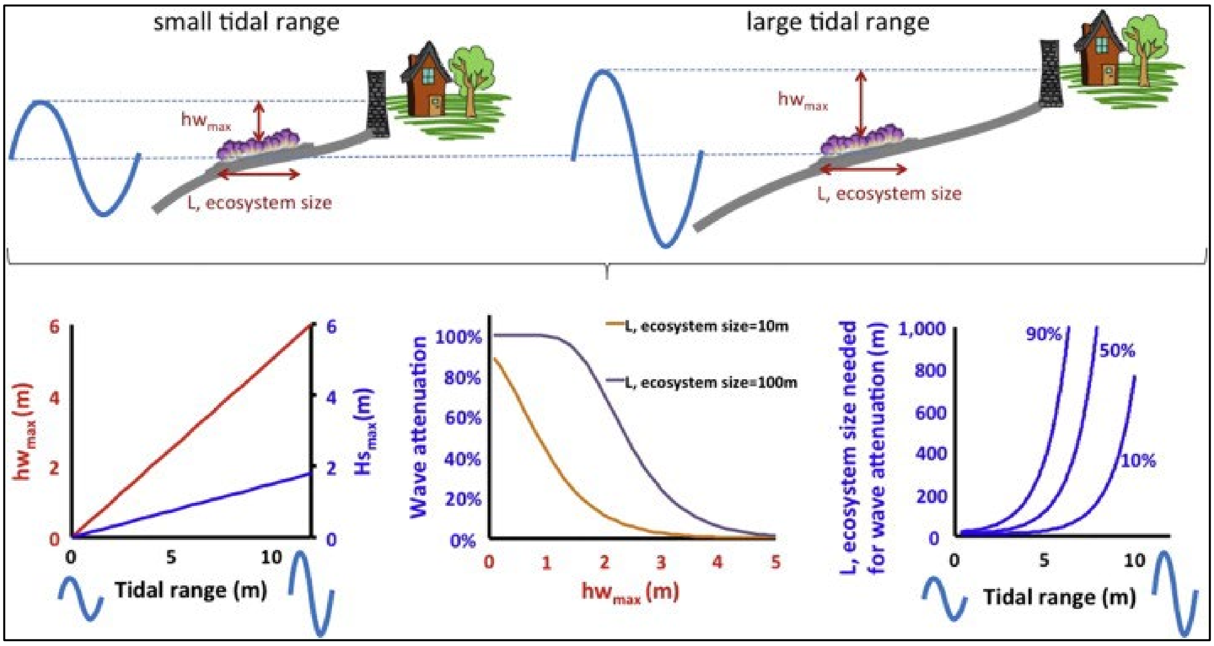

Figure 2: General relationship of the influence of tidal range and amplitude on wave attenuation of coastal habitats. Source: Bouma *et al.* (2014); $hw_{max:}$ maximum flood depth, hs_{max}: maximum wave height encountered by intertidal ecosystems.

Vegetation characteristics of saltmarshes also play an important role in the degree of wave attenuation. A meta-analysis of several papers by (Shepard, Crain and Beck, 2011) for example, which analysed the factors affecting the wave attenuation effects of saltmarshes found that the presence of vegetation and vegetation height has a significant positive effect on wave attenuation (d= 0.52m± 0.24). This process is complex and depends on different biophysical and hydrodynamic factors and the effects tend to be much smaller than those relating to changes in water depth (Jordan and Fröhle, 2022).

Generally, the energy of wind waves passing through a vegetated surface are dissipated by the work that is done by the waves on the vegetation. Dalrymple *et al.* (1984) used modified equations that were initially outlined by Morison *et al.* (1950) to demonstrate that this was a result of frictional drag forces exerted by vegetation on moving water whose cumulative effect leads to dissipation of wave energy and the reduction in wave height. This leads to reduced wave set-up and run up which can lead to lower flood water levels and minimises the effects of erosion on the shoreline. The general effects of these interactions can be broadly visualised in the diagram below

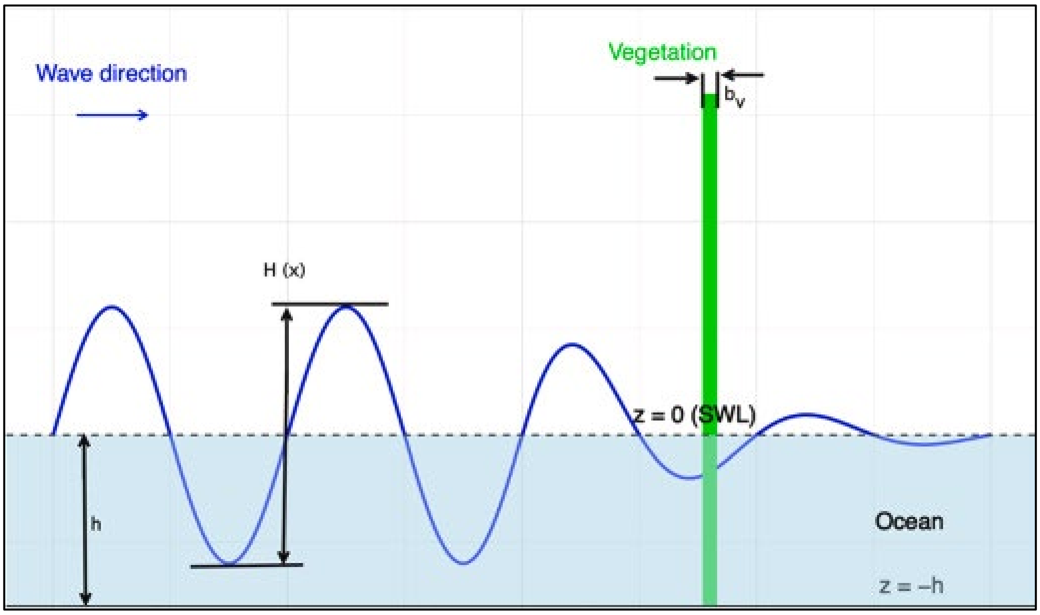

Figure 3: Schematic diagram of wave-vegetation interactions. Source: Daro Justine and Seenath (2025).

For saltmarshes, dissipation of wind waves increases with increasing relative wave height (the ratio between wave height and water depth) and a decreasing submergence ratio (ratio between water depth and plant height) (Leonardi et al., 2018). The degree of attenuation is also affected by plant characteristics such as standing biomass, geometry, stem density, spatial coverage and stiffness, and their interaction with incident wave characteristics such as wave height, period and length and hydrodynamic factors such as water depth and inundation (ibid.).

A key factor is also plant flexibility which impacts on the amount of resistance to wave flow (Jordan and Fröhle, 2022). The effect on wave attenuation tends to be strongest for stiff and dense vegetation and for the time that the water-level is relatively low compared to the vegetation (expressed as the Hw/Hp-ratio: or the water depth at high tide to average height of the tallest 33 % of plant stems) (Yang, 2011 in Pétillon, J *et.al*, (2023)). Seasonal patterns in vegetation cover over saltmarshes can also play a role in the degree of attenuation with studies suggesting that average wave attenuation is highest during the cycle of seasonal vegetation growth (Möller and Spencer, 2002).

Rupprecht *et al.* (2017) also explored vegetation-wave interactions in two typical NW European saltmarsh grasses - *Puccinellia maritima* (*Puccinellia*) and *Elymus athericus* (*Elymus*)- and tested the impacts when wave heights and water levels were at their highest, such as during storm (surge) events. They found a species-specific control of wave dissipation where plant flexibility and height, together with wave conditions and water depth play an important role in how the saltmarsh interacted with waves. Under low water levels (1m) and short wave periods (2.9s) they found that *Elymus* reduced near-bed velocity more than *Puccinellia*. However, under high water levels (2m) and long wave periods (4.1s), orbital velocities were reduced by 35% within the flexible, low-growing *Puccinellia* canopy. But in the more rigid, tall *Elymus* canopy, wave deflection and folding of stems occurred, but no significant effects on orbital velocities were found. The results highlight the potential species-specific controls that can influence wave dissipation which the authors argue could help to inform predictions of the wave dissipation capacity of marshes and their resilience to storm surge conditions.

Castagno et al. (2022) aimed to assess how much marsh restoration is enough to deliver measurable coastal protection benefits through using model simulations to develop empirical relationships between wave attenuation and vegetated and unvegetated surfaces and different morphological configurations of marsh sites. They found a substantial reduction in storm wave energy (up to 95%) when the first 100m of marsh is even as low as 50% vegetation cover. In 50% vegetated scenarios, for example, wave heights fell from almost 2 m to approximately 40 cm in the high-intensity wave scenario and from 0.9 m to less than 20 cm in the low-intensity wave scenario. The 50% vegetated benchmark was consistent across a wide range of wave intensities and marsh morphologies. They argue that the findings provide evidence for restoration practitioners to determine appropriate restoration planting density and distribution targets to maximize wave attenuation.

The importance of vegetation in dampening the effects of waves is notable in the difference in wave attenuation between saltmarshes and mudflats and sandflats, with studies suggesting that wave attenuation is greater across marsh vegetation than across the latter habitats (Shepard, Crain and Beck, 2011). Möller *et al.* (1999) for example, studied the difference in wave attenuation on a contiguous sand flat and saltmarsh system in Norfolk, England and found that wave energy dissipation/reduction rates were significantly higher over the saltmarsh (average of 82%) compared to the sand flat (average of 29%). They argued that the difference in wave attenuation could not be attributed to the difference in water depth between the two sections but was primarily due to an increase in surface friction over the saltmarsh. They also found that whereas saltmarsh appears to attenuate waves of all amplitudes to broadly the same degree, the sand flat attenuated waves of a low amplitude to a higher degree, which may be attributable to their rippled surface. The reduction in wave heights over the saltmarsh was also approximately four times higher (average 60·96%) than over the sand flat (average 15·29).

In a separate study, Möller *et al.* (2014) found that the presence of saltmarsh vegetation caused considerable wave attenuation even when water levels and waves were at their highest. In their experiment they assessed wave dissipation for regular and irregular waves under storm surge conditions in a 300m long flume tank for 7 different wave heights (between 0.1 and 0.9m in 2m water depth above the vegetated bed) for a marsh section of 40m in length. In their study, although waves caused damage and breaking of vegetation stems, the marsh substrate remained stable and resistant to surface erosion under all conditions. They estimated that up to 60% of observed wave reduction was attributable to the presence of vegetation. They argue that saltmarsh could form a valuable component of coastal protection schemes, but projects must also consider factors such as incident wave heights and water depths, wave dissipation requirements and the ecological conditions necessary for the maintenance of a healthy vegetation canopy.

A subsequent experiment also found that saltmarsh surfaces underneath a vegetation canopy can experience high geomorphological resilience to storm surge events (Spencer *et al.*, 2016). In the experiment, the marsh experienced less than 0.6cm average vertical lowering in response to a series of simulated storm surge conditions- despite the hydrodynamic stress tested being higher than in real surge conditions. The organic matter content and plant species exerted an important influence on the degree and variability of soil surface stability, with surfaces covered by the grass *Puccinellia* showing a higher resilience to wave forcing and lower and less variable elevation loss than those covered by *Elymus* or *Atriplex*. Studies to date also suggest that with increasing wave energy, high vegetation stiffness can enhance turbulence and surface erosion around plant stems (Leonardi *et al.*, 2018).

In laboratory flume experiments Gillis et al. (2022) found that saltmarsh vegetation was found to slow uni-directional current flow by almost 50% within the first 2.5m of the studied vegetation patch and the decrease in flow speeds led to sediment deposition after 1m. They also noted a reduction of turbulent kinetic energy from waves of up to 40% which led to sediment deposition at the leading edge of the marsh between 1.5-2.5m. The authors also analysed the impact of vegetation density on combined waves and currents and found decreases in velocity from 20-24% in cases of low density and 20 to 40% for higher densities of marsh.

Recent research has also sought to highlight how particular soil properties can impact on saltmarshes' capacity to mitigate coastal flooding and erosion risks. Marin-Diaz *et al.*, (2022) for example assessed different soil types within saltmarshes and bare tidal flats and quantified their ability to resist topsoil erosion, specifically in relation to how they can help to reduce breach depth under fast flow conditions following the failure of a dike. Their results suggest that, overall, established marshes are much more resistant to topsoil erosion following fast water flow (2.3 m/s) compared to bare tidal flats. All samples from the tidal flats were completely eroded, regardless of sediment type but by contrast, all samples from well-established marshes were stable as long as no disturbance was made. Within the different types of marshes, silty mature marshes were found to be the most stable.

Marin-Diaz *et al.* (2021) also explored how impacts of management activities affect soil stability and consequently their coastal protection capacity. They collected soil core samples from high and low marshes of different ages in the Netherlands and explored how different saltmarsh management practices combined with marsh elevation and age affect soil stability (collapse) and lateral erosion. The results from their wave flume experiments found that grazing and artificial mowing can increase the erosion-resistance of fine-grained soils and this was positively influenced by:

- The presence of large grazers (cattle) that compacted the soil by trampling.
- Mowing practices that exclude soil-bioturbating species, and
- Small grazers that promote vegetation with higher root density.

However, they noted that compaction by larger grazers can lead to thinner fine-grained layers and lower elevation which potentially could lead to more inundation by sea-level rise. In addition, marshes with thinner and/or fine-grained top layers were more sensitive to lateral erosion than marshes with deep cohesive soils, independent of any management practices. Similarly, Pagès *et al.* (2019) found the net effect of grazing to be a reduction in saltmarsh lateral erodibility and an increase in marsh resilience and highlight that grazers can act not only as modifiers of the abiotic environment, but also as controllers of the flow of energy and materials through the trophic web.

Marin Diaz (ibid.) propose the following methods to manage saltmarshes effectively to enhance their contributions to coastal protection, namely i) use moderate/rotational livestock grazing and avoid high intensity grazing in sediment-poor systems sensitive to sea-level rise, and ii) investigate measures that can be used to preserve small grazers. The findings are particularly relevant for Wales given the large percentage of saltmarsh that is owned by local farms and used for grazing practices (McKinley *et al.*, 2022).

In general, wave attenuation tends to be higher the larger (wider) the saltmarsh is (Jordan and Fröhle, 2022). A study by Möller and Spencer (2002) at Tillingham in Essex found wave height attenuation rates of 87.37% over a 163m (0.54% m^{-1}) section of marsh and a reduction of wave energy of 98.92% (0.61%/m). In contrast, a reduction of wave height of 21% and of wave energy attenuation of 35.25% was recorded over 147m of the mudflat. For smaller saltmarshes (transects <10m) attenuation rates are highly variable but there is some evidence to suggest that significant attenuation can occur within the marsh edge (Shepard, Crain and Beck, 2011). For example, a value of 43.81% (4.38% m^{-1}). for wave height attenuation and a 79.13% reduction in wave energy (7.91% m^{-1}) was recorded over a 10m section of Bridgewick saltmarsh in Essex (ibid.). Möller *et al.* (2014) also recorded wave dissipation rates of 20% over a 40m section of marsh in flume tank experiments. They found that the contribution was not only due to the presence of the marsh platform, but also significantly by the vegetation canopy.

However, studies also suggest that wave attenuation does not vary linearly with distance across a marsh. Möller and Spencer (2002) highlight how most of the wave energy dissipation occurs within the first few seaward tens of metres of saltmarsh vegetation. Field experiments in Stiffkey marshes in north Norfolk recorded a 63% wave height reduction for saltmarsh width >200 m with most wave height energy dissipated in the first 10 – 50 m (Möller *et al.* 1999). At the studies at Tillingham marsh, after the initially high reduction in wave energy (greater than 4%/m over the first 10 meters of vegetated marsh), wave attenuation rates decreased rapidly to 0.5%/m after approximately 80m (Möller and Spencer, 2002). Ultimately, wave attenuation varies across marsh surfaces, so it is misleading to assume an average figure that applies over the whole marsh surface (ibid.).

Bouma *et.al* (2014) developed a simplified model to estimate the dimensions of intertidal habitats needed to significantly contribute to wave attenuation in environments with different tidal amplitudes and where wave attenuation mainly occurs from friction and not breaking. This model assumes that the decrease in wave height produced by an intertidal ecosystem follows an exponential decay, with the main modifying influences being the cross-shore length of the habitat over which the waves attenuate and the water depth which determines the friction the waves experience from the intertidal habitat.

Storm surges and extreme events

Storm surges occur where there is a temporary increase in the height of the sea due to meteorological conditions (low atmospheric pressure and strong (offshore) winds) which causes a corresponding rise in sea level height. They can change the time of high water from the normal pattern of HAT and where this occurs it can lead to coastal flooding.

The ability of tidal marshes to attenuate storm surges is usually expressed as the reduction of high-water levels (HWLs) per distance that the surge has travelled through a tidal wetland (the storm surge attenuation rate in cm/km) (Stark *et.al* 2016). Coastal storm surges are mainly driven by momentum that is transmitted to the water column in situ by winds and momentum that enters the water column after being transported over a distance by waves (Resio and Westerlink, 2008).

Systematic evidence and mechanistic studies of storm surge attenuation have only started to accumulate over roughly the past twenty years. Previous studies had expressed the potential role of wetlands and marshes in reducing storm surges through a constant attenuation rate, but it was recognised that the relationship was more complex, as the empirical data showed a large degree of scatter due to complex interactions between governing physical processes dependent on local bathymetry, topography and the intensity, track and speed of storms (Wamsley *et al.*, 2010). One source of empirical evidence has come from direct measurements of storm surge height reductions within and behind large marshes. There is a large variation in the data which highlights that storm surge attenuation by saltmarshes is complex, and the effectiveness of marshes to reduce surge heights depends on local specific characteristics, such as the profile and characteristics of the storm, marsh ecosystem properties and larger-scale coastal landscape settings (Leonardi *et al.*, 2018).

Another source of evidence has been hydrodynamic modelling studies which have enabled a more refined understanding of what are the controlling factors on storm surge height reduction. The evidence suggests that saltmarshes can effectively dissipate high-water levels and wave energy under storm and extreme water level conditions. However, the modelling studies to date have found several key influences that affect their ability to provide storm surge attenuation, namely:

- characteristics of the marsh ecosystem (marsh size and soil elevation, vegetation type, density and continuity, and within-marsh-channel dimensions) (ibid.) (Kiesel *et al.*, 2022).
- characteristics of the storm surge, (including storm intensity, track and duration) (Leonardi *et al.*, 2018) and
- larger-scale coastal landscape settings (off-shore bathymetry, shoreline shape, open coast, back-barrier, estuarine or deltaic setting, levees or dikes behind marshes).

Characteristics of marsh ecosystems

In terms of the characteristics of marsh ecosystems, the size of marsh habitats influences the ability of marshes to attenuate HWLs and dissipate storm surges, with larger marsh widths being more effective in dissipating surges. Kiesel *et al.* (2022) highlight that mean flow velocities decrease logarithmically with increasing distance from the marsh margin in the direction of current flow which means that within-wetland and along-estuary attenuation of HWLs should therefore increase with larger wetland surface areas. Leonardi *et al.*, (2018) based on a review of studies to date, suggest that marshes at least 10km wide are more effective in dissipating storm surges.

Other characteristics of marshes that influence the degree of surge attenuation include marsh elevation. Smolders *et al.* (2015) for example, suggest that for spring tides, lower marsh/wetland elevations resulted in greater attenuation of high water-levels along the studied estuary. For larger storm tides however, the results were more complex, but broadly the results suggest that higher marsh (platform) elevations provide more attenuation than lower wetland elevations. Leonardi *et al.* (2018) argue that this means that marshes that have a sediment accretion deficit and decreasing surface elevation relative to rising sea level could be less effective at storm surge attenuation.

Other marsh characteristics that impact on surge attenuation include the dimension of tidal channels, with deeper or wider channels within a marsh system leading to lower storm surge height reductions due to the reduction in friction on waves (Temmerman *et al.* 2012) (Stark *et al.*, 2016) although Stark *et al.* (ibid.) did not find a distinct relationship between water depth in the channel and attenuation rates for tides with varying HWLs.

Stark *et al.* (2015) found that attenuation rates can vary depending on the geomorphology of the marsh. In an in-situ analysis of tidal and storm surge attenuation in an intertidal marsh in the Netherlands, they found that attenuation strongly depends on the marsh inundation depth and the size of marsh channels with rates being lower in the deeper and wider main channels of the marsh, but higher for narrower side channels. Other studies have also found that the effectiveness of storm surge attenuation also increases with higher ratios of marsh vegetation to open water and where marshes experience patch patterns of gradual marsh degradation this may lead to a loss in their ability to provide storm protection (Leonardi *et al*. 2018).

Characteristics of storm surges

The characteristics of storms, including the structure and duration of the forcing produced by wind and waves, will also have an impact on the degree of storm surge attenuation provided by marshes. Broadly, attenuation rates are higher for shallow to moderate storm surge levels (Leonardi *et al.*, 2018). However, attenuation rates can decrease for more extreme events and longer storm surges that deeply submerge the marsh or where the wind blows for long enough over the water where the frictional resistance across the marsh surface may decrease or be insufficient to fully prevent rises in water levels (Resio and Westerink, 2008).

Stark *et al.* (2015) also found lower attenuation rates for extremely high inundation events at a macro-tidal estuarine marsh in the Netherlands and argued that this was due to limitations in storage area, vegetation submergence and the decreasing effect of bottom friction on the marsh. They found that attenuation rates can vary significantly between flood events depending on the height of the peak water level. The overall attenuation rate increased from the marsh edge to inner marsh locations for HWLs to a maximum of 4-5cm/km for flood events with a peak water level of 0.5-1cm above the marsh platform elevation. However, they found that the highest recorded storm tides were not effectively attenuated. They hypothesised that this was likely due to long flood durations (>6h in length) which meant that there was more time for the storage area on the marsh to become inundated with water which also matched findings of previous modelling studies.

Larger-scale coastal landscape settings

Finally, the precise rates of storm surge attenuation by saltmarshes will also depend on specific larger-scale landscape characteristics and settings such as estuary level characteristics and how these interact with the strength and duration of the storm as it approaches the landscape (Wamsley *et al.*, 2010), or limitations imposed by man-made structures such as coastal developments and defence structures which constrain the movement of marsh habitats (Leonardi *et al.* 2018).

Smolders *et al.* (2015) distinguished between two different forms of HWL attenuation, namely within-wetland attenuation and along-estuary attenuation. The former occurs over a wetland itself and is a result of shallow water depths and the impacts of vegetation, whilst the latter refers to how estuarine intertidal areas reduce the height of storm surges that propagate upstream along an estuary (also known as water retention or flood water storage). They found for saltmarshes of the same size but located in different parts of the funnel shaped Scheldt estuary in Belgium and the Netherlands that those marshes located further upstream were more effective in attenuating surges propagating upstream along the estuarine channel.

Recent research by Fairchild *et al.*(2021) used hydrodynamic modelling to explore the role that saltmarshes can play in providing storm protection in wider-scale estuarine environments compared to their direct effects at more localised wave-exposed coastal settings. They focussed on eight different estuaries in Wales, using hydrodynamic modelling to simulate storms of varying intensity, and coupled the flood predictions to damage valuation. The study also focussed on whether vegetation state (between fully vegetated, grazed and non-vegetated marshes led to differing effects for storm and flood mitigation. They found that local-scale surge and wave attenuation work in combination with larger-scale upstream surge attenuation to deliver substantial mitigation of coastal flooding, and subsequent flood damages, under a range of storm scenarios and estuary contexts.

Saltmarshes reduced flooding across all the estuaries, particularly for the largest 100-year storms, for which they reduced average flood extents by 35% and damages by 37% (£6.18million) (2021 values). Across all scenarios, they delivered mean annual damage savings of nearly £1.99million per estuary through the effects of localised wave attenuation and estuary-scale surge attenuation. Flood mitigation arose from both localised wave attenuation but also through the less recognised role of larger estuary-scale surge attenuation where benefits magnified moving upstream along the estuary. The greatest reductions in localised wave attenuation occurred across wider marshes whilst the strongest wave attenuation at the larger-scale in estuaries was found in those with extensive marsh areas, which highlights that greater relative marsh area has both local and large-scale flood mitigation benefits. They found that both vegetated and grazed marshes were more effective than unvegetated marsh platforms at reducing localised flooding and flood extent. Compared to non-vegetated marshes, vegetated saltmarsh also reduced up-stream propagation of waves through estuary channels, particularly under the largest storms. In addition, vegetated marshes led to substantially greater savings in relative flood cost as storm magnitude increased.

The authors argue that current valuation tools based on local-scale interactions which do not integrate processes operating across scales tend to oversimplify and underestimate contributions by coastal marshes to flood mitigation in estuaries. They emphasise that marsh conservation and restoration must be treated at the whole estuary scale and with the understanding that marshes in highly wave-sheltered locations or fronting areas with low flood vulnerability could still provide essential flood mitigation services further upstream.

More recently, a study by Bennett, W.G *et al.* (2023) used computational models to investigate the impact of saltmarsh vegetation on tidal dynamics and residual currents in three different estuaries in Wales (Mawddach, Taf and Loughor). Their results suggest that the presence of saltmarsh vegetation reduced altered tidal constituents in all three of the estuaries with the most prominent and significant changes in the smaller Taf and Mawddach estuaries. Saltmarsh vegetation reduced the amplitude of primary and shallow water tidal constituents not only on and at the proximity of the marsh but also within the wider estuary, with the most notable changes being found in the middle and upper parts of estuaries. Notable changes to residual current velocities were also observed on marsh flat areas and in tidal channels and creeks. Their findings indicate the importance of marsh vegetation loss or growth on estuary hydrodynamics and flood mitigation which they argue should be considered when assessing the use of marshes for farming, tourism and other ecosystem service provisions.

Limitations imposed by the presence of physical structures can also have an impact on the capacity of marsh sites to provide effective storm surge attenuation. Stark *et al.* (2016) found that limitations in storage area or marsh extent can impact on storm surge attenuation. This can occur in cases where, for example, dikes or similar structures impede the marsh which causes a build-up of water levels (blockage) against the structure and prevent the marsh reaching its full attenuation capacity, particularly where the hydrodynamic forcing is long compared to the time needed to fill the available storage area. In a hydrodynamic modelling of the effect of storm surges on tidal marshes in the Verdronken Land van Saeftinghe marsh in the Netherlands they found that the propagating flood wave can be blocked or reflected before HWLs reach the end of a basin or marsh platform, leading to higher HWLs at the landward end of the marsh and lower attenuation rates They argue that in such cases, a minimum wetland size exists of between 6 and 10km to completely avoid reductions in attenuation capacity for the highest storm tides.

They highlight that if blockage does not affect flood wave propagation, variations in attenuation rates between different locations in the marsh and between tides with varying HWLs can be explained by a single relationship: based on the ratio between the water volume on the marsh platform and the total water volume on the platform and in the channels. Attenuation starts to occur when this ratio exceeds 0.2–0.4 and increases from there on up to a maximum of 29 cm/km for a ratio of about 0.85.

Kiesel *et al.* (2019) assessed HWL attenuation rates in saltmarshes within, and in front of the open coast of a managed realignment site at Freiston Shore in Lincolnshire. They found the capacity of the site to provide HWL attenuation was limited during the test conditions (during the highest spring tides of 2017) and negative attenuation (i.e amplification of waves) was experienced for about half of the measured tides. In contrast, attenuation rates were significantly higher over the natural saltmarsh in front of the managed realignment site (between 0 and 101 cm km^{-1}).

In a subsequent study at the site, (Kiesel *et al.*, 2022) explored the relationship between the width (area), vegetation cover and surge attenuation against a range of extreme water levels and managed realignment site widths (sites ranged in size from 118-205ha and had widths between 900-1500m). They found that surges were amplified for all but the largest two site scenarios and substantial surge attenuation (up to 18cm km^{-1}) was only achieved at the largest site. They suggest that only larger sites greater than 1148m width can provide effective coastal flood risk reduction of very high storm surge levels- attenuation of surges with return periods greater than 10 yrs.

Schoutens *et al.* (2022) used excavated sections from marshes (composed of *P. australis*) in front of a dike in the Scheldt Estuary on the Dutch-Belgian border in experimental test runs to explore the responses of tidal marshes to high flow velocities. They found that erosion was limited even after a cumulative 12-hour exposure to high flow velocities (up to 1.75m s^{-1}) and water depths (up to 0.35m for 2 hours), and the saltmarsh was able to maintain a stable sediment bed- potentially due to the strong consolidated clay and silt rich sediment and root system of *P. australis*.

Although the results cannot be generally extrapolated to all other marsh types, the authors note that it provides good indications that marshes can remain stable under high flow conditions and their potential to act as an extra barrier to reduce flood discharges following dike breaches. However, they stress that this requires stable high marshes that are given time to develop and adapt to changing environmental conditions (particularly sea-level rise). In addition, sufficient space in front of defence structures is needed. In addition the water depths in their experiment were limited to a maximum of 0.35m, whereas water depths of up to 1.5 to 2.5m can be achieved in extreme surge conditions and the authors argue that further testing under larger water depths and higher flow velocities is needed.

These findings have potential implications for managed realignment sites to provide effective coastal protection. A large percentage (roughly 66%) of managed realignment schemes in England to date, for example, are small in size (<20ha) (Kiesel *et al.*, 2019) but (Kiesel *et al.*, 2022) suggest that the capacity of managed realignment schemes equal in size or smaller than Freiston Shore (66 ha) to effectively provide within-wetland attenuation may be more limited. In Wales, there are currently two managed realignment sites, namely, Cwm Ivy (39 ha) on the Gower peninsula and Morfa Ffriog in the Mawddach estuary (6 ha). Both these sites, however, were aimed at the delivery of compensatory habitat through the National Habitat Creation Programme and were not designed with the specific purpose of flood protection.

Vegetation communities on managed realignment sites also tend to be less well developed than on natural salt marshes and can take time for maturation to a more natural state which can also impact on wave attenuation. In the initial study at Freiston shore Kiesel *et al.* (2019) highlight how the weak attenuation performance of the site was a result of internal hydrodynamics caused by scheme design and meteorological conditions. Kiesel *et al.* (2022) argue that where larger managed realignment sites are implemented for the purpose of coastal protection, the successful re-establishment of vegetation is crucial to attenuate very high storm surge levels (e.g a 200-year event) which requires careful consideration of actual inundation frequencies and the establishment of diverse vegetation communities.

Some studies have also pointed to how it can take time for managed realignment sites or those that have been breached by floodwaters to provide effective coastal protection due to the need for the establishment of more natural topographical variability and mature vegetation communities.

Williams and Dale (2023) for example, assessed the morphological evolution of ten sites on the English coast where defences were naturally breached without costly site design, engineering or landscape works performed prior to site breaching, i.e a form of un-managed realignment. They found a general lower topographic variability and higher density of creeks within sites before breaching in comparison to the adjacent areas of marsh. Following breaching, the un-managed realignment sites became less topographically diverse with some evidence of subsequent increases in topographic variability at the two oldest sites. They posit that the findings suggest that is likely that the sites are not yet delivering the full range of ecosystem services found in established marshes. However, they argue that further research is needed assess the impacts of morphology on vegetation colonisation.

Similarly, Chirol *et al.* (2024) monitored the evolution of creek networks- networks of water channels found in saltmarshes- at 10 managed realignment sites in the UK over a period of between 2-20 years. They found that although initially they exhibit less branching complexity and volume to catchment area compared to fully developed natural systems, after around 5 years the creeks developed into larger, more complex and better distributed systems whose length and volume became more similar to natural marsh counterparts. However, they found that creek volume was still poorly distributed with larger distances between them than in natural saltmarshes, and they were also clustered around the area where the initial breach was made which results in the saltmarsh interior being poorly drained.

Managed realignment schemes often involve complicated negotiations between various stakeholders who have an interest in the design of schemes. As Schuerch *et al.* (2022) note, trust in the efficacy of such schemes is an important factor for communities that will be affected and to gain their support and endorsement for schemes. They also argue that new approaches of stakeholder and community engagement are needed where stakeholder are actively involved in project development and design in a way that promotes agency.

Stark *et al.* (2015) studied the effects of a range of tidal events, including storm surge events at a large 3,000 ha brackish tidal marsh along the Western Scheldt estuary in the Netherlands. They found that the protection afforded by coastal wetlands to storm surges is optimal only for flood events that cause a specific range of inundation heights above the wetland elevation (or an optimal ratio between storm surge peak water levels and marsh platform elevation which in the case of the marsh that they studied this was 0.5-1m). They suggest that reductions in attenuation rates for higher inundation events could be the result of limitations in storage area on the marsh during long events but also interlinked to the decreasing influence of bottom friction during higher inundation events and the submergence of vegetation which reduces friction flow. As per the aforementioned effects of tidal range, they found that high marshes would be more effective in attenuating severe storm surges, whilst low marshes would be more effective for attenuating lower flood waves or regular tides.

Shoreline stabilisation and erosion protection

Shoreline stabilisation refers to the processes by which saltmarsh vegetation encourages sediment deposition, increases marsh elevation, and stabilises marsh sediments. The processes involved with maintaining marsh elevation also contribute to the maintenance of marsh shorelines and reduction in erosion from storm events as a minimum elevation must be maintained to prevent marsh plants from drowning and loss of the edge of the marsh.

The main mechanism contributing to elevation gains on a marsh surface is sediment deposition, but root production processes also contribute to this, together with subsidence and compaction (Shepard, Crain and Beck, 2011). Above ground vegetation and biomass has a direct effect on hydrodynamic loads from waves and currents and promotes sedimentation (Jordan, P & Fröhle, P, ibid.). Belowground biomass, including root structures and rhizomes, can also help to stabilise soils by reinforcing substrates and increasing the shear strength of the soil (Shepard, Crain and Beck, 2011) and below-ground biomass from decaying roots can have a positive effect on erosion stability through the build-up of humus material (Jordan, P & Fröhle, P, ibid.). Möller *et al.* (2014) found that this stabilising function is maintained even after larger storm events.

Marshes will however experience lateral erosion in the long-term as part of inherent cyclical dynamics of lateral erosion and expansion. The rates of erosion are affected predominantly by i) sediment type, where mud content is a key factor, ii) the landscape setting (and mainly the length of fetch), and iii) plant species where root biomass is a key driver (Pétillon *et al.*, 2023).

For example, (Shepard, Crain and Beck, 2011) reviewed the effect of vegetated and non-vegetated areas on shoreline stabilisation functions (namely accretion, erosion, and vegetation change). They found a reported significant positive effect of vegetation on shoreline stabilisation in 58% of studies, and across all those included within their meta-analysis- including those that controlled for the effects of tidal elevation. The main factors that were found to be correlated with shoreline stabilisation included vegetation characteristics including species identity, vegetation density, height and biomass production.

The efficacy of saltmarshes to provide coastal protection is also dependent on sediment type and the degree to which sediment beds are erosion resistant. Stoorvogel *et al.*, (2024) undertook experiments to assess the factors that contribute to the development of sediment strength mimicking the conditions found in marshes in the Western Scheldt estuary in the Netherlands. They found that sandy muds led to stronger sediments than finer muds and sediment strength was also higher in the treatments with deeper tidal drainage depth and longer drainage duration. As per the above findings, the presence of vegetation also increased sediment strength through enhanced evaporation and transpiration and the effect was stronger with the species *Scirpus maritimus* than with *Spartina anglica*. They note that to restore or create erosion-resistant saltmarshes to support flood defence, it is essential to ensure that marshes can form at relatively high elevations from well-draining sand-mud mixtures which can also ensure vegetation growth.

Brooks *et al.* (2022) assessed the response of saltmarsh substrates to applied shear and vertical stress from waves, currents and water level changes to understand the impacts on marsh edge erosion. They found that the magnitude of displacement and recovery potential of a marsh substrate were affected by past stress conditions on the marsh (particularly due to desiccation). However, they found that desiccation of Tillingham and Warton marsh substrates resulted in lower magnitudes of vertical displacement during loading than if desiccation had not taken place, and that this vertical displacement was also recoverable. They note that desiccation processes may therefore increase marsh resistance to compression.

Where saltmarshes have been eroded, it is likely that coastal wave heights would increase due to reduced surface roughness and a reduction in foreshore elevations associated with increased water depths and wave heights (Fagherazzi and Wiberg, 2009). Management measures such as cattle grazing may also directly or indirectly affect marsh erosion through affecting sediment compaction and plant traits (Pagès *et al.*, 2019 in Pétillon, J *et al.*, 2023), and the effects of eutrophication may also impact on erodibility (Pétillon, J *et al.* 2023). Marsh erosion rates are also more determined by average wave conditions that are present all the time, rather than rare extreme storm events (Leonardi *et al.*, 2016 in Pétillon, J *et al.*, 2023).

Floodwater attenuation

Saltmarshes also help to reduce flooding and storm surge duration through their large water retaining capacity. This can help to reduce the impact of flooding events by reducing storm surge duration and flood peaks through water holding capacity and uptake (Jordan and Fröhle, 2022). There are, however, limited studies that have quantified floodwater storage or flood peak attenuation in a controlled or paired experiment. The studies that have analysed these effects have come from assessments of wetlands in the United States, which suggest that natural marshes can drain water more efficiently compared to those that have been altered (e.g marshes that have been converted or impacted by drainage for agriculture, channelization for water supply, and affected by urban development) and help to store and drain waters away from adjacent developed areas (Shepard, Crain and Beck, 2011). The findings also suggest that wetland alteration can lead to increased flooding on regional scales (ibid.).

Cost-benefit assessments/ecosystem service valuation

Several research and case studies have attempted to assess the economic values and cost-benefits of coastal protection and flood risk mitigation provided by saltmarshes and intertidal wetlands.

The UN System of Environmental Accounting (United Nations (UN), 2021) provides the standard recommended framework which has been used by most studies to try to estimate values of ecosystem services in natural capital accounting.

In order to make the contribution of the service visible to economic activity, the frameworks propose assigning exchange values- as opposed to welfare values- to the service, which relate to the exchange of a service between a supplier and a user (Office for National Statistics (ONS), 2023) or the price that would prevail if a market for the service were to exist. This allows consistency and comparability with measurements used in national accounts for goods traded in markets and therefore an assessment of the contribution of ecosystems to economic activity (Barton *et al.*, 2019). Welfare values, by contrast, try to capture how the social allocation of resources and goods affects social welfare, through using tools such as cost-benefit analysis.

3 methods have generally been employed to estimate a monetary value for the service of natural hazard protection. These broadly are:

- **Replacement cost methods**: which values the cost of replacing the service provided by the natural habitat with a feature that provides the same benefits but for which there are established costs or prices (UN, ibid.). In terms of most coastal protection studies, this involves valuing the replacement of natural habitat by artificial defence structures (or the difference in cost between building a defence structure and maintaining the natural habitat) (Beaumont *et al.*, 2010).

- **Avoided damage costs**: estimates the value of the ecosystem service based on the costs of the damages that would occur if the service were lost, i.e. that are avoided by the presence of the natural habitat protecting the coast. This method can provide a more accurate assessment of the costs and benefits of a specific flood scheme than other methods, but usually requires better data availability (UN, ibid). Both the avoided cost and replacement cost methods can also be applied to estimate peak flow mitigation services which value the ability of coastal habitats to absorb and store water and thereby mitigate the effects of flood and extreme water-related events (ibid.).

- **Value transfer**: uses existing economic values from other similar studies and applies them to the new context. One of the key limitations of this approach is that many values that have been produced to date relate to changes in welfare values and not exchange values, and their reliability depends on finding strictly comparable study sites. However, it is argued that where estimates are based on a large number of valuations, this can help to minimise the limitations and the values are more likely to be suitable for accounting purposes (Connors, 2016).

Building on previous estimates from the National Ecosystem Assessment, Thornton *et al.* (2019) used a replacement cost method approach to estimate values for coastal protection services provided by saltmarshes. They calculated a value of just over £105,000 per ha of saltmarsh in savings made from not having to build seawalls- and a total natural hazard protection provided by saltmarsh of £5.59 billion UK wide.

However, there are several limitations associated with the use of replacement cost approaches that are important to consider. Firstly, as Thornton *et al.* (ibid.) note, the figure likely overestimates the value of the service, as it assumes that all saltmarshes provide the same level of protection at the locations where it occurs. In addition, the replacement cost approach does not consider the value of the land and assets which are being protected (Beaumont *et al.*, 2010). Replacement cost approaches also do not necessarily capture the full economic value of ecosystem services provided. For instance, the replacement of a natural structure with artificial defences may result in the loss of other services which the habitat provided. The method also assumes a replacement is used when in some circumstances it might not be cost-effective (nor might society be willing to pay) to replace the natural structure with coastal defence and continue to defend some areas of land from flooding with artificial structures (ibid.) (Connors, 2016). The approach also does not consider the risk of flooding, as the topography of land behind defences is not considered.

It is also important to highlight that replacement cost values should be explicitly distinguished from habitat restoration costs as these usually cover the supply of multiple ecosystem services, and they cannot, therefore, be used to directly value the specific hazard reductions service (UN, ibid.). However, Obst *et al.* (Obst, Hein and Edens, 2016) have argued that replacement cost measure approaches can be useful for accounting where the valuation is based on the least-cost alternative and the replacement of the service is expected in case it would be lost.

A recent study by the Office for National Statistics (Watson and McGirr, 2022) estimated an annual value of £9 million for saltmarsh flood mitigation in Wales based on an avoided cost assessment, which looked at the reductions in flooding that would be expected across several land types due to the presence of saltmarshes at the sites. The analysis also produced an estimate of the total value of assets benefitting from this service at £0.26 billion each year in Wales. These are however experimental statistics and there is a degree of uncertainty around the estimates.

Gilbertson, Adams and Burrows (2020) developed a metric for coastal protection provided by saltmarshes across the UK based on proximity to human infrastructure and farmland. The analysis produced a baseline identification of the habitats that are of greatest value to humans based on their provision of sea defence through wave attenuation. They found that the greatest protection to human infrastructure was from marshes in the east and south of the UK, where the saltmarshes are shielding a high density of buildings and agricultural land from coastline with high wave fetches. The analysis did not however focus on areas where saltmarshes bound coastal defence structures and the protection values for Wales only focussed on buildings due to the lack of availability of agricultural land data. The study also did not assess the financial and economic values to the coastal protection, which the authors note would could help coastal managers in balancing the disadvantages of protecting marshes in areas where they might be lost to coastal squeeze vis-à-vis protecting high-value infrastructure.

More broadly, Narayan *et al.* (Narayan, Beck, Reguero, Losada, van Wesenbeeck, *et al.*, 2016) assessed the costs and associated wave reduction potential of 6 saltmarsh sites- 5 of which were based in the UK- and found that they can be up to two to five times cheaper than alternative submerged breakwaters for the same level of protection (wave heights up to half a metre) and that they can become more cost effective at greater depths (within limits) due to the increases in breakwater costs with scale.

However, Vuik *et al.* (2019) assessed the cost-benefits of saltmarshes for flood risk protection in front of dike defence structures in the Netherlands by comparing different interventions on the foreshore with traditional dike heightening. They found that the cost-effectiveness of using vegetated foreshores such as saltmarsh in front of defence structures depends primarily on, i) the probability of failure of the dike and how this would be affected by foreshores, ii) the investments required to construct and maintain the foreshores in comparison to defence structures, and iii) the economic value of the protected area- with nature-based solutions being more attractive for lower economic values.

They found that dike heightening and construction of a foreshore that resembles saltmarsh were most positive in terms of cost-effective flood risk reduction. The construction of a foreshore that resembles saltmarsh can be more cost-effective than dike heightening, but only where small to moderate damage occurs in the dike breaching as they are limited to approximately mean high water (MHW), where natural accretion can take place. They also found that artificial high zones and breakwaters on the salt marsh can improve the flood defence reliability with relatively low costs, particularly if constructed well above MHW level, but they can lose their efficacy without further interventions due to sea-level rise and loss of natural sediment accretion. Sheltering structures such as bamboo dams or brushwood can also enhance sediment accretion. However, the continuous maintenance costs and delayed benefits/effects on flood risk mean that brushwood dams are a less effective strategy for flood risk reduction.

However, the authors stress that the conclusions are valid for the specific study and design options and cannot necessarily be extrapolated to other locations and site-specific analyses would be required to test whether the same results hold.

There is some evidence to suggest that managed realignment schemes can be a more cost-effective method to reduce flood risk compared to maintaining or rebuilding sea defences in increasingly exposed locations. This will however vary between sites as there can be high capital costs associated with the purchase of land to be flooded, the costs of building new sea walls and the amount of re-profiling and works required on the land (Smith and Chausson, 2021)

Medmerry managed realignment scheme

Medmerry in Sussex is one of the largest open-coast managed realignment schemes in Europe. The 183 ha of intertidal saltmarsh and mudflat habitat was created from former farmland to address regular flooding which occurred from the breaching of the previous shingle bank defence structure. This threatened 348 houses, a wastewater treatment plant, a holiday park and road infrastructure and required up to £300,000 per annum to maintain the shingle defence (McAlinden, 2015). In March 2008, a major storm led to widespread flooding inland and caused over £5 million of damage to local businesses.

The scheme was implemented between 2011 and 2013 and involved the construction of seven kilometres of new flood bank (to a height of 5.6m Above Ordnance Datum (AOD)) inland from the sea between the towns of Selsey and Bracklesham which was built using 450,000 cubic metres of clay that was extracted from shallow 'borrow pits' within the site. Two rock revetments (eastern and western rock armours) constructed to a height of 6.6m AOD were also created to strengthen the bank where it meets the coast (Environment Agency, 2016). Four large-scale sluices were also included to maintain the freshwater drainage landward of the defences.

Once the bank had been completed, the previous shingle sea defence was breached which allowed the creation of the intertidal habitat (Hou-Jones, Roe and Holland, 2021). A series of new freshwater ponds and reedbeds were also created as part of the scheme. The saltmarsh is also grazed at a low density by sheep and cattle and managed to maintain the grasses at a height for benefits for wildlife.

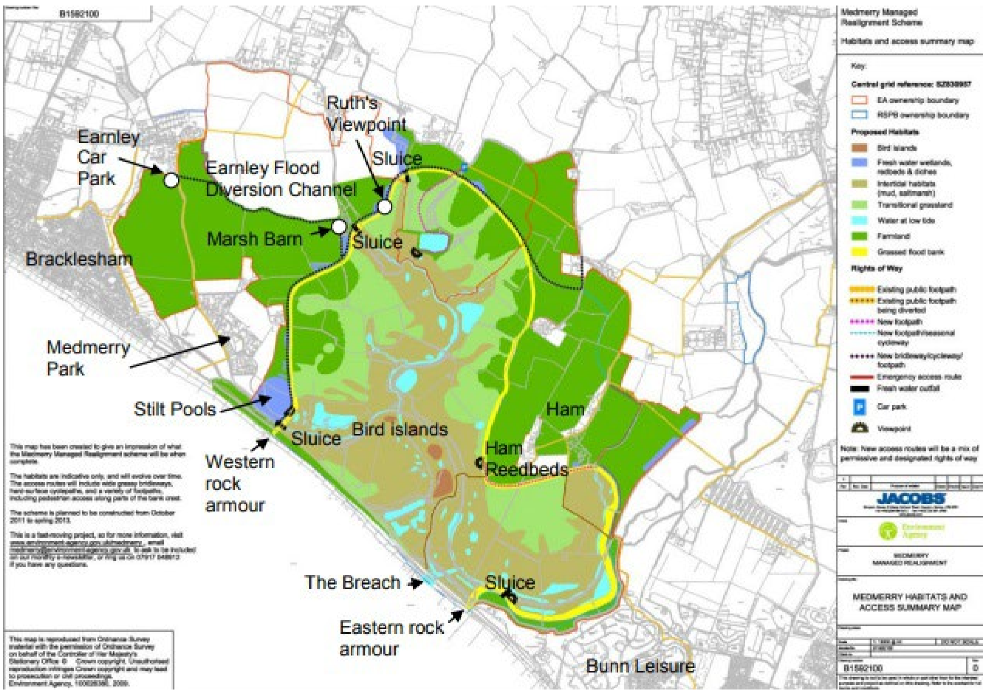

Figure 4: Initial design map of the scheme indicating the created breach, armours and sluices and key features. Source: Environment Agency (2016).

Following completion of the scheme, the annual risk of flooding was reported to be reduced from 100% to 0.1% (0.33% in 100 years time) and save £78 million (in present values over 100 years). The site is now managed as a nature reserve and also provides other benefits including recreation (estimated at £6.3m), carbon sequestration (£3.3m) and up to £87m based on a willingness to pay for the biodiversity at the site (Smith & Chausson, 2021). The scheme also included the enhancement of Sites of Special Scientific Interest (SSSI) from, ‘unfavourable’ to ‘recovering’ condition. The project has produced wider benefits for local wildlife including significant increases in breeding and wintering populations of wading birds such as avocets, lapwings and oystercatchers (Hou-Jones, ibid.). The total benefits of the project exceeded the initial project costs of £28m. However, the habitat was created as offset for future losses of habitat in the region due to coastal squeeze and as Smith and Chausson (ibid.) note that total net impacts should factor these losses in the analysis.

MacDonald *et al.* (2020) also attempted to quantify the benefits derived from a managed realignment site at Hesketh Outmarsh West in the North-West of England. In this scenario, managed realignment was carried out with improvements to the inner seawall defences. They estimated the net annual provision of services provided by the marsh at £262,935 (£1460.75/ha) which was increased by the reduction to flood risk arising from coastal managed realignment action which was estimated at £164,905 annually. The figures are based on assessments from the local SMP of the estimated increase in tidal capacity of the Ribble Estuary (by 0.1% on a mean spring tide and by 1.2% on a tide reaching the level of HAT) as the basis for calculating the flood risk. Overall, the financial loss to farmland services through the inundation of land was outweighed by the benefits provided by other services. However, as previously noted, it can take several years for the maturation of vegetation communities and topographical variability to deliver the level of ecosystem services and benefits that are provided by natural saltmarshes.

Evidence also suggests that there is support amongst the Welsh public to pay for coastal flood protection, especially through nature-based solutions, including expanding saltmarsh area and increasing saltmarsh with high vegetation, as opposed to using traditional defence structures. Using a discrete choice experiment, Rendón, Sandorf and Beaumont, (2022) found preferences for nature-based solutions, including support for managed realignment projects and specific coastal area targets in financial schemes which are initially aimed at other benefits such as habitat creation for biodiversity and environmental or livestock management. However, there were, differences in responses by different groups. Those who had directly experienced floods were more likely to support further adaptation measures, and knowledge and direct experience of flood events was correlated to more support for these measures, which lends weight to the argument that environmental/flood education and direct contact with habitats are important for securing support and buy-in for flood protection measures.

Several international studies also provide a broader understanding at a high-level of the potential cost benefits of saltmarsh for coastal protection although it is important to note that the detail of these studies will be less relevant at the local scale in Wales and the UK due to specific geographies and local characteristics.

An assessment of the potential flood risk reductions and adaptation benefits that could be achieved through conserving foreshore vegetation was undertaken by Tiggeloven *et al.*, (2022). They found that globally, foreshore vegetation can contribute to a large decrease in both absolute and relative flood risk and they estimate a total reduction in expected annual damages (EAD) provided by present-day foreshore vegetation at US $2.5 billion which amounts to 13% of global EAD and 0.4% of total GDP exposed. They found that if present-day foreshore vegetation is conserved, EAD could be reduced by US $71 billion, which amounts to 8.5% of EAD globally in the scenario broadly aligned with the Paris Agreement targets. In both scenarios that they analysed risk reduction relative to total exposed GDP was doubled to 0.8% compared to present-day estimates.

Narayan *et al.* (Narayan, Beck, Wilson, Thomas, Guerrero, *et al.*, 2016) also quantified the economic value of temperate coastal wetlands for property damage reduction following Hurricane Sandy that hit the United States in 2012 using insurance-based flood risk models. They estimated the effects that saltmarshes would have had on reducing flood losses on an annual basis to properties in New Jersey and found that coastal wetlands saved more than US $625 million in avoided flood damages across the northeastern USA. On average, there was a 10% reduction in property damages across the region for census tracts with wetlands. Additionally, in terms of annual flood losses experienced in New Jersey, they predicted that areas behind existing marshes have on average 20% less property losses than areas where marshes have been lost.

Hybrid coastal protection schemes could also provide cost-effective mechanisms for coastal protection. Van Zelst *et al.* (2021) for example, evaluated the use of ecosystems in front of levees (specifically mangroves and saltmarshes) to reduce global protection costs. They found that if vegetated foreshore levee systems were established along populated coastlines that are susceptible to flooding, the required levee crest heights could be considerably reduced. For nearly 30% (27.6%) of populated susceptible coastlines, the current presence of coastal vegetation allows for lower levee crest heights while maintaining the same protection standard (100-year protection). The current presence of coastal vegetation would also allow for a reduction in the required crest height equal to or greater than the projected sea-level rise of 0.49m by the end of the 21st century in over 20% (22.1%) of susceptible coastlines. In addition, they estimated a reduction in costs resulting from the presence of current foreshore vegetation at $US 320.2 billion- compared to if levees with a 100-yr protection standard were constructed along all populated susceptible coastlines.

Changes with relative sea-level rise

Estimates of mean sea-level change vary across the UK by emissions change scenario and geographic location. Scenarios produced for Cardiff project a mean sea-level rise between approximately 0.27-0.69m by 2100 for the lowest scenario equivalent to global warming +2°C above preindustrial emissions and 0.51-1.13 for the highest modelled emissions scenario equivalent to global warming of just over 4°C above preindustrial emissions (Met Office, 2019). For the highest emissions scenario (RCP 8.5) mean sea-level rises range from 1.15-1.28m for the counties in mid and North Wales for the 95th percentile (95% probability of non-exceedance) to 1.30-1.33m for counties in South Wales (Welsh Government, 2021).

This will likely lead to an increase in the frequency and magnitude of extreme water levels across the UK coast and increase flood risks. There is also the potential for increased storm surges and waves, although there is lower confidence in the regional projections (Haigh, I.D et al. 2022). In addition, future coastal flooding might also vary due to changes in sediment pathways and morphology as a result of mean sea-level rise or variations in the wave climate (ibid.). These changes may place additional pressures on coastal habitats and saltmarshes and their ability to provide coastal protection functions in the future.

There have been debates as to whether saltmarshes can sustain vertical accretion rates relative to future sea level rise rates through processes which involve the interplay between plant sediment trapping, organic matter incorporation and increased inundation (Ladd, 2021). Some recent studies using dynamic models have suggested that tidal marshes could adapt to the effects of relative sea level rise (RSLR) and that globally, marshes are usually accreting sediment at the same, or higher pace than current RSLR (Kirwan *et al.*, 2016). According to Kirwan *et al.* (ibid.) a feedback loop operates between inundation and accretion whereby increased tidal inundation promotes more frequent and longer episodes of mineral sediment settling on the marsh platform, leading to enhanced vegetation growth and faster rates of organic matter accumulation and this feedback leads to accretion rates that have accelerated with historical SLR.

Ladd *et al.* (2019) argue that long-term patterns of lateral saltmarsh change in Great Britain can be explained by large-scale variation in sediment supply and its wave-driven transport rather than by sea-level rise. They note that vertical marsh accretion trends should continue, providing the supply and transport of sediment is sufficient to compensate for future sea-level rise rate increases. However, in their study they found that over roughly the past 150 years, northern marshes in Great Britain expanded while most southern marshes eroded, and this was a result of a north-south reduction in sediment flux and fetch-driven wave sediment resuspension and transport. Coleman *et al.* (2022) also suggest that low-elevation marshes are more efficient at accreting sediment vertically than high-elevated marshes due to their being inundated more frequently and which allows more sediment to be deposited.

Masselink & Jones (2024) also estimated long-term saltmarsh accretion rates from the elevation difference between natural marshes and neighbouring reclaimed marshes (reclaimed saltmarsh method) applied to 19 saltmarshes in the UK. They found an average accretion rate of 4.5mm/yr, although there was considerable variability between sites (between 0.68–7.88 mm/yr) and accretion rates increased with mean spring tide range. The long-term accretion rates for all saltmarshes studied (except the Erme Estuary) exceed the long-term rate of sea-level rise. The rates were found to be generally larger than predicted for sea-level rises based on a RCP2.5 scenario, comparable to those predicted for a RCP 4.5 scenario but lower than in a RCP 8.5 scenario. The authors suggest that the findings indicate that UK saltmarshes in macrotidal settings are likely to be more resilient to sea-level rise than those in micro- and meso-tidal settings.

Pannozzo *et al.*(2021) investigated saltmarsh resilience under the combined impact of various storm surge and sea-level rise scenarios using hydrodynamic models based in the Ribble Estuary, North-West England. They found that sea-level rise can threaten the stability of saltmarshes by promoting ebb dominance and a net export of sediment. However, storm surges can counteract this effect and might positively contribute to the resilience of saltmarsh and related estuarine systems by promoting flood dominance and triggering a net import of sediment, particularly for storms with the highest intensities (>3m surges).

However, in those cases where there has been coastal development around marshes there is the potential that the impacts of sea-level rise and coastal squeeze may lead to a decline in their extent where they are prevented from migrating inland due to the presence of the structures and are submerged by rising sea levels (Pétillon, J, *et al.* 2023).

Recent estimates of loss of saltmarsh at a national level in Wales, predict losses in the range of 21-25% nationally by 2155 under a scenario where current defences are maintained. However, habitat losses would reduce nationally to between 2-4% by 2055 and between 9-12% by 2155 if SMPs are implemented (Oaten, Finch and Frost, 2024b).

Kirwan *et al.* (ibid.) highlight, for example, that the inundation/accretion feedback loop that would allow marsh survival even under high rates of sea-level only holds if marshes can transgress inland and compensate marsh erosion at the ocean boundary inland without encountering natural or artificial obstacles. As previously noted, marshes that have a sediment accretion deficit and decreasing surface elevation relative to rising sea level could be less effective at storm surge attenuation (Leonardi *et al.*, 2018).

As highlighted by Smith, A and Chausson, A (2021), long-term planning together with adaptive management will be needed to enable dynamic coastal habitats to move and adapt to changing conditions and maintain the resilience of saltmarsh features. For instance, gains in saltmarsh extent of 47% (70^{th} percentile sea-level rise allowance) by 2055 and an additional 22% increase by 2155 are expected where SMPs are implemented and which allow habitats to roll back into adjacent areas (Oaten, Finch and Frost, 2024b).

Gaps/further evidence needs

There are several areas where there are gaps in the understanding of the evidence related to the mechanisms affecting the capacity of saltmarshes to provide coastal protection services. These include:

- The combined project costs and wave attenuation capacities at the same location/sites. This would enable a better understanding of variations in project costs with site conditions and habitat and wave characteristics and effects. Narayan *et al.* (2016) note that this will be particularly useful to assess levels of effectiveness and costs in response to future sea-level rise and changing variability in wave heights.
- The ability of managed realignment sites to provide flood and storm protection as they evolve over time and morphologically. Williams and Dale (2023) argue that further research is also needed to assess the impacts of morphology on vegetation colonisation to better understand the changes in delivery of ecosystem (and coastal protection) services at such sites.
- Kiesel *et al.* (2019) note that further research is needed to examine the driving forces of HWL attenuation in both space (looking at variables such as site geometry and orientation, surface morphology, tidal creek, network characteristics, vegetation canopy types and their site coverage) and time (e.g wind strength, duration and direction and associated wave fields and depths) to establish better guidelines for managed realignment scheme design and implementation and achieve more effective HWL attenuation in such schemes.
- In terms of wave attenuation functions of saltmarshes, although there is a good understanding of the way in which saltmarshes attenuate waves across their surfaces, there are gaps in the understanding of lateral dynamics and the impacts of aboveground biomass on wave attenuation functions (Pétillon, J *et al.*, 2023).
- Further testing is needed of the response of marshes in front of defence structures such as dikes to large water depths (e.g up to 1.5-2.5m) and higher flow velocities in extreme storm surge conditions (Schoutens, 2022).
- More assessments of tidal flat extent change and sediment supply monitoring is needed to anticipate where marshes are vulnerable to net losses and erosion under sea level rise and understand the success of marsh restoration schemes. These should also factor in wider local determinants and impacts on sediment budgets and supply dynamics such as impacts of defence structures and dredging (Ladd, 2021).
- Ladd (2021) highlights that further forecasting of the long-term ecosystem service value of saltmarshes should also incorporate cyclical marsh dynamics which operate over varying spatio-temporal scales.

Seagrass meadows

Seagrass meadows can dampen wave energy and height through friction created by the presence of vegetation in the water column.

In terms of wave flows, orbital motions of the wave produce a periodic movement of the seagrass leaves where the amplitude is highly dependent on plant stiffness. The orbital velocities at the top of the canopy are modified due to drag forces which propagates in the wave direction (Ondiviela *et al.*, 2014). In the case of currents, seagrass meadows can reduce the current velocity due to the deflection of water flow over the canopy and currents lose momentum within the canopy due to the frictional effects produced by vegetation.

The main biological and physical (hydrodynamic) factors that influence the degree of wave attenuation include the standing biomass, shoot density and leaf length, plant stiffness and the height of the canopy (Ondiviela *et al.*, 2014) (Jordan and Fröhle, 2022). The (wave) incident energy flux, wave height and period and water depth also play a role in the degree of attenuation (ibid).

Seagrass is more effective at attenuating waves if a larger proportion of the water column is occupied by meadows which results in less wave energy reaching the shoreline (Koch *et al.*, 2006). Therefore, shallow water and low wave energy environments- where there is a high interaction at the vertical and horizontal dimension between water flow and the seagrass surface- are more likely to provide optimal conditions for the protection that seagrass can provide compared to deeper waters (Ondiviela *et al.*, ibid.). In temperate regions, seasonal changes can impact on the ability of meadows to attenuate waves. For example, Ondiviela *et al.* (ibid.) highlight that during winter months when hydrodynamic forcing in coastal waves is highest in such regions, most above-ground seagrass dies which reduces wave attenuation capacity.

Paquier *et al.* (2019) assessed the interactions between a patchy degraded *Zostera noltei* seagrass meadow and waves, currents and sedimentary processes in a coastal brackish water lagoon in the south-east of France. Overall, they found that the meadow could provide coastal protection against erosion although the relationship was seasonal. They observed varying positive attenuation (wave decay rates) rates, between values of 0.018m over the offshore non-vegetated sections, 0.03m in the meadow section, and up to 0.042m over the front section of the meadow. The main impact of the meadow on wind-wave transformation was on attenuation of waves further offshore than in the absence of vegetation.

The data suggest that the meadow did not attenuate small and short waves (with shorter periods), particularly when the water levels are high, but similarly to saltmarshes it did have the capacity to attenuate relatively high and long waves. Erosion and sedimentation were mainly controlled by the hydrodynamics, but the seasonal state of the meadow played a role in modulating the hydrodynamics, which in turn influenced the protection of the shoreline.

Studies by Paul and Amos (2011) at beaches in the north coast of the Isle of Wight found a seasonal change in wave attenuation from seagrass meadows (*Zostera noltii*) which varied with shoot density, which displayed strong seasonality, being highest in summer and lowest in winter. However, a minimum density was required before attenuation can be observed and this threshold also varied based on hydrodynamics- with higher wave periods requiring a lower density to initiate wave attenuation. A change in energy dissipation toward the shore was observed once this threshold was exceeded. They suggest this could lie between 2,000-4,000 shoots/m^2 above which the seagrass changes the wave attenuating function of the bed, causing higher friction and attenuating waves more effectively. In addition, Paul, Bouma and Amos (2012) found a positive correlation between the blade stiffness of seagrass and wave attenuation.

Despite current efforts to restore the extent and condition of seagrass beds, seagrasses are deemed as scarce in Wales (present in only 16-100 ten km squares) (Armstrong *et al.*, 2020). At present, shoot densities in Wales tend to be substantially lower than this threshold figure. For instance, a recent survey of the *Zostera Marina* seagrass bed in North Haven, Skomer, recorded an average figure of 47.4 shoots/m^2 in 2023 with the highest recorded value as 89 shoots/m^2 (Massey *et al.*, 2024).

Seagrass can also be effective at attenuating current flow and velocity. Above and below ground biomass can reduce erosion and help trap sediment which when deposited is bound into long-term accretion through their extensive root and rhizome systems (Jordan, P & Fröhle, P, ibid.). The presence of seagrass beds can also indirectly promote sedimentation which dampens the effects of waves and currents on the sea floor and prevent the scouring action of waves.

Coastal protection benefits

Based on an analysis of several studies, Narayan *et al.* (2016) estimated that seagrass meadows and kelp beds could lead to a reduction of wave heights by an average of 36%.

A number of recent studies have also begun to develop our understanding of seagrass' potential to provide coastal protection. Reidenbach and Thomas (2018) for example studied the influence of seagrass meadows (*Zostera marina*) on levels of wave attenuation within a shallow coastal bay in Virginia, United States. They found that wave height was reduced by 25-49% compared to an adjacent bare site and 13-38% compared to an analytical model of attenuation over an unvegetated seafloor with the same bathymetry.

Some studies have also looked at the use of hybrid combinations of seagrass in conjunction with other coastal habitats to provide coastal protection. Unguendoli *et al.* (2023) assessed the effects of seagrass meadows and artificial dunes- both separately and combined- in reducing coastal erosion and inundation risks under three historical storms along the Emilia-Romagna coast in Italy at Lido di Spina a large sandy beach (3km) infront of a coastal lagoon. The presence of the seagrass meadows (*Zostera marina*) led to an average attenuation of 32% of the storm peak and helped to prevent the adjoining beach from further erosion. The artificial dunes were more effective in reducing inundation of the lagoon with attenuation rates between 51-75%. However, the combination of the seagrass and dune system as a synergic solution produced the best benefits in terms of wave attenuation (up to 77% in cases without any defences) and in reducing inundation and erosion during the worst storm conditions. The modelling results suggest that the seagrass acts as a protection for not only the beach but also the dunes, helping to preserve their stability and functionality for longer.

Another example of the application of hybrid methods with seagrass is a recent study conducted by Chen *et al.* (2022) who used a coastal morphodynamic model and simulation to assess the effects of using seagrass in combination with shoreface (sand) nourishment as a nature-based solution to mitigate flooding and coastal erosion in the North Sea. The wave reduction by green nourishment was up to 80% under mild wave conditions, which they highlight is higher than the effect of the protection provided solely by seagrass meadows as demonstrated by previous studies (e.g Reidenbach and Thomas, 2018).

The nourishment provided a sand input to the system which created a sheltered area landward that was conducive for seagrass establishment and growth, whilst the seagrass stabilised the sand substrate and enhanced the wave energy dissipation provided by the nourishment. They argue that the method could act as a particularly effective nature-based solution to mitigate coastal erosion when implemented in sheltered nearshore area on sandy coasts. However, they note that to survive a strong storm event, the size of the seagrass meadow should be sufficiently large which requires careful planning in terms of seed planting techniques and their timings.

However, in comparison to saltmarsh (vegetation), the coastal protection functions of seagrass tend to be more limited. Paul and Amos (2011) highlight how seagrass tends to have a higher flexibility which makes it less effective at attenuating waves unless there is a very high biomass. Narayan *et al.* (2016) found that in general, seagrass and kelp beds are about half as effective as saltmarshes in providing wave attenuation. Other estimates also suggest that seagrass has less capacity than other habitats in different parts of tidal ranges to attenuate wave heights (Table 1).

Habitat	**Maximum tidal range at which habitat can reduce 50% of wave height for 50m ecosystem ($Mt_{50/50}$)**	**Maximum tidal range at which habitat can reduce 50% of wave height for 100m ecosystem ($Mt_{50/100}$)**
Saltmarsh	22.6	33.2
Seagrass meadows		0.7
Mussel beds	1.8-3.2	2.7-4.2
Oyster reefs	2.8-3.5	3.5-4.3
Sabellaria reefs	-	Unknown

Table 1: The effects of tidal range on wave attenuation (source: Bouma et al. (2014)): the authors estimated the maximum tidal range at which different habitats can still attenuate 50% of the incident wave height over lengths of 50m (Mt50/50) and 100m (Mt50/100).

In addition, seagrass shoots can easily bend when exposed to currents which reduces their wave-attenuating capacity in macro-tidal areas which have strong currents (Paul, Bouma and Amos, 2012). Water quality issues can also jointly influence the ability of seagrass to provide effective coastal protection. For example, there is some evidence to suggest that seagrass plants may become more brittle and easily break when exposed to waves in nutrient-rich environments (La Nafie *et al*., 2012 in (Bouma *et al.*, 2014)).

Ondiviela *et al.* (2014) argue that seagrass meadows cannot protect shorelines in every location and/or scenario and that the most favourable protection might be provided by large, long living and slow growing species and where biomass is largely independent of seasonal fluctuations and with the maximum standing biomass reached under the highest hydrodynamic forcings (ibid.).

Gaps/further evidence needs

There are several areas where there are gaps in our understanding of the capacity of seagrass to provide coastal protection services and which would help to improve the understanding of the efficacy to be deployed in projects. These include:

- Given the macro-tidal ranges experienced in Wales, more evidence is needed of the efficacy of seagrass for coastal protection benefits along the Welsh coast. In addition, more projects and trials are needed to build the evidence base of the efficacy of using seagrass as part of a hybrid coastal protection solution.
- The analysis undertaken by Chen *et al.* (2022) looked at the effects of implementing green nourishment in nearshore areas, but they argue that further field experiments are needed to test the effects of dense seagrass meadows on open coasts to validate their method. The study focussed on cross-shore currents and therefore a better understanding is also required of the outcomes in localities where long-shore currents prevail and on coasts where the effects of tides are significant (i.e large tidal ranges).
- In addition, a better understanding of the effects of storms and high wave energy conditions on seagrass meadows is needed. For instance, models to date have not accounted for seagrass which ends up being buried or destroyed by strong currents or sediment deposition in strong storms which could affect the capacity of seagrass to provide protection, and which without accounting for, may lead to the overestimation of attenuation rates in such conditions.
- Bouma *et al.* (2014) highlight how there is a relative lack of knowledge on the indirect effects of water quality on wave attenuation and stability of intertidal ecosystems and how they affect vegetation development and the effects of tidal currents on seagrass wave attenuation.

Beaches and dunes

Beaches are areas of mobile sediment which typically extend from above the high tide line to a lower limit offshore, often defined by the depth at which waves can no longer move sediment (the depth of closure).The morphology of a beach will vary with time based on how it responds to hydrodynamic forcing from waves and tides and the variability in environmental conditions and processes (e.g sediment and geology). They can be maintained by wave, tidal or fluvially supplied sediment, although they may sediment limited if there are no current sources of sediment available.

Over time, a number of classifications have been made of beach types, the most widely used of which classifies them as to whether they reflect or dissipate wave energy and related to wave power and dimensions and the morphology of the shore (Bird, 2008) (Wright and Short, 1984).

Gently sloping and flatter (usually sandy) beaches dissipate high wave energy associated with spilling breakers across a wider surf zone, whilst steeper beaches (> 3^{o}) (especially shingle beaches) will tend to partially reflect waves and be associated with lower energy surging breakers (a breaking wave that surges up a steep beach by forcing water out of the front of the wave). An intermediate classification is also recognised. However, the changes in morphological response are reduced with variations in sediment type. For example, higher energy waves arriving at a shingle beach may not produce a wide, flat beach profile as much of the energy of the wave will be dissipated by friction and percolation (Pethick, 1984). The original models have subsequently been revised by other authors, including Masselink and Short (1993) who expanded them to account for the interactions of wave height with tidal range to distinguish different categories of wave-dominated beach morphology as relative tide range increases.

However, the framework was primarily based on studies of sandy beaches along the high wave energy and microtidal coastline (mean spring tidal range MSR < 2 m) of New South Wales, Australia and the relationships are most clear in beaches in low tidal ranges and on swash-dominated beaches (Scott, Masselink and Russell, 2011). The classification does not hold as well for beaches located in larger tidal ranges and in drift-aligned beaches and has not been used so extensively in Great Britain, likely as Bird (ibid.) notes, due to the fact that shingle beaches are normally reflective, storm waves are commoner than long swells, and tide ranges are relatively large. Some beaches in the UK can exhibit behaviour of passing frequently from reflective to dissipative states in the course of cut-and-fill sequences, such as the gravel-backed sandy beach at Porth Neigwl on the Llyn Peninsula which is reflective at high tide and dissipative at low tide. Scott, Masselink and Russell (ibid.) have recently tried to apply a similar framework for England and Wales to develop a classification of 9 beach types based on an assessment of 92 beaches around the coastline.

The energy of waves that reach the shore are directly attenuated or dissipated by the slope of a beach which affects both beach morphology and hydrodynamics. Other factors which affect flooding and coastal erosion arising from the impact of waves and storms that interact with a beach, include, air pressure, mean water level, wind speed and direction and wave height (Jordan and Fröhle, 2022).

Wave energy is dissipated in different ways along the cross-section of a beach and this is a non-uniform process as demonstrated in Figure 5. At the foreshore, wave-bottom interactions are the primary influence, but in the surf zone the dominant influence is turbulence due to wave breaking (ibid.). Where a wave's initial energy has not been dissipated as it hits the shore, these can result in waves (or bores) running up the swash zone, which can sometimes cause considerable damage on beaches, to dunes or to property in the adjacent hinterland (Jordan & Fröhle, ibid.). Waves tend to lose energy in the swash zone due to the effects of turbulence, bottom friction and percolation, therefore wider beaches afford greater protection than narrow, fringing beaches.

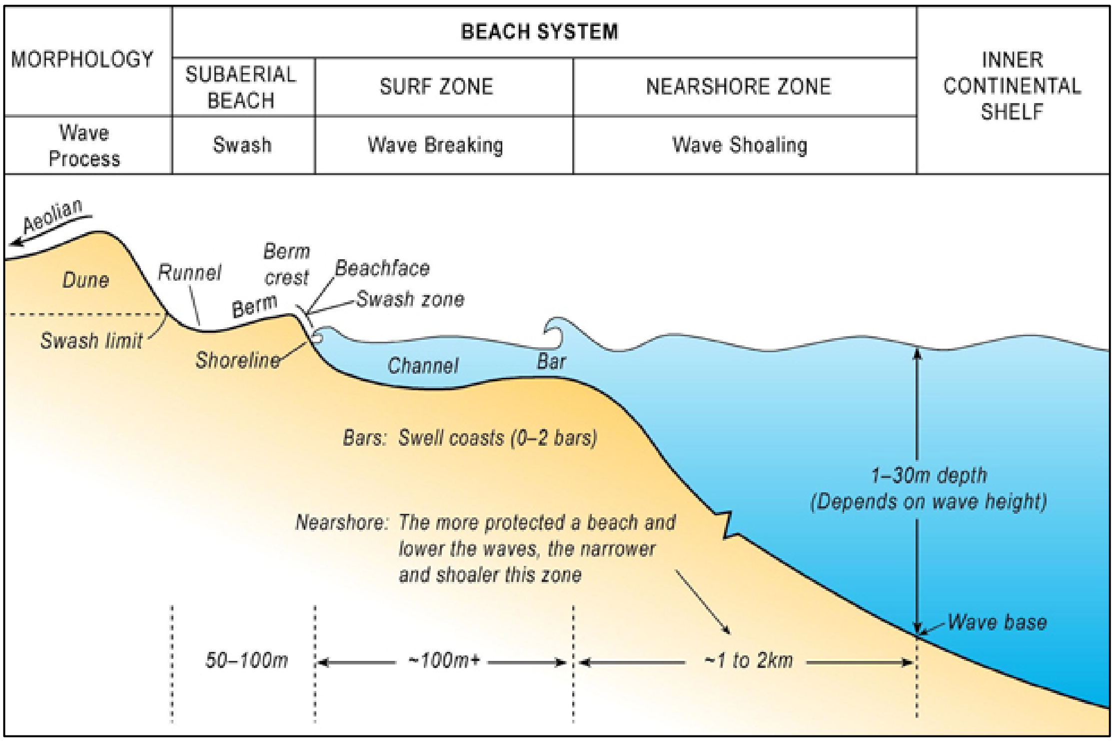

Figure 5: idealised cross-section of a wave-dominated beach system. The swash zone contains the 'dry' beach dominated by swash processes; the surf zone comprises bars and channels subject to higher energy breaking waves and surf zone currents and the near shore zone extends to the wave base where waves become shallow. Source: Short and Woodroffe, 2009 in*(Short, 2012)*).

Palmer and Limited (1996 in Jordan and Fröhle 2022) outline how through these various interactions with alignment and beach morphology, beach ecosystems can absorb up to 90% of the initial energy of waves when they arrive at the coast.

One of the key issues that has impacted on beach systems in the UK over the past few decades has also been the long-term effects of coastal development and defence structures such as groynes, revetments, sea walls and breakwaters on sediment supply of natural beach and shingle features, which have significantly impacted on their ecological and natural characteristics (ibid.). Welsh beaches have also been adversely affected through the impacts of erosion and presence of manmade defences which has significantly reduced sediment supplies on some beaches and led to their narrowing and/or lowering (McCue, Pye and Wareing, 2010). Substantial risks to beach ecosystems also exist from the combined effects of climate change and sea-level rise which will compound the risks associated with coastal squeeze where beaches and shingle are constrained in their ability to rollover landwards by urban development or infrastructure (Natural Resources Wales, 2020).

Sandy beaches

Sandy beaches play an important role in protecting against the effects of waves and storms at the coast. Sandy beaches and shorelines respond to changes in the energy of forcing conditions so as to maximise the persistence of their structure and minimise the impacts of energetic hydrodynamic events (Hanley *et al.*, 2014). They are more likely to be dissipative than shingle beaches, particularly where situated at low tides, and have gentler shore profiles, typically with one of more sand bars and produce longer edge waves and more widely spaced rip currents and beach cusps, whereas shingle beaches tend to be steeper and reflective.

Beach profiles can change in response to seasonal conditions, with complex interactions between the weather conditions, wave characteristics and the beach profile and geomorphology. During periods where beaches are exposed to higher energy conditions or higher frequencies of wave action (such as during storm conditions), sandy beaches usually respond by flattening their profile to form a gentler gradient as the ability of swash to transport sediment up the beach is reduced which leads to a net seaward sediment transport. (Haslett, 2009). Under storm conditions, sand and sediment is increasingly shifted offshore to the sublittoral zone creating a shallower foreshore where one or more rows of submerged bars can develop and an area where bigger waves break well offshore which results in a reduced impact of waves on the beach and dunes (Hanley *et al.*, 2014) (Jordan and Fröhle, ibid.). A wider dissipative surf zone also develops which reduces the wave energy incident on the shoreline.

In less energetic conditions where the frequency of waves hitting the shore is reduced, waves wash onto a more permeable, less saturated beach face. Under such conditions where there is a relatively long time between consecutive waves, the backwash will have sufficient time to return before the approach of the next breaking wave. As the energy of the incoming swash is greater than the backwash – and providing the swash of the subsequent wave is not reduced by the backwash of the previous one- this causes sediment to be transported up the beach (Haslett, 2009) causing an accretion and build-up of sediments and a steepening of the beach which in turn becomes more reflective to waves (Jordan and Fröhle, ibid.). In cases where inundation times are low enough to allow sand in the upper parts of the beach to dry out, onshore winds can move sand for example back onto adjacent dune systems.

The permeability of the beach and its sediments will also influence the response. If the sediments are highly permeable, under any wave conditions it may allow the backwash of waves to return to the sea via the beach rather than the beach surface, which eliminates backwash and allows swash waves to travel up the beach unimpeded and build up the beach and increase its gradient (Haslett, 2009). Where permeability is lower, the backwash will return to the sea or at the near surface and potentially interfere with the swash resulting in a lower gradient beach.

These environments are part of dynamic, inter-linked systems where tides, waves, currents and weather exchange and rework sediment between offshore areas, beaches and associated dune systems with different timescales of morphological response which are dependent on climatic change and isostatic forcing

Beaches are dynamic systems that can regenerate from the damages incurred from the effects of wave action and coastal erosion within weeks of the event depending on sediment availability and hydrodynamic transport conditions (ibid.). These natural and dynamic formation and shaping processes play a key role in the coastal protection that they afford. Sediment composition will also affect the type of response. Sandier beaches respond more rapidly as they are more mobile than beaches that are composed of coarser sediments such as shingle beaches (Burgess-Gamble *et al.*, 2018).

Where beach systems become depleted, this can reduce their effectiveness in mitigating flood and erosion risks (Environment Agency, 2017). The main issue for flood and coastal erosion risk management of beaches is the loss of beach sediment which results in diminishing beach volumes and levels and disruptions to sediment balances and dynamics which would likely lead to a reduction in their flood defence value unless remedial works are carried out (ibid.). This can be caused by several factors, including, reductions in the natural supply from offshore, changes in the composition of materials supplied, and increased storminess.

There are a range of techniques that can be employed to beach systems to support flood and coastal erosion risk management (FCERM). There are four broad approaches which will depend on the broader policy objectives at the site, namely:

- Non-interference: allowing natural processes to take course and acceptance of losses of assets (associated with no-active intervention (NAI) or managed realignment (MR) SMP policies)
- Erosion slowing: measures that can delay erosion, including beach nourishment techniques and reprofiling, but which do not disrupt natural processes or the wider landscape (MR or hold the line (HTL) SMP policies).
- Selectively defend: local or medium-term measures that will minimise erosion but impact on natural processes and the wider landscape e.g rock or gabion headlands and groynes (MR or HTL SMP policies)
- Establishment of a fixed shoreline: tend to be associated with larger-scale, longer-term defences but that have a significant impact on natural processes and the wider environment, e.g seawalls, rock and timber revetments (HTL SMP policies).

Descriptions of the various approaches associated with erosion slowing measures together with the various considerations and benefits can be found on pp.201-210 of Burgess-Gamble *et al.* (2018). These approaches also apply to shingle and gravel beaches which are detailed below. It must be noted that a number of the measures could be employed in different categories and different measures can be used in combination or as hybrid approaches in combination with other habitats.

Beach nourishment activities for example can be used to address the threats to beach systems from climate change and sea-level rise and through the results of squeeze imposed by the existence of sea defences (McCue, Pye and Wareing, 2010). These activities broadly comprise re-building beaches through the addition of sand or shingle to the existing beach to make it wider, higher and more gently sloping (Winnard, McCue and Pye, 2011). This helps to move waves away from the upper parts of the beach and reduces the risk of flooding and erosion to buildings and properties located behind the beach.

McCue, Pye, and Wareing (2010) undertook a pilot study of 10 case study beaches in Wales to assess the likely requirements for beach nourishment that would be needed to re-build and maintain them through carrying out an initial nourishment followed by re-nourishment at 5 yearly intervals over a 20-year period. The values varied between sites - depending on factors such as the length of the shoreline, tidal range, beach width and rate of sea-level rise and ranged from 142,000m^3 at Tenby North Beach to 2,017,000m^3 at Aberavon.

Winnard *et al.* (2010) highlighted that there is potentially a sufficient sand and gravel resource available to meet these needs from the Welsh seabed but this is not all licenced for aggregate extraction (ibid.). They also found the costs of beach nourishment to be broadly similar to, ‘traditional’ coastal defence schemes over 20 years, but they can vary considerably depending on size, location, design life and standard of protection required. Further cost-benefit analyses are ultimately needed to improve the understanding of the cost-benefits of using beach nourishment activities and of the material resource to supply schemes.

A subsequent review by Winnard (2012) assessed the ecological impact of beach nourishment at the beaches contained in the previous study (focussing only on the effects on the intertidal ecology) which can result from activities such as the impacts to species or features from the presence or disturbance from machinery and impacts from the nourishment material used. 70% of all biotopes found in the case study areas were assessed to be at most, moderately affected by one or more of the twelve possible factors that beach nourishment activities may influence. 14% of the biotopes or species were assessed to be highly or very sensitive to one or more of the effects that may be caused by beach nourishment and these were confined to very specific local areas. They highlight that for most sandy beaches that do not contain any particularly important habitats, that beach nourishment will not have long-term ecological impacts as long as the sediment used is of a similar composition and material and well matched to that on the beach.

As noted by Hanley *et al.* (2014), any beach nourishment activities should take into consideration the provenance of, and type of sediment used. Depending on the source of the material this could have deleterious implications for sediment budgets (and knock-on erosion effects) or may have an ecological impact on particular species (e.g sand-dwelling invertebrate communities) which are highly sensitive to changes in sediment type. Beach nourishments are considered a soft coastal protection approach as they work with natural aggregates transferred from the same coastal shelf system. However, as noted by Staudt *et al.* (2021), many of the long-term effects of their application and sediment extraction are not fully understood, and there are large uncertainties as to their environmental impacts and the potential over the long-term for reoccurring nourishment activities to inadvertently geoengineer large stretches of coastline and alter coastal ecosystems.

Ultimately the most suitable solution will be dependent on specific local site characteristics and factors such as physical setting, environmental impact, availability and costs of suitable sediments, and aesthetics, and a project appraisal should consider the technical, economic and environmental factors prior to the development of a scheme. Ideally these should also factor in the effects of potential sea-level change at the specific locality.

One example case study of beach nourishment comes from the West coast of Jutland in Denmark near Ringkøbing Fjord where the solution was used to tackle the effects of coastal erosion. The low-lying areas in the hinterland of the coast are protected by an 10km belt of dunes which without any intervention, could, in some places experience coastline recession of up to 8 m/yr a year (The European Climate Adaptation Platform (ADAPT), 2023).

Since the mid 1980’s the Danish Coastal Authority worked with the local authorities to set up a system of coastal protection which involved a combination of breakwaters, slope protection and beach nourishments. Up until the 1990s, the coastline had been protected through the use of 145 breakwaters which were intended to reduce sand transport from the beach although these did not significantly slow the erosion rate. The complementary use of the beach nourishment helped to substantially slow erosion and recession rates and since the late 1990s the construction of revetments and breakwaters was phased out and now sand beach nourishment is the only solution used. The majority of the sand has been removed from 5-10km offshore before being placed on the sandbars or directly on the beach. Since the start of the project, it is estimated that more than 59 million m³ of sand have been replenished at average annual costs of approximately €10 million per year. Results from the project suggest that the previous high erosion rates have been reduced to an average of 0.1m since 1998 and have been more cost effective than previous approaches (ibid.).

In Wales, the Colwyn Bay Waterfront Project was recently completed to address the deterioration of existing coastal defences along the waterfront. The decline in the beach levels was leaving the extant coastal defences exposed which threatened properties and infrastructure (Conwy County Borough Council, 2025). The scheme (Phase 1b/c), which was completed in 2016 to a cost of £7.5 million, involved the installation of a secondary seawall, and concrete revetments but complemented by beach nourishment activities which involved a million tonnes of sand being recharged onto the beach to bring beach levels up west of Porth Eirias up to the level of the existing promenade. The project has resulted in an increased level of protection from coastal flooding and erosion to 200 homes and businesses and critical transport infrastructure (Institution of Civil Engineers, 2025).

More widely, large-scale renourishment projects have been used to address flood and erosion risks in the Netherlands such as the, ‘Sand Motor’ project. The project was undertaken in 2011 to provide protection for the low-lying Delfland coastal zone which had become exposed to increased risks of coastal erosion and future sea-level rise due to a reduction in the natural supply of sediment supply to the coast from previous human interventions in the catchment and sea-level rise which has led to the seabed becoming deeper, limiting the supply from the sea (Taal *et al.*, 2016).

The project involved the deposition of 21.5 million cubic metres of sand onto the coast and two complementary foreshore nourishment operations were undertaken on either side of the peninsula. The sand that was used for the scheme was extracted from ten kilometres offshore. The nourishment produced a hook-shaped peninsular of 128 ha, including a dune lake and lagoon. Since the completion of the project, natural processes have enabled the sand to spread along the coast with coastal accretion both to the north and south of the original feature. The project was designed with a lifetime of at least 20 years and the benefits are anticipated to last for at least this time period. The total cost was 70 million euros. Preliminary results indicate benefits for coastal protection, particularly in the vicinity of the Sand Motor, and after four years, 95% of the sand used is still in the monitoring area and 80% of that sand is still within the contours of the sand body created in 2011 (Taal, Girwar and Van Gelder-Maas, 2019).

Shingle/gravel beaches and barriers

Shingle beaches and ridges are typically composed of sediments with a mean grain size of between 2mm and 200mm and gravel and cobble beaches generally fall under this classification of beach type. They often occur as fringing beaches at or near the limits of high tide and in exposed areas where there is abundant sediment, they can develop into stony banks which often form a sequence of ridges which reflect the prevailing direction of alongshore drift and storms (Jones *et al.*, 2011).

Shingle and gravel beaches tend to have steeper beach face slopes than sand beaches which makes them reflective beaches as opposed to sand beaches that are dissipative (Ions *et al.*, 2023). The steeper beach face also means that waves can advance further inshore before breaking and transform almost directly into swash motion over a narrow region. Swash zones in gravel beaches are narrow and are of a comparable width to gravel beach surf zones. The rapid nearshore wave transformations associated with shingle and gravel beaches also means that energy dissipation is concentrated close to the shoreline (Austin and Masselink, 2006).

Many shingle and gravel beaches are located on parts of the coast that receive high wave energy from occasional storm waves and surges (May and Hansom, 2003). Their distribution depends on the nature and provenance of beach material and patterns of waves and currents at the coast.

In Wales, three main types of shingle beach have been identified based on cross shore sedimentological variation, namely:

- **Type 1 beaches** dominated by shingle down to mean low water level

- **Type 2 beaches** which are the most common in Wales. These tend to have an upper beach face and storm ridge composed of shingle and a lower beach composed largely of sand, although patches of shingle may also be present, and
- **Type 3 beaches** where mixtures of shingle and sand occur across most or all of the intertidal profile

Shingle and gravel beaches and barriers can be effective in dissipating wave energy and act as a barrier to overtopping of waves in all but the highest tides and storm conditions as they tend to be located above MHW level (Pye and Blott 2018). However, they cannot provide full protection against wave overtopping as the crest height of a beach will be limited by run-up under swell conditions and may be lowered by overtopping, cliffing and/or breaching during severe storms as opposed to sand dunes that can grow vertically upwards.

During storms, for example, gravel barriers can undergo significant morphodynamic changes ranging from erosion of the barrier foreshore to breaching or inundation and rollback (Ions et al., 2023). Attempts have been made to assess how gravel barrier beaches respond to hydrodynamic changes in order to predict their morphological change. Understanding this is particularly important to develop sustainable strategies for maintenance given the pressures that they face such as reductions in sediment supply or squeeze and the potential effects of climate-induced sea-level rise and increasing storm frequency.

Orford and Carter (1993 in Ions *et al.*, 2023) proposed a classification of how gravel beaches evolve from changes in physical and forcing conditions which causes the beach to switch from one regime to another. This has subsequently been modified through further research, but broadly, this classifies regimes or states of shingle beaches along an increasing severity of impact, from a *swash regime* where run up is confined to the barrier foreshore and does not impact the crest of the barrier through to *catastrophic overwashing* or an *inundation regime* where the still water level is almost equal to or higher than the crest height of the barrier which can result in crest roll-over, landward migration or breaching of the barrier.

To date, empirical models have largely been used to try to predict how shingle and gravel beaches and barriers will respond to storm events and associated flood risks to support coastal management decisions. However, despite providing indications of overtopping and flooding these models do not provide any assessment as to morphological changes in the beaches and barriers following such events. As noted by McCall *et al.* (2015), they have also been limited by the range of conditions and data from which they are derived and are often from idealised laboratory studies.

Recently, attempts have been made to apply numerical models to simulate the morphodynamic response of shingle and gravel beach and barriers to storm events to overcome some of these limitations. For example, McCall *et al.* (ibid.) developed a model which can predict morphodynamic responses across a wide range of forcing conditions and barrier response types and which was most accurate in predicting responses to very energetic storms. Almeida *et al.* (2017) assessed the impacts of storm events on a fine gravel barrier at Loe Bar in the South West of England and modelled the hydrodynamic conditions that define the thresholds for different storm impact events with a range of water levels and heights. They found that short period waves dissipate most of their energy by breaking before reaching the swash zone, which produced short runup excursions. However, long period waves, due to their low steepness, arrived at the swash zone unbroken with enhanced heights and this led to larger runup excursions. They also found that strongly bimodal waves can result in enhanced wave runup and reduce the thresholds for gravel barrier overtopping or overwashing.

However, these studies are limited to assessments of hydrodynamics and do not look at other factors such as sediment transport (Ions *et al.*, 2023). In addition, Ions *et al.* (2021) also note that their wider applicability, particularly for coastal engineers, may be limited due to the time and cost required to develop them and they require a large number of simulations to address uncertainties with their input parameters and processes-descriptions.

Ions *et al.* (ibid.) produced a model to assess gravel barrier beach responses to storm wave conditions and to estimate the change in barrier volume under a range of storm and water level scenarios. The model was tested against conditions at Hurst Castle Spit located in SW England. Their model displayed good accuracy in comparison with experimental measurements and was capable of simulating barrier volume change and overwash volume. They found, for example, that when energetic storm wave conditions (particularly with large wave periods) coincided with large surges, wave run-ups would exceed the barrier freeboard and sediment was overwashed and deposited at the back of the barrier which resulted in crest lowering. Waves with low steepness were found to increase overtopping. In addition, where the storm surge elevation was significantly large, overwashing occurred even during low wave energy conditions. Where the most energetic storms combined with the largest storm surges, overwash sediment was deposited far behind the barrier and sediment was lost from the barrier system which could lead to them being more vulnerable to future wave attack without future management interventions.

Ions *et al.* (2023) built upon these classifications and simulated the spatio-temporal and morphodynamic response of a shingle barrier beach in Christchurch Bay in the South West of England to storms and compared the response between unimodal storms and bimodal storms. The latter are where high energy swell waves generated over the ocean occur alongside locally generated wind waves (as demonstrated in Figure 6) which can result in higher energy conditions and have not generally been assessed in research into the morphodynamic response of gravel beaches.

Their results suggest that the morphodynamic response of the barrier beach is strongly influenced by the combination of storm wave height and still water level with the presence of swell waves also as a controlling factor in the response. The response of the gravel barrier regime increased in severity where there were higher magnitude combinations of wave height, peak wave period and high still water levels. Low-intensity unimodal storms led to the barrier remaining in a collision regime (see above), but higher intensity unimodal storms led to overwashing, and where the barrier freeboard was small (the vertical height from the MHWS and the storm surge level to the top of the crest) it led to a reduction in the height of the crest. They found that bimodal storms can increase the rate of sediment being overwashed behind the back of the barrier, and where the swell component is >35%

this can lead to a significant increase in the amount of sediment being transported up and over the barrier crest and can occur irrespective of wave height and periods.

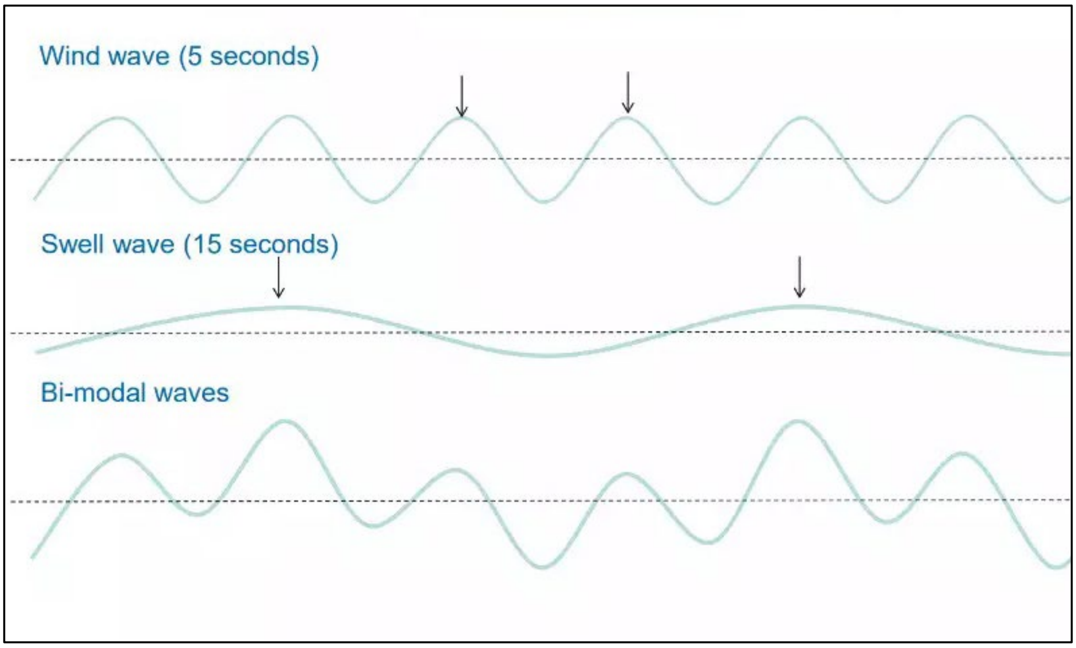

Figure 6: An illustration of how bi-modal waves are formed. Source: Coastal Partners (2025).

Pye and Blott (2018) identified 403 shingle beaches on the Welsh coast that have an FCERM function, and of these 42 sites were identified as having a high or medium value. The classification of sites incorporated a variety of (site-specific) factors, including, their geomorphological features and size (the crest height and width at MHWS level), the presence of flood defence structures, the value of assets protected and the elevation of the surrounding hinterland level.

In general, the presence of a naturally wide and high beach and barrier profile will provide maximum opportunity for the absorption of wave energy and reduction of flood risks (Forbes, Ball and McLay, 2015). Where barrier crests are lowered or fall relative to tide levels their effectiveness to provide the defence function will be reduced (Pye and Blott, 2018).

For example, the presence of the harbour arms at the seaward entrance of Shoreham harbour in West Sussex have presented an obstruction to the natural processes of sediment movement by littoral drift along the coastline. This resulted in the accumulation of gravel on the west of the harbour entrance and the lowering of beach levels to the east which threatens seawall and defence structures and increases the risks of flooding to the port and adjoining infrastructure (including a power station, road networks and wastewater treatment works) (Parker and Dornbusch, 2017). The shingle transfer (bypassing) has been in operation since 1992, and is intended to replicate the natural longshore drift that would occur if the harbour structures had not been built and to maintain beach levels and standards of coastal protection to the structures to the east of the harbour. The transfer occurs biannually and has been effective in addressing the updrift accumulation and downdrift erosion issues.

Without the presence of hard defence structures, shingle beaches will naturally tend to migrate landwards where the ridge crest will tend to move landward and adopt a more natural profile. A range of management methods have been deployed to shingle beaches and ridges in Wales and the UK to support flood risk reduction. This has, in many areas without defence structures present, for example, often involved the use of artificial beach profiling to maintain high crest levels above selected probability levels associated with the highest waves and storm levels, or through the use beach nourishment that uses imported shingle and cobble materials. Artificial structures such as groynes, breakwaters to control sediment movement along shores have often been used in areas where shingle beaches and ridges are located near to defence structures (Pye and Blott 2018).

However, these techniques have caused several issues in terms of beach management for flood risk protection. Where beaches are artificially profiled they will not be in equilibrium with incident waves and storm run-up and exposes them to the action of greater wave energy and can be easily modified in strong wave or high tide conditions, there is usually a progressive loss of sediment from the embankment as it gets eroded (ibid.) (Forbes, Ball and McLay, 2015). Beach replenishment and nourishment activities have also tended to use imported materials that may not be of the same sedimentological composition as the beach system, largely due to the costs of transporting suitable materials (ibid.).

Artificial defence structures such as groynes where correctly designed can be used in conjunction with nourishment techniques to provide flood defence, but they can also impede sedimentary supply where used without consideration of local beach and tidal dynamics which can lead to falling beach levels, increased risk of overtopping or sea wall collapse.

As highlighted by (Pye and Blott, 2018), any interventions should ideally try to replicate natural beach profiles as closely as possible. They highlight a range of management options where hard defence structures are not present, but detail that beach nourishment techniques may provide the best compromise in terms of balancing the effectiveness against flood and erosion risk, cost and ecological/geomorphological impact.

Where there are maintained coastal defences and assets of high-value located behind shingle ridges, management interventions can still provide complementary flood risk defence. In such scenarios, the creation of a wide, high beach can provide an additional level of support to defence structures and prevent impacts from wave reflection and overtopping. Where these are not present, they highlight that beach nourishment can be a cost-effective approach to provide complementary flood risk benefits at lower environmental impacts, but the flood risk benefits will not necessarily be as high as using artificial defence structures and requires continued recharge of sediment supply.

It is advised that nourishment activities should be undertaken using rounded material of a similar size or slightly coarser than existing shingle (Poate, Hamilton and Masselink, 2024). However, there are challenges in securing suitable nourishment material within an economically viable transportable distance. Poate, Hamilton and Masselink, (ibid.) assessed the opportunities for sourcing nourishment materials for 5 shingle beach sites in Wales that were classified by Pye and Blott (2018) for having a high flood and coastal erosion risk importance. For the sites that they studied in North Wales, they found that there were suitable sources of materials (Cefn Graianog Quarry), however for the sites in South Wales, land-based sources of gravel and cobbles are more limited but sourcing from multiple quarries might offer a solution for materials.

There are some recent case study examples which provide modelled and observed data on the effectiveness of shingle beach nourishment to retain protection standards of landward defences (Environment Agency, 2017).

For example, at Pagham Harbour in England a project was undertaken to address the loss of beach material that was increasing the erosion risk to 76 residential and commercial properties. This was resulting from the expansion of the spit feature which was extending in a north-easterly direction with the littoral drift and created an extended tidal channel in front of the adjacent foreshore. Shingle and sediment became locked up in the spit (approximately 390,000m^3) and was prevented from moving ashore due to the strong flows occurring through the now elongated tidal channel which inhibited transport through natural long-shore sediment pathways (ABP Mer, 2015). As the ebb delta and spit developed, the tidal inlet channel was diverted north-eastwards, and caused erosion of Pagham Beach (Scott, Harris and Townend, 2020) and the erosion risk had dropped from a target of 1:200 to 1:180.

The area is highly designated and includes SPA and Ramsar sites and a SSSI which needed consideration in the flood risk approach taken. The initial project to address the issue entailed the transfer of 10,000m^3 shingle from the intertidal ebb delta across the Pagham Harbour outflow channel onto the beach and a further 20,000m^3 to bring the beach back into a reasonable condition to provide a suitable defence. Following the application of shingle nourishment, the target standard risk level was re-achieved, and it was designed to last between 5-10 years. The total cost of the project was £43,000 and achieved a benefits to cost ratio of 3:1 (R. Spencer and Dornbusch, 2017). The transfer of the shingle from delta onto the beach had a minimal impact at that time on the vegetated shingle and on some aspects of the SPA, and provided a benefit to beaches further down drift, both in terms of providing additional protection and potentially additional area for vegetated shingle to form (ibid.).

However, following severe storm events between 2013 and 2015 there was further erosion of the beach and threats to the properties. Following the events, the community and stakeholders consulted on options to address the underlying issue and considered the option of breaching the spit to restore the inlet to its pre-2004 position in order to move the tidal channel away from the beach and then allow the separated end of the spit to migrate eastwards to allow the re-supply of the eroded beach through natural processes (Scott *et al.*, ibid).This approach was not initially adopted due to a variety of issues, including, concerns that it could have an impact on protected nature conservation sites, the more detailed and longer planning process involved, the higher perceived costs of implementing it, and the certainty of outcomes in terms of impacts and benefits of the approach (and to inform HRA and coastal protection funding) (ABP Mer, 2015) (Scott, C.R *et al.*, ibid.).

Beach management and revetment activities were also seen as suitable for the provision of pre-determined, objective and measurable criteria for decision-making. In the intervening period, rock revetment and geotextile bags were used alongside additional shingle recycling to address the issue together with the installation of a reinforced cross shore groyne that deflected the tidal channel seawards across the (distal) end of the spit. During the period between 2014 and 2015 the southern spit was 1.1km in length and remained relatively stable and was unable to progress or roll back due to the presence of the emergency revetment works protecting homes on the beach. The local community continued with efforts to adopt the breaching of the spit approach and subsequently obtained planning permission to undertake the measure. However, during this time, the spit naturally breached and many of the anticipated benefits have been realised from the change as the beach now receives a natural flow of sediment.

Recent experiments have tested the use of novel nature-based solution approaches which have had limited use to date, including the use of dynamic cobble berm revetments. These involve the artificial placing of a berm of cobbles at the high tide wave-run up limit on a sandy beach to mimic the cobble berm of composite beaches and stabilise the upper beach by providing overtopping protection to the hinterland and translate with water level rise.

Bayle *et al.* (2020) undertook laboratory flume experiments under controlled conditions to assess the impacts of storm waves and rising sea levels on their morphology and compared these to a sand only case without revetments. The authors found that even with large storm waves and 50% overtopping, the revetments remained a cohesive structure/remained dynamically stable, with only a temporary loss of cobbles (volume did not drop below 97% of original structure). The presence of the dynamic cobble berm revetment also reduced the shoreline and berm retreat and significantly reduced the vertical and horizontal runup compared to the sand beach on its own. Angular revetments (as opposed to rounded ones) were found to form a more stable, peaked crest and provide a higher wave overtopping protection, as the crest grows with water level rises and could potentially maintain a similar level of overtopping protection given with sufficient accommodation space and volume. The authors argue that the results suggest that they could be a cheap and efficient solution to provide coastal erosion protection for sandy coastlines in a changing climate in locations where complete protection from coastal hazards is not needed and some coastal retreat is acceptable (where accommodation space is available).

Blenkinsopp *et al.* (2022) used high-resolution measurements of wave runup from five field and large-scale laboratory experiments to developed a methodology to predict wave runup on dynamic cobble revetments. They found that as the swash zone transitions from the sand beach to the gravel berm, the short-wave component of significant swash height rapidly increases during a rising tide and dominates over infragravity wave components (surface gravity waves with frequencies lower than wind waves). When the gravel berm toe is submerged at high tide, the wave runup is strongly controlled by water depth at the toe of the berm due to the decoupling of the significant wave height at the berm toe from the offshore wave conditions due to the dissipative nature of the fronting sand beach.

Cost-benefit assessments/ecosystem service valuation

In terms of the economic valuation of beach nourishment activities, Coelho, Lima and Ferreira (2022) used a cost-benefit analysis approach to assess the physical and economic performance of artificial beach nourishments to tackle erosion rates on a stretch of coast in northern Portugal over a 20-year time horizon. The economic benefits varied depending on the scenario analysed (e.g depending for example on the frequency, volume and siting of nourishment and land values adjacent to nourishment areas). Overall, they found that erosion effects represent important economic losses, and that the application of artificial nourishments allowed for the mitigation of shoreline retreat rates. However, at the tested site of Barra-Vagueira the economic viability of the intervention was achieved for only one of the tested scenarios. They highlight that the performance of the solution and the consequent economic evaluation depends on the design parameters and site-specific conditions together with the associated valuation of land uses and ecosystem services. The authors argue however that a similar methodological approach could be applied in other locations to assess the viability of using beach nourishment and the specific shoreline evolution change with the costs and benefits of measures deployed.

Within the wider cost-benefit approach, they also note that previous studies have highlighted that artificial nourishment effects can have impacts on changing consumption of users i.e for recreation, whereby reductions or alterations in beach width could lead to potential changes to recreational income in the surrounding areas.

Gaps/further evidence needs: beach systems

- There are large gaps in terms of cost-benefit analyses and economic appraisals of management measures and projects and in combination with the assessments of the services that they provide in reducing flood risk (Narayan *et al.*, 2016).
- There are still gaps in the quantification of the level at a general or localised level as to how sand and shingle beaches reduce flood risks, for example relative or percentage reductions in wave and storm energy.
- Further work is needed to improve our understanding of the material resource available to supply beach nourishment schemes in Wales, including from off the Welsh coast, and from wider sources (including from land-based sources and smaller harbours and ports) (Winnard, McCue and Pye, 2011).
- More detailed reporting and evidence is needed on the effectiveness of recent trials and projects around the coast. Projects should build in continued monitoring and evaluation which will help to improve understanding of the best ways to deploy management techniques (Burgess-Gamble *et al.*, 2018).
- As per the above, further research and trialling is needed of potentially effective nature-based solutions but which have had limited use to date, such as dynamic cobble berm revetments.

Sand dunes

Sand dunes can act as a physical barrier to protect the hinterland from flooding. To provide a coastal defence function, dunes need to withstand periodic erosion and storm damage. This depends on geomorphological characteristics, including dune morphology, sediment supply, accumulation, and stabilisation (Hanley *et al.*, 2014).

Dunes are dynamic systems and erode during storm surge events and need to be able to withstand some erosion and storm surge damage (Jordan and Fröhle, 2022). For instance, depending on the intensity of a given storm, sand is eroded from either the foredune or seaward foot/face of low-lying and yellow dunes (Figure 7) and then moved onto the beach or in some cases to the foreshore area. This sand is not lost during the storm event but re-deposited within the dynamic system and stays within the breaker zone, helping to replenish the beach and foreshore area. Following a storm, sand is gradually transported back to the beach by waves, where it dries before being transported back to the dune system by wind as demonstrated in Figure 8 below.

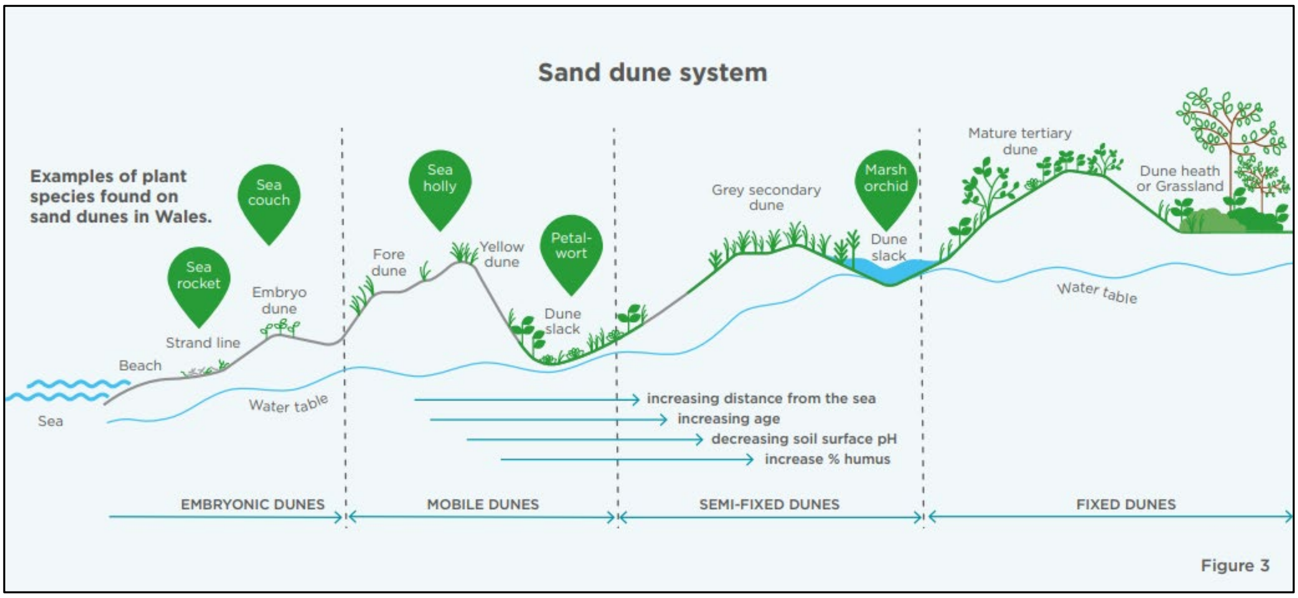

Figure 7: typical profile of a sand dune system in Wales. Source: Natural Resources Wales (2024a)

Higher elevated dunes and those in the mobile section of dune ranges (e.g yellow dunes and above) also serve an important coastal protection function and act as a natural barrier to high water levels and reduce wave action by acting as a sediment reserve, stabilising sandy coasts and shielding the hinterland from elevated water levels and flooding. They can thereby act to protect flood defence structures or cliffs behind from direct wave attack and erosion and enhance the design-life of traditional flood infrastructure (Environment Agency, 2017).

Broadly, the maximum crest height and cross-sectional area of a dune system are important determinants as to the level of defence which they can provide against coastal flooding (Pye, Blott and Guthrie, 2017), together with their interactions with maximum still water level (the water level without the influence of wave action) and the maximum wave energy experienced in a setting.

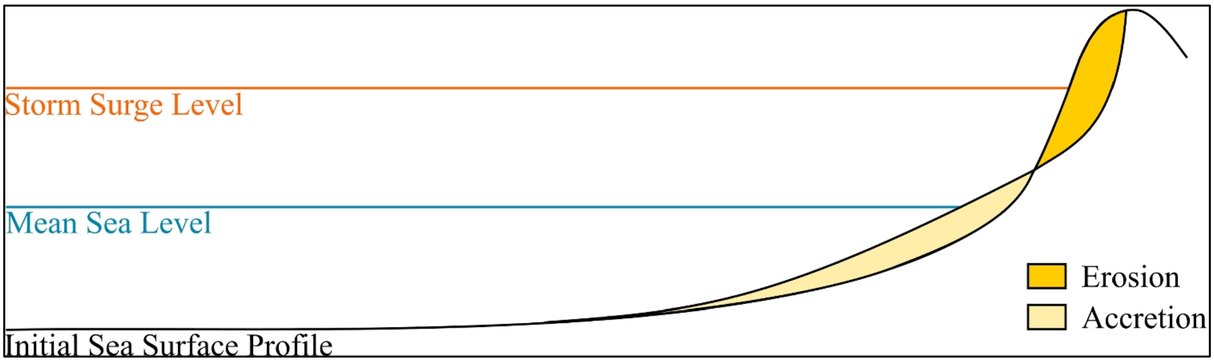

Figure 8: A cross-shore profile of sand dune mechanisms during a storm surge event. Source: Jordan and Fröhle, (2022).

Hanley *et al.* (2014) outline how the evolution of a dune and response to wave action will vary depending on sand delivery rates:

- Where rates are high, the fore-dunes become wider as the sand is deposited over an ever-expanding area which creates a series of long, low fore-dune ridges.
- Where rates are negligible (slightly positive or negative), the dunes become taller as the sand from the beach is deposited over a smaller area, and
- If supply is negative, beach erosion and scarping will result in shorter, narrower foredunes with a greater chance of over-wash by waves.

Saye *et al.* (2005) found a general relationship between beach parameters and the erosion/accretion status of frontal dunes of based on an analysis of LiDAR data and topographic and bathymetric surveys at five dune sites across England and Wales. Accreting and higher, more developed dunes were fronted by wider, low-angle beaches, corresponding with a large tidal range, whilst eroding dunes were associated with narrower steeper beaches. However, they note that local factors will lead to variation in the relationship such as sediment supply, grain size characteristics, the wind/wave climate, vegetation characteristics and management practices.

Pye, Blott and Guthrie (2017) highlight that where dunes act as a complete physical barrier to flooding, the efficiency of the barrier is related to three factors, namely, i) the minimum crest height of the dune, ii) the width of the dune barrier and, iii) the sediment volume of the barrier. They highlight a general relationship between the standard of coastal flooding protection to the dune crest level and width, with the highest protection provided by dune systems which consist of several shore parallel dune ridges with each having a crest level several metres higher than the predicted maximum storm surge wave run up level as shown in Figure 9.

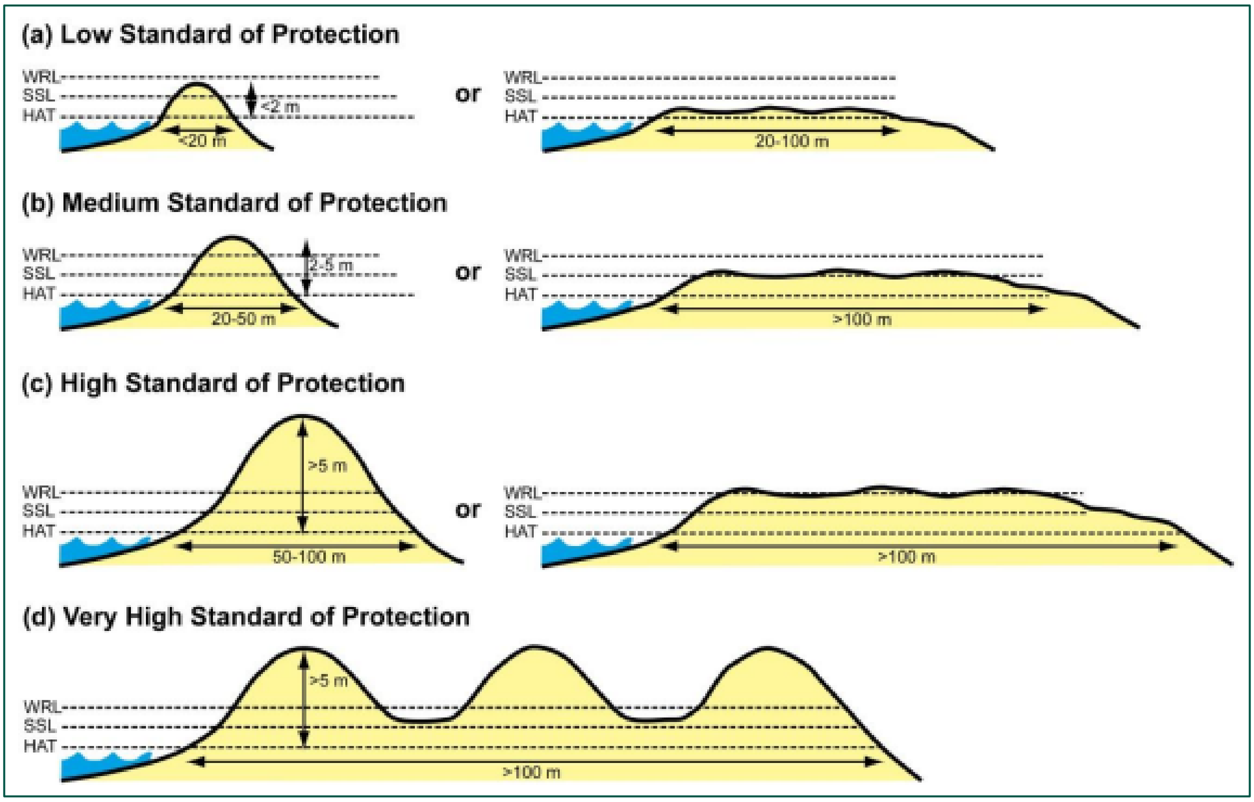

Figure 9: A conceptual diagram of the difference in flood protection provided by different sand dune barriers depending on sand dune width and crest height: WRL: wave-run up level, SSL: storm surge level; HAT: highest astronomical tide. Source: Pye, Blott and Guthrie (2017)

Mehrtens *et al.*(2023) examined how the coastal protection potential of a coastal foredune system evolves depending on its spatio-temporal growth at a series of foredunes in the North sea region of Germany over a time period between 1949 to 2015. The dunes are located in a diurnal meso-tidal regime with an average tidal range of approximately 3m near the coast. They currently lie behind a large beach system and in front of sea-dike defences with a mean crest height of 8m which protects the hinterland from flooding- which are also split by an established dune system.

The authors used a method to determine a critical storm surge level (CCSL) as an indicator for the protection needed against a 100 year storm event, based upon a defined size criterion of how much sand is stored in the cross-sectional area of the frontal half of a dune above the 100-year still-water elevation (SWEL)- in this case it equated to 50m^3/m for the locality. When the amount of sand within the cross-sectional area fell below this value, the dunes erode and form a low, gently sloped profile which would have consequent negative impacts on their ability to provide the requisite level of coastal protection.

By the 1980s an initial line of young foredunes had developed, but by 2015, this had continued to develop into a stretch of over 6.5km of the coastline. In addition, there was an overall increase in the critical storm surge level over time due to the successive growth and development of the foredunes which grew at a mean annual growth rate of 7.4m^3/m and a mean critical storm surge level of 3.4m above German standard elevation level was recorded by this date with some dune profiles providing a potential critical storm surge level of 6m. The dune system also shifted seaward during this time period by an average of 2.3m/yr and increased in height by an average of 1.1 cm/yr and established a new line of defence in front of the existing dike system. They highlight that the method provides a relatively quick and straightforward assessment of the level of protection provided in large coastal areas and can be used, for example, as a tool to forecast vulnerable dune sections and identify areas in need of reinforcement e.g through sand nourishment practices or sand-fencing. However, it only considers the cross-sectional profile of a dune and neglects other influencing factors, including wave and wind characteristics.

Sand dune systems cannot however always provide full protection from flooding against storm surges, even if they can provide significant protection against wave action during such conditions. This will depend on the nature of the dune system and morphology. In their study, Mehrtens *et al.* (2023) for example, noted how there can be a non-uniform spatio-temporal dune growth response which can lead to variation in dune height and volume which impacts on the level of storm surge protection that is provided by a foreshore dune system, as gaps in the system along the foredune line can allow flood water to pass through these sections. Similarly, Fernández-Montblanc, Duo and Ciavola, (2020) highlight how breaks or interruptions in the linear continuity of foredune systems (e.g by man-made structures or channels) can reduce their efficacy to minimise flood inundation of adjacent landward areas.

As noted by Hanley *et al.* (2014), although geomorphological and sediment supply characteristics play important roles, the presence of vegetation is more important for dunes than any sandy habitat for wave attenuation and coastal protection, as it aids the accumulation of sediment. In recent years, there has been a shift away from stabilising dunes with vegetation, largely due to the negative ecological impacts that have arisen from the introduction of monocultures and non-native plant species. However, planting native dune vegetation can help to support the coastal protection functions of dunes whilst minimising adverse ecological impacts (ibid.).

For example, in South Milton, Devon, previous development activities had led to the deterioration of the extant sand dune systems. In 2009, the National Trust undertook a project to reconstruct the original dune system, consisting of three new dune ridges, each around 200 m long and 30 m wide, using sand moved from the fronting beach. As part of the project, over 15,500 plugs of native dune grass *Ammophila arenaria* species were planted across the seaward side of the dunes to stabilise the dunes. *Ammophila* are dune builders that help to stabilise dune systems due to their extensive root systems and ability to grow under constant sand burial.

The authors found a significant increase in *Ammophila* cover through time which indicated that the plugs had been successful and they also witnessed enhanced growth where sand deposition was relatively high. However, although the establishment of *Ammophila* had been successful, overall plant community biodiversity was limited, and they argue that this was possibly due to limited movement of propagules from nearby natural sand dunes. They also found mixed results in subsequent trials where they attempted to introduce seeds of a range of dune building and stabilising species to dunes (through a combination of direct sowing and geotextile mattings) which highlighted the challenges of introducing vegetation by seed in such highly dynamic systems.

Sigren, Figlus and Armitage, (2014) undertook a small-scale mobile-bed wave flume experiment to test the effects of the presence of vegetation on wave-induced erosion on dune surfaces. They found that the presence of the vegetation reduced wave-induced erosion by up to 33% and scarp retreat and increased the dune's protective ability by prolonging the amount of time it acts as a storm buffer. They also found that the presence of dune roots contributed to the mechanical strength of noncohesive dune sediments.

Other studies also attest to the positive effect of vegetation on reducing erosion, including Silva *et al.* (2016) who used flume experiments to test the effects of the density of vegetation cover on beach-dune erosion under different modelled storm conditions and found that vegetation reduced net erosion on dune faces, regardless of the type of wave condition through reducing wave transmission and reinforcing the soil or by retarding wave up-rush and decreased overwashing rates and wave overtopping.

Feagin *et al.* (2019) also used experiments to measure the effect of beach and dune plants on erosion under controlled conditions and found that in general, erosion was higher when any part of vegetation (above or below ground) was absent. Aboveground dune plants reduced erosion by attenuating wave swash and run up bores with their stems and leaves. Plant roots (belowground biomass) had the effect of initially enhancing erosion through uprooting, but after excavation the roots also attenuated waves and reduced erosion. They found that herbaceous non-graminoid (non-grass) species located closest to the water were found to have the most efficient structures for erosion reduction. They suggest that their results indicate the presence of the vegetation translated into a reduction of wave run up erosion by approximately 40% for dunes.

De Battisti and Griffin (2019) also investigated the capacity of three widespread pioneer foredune species to resist dune erosion, comparing the perennial species *Ammophila arenaria* and two annuals *Cakile maritima* and *Salsola kali*. They found that all three species reduced erosion and *Ammophila* had the strongest effect (36% erosion reduction versus unvegetated cores) due to its large below-ground biomass. In addition, they found that all of the below-ground biomass (the roots, rhizomes and shoots) was important for erosion resistance, rather than any single component, although buried shoots had the clearest individual contribution. The authors argue that the results highlight the potential role that annual species can play in providing sediment stabilization of dunes.

However, Silva *et al.* (2016) highlight that results from experiments suggest that there are thresholds which exist beyond which the amount of vegetation can disrupt the natural dynamic properties of dune-beach systems through decreasing the wave runup (due to greater friction) and preventing the delivery of sediment from the dune to the beach system during storm erosion (due to sediment stabilisation properties of stems and roots). This ultimately has impacts for management decisions with regards to the assessment of what is suitable in terms of levels of vegetation cover and how this interacts with the ability to maintain the dune in a relatively dynamic state and vis-à-vis the vulnerability of the landward area that it is protecting and level of protection needed.

Pressures and management

Various pressures have impacted on the condition and connectivity of sand dune systems in Wales and the UK in recent decades, including from coastal development and artificial defence structures, tourism, and recreation. These have had impacts not only on the condition of the dunes themselves but also on wider aspects associated sub-littoral and beach systems through the alteration of hydrodynamic regimes of sediment supply, transport and deposition (Hanley *et al.*, 2014). For example, it is estimated that approximately 30% of the original sand dune area in Wales has been lost to development and erosion since 1900 (Pye, Blott and Guthrie, 2017).

In addition, various management activities have impacted the condition of dunes in Wales and across Europe. Over the last 80 years, nearly 90% of open sand on dune systems has disappeared and been replaced by dense grass and scrub to promote dune stabilisation (Natural Resources Wales, 2024b) and dune systems have also been impacted by the plantation of non-native trees or drainage practices.

Flood and coastal erosion risk management practices have also tended to focus on stabilising seaward dune faces and/or dune crests through the placement of rock armour and gravel upper beach berms or similar structures at dune toes/upper beach interface, rather than maintaining the natural functioning of dune systems (Pye, Blott, and Guthrie 2017). These have often tended to have detrimental impacts, such as cutting off or significantly reducing sediment supply between beach and dune systems and/or in some cases, have led to beach lowering from wave reflection processes.

The effects of climate change from the combination of future sea-level rise and potential increased winter storminess will pose increased risks of erosion and deterioration of dune systems (Haigh *et al.*, 2022) particularly in settings where there are no significant inputs to the beach and dune systems from longshore sources (Masselink *et al.*, 2022). Those dune systems that have space to roll back in response to sea-level rise will have more resilience to these changes. However, dune systems that are buffered by coastal infrastructure and artificial defences will be squeezed and this could lead to their deterioration from further inundation and erosion and reductions in the dune area. It is difficult to predict the full extent of threats to sand dunes due to the difficulties in predicting sediment and erosion pathways (Hanley *et al.*, 2014). However, Saye and Pye (2007) estimated that some Welsh dune systems will lose up to 100 m of shoreline as a result of increased erosion driven by sea-level rise.

There are a range of different management techniques that can be utilised to support the wider coastal protection benefits provided by dunes. Pye, Blott and Guthrie (2017a; 2017b) identified 87 dune sites in Wales that have a medium/high, high or very high FCERM significance. They provide a series of decision trees (see pp.57-59 of report) (2017a) to decide which intervention and management approach is suitable for both SMP policies and the standard of flood protection required.

They highlight that where dunes have low-medium FCERM significance, the focus should be on minimising the use of intervention measures and allowing the dune system to evolve as naturally as possible. In those areas associated with hold the line policies, hard defences have often been constructed along dune frontages such as sea walls, rock revetments, groynes and beach reinforcement using natural gravel and quarried rock. In such settings, methods such as sand-filled geotextile bag revetments, beach and frontal dune nourishment and sand fencing, thatching and vegetation planting can be used to maintain natural sediment exchange processes between beaches and dunes. However, where hard defences are due to be replaced or upgraded, or where short lengths of new defence need to be constructed, there are opportunities to support dune creation and/ or maintenance for multiple benefits, which could include options such as creating a gently sloping seaward revetment to a sea wall, backed by a relatively low wave return wall, which allows the free movement of blown sand across the structure to feed dunes behind.

The technique(s) used will depend upon whether there is a need to increase the height and/or width of the dune system and the degree to which sand form mobility can be permitted at the particular location. It should form part of an overall management strategy that considers the sediment budget status of the beach and frontal dunes and vegetation cover, and which takes into account the range of flood defence, nature conservation, recreational, geomorphological, historical and archaeological interests of the site (ibid.).

Several projects have been undertaken along the Welsh coast and more widely in Europe to rehabilitate sand dune systems and address the impacts derived from previous management activities associated with the attempts to stabilise dune systems. These activities aim to restore a more natural and dynamic development of the dune systems and improve their resilience and adaptive capacity to future climatic change and pressures. For example, the Sands of Life project in Wales (Natural Resources Wales, 2024b) has included activities such as sustainable grazing, sand dune reprofiling and scrub management to control vegetation at the sites and restore more dynamic conditions in the dunes.

Hightown sand dune scheme

One example of works that have been undertaken to reinforce or enhance dunes specifically for flood protection was at Hightown near Liverpool, where a programme of work was undertaken to reinstate sand dunes to the same position that they were in over 30 years ago. Prior to this, the site was losing on average 1,000 cubic metres of sand per year leading to an erosion rate of 0.5-1m per year with potential impacts on 125 properties and assets (Figure 10) (Lymbery, 2017).

Figure 10: erosion of the dunes at Hightown following a storm event. Source (Lymbery, 2017).

It was not possible to do a traditional beach recharge at the site due to presence of the remains of a Neolithic forest. The overall scheme was a hybrid solution, with the decision made to reinstate the sand dunes to their former position (extent in the 1970s), the rebuilding of the existing hard defence as a sloped revetment and the placement of a rock groyne alongside the vertical face of the outfall features to prevent reflection/dissipation of wave energy against the dunes. The total costs of the project were £1.4 million.

The scheme bought approximately 30 years of protection to the communities, principally due to the sand dune works, and the area of the dunes protected by the rock groyne has also benefited from being protected from reflected wave energy and through increased beach levels. As many of the cost benefits would be realised later in time, the discount factor applied to the cost benefit analysis substantially reduced the current day benefits (technically the protection is costing roughly £45,000 per year) but the community wanted the scheme and the sand dunes to be maintained (ibid.).

Fernández-Montblanc, Duo and Ciavola (2020) assessed the effectiveness of dune restoration and revegetation to minimise the impacts of coastal erosion and flooding at a rapidly eroding beach system in Emilio Romagna in Italy. The effectiveness of the solutions were assessed against the simulation of an extreme coastal storm event for the area (with a significant wave height Hs ≥ 3.3 m and observed tide (surge + tide) ≥ 0.8 m). The results suggested that the combination of both dune reconstruction and revegetation (where the dunes were virtually reconstructed to a crest height of 1.7m above mean sea level over 1.4km and revegetated with native botanical species), provided the best solution to minimise coastal erosion and flooding both under current conditions and against future mean sea-level scenarios to 2090 (low scenario: 0.61m, high scenario: 0.91m) and compared to just revegetation alone. The combination led to a reduction in the maximum water volume of flooding by 42% under current sea-level and between 25%-59% under high and low hazard future sea-level scenarios respectively. The dune systems captured sediment during landward wind episodes which reduced sediment erosion during overwash and overtopping episodes. They found that revegetation had the effect of enhancing dune stability and reducing overwash and increased flow attenuation and wave energy dissipation and hence caused reductions in flooding even without dune reconstruction under all scenarios. However, the dunes are located in a micro-tidal regime (neap tidal range of 0.3m-0.4m and spring tidal range of 0.8-0.9m) and in a typically low energy area with respect to wind waves (with typical average significant wave heights of 0.4m).

Another technique that can be used to stabilise dune systems is through the use of sand fences which work by reducing wind speeds to allow sand to accumulate which then enables their colonisation by early successional species. The approach can help to support reductions in erosion and wind speeds across the sand surface and encourage the development of foredunes which can subsequently help to reduce some of the erosion potential of waves near the limit of the uprush (The European Climate Adaptation Platform (ADAPT), 2023). However, the approach cannot prevent erosion where wave action is both frequent and damaging. The technique has the benefit that it is inexpensive and easy to construct, but to make them effective, the fencing needs to be positioned so that it creates maximum topographical complexity within a restricted area (Grafals-Soto, 2012 in (Hanley *et al.*, 2014)).

A recent trial project was set up in Swansea Bay in 2016 to address ongoing issues in relation to periodic incursion of wind-blown sand onto the main promenade and infrastructure. This was principally due to the artificial narrowing of the eastern part of Swansea Bay by the construction of coastal defences and infrastructure across the upper part of the beach and former sand dune areas in the mid-19th century and during the 20th century (Pye & Blott, 2022). During stable periods, with few severe storms, the sand is moved landwards from the subtidal and lower intertidal areas of the bay and builds on the upper beach which allows dunes to form where the backshore is sufficiently wide. During severe storm events and/or where several storms happen in quick succession, the upper beach and dunes experience wave erosion and sand is moved seawards and deposited in the lower intertidal and subtidal zones (ibid.).

In 2016, dune fencing was installed on the upper beach west of the Civic Centre on both sides of the Oystermouth Road underpass to encourage the development of extant dunes and mitigate the problems with blown sand. There has been significant sand accretion since the start of the project (Pye and Blott, 2019) and priority sand dune habitats have become established. This has been successful in reducing the level of sand being blown onto the main cycleway, promenade and coastal road behind. In 2020, Swansea council installed additional fencing on the landward side west of the Oystermouth road underpass. Since then, there has been further significant growth of the dunes within the fenced compartments, although there has been some damage in places by recreational visitors which has reduced its efficiency (Pye and Blott, 2022).

Further assessments suggest that there are opportunities to encourage the development of vegetated dunes on other sections of the seafront within the backshore areas which could help to build reserves of sand that can replenish the beach during future storms and reduce the likelihood of waves breaking directly against the sea wall. This would also help to reduce the quantity of sand which is blown and deposited on the cycleways, promenade and adjoining infrastructure. The dunes within the current fenced area are also approaching their storage capacity and additional accommodation space would be required (ibid.). The project has led to multiple benefits, including cost savings to the Council in terms of sand removal and disposal works and reduced risks to users of the road and cycleways (Y Lab, 2024). It is also expected that the dunes will help to reduce risks from flooding and erosion as they continue to develop.

There are limited cost-benefit studies that have assessed the coastal protection functions provided by sand dunes. However, Beaumont *et al.* (2010) using data on the linear length of dune systems in England and Wales from Pye, Saye, and Blott (2007) estimated a sea defence value for sand dunes of £173.7 million (£304 million 2024 value) in England and £54.2 million (£94.9 million 2024 value) in Wales based on a replacement cost method. This estimate, however, only took into account dunes that protect high value land and which lacked artificial defence structures, thus they note that it is likely to be an underestimate of the true value. The aforementioned considerations in relation to replacement cost approaches similarly apply to these values.

Gaps/further evidence needs

Compared to case studies that are available for other habitats such as saltmarsh and wetlands, there is limited information on the flood risk benefits provided by sand dunes and in Wales. Much of the work and projects associated with dune systems in recent years has focussed primarily on other benefits, such as in relation to their value for biodiversity. A better understanding of their value for FCERM could help to build a wider and more complementary assessment of their multi-functional roles. There are several areas that would help to improve the evidence to support their use as nature-based solutions for coastal flood and erosion risk programmes:

- There are large gaps in terms of cost-benefit analyses and economic appraisals of management measures and projects and in combination with the assessments of the services that they provide in reducing flood risk (Narayan *et al.*, 2016).
- More detailed reporting and evidence is needed from trials and projects around the coast in Wales. Projects should build in continued monitoring and evaluation which will help to improve understanding of the best ways to deploy management techniques (Burgess-Gamble *et al.*, 2018).
- More observed data is needed to understand how dunes respond to storms and series of storm events and future sea-level rise which will help to predict the future evolution of dune systems and management measures required (Environment Agency, 2017).More evidence is also needed to assess how gaps in dune systems can impact on water flow and flooding during storm surge events (Mehrtens *et al.*, 2023).
- A better understanding is needed of how dune vegetation and changes in beach ecology species diversity and functional characteristics affect the stability of dune systems to promote resilience to storms and extreme weather events (Hanley *et al.*, 2014). In addition, more studies are needed of how management options can

promote seedling and vegetation establishment on dunes (through for example sand fencing) to support dune stabilisation.

- Dune stabilisation is not always appropriate and over-stabilisation (primarily through vegetation) may reduce the resilience of dunes to storm erosion through reducing the beach-dune connectivity and by promoting persistently cliffed frontal dunes which are less likely to recover after storm events. However there is very little research on the severity of this effect.

Biogenic reefs (oysters, mussels, honeycomb worms)

Biogenic reefs include habitats such as oyster reefs, mussel beds, and sabellaria reefs which tend to be found in the lower parts of the intertidal zone. The capacity for these ecosystems to provide coastal protection depend on the local tidal amplitude and size of the ecosystem.

As previously noted, habitats and ecosystems in these zones tend to be less effective than those high in the intertidal zone for wave attenuation due to higher maximum wave flooding depths. However, the exact values for particular ecosystems will be determined by their specific location within the tidal range and local tidal amplitude and the size of the habitat (Bouma *et al.*, 2014). There is limited evidence on the specific wave attenuation effects of biogenic reefs. Narayan *et al.* (2016), for example, highlight how their review of the coastal protection functions of coastal habitats found no wave reduction field measurements for oyster reefs.

A study experiment by Scyphers *et al.* (2011) in the United States looked at the efficacy of breakwater reefs constructed of oyster shells at two sites in Alabama to protect eroding coastal shorelines, and the impact on nearshore fish and shellfish communities. The results at one site suggest that the reefs could mitigate shoreline retreat by more than 40%, although it only had a marginally significant effect ($p=0.089$), but overall recorded vegetation retreat and erosion rates were still high at both sites tested.

However, reefs can play an important indirect role in stabilising substrate and the sediment bed and thereby protect ecosystems higher in the tidal range- particularly intertidal flats- from hydrodynamic energy, thereby protecting them from erosion and helping to increase sediment inputs to intertidal flats (ibid.) (Borsje *et al.*, 2011). Their rigidity also makes them effective breakwaters particularly in comparison to flexible vegetation. In addition, oyster reefs can adapt to sea-level rise with vertical growth rates faster than expected rates of relative sea-level rise (Hynes *et al.*, 2022).

Marin-Diaz *et al.* (2022) set up an experiment on the tidal flats in the Dutch Wadden Sea and installed biodegradable artificial reefs along a stretch of 630m of the flat as an alternative to hard engineering structures. The aim of the research was to assess their effects on tidal flat accretion and their ability to stabilise wave-attenuating high intertidal coastal habitat systems through cross-habitat connectivity.

They found that the structures attenuated wave height by 30% compared to adjacent bare tidal flat where water levels were below 0.5m and could reduce wave heights by up to 60% despite being placed in a highly exposed area. The results provided evidence that such structures could be used to protect foreshore ecosystems such as saltmarshes, by trapping and stabilising sediments and thereby reducing hydrodynamic loads on the marsh edge. However, the authors note that a larger spatial scale design than used in the experiment would be needed for larger-scale connectivity between tidal flats and high intertidal systems and stronger materials would be needed if situated in a more exposed location.

A study by Hynes *et al.* (2022) looked at the recreational use values associated with a coastal walking trail under threat from coastal flooding and erosion and compared the costs of defending it from using nature-based solutions, through restoration of a native oyster reef compared to grey infrastructure. The cost-benefit analysis found that although both options had a positive net benefit over a 20-year time period, the restoration of the reef had a benefit/cost ratio multiple times larger than using the grey infrastructure option. These conclusions were also valid following a sensitivity analysis. The analysis also did not account for other potential regulating ecosystem service benefits that the oyster reefs could supply, nor the negative impacts of grey infrastructure on marine ecosystems, which they argue would likely further increase the costs benefits of the native oyster reef solution. However, the study did not assess the efficacy of the oyster reefs in terms of their coastal defence protection as part of the analysis.

Gaps/further evidence needs

There are several evidence gaps that would improve our understanding of the ability for biogenic reefs to be used as a nature-based solution to support mitigating flood and erosion risks. These include:

- There is a lack of direct studies on the wave attenuation effects of biogenic reefs in temperate areas, in particular focussing on localities in the UK. Further work is needed to assess the optimal conditions and mechanisms by which they can provide coastal protection and of their ability to provide a complementary coastal protection function with other coastal habitats further up the tidal range.
- Further work is needed to refine cost-benefit analyses of biogenic reefs and in conjunction with their effectiveness for coastal defence, to support their inclusion in cost-benefit analyses for coastal defence and restoration programmes. Cost-benefit analyses could be improved by combining these with an analysis of the broader services that are provided (e.g waste remediation, improvements to water quality, supporting local fisheries).

Conclusions

The aim of this study was to assess the evidence relating to the processes and ways in which coastal habitats and nature-based solutions help to mitigate flood and erosion risk at the coast in Wales and of valuations of these services.

The review highlights that marine and coastal habitats such as saltmarshes, shingle beaches and sand dunes can play an important role in helping to mitigate coastal flood and risk and support climate change adaptation. However, the degree of coastal protection varies between habitat type and is dependent on a range of site-specific characteristics.

A large body of evidence has been built up in recent decades of the effectiveness of saltmarsh to provide protection against flooding and erosion, and under extreme high-water levels and storm-surge events, but these depend on local site characteristics. They can also provide protection through their ability to provide shoreline stabilisation and floodwater attenuation. The evidence suggests, however, that newly established managed realignment sites do not provide the same level of ecosystem service benefits as natural marshes and need time to mature morphologically and in their vegetation composition to achieve this. More recently, several studies have attempted to estimate the cost-benefits of such protection, which suggest that they can provide significant value for flood protection and avoiding damage costs.

Other habitats such as sand dunes, shingle beaches and seagrass meadows can also provide flood and erosion protection, but there is more limited evidence on their effectiveness in terms of either specific morphological indicators and processes, case studies from Wales and/or the cost benefits of using management techniques associated with these systems and more work is needed to address this evidence gap to assess their utility from a coastal defence perspective in Wales.

An important determinant on the effectiveness of habitats in providing wave attenuation is their position within the tidal range. As highlighted, there is a large geographical variation in tidal range in Wales, with the North and South Wales coastlines being mega-tidal (>8m range) and the West coast macro-tidal (>4m range) (Horrillo-Caraballo *et al.* 2021). Therefore, if viewing them in isolation, habitats that are found higher in the intertidal system are more likely to be effective in providing flood and erosion risk benefits along the Welsh coastline, such as saltmarsh, sand dune and beach systems. The evidence suggests that other habitats such as seagrass may work better in hybrid coastal protection systems where combined with other habitats e.g seagrass and sand nourishment or in front of dune systems.

The review highlights the importance of continuing efforts to ensure that extant coastal and marine habitats are managed effectively to maintain and enhance their condition and resilience to current and future pressures and thereby ensure that they can continue to provide coastal protection benefits as well as a wide array of other ecosystem services that can provide benefits for people and nature.

The findings also demonstrate the potential to explore the opportunities to restore habitats and ecosystems and utilise nature-based solutions to support current (or future) flood defence projects, including management techniques such as beach and shingle nourishment or hybrid solutions that can help to support more natural coastal processes and mitigate flood and erosion risks. Aside from the evidence gaps outlined, more work is needed to quantify the value of flood protection services and to trial their use in projects in the field in Welsh settings. These will help to build further evidence to enable the consideration of and integration of natural flood management techniques within future flood projects and programmes.

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Appendices

Appendix 1 – Evidence Review Protocol

The following protocol was agreed with relevant experts in Natural Resources Wales prior to undertaking the review. The Protocol included the primary question and secondary objectives to be considered, the Population, Intervention, Comparator, Outcome (PICO) elements, search methods and quality/validity assessment criteria. These are detailed below.

Primary question

The primary question addressed by the review is, 'What are the flood risk benefits provided by coastal habitats?'

Objectives

A number of secondary questions and objectives were included within the review. These are:

- What is the effectiveness of different coastal habitat types in helping to mitigate flood and erosion risks?
- What impact does habitat condition have on the realisation of these benefits?
- What economic valuations exist of the flood protection services provided by coastal habitats (and in Wales).
- Whether there is any information or estimates of land and properties that are protected by coastal habitats and natural flood management solutions, including levels of confidence.

PICO elements

The Population, Intervention, Comparator, Outcome (PICO) are included in Table <> below.

	PICO elements for this Review
Population	Coastal habitats, coastal ecosystems, seagrass, shingle, sand dunes, intertidal sand, intertidal mud, saltmarsh, coastal wetland(s)

Intervention	Flood risk mitigation, flood protection, storm flood mitigation, storm protection, erosion, erosion protection
Comparator	Traditional coastal defence, hard defence(s)
Outcome	Benefits, cost benefits, economic/financial benefits, properties protected, reduced damages

Search methods

A wide search was carried out in Web of Science using search terms derived from the PICO elements above. The results of these searches were saved and analysed.

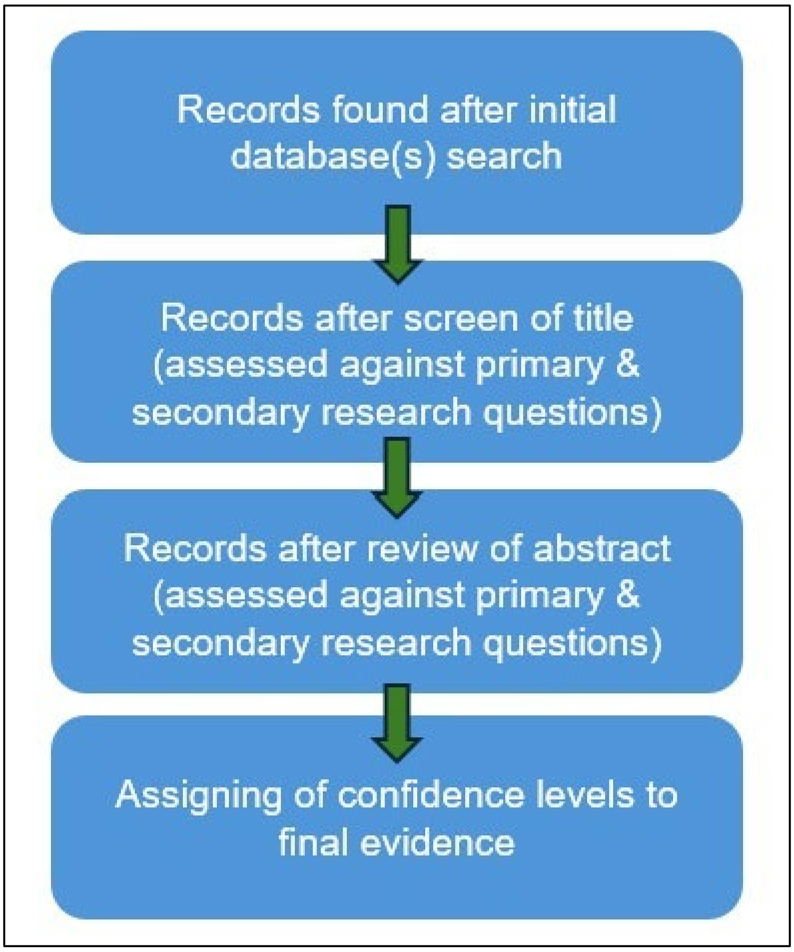

Figure 11: Flow chart of the evidence review process used in the report.

Two separate searches were undertaken with the following search terms, one with specific Geographic locations, the other a more general search:

1st search

TS=(“coastal habitats” OR “coastal habitat” OR “coastal wetland” OR “coastal wetland” OR “coastal ecosystems” OR “saltmarsh” OR “salt marsh” OR “tidal marsh” OR “tidalmarsh” OR “marsh” OR “marshes” OR “seagrass” OR “shingle” OR “shingle beach” OR “gravel” OR “gravel beach” OR “gravel barrier” OR “sand dunes” OR “intertidal sand” OR “intertidal mud” OR “nature based solutions” OR “nature-based solutions” OR “beach nourishment” OR “beach-nourishment”)

AND TS=(“UK” OR “United Kingdom” OR “Great Britain” OR “Scotland” OR “England” OR “Ireland” OR “Wales”)

AND TS=(“flood risk” OR “flood risk mitigation” OR “flood protection” OR “flood” OR “storm protection” OR “storm flood” OR “storm flooding” OR “storm flood mitigation” OR “storm flood protection” OR “coastal adaptation” OR “adaptation” OR “protective” OR “wave attenuation” OR “coastal protection” OR “erosion” OR “erosion risk” OR “erosion protection”)

2nd search

TS=(“coastal habitats” OR “coastal habitat” OR “coastal wetland” OR “coastal wetland” OR “coastal ecosystems” OR “saltmarsh” OR “salt marsh” OR “tidal marsh” OR “tidalmarsh” OR “marsh” OR “marshes” OR “seagrass” OR “shingle” OR “shingle beach” OR “gravel” OR “gravel beach” OR “gravel barrier” OR “sand dunes” OR “intertidal sand” OR “intertidal mud” OR “nature based solutions” OR “nature-based solutions” OR “beach nourishment” OR “beach-nourishment”)

AND TS=(“flood risk” OR “flood risk mitigation” OR “flood protection” OR “flood” OR “storm protection” OR “storm flood” OR “storm flooding” OR “storm flood mitigation” OR “storm flood protection” OR “coastal adaptation” OR “adaptation” OR “protective” OR “wave attenuation” OR “coastal protection” OR “erosion” OR “erosion risk” OR “erosion protection”)

An additional search string was also added to both searches for any additional papers related to economic valuations that were not capture in the initial search:

AND TS=(“Benefits” OR “Cost-benefits” OR “Economic benefits” OR “Properties protected” OR “Reduced damages”)

In addition, searches were also made within grey literature including technical reports and publications. The following archives from devolved administrations of the UK and statutory/non-statutory nature conservation bodies were also included as part of the search for any relevant publications:

Natural England

Environment Agency

Defra

Natural Scotland

GOV.UK

JNCC

Scottish Environment Protection Agency (SEPA)

British Ecological Society

Critical Appraisal

A critical appraisal of the evidence was undertaken to help to inform the appraisal of the evidence that was found and included the following:

Conceptual framing

- Does the study acknowledge existing research?
- Does the study pose a research question or outline a hypothesis?
- Related existing research or theories are acknowledged

Transparency

- Is the geography/context in which the study was conducted clear?
- Does the study present or link to the raw data it analyses?
- Does the study declare sources of support/funding?

Appropriateness of method

- Does the study identify research design, data collection, and analysis methods?
- Does the study demonstrate why the chosen design and method are well suited to the research question (methodology used is clearly and transparently presented)?

Internal validity

- To what extent is the study internally valid? (e.g the extent to which a study establishes a trustworthy cause-and-effect relationship between a treatment and an outcome).

Context sensitivity

- Does the study explicitly consider any context-specific factors that may bias the analysis/findings?
- Are the assumptions made outlined?

Cogency

- To what extent does the author consider the study's limitations and/or alternative interpretations of the analysis?

The information from the relevant articles was extracted in a template which detailed the following: date, study location, population (habitat) studied, experimental design/methods, description of main findings, evidence related to primary research question, evidence related to secondary questions, critical appraisal.

The data and evidence in the review has been presented in narrative outcomes as it was not the intention to produce a quantitative synthesis of the body of evidence on coastal habitats and flood and erosion risk mitigation. No transformations were conducted on the extracted data.

Data Archive Appendix

Data outputs associated with this project are archived in [NRW to enter relevant corporate store and / or reference numbers] on server–based storage at Natural Resources Wales.

Or

No data outputs were produced as part of this project.

The data archive contains: [Delete and / or add to A-E as appropriate. A full list of data layers can be documented if required]

[A] The final report in Microsoft Word and Adobe PDF formats.

[B] A full set of maps produced in JPEG format.

[C] A series of GIS layers on which the maps in the report are based with a series of word documents detailing the data processing and structure of the GIS layers

[D] A set of raster files in ESRI and ASCII grid formats.

[E] A database named [name] in Microsoft Access 2000 format with metadata described in a Microsoft Word document [name.doc].

[F] A full set of images produced in [jpg/tiff] format.

Metadata for this project is publicly accessible through Natural Resources Wales' Data Discovery Service https://metadata.naturalresources.wales/geonetwork/srv (English version) and https://metadata.cyfoethnaturiol.cymru/geonetwork/cym/ (Welsh Version). The metadata is held as record no [NRW to insert this number].

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