Department for Environment Food & Rural Affairs

Llywodraeth Cymru
Welsh Government

Cyfoeth Naturiol Cymru
Natural Resources Wales

Environment Agency

What is coastal squeeze?

Project FRS17187

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

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Executive summary

The purpose of this project is to better understand what causes ‘coastal squeeze’. This is particularly relevant where there is a legal obligation to compensate for the impacts of maintaining coastal flood management infrastructure or management activities that could lead to coastal squeeze. Compensation in these cases has normally involved creating new habitat, which can be costly.[1] Accordingly, there is a strong economic impetus to improve the understanding of coastal squeeze impacts, including a need to consistently define, measure and better appreciate the uncertainty of habitat losses due to coastal squeeze.

There are, nevertheless, other policy and legislative influences for positively managing, enhancing and creating coastal priority habitats (for example, as set out in national biodiversity strategies and climate change national adaptation programmes). It is anticipated that aspects of this ‘What is coastal squeeze?’ report will also be helpful in improving our understanding of the likely rate and scale of the impacts of accelerating sea level rise on coastal habitats and promoting the need to periodically review the evidence available.

A number of studies carried out for the Environment Agency around England have highlighted inconsistencies in the definition of ‘coastal squeeze’, and demonstrated several problems in quantifying it. This project aims to improve understanding of what coastal squeeze is, and also to set out best practices for assessing the historic and future impacts of coastal squeeze at different scales.

The main outputs from the work are:

- a new definition of coastal squeeze that clarifies the habitats that can be affected and the causes of habitat loss not caused by coastal squeeze
- a standard method and guidance for consistently assessing coastal squeeze
- four case studies that demonstrate how the method can be applied to mudflats, saltmarshes and sand/shingle beaches

The revised definition we have produced is as follows:

“Coastal squeeze is the loss of natural habitats or deterioration of their quality arising from anthropogenic structures, or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to sea level rise (SLR) in conjunction with other coastal processes. Coastal squeeze affects habitat on the seaward side of existing structures.”

The definition must be read together with the points of clarification in section 5.1 - Definition and points of clarification.

The method has been summarised in 2 flow diagrams: past changes (Figure 6.1) and future changes (Figure 6.2). An initial scoping stage defines the study area, the habitats to be included and the period of interest. A subsequent screening stage allows a rapid assessment of whether or not coastal squeeze is likely to be a potential cause of habitat change. The method outlines how to quantify these changes, the relevant data sources and causes of uncertainty that apply to each step of the method. The final stage of the assessment requires expert judgement to assess whether the observed/predicted changes actually represent coastal squeeze. The method outlines

[1] Providing the 11,500 compensatory habitat hectares identified by Shoreline Management Plan (SMP) policies over the next 44 years will cost at least £575 million in present day terms (Pontee, 2017).

how an assessment of confidence in the findings - ‘high’, ‘medium’, or ‘low’ - should be made. Where there is low confidence, 2 approaches can be taken:

- adopt the ‘precautionary principle’, assuming that habitat losses are, in fact, the result of coastal squeeze, and review the assessment in the future
- carry out further studies to increase confidence in the findings

The main conclusions from the work are:

- To identify whether coastal squeeze is happening, an assessment must be made of the effect structures or management actions have in preventing habitat from moving landwards (transgress) or slowing its progress in response to sea level rise. This project has demonstrated that even under natural baselines (in other words, without defences), the area (extent) of habitat (for example, saltmarshes) may decrease over time if steeply rising land means there is not enough room for habitat to migrate landwards. If this happens, any resulting habitat losses would be a form of natural change (accepting that accelerated sea level rise is not really ‘natural’).
- Previous assessments of coastal squeeze have often lacked basic data to scientifically assess the causes of habitat loss. The limitations of past studies include the failure to scientifically demonstrate that:

    (i) habitat losses have been due to sea level rise

    (ii) habitat losses have not been due to other causes (for example, increases in wind waves, lateral channel movements)

  Increasing the level of confidence is vital, using the best available data from scientific studies and other sources. In some cases, additional data sets and/or analysis already exist to improve scientific understanding.
- The case studies suggest that historic coastal squeeze losses could be smaller than previous assessments have suggested. This is due to a number of reasons: (i) the habitat losses may have been caused by factors other than sea level rise against the defences. As noted above, other causes of habitat loss were commonly overlooked in previous assessments, and (ii) the natural losses of habitats due to steeply rising land may not have been fully accounted for.
- Although the role of coastal squeeze as a cause for past habitat losses may have been overstated in some instances, it is important to carefully consider that it could become more widespread in the future due to increased rates of sea level rise. Sediment supply will be an important factor in determining this.
- Some previous assessments of future coastal squeeze losses have been based on an extrapolation of past losses. This may have led to future losses being over predicted, although, as described above, future rates of sea level rise are likely to be higher than present/past rates.
- Full assessments of coastal squeeze need further data and studies to better understand past changes in habitat extents and the causes of these changes. This understanding is needed to make informed judgements about likely future coastal squeeze losses.
- Implementing the new approach is likely to require collaboration between developers, the Environment Agency (as developer or competent authority), Natural England, National Resources Wales and perhaps others (for example, other competent authorities, including local planning authorities, wildlife groups

and research bodies) to both source baseline data and provide expert opinion to reach agreement on the results.

- It is not anticipated that this guidance will be used to make an immediate wholescale review of coastal squeeze assessments in England and Wales, but that the new approach should be taken at the next scheduled review point for Shoreline Management Plans (SMPs) and strategies. Indeed, the guidance can be used to help shape the operational approaches as compensatory habitat provision and indeed ‘net gain’ restoration progresses into the next 6-year flood and coastal erosion risk management (FCERM) investment programme and beyond. This will be integral to the wider work arising from the current ‘SMP Refresh’ programme to ensure FCERM remains environmentally sustainable in the long term.

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1 Introduction

1.1 Project context

The main purpose of this project is to better understand what causes ‘coastal squeeze’. This is particularly relevant where there is a legal obligation to compensate for the impacts of maintaining coastal flood management infrastructure or management activities that could lead to coastal squeeze. Compensation in these cases has normally involved creating new habitat, which can be costly[2]. Accordingly, there is a strong economic impetus to improve our understanding of coastal squeeze impacts so we may consistently define, measure and recognise the uncertainty of habitat losses due to coastal squeeze.

There are, nevertheless, other policy and legislative influences for positively managing, enhancing and creating coastal priority habitats (for example, as set out in national biodiversity strategies and climate change national adaptation programmes). It is anticipated that aspects of this ‘What is coastal squeeze?’ report will also be helpful in improving understanding of the likely rate and scale of impacts of accelerating sea level rise on coastal habitats in general, and promoting the need to periodically review the evidence available.

[2] Providing the 11,500 compensatory habitat hectares identified by Shoreline Management Plan (SMP) policies over the next 44 years will cost at least £575 million in present day terms (Pontee, 2017)

Figure 1.1 A number of saltmarshes in southern and eastern England display internal fragmentation – this is where former vegetation appears to have been replaced by mud. These changes could potentially represent coastal squeeze. The image shows saltmarshes north of Waldringfield, on the Deben, March 2019.

Photo courtesy of Nick Williams, Natural England.

1.2 Background

Past and predicted coastal squeeze losses drive a significant part of the Environment Agency's compensatory habitat creation programmes and the National Habitat Creation Programme in Wales. Work commissioned by the Environment Agency in a number of areas has highlighted inconsistencies in the definition of 'coastal squeeze', and demonstrated several problems in quantifying it. This work has included:

(i) sediment cell 11 (Great Orme Head to Solway Firth) and its constituent estuaries (Halcrow, 2010)

(ii) Severn Estuary (Atkins and ABPmer, 2013)

(iii) Poole Harbour (Atkins and Halcrow, 2012a, b)

(iv) Exe Estuary (Atkins and Halcrow, 2012c, d)

(v) Thames Estuary (TE2100, 2012)

(vi) Humber Estuary (Jacobs, 2019c)

(vii) several journal/conference papers (for example, Phillips et al., 2011; Pontee, 2017)

The inconsistencies in definition and assessment mean that the approach to setting compensatory habitat targets may be different across England and Wales.

To date, there has been a tendency to assume that observed habitat losses in front of defences are caused by coastal squeeze when, in fact, there may be a number of contributory factors involved (see Figure 1.2). Furthermore, compensatory habitat creation targets have generally not been determined based on the specific coastal squeeze impacts predicted to be caused by flood and coastal erosion risk management (FCERM) structures. Instead, these targets have generally been based on considering all the 'Hold the Line' policy areas identified in the Shoreline Management Plans and assuming that coastal squeeze is occurring in them, regardless of structure, ownership or purpose. In terms of addressing coastal squeeze impacts on Natura 2000 sites and Sites of Special Scientific Interest (SSSIs), it is necessary to understand the impacts regardless of who owns or maintains a structure. Therefore, it may be necessary to apportion losses/impacts to different asset owners so that the responsibility for and cost of compensation can be shared appropriately.

Recognition of the above issues, led to the creation of the current research and development (R&D) project led by the Environment Agency, in partnership with Natural England, Defra, Natural Resources Wales/Cyfoeth Naturiol Cymru (NRW) and Welsh Government. This project aims to define which factors are relevant when considering coastal squeeze, and to develop a way of predicting and measuring its effects.

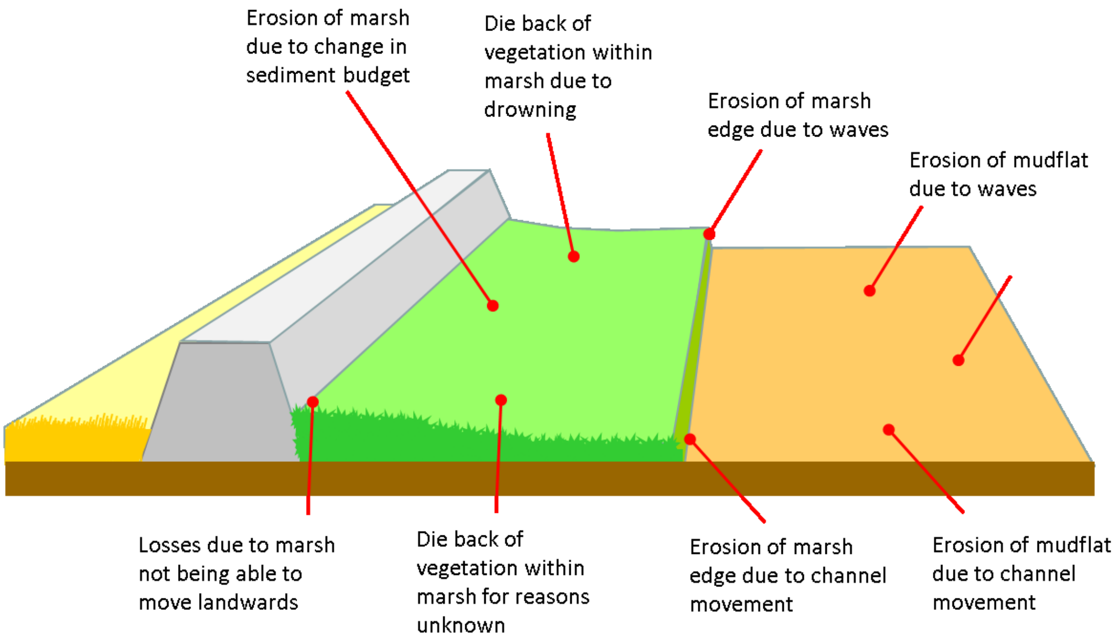

Figure 1.2: An illustration of some of the causes of changes in intertidal habitat extent in front of defences. Some of these changes are due to the presence of the defence, while others are due to other causes.

1.3 Aims

This project aims to improve understanding of coastal squeeze, and to set out best practices for assessing its past and future impacts at different scales (for example, Shoreline Management Plan/FCERM strategy/scheme). Best practice needs to take account of the different amounts and quality of data that may exist in different areas. This in turn will:

- inform consistent and efficient habitat management decisions that represent good value and can be agreed upon by all main consenting bodies
- provide guidance on how to agree and verify the quality/reliability of habitat loss/gain assessments efficiently and consistently by a number of players (for

example, those doing the analysis, technical reviewers and Environment Agency/Natural England/Natural Resources Wales staff)

- help to identify which elements of coastal squeeze assessments are most uncertain and, therefore, require the most investment, both when carrying out a project and for future research and development

At the start of the project, a number of important questions and considerations were identified (Box 1).

1.4 Report structure

The report structure is as follows:

- Chapter 1 – Introduction to the project.
- Chapter 2 – Current definitions of coastal squeeze.
- Chapter 3 – Factors that influence coastal change.
- Chapter 4 – Outputs from stakeholder workshop relating to definition.
- Chapter 5 – Definition of coastal squeeze.
- Chapter 6 – Method.
- Chapter 7 – Summary and discussion.
- Chapter 8 – Conclusions.

Four case studies are described in Appendix A:

- Case study 1 – Lymington.
- Case study 2 – Blackwater Estuary.
- Case study 3 – Slaughden and Sudbourne.
- Case study 4 – Aber Dysynni and Broadwater.

Box 1: Main issues relating to defining and assessing coastal squeeze

Practical considerations:

- What is the purpose of a definition?
- Who is the definition for?
- What aspects of coastal squeeze are associated with scientific principles?
- What aspects of coastal squeeze are associated with legislative compliance?
- How can we make the definition future proof?
- What level of confidence can be placed in predictions of future habitat extent?

What is included:

- Is coastal squeeze solely the loss of habitat due to defences preventing the landward transgression of habitats, or does it apply to all potential impacts of defences?
- What habitats are included/excluded? (for example, shingle and gravel beaches, intertidal mudflat and sandflat, saltmarsh, rocky tidal platforms, dunes, shingle ridges, saline lagoons).
- What dynamic features should be embraced as part of coastal squeeze assessment? (for example, mid-channel islands and bars).
- What is the landward and seaward limits of 'intertidal' habitats? (for example, a tidal contour or specific species range).
- Should indirect changes which have arisen from other human interventions be included in the term 'coastal squeeze'?
- Does coastal squeeze apply to newly created habitats in realigned areas?

Identification:

- How do we identify when a defence is holding up landward transgression?
- Where/how can coastal squeeze be identified on cross-shore transects?
- What sources of data are needed to identify past coastal squeeze?

Factors in changing habitat extent:

- What things do not constitute coastal squeeze?
- What are the factors governing erosion/accretion?
- What factors govern the changing extent of habitats (beyond SLR and impacts of defences)?
- How do we distinguish short versus long-term trends and cycles (for example, 18.6 year lunar tidal cycle)?
- When is change due to natural species decline and expansion rather than coastal squeeze?
- What are the implications of variable rates of SLR and sediment supply around the UK?
- What is the range, availability and quality of data sources in different geographical areas?

Compensation:

- Is compensation only required for internationally designated habitats?
- What is the start date for assessment of coastal squeeze losses?

2 Current definitions of coastal squeeze

This chapter provides a brief review of how other studies have defined coastal squeeze. It includes coastal flood risk management strategies, Shoreline Management Plans (SMPs) and habitat creation programmes. It also includes definitions from a range of journal papers and guidance notes produced by English Nature (EN), Natural England, the Environment Agency and Defra.

The section will identify elements of existing definitions that are:

- similar/different
- unclear

2.1 Approach

The following studies were examined (Table 2.1, Table 2.2):

- Humber – Humber Estuary Shoreline Management Plan (Black and Veatch, 2004)
- Tees – Tidal Tees Flood Risk Management Strategy (Black and Veatch, 2007a, b)
- Solent – Solent Dynamic Coast Project (Channel Coastal Observatory, 2008)
- Thames – Greater Thames CHAMP (Environment Agency, 2008), TE2100 Flood Risk Management Plan (Environment Agency, 2010)
- Essex and South Suffolk – Essex and South Suffolk Shoreline Management Plan (Royal Haskoning 2010a)
- North West SMP – North West England and North Wales Shoreline Management Plan 2 (Halcrow, 2010, 2012b,c)
- South Coast – Poole and Christchurch Bays SMP2 (Royal Haskoning, 2011b)
- South Wales SMP – Lavernock Point to St Ann's Head SMP2 (Phillips et al., 2011)
- Exe Estuary – Exe Estuary Flood and Coastal Risk Management Strategy (Atkins and Halcrow, 2012c,d)
- Poole Harbour – Poole and Wareham Flood and Coastal Risk Management Strategy (Atkins and Halcrow, 2012a,b)
- Severn Estuary – Severn Estuary SMP (Atkins and ABPmer, 2013, Canning and Pontee, 2011)

A review was initially carried out as part of the Humber Estuary Strategy Review in 2016 (CH2M, 2017) using published documentation and interviewing Environment Agency and staff/project managers from the consultancy companies that carried out the work. The results of the previous work have been re-analysed and some additional aspects of the definitions examined.

A number of definitions were also reviewed from the following documents (Table 2.3):

- Report - Guidance Note on Managed Realignment (Defra, 2003)
- Report - Living with the Sea Life Project (English Nature et al., 2003)
- Report - England's best wildlife and geological sites: The condition of Sites of Special Scientific Interest in England in 2003. (English Nature, 2003a)
- Report - Guidance note on unfavourable condition definitions for coasts and estuaries (English Nature, 2003b)
- Report - Eurosion: Living with coastal erosion in Europe (Salman et al., 2004)
- Report - Shoreline management plan guidance Volume 1: Aims and requirements (Defra, 2006)
- Report - Coastal Squeeze, saltmarsh loss and Special Protection Areas (English Nature, 2006)
- Journal paper - Reappraising coastal squeeze: a case study from north-west England (Pontee, 2011)
- Journal paper - Coastal squeeze and managed realignment in south-east England (Doody, 2013)
- Report - Managing the land in a changing climate (Adaptation Sub-Committee, 2013)
- Report - Coastal Management Theme Plan (Natural England, 2015)
- Report - Healthy Estuaries 2020 (Natural England, 2016)
- Report - South Inshore and South Offshore Marine Plan (MMO, 2018)

Finally, a range of sources from outside the UK were also reviewed (Table 2.4):

- Australia - Report - Climate Change Risk to Australia's Coast: (Climate Council of Australia, 2009)
- Australia - Journal Paper - Assessing coastal squeeze of tidal wetlands: (Torio and Chum, 2013).
- Australia - Journal Paper - Reconciling development and conservation under coastal squeeze from rising sea level: (Mills et al., 2016)
- Germany - Journal Paper - Assessment of Vulnerability and Adaptation to Sea-Level Rise for the Coastal Zone of Germany (Sterr, 2008)
- Germany - Report - Country overview and assessment – 8. Germany (European Commission, 2009)
- New Zealand - Report - Planning for Climate Change Effects on Coastal Margins (Ministry for the Environment, 2001)
- Scotland - Report - Scotland's Climate Change Adaptation Framework (SEPA, 2009)
- USA - Journal Paper - Managing the Coastal Squeeze: Resilience Planning for Shoreline Residential Development (Lester and Matella, 2013)
- USA - Journal Paper - Greenhouse-effect and coastal wetland policy - how Americans could abandon an area the size of Massachusetts at minimum cost (Titus, 1991)

Table 2.1: Various definitions of coastal squeeze used in England and Wales.

Shoreline Management Plans and strategies
Adaptation Sub-Committee (2013) *"The process by which coastal habitats and natural features are progressively lost or drowned, caught between coastal defences and rising sea levels.* *"… Coastal squeeze and, subsequently, the loss of coastal habitats are the result of many factors linked to SLR and climate change: submergence, coastal erosion and storm surges."*
Defra (2003) *"The process by which coastal habitats and natural features are progressively lost or drowned, caught between coastal defences and rising sea levels."*
Defra (2006) *"The process by which coastal habitats and natural features are progressively lost or drowned, caught between coastal defences and rising sea levels."*
Doody (2013) *"The term coastal squeeze describes the process where rising sea levels and other factors such as increased storminess push the coastal habitats landward. At the same time in areas where land claim or coastal defences has created a static, artificial margin between land and sea or where the land rises relative to the coastal plain, habitats become squeezed into a narrowing zone. Manifestation of this process is most obvious along the seaward margins of coastal habitats, especially saltmarshes, when erosion takes place."*
English Nature (2003a) *"…seawalls or other man-made structures prevent 'roll-over' or 'migration' of habitats in response to SLR and other coastal processes. Without natural migration of vegetation, this results in the loss of intertidal habitats and is known as 'coastal squeeze'…."* *"…Coastal squeeze is a major cause of unfavourable condition"*
English Nature (2003b) *"A subset of inappropriate coastal management; largely (but not exclusively) confined to estuaries, where 'roll-over' or 'migration' of the feature of interest, in response to SLR and other coastal processes, is prevented by seawalls (flood defences) or other manmade structures. In such situations SLR and increased storminess either erodes away the feature of interest (e.g. saltmarsh or mudflat) or reduces its extent (e.g. saline lagoons)."*
English Nature (2006) *"In many coastal and estuarine environments, flood and coastal defences constrain the ability of intertidal habitats (notably saltmarsh) to naturally move landward in response to sea-level rise. This effect results in intertidal habitat loss and is commonly termed 'coastal squeeze'."*
English Nature *et al.* (2003) *"'The process by which coastal habitats are progressively reduced in area and lose functionality when caught between rising sea level and fixed sea defences or high ground."* *"Flood defence can play a beneficial or detrimental role in the maintenance of designated features by preventing flooding of freshwater habitats or by causing coastal squeeze. This creates dilemmas for organisations advising on and implementing flood defence."* *"… in the face of relative SLR and shoreline change, these defences will lead to a continued 'squeeze' on designated intertidal habitats from SLR…."*
Essex and South Suffolk SMP (Royal Haskoning 2010a) *"The reduction in habitat area that can arise if the natural landward migration of a habitat due to SLR is prevented by the fixing of the high water mark, for example a sea wall…"* *"The natural response of saltmarsh to SLR is to migrate in a landward direction. If this landward migration is blocked by natural high ground or by flood defences, then this is referred to as 'coastal squeeze'."*
Exe Estuary Flood and Coastal Risk Management Strategy (Atkins and Halcrow, 2012c) *"…one form of coastal narrowing, where intertidal habitat is lost due to the high water mark being fixed by a defence (i.e. the HWM resides against a hard defence such as a sea wall), whilst the low water mark migrates landwards in response to SLR. (Pontee, 2011)."*

Shoreline Management Plans and strategies
Humber Estuary SMP (Black and Veatch, 2004) "*One of the major impacts of SLR on a shoreline defended by flood defences is a reduction in intertidal area because the rise in low water levels means that the tide in future would not go as far out as at present, but the high tide cannot flood further inland because of the presence of the flood defences. This reduction in intertidal area is known as coastal squeeze."*
MMO (2018) / Doody (2013) *"Coastal narrowing (or coastal squeeze) is one manageable aspect of coastal change that can be influenced by (climate change)* *…Where coastal narrowing can be defined as a reduction in the coastal zone width caused by human and/or natural processes (Doody 2013)"* *… "coastal squeeze, a process where habitats have decreasing space between rigid coastal structures and rising sea level or coastal erosion. Coastal squeeze occurs due to development, industrial expansion and provision of hard sea defences and is already affecting habitats such as saltmarsh. SLR as a result of climate change will add to this pressure particularly along the coast and within estuaries"*
Natural England (2015) *"Sites largely (but not exclusively) within estuaries where migration of the interest features/Annex I habitats in response to SLR and other coastal processes are prevented by a fixed sea wall or other man-made structures which is being maintained. These structures were constructed to cut off intertidal land from the sea in order to convert it for agriculture or development. The original coastal flood plain has therefore been reduced in size. This results in the intertidal habitats being trapped between rising sea levels and a fixed landward boundary, and there have been observed declines in extent and/or quality over time that are likely to continue.* *… It would not apply to a situation where fixed structures were absent and the intertidal area was backed by naturally rising ground: in such cases this would be considered as 'natural change'."*
Natural England (2016) *"Narrowing of the intertidal zone due to the prevention of its natural landward migration in response to sea-level rise; for the purposes of this project where this is a result of defences such as sea walls preventing migration and causing intertidal erosion."*
North West SMP (Halcrow, 2010, 2012b, 2012c) *"…we define coastal squeeze as the loss of inter-tidal area due to a combination of SLR and the presence of coastal defences or structures, which cause a narrowing of the intertidal zone. As such coastal squeeze can only be considered to occur when intertidal habitat is being lost where the high water mark is fixed by defences and the low water mark is migrating landwards. However, even where these conditions are met the loss of habitat may often not be just due to the defences, since a number of other factors can also influence the position of the high and low water marks and thus the width…"*
Pontee (2011) *"Where the process of landward translation of coastal habitats under rising sea level is held up by anthropogenic structures, this can result in a loss of habitat. In the UK, the term 'coastal squeeze' has become widely used to describe this process."*
Poole and Wareham Flood and Coastal Risk Management Strategy (Atkins and Halcrow, 2012a, 2012b) *"one form of coastal narrowing, where intertidal habitat is lost due to the high water mark being fixed by a defence (i.e. the HWM resides against a hard defence such as a sea wall), whilst the low water mark migrates landwards in response to SLR. (Pontee, 2011)"*
Salman *et al.* (2004) *"Coastal squeeze" occurs especially in low-lying and inter-tidal areas, which would naturally adjust to the changes in sea level, storms and tides, but cannot do so due to the construction of inflexible barriers such as roads, dykes, urbanisations, leisure parks, industrial and other facilities. This causes a direct loss of natural habitats. In areas where relative sea level is rising or where sediment availability is reduced, there is a further coastal squeeze resulting from a steepening beach profile and foreshortening of the seaward zones."*
Severn Flood Risk Management Strategy (Atkins and ABPmer, 2013) No definition given.

Shoreline Management Plans and strategies
Solent, Solent Dynamic Coast Project (Channel Coastal Observatory, 2008) *"Coastal squeeze definition used in the SDCP: where a sea defence inhibits rollback of designated intertidal habitats."*
South Coast – Poole and Christchurch Bays SMP2 (Royal Haskoning, 2011b) *"The reduction in habitat area that can arise if the natural landward migration of a habitat under SLR is prevented by the fixing of the high water mark, e.g. a sea wall"* *…" Narrowing of the intertidal zone due to the prevention of its natural landward migration in response to sea-level rise, e.g. by permanent barriers (human-built or natural)."*
South Wales SMP (Phillips et al., 2011) *"Coastal squeeze is the term used to describe the loss of intertidal habitats under rising sea levels due to the natural landward migration of intertidal habitats being prevented by a man-made defence."*
Tees Tidal Tees Flood Risk Management (Black and Veatch, 2007a,b) *"Coastal squeeze is the reduction in the area of inter-tidal habitat as a consequence of SLR and the action of flood defences."*
Thames Greater Thames CHaMP (Environment Agency; Environment Agency, 2010) *"An increase in Mean Sea Level (MSL) typically results in the landward advancement of Mean Low Water (MLW). With sea defences in place there is frequently limited scope for an equivalent advance in MHW resulting in an overall reduction in the potential area of intertidal zone. This phenomenon is commonly referred to as coastal squeeze."*

Table 2.2 Elements included in coastal squeeze definitions and methodologies used in a range of coastal strategy studies in England and Wales (*abbreviations provided below table).

Elements included in definition	Humber SMP (Black & Veatch, 2004)	Tees Strategy (Black and Veatch, 2007a,b)	Solent (Channel Coastal Observatory, 2008)	Thames CHAMP (Environment Agency, 2008, Environment Agency, 2010)	Essex and Suffolk SMP (sub cell 3d) (Royal Haskoning 2010a)	North West SMP (Cell 11) (Halcrow, 2010, 2012b, 2012c)	Poole and Christchurch Bays SMP2 (Royal Haskoning 2011b)	South Wales SMP (Cell 8) (Phillips et al., 2011)	Exe Strategy (Atkins and Halcrow, 2012c,d)	Poole and Wareham Strategy (Atkins and Halcrow, 2012a,b)	Severn Strategy (Atkins and ABPmer, 2013; Canning and Pontee, 2011)
Defences	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Direct losses due to reclamation	No	No	No	No	No	No	No	No	No	No	No
Habitat quality	No	No	No	No	No	No	No	No	No	No	No
Habitat types	• Intertidal in definition	• Intertidal in definition but subtidal also included in study • Saltmarsh, mudflat, sandflat, intertidal sand, and shallow coastal	• Mudflat • Saltmarsh • Also, consequent effect to coastal grazing marsh	• Saltmarsh • Mudflat • Sandflat • Also, consequent effect to coastal grazing marsh	• Intertidal area • Saltmarsh • Mudflat	• Looked at supra-tidal (dunes) and intertidal	• Intertidal in definition	• Saltmarsh • Mudflat	• A range of supratidal habitats were included in change analysis - heath, fen, acid grass, scrub etc • Saltmarsh, Transitional saltmarsh & reedbed were grouped	• A range of supratidal habitats were included in change analysis - heath, fen, acid grass, scrub etc • Saltmarsh, Transitional saltmarsh & reedbed were grouped	• Mud/sand flat • Saltmarsh • Rock outcrops

Elements included in definition	Humber SMP (Black & Veatch, 2004)	Tees Strategy (Black and Veatch, 2007a,b)	Solent (Channel Coastal Observatory, 2008)	Thames CHAMP (Environment Agency, 2008, Environment Agency, 2010)	Essex and Suffolk SMP (sub cell 3d) (Royal Haskoning 2010a)	North West SMP (Cell 11) (Halcrow, 2010, 2012b, 2012c)	Poole and Christchurch Bays SMP2 (Royal Haskoning 2011b)	South Wales SMP (Cell 8) (Phillips et al., 2011)	Exe Strategy (Atkins and Halcrow, 2012c,d)	Poole and Wareham Strategy (Atkins and Halcrow, 2012a,b)	Severn Strategy (Atkins and ABPmer, 2013; Canning and Pontee, 2011)
		waters (for one site)							• Intertidal included mudflat, sandflat, rock and boulders, dunes, and littoral sediment.	• Intertidal included mudflat, sandflat, rock and boulders, dunes, and littoral sediment	
Losses in marsh surface area due to internal erosion	No	No	No	No	No	No	No	No	No	No	No
Losses in width and therefore areas of intertidal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Natural high land	No	No	No	No	Yes	No	Yes (*"permanent natural barriers"*)	No	No	No	No

Elements included in definition	Humber SMP (Black & Veatch, 2004)	Tees Strategy (Black and Veatch, 2007a,b)	Solent (Channel Coastal Observatory, 2008)	Thames CHAMP (Environment Agency, 2008, Environment Agency, 2010)	Essex and Suffolk SMP (sub cell 3d) (Royal Haskoning 2010a)	North West SMP (Cell 11) (Halcrow, 2010, 2012b, 2012c)	Poole and Christchurch Bays SMP2 (Royal Haskoning 2011b)	South Wales SMP (Cell 8) (Phillips et al., 2011)	Exe Strategy (Atkins and Halcrow, 2012c,d)	Poole and Wareham Strategy (Atkins and Halcrow, 2012a,b)	Severn Strategy (Atkins and ABPmer, 2013; Canning and Pontee, 2011)
Other shore parallel structures (e.g. roads, railways, quay walls)	No	No	No	No	No	Yes	Yes (*"permanent barriers"*)	No	No	No	No
SLR as driving force	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tidal/other limits for defining intertidal area	HW to LW	MHWS or toe of defence line (whichever is lower) MLWS	HAT MHWN MLWS	MHWS MHWN MLWS	Limits of marsh defined from aerial photograph	BoB (supratidal) MHM MLW As derived from old OS maps	HW	HAT MHWN MLWS Excludes intertidal areas backed by natural high ground	HAT MHWS MHWN MLWS	HAT MHWS MHWN MLWS	HAT MHWS MHWN MLWS
Waves as driving force	No	No	No	No	No	No	No	No	No	No	No

HW= High Water, LW = Low Water, MHWS – Mean High Water Spring, MWLS = Mean Low Water Spring, Mean High Water Neap, HAT = Highest Astronomical Tide, BoB = Back of Beach, MHW = Mean High Water, MLW = Mean Low Water.

Table 2.3 Elements included in coastal squeeze definitions used in a range of other documents from England and Wales.

Elements included in definition	Defra (2003)	English Nature et al. (2003)	English Nature (2003a)	English Nature (2003b)	Salman et al. (2004)	Defra (2006)	English Nature (2006)	Pontee (2011)	Doody (2013)	Adaptation Sub - Committee (2013)	Natural England (2015)
Defences	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Direct losses due to reclamation	No	No	No	No	No	No	No	No	Yes	No	No
Habitat quality	No	Yes	No	No	No	No	No	No	No	No	Yes
Habitat types	Coastal habitats Natural features Intertidal areas	Intertidal Designated habitats Coastal habitats	Intertidal Designated habitats Saltmarsh Shoreline habitats	Mudflat Saltmarsh	Low-lying intertidal areas	Saltmarsh Mudflat	Intertidal habitats "Notably Saltmarsh"	Coastal habitats	Coastal habitats Particular reference to saltmarshes	Coastal habitats Saltmarsh Mudflat	Intertidal land
Losses in marsh surface area due to internal erosion	No	No	No	No	No	No	No	No	No	No	No
Losses in width and therefore areas of intertidal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Natural high land	No	Yes	No	No	No	No	No	No	No	No	No
Other shore parallel structures (for example, roads,	No	No	Yes	Yes	Yes	No	No	Yes 'anthropogenic (man-made) structures'	No	No	Yes

Elements included in definition	Defra (2003)	English Nature et al. (2003)	English Nature (2003a)	English Nature (2003b)	Salman et al. (2004)	Defra (2006)	English Nature (2006)	Pontee (2011)	Doody (2013)	Adaptation Sub - Committee (2013)	Natural England (2015)
railways, quay walls)											
SLR as driving force	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tidal/other limits for defining intertidal area	None specified	High and low water mark	None specified	None specified	High and Low water mark	HAT MHWN MLWS Excludes intertidal areas backed by natural high ground	Saltmarsh extent from aerial photography	None specified	None specified	None specified	None specified
Waves as driving force	No	No	No	Yes ('other coastal processes')	Yes ('storminess and tides. Also mention of sediment availability as a cause')	No	No	No	Yes ('storminess')	No	Yes ('other coastal processes')

2.2 Use of the term coastal squeeze outside of the UK

Examples of international uses of the term coastal squeeze are shown in Table 2.4.

Table 2.4 International uses of the term coastal squeeze.

Country and Source	Definition
Australia – Climate Council of Australia (2009) – official government document	*"coastal squeeze', where built infrastructure such as housing development prevents… inland or poleward[3] migration…of ecosystems in response to climate change …* *It is expected that initial responses from ecosystems in response to climate change will be either inland or poleward migration. In southern Australia, the effect of 'coastal squeeze', where built infrastructure such as housing development prevents such movement, could constrain this natural adaptation response."*
Australia – Mills **et al.** (2015) – authors predominately Australian and published in an American journal	*"Driven by the desire to protect existing infrastructure, coastal armouring through levees and seawalls (hereafter called "defend") has historically been the main response to an encroaching sea. This strategy typically prevents the spread of ecosystems, such as saltmarsh or mangrove inland (Nicholls & Cazenave, 2010) resulting in "coastal squeeze." Coastal squeeze is defined as the loss of intertidal habitat "due to the high water mark being fixed by a defence or structure . . . and the low water mark migrating landwards in response to SLR" (Pontee, 2013)."*
Canada – Torio and Churma (2013) – published in US scientific journal	*"The accelerated rates of SLR accompanying anthropogenic climate change are likely to increase the frequency and duration of flooding beyond the tolerance of the vegetation, which is largely responsible for soil accumulation (e.g. Cahoon et al., 2006; FitzGerald et al., 2008). As a result, the seaward edge of many wetlands is likely to retreat. At the same time, development of coastal regions and steep gradients in some locations will block migration of tidal wetlands inland (e.g. Feagin et al., 2010; Gilman, Ellison, and Coleman, 2007), placing them in what Doody (2004) has termed "coastal squeeze."* *"This means loss of ecosystem services tidal wetlands provide, such as buffers to erosion and storm flooding (Anthoff, Nicholls, and Tol, 2010; Jolicoeur and O'Carroll, 2007; Schleupner, 2008; Sterr, 2008), carbon storage (e.g. Mcleod et al., 2011), and subsidies of coastal fisheries (Boesch and Turner, 1984). Coastal squeeze might also increase fragmentation of tidal wetlands, reducing their value as habitat for wildlife and fisheries (Bulleri and Chapman, 2010; Chmura et al., 2012; Mazaris, Matsinos, and Pantis, 2009). Coastal squeeze arises from a combination of factors. Anthropogenic barriers prevent wetlands from migrating inland, and steep slopes bordering wetlands stall or completely halt wetland migration (Brinson, Christian, and Blum, 1995)."*
Germany – European Commission (2009) – published in official EU document	*"Hard coastal defence measures in combination with accelerated SLR could result in 'coastal squeeze' along the North Sea coast, thus threatening important Wadden Sea ecosystems such as saltmarshes and the tidal mud flats."*
Germany – Sterr (2008) – published in US scientific journal	*"coastal squeeze" (the transgression of the sea across these wetlands, which are prevented from migrating landward by existing dike structures"*
Netherlands – Aukes (2017) - PhD. Thesis	*"Coastal squeeze as a concept stems from the British coastal management tradition (Doody 2004). Its original meaning pertained to ecological problems in coastal areas that were due to human interference, mostly hard sea defences, thereby inhibiting natural mechanisms coping with changing water levels and extreme weather events (Birchenough et al. 2015, Cooper and McKenna 2008). While Pontee (2013, 2016) attempts to restrict the conceptual definition to the afore-mentioned, others also include*

[3] that is, towards the Earth's South Pole in this case.

	effects of urbanization (Schlacher et al., 2007), agriculture (Hanley et al., 2014), and other human processes as drivers of ecological problems in coastal areas leading to coastal squeeze."
New Zealand – New Zealand Ministry for the Environment (2001) – Official government document	*"With sea-level rise, the present-day low tide mark will be raised higher and will move inland by a distance that depends on how much extra sedimentation occurs from other climate change factors. In contrast, the corresponding high-tide mark may be prevented from moving any further inland in some localities by shoreline constraints such as a stopbank (unless the structure is overtopped occasionally during storms). Consequently, this type of 'coastal squeeze' will mean intertidal areas (and habitats) may be lost, especially where sedimentation rates do not increase along with sea-level rise. Coastal squeeze may also occur on open coast beaches protected by a structure, and where, as the intertidal beach sediment is gradually lost, the capacity of coastal margins to protect the hinterland during storms is reduced."*
Scotland – SEPA (2009) – Scottish Government Water Resource Management	*"…SLR claiming some lower lying intertidal zones and broader competition for land, may contribute to 'coastal squeeze'."*
U.S.A., California – Lester and Matella (2013) – Stanford Law journal	*"Where shoreline protection like seawalls is the answer to SLR, one consequence is the "coastal squeeze" - the incremental loss of recreational beach area and shoreline habitats in front of immovable shoreline structures."*
U.S.A., East/South Coast – Titus (1991) – US scientific journal	*"Wetlands have been able to keep pace with the slow rise in sea level that most areas have experienced during the last few thousand years. Thus, areas that might have been covered with two to ten meters of water have wetlands instead. But if SLRs more rapidly than the ability of wetlands to keep pace, the increase in wetland acreage of the last few thousand years will be negated.* *Moreover, if the adjacent development is not removed, all the wetlands could be squeezed between the rising sea and the dikes or bulkheads used to protect the development."*

2.3 Discussion

In the UK, the origin of the term 'coastal squeeze' was documented by Doody (2004) who cited it as having arisen from observations of the loss of saltmarsh and mudflat in the Wash, due to reclamation, and the loss of seaward portions of saltmarshes in Essex, due to erosion. At this time, in the late 1980s and early 1990s, the term 'coastal squeeze' was being used as part of a conservation argument against further saltmarsh reclamation in the Wash. In this regard, the term 'coastal squeeze' was an attempt to describe a process for non-specialists and was not defined precisely (Doody, pers. comm., *2013).*

Sweeting (pers. comm., 2018) notes the ambiguity surrounding the term coastal squeeze which has sometimes been incorporated into Marine Policy Statements under the term 'coastal change'. Sweeting (2018) notes "The Marine Policy Statement (MPS) guides marine planning nationally and applies in areas where a marine plan is not yet in place (most of England). The MPS has remit up to MHWS and encompasses topics that intersect with existing coastal squeeze definitions including "Climate change adaptation and mitigation" and "Coastal change and flooding" but does not define or use the term. Instead the MPS employs a more general and encompassing description, coastal change, that includes potentially relevant elements like "permanent inundation" alongside terms traditionally outside of coastal squeeze e.g. accretion and erosion. In implementing the MPS and to enhance integration with terrestrial systems, marine plans (e.g. South Marine Plan) have adopted use of more specific terms applying the definition of Doody (2013) for coastal squeeze."

In the international context, one of the earliest references to the term squeeze comes from Titus (1991) in the USA. This publication notes that wetlands losses might occur in the future if:

(i) rates of SLR exceed rates of vertical sediment accretion

(ii) dikes or bulkheads used to protect the development restrict the natural ability of habitats to transgress landwards under rising sea levels

Table 2.1, Table 2.2 and Table 2.3 show that in England and Wales most definitions for coastal squeeze refer to the impact of sea defences in restricting the landward transgression of habitats in response to sea level rise (SLR). They, therefore, include the following elements:

- SLR
- defences preventing landward movement of habitats
- resulting losses in area being termed coastal squeeze
- intertidal habitats
- saltmarsh and mudflat loss in estuary environments
- reference to tidal levels to delineate habitats
- loss of designated – usually habitats - Special Protection Areas/ Special Areas of Conservation (SPA/SAC).

The majority of definitions exclude:

- direct losses due to reclamation
- losses due to naturally rising land
- changes in wind-wave climate and other coastal processes (for example, sediment supply)
- changes in habitat quality
- internal erosion of saltmarsh
- other impacts of defences
- other anthropogenic structures

Significant differences between definitions include:

- the processes driving the landward transgression of habitats – for example, Doody (2013) refers to rising sea levels and “other factors such as increased storminess”. Natural England (2003) also refers to coastal processes and storminess involved in the coastal squeeze process

- the treatment of habitat quality – the definitions used within strategies and SMPs and the majority of other definitions do not include this. However, some definitions (for example, English Nature et al. (2003) and Natural England (2015)) do include mention of habitat condition/quality[4]. It is not always clear whether the term coastal squeeze includes habitat quality per se or whether coastal squeeze is a cause of deterioration in quality
- delineation of upper and lower limits of intertidal zone (for example, highest astronomical tide (HAT), mean high water springs (MHWS), high water (HW), back of beach, visible limit of habitat from aerial photographs). The boundary between mudflat and saltmarsh is universally taken to be mean high water neaps (MHWN). The upper limit of marsh is taken variously as MHWS or HAT. In reality, the limit of intertidal habitats may vary around these limits due to other impacts such as storm surge and wave action
- range of habitats included - most studies include mudflat and saltmarsh as intertidal habitats. Some studies also include sand flats, rocks and boulders. A number of studies cover transitional habitats at the top of marshes (transitional saltmarsh, transitional grassland, grazing marsh). One study (North West SMP) includes dunes, which are not intertidal habitats, while another (the Tees) covers shallow coastal waters. The Poole and Exe Strategy also examines other terrestrial habitats, although these don't appear to be included when setting compensatory habitats' targets
- structures included – although most studies refer to flood and coastal erosion risk management (FCERM) defences, a range of terms are used, including sea wall, flood defences, fixed sea defences. Some studies also refer to man-made defences, man-made structures, structures (generally), inflexible structures (for example, roads, dykes, urbanisations, other facilities)

A brief review of the use of the term coastal squeeze outside of the UK shows that there is:

- inclusion of urbanisation and infrastructure (Climate Council of Australia, 2009; Aukes, 2017)
- recognition of the role of increased inundation frequencies driving changes in wetland vegetation
- recognition of the importance of vertical sedimentation in determining the resilience of habitats to SLR (for example, Titus, 1991; New Zealand Ministry for the Environment, 2001)
- reference to wetland habitats such as mangroves and saltmarshes (for example, European Commission, 2009; Torio and Churma, 2013), but also sandy beaches (for example, Lester and Matella, 2013)

2.4 Summary

The review highlights that the various studies carried out to date have given subtly different definitions of the term 'coastal squeeze'. Most definitions include:

- SLR

[4] Natural England considers that changes in habitat quality, in terms of changes in species composition and vegetation zonation, can arise due to the natural landward translation of habitats being prevented (for example, by a flood defence). It is believed that this change in quality can precede an overall loss in the areas of a general habitat type (for example, overall decrease in the area of saltmarsh).

- defences preventing landward movement of habitats
- intertidal habitats
- saltmarsh and mudflat loss in estuary environments
- reference to tidal levels to delineate habitats
- loss of internationally designated habitats SPA/SAC

Most definitions exclude:

- direct losses due to reclamation
- losses due to naturally rising land
- changes in wind wave climate and other coastal processes
- changes in habitat quality
- internal erosion of saltmarsh
- other impacts of defences
- other man-made structures

Significant differences between definitions include:

- the processes driving the landward transgression of habitats
- the treatment of habitat quality
- delineation of upper and lower limits of intertidal zone
- range of habitats included

Outside of the UK, coastal squeeze definitions:

- may include the effects of urbanisation and infrastructure
- recognise the role of increased inundation frequencies driving changes in wetland vegetation
- recognise the importance of vertical sedimentation in determining the resilience of habitats to SLR
- most commonly refer to wetland habitats, such as mangroves, but also refer to sandy beaches

3 Factors that influence coastal change

3.1 Introduction

As noted in Chapter 1 there are many factors that influence the type and extent of coastal habitat (see Figure 1.2). It is important to identify and understand these various factors so that coastal squeeze can be correctly identified. This chapter describes the influences on coastal habitat in terms of 2 categories, those arising from:

- plans or projects
- non-project or plan sources

These are summarised in the following sections. Those factors that are relevant to coastal squeeze are identified.

3.2 Influences from plans and projects

Flood and coastal erosion risk management (FCERM) activities and other human interventions in the coastal zone (for example, dredging for ports or reclamation) can have important impacts on coastal habitats. These impacts can arise directly through footprint losses or indirectly by influencing coastal processes or water and sediment quality or encouraging the spread of invasive species.

Table 3.1 and Table 3.2 show the human interventions that could potentially cause deterioration in coastal habitats and, therefore, Natura 2000 sites. These have been split into FCERM and non-FCERM activities, but it is recognised that there is some overlap between these categories.

Table 3.1 FCERM interventions and potential influence on coastal habitats. Those interventions that have the potential to be relevant to coastal squeeze are indicated.

Human Intervention	Explanation	Potential influence on habitats
Barrages	• Permanent reductions in tidal range upstream • Reductions in tidal and fresh water flows • Reductions in marine sediment supply • Trapping of fluvial sediments • Concentration of wave energy around shorelines	• Direct losses of habitats under footprint of schemes • Indirect losses or changes as a result of changes in geomorphology • Indirect losses caused by changes to tidal currents • Changes in upstream tidal habitat zonation patterns • Changes in the salinity profiles of estuaries and tidal rivers as a result of changes in freshwater volumes and annual flow patterns, and consequent changes in species communities
Barriers	• Localised increases in tidal and freshwater flow leading to scour • Localised decreases in tidal and freshwater flow leading to deposition	• Direct losses of habitats under footprint of schemes • Indirect losses or changes because of changes in geomorphology • Indirect losses caused by changes to tidal currents • Changes in the salinity profiles of estuaries and tidal rivers as a result of changes in freshwater volumes and annual flow patterns, and consequent changes in species communities
Beach recharge	• Migration of beach lobes or forelands under longshore drift, causing cycles of shoreline advance and retreat	• Increase in intertidal areas • Change in nature of existing intertidal areas • Increased area for plant communities living on sand/ shingle
Cliff remediation	• Reduction but not cessation of retreat, beach management or toe protection without slope stabilisation	• Indirect losses or changes as a result of changes in geomorphology • Species of landslip removed
Cliff stabilisation	• Cliff drainage, re-profiling and toe protection • Reduced supply of sediment to fronting and downdrift beaches • Reduced cliff recession	• Stabilisation measures may impact on dynamic cliff habitats, but manages erosion losses • Indirect loss of intertidal habitats • Less landslips • Maritime cliff communities protected
Culverts	• Regulates water movement	• Inundation of freshwater or brackish habitats • Changes in freshwater supply to estuarine habitats • Changes in salinity profiles as a result of changes in saline water volumes and consequent changes in species communities
Dune stabilisation	• Stabilisation measures to encourage dune accretion/integrity	• Increase in stable dune vegetation communities • Decrease in mobile dune vegetation communities

		• Indirect increase in intertidal habitats • Insensitive planting of dunes destroys natural/native plant communities
Flood embankments	• Can cause changes in sedimentation within estuaries leading to estuary wide changes • Changes to tidal levels and flow speeds in surrounding areas	• Direct losses of habitats under footprint of schemes • Indirect losses or changes as a result of changes in geomorphology • Prevention of landward migration of habitats (relevant to coastal squeeze)
Groynes	• Reduction in sediment supply from alongshore due to interception of longshore drift	• Updrift increase in intertidal habitat area • Downdrift decrease in intertidal habitat area • Provision of structures for plants and animals to adhere to
Land drainage	• Could cause rise in the beach water table, rendering the sand more erodible	• Indirect loss of beach habitats • Loss of saline lagoons and their specialised flora and fauna • In some dune systems with important slacks, a long-term fall in the water table has led to loss of the specialist slack flora and invasion by coarse vegetation and scrub
Jetties, piers or breakwaters (shore connected)	• Can cause changes in wave and tidal conditions, sediment transport and therefore coastal morphology	• Indirect losses or changes as a result of changes in physical processes and geomorphology • Jetties and breakwaters provide structures for plants and animal communities
Managed realignment and no active intervention	• Return of former intertidal to the sea • Changes to tidal levels and flow speeds in surrounding areas (locally and potentially further afield in estuaries)	• Creation of new intertidal areas • Inundation of freshwater or brackish habitats • Existing habitats destroyed but replaced by new mudflats/saltmarsh and inundation grassland
Offshore breakwater	• Reduces wave energy at the coast • Reduction in offshore and alongshore sediment transport	• Increase in local intertidal areas due to changes in physical processes • Direct losses of habitats under footprint of scheme • Downdrift decrease in intertidal area due to changes in physical processes • Provision of structure for reef communities
Seawalls/revêtments	• Reflection of storm waves and consequent beach lowering • Intensification of wave attack due to beach lowering on an adjacent shore • Increased loss of sediment due to changes in the angle of approach of dominant waves • Erosion protection works can cause reduction in sediment supply to the coast from eroding cliffs, dunes and foreshore	• Direct losses of habitats under footprint of schemes • Indirect losses or changes as a result of changes in geomorphology • Diverted wave energy has an impact on habitats along the shore • Prevention of landward migration of habitats (relevant to coastal squeeze)

	outcrops, for example, due to construction of coastal defences	

Table 3.2 Non-FCERM interventions and potential influence on coastal habitats. Those interventions that could potentially be relevant to coastal squeeze are indicated.

Human intervention	Explanation	Potential influence on habitats
Beach mining	• Removal of sediment from the beach by quarrying or ad hoc extraction can reduce beach levels and increase erosion	• Direct losses of intertidal habitats • Potential loss of backshore habitats as a result of increased erosion • Indirect loss of sediment from nearby beaches and near subtidal habitats • Destruction of shingle and/or sand dune plant and animal communities
Changes in land use	• Deforestation or mining practices leading to changes in fluvial input of sediment to estuaries • Changes in water and sediment quality due to erosion or run-off from changed agricultural use, urban areas or infrastructure, for example, landfill sites	• Increases or decreases sedimentation and therefore affects intertidal habitat character and extent in estuaries
Changes in grazing regime	• Numbers of grazing livestock, types of livestock (for example, horses to sheep) or distribution of livestock changes	• Grazing can produce positive or negative impacts on habitats • Habitats that can be affected by grazing are saltmarsh, sand dunes, vegetated shingle and maritime cliff and slopes • Effects on sward height • Change in flora and fauna species diversity, abundance and distribution • Prevention of ecological succession through grazing of shrub and tree species
Channel training works	• Can cause changes in sedimentation within estuaries leading to estuary wide changes	• Indirect losses or changes to habitat as a result of changes in sedimentation
Dams	• Can cause reduction in sediment supply to the coast from rivers	• Indirect losses or changes to coastal habitat as a result of changes in sedimentation and freshwater supply • Removal of seasonal variation in flow impacts on communities along rivers and mudflat dwelling species in estuaries
Dredging	• Dredging can cause changes to nearshore wave conditions by changing nearshore water depths or positions of channels and banks	• Direct losses of habitats at the dredge site • Indirect losses or changes as a result of changes in physical processes and seabed morphology • Changes in seabed and benthic communities associated with a change in depth

Human intervention	Explanation	Potential influence on habitats
Intakes/outfalls	• Change to local flows causing scour • Interruptions to longshore drift	• Indirect losses or changes as a result of changes in geomorphology due to scour • Updrift increase in intertidal area • Downdrift decrease in intertidal area • Certain species are associated with intakes and outtakes and will subsequently be affected (some positively and some negatively)
Introduction of invasive species	• For example, the introduction of non-native species of *Spartina*	• Colonisation and creating of new saltmarsh habitats at the expense of existing mudflat habitats
Industrial activities and traffic near habitat	• Changes in water and sediment quality due to outfalls • Changes in water and sediment quality due to deposition of airborne pollutants, for example, oxides of nitrogen (NOx) • Changes in water temperature due to cooling water discharge	• Eutrophication of water bodies • Increased algal growth • Die back of vegetation
Other changes in agricultural practices	• Change in water and sediment quality due to, for example, leaching of fertiliser or other agro-chemicals from past or present agricultural practices	• Eutrophication of water bodies • Increased algal growth • Die back of vegetation
Railway/road embankments/quay walls	• Reflection of storm waves and consequent beach lowering • Intensification of wave attack due to beach lowering on an adjacent shore • Increased loss of sediment due to changes in the angle of approach of dominant waves • Erosion protection works can cause reduction in sediment supply to the coast from eroding cliffs, dunes and foreshore outcrops, for example, due to construction of coastal defences • Prevention of landward transgression	• Direct losses of habitats under footprint of schemes • Indirect losses or changes as a result of changes in due to changes in physical processes and geomorphology • Diverted wave energy has an impact on habitats along the shore • Prevention of landward migration of habitats (relevant to coastal squeeze)
Reclamations	• Can cause changes in sedimentation within estuaries leading to estuary wide changes • Changes to tidal levels and flow speeds in surrounding areas	• Direct losses of habitats under footprint of schemes • Indirect changes in habitats elsewhere in the estuary due to changes in physical processes • Prevention of landward migration of habitats (relevant to coastal squeeze)

Human intervention	Explanation	Potential influence on habitats
Recreational activities	• Sand dunes are used heavily for recreational purposes. Excessive use, and vehicular use in particular, causes unacceptable erosion • Illegal activities also include non-regulated activities which could for example include wildfowl shooting	• On some heavily used beaches the formation of embryo dunes is inhibited by beach cleaning using mechanical methods, which impedes the seaward accretion of dune systems • Trampling of flora species on sand dunes and vegetated shingle • Fauna species may be disturbed by noise or physical presence or even deliberately killed. This may then have an indirect corresponding effect on the habitat they use
Water abstraction	• Water abstraction can impact on habitats that are highly dependent on water levels. Dune slacks support characteristic communities dependent on a seasonally high water table, including the formation of temporary or even permanent ponds	• Indirect loss of beach habitats • Loss of saline lagoons and their specialized flora and fauna • In some dune systems with important slacks, a long-term fall in the water table has led to loss of the specialist slack flora and invasion by coarse vegetation and scrub

3.3 Influences from non-project or plan sources

There are a number of physical, biological and chemical factors from non-project or plan sources that can bring about changes in habitat extent:

- long-term geological and geomorphological trends
- climate change and SLR
- shorter term climatic variations
- 'sudden' events: natural disasters, storm surges and landslides
- ecological succession
- impact of invasive and or alien species

3.4 Long-term geological and geomorphological trends

Long-term geological and geomorphological trends include:

- glacial isostatic adjustment
- long-term decreases in sediment availability
- long-term patterns of sedimentation leading to changes in habitats type, for example, accretion of mudflats and development into saltmarshes within estuaries, lateral shifts in channel position
- long-term growth of spits, leading to the closure of estuaries and creation of lagoons and freshwater/brackish marshes or the reverse of this

The ongoing trend of glacial isostatic adjustment has a significant effect on the rates of relative SLR that are experienced around the UK, with greater rates of relative rise occurring in the south of the country (Shennan et al., 2009).

In a temporal sense, there are a number of factors that combine to cause variations in retreat rates and the width of the coastal zone at individual locations (see Table 3.3). Changes in these factors, which may be man-made or natural, over time can explain why the coastal zone may be narrower in some years or narrower under present day conditions than it was during historical times. For example, in Scotland it has been suggested that the main causes for the predominance of coastal erosion under contemporary conditions are the increased rate of SLR, increased wave energy and sediment supply which has decreased over the Late Holocene (Pontee, 2006). At Formby Point, Pye and Blott (2008) concluded that habitat losses have been predominantly caused by a change in the occurrence of storms rather than SLR. In a broader UK context, several previous publications have shown that SLR has been a minor factor leading to loss of saltmarsh and intertidal flats, compared with other factors such as fluctuations in wind-wave climate (for example, Pye, 2000; van der Wal and Pye, 2004).

Table 3.3. Natural causes of coastal erosion (modified from Lees, 2003). Those processes that could potentially be relevant to coastal squeeze are indicated.

Cause
Increased wave attack upon coast due to a relative rise in sea level (relevant to coastal squeeze)

Cause
Increases in wave attack due to changes in nearshore water depths due to changing positions of channels and banks
Increased wave attack on shoreline due to more frequent, long lasting or more severe storms arising from climate change
Increased wave attack due to a shift in direction in the wind/wave climate
Intensification of wave attack due to beach lowering on an adjacent shore
Increased loss of sediment due to changes in the angle of approach of dominant waves
Reduction in sediment supply from the adjacent seabed, for example, because natural supply has run out
Reduction in sediment supply from alongshore due to interception of longshore drift, for example, because of emergence of headlands
Reduction in sediment supply to the coast from rivers, for example, due to reduced rainfall or changes in land practice
Reduction in sediment supply to the coast from eroding cliffs, dunes and foreshore outcrops, for example, due to changes in slop failures caused by changes in rainfall, wave action or vegetation coverage
Migration of beach lobes or forelands under longshore drift, causing cycles of shoreline advance and retreat
Rise in the beach water table, for example, due to increased rainfall or local drainage modification, rendering the sand more liable to erosion
Reduction in sediment trapping due to a decline in vegetation, for example, decline of saltmarsh vegetation

3.5 Long-term climate change and sea level rise (SLR)

Climate change can be defined as a significant and lasting change in the statistical distribution of weather patterns. These changes can occur over periods ranging from decades to millions of years and include changes in average weather conditions or in the distribution of weather around these average conditions. Climate change can be brought about by many factors, including factors internal to the Earth's atmosphere, such as volcanic eruptions and changes in ocean circulation patterns, and factors external to the Earth, such as variations in the amount of incoming solar radiation.

Added to these natural causes of climate change are the impacts of humans, which could either make the impacts of climate change better or worse.

When the term 'climate change' is used, it is often being used as shorthand for 'anthropogenically induced climate change', that is climate change due to human activities. Human impacts are changing the global climate, mainly due to the release of elevated levels of carbon dioxide (CO_2) and other 'greenhouse gases' resulting from past and ongoing human activities (IPCC, 2018). Climate change, via temperature increases, influences the rate and amount of SLR by the thermal expansion of water and accelerating the rate of ice sheet melting (Lowe et al., 2018). Increased atmospheric CO_2 is also causing the acidification of saline and freshwater around the world, which, in turn, can affect habitats and species. Different studies and climate specialists either include 'SLR' within the term 'climate change' or else refer to 'climate change and SLR'.

Table 3.4 shows the potential impacts of SLR, storm surge and various other climate change effects on coastal habitats. It is important to note that the impacts of climate change on habitats is subject to ongoing research. The responses are likely to be complex due the interaction of the various factors such as temperature, carbon dioxide and rainfall. Further information on the impacts of climate change and SLR on different habitat types can be found in Natural England and RSPB (2020).

There are high levels of uncertainty in predicting future conditions. This is due to uncertainties in future greenhouse gas emissions and the ability to model certain climate parameters, such as future storminess, the interaction of the oceanic and atmospheric systems in exchanging heat or the rate of ice sheet melt (Fung et al., 2018). However, there is general agreement regarding the direction of change for most key variables, e.g. increasing atmospheric temperatures and accelerated SLR (Lowe et al., 2018, IPCC, 2018).

Table 3.4 Aspects of climate change and potential influences on coastal habitats. Those processes that are potentially relevant to coastal squeeze are indicated.

Aspect	Explanation	Potential impacts on habitats and species
Accelerated mean SLR	• Mean sea level rise accelerating • Tidal patterns could be influenced • Reduced depth limitation of waves (greater energy) • Increasing saline penetration up estuaries • Increase saline intrusion into coastal aquifers	• Inundation of freshwater or brackish coastal wetlands (relevant to coastal squeeze) • Changes in habitat zonation patterns (relevant to coastal squeeze) • Wetland inundation if accretion less than SLR (relevant to coastal squeeze) • Barrier island overtopping/breach/landward movement (relevant to coastal squeeze) • Dunes/barrier beach overtopping/breach/landward movement (relevant to coastal squeeze) • Increased erosion in areas with limited sediment supply (relevant to coastal squeeze) • Loss of existing freshwater and brackish habitats • Loss of terrestrial habitats to sea • Reduction in intertidal areas where landward transgression is prevented by defences or high land (relevant to coastal squeeze) • Drowning of lower intertidal habitats and conversion to subtidal (relevant to coastal squeeze) • Changes in salinity gradients and zones in estuaries, and effects on zonation and productivity of estuarine habitats and species • Conversion of terrestrial plant communities to those more characteristic of areas occasionally inundated by saltwater
Annual rainfall patterns	• Rainfall will show changes in distribution and pattern • Wetter winters, drier summers	• More frequent low flow conditions in rivers and estuaries, with potential drying of river and riparian habitats during summer • Changes to the pattern and rate of sediment transport in rivers and estuaries • Soil erosion • Drought condition impacts on habitats in summer • Increased inundation periods for terrestrial habitats due to surface water flooding • Changes in soil water levels and their seasonal patterns, leading to changes in plant community composition • Increased magnitude of high flow conditions in rivers and estuaries due to higher rainfall events during winter periods
CO_2 level	• Increased anthropogenic emissions are producing higher levels of CO_2 in the atmosphere	• The impacts of increased CO_2 on plant species are complex and the subject of ongoing research • Differences in responses are likely to exist between species, and also within the same species, depending upon other controlling factors. (for example, in areas where water and nutrients are not limiting factors, competitive species will have higher growth rates. However, in stressed environments the increase in growth rates may be limited by other factors) • Increased growth rates would be expected to increase sediment trapping and surface elevations in dunes and marshes

Extreme rainfall	• Higher intensity storm events • Increases in direct precipitation (surface water flooding) • Overland and subsurface flow from adjacent uplands (surface and groundwater flooding) • High water tables (groundwater flooding)	• More frequent ground movement in landslide systems • Increased soil erosion • Flooding of ground dwelling animals, for example, ground nesting birds • Increased peak flows within rivers and estuaries (see below). Resulting increase in stream power will allow transport of larger sized sediment, potentially impacting habitats and engineering structures • Plants and animals sensitive to high flow rates will be lost
Increased freshwater peak flows	• River/estuarine flooding • Lake water inundation • Freshwater estuarine inundation • Changes to bio-chemical fluxes	• Changes to the pattern and rate of sediment transport in rivers and estuaries with erosion of river bank habitats as the channel adapts to increases in seasonal discharge (for example, larger/more dynamic channels) • More frequent flooding of riparian habitats (and habitats not normally considered riparian) • Improved ecological connection between rivers/estuaries and flood plains • Changes in salinity gradients and zones in estuaries, and effects on zonation and productivity of estuarine habitats and species
Storm surge	• Storm surges may increase in height and frequency • Extreme water levels could show significant increase • Coastal flooding by salt and brackish water (tidal)	• Increased temporary inundation of freshwater or brackish coastal wetlands and terrestrial habitats • Changes in vegetation zonation (relevant to coastal squeeze) • Barrier island overtopping/breach/landward movement (relevant to coastal squeeze) • Dunes/barrier beach overtopping/breach/landward movement (relevant to coastal squeeze) • Increased erosion (relevant to coastal squeeze) • Conversion of terrestrial plant communities to those more characteristic of areas occasionally inundated by saltwater • Loss of freshwater species not able to exist with any level of saltwater inundation • Gain of species characteristic of brackish water • Large-scale movement of dune systems (relevant to coastal squeeze)
Temperature	• Rate of temperature rise expected to show significant increase	• Species migration due to temperature change – generally northwards or to higher ground, leading to changes in plant and animal communities and ultimately change in habitats • Changes to patterns of species reproduction • Changes to predator-prey linkages and food webs • At any given location, higher temperatures will reduce the effective rainfall (that is, rainfall less than that lost to evapotranspiration by plants), lowering net groundwater levels

		• Such changes could improve the stability of coastal cliffs and prevent landslides. However, were vegetation to die off due to a lack of moisture, then the soil stability could be increased
Wave climate	• Wave heights may change • Wave direction may change • Changes in coastal sediment transport • Resulting changes in coastal geomorphology	• Barrier island overtopping/breach/landward movement (relevant to coastal squeeze) • Dunes/barrier beach overtopping/breach/landward movement (relevant to coastal squeeze) • Increased erosion (relevant to coastal squeeze) • Inundation of freshwater or brackish coastal wetlands and terrestrial habitats • Loss or change of freshwater, brackish and terrestrial habitats (relevant to coastal squeeze) • Change of plant and animal communities and zonation patterns (relevant to coastal squeeze)
Wind direction	• Potential changes in wind direction	• Change local wind generated wave directions, resulting in altered littoral drift patterns (see below), in time potentially leading to changes in coastal alignment • Changes in dune morphology (relevant to coastal squeeze) • Loss of tall woodland
Wind speed	• Increase in extreme wind speeds	• Changes to wave climate (see below) • Changes in dune morphology (relevant to coastal squeeze) • Landward movement of dunes (relevant to coastal squeeze) • Changes in proportion of vegetated versus unvegetated dunes (relevant to coastal squeeze)

3.6 Shorter term climatic variations

Shorter term variations arise due to climate patterns. A climate pattern is any recurring characteristic of the climate. Such patterns can, at one extreme, last tens of thousands of years (for example, glacial and interglacial periods within ice ages), or, at the other extreme, they can be annual. Climate patterns may be regular cycles (for example, winter/summer), quasi-periodic events (for example, El Niño) or highly irregular events (for example, a volcanic winter).

Two well-known climatic patterns are El Niño and the North Atlantic Oscillation (NAO), which can affect temperature, wind speed and rainfall in the UK, and can have similar effects to those outlined for climate change, albeit over shorter timescales.

El Niño, also termed the Southern Oscillation (ENSO) is a quasi-periodic change in the currents of the Pacific Ocean that occurs every 5 to 8 years and brings unusually warm water to the coast of northern South America. El Niño refers to variations in the temperature of the surface of the tropical eastern Pacific Ocean and in air surface pressure in the tropical western Pacific. The 2 variations combine: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific. The extremes of this climate pattern's oscillations, El Niño and La Niña, cause extreme weather in many regions of the world, especially those around the Pacific. There is evidence that ENSO can affect weather patterns in Europe. For example, some studies show a direct link between a warm ENSO season and rainfall/temperature anomalies across western and central Europe.

The North Atlantic Oscillation (NAO) is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. The corresponding index varies from year to year, and variations in the NAO affect the strength and direction of westerly winds and storm tracks across the North Atlantic. But, it also exhibits a tendency to remain in one phase for intervals lasting several years. The NAO is considered to be the dominant mode of winter climate variability in the North Atlantic region. However, recent investigations have suggested that the Western Europe Pressure Anomaly (WEPA), which is a measure of atmospheric pressure differences between the Canary Islands and Ireland, is more important in influencing extreme wave conditions along the SW coast of the UK than the NAO (Castelle et al., 2017).

Local wind and wave conditions around the UK are heavily dependent on the tracks taken by mid-latitude depressions, and on the persistence or otherwise of high pressure over Scandinavia, both of which are linked to the behaviour of the mid and high-level jet-stream. Rapid erosion of saltmarshes and upper tidal flats in south-east England between the late 1950s and late 1970s was linked to a relatively high frequency of easterly, north-easterly and south-easterly winds associated with frequent and persistent anticyclonic conditions over Scandinavia (Carpenter & Pye, 1996). However, during this time, rapid saltmarsh expansion occurred at many locations on the west coast of Britain. Conversely, between the mid-1980s and 2010 south-westerly and westerly winds were more frequent across England and Wales, resulting in a reduction in rates of saltmarsh erosion on the east coast and a cessation of accretion, with occasional changes to erosion at many locations on the west coast.

3.7 Sudden events: natural disasters, storm surges and landslides

There is potential for natural disasters such as earthquakes and tsunamis to have irreversible impacts on habitats, leading to deterioration and loss of site integrity. Since tsunamis and earthquakes do not typically affect Britain they have not been considered further in the present project.

The UK is, however, exposed to low pressure atmospheric systems that can generate strong winds, elevated sea levels and high rainfall. These storms are known variously as mid-latitude depressions, extra-tropical storms and cyclones. Such events are more common in the autumn and winter. These storms are typically a few hundred kilometres in size, travelling approximately eastwards across the North Atlantic and lasting several days,

High water levels can also lead to the flooding of low-lying areas along coasts and within estuaries. The strong winds can generate large waves which can lead to significant changes in coastal habitats, including the lowering of beach levels, breaching or retreat of coastal barriers, increased cliff recession, and erosion of the seaward edges of saltmarshes. Within estuaries the elevated water levels can cause strong currents and erosion of intertidal and subtidal areas. Intense rainfall associated with storms can also lead to high freshwater flows in estuaries, which can cause erosion and alterations to the positions of channel and banks. Periods of high rainfall may also trigger landslides in coastal areas.

3.8 Ecological succession

This refers to the gradual and orderly process of change in an ecosystem brought about by the progressive replacement of one community by another until a stable 'climax community' is established. The process of succession can be influenced by human activities and natural changes. These external influences can alter the distribution and abundance of flora species and assist the process of succession in favour of specific species. For example, drier summer weather caused by climate change could lead to habitats being colonised by more drought-tolerant species.

Examples of ecological succession include those shown in Table 3.5.

Table 3.5 Ecological succession.

Potential impacts on habitats and species	Explanation
Formation of saltmarshes, which in turn could be succeeded by terrestrial habitat	Saltmarshes form when salt tolerant plants in mudflats first trap mud and silt. As the sediment builds up, the mud surface rises and the saltmarsh develops outwards from the land, whilst accreting vertically to a level around mean high water spring tides.
Ponds and lakes are succeeded by terrestrial scrub and woodland habitat, the latter of which represents the climax community	Planktonic organisms and plants sink to the bottom when they die along with any silt that accumulates from streams feeding into the pond. Gradually, as the pond fills in with this material the reeds invade further into the middle of the pond. The older reed areas slowly dry out and a swamp area behind them can be colonised by alder. Together with other plants, water is steadily removed and with the drier conditions birch may colonise.
Sand dunes and other habitats become woodland	Small plants such as Sand Couch-grass and Marram grass stabilise dunes with their root systems, causing sand to stay in place. Nutrients from animal droppings and decaying grass make an environment suitable for lichens and mosses to grow. Further decaying vegetation creates a sandy soil suitable for scrub such as

Potential impacts on habitats and species	Explanation
	hawthorn. Eventually trees will find the soil suitable for growing in and the dune will become woodland. This process can occur over hundreds of years.

On natural coasts, the orderly succession to mature systems may be interrupted by changes in driving forces such as those described sections 3.4, 3.5, 3.6, 3.7.

3.9 Invasive and/or alien species

Invasive species of flora and fauna could lead to changes in coastal habitat or species and potentially cause the habitat to deteriorate. They can be introduced directly by people, either intentionally or accidentally, for example, via ship ballast water. Species can also migrate to new areas as a result of short or long-term variations in climate. Invasive species particularly relevant to coastal habitats include, but are not limited to:

- Chinese mitten crabs (Eriocheir sinensis*)* that can cause damage to river banks, modify natural habitats and compete with native species
- Cord grass (Spartina anglica) invasion has had most impact on pioneer communities of saltmarsh, especially on Salicornia communities. As a result, attempts have been made to control it at several locations, although in some areas it is undergoing dieback for reasons not fully understood

3.10 Changes in habitats due to multiple causes

The previous sections have illustrated that numerous factors can combine to cause change in the extent of coastal habitat. Therefore, it may not always be possible to identify a single dominant cause of change.

The deterioration of saltmarsh vegetation known as 'dieback' is one such example where there may be multiple causes for habitat loss, or even different causes at different locations. The general effect of saltmarsh dieback is that the plants in the marsh die off and brown, leaving dead organic matter, and ultimately open sediment. Without strong plant roots holding the sediment, these open areas of land erode, causing the saltmarsh to retreat back to the mainland. Dieback zones lack their main producers, such as the saltmarsh cord grass or Spartina alterniflora and ultimately become completely unproductive. A number of causes have been suggested, some of which may be interlinked:

- drought
- fungal pathogens
- herbivore activity (for example, snails, crabs)
- SLR leading to increased tidal inundation
- soil chemistry (for example, changes in water-logging, redox potential, salinity)
- wrack damage (Alber et al., 2008)

Several of the factors listed above potential relate to SLR and, therefore, coastal squeeze. For example, increased tidal inundation and the waterlogging of sediments may be due to the failure of saltmarsh surfaces to accrete vertically in line with SLR.

3.11 Summary

Flood and coastal defence structures can impede the natural landward transgression of coastal habitats – this is central to the definition of coastal squeeze. Some FCERM management activities can also impede the natural landward transgression of coastal habitats.

However, there are numerous other factors that can cause a decrease in habitat area or quality. Some of these factors are natural, some are man-made, and some are a combination of both. Some, but not all, human impacts relate to plans or projects. This chapter has reviewed these factors and identified those that potentially relate to coastal squeeze and those that do not.

A number of human interventions (including flood and coastal defences and other structures) can potentially impede the natural transition of habitats, including:

- flood embankments
- railway/road embankments/quay walls
- reclamations
- seawalls or revêtments

SLR can potentially bring about changes to habitats in a number of ways, including:

- increased wave attack, leading to erosion of seaward edges of habitat
- increased inundation of habitats, leading to changes in habitat zonations (including extent, position and type)
- overtopping/breaching/landward movement of dunes/barrier beaches/barrier islands

The relevance of factors, plus the type and scale of impacts on coastal habitats are likely to vary according to geographic location and specific site conditions. In many instances, habitat change is likely to result from multiple causes. In these circumstances, the causes of the change may be difficult to identify and may require a number of investigations.

When examining changes in coastal habitats it is important to consider whether the changes are part of a progressive long-term trend or a shorter cycle. The width of the coastal zone and its component habitats can vary over a range of spatial and temporal scales. For example, sandy beaches might vary significantly in width in response to differences in wave conditions between the summer and winter. Therefore, losses of width that occur in the winter months might be reversed in the summer months, resulting in no net change when measured over the whole year. Similar patterns can occur over periods of years in response to periods of increased/decreased storminess. Therefore, identifying progressive long-term trends such as coastal squeeze needs to consider an appropriate time span.

4 Outputs from stakeholder workshop

A workshop with a range of stakeholders was held in London on 9 July 2018. This chapter summarises the main points discussed in relation to the definition of coastal squeeze. Notes from the workshop are provided in Appendix B.

The workshop was attended by 20 people from the following organisations: the Environment Agency, University College London, Network Rail, Denbighshire County Council, Natural Resources Wales, Marine Management Organisation, Jeremy Benn Associates, ABPmer, Natural England, Defra, and Kenneth Pye Associates. There were no representatives from the Crown Estate or local authorities in England.

The workshop involved 2 exercises:

- defining 'coastal squeeze'
- exploring methods to assess coastal squeeze

A number of stakeholders stressed that any definition of coastal squeeze must be simple and pragmatic.

There was general agreement between the stakeholders that coastal squeeze is one type of habitat loss associated with:

- man-made structures such as defences
- sea level rise (SLR)
- landward transgression of habitats being held-up

A definition containing the above elements would agree with most definitions that have been used to date in the UK (see Chapter 2). Such a definition would exclude other causes of habitat loss (for example, deterioration due to pollution or erosion due to channel movements), but would not necessarily mean that these losses would not need to be considered or compensated for as part of a coastal habitat management strategy.

One group suggested that as well as SLR, coastal squeeze assessments also needed to consider changes in tidal levels that may have been brought about by works within estuaries, such as reclamation or dredging. It is noted that identifying whether these changes have occurred and establishing their size is likely to require detailed studies.

The consensus of the workshop was that coastal squeeze should not include effects such as changes in longshore sediment supply. In contrast, one of the written contributions believed that such processes should be captured within a definition of coastal squeeze.

The workshop agreed that the definition of coastal squeeze should not include habitat quality. It is noted that habitat quality is included in some of Natural England's definitions (for example, English Nature et al., 2003; Natural England 2015). The workshop concluded that habitat quality was a complex issue that would require future work to develop a transparent and robust method of assessment.[5]

[5] Subsequent to the workshop, after several rounds of discussion, it was decided to include 'habitat quality' within the definition.

Some participants at the workshop suggested that the term 'inappropriate coastal management' (for example, English Nature, 2003a) needed clarifying to recognise that while some forms of FCERM might have detrimental impacts on habitats (in other words, be inappropriate from a habitats perspective), they were successful (not inappropriate) in terms of reducing flood and erosion risk.

There were 2 opinions on which habitats should be included:

- Opinion 1 - saltmarsh and mudflat only. The rationale for this was that these habitats were referred to in most instances when currently using the term coastal squeeze in the UK. If this definition of habitats were chosen, the driving forces could be limited to SLR since tidal levels determine the landward boundary of mudflat and saltmarsh habitats.
- Opinion 2 – all relevant coastal Annex 1 Natural Environment and Rural Communities (NERC) priority habitats (Table B 1). If this definition of habitats were chosen in addition to SLR processes such as aeolian transport (for example, sand dunes) and wave overwash (shingle ridges) would be need be considered.

The consensus at the workshop was that the loss of habitat due to natural steeply rising land was not coastal squeeze. However, it was acknowledged that these losses may need to be assessed to provide a baseline against which coastal squeeze losses due to defences could be assessed. This led to the suggestion that future coastal squeeze losses needed to consider the potential for transgression that would exist if the defences were not present. Two scenarios were discussed:

i. Coastal defences backed by rising land – in this case, even if the defences were not present, there would be restricted potential for the natural landward transgression of habitat.

ii. Coastal defences backed by a large expanse of low-lying land – in this case, if the defences were not present, there would be a large potential for the natural landward transgression of habitats (relative to the current landward boundary against the defences).

The workshop agreed that losses of intertidal habitats due to historic reclamation did not constitute coastal squeeze. However, one of the written contributions suggested that coastal squeeze was likely to be increased where a greater width of the flood plain had been reclaimed in the past. It is suggested that the extent of coastal squeeze losses in front of the habitats requires specific assessments of the physical and ecological processes taking place to judge whether the habitats are at risk of coastal squeeze rather than just relying on general principles.

The workshop raised an interesting question related to determining future losses, namely 'what happens when all the intertidal habitat fronting defences has been lost?' For example, does this mean:

i. that no further compensation is required after this time?

ii. that compensation should continue after this time?

If perspective (ii) were to be taken, then some ongoing future allowance for coastal squeeze would need to be agreed. This would require data of historical rates of loss against the structure, which might not exist if the intertidal habitat had been lost at some point in the past.

5 Definition of coastal squeeze

5.1 Definition and points of clarification

After considering the common elements of published definitions used in the UK (Chapter 3), the majority of views expressed at the workshop (Chapter 4) and several rounds of discussions with the project board members, the following definition has been arrived at:

"Coastal squeeze is the loss of natural habitats or deterioration of their quality arising from anthropogenic structures, or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to sea level rise (SLR) in conjunction with other coastal processes. Coastal squeeze affects habitat on the seaward side of existing structures."

It is essential this definition is read together with the points of clarification below.

Points of clarification:

1. 'Anthropogenic (man-made) structures' includes features that act as barriers to the inland progression of marine waters and habitats. These would include flood and coastal erosion structures, quay walls and road/railway embankments. 'Anthropogenic actions' include activities that artificially prevent the landward transgression of habitats.

2. 'Natural habitats' include all relevant Annex I coastal/intertidal habitats found in the UK as defined in policy and legislation (including NERC s41 priority habitat or Environment Act Section 7 for Wales). Annex I habitats (of the EU Habitats Directive) are listed in Appendix C. The relevant habitats will need to be identified at a site level. Further detail regarding those habitats subject to coastal squeeze is provided in section 5.2.

3. Habitat loss is considered in terms of planform area of the habitats. The planform area should include changes arising from frontal retreat (for example, of a saltmarsh edge) as well as internal erosion (for example, expansion of creeks within marshes).

4. Coastal processes relevant to identifying coastal squeeze should include those which, under natural unconstrained conditions, can lead to the landward migration of habitats under a scenario of SLR - such as waves for shingle beaches, winds for aeolian dunes, and tidal inundation for saltmarshes.

5. The assessment of coastal squeeze in estuaries should consider whether the extent of any intertidal islands is affected by flood defences on the islands themselves or within the wider estuary. This consideration should also take into account the role of natural changes in channel position over time which can influence the size and location of intertidal islands.

6. Coastal squeeze as defined excludes:

   i) the historic drainage and land claim of habitat landwards of currently existing structures

ii) other impacts of hard defences such as reductions in sediment supply caused by protecting eroding sediment sources or interrupting longshore transport pathways[6]

iii) impacts of other human activity/structures on habitats, such as alteration of estuary channel morphology due to dredging, training walls or piers, or impacts on habitat quality due to management practices or pollution

iv) other natural or human causes of habitat loss unrelated to creating barriers to landward transgression, for example, the lateral movement of channels which may be unrelated to SLR and, while it would erode seaward edges of habitats, would not create landward transgression even under unconstrained conditions

v) habitat loss against natural steeply rising land (that is, sloping coastal hinterlands) – such losses may need to be considered as a baseline scenario ('without defences') against which to judge coastal squeeze losses. It should be noted that some areas of rising land formed from unconsolidated sediments may erode relatively rapidly in the future to provide accommodation space for habitats.

The above impacts should be assessed, described and accounted for separately, even though the remedial measures may be linked or packaged with those taken to address coastal squeeze.

7. SLR is taken to be the net trend in relative sea level resulting from global eustatic variations (changes in ocean volume) and regional or local isostatic change (changes in land level). SLR excludes changes in water levels due to human interventions, for example, dredging, land claim, creation of flood storage/managed realignment areas. If these changes are relevant to an area, they should be assessed separately.

8. Assessing coastal squeeze should consider whether there is deterioration in habitat quality or changes in vegetative species composition which may be occurring as a result of human structures/actions impeding the landward transgression of habitats. For example, in saltmarshes, SLR might lead to high marsh communities being replaced with lower marsh communities. These changes may occur ahead of, or at the same time as, areal losses.

5.2 Which habitats are included?

The project board recommended that 'natural habitats' should include all relevant Annex I, Section 41 or Environment Act Section 7 for Wales priority coastal/intertidal habitats found in the UK as defined in policy and legislation (see Appendix C). This long list of habitats has been examined and a number of habitats, where the concept of coastal squeeze would not apply, screened out.

For the purposes of this project, the following marine habitats have been excluded as they are subtidal:

- subtidal rocky habitats
- horse mussels
- maerl beds

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[6] It is noted that decreases in sediment supply can potentially make downdrift habitats more susceptible to coastal squeeze. The role of these factors, and the implications for any mitigatory actions, would need to be appraised on a site by site basis.

- mud habitats in deep water
- subtidal chalk
- subtidal sands and shingle

Note that Seagrass beds have been included since they can occupy intertidal areas as well as subtidal.

A number of habitats have been implicitly included since they occur on existing intertidal flats or beaches which are included. The habitats that are explicitly included are:

- blue mussels
- Sabellaria alveolata reefs
- Sabellaria spinulosa reefs
- tide swept channels

Additionally, grazing marsh habitat has been excluded since this habitat type is largely artificial and created behind sea walls.

Finally, sea cliffs have been excluded since it is unlikely that a structure could be built inland of a cliff to prevent its landward transgression.

The resulting shortlist of habitats that could be subject to coastal squeeze is as follows:

- boulder beaches
- shingle beaches and barriers
- intertidal seagrass beds
- intertidal reedbeds
- intertidal rock platforms
- mud and sandflats
- saline lagoons located in front of structures
- saltmarsh
- sand beaches
- sand dunes

The relationship between these simple habitat names and the original habitat names types listed in Annex 1/Section 41 is given in Appendix C (Table B 1 and Table B 2). A brief description of the above habitats is given in Table B 4.

It should be noted that there may be some site-specific variations around the UK. For example, in some areas 'Estuaries' (EU code 1130) may contain mudflats and sandflats, while in others they contain mudflat and intertidal rock platforms. Habitat types therefore need to be identified at a local level.

All of these habitats meet the following criteria:

- The habitat, in an unconstrained scenario, is capable of transgressing landward in response to ‘SLR and other coastal processes[7]. This means that the physical and/or biological components of the habitats are capable of being mobilised.
- The habitats have a measurable area which could potentially be reduced in response to landward transgression being prevented.
- There are relevant structure/s and/or management actions that could prevent the landward transgression of the habitat.

The criteria management actions that could prevent the landward transgression of the habitat’ applies most readily to shingle beaches and sand dunes in the form of reprofiling activities or the planting of stabilising vegetation.

Figure 5.1: The concept of coastal squeeze, although most commonly applied to saltmarshes, can also apply to other coastal habitats such as shingle beaches that are backed by structures such as sea walls.

Photo courtesy of Jacobs.

[7] It should be noted that landward transgression is one habitat’s response to SLR. Other responses include (i) accreting vertically to maintain habitat extent with moderate sediment supply, (ii) prograding to increase habitat extent due to high rates of sediment supply, and(iii) drowning in situ due to rapid rates of SLR or insufficient sediment supply or both. The behaviour of habitats in the coastal zone in response to SLR depends very much on the availability of sediment in relation to the driving forces such as SLR and wave activity.

6 Method

6.1 Introduction

The definition of coastal squeeze that was agreed by the project board is shown in Chapter 5 along with a number of important clarifications.

The project board requested that 'natural habitats' should include all relevant Annex I, Section 41 priority coastal/intertidal habitats found in the UK, including those listed in Environment Act Section 7 for Wales, as defined in policy and legislation. These habitats have been reduced down to a shorter list of habitats to which coastal squeeze could potentially apply (see Appendix C).

This chapter describes the proposed approach for all relevant habitats.

The method is divided into two parts to determine:

1. past losses of habitat due to coastal squeeze - outlined in section 6.2
2. future losses of habitat due to coastal squeeze - outlined in section 6.3

The final determination of coastal squeeze should be accompanied by an assessment of confidence – 'high', 'medium', 'low'. Guidance is provided on what each of these categories looks like in section 6.2.6 (Table 6.16).

In some cases, it may be difficult to determine whether coastal squeeze has or is likely to lead to losses of intertidal habitats. In these circumstances, it is unlikely to be possible to demonstrate that coastal squeeze is having 'no adverse effect'. This may be due to a lack of data or a number of other potential factors that could be responsible for intertidal habitat loss (see Table 6.13 to Table 6.15). In these cases, two approaches can be taken:

1. Adopt the precautionary principle and assume that habitat losses or deterioration in quality result from coastal squeeze. These potential coastal squeeze losses should be reviewed in the future when further understanding or monitoring may be available.
2. Carry out additional studies to improve confidence in the findings. These studies might include more detailed morphological or ecological assessments to document the extent and cause of habitat loss or deterioration.

It should be noted that habitat losses not attributed to coastal squeeze may still require assessment and mitigation/compensation.

This chapter will outline a method for identifying past and future coastal squeeze losses of habitat. The method for identifying past losses is shown in Figure 6.1, while the method for future losses is shown in Figure 6.2.

Implementing the approach is likely to require collaboration between developers, the Environment Agency (as developer or competent authority), Natural England, Natural Resources Wales and perhaps others (for example, local authorities, wildlife groups and research bodies) to both source baseline data and provide expert opinion to reach agreement on the results.

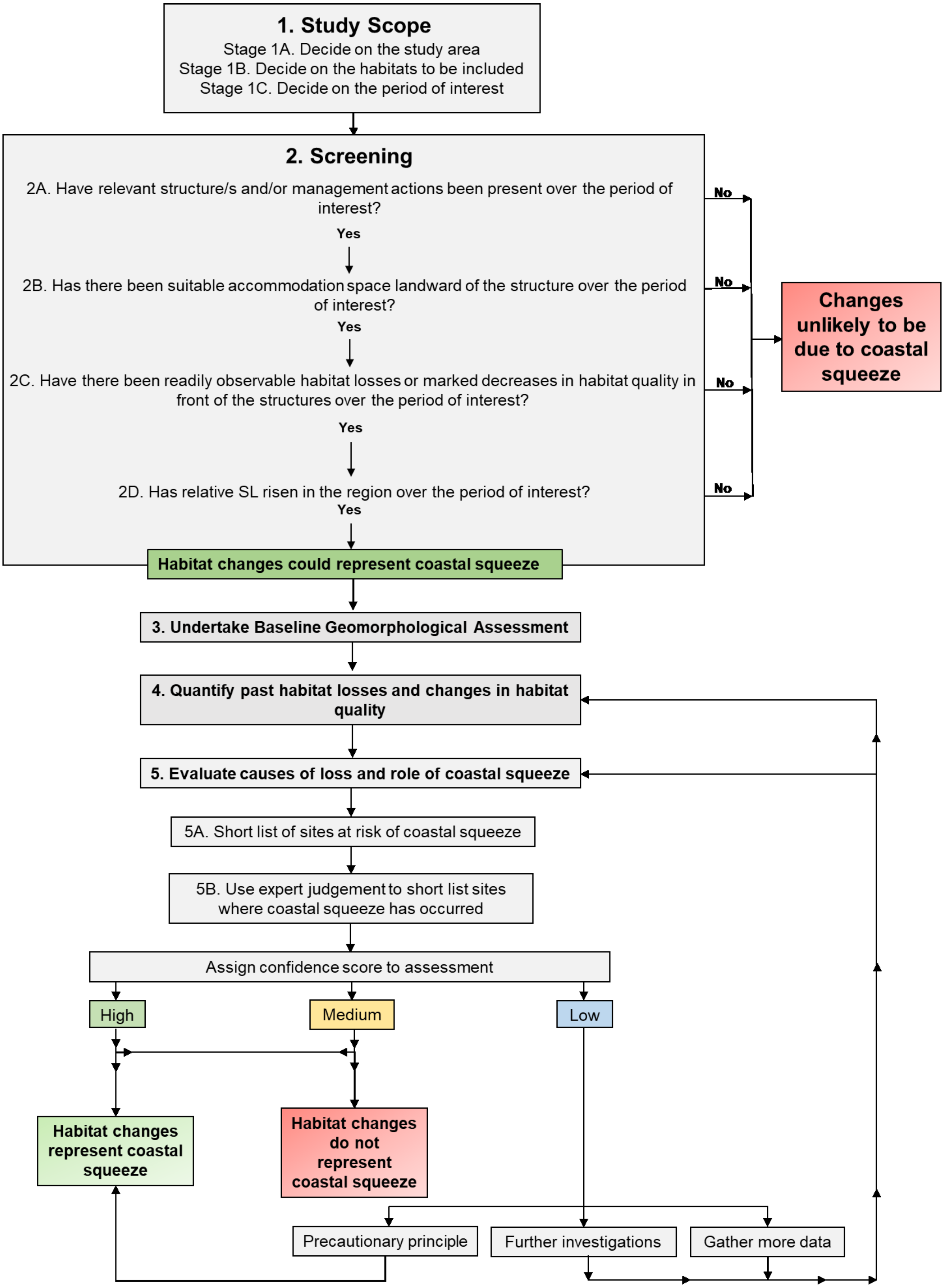


Figure 6.1: Flow diagram of the methodology for identifying past habitat losses attributable to coastal squeeze.

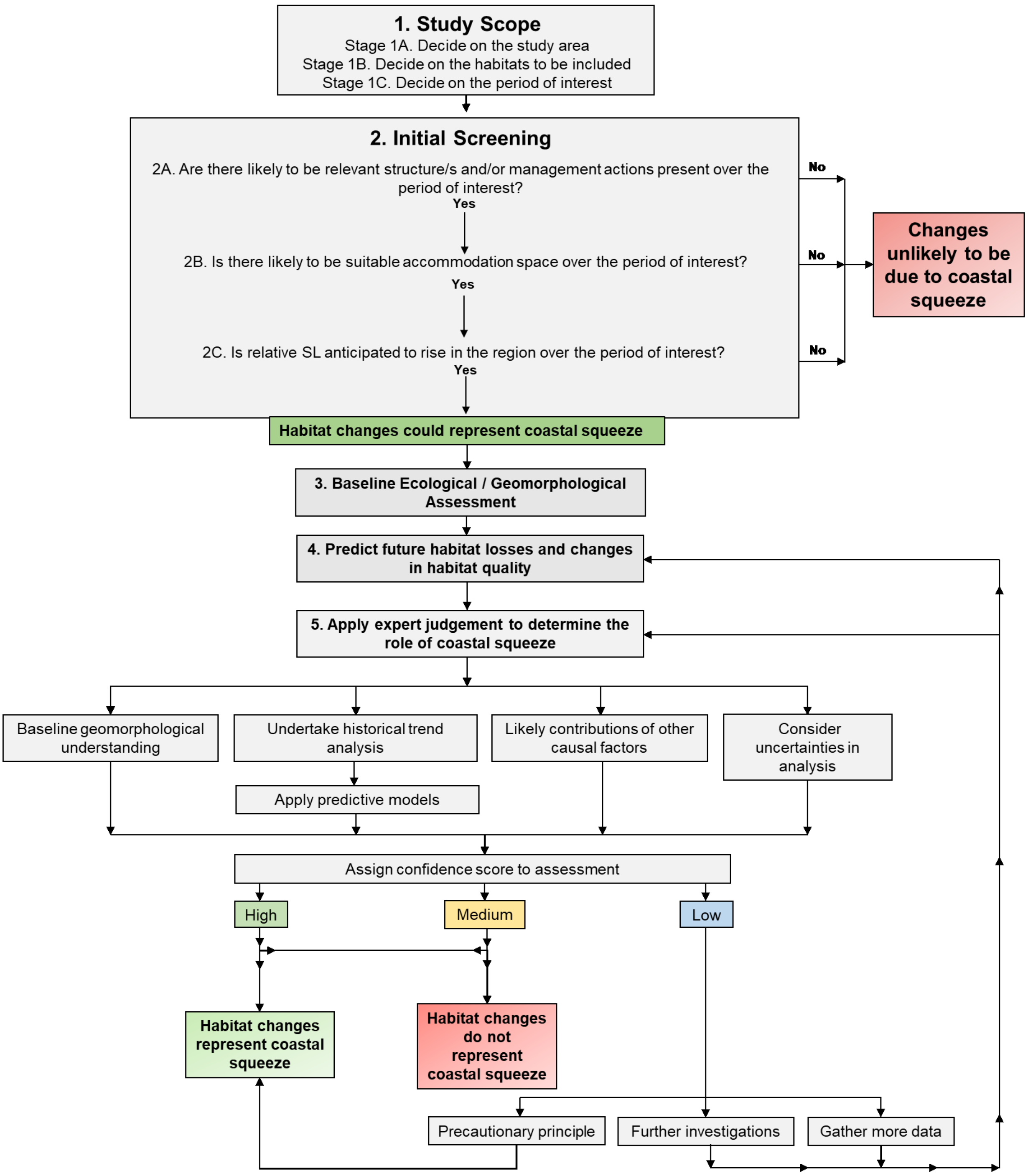


Figure 6.2: Flow diagram of the method for identifying future habitat losses attributable to coastal squeeze.

6.2 Determining past coastal squeeze losses

The assessment of past habitat losses due to coastal squeeze consists of 5 main stages:

1. Scoping.
2. Screening.
3. Baseline assessment.
4. Quantifying past habitat losses.
5. Evaluating the causes of loss and the role of coastal squeeze.

6.2.1 Scoping

Three items need to be decided at the scoping stage:

1. Study area.
2. Habitats to be included.
3. Period of interest.

Study area

To quantify habitat loss the area of interest must be defined. This could be a specific length of defence/structure, a whole estuary for an estuary strategy or an entire Shoreline Management Plan (SMP) area (typically corresponding to one or more coastal sediment cells). It should be noted that in order to understand the changes taking place at a specific location, it is necessary to consider the wider coastal system, for example, embayment, estuary, coastal sediment cell (See section 6.2.3).

Habitats to be included

The habitats to be included in the assessment need to be reviewed at a site level. This project has determined that a number of Annex 1, Section 41 Environment (Wales) Act Section 7 habitat could potentially be affected by coastal squeeze:

- boulder beaches
- shingle beaches and barriers
- intertidal seagrass beds
- intertidal reedbeds
- intertidal rock platforms
- mud and sandflats
- saline lagoons located in front of structures
- saltmarsh
- sand beaches
- sand dunes

The relationship between these simple habitat names and the original habitat names types listed in Annex 1 and Section 41 is given in Appendix C.

Period of interest

To quantify habitat loss a start date and end date must also be identified. At present in the UK most assessments have been concerned with the impacts on the Natura 2000 network (Special Protection Areas - SPAs, Special Areas of Conservation - SACs and Ramsar sites) and deriving appropriate targets for providing compensatory habitat.

In England, Defra, the Environment Agency and Natural England (formerly English Nature) previously agreed that habitat should be restored to 1992 levels, the year the Habitats Directive was adopted[8]. Note that this is earlier than the implementation date of the Habitats Directive, which in England and Wales was through the Habitats Regulations in 1994 (Miles and Richardson, 2018).

In some areas, it might also be appropriate to consider using 1985 as a start date to broadly coincide with the Sites of Special Scientific Interest (SSSI) notification under the 1981 Wildlife and Countryside Act. However, in practice, the start date of the assessment may be limited by the availability of data – with LiDAR coverage commonly starting around 2000.

For an assessment of past coastal squeeze losses, the end date is likely to be the present day or the most recent source of data covering habitat extent (often the most recent coastal monitoring data such as LiDAR or aerial surveys).

However, it is possible that in some scenarios the assessment of changes in coastal habitat may wish to consider different periods of time, for example, if assessments are being made for a structure that has been in place for a shorter period of time. In this approach, we therefore use the term 'period of interest'.

6.2.2 Screening

The purpose of the initial screening stage is to rapidly determine whether the site may have experienced coastal squeeze losses in the past using a number of basic tests:

1. Have relevant structures and/or management actions been present/occurred over the period of interest?
2. Has there been suitable accommodation space landward of the structure over the period of interest?
3. Have there been observations of habitat losses or marked decreases in quality in front of the structures over the period of interest?
4. Have relative sea levels risen in the region over the period of interest?

These tests can be addressed in any particular order but it is suggested that the order above is helpful in that it helps screen out areas (where coastal squeeze is unlikely to have occurred) early in the process.

If the answers to any of the above tests are negative, it is unlikely that there has been any coastal squeeze in the area. If the answers are positive, then it is possible that losses due to coastal squeeze have occurred and further assessment should be carried out. If none of these questions can be answered, it will be necessary to gather more data and/or carry out more detailed studies (see section 6.2.2 to 6.2.5).

Further details of the above 4 tests are given in the subsequent sections. There is a range of data sets to answer each of the screening questions. While some sites might have more data than others, even those sites with very little data should have enough

[8] - note: this does not mean that the 1992 area represented favourable overall status, just a baseline against which to work.

information to make an initial assessment of whether coastal squeeze may have occurred.

The site in question may vary from a short length of frontage corresponding to one structure (for example, 10s of metres in length) to a larger length of shoreline composed of several structures (for example, 100s of metres in length) to a whole sediment cell of estuary (10s to 100s of km). If the tests are applied over larger lengths of coast, it may be possible to screen out those areas where coastal squeeze is unlikely to have occurred, for example by identifying areas where there are no defences and no shoreline management actions have been carried out or areas where there is high ground.

Figure 6.3: The processes responsible for the landward transgression of different habitats vary between habitats. For shingle ridges, wave action is responsible for over washing behaviour which moves material landwards in wash over lobes. The image above shows where this occurred on the Dunwich-Walberswick barrier in 2017. In this instance, the wave and tidal action led to the creation of a breach in the ridge.

Photo courtesy of Nigel Pontee, Jacobs.

Test 1: Have relevant structure/s and/or management actions been present over the period of interest?

Explanation

The purpose of this test is to determine whether there have been structures capable of preventing natural landward migration of habitats over the period of interest. It is also important to consider known management actions that could have restricted the landward migration of the habitats over the period of interest.

There is likely to be some variability in the type of structure according to the site being investigated, but such 'structures' could include:

- shoreline defences: sea walls, embankments, sheet pilling, and rock revetments
- embankments constructed for transport infrastructure, rail and road
- areas of artificially or anthropogenic raised land, for example areas raised out of the flood plain
- other marine structures associated with docks, harbours

Further information on the processes that control the landward transgression of different habitats is given in Box 2 and Table 6.1. This test seeks to assess whether these processes have been interrupted by structures or management actions.

Further information on the type of structures and management actions that can prevent the landward migration of different habitats is given in Table 6.2.

Box 2: Transgressive processes for habitats

The natural landward transgression of habitats requires the landward movement of both the landward and seaward limit of the habitat. The processes that control the landward movement of the seaward limit of the habitat may differ from those that control the landward limit. Furthermore, the controlling processes differ between habitats. For example, the recession of dune fronts may be due to wave action at high water, while the landward limits of dunes may be controlled by the occurrence of strong onshore winds which can blow sand inland. For saltmarshes, the lower limits may be controlled by erosive forces of waves which lead to the development of cliffs and the inundation frequency; while the upper limits are more likely to be determined by inundation frequency than wave action. Table 6.1 summarises the relevant processes involved in the transgression of various coastal habitats.

For the areal extent of coastal habitats to be maintained during landward movement, it is necessary for the seaward and landward extents to migrate at the same rate. Variations in these rates will lead to losses or gains of habitat extent. These gains or losses may exist for different lengths of time. For example, there might be short-term losses associated with the erosion of the seaward edge of habitats during storms (for example, saltmarsh cliffing), followed by the longer term development of habitats further landwards after the repeated inundation of areas and colonisation by vegetation. Coastal squeeze losses, being driven by SLR, would be expected to persist beyond short-term variations (for example, seasonal difference between summer and winter, differences arising from periodical variations in tidal height (for example, spring/autumn equinoxes, 18.6-year lunar nodal tidal cycle).

Table 6.1: Processes involved in the transgression of coastal habitats.

Habitat	Processes governing the transgressive response of habitats	
	Seaward boundary	Landward boundary
Boulder beaches	• Increases in wave and tidal energy cause direct erosion of the lower parts of habitat • Sediment is drawn down into subtidal region of the fronting areas or moved alongshore • Seaward limit of habitat moves landwards • Increases in tidal inundation cause former intertidal areas to be replaced by subtidal areas	• Increases in wave energy move sediment landwards • Increases in wave energy cause erosion of backing hinterland which may expose new boulders beach sediment • Landward boundary of habitat moves inland

Habitat	Processes governing the transgressive response of habitats	
	Seaward boundary	**Landward boundary**
Intertidal reedbeds	• Increases in wave and tidal energy cause direct erosion of the lower parts of reed beds • Sediment is drawn down into the subtidal region of the fronting areas or moved alongshore • Increases in tidal inundation cause vegetation to die off and be replaced by saltmarsh/mudflat • Seaward limit of habitat moves landwards	• Increase in tidal inundation creates suitable conditions for vegetation to move landwards into former transitional/terrestrial areas • Landward boundary of habitat moves inland
Intertidal rock platforms	• Increases in wave and tidal energy cause erosion of soft rock platforms • Seaward limit of habitat recedes landwards • Increases in tidal inundation cause intertidal species to be replaced by subtidal species • Seaward limit of habitat moves landwards	• Increases in wave energy cause new areas of soft rock cliffs to be eroded to create rock platforms • Increase in tidal inundation creates suitable conditions for species to move landwards up existing rock platforms • Landward boundary of habitat moves inland
Intertidal seagrass beds	• Increases in wave and tidal energy cause direct erosion of the eelgrass bed • Sediment is drawn down into the subtidal region of the fronting areas or moved alongshore • Increases tidal inundation cause vegetation to die off • Seaward limit of habitat moves landwards	• Increase in tidal inundations creates suitable conditions for vegetation to move landwards into former higher intertidal areas • Landward boundary of habitat moves inland
Mud and sand flats	• Increases in wave and tidal energy cause direct erosion of the lower parts of mud/sandflat • Sediment is drawn down into subtidal region of the fronting areas or moved alongshore • Increases in tidal inundation cause former intertidal areas to be replaced by subtidal areas • Seaward limit of habitat moves landwards	• Increased tidal and wave inundation creates suitable conditions for mudflats/sandflats to move landwards into former transitional/terrestrial areas • Landward boundary of habitat moves inland
Saline lagoons located in front of structures	• Increased wave and tidal action breaches sedimentary feature forming the seaward limit of the lagoon (for example, shingle barrier, sand bank) or overtops fixed rock sill • Lagoon habitat ceases to exist • Increased wave and tidal action moves the sedimentary feature forming the seaward limit of the lagoon (for example, shingle barrier, sand bank) further landwards • Seaward limit of habitat moves landwards	• Increased tidal and wave inundation creates suitable conditions for lagoon to move landwards into former transitional/terrestrial areas • Landward boundary of habitat moves inland
Saltmarsh	• Increases in wave and tidal energy cause direct erosion of the marsh front. Marsh front moves inland • Sediment is drawn down into the subtidal region of the fronting areas or moved alongshore • Increases in tidal inundation cause vegetation to die off and be replaced by mudflat • Seaward limit of habitat moves landwards • Increases in tidal inundation cause vegetation at any one point in marsh to be replaced by vegetation that can tolerate greater inundation	• Increase in tidal inundation creates suitable conditions for vegetation to move landwards into former transitional/terrestrial areas • Landward boundary of habitat moves inland
Sand beaches	• Increases in wave energy cause direct erosion of the lower parts of beach • Sediment is drawn down into subtidal region of the fronting areas or moved alongshore • Seaward limit of habitat moves landwards	• Increases in wave energy cause over washing of beach crest and carry some sediment landwards • Beach adopts wider flatter cross section • Landward boundary of habitat moves inland
Sand dunes	• Increases in wave and tidal energy cause erosion of the dune front • Sand is drawn down into the intertidal and subtidal region of the fronting areas or moved alongshore • Dune front recedes landwards • Former areas of dunes may become replaced by sand beach or sandflat habitats	• Winds blow sand inland where it is deposited to develop new dune habitats • Landward boundary of habitat moves inland

Habitat	Processes governing the transgressive response of habitats	
	Seaward boundary	Landward boundary
Shingle beaches and barriers	• Increases in wave energy cause direct erosion of the lower parts of shingle beach • Sediment is drawn down into subtidal region of the fronting areas or moved alongshore • Sediment is moved landwards towards or over the beach crest • Seaward limit of habitat moves landwards	• Increases in wave energy cause over washing of beach crest and carry sediment landwards • Beach adopts wider flatter cross section • Landward boundary of habitat moves inland

Table 6.2: Examples of structures and management actions that could prevent the landward transgression of coastal habitats and result in coastal squeeze.

<table>
<tr><th>Habitat</th><th>Example management action</th><th>Example structure</th></tr>
<tr><td>Boulder beaches</td><td>n/a</td><td rowspan="7">Earth embankments
Seawalls/revetments
Sheet piled quay walls
Road/railway earth embankments</td></tr>
<tr><td>Shingle beaches and barriers</td><td>Reprofiling (for example, holding crest in place by bulldozing)</td></tr>
<tr><td>Intertidal seagrass beds</td><td>n/a</td></tr>
<tr><td>Intertidal reedbeds</td><td>n/a</td></tr>
<tr><td>Mud and sand flats</td><td>n/a</td></tr>
<tr><td>Saltmarsh</td><td>Mowing
Pesticide use
Grazing</td></tr>
<tr><td>Sand beaches</td><td>Sediment removal/recycling (for example, bulldozing sand off roads located on landward side of dunes)
Reprofiling</td></tr>
<tr><td>Sand dunes</td><td>Vegetation that prevents wind mobilisation of sand (for example, forestry)
Sediment removal/recycling (for example, bulldozing sand off roads located on landward side of dunes)</td><td>Very large (high) seawalls
Other new development requiring additional walls, raised earth embankments</td></tr>
</table>

Figure 6.4: Beach reprofiling at Chesil Beach, Dorset following 2014 winter storms. Sediment is moved from the lower to the upper beach, to maintain the crest elevation which prevents breaching and natural landward transgression.

Photo courtesy of James Tempest, Jacobs.

Data sources

Several data sets may be used to identify structures - see Table 6.3.

Table 6.3: Potential data sources used to identify structures listed in order of likely availability. Those at the top of the table are likely to be available for most sites, while those listed lower down in the table may only be available for some sites. Associated metadata such as date of survey should also be collected where applicable.

Data source	Coverage/ availability	Source
Aerial Images (including use of satellite and multispectral and hyperspectral imagery)	Nationwide - limited	Environment Agency/(Natural Resources Wales (NRW)/Data.gov.uk /lle.gov.wales /CCO website/USGS/ ESA
AIMS/AMX database	Regional - limited	Environment Agency/ NRW/Data.gov.uk /lle.gov.wales
Asset inspection reports	Regional - limited	Environment Agency/NRW/Local authorities /Regional monitoring programmes
Drone surveys	Site specific - limited	Environment Agency/NRW/Local authorities and stakeholders

Data source	Coverage/ availability	Source
GIS databases	Regional - limited	Environment Agency/NRW/lle.gov.wales/home/local authorities and stakeholders
Historic maps	Nationwide - total	National Library for Scotland/online resources
Information from Local Flood Manager	Site specific - limited	Environment Agency/NRW/Local authorities and stakeholders (including Natural England and port authorities)
LiDAR (England Wales)	Nationwide – virtually total	Environment Agency/ NRW/Data.gov.uk /lle.gov.wales/CCO website
Oblique photos	Nationwide/regional /site specific - limited	Data.gov.uk/Welsh Coastal Monitoring Centre/ welshcoastalmonitoringcentre.cymru/eng /regional monitoring programmes/online resources/individual photos
Ordnance Survey Map	Nationwide - total	Ordnance Survey/MAGIC map
Satellite imagery	Nationwide - total	Google/USGS /ESA
Technical reports	Regional/site specific - Limited	Environment Agency/NRW/local authorities and stakeholders
Walkover surveys	Site specific - limited	Environment Agency/NRW/local authorities and stakeholders

In those areas where data is likely to be limited, users should take advantage of nationwide and regional data sets such as satellite imagery and historic maps. It should be noted that these data sets may have higher associated errors or lower resolutions than more site-specific data.

Several data sets may be used to identify management actions as outlined in Table 6.4.

Table 6.4: Potential data sources used to identify management actions listed in order of availability. Those at the top of the table are likely to be available for most sites, while those listed lower down in the table may only be available for some sites.

Data source	Coverage/availability	Source
Academic literature	Regional/site specific - limited	Libraries/Internet resources
Anecdotal evidence	Site specific - limited	Environment Agency/NRW/local authorities and stakeholders
Asset inspection reports	Site specific - limited	Environment Agency/local authorities and stakeholders
CHaMPs, SEA, HRA	Local offices/teams/site specific	Environment Agency/NRW/ Data.gov.uk
Coastal strategies	Regional	Environment Agency/NRW/local authorities and stakeholders
FCERM strategy plans	Nationwide and site specific - limited	Environment Agency/NRW/ Data.gov.uk /local coastal groups
SMP	Nationwide - total	Environment Agency/NRW/national coastal groups

If there is not enough data to indicate whether structures or management actions could have affected the landward transgression of the habitat, then additional survey data and analysis may be required. A starting point for this would be a site walkover visit.

Uncertainty

Sources of uncertainty include:

- the type of structure and its influence on the type of the habitat (that is, whether it could have prevented the habitat from migrating landward, such as failed sluices in former embankments)
- the age of the structure
- lack of detail about historical management actions and their influence

Test 2: Has there been suitable accommodation space landward of the structure over the period of interest?

Explanation

The purpose of this test is to determine whether there has been suitable accommodation space landward of the structure that the habitats could have migrated into if they were not constrained by a structure or management action. If no such space exists (for example, due to the presence of naturally occurring high land[9]), then the landward migration of the habitat would have resulted in their loss anyway, and the resulting loss would not represent coastal squeeze.

Accommodation space is defined as the area landward of the current landward limit of the habitat which is within the elevation range for the habitat under investigation. Table 6.5 explains the physical process controls on the landward limits of different coastal habitats. Under present day conditions these processes may be limited by structures, for example, tidal inundation may be limited by flood embankments, so the landward limit of saltmarshes may lie against the embankments. These processes also determine the possible landward extent of the accommodation space behind any structures. For example, the possible accommodation space for a saltmarsh currently backed by an earth embankment on the landward side may extend over the estuary flood plain to areas of higher natural elevation (for example, valley sides) further inland. If there is high land behind a defence, there may be a limit to how much squeeze can occur against the defence, because even with no defences, habitat would be lost against the rising land levels.

If it is possible to determine whether the land behind the defences has been modified through human actions (such as modifying the elevation), then these areas should also be considered as having removed accommodation space.

The landward limits on accommodation space should be derived at a site level to account for local variations in habitat extents due to factors such as wave run-up and surge. For intertidal flats and saltmarsh habitat, the accommodation space would typically be defined as all land from the highest astronomical tide (HAT) to the lowest

[9] Note that in some instances the natural land surface might have been raised artificially for development purposes. In these instances, the assessment of accommodation space should be based on accommodation space before the development.

astronomical tide (LAT) that could be hydraulically connected to the present habitat assuming the absence of the structure.

Table 6.5: Main coastal process controls on the landward extent of different coastal habitats.

Habitat	Landward limit of habitat controlled by
Boulder beaches	Landward limit of tidal inundation and wave runup
Intertidal reedbeds	Landward limit of brackish water (combination of freshwater and tidal inundation)
Intertidal seagrass beds	Landward limit of tidal inundation
Mud and sand flats	Landward limit of tidal inundation
Saline lagoons located in front of structures	Landward limit of tidal inundation and wave runup
Saltmarsh	Landward limit of tidal inundation
Sand beaches	Landward limit of tidal inundation and wave runup
Sand dunes	Landward limit of aeolian action
Shingle beaches and barriers	Landward limit of wave overwash

Data sources

Table 6.6 lists the data sets that may be used to identify suitable accommodation space.

Table 6.6: Potential data sources used to identify accommodation space listed in order of availability. Those at the top of the table are likely to be available for most sites, while those listed lower down in the table may only be available for some sites. Associated metadata such as date of survey should also be collected where applicable.

Data source	Coverage/availability	Source
Aerial images	Nationwide - limited	Environment Agency/NRW/ Data.gov.uk/lle.gov.wales/CCO website
GIS databases	Regional - limited	Landscape layer MAGIC map/CEH/ lle.gov.wales
Historic maps	Nationwide - total	National Library for Scotland/online resources
Information from local Flood Manager	Site specific - limited	Environment Agency/NRW/local authorities and stakeholders (including Natural England and port authorities)
LiDAR (England Wales) – Digital Terrain Model (DTM)	Nationwide – virtually total	Environment Agency/NRW/ Data.gov.uk/lle.gov.wales/CCO website
Ordnance Survey Map	Nationwide - total	Ordnance Survey/MAGIC map
Technical reports	Regional/site specific - limited	Environment Agency/NRW/local authorities and stakeholders
Tidal ranges	Nationwide – discrete locations	Admiralty tide tables/local tide tables
Walkover surveys	Site specific - limited	Environment Agency/NRW/local authorities and stakeholders

In those areas where data is likely to be limited, users should take advantage of nationwide and regional data sets such as satellite imagery and historic maps. It should be noted that these data sets may have higher associated errors or lower resolutions than more site-specific data.

If there is still not enough data to document the existence or otherwise of accommodation space, then additional survey data will need to be acquired. A starting point for this would be a site walkover visit.

Uncertainty

Sources of uncertainty include:

- accuracy of information on past tidal levels which could be used to define accommodation space
- accuracy of the LiDAR elevation data (DTM) especially where the accommodation space is covered with vegetation
- the extent to which a feature located in the coastal flood plain (for example, roads, railways, former defence lines) could have prevented development of habitat landwards and, therefore, caused coastal squeeze – many such structures have sluices or culverts in place, for example

Test 3: Have there been readily observable losses of habitat or marked decreases in quality in front of structures (either low water mark (LMW) retreat or internal erosion) over the period of interest?

Explanation

The purpose of this test is to perform a high-level assessment to determine whether there is any clear evidence of habitat loss or marked decreases in quality in front of defences over the period of interest. If there have been no such changes, then there cannot have been any coastal squeeze. The aim of this test is to rule out areas that have been clearly stable or have prograded. If the results of this high-level test are ambiguous, then it will be necessary to carry out more detailed assessment (see section 6.2.4). Observable losses could include the landward migration of low water mark (LWM) or the internal dissection (fragmentation and creek widening) and reduction in aerial extent of perennial saltmarsh vegetation.

Data sources

Several data sets may be used to identify habitat extent as outlined in Table 6.7.

Table 6.7: Potential data sources used to identify the extent of habitats listed in order of availability. Those at the top of the table are likely to be available for most sites, while those listed lower down in the table may only be available for some sites. Associated metadata such as date of survey should also be collected where applicable.

Data source	Coverage/availability	Source
Academic papers	Regional/site specific - limited	Libraries/Internet resources
Aerial Images (including use of satellite and multispectral and hyperspectral imagery)	Nationwide - limited	Environment Agency/NRW/Data.gov.uk/ lle.gov.wales/CCO website/USGS/ESA
Anecdotal evidence	Site specific - limited	Environment Agency/NRW/local authorities and stakeholders

Data source	Coverage/availability	Source
Bathymetric data	Nationwide - total	Environment Agency/Data.gov.uk/INSPIRE Admiralty/local port authority/CCO website
GIS database – habitat mapping	Nationwide – virtually total	Environment Agency – saltmarsh extent layer
LiDAR (England Wales)	Nationwide – virtually total	Environment Agency/NRW/Data.gov.uk/ lle.gov.wales/CCO website
Ordnance Survey Maps	Nationwide - total	Ordnance Survey / MAGIC map
Saltmarsh zonation and extent	England/Wales	NRW/lle.gov.wales/Data.gov.uk/Environment Agency BIOSYS
Satellite imagery	Nationwide - total	Google/USGS/ESA
Shoreline migration	Scotland only	Scottish Natural Heritage
Technical reports	Regional/site specific - limited	Environment Agency/NRW/local authorities and stakeholders
Walkover surveys	Site specific - limited	Environment Agency/NRW/local authorities and stakeholders

In those areas where data is likely to be limited, users should take advantage of nationwide and regional data sets such as satellite imagery and historic maps. It should be noted that these data sets may have higher associated errors or lower resolutions than more site-specific data.

Uncertainty

Sources of uncertainty include:

- the accuracy of the data sets (for example, vertical and positional accuracy of geospatial data)
- difficulty in determining seaward boundary of habitat due to resolution or data coverage issues
- difficulty in distinguishing short-term variations in habitat extent from long-term changes
- period of time over which the data has been collected and how representative it is of long-term trends

Test 4: Has relative sea level (SL) risen in the region over the period of interest?

Explanation

The purpose of this test is to determine whether there has been a rise in relative SL to drive the landward transgression of habitats over the period of interest. If there has been a rise in SL, then coastal squeeze could potentially have occurred. If there has been no rise, no coastal squeeze can have occurred.

In England and Wales, most areas have experienced sea level rise (SLR) over the past 500 years. Exceptions to this are some areas of Northern England and Scotland where vertical land uplift has exceeded increases in eustatic sea level (worldwide changes in ocean volume), leading to a fall in relative SL over parts of the Holocene (current geological epoch). Uplift rates have been declining over time, while rates of eustatic sea level rise have been increasing (Rennie and Hansom, 2010). This has led to some uncertainty over the short-term past (since 1992) and future rates of relative SL in Northern England and Scotland.

This uncertainty arises due to variations in the type and length of the data set used in the calculation. For example, Rennie and Hansom (2010) used recent land-level changes with tidal gauge records over the past 15 years to conclude that uplift has reduced SLR in some parts of areas of Northern England and Scotland. However, Woodworth et al., (1999) and Shennan et al., (2009) used a longer tidal gauge record which was acknowledged by Rennie and Hansom (2010) to be more reliable and crucially (in the case of Shennan et al., 2009) included rates of sediment compaction to provide a potentially more accurate estimate of relative SLR across the UK (Figure 6.5, Table 6.8). Using this data and method, Shennan et al. (2009) concluded that relative SL was falling in Northern England and Scotland.

Recently UK Climate Projections 2018 (UKCP18) (Palmer et al., 2018) updated their predictions of SLR over the coming century, which indicated that even under the lowest emission scenario rates SLR were expected to be greater than land uplift across all of the UK. However, it was acknowledged in the report that these estimates did not incorporate sediment compaction as used in the estimate by Shennan et al., (2009). Therefore, in Northern England and Scotland prior to the 1990s, it is likely that the rate of land uplift was greater than relative SLR. At present, it may be the case that land uplift rates are still greater or are approaching the same rate as SLR. In future, it is likely that rates of sea level will accelerate and outpace land uplift.

Table 6.8: Trends in mean SL recorded from tidal gauges since 1901 until 1990, along with rates of land subsidence with the same regions taken from the geological record (Data taken from Woodworth et al., 1999). Note that these rates are likely to increase in future.

Location	Trends in mean SL (mm/yr)	Region	Rates of emergence /submergence (mm/yr)
Aberdeen	0.69 ± 0.11	NE Scotland	0.47 ± 0.06
Liverpool	1.39 ± 0.19	Mersey	-0.18 ± 0.04
Newlyn	1.68 ± 0.12	South-west	-1.41 ± 0.10
North Shields	1.87 ± 0.14	Tyne	-0.08 ± 0.17
Sheerness	2.14 ± 0.15	Sheerness	-1.11 ± 0.38

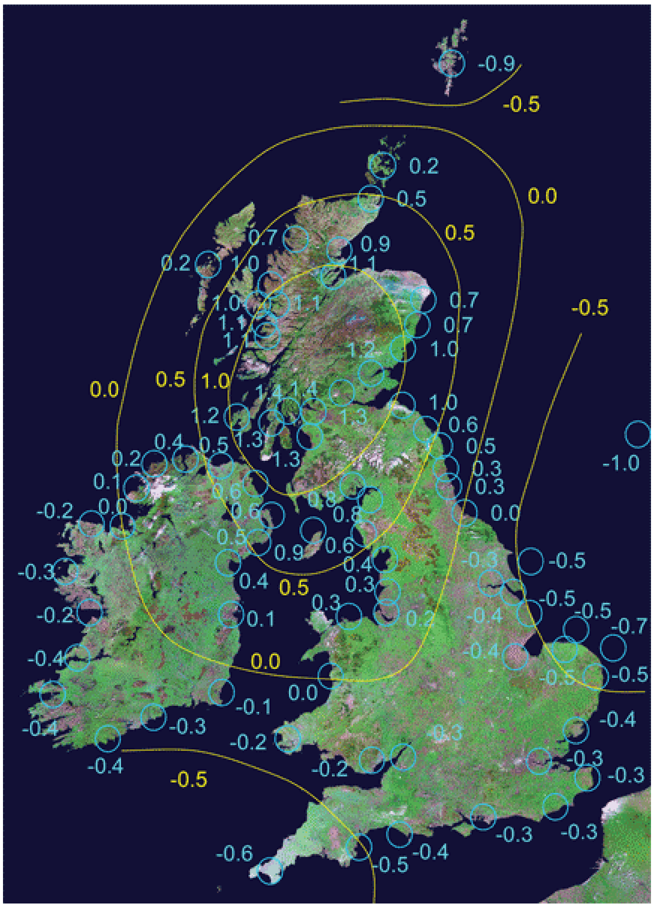


Figure 6.5: Rates of relative land and sea level change in the British Isles in mm/yr, showing relative land uplift as positive and relative subsidence as negative. Note blue values are at point locations, yellow values are contours Source: Shennan et al., 2009 (Permission to reuse granted by Shennan Nov 2020).

Data sources

Several data sets may be used to identify statistically valid rates of SL change as outlined in Table 6.9.

Table 6.9: Potential data sources used to identify past sea level records listed in order of availability.

Data source	Coverage/subject
Bradley et al., 2009	Nationwide vertical land movement
Shennan et al., 2009	Current UK SLR
Tide gauge records (Environment Agency, Local port authorities, PSMSL)	Nationwide – discrete locations
Wahl et al., 2013	UK historic SLR
Woodworth 2018	UK historic SLR
Woodworth et al., 1999	UK historic SLR

In those areas where there are no tidal gauges, the nearest tidal gauge should be used to consider regional land uplift in Northern England and Scotland. If a large degree of uncertainty still exists, then the precautionary principle should be adopted, and it should be assumed that sea level has risen over the period of interest. In general, mean sea level has risen by around 12 to 16cm across the UK since 1900 (Baker-Austin et al., 2020).

Uncertainty

Sources of uncertainty include:

- poor coverage and data quality with estimations of SLR
- absence of tide gauge close to the area of interest
- poor quality of tide gauge record

6.2.3 Baseline ecological and geomorphological assessment

Explanation

If the initial screening indicates that there have been losses of habitats that may have been a result of coastal squeeze, it is likely that further, more detailed, ecological and geomorphological understanding will be needed to determine whether these losses were actually due to coastal squeeze or whether they could have resulted from other causes.

In some cases, this understanding may already exist, in other instances additional studies may be needed. It is good practice to write a baseline document which provides a conceptual model of the area being considered and explains the main changes that have occurred in the past, the relevant influences and the likely future behaviour. Collaboration with/between developers, the Environment Agency (as developer or competent authority), Natural Resources Wales, Natural England, wildlife groups and others will likely be needed to source appropriate data and understanding.

In terms of geomorphology, a baseline assessment would typically cover the following sections:

- geology
- geomorphological characteristics
- geomorphological changes (including cycles and trends)
- anthropogenic influences
- hydrodynamics (including fluvial/tidal inputs)
- waves
- storms (including atmospheric surges)
- sedimentary processes (sediment type, transport and budget)
- SLR and climate change
- future evolution
- conclusions (main characteristics, data gaps, recommendations for further studies)

Typically, an ecology baseline assessment might include:

- an (extended) phase 1 habitat survey and review of similar historic information on habitat types and extent, perhaps using aerial photography and satellite imagery. Ground truthing may highlight ecological/environmental influences for change such as grazing, invasive species, water quality, waterlogging and sediment conditions. National Vegetation Classification (NVC) surveys provide details of vegetation communities (species presence and abundance)

- macro-invertebrate and sediment analysis for intertidal habitats
- wetland bird communities (Wetland Bird Survey, WeBS)

In the context of assessing coastal squeeze, it is particularly important for the baseline assessments to consider the sediment supply relative to SLR. With very high rates of sediment supply, habitats may prograde laterally and increase their elevations within the tidal frame (even under SLR). For moderate rates of sediment supply, habitats may maintain their lateral extent and accrete vertically to keep pace with SLR. For low rates of supply, habitats may fail to keep pace with SLR and may become inundated more often. It should be noted that sediment supply is likely to vary within and between estuaries. For example, estuaries such as the Severn, Thames and Humber have very high levels of suspended sediment within their waters, while other estuaries, such as those in the Solent, have much lower values. Within estuaries, sediment supply may also vary spatially due to the proximity to sediment sources. Finally, it should be noted that sediment supply rates can change over time in response to changes in the availability of sediment sources (for example, extent of eroding source areas, rates of erosion driven by SLR and degree of storminess).

For coastal squeeze assessments, it can be particularly useful to collate some basic parameters for the area being considered, including:

- total length of shoreline (km)
- total length of defended shoreline (km)
- tidal floodplain extent
- intertidal area and subtidal area

Determining the likely causes of habitat change in a coastal or estuarine setting requires a broad understanding of how the coastal or estuarine system functions as a whole. An important element of these assessments is that they need to consider appropriate temporal and spatial scales, which may exceed the initial scale of investigation. For example, the loss of habitat in front of a structure built in 1980 may, in a temporal sense, need to consider changes that occurred before the structure was built. In a spatial sense, studies may also need to consider changes in the updrift and subtidal areas (for coasts) or upstream/downstream and subtidal areas (for estuaries). Within a study area, it may also be useful to look at the response of habitats that have not been affected by defences to understand how they respond to SLR.

A wide range of tools and techniques is available to inform coastal managers about historical coastal changes and to predict future change. However, at present, there is no single method or model that can answer all the questions, so a degree of expertise will always be required when assessing and predicting large-scale, long-term coastal change (Defra/Environment Agency, 2009a). The successful analysis and projection of change requires the appropriate selection and use of these tools for the nature of the coastline under investigation, the critical interpretation of the outputs, and the synthesis of the resulting information into a conceptual understanding of coastal geomorphological behaviour. This approach is often called ‘expert geomorphological assessment’ (EGA). This approach would typically integrate information from various sources, including historical trends analysis, the results of both short-term and long-term modelling, application of empirical tools, and conceptual understanding based on field and laboratory studies carried out elsewhere. It takes account of the geological and geomorphological framework, the nature of present, past and possible future environmental conditions and processes (wind, waves, tides, currents, SL, sediment supply (Defra/Environment Agency, 2009a).

Further details on the process of expert geomorphological assessment, plus the wide range of individual techniques, have been described in several previous reports and websites (for example, EMPHASYS Consortium, 2000; HR Wallingford et al., 2006; Defra/Environment Agency, 2009a; Defra/Environment Agency, 2009b, Estuary Guide (http://www.estuary-guide.net). Some important sources of data are listed in Table 6.10.

Data sources

Table 6.10: Useful resources to inform geomorphological baseline studies.

Data sets/source	Coverage	Notes
Academic papers	Regional/ site specific	Academic papers can also provide useful background geomorphology of the area of interest.
Coastal directories: http://jncc.defra.gov.uk/page-2,157 Estuaries directory: http://jncc.defra.gov.uk/page-2,160 Saltmarshes directory: http://jncc.defra.gov.uk/page-2,159	Nationwide	Baseline information for coastal and estuarine habitats.
Coastal Habitat Management Plan (CHaMPs)	Regional/ local	Evaluation of future gains and losses of habitat.
Estuary Guide website (http://www.estuary-guide.net)	Nationwide	Explanation of concept of 'synthesis' to derive a sound geomorphological understanding in estuaries. Explanation of various techniques for estuary environments.
Futurecoast - http://coastalmonitoring.org/ccoresources/futurecoast/	Nationwide	Explanation of coastal processes, past and future morphological development for most areas of the England and Wales, including open coasts and estuaries. Explanation of habitat responses to SLR.
Geological Conservation Review (GCR) site reports http://jncc.defra.gov.uk/page-2,947	Nationwide	Outlines geomorphological processes operating on GCR sites.
iCoasst - Nicholls et al., 2012 http://www.channelcoast.org/iCOASST/introduction/	Regional/ site specific	Explanation of techniques for assessing morphological change.
JNCC (1995) Coastal Directory http://jncc.defra.gov.uk/page-2,157	Nationwide	Collates extensive baseline environmental and human use information, including fisheries, for the coastal and nearshore marine zone of the whole of the UK.
JNCC coastal geomorphology of Great Britain http://jncc.defra.gov.uk/page-3,012	Nationwide	Outlines main coastal processes operating throughout the UK. Also contains examples of sites.
JNCC Monitoring guidance (2004) http://jncc.defra.gov.uk/page-2,204	Nationwide	Details main features of certain coastal geomorphology and evidence of processes.
Living with the Sea	Regional/ local	Evaluation of future gains and losses of habitat.

Data sets/source	Coverage	Notes
LOIS Project	Regional/ site specific	Land Ocean Interaction Study contains some useful data sets recorded around the UK, for example, suspended sediment data.
Saltmarsh management manual www.defra.gov.uk/environ/fcd/research	Nationwide	Outlines geomorphological processes operating within saltmarshes.
SCOPAC Sediment Transport Study http://www.scopac.org.uk/scopac%20sediment%20db/index.htm	Regional/ site specific	Baseline information for coastal processes for the area between Lyme Regis and Shore-by-the Sea.
Shoreline Management Plans (SMPs) and Flood and Coastal Erosion Risk Management (FCERM) strategies	Nationwide	Present day and future management policy, baseline coastal processes, estimation of future coastal behaviour, evaluation of future gains and losses of habitat.
Southern North Sea Sediment Transport Study: http://www.sns2.org/	Regional/ site specific	Baseline information for coastal processes in the southern North Sea area.

Uncertainty

- Changes in dominant processes over time.
- Limited information on past changes or driving processes.
- Conflicting expert opinion on dominant processes and responses.

6.2.4 Quantifying past habitat losses

Explanation

The purpose of this stage is to carry out a more detailed assessment of past changes (over and above the initial assessment carried out in section 6.2.2 - Test 3) in order to quantify the changes in area of habitat over the time period of interest.

As noted in Chapter 3 (Factors that influence coastal change), the processes by which the seaward and landward limit of a habitat migrate landwards differ. For example, there might be short-term losses associated with the erosion of the seaward edge of habitats during storms (for example, saltmarsh cliffing), followed by the longer term development of habitats further landwards after the repeated inundation of areas and colonisation by vegetation. The various timescales of coastal change are illustrated in Figure 6.6. Coastal squeeze losses, being driven by SLR, would be expected to persist beyond short-term variations (for example, seasonal difference between summer and winter, differences arising from periodical variations in tidal height (for example, spring/autumn equinoxes, 18.6-year lunar nodal tidal cycle).

The analysis will, therefore, be made easier where the data sets extend over many decades and contain numerous surveys carried out every few years. For saltmarshes, a previous report prepared by the Environment Agency Geomatics department (Environment Agency, 2013) explains a number of methodological issues that can arise when digitising habitat extents.

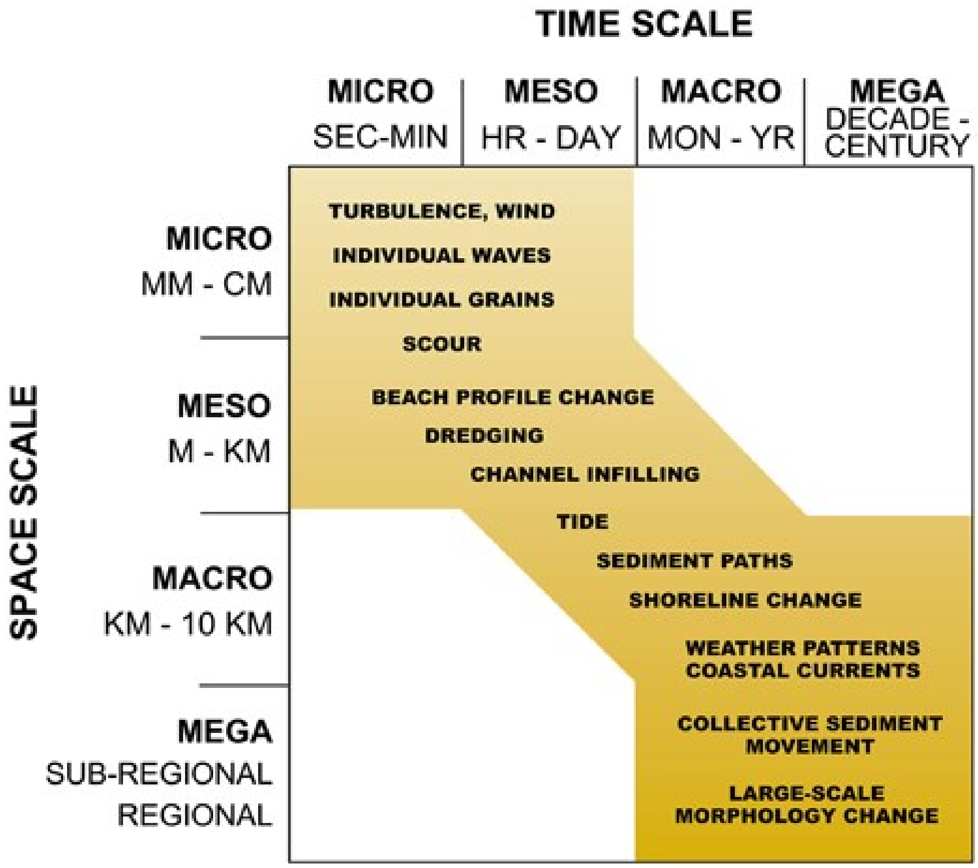


Figure 6.6: Space and time in geomorphology by Gallop (2015) and Larson and Kraus (1995).

For tidal flat and saltmarsh habitats, the assessment of past losses would typically follow these steps:

1. Define upper and lower limits of tidal flats. The lower extent of the habitat is defined by the LWM. The LWM that is chosen will depend on the availability of data. Ideally, lowest astronomical tidal (LAT) tidal level would be used. However, in many estuaries data might only be available down to mean tide level (MTL). The upper limits of the tidal flat could be either toe of defence/structure or seaward extent of saltmarsh (typically, mean high water neap (MHWN) level).

2. Define the current extent of saltmarsh by identifying its upper and lower limits. The lower extent is defined by the seaward edge of saltmarsh which is expected to be around MHWN and could take the form of an abrupt cliff or gradual gradation into mudflat. The upper limit could be either toe of defence/structure or the seaward extent of adjoining terrestrial habitat. Saltmarshes commonly extend to the level of highest astronomical tide (HAT) and this commonly lies against the flood embankments.

3. Digitise the upper and lower limits of mudflat and saltmarsh from suitable data sources, including LiDAR, aerial imagery and bathymetry charts over the period of interest. Care should be taken to note the position of any structures such as sea defences, and changes in their configuration over time. The process should be repeated for different dates.

4. Digitise any additional features needed to defend the areal extent of the saltmarsh habitats, for example, extent of bare mud or creek channels if these have shown significant changes over time, to assess internal dissection.

5. If topographic data is available, it may be appropriate to use it to construct cross-shore transects to help characterise the shoreline response. For example, this could show the reduction of elevations in some habitats.

6. Tabulate the results of the analysis in terms of areas of mudflat and marsh over time, and chainage to habitat boundaries.

Data sources

Suitable data sets are outlined in Table 6.11.

Table 6.11: Data sources that may be used to determine habitat specific losses.

Data source	Source
Bathymetric data	Environment Agency/Data.gov.uk/INSPIRE Admiralty/local port authority
GIS database – habitat mapping	Environment Agency – Saltmarsh Extent layer/NRW/ lle.gov.wales
Historic maps	National Library for Scotland/online resources
LiDAR (England Wales)	Environment Agency/NRW/Data.gov.uk/lle.gov.wales/CCO website
Ordnance Survey Maps	Ordnance Survey/MAGIC map
Saltmarsh zonation and extent	NRW/lle.gov.wales/Data.gov.uk/Environment Agency BIOSYS
Shoreline migration (Scotland only)	Scottish Natural Heritage

Uncertainty

Sources of uncertainty include:

- varying spatial resolution of data sets over time and incomplete coverage
- obscured images, from tides or cloud cover, and general photographic quality
- accuracy of data sets, including vertical error of LiDAR data
- difficulties in determining boundary between mudflat and saltmarsh habitat due to resolution of data, presence of algal matts on the mudflats, seasonal colonisation of mudflats with saltmarsh vegetation, fragmented boundaries composed of ‘islands’ of vegetation
- difficulties in determining lower extent of mudflat due to airborne surveys (for example, LiDAR, aerial photographs) not being carried out close enough to MLWS

6.2.5 Quantifying past changes in habitat quality

Explanation

When considering coastal squeeze losses, it is necessary to consider changes in habitat quality as well as aerial changes. It is recognised that changes in habitat quality may have different causes (for example, development of reeds at the expense of saltmarsh, deterioration in vegetation due to pollution). With respect to coastal squeeze, the assessment is only concerned with changes in quality due to the prevention of landward transgression.

For example, in the case of saltmarshes, this may result in high marsh communities being progressively replaced with lower marsh communities (Natural England, pers. comm., 2019). This type of change is believed to have been observed in the Deben Estuary (Natural England, 2013). These changes are more likely to occur when rates of SLR exceed the vertical accretion rates of marshes. Where the zonation and variation in saltmarsh are reasons for site designation, such changes in vegetation are likely to constitute a deterioration in habitat quality. Such changes may potentially occur ahead of, or at the same time as, decreases in the area of vegetation (Natural England, pers. comm., 2019). In some areas, these changes could see more diverse marsh being replaced with monocultures of Spartina.

As with changes in the aerial extent of vegetation, areas shown to have experienced a reversion of marsh communities to lower marsh communities will need expert geomorphological and ecological judgement to confirm that these changes have arisen due to coastal squeeze (that is, as the result of landward transgression due to SLR being prevented), rather than other causes.

Assessing changes in quality, therefore, requires information about the species composition and zonation of vegetation.

A starting point for changes in saltmarsh quality area is the SSSI condition status reports which are available from https://designatedsites.naturalengland.org.uk/ . Assessments are based on the Common Standards Monitoring guidance for saltmarsh (http://jncc.defra.gov.uk/page-2204). The available survey data on which assessments of condition are based can vary between locations (both locally and national). Summaries of information used are provided but, where available, more detailed information would need to be requested from Natural England. Natural England carries out a rolling programme of site checks and assessments to update the SSSI condition reports. These surveys can include National Vegetation Classification (NVC) surveys, which identify the following vegetation zonations:

- mudflat
- pioneer
- low-mid
- mid-upper
- upper
- transitional
- terrestrial

The reports also contain information on the potential reasons for unfavourable condition (for example, grazing, litter). In many cases, further data might be needed to identify the main ways of restoring favourable condition. These reports may be available from Natural England to help determine whether there have been any changes in habitat quality due to coastal squeeze.

Natural Resources Wales also holds data on the condition of designated habitats, such as the Indicative Feature Condition Assessment reports for Marine Special Areas of Conservation (https://naturalresources.wales/guidance-and-advice/environmental-topics/wildlife-and-biodiversity/protected-areas-of-land-and-seas/indicative-feature-condition-assessments-for-european-marine-sites-ems/?lang=en). In addition, Natural Resources Wales has more detailed site surveys, including NVC surveys and Phase 1 Intertidal Surveys, which can be provided on request.

At a national level, the Environment Agency has recently started collecting data on saltmarsh vegetation zonation (Environment Agency 2020). The data, which was collected for Water Framework Directive (WFD) compliance, covers a number of vegetation zones:

- reedbeds
- upper marsh
- mid-lower
- pioneer
- *Spartina*

These zones reflect ecological communities within saltmarsh habitats required for Water Framework Directive assessment purposes. The data set covers a selection of surveillance and operational water bodies across England and Wales. The data set does not include all areas of saltmarsh habitat in England and Wales, but does cover those areas where the Environment Agency and National Resources Wales have carried out sufficient aerial and ground-based surveys, often complemented by other information from Natural Resources Wales, Natural England or the Regional Coastal Monitoring Programme.

The Environment Agency saltmarsh layer data set has been developed from aerial imagery (with some ground survey) data collected from the period 2006 to 2012 (Phelan et al., 2011). At the time of writing (2019), the saltmarsh layer, which covers most areas of saltmarsh in England (Environment Agency, 2019a) and Wales (Natural Resources Wales, 2017), exists for at least 2 time periods, although these time periods vary between estuaries. For example, for the Severn Estuary, data exists for 2008 to 2009 and 2014, while for the Humber Estuary there is data for 2007 to 2010 and 2011.

The Environment Agency recommends that the Saltmarsh Zonation layer should be interpreted together with a separate data set on Saltmarsh Extent (Environment Agency, 2019a).

The saltmarsh extent data sets consist of a polygon data layer showing the extent of saltmarsh in coastal and transitional waters for use in both flood and coastal erosion risk management and implementing the Water Framework Directive (WFD). At the seaward end of the transect, the final demarcation is where the saltmarsh vegetation cover has become so sparse that it only covers 5% whether it is upper, mid, lower or pioneer saltmarsh.

A similar data set is available for Wales from National Resources Wales using aerial imagery collected between 2007 and 2019. The saltmarsh extent layer is available on the ‘Lle Geoportal’ (National Resources Wales, 2019).

A zonation layer is also available on request from National Resources Wales, with a ground truthing layer being developed.

Determining The changes of past habitat quality at a broad scale may also be broadly determined using multi and hyperspectral aerial imagery (including satellite imagery such as CASI).

6.2.6 Evaluating causes of loss and the role of coastal squeeze

Explanation

The purpose of this section is to determine if all/some of the habitat losses or changes in quality should be attributed to coastal squeeze or to other potential causes.

There are 2 steps:

A. Identify a shortlist of sites within the study area where coastal squeeze might have occurred.

B. Apply further expert judgement to identify those sites where coastal squeeze is believed to have occurred.

A. Identify a shortlist of sites at risk within the study area

The purpose of this step is to develop a shortlist of potential sites within the study area (see section 6.2.1) where coastal squeeze may potentially have occurred.

These sites will have the following characteristics:

(i) They will have experienced habitat losses/decreases in quality in front of the structures over the period of interest.

(ii) They will have experienced a rise in sea level which would be expected to have driven the landward migration of habitats in the absence of (iii).

(iii) They will be backed by structures and/or will have experienced management actions that could have limited the landward migration of habitats.

(iv) They will be backed by an area landward of the present-day structure that could have allowed the habitats to migrate landwards in the absence of (iii), in other words, the area provides a suitable accommodation space.

In the case of saltmarshes and mudflats, changes in cross-shore profile form can be used to investigate the occurrence of coastal squeeze. Profiles can be generated from a range of data, including LiDAR and bathymetric surveys/charts (see Table 6.7).

LiDAR data should be available for the majority of coastal settings. Where this is not available, historic maps may be used to examine the widths and gradients of the intertidal zone over time (see Taylor et al., 2004).

Examining cross-shore profiles allows:

- some forms of profile responses that do not represent coastal squeeze to be screened out
- some forms of profile responses that could represent coastal squeeze (but could also be due to other processes) to be screened in

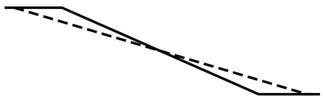
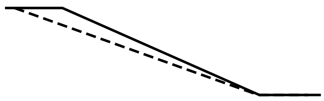
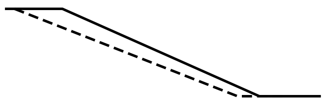
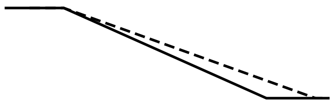
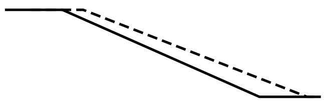
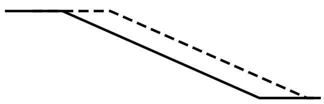
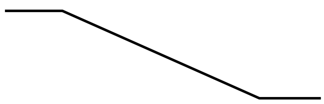
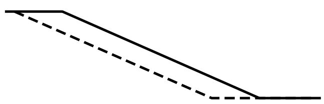
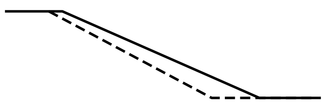
This approach was adopted to describe profile steepening or flattening on open coast beaches in the Futurecoast study based on historic map information (Defra 2002; Taylor et al., 2004). The approach was also applied to estuarine shores in north-west England (Pontee, 2011). More recently, the approach has been refined further and applied in the Humber Estuary to assess coastal squeeze of saltmarsh and mudflat habitats (Jacobs, 2019c).

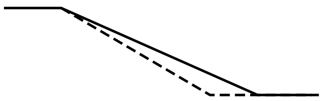
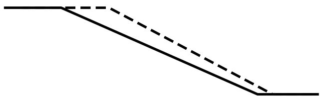
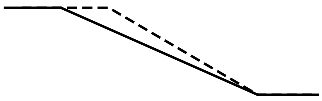
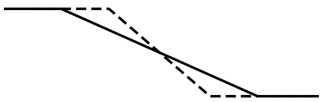
The approach considered 13 possible intertidal profile behaviour categories and assigned a numerical score ranging from +6, which represents the most extreme case of intertidal flattening to -6, which represents the most extreme case of coastal steepening, with the value 0 assigned to the case with no movement of either the HAT or LAT, consequently with no profile rotation (Table 6.12).

Behaviour codes -2, -3 and -6 can potentially indicate coastal squeeze (see Table 6.12 for rationale). However, such profile responses can also be caused by factors other than coastal squeeze.

In the Humber, profile modes were used to create a shortlist of sites that could be investigated further to ascertain whether the changes were, in fact, due to coastal squeeze.

Table 6.12: Possible modes of shoreline profile response based on position of HAT and LAT. Solid lines indicate starting profile, dotted lines indicate end profile. Source: Jacobs, 2019b,c.

Code	HAT	LAT	Slope	Visual description	Consistent with coastal squeeze?
+6	Retreat	Advance	Flattening		No because: • HAT has migrated landwards (has not been constrained) • LAT has moved seawards (has not retreated)
+5	Retreat	No movement	Flattening		No because: • HAT has migrated landwards
+4	Retreat	Retreat	Flattening		No because: • HAT has migrated landwards
+3	No movement	Advance	Flattening		No because: • LAT has migrated seawards
+2	Advance	Advance	Flattening		No because: • HAT has migrated seawards • LAT has migrated seawards
+1	Advance	Advance	No rotation		No because: • HAT has migrated seawards • LAT has migrated seawards
0	No movement	No movement	No rotation		No because: • no movement of either HAT or LAT
-1	Retreat	Retreat	No rotation		No because: • HAT has migrated landwards
-2	Retreat	Retreat	Steepening		Yes because: • landward retreat of HAT could be

Code	HAT	LAT	Slope	Visual description	Consistent with coastal squeeze?
					being slowed by defence • landward movement of LAT might be due to SLR
-3	No movement	Retreat	Steepening		Yes because: • HAT could be being held by defence • Landward movement of LAT might be due to SLR
-4	Advance	Advance	Steepening		No because: • LAT has moved seawards
-5	Advance	No movement	Steepening		No because: • HAT has moved seawards • LAT has remained in place
-6	Advance	Retreat	Steepening		Yes because: • HAT could be being held by defence • landward movement of LAT might be due to SLR

B. Expert judgment to identify losses due to coastal squeeze

Once a shortlist of potential sites within the study area (see section 6.2.1) where coastal squeeze could have occurred has been identified, it is necessary to use expert judgement to determine whether the responses actually constitute coastal squeeze.

The central question is: "Have the observed losses of coastal habitats been due to the prevention of the landward transgression?"

The expert judgment should consider all of the collated data, including:

- the baseline geomorphological understanding
- any additional ecological understanding that is available
- the measured historical habitat losses
- the likelihood of habitat loss being due to other (non-coastal squeeze) causes
- whether temporal and spatial patterns of habitat loss are consistent with coastal squeeze

As set out in Chapter 3 (Factors that influence coastal change), there are many causes of changes in the extent of coastal habitat. Table 6.13 to Table 6.15 list those causes of habitat loss that do not represent coastal squeeze. These other factors could act together with each other and coastal squeeze or they could act alone.

Specifically, coastal squeeze, as defined in this project (Chapter 5), excludes:

i. the historic drainage and land claim of habitat landwards of currently existing structures

ii. other impacts of hard defences such as reductions in sediment supply caused by protecting eroding sediment sources or interrupting longshore transport pathways

iii. impacts of other human activity/structures on habitats, such as the alteration of estuary channel morphology due to dredging, training walls or piers, or impacts on habitat quality due to management practices or pollution

iv. other natural or man-made causes of habitat loss unrelated to creating barriers to landward transgression, for example, the lateral movement of channels which may be unrelated to SLR and, while they would erode seaward edges of habitats, would not create landward transgression even under unconstrained conditions

v. habitat loss against naturally rising land (sloping coastal hinterlands). These losses may need to be considered as a baseline scenario (‘without defences’) against which to judge coastal squeeze losses. It should be noted that some areas of rising land formed from unconsolidated sediments may erode in the future

The above impacts should be assessed, described and accounted for separately, even though the remedial measures may be linked or packaged with those taken to address coastal squeeze.

One UK estuary where the deterioration of saltmarsh is often said to be due to coastal squeeze is the Blackwater Estuary. In this estuary, some areas of marsh vegetation have been replaced by bare mud. This could potentially be due to the combination of SLR and the presence of defences – this is investigated further in Appendix A.

It can be difficult to work out the various causes of change in coastal habitats because:

- the geomorphological expression of coastal squeeze losses (for example, as shown by cross-shore changes in profiles) may be similar to those caused by other factors
- the spatial patterns of coastal squeeze are likely to vary in response to differences in estuarine or coastal settings. So, for example, it is not possible to say that coastal squeeze is generally more likely to occur in a specific part of an estuary
- there may also be other ecological, in addition to geomorphological, processes, responsible for changing extents of habitats

Figure 6.7: Saltmarsh near Abbotts Hall in the Blackwater Estuary which is undergoing deterioration (Natural England, pers. comm.). Visual indicators such as this and in Figure 1.1 could potentially indicate that coastal squeeze is occurring (vegetation is being lost due to the marsh failing to accrete vertically in line with SLR). Such indicators could, therefore, mean further investigations are needed. The Blackwater Estuary is examined in more detail in section 7.3. It is concluded that there is only weak evidence that the deterioration is due to SLR and that there are a range of other factors that are more important.

Photo courtesy of Sue Rees, Natural England.

However, a good starting point for identifying coastal squeeze losses is to have a sound understanding of coastal processes, geomorphology and the impacts of human activity in the areas of interest. This helps to rule out habitat changes that do not represent coastal squeeze. For example, knowledge of estuary morphology may demonstrate that the main cause of changes in the extent of saltmarshes in an estuary is due to natural cycles of lateral channel migration, or that changes in the area of mudflats is due to the short-term lowering of intertidal banks in response to high freshwater flow events. An understanding of ecological processes is also required to distinguish coastal squeeze losses from other causes, such as the introduction of new species, disease, or changes in water quality.

In the case of mudflats and saltmarshes, the expert judgement process should consider the following:

- Coastal squeeze effects would be expected to be more likely to occur where sediment supply is low and relative SLR is high. In these situations, habitats may fail to accrete vertically in line with SLR, and, therefore, may experience increased inundation, reversion to lower marsh species and decreases in vegetated extent. Figure 6.7 shows a saltmarsh near Abbotts Hall in the Blackwater Estuary which is undergoing deterioration (Natural England, pers. comm.).

- Only SLR (by affecting tidal water levels) can cause the landward boundary of tidally dominated features, such as a saltmarsh and mudflat, to move landwards. The impacts of SLR (together with the presence of a defence) should be visible in areas protected by wave energy as well as areas of higher wave energy.
- Increased wave energy on its own can cause erosion of the lower part of the marsh or mudflat, but is not likely to cause the landward movement of the upper limit of the habitat. Therefore, waves alone cannot bring about landward transgression of these types of habitat. Additionally, wave erosion of the lower part of saltmarsh or mudflat habitats can occur without a defence being present. Therefore, erosion of marsh edges due to wave action alone does not constitute coastal squeeze.

The case studies for Slaughden and Sudbourne Beach (section 7.4) and Aber Dysynni (section 7.5) both consider shingle beaches. These case studies indicate that it can be difficult to assess how much of the past changes represent coastal squeeze as there are a number of causes for a reduction in beach area in front of defences. Non-coastal squeeze factors that can be ruled out include decadal increases in storminess, changes in nearshore waves due to changes in bathymetry and reduced longshore sediment transport rates. It is acknowledged that it may be difficult to conclusively identify coastal squeeze as the only cause of habitat loss on open coast landforms (for example, shingle beaches and dune habitats) and this may result in little confidence in the final assessment. In these situations, the approach recommends either adopting a precautionary principle, where changes are assumed to represent coastal squeeze, or gathering more data through further studies.

Table 6.13: Human actions that could potentially impact on coastal habitats but that do not constitute coastal squeeze.

Human intervention		**Potential influence on habitats**
FCERM	Barrages and barriers	• Direct losses of habitats under footprint of schemes • Indirect losses or changes as a result of changes in geomorphology • Indirect losses caused by changes to tidal currents • Changes in upstream tidal habitat zonation patterns • Changes in the salinity profiles of estuaries and tidal rivers as a result of changes in freshwater volumes and annual flow patterns, and consequent changes in species communities
	Cliff remediation	• Indirect losses or changes as a result of changes in geomorphology
	Cliff stabilisation	• Stabilisation measures may impact on dynamic cliff habitats, but manage erosion losses • Indirect loss of intertidal habitats • Fewer landslips • Maritime cliff communities protected
	Culverts	• Inundation of freshwater or brackish habitats • Changes in freshwater supply to estuarine habitats • Changes in salinity profiles as a result of changes in saline water volumes and consequent changes in species communities
	Groynes	• Updrift increase in intertidal habitat area • Downdrift decrease in intertidal habitat area • Provision of structures for plants and animals to adhere to
	Jetties, piers or breakwaters (shore connected)	• Indirect losses or changes as a result of changes in physical processes and geomorphology • Jetties and breakwaters provide structures for plants and animal communities
	Managed realignment and No active intervention	• Creation of new intertidal areas • Inundation of freshwater or brackish habitats • Existing habitats destroyed but replaced by new intertidal habitats – most commonly mudflats/saltmarsh and inundation grassland • Managed realignment/no active intervention can also be applied to cliffs or beaches to allow the landward migration of coastal features
	Offshore breakwater	• Increase in local intertidal areas due to changes in physical processes • Direct losses of habitats under footprint of scheme

Human intervention		Potential influence on habitats
		• Downdrift decrease in intertidal area due to changes in physical processes • Provision of structure for reef communities
Non-FCERM	Beach mining	• Direct losses of intertidal habitats • Potential loss of backshore habitats as a result of increased erosion • Indirect loss of sediment from nearby beaches and near subtidal habitats • Destruction of shingle and/or sand dune plant and animal communities
	Changes in grazing regime	• Habitats affected by overgrazing are saltmarsh, sand dunes, vegetated shingle and maritime cliff and slopes • Effects on sward height • Change in flora and fauna species diversity, abundance and distribution • Prevention of ecological succession through grazing of shrub and tree species
	Changes in land use	• Increases or decreases sedimentation and, therefore, affects intertidal habitat character and extent in estuaries
	Channel training works	• Indirect losses or changes to habitat as a result of changes in sedimentation
	Dams	• Indirect losses or changes to coastal habitat as a result of changes in sedimentation and freshwater supply • Removal of seasonal variation in flow impacts on communities along rivers and mudflat dwelling species in estuaries
	Dredging	• Direct losses of habitats at the dredge site • Indirect losses or changes as a result of changes in physical processes and sea bed morphology • Changes in sea bed and benthic communities associated with a change in depth
	Industrial activities and traffic near habitat	• Eutrophication of water bodies • Increased algal growth • Dieback of vegetation, for example, atmospheric nutrient deposition on dune slacks can lead to a speeded up succession away from dune slack vegetation
	Introduction of invasive species	• Colonisation and creating new habitats at the expense of existing habitats
	Other changes in agricultural practices	• Eutrophication of water bodies • Increased algal growth • Dieback of vegetation, for example, atmospheric nutrient deposition on dune slacks can lead to a speeded up succession away from dune slack vegetation
	Railway/road embankments/quay walls	• Direct losses of habitats under footprint of schemes • Indirect losses or changes as a result of changes in due to changes in physical processes and geomorphology • Reductions in intertidal habitats due to coastal squeeze • Diverted wave energy has an impact on habitats along the shore
	Reclamations	• Direct losses of habitats under footprint of schemes • Indirect changes in habitats elsewhere in the estuary due to changes in physical processes
	Recreation and beach management	• On some heavily used beaches the formation of embryo dunes is inhibited by beach cleaning using mechanical methods, which impedes the seaward accretion of dune systems • Trampling of flora species on sand dunes and vegetated shingle • Fauna species may be disturbed by noise or physical presence or even deliberately destroyed. This may then have an indirect corresponding effect on the habitat they use
	Water abstraction	• Indirect loss of beach habitats • Loss of saline lagoons and their specialised flora and fauna • In some dune systems with important slacks, a long-term fall in the water table has led to loss of the specialist slack flora and invasion by coarse vegetation and scrub

Table 6.14: Climate change related factors that do not lead to coastal squeeze directly.

Aspects	Potential influence on habitats
Changes to annual rainfall patterns	• More frequent low flow conditions in rivers and estuaries, with potential drying of river and riparian habitats during summer • Changes to the pattern and rate of sediment transport in rivers and estuaries • Soil erosion • Drought condition impacts on habitats in summer • Increased inundation periods for terrestrial habitats due to surface water flooding

Aspects	Potential influence on habitats
	• Changes in soil water levels and their seasonal patterns, leading to changes in plant community composition
Increase in CO_2 leve[10]l	• Plant species will react differently to increased CO_2. In areas where water and nutrients are not limiting factors, competitive species will have higher growth rates. In stressed environments, for example, saltmarsh plant growth rates will increase but will be limited by other factors • The absorption and dissolution of atmospheric CO_2 in water-dependent freshwater or tidal habitats could cause acidification and subsequent habitat change
Increase in drought	• Increases stress on vegetation and habitats • May lead to shrinkage of sediments and modified hydrological regime
Increase in extreme rainfall	• More frequent ground movement in landslide systems • Increased soil erosion • Flooding of ground dwelling animals, for example, ground nesting birds • Increased peak flows within rivers and estuaries (see below). Resulting increase in stream power will allow transport of larger sized sediment, potentially impacting habitats and engineering structures • Plants and animals sensitive to high flow rates will be lost
Increase in freshwater peak flows	• Changes to the pattern and rate of sediment transport in rivers and estuaries, with erosion of river bank habitats as the channel adapts to increases in seasonal discharge • More frequent flooding of riparian habitats (and habitats not normally considered riparian) • Improved ecological connection between rivers/estuaries and flood plains • Changes in salinity gradients and zones in estuaries, and effects on zonation and productivity of estuarine habitats and species
Increase in temperature[10]	• Species migration due to temperature change – generally northwards or to higher ground, leading to changes in plant and animal communities and ultimately change in habitats • Changes to patterns of species reproduction • Changes to predator-prey linkages and food webs • High temperatures will reduce the effective rainfall (that is, rainfall less than that lost to evapotranspiration by plants), lowering net groundwater levels. This will improve the stability of coastal cliffs and prevent landslides up to the point where vegetation dies due to a lack of moisture leading to reduced soil stability
Short-term cyclical changes in wind direction	• Change in local wind generated wave directions, resulting in altered littoral drift patterns (see below), in time potentially leading to changes in coastal alignment • Loss of tall woodland
Short-term cyclical increases[11] in SL	• Temporary changes in morphology, including erosion and accretion, resulting in gains/losses of habitat • Increased temporary inundation of freshwater or brackish coastal wetlands and terrestrial habitats • Changes in vegetation zonation
Short-term cyclical increases in wave climate or change in direction	• Barrier island overtopping/breach • Increased erosion • Inundation of freshwater or brackish coastal wetlands and terrestrial habitats • Loss or change of freshwater, brackish and terrestrial habitats • Change of plant and animal communities and zonation patterns
Short-term cyclical increases in storm surge frequency or magnitude	• Increased temporary inundation of freshwater or brackish coastal wetlands and terrestrial habitats • Changes in vegetation zonation • Beach/dune barrier overtopping/breach • Increased erosion • Conversion of terrestrial plant communities to those more characteristic of areas occasionally inundated by saltwater • Loss of freshwater species not able to exist with any level of saltwater inundation • Gain of species characteristic of brackish water • Large-scale movement of dune systems
Short-term cyclical increases in wind speed	• Changes to wave climate (see below) • Changes to coastal dune systems and their ecology

[10] It is noted that CO_2 and temperature contribute to SLR but are indirect factors in coastal squeeze.
[11] It is implicit in the definition of coastal squeeze that it is driven by a net rise in SLR over the long term. Therefore, short-term variations in sea level (for example, due to the lunar nodal tidal cycle) or wind-wave climate (for example, decadal increases or decreases) do not cause coastal squeeze. **)**

Table 6.15: Other factors that do not constitute coastal squeeze

Factor	Explanation
Changing positions of banks and channels in estuaries	• Natural changes in channel position due to meandering activity • Changes in extent of shore attached to intertidal arising from shifts in channel and bank position
Changes to soil chemistry (for example, water logging, redox potential, salinity) that are not due to SLR	• Conditions become unsuitable for habitats • May lead to habitat loss
Fungal pathogens	• Can cause damage to certain species which encourages ecological succession or, in some cases, erosion
Herbivore activity	• Grazing of habitats can cause damage to habitats • In some settings grazing can also produce beneficial changes in habitats
Introduction of invasive species	• Invasive species dominate and create changes to habitat that may be detrimental to other species • Potential for habitat loss
Wrack damage	• Stripping of vegetation and habitat damage

Uncertainty and data availability

Sources of uncertainty include:

- difficulties in establishing contribution of different factors to resulting habitat losses
- difficulties in separating short-term cyclical responses from longer term trends

Given the potential difficulties in identifying coastal squeeze due to multiple causes and possible limitations in data availability, a confidence banding should be given to the final expert judgement - 'high', 'medium' or 'low'. Some guidance on each of these categories is given in Table 6.16.

Table 6.16: Criteria to assess confidence in coastal squeeze assessment.

Confidence band	Criteria		
	Where habitat losses are likely to be due to coastal squeeze	Where there are no habitat losses	Where habitat losses are unlikely to be due to coastal squeeze
High	• Clear evidence (for example, from maps/aerial photograph/ecological surveys) indicating habitat loss or deterioration over time • Clear evidence indicating that habitat loss or deterioration is due to SLR (for example, from correlations between rates of habitat loss and local tidal gauges) • Clear evidence indicating that SLR exceeds sedimentation rates (for example by comparing	• Clear evidence (for example, from maps/aerial photograph/ecological surveys) indicating no habitat loss or deterioration over time • Analysis indicating that SLR is less/equal to than sedimentation rates (for example, by comparing measured sedimentation rates and local tidal gauges)	• Clear evidence (for example, from maps/aerial photograph/ecological surveys) indicating habitat loss or deterioration over time • Clear evidence indicating that SLR is less than sedimentation rates (for example, by comparing measured sedimentation rates and local tidal gauges) • Clear evidence indicating that habitat loss or deterioration is due to other causes (for example, correlations between rates of habitat loss and other parameters such as

Confidence band	Criteria		
	Where habitat losses are likely to be due to coastal squeeze	**Where there are no habitat losses**	**Where habitat losses are unlikely to be due to coastal squeeze**
	measured sedimentation rates and local tidal gauges) • Clear evidence that there are no other likely or attributable cause for habitat loss or deterioration (for example, absence of correlations with wind-wave climate)		wind-wave climate, evidence of existence of lateral channel movement)
	• Level of supporting documentation: peer reviewed publications, grey literature (for example, consultancy reports) based on verifiable data analysis		
Medium	• Clear evidence (for example, from maps/aerial photograph/ecological surveys) indicating habitat loss or deterioration over time • Some evidence that habitat loss or deterioration is due to SLR (for example, from correlations between rates of habitat loss and regional tidal gauges) • Sedimentation rates believed to exceed SLR (for example, by comparing sedimentation rates and regional rates of SLR) • Some evidence that there are no other likely or attributable cause for habitat loss or deterioration (for example, absence of correlations with decadal increases in wind-wave climate)	• Clear evidence (for example, from maps/aerial photograph/ecological surveys) indicating no habitat loss or deterioration over time • Sedimentation rates believed to equal/exceed SLR (for example, by comparing sedimentation rates and regional rates of SLR)	• Clear evidence (for example, from maps/aerial photograph/ecological surveys) indicating habitat loss or deterioration over time • Sedimentation rates believed to equal/exceed SLR (for example, by comparing sedimentation rates and regional rates of SLR) • Some evidence that habitat loss or deterioration is due to causes other than SLR (for example, demonstrable link between rates of habitat loss and known periods of increased storminess, evidence of existence of lateral channel movement) • Losses due to SLR generally thought to be minimal or negligible
	• Level of supporting documentation: Non-peer reviewed publications (for example, conference papers), grey literature (for example, consultancy reports) based on data analysis		
Low	• Some evidence for habitat loss or deterioration over time (for example, from maps/aerial photograph/anecdotal reports) • No clear evidence that SLR is the cause of habitat loss (no demonstrated correlation between rates of loss and local SLR)	• Some evidence for no change in habitat loss or deterioration over time (for example, from maps/aerial photograph/anecdotal reports) • Sedimentation rates believed to equal/exceed SLR (but no available comparisons of between sedimentation rates and SLR)	• Some evidence for habitat loss or deterioration over time (for example, from maps/aerial photograph/anecdotal reports) • Sedimentation rates believed to equal/exceed SLR (but no available comparisons of between sedimentation rates and SLR) • Multiple possible causes for habitat loss or deterioration

Confidence band	Criteria		
	Where habitat losses are likely to be due to coastal squeeze	**Where there are no habitat losses**	**Where habitat losses are unlikely to be due to coastal squeeze**
	• Sedimentation rates believed to exceed SLR (but no available comparisons of between sedimentation rates and SLR) • Multiple possible causes for habitat loss or deterioration and no supporting data to evaluate		and no supporting data to evaluate
	• Level of supporting documentation: Absent or limited to suggestions for causes of habitat loss without supporting data analysis		

Where confidence is low, there are 2 possible approaches to take:

- Adopt the precautionary principle and assume that the past habitat losses represent coastal squeeze. It is possible to follow this approach whilst further studies or data are collected (see below). This approach may be followed where the past losses or deterioration of habitat are not believed to be large or require extensive amounts of habitat creation to be provided.

- Carry out further studies to investigate the causes of past habitat change, with a view to achieving a higher level of confidence. For example, additional historic data or habitat extent may be digitised and analysed. Additional studies might include more detailed morphological or ecological assessments of the cause for habitat loss. This approach may be adopted where past losses could be large and require extensive amounts of habitat creation to be provided.

The choice between these 2 options is likely to be determined by the size of the coastal squeeze losses that may have occurred, the need for further compensatory habitat and the available budgets. The choice between these 2 approaches should involve discussion between the Environment Agency/local authority/land/asset owner and Natural England/Natural Resources Wales.

In some cases where a lack of data prevents any assessment from taking place, then the low confidence band should be assumed, and the precautionary principle adopted until new studies can investigate coastal squeeze losses further.

Where a frontage is backed by a number of structures owned by different parties, it may be necessary to apportion the coastal squeeze losses and resulting compensatory habitats requirement to the various parties, for example, on the basis of frontage lengths.

6.2.7 Summary of method to determine past habitat losses

In summary, the method consists of 5 main stages:

1. Scoping.
2. Screening:

   a. Test 1: Have relevant structure/s and/or management actions been present over the period of interest?
   b. Test 2: Has there been suitable accommodation space landward of the structure over the period of interest?
   c. Test 3: Have there been readily observable losses or deterioration in quality of habitat in front of structures (either LWM retreat or internal erosion) over the period of interest?
   d. Test 4: Have relative sea levels risen in the region over the period of interest?
3. Baseline geomorphological assessment.
4. Quantifying past habitat losses and changes in habitat quality.
5. Evaluating causes of loss and the role of coastal squeeze:
   a. Identify a shortlist of sites at risk.
   b. Expert judgment of habitat loss attributable to coastal squeeze.

6.3 Determining future coastal squeeze losses

Future habitat losses due to coastal squeeze can be predicted using a similar approach to that described in section 6.2.1:

1. Scoping.
2. Screening.
3. Baseline assessment.
4. Quantifying future habitat losses.
5. Evaluating causes of loss and the role of coastal squeeze.

6.3.1 Scoping

The same approach can be adopted as for determining past losses - see section 6.2.1.

In regard to the period of interest for an assessment of future coastal squeeze losses, the end date for these assessments typically coincides with the 3 time periods used in Shoreline Management Plans (SMPs) and Flood and Coastal Erosion Risk Management (FCERM) strategies: 0 to 20 years, 20 to 50 years, 50 to 100 years.

However, it is possible that in some scenarios the assessment of changes in coastal habitat may wish to consider different periods of time, for example, if assessments are being made for a structure which has been in place for a shorter period of time. In this approach, we therefore use the term 'period of interest'.

6.3.2 Screening

There are 3 main tests to determine the likelihood of a site/habitat being subject to coastal squeeze in the future:

1. Are there likely to be relevant structure/s and/or management actions over the period of interest?
2. Is there likely to be an absence of a potential accommodation space landward of the structure over the period of interest?
3. Are relative sea levels anticipated to rise in the region over the period of interest?

If there is evidence that coastal squeeze has occurred in the past (see section 6.2), then it is likely that it will continue in the future. However, it is possible that future scenarios may differ in a number of ways, for example, accommodation space, SLR, sediment supply, management actions. The change in these parameters may also mean that coastal squeeze may occur in the future in areas where it has not occurred in the past.

Test 1: Are there likely to be relevant structure/s and/or management actions present over the period of interest?

Explanation

This approach will follow that outlined in section 6.2.2 – Test 1. The assessment should consider the structures/management actions that are there at present and whether they will continue in their same form in the future or will be altered.

Data sources

The method and data sources include those described in section 6.2.2 – Test 1. The future of structures or management actions should be obtained from SMP and FCERM strategies.

Uncertainty

Sources of uncertainty, in addition to those reported in section 6.2.2 – Test 1, include:

- the timing and application of shoreline management interventions
- the presence of other structures such as roads or railway embankments

Test 2: Is there likely to be suitable accommodation space landward of the structure over the period of interest?

Explanation

This test will involve a slightly more complex approach than that listed in section 6.2.2 – Test 2, to take into account future SLR. Future accommodation space needs to consider increasing SL and tidal limits (HAT in the context of intertidal flats and saltmarsh) which determine the accommodation space. Higher water levels are likely to increase the potential accommodation space, but this will depend on the topography of the land.

Data sources

The data sources used to determine suitable future accommodation space include those described in section 6.2.2 – Test 2, but additionally need to consider the new tidal levels or water height resulting from projected future rates of SLR such as UKCP18 by Palmer et al., 2018 and shown in Figure 6.8.

At the time of writing (July 2019), Defra guidance for FCERM projects in England is to use the H++ scenario, which is then factored according to the 95% emissions scenario (UKCP09) for the relevant location (Environment Agency 2016). For the case studies in this report we have used the high emission scenario (RCP 8.5) from UKCP18 guidance at the 50th percentile. In the future, it is likely that these guidelines will be updated to take account of the latest UKCP18 guidance on climate change.

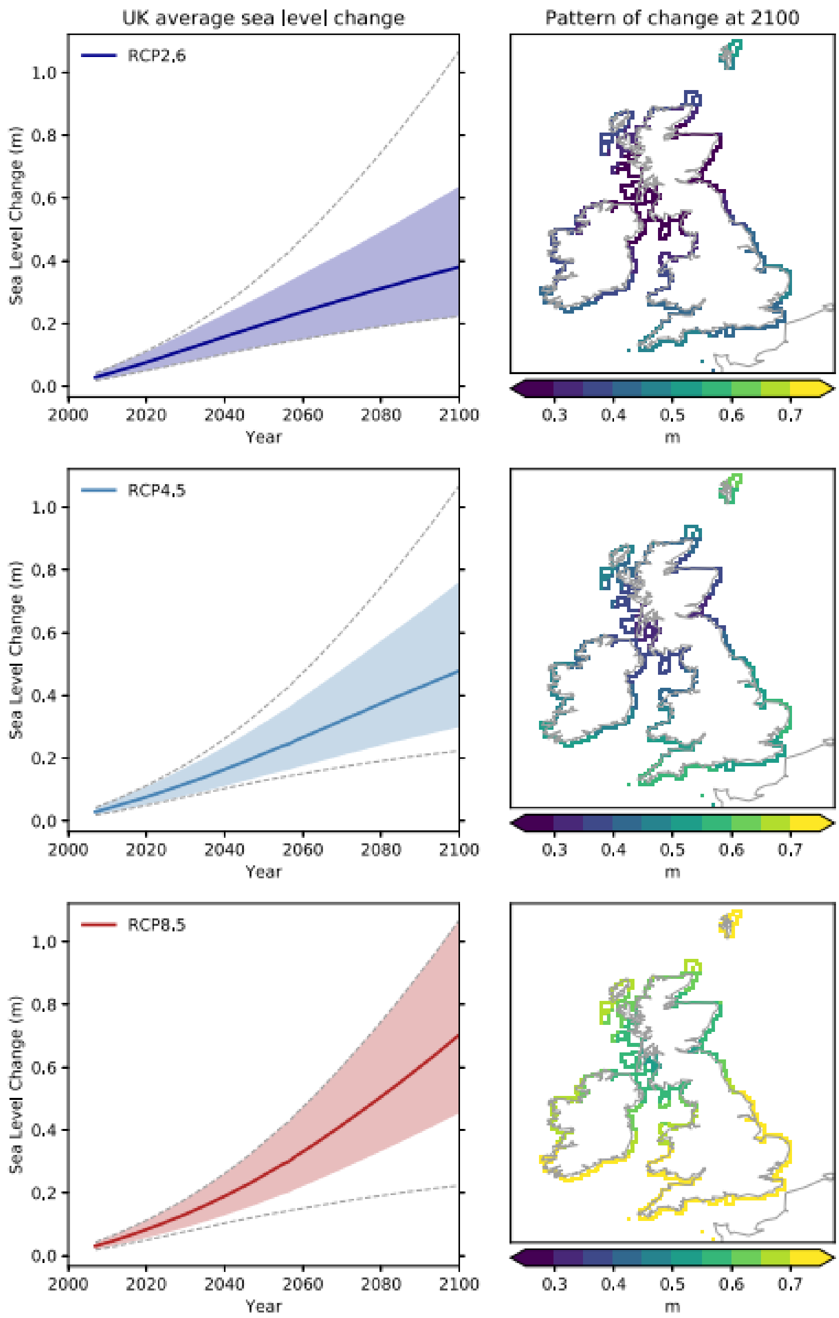


Figure 6.8: Predicted increases in mean sea level under 3 climate change scenarios (varying emission scenarios) resulting in varying increases in sea level around the UK.

Source: Palmer et al., 2018.

Uncertainty

Sources of uncertainty include those described in section 6.2.2 – Test 2, but also a number of additional uncertainties related to SLR:

- estimations of future SLR associated with emissions scenarios in general
- estimations of future SLR within estuaries where complex morphological interactions can significantly influence water levels

- specific to estuaries, there are uncertainties regarding the effects of SLR on tidal range which will be determined by HAT limit and, therefore, the accommodation space

Test 3: Is relative SL anticipated to rise in the region over the period of interest?

Explanation/definition

The purpose of this test is to determine whether SL is predicted to rise in the area of interest.

Data sources

Several data sets may be used to identify whether sea level is likely to rise over the period of interest - Table 6.17.

Table 6.17: Potential data sources used to identify predicted SLR listed in order of availability.

Data source	Coverage/subject
Academic papers	Region and site specific accessed via Internet
Environment Agency (2018, 2020)	England only
Technical reports	Region and site specific accessed via Internet
UKCP18	UK predicted rates of SLR for regions throughout U.K.– Palmer et al., 2018

6.3.3 Baseline ecological and geomorphological assessment

A baseline understanding of coastal/estuarine behaviour (see section 6.2.3) is needed to inform the assessment of future habitat losses and the role of coastal squeeze. Additionally, it may be necessary to carry out further detailed studies of important ecological and geomorphological processes to assess future changes.

6.3.4 Predict future habitat losses

The approaches can be categorised into 2 main types:

A. extrapolation of past losses – based on historical trend analysis (HTA)

B. predictive model

The results of these 2 approaches can be brought together in an expert assessment.

A - Extrapolate past losses – historical trend analysis (HTA)

Explanation

This is the simplest approach to predict future losses. It relies on carrying out an HTA to establish rates of loss and then extrapolating these trends into the future. Further explanation of HTA is given in Defra/Environment Agency (2006, 2009a). This extrapolation can take a number of forms:

- Assume that past losses will continue at the same rate in the future and, therefore, carry out a straight extrapolation of past rate habitat losses (ha/year) into the future.

- Assume that the rates of loss are proportional to the rate of SL rise and, therefore, ‘factor’ the extrapolation to take account of differing rates of SLR in the past and the future. Higher rates of SLR are assumed to result in higher rates of habitat loss.

- Acknowledge that there is some uncertainty in determining future scenarios and create a range of predictions based on SLR and uncertainty/variability of historic data. For example, this could be in the form of maximum and minimum predictions based on combinations of SLR and sediment supply.

Data sources

The past rates of habitat loss and SLR will have been defined from a number of data sources (sections 6.2.2 to 6.2.5). Future rates of SLR will have been defined or assumed from other data sources (see section 6.2.2 – Test 3).

Uncertainty

Sources of uncertainty are:

- accuracy of future predictions of SLR
- accuracy of historic rates of habitat loss
- assumption that the rate of habitat loss is proportional to the rate of SLR
- assumption that historic/present day geomorphological processes will continue into the future
- uncertainties related to future sediment budgets

B - Use of predictive models

Explanation

There is a wide range of predictive numerical or conceptual models for assessing future coastal and estuarine processes and morphology.

Table 6.18 lists those approaches recommended for tidal flats, saltmarshes, channels, banks and inlet. It suggests how such approaches could be used in the context of understanding and predicting coastal squeeze. Further details on using these models can be found in several publications (for example, Defra/Environment Agency, 2009a, b; Estuary Guide (http://www.estuary-guide.net)). The choice of models will depend on the available resources and skills of those carrying out the assessment and the available data.

The choice of model and/or analysis identified below will depend on several factors including, but not limited to, the following:

- guidance from the Estuaries research project (see reference above), which suggests that a range of approaches should be used rather than just one
- the type of estuary, including morphology
- the availability of data needed for various approaches
- the skill of the operator versus the complexity of model/analysis
- available budget for carrying out the work

Table 6.18: Approaches used to assess morphological change of coastal habitats (Adapted from Defra/Environment Agency 2009).

Environment	Tool/method	Data requirements	Limitations	How could approach be used in the context of assessing coastal squeeze?
Tidal flats and saltmarshes	• Inundation (hypsometric analysis)	• Topography (for example, LiDAR) • Knowledge of present day habitat extents (for example, aerial photo/ground surveys) • Present and future water levels	• Difficult to adequately take account of future sediment erosion/accretion /morphological change • Excluding sediment accretion over predict loss of habitats under SLR	• Simple assessment of future possible habitats extents (but needs to take account of potential for vertical accretion)
	• Historical trend analysis (HTA)	• Historic maps and charts • Repeat topographic surveys/LiDAR surveys • Aerial photo and remote sensing – give information on vegetation cover and type • Core data • Sediment stratigraphy • Particle size distribution • Geotechnical information	• Spatial accuracy • Temporal resolution - only ~20 years of LiDAR data • Limit on time of year taken • Density of coverage for core data	• Helps inform extrapolation of past rates of habitat change into the future
	• Expert geomorphological assessment (EGA)	• Microfossils • Morphology, profiles • Drivers • Water level • Waves • Sediment supply • Sediment distribution • Biology	• Needs surface and subsurface data • Degree of expertise • Trends versus episodic changese • Antecedent conditions • Lack of data, for example, for waves in estuaries	• Development to conceptual model to explain driving forces governing habitat extent
	• Empirical approaches (Kirby, 1992 and Dyer, 1998) • Translation (Bruun concept)	• Tidal datum and range • Waves • Morphology • Channel width • Relative SLR	• Sediment type not represented • No account of sediment load, rate of transport	• Prediction of future cross shore profile to determine habitat loss

Environment	Tool/method	Data requirements	Limitations	How could approach be used in the context of assessing coastal squeeze?
	• Analytical and numerical process models - Friedrichs and Aubrey (1996), Roberts et al. (2000), Pethick (2002), Pritchard et al. (2002), Capucci et al. (2004) - 0D models	• Tidal datum and range • Waves • Morphology • Channel width • Relative SLR	• Concepts used need to be assessed for each application	• Prediction of future cross shore profile to determine habitat loss
Banks, channels and inlet associated banks	• Historical trend analysis (HTA)	• Historic charts • Bathymetric surveys	• Datum for surveys • Positional accuracy (x,y) • Vertical accuracy (z) • Trend versus episode • Gap between survey in time too long or too short	• Helps inform extrapolation of past rates of habitat change into the future
	• Expert geomorphological assessment (EGA), including sediment trend analysis	• Particle size distribution • Surface and subsurface data (geophysics, cores) • Surface features • Process, waves, tides understanding • Geological context	• Expensive. • Datum for survey • Positional accuracy (x,y) • Vertical accuracy (z) • Trend vs episode. • Gap between survey in time too long or too short	• Development to conceptual model to explain driving forces governing habitat extent
	• Empirical methods based on volumes or prism	• Morphology • Estuary information including – volume and tidal prism	• Crude (volume only) • No information on form	• Prediction of future estuary plan-shape to determine habitat loss
	• Numerical process modelling	• Bathymetry • Sediment particle size distribution • Wave data • Tide levels • Currents	• Infers bank behaviours from short-term process results • Requires one or more models with bathymetry based on charts/surveys and models that are calibrated and validated	• Development to conceptual model to explain driving forces governing habitat extent • Prediction of future habitat loss
	• Empirical models (Bruun and Gerittsen, 1960) for inlets	• Freshwater flow • Tidal prism • Longshore drift	• Categorisation through broad parameters • Simplistic	• Prediction of future cross shore profile to

Environment	Tool/method	Data requirements	Limitations	How could approach be used in the context of assessing coastal squeeze?
	• O'Brien (1931) Regime Models, Healthy Estuaries Regime approach (Natural England 2016)	• Cross-section area	• No timescale information	determine habitat loss • Prediction of future estuary plan-shape to determine habitat loss

Data sources

Depending on the type of model, a variety of data sources are necessary, not all of which may be available for some sites (Table 6.19).

Table 6.19: Typical data sources required for modelling.

Data source	Source
Aerial Images	Environment Agency/NRW/Data.gov.uk/lle.gov.wales/ CCO website
Bathymetry	Environment Agency/NRW/Data.gov.uk /lle.gov.wales/ CCO website
Hydrodynamic data sets – Tides, river flow, waves	Environment Agency/NRW/lle.gov.wales/Admiralty/ CEFAS/Technical reports/National Tidal and Sea Level Facility
LiDAR (England Wales)	Environment Agency/Data.gov.uk/INSPIRE Admiralty/ Local port authority
River flows	National River Flow Archive
Sediment data	Reports/scientific literature/technical reports

Uncertainty

- Uncertainty in rates of SLR - UKCP18 (Palmer et al., 2018) Climate change emission scenarios (values provided in Figure 6.8): high (RCP[12] 8.5), medium (RCP 4.5), low (RCP 2.6).
- Uncertainty related to individual predictive model assumptions.
- Uncertainties in determining future sediment supply, for example, maintenance of present-day levels of supply reduced supply, increased supply.

6.3.5 Predicting future changes in habitat quality

Future changes in habitat quality may be predicted by assessing the potential for intertidal surfaces to maintain their elevations within the tidal frame.

For saltmarshes for example, if the saltmarsh surfaces accrete vertically at a lower rate than SLR, then they will become inundated more frequently and, therefore, high marsh communities may be replaced with lower marsh communities. An assessment of likely future vertical accretion rates can be made based on knowledge of past measured

[12] RCP stands for Representative Concentration Pathways

accretion rates and expert judgement of likely future sediment supply conditions. Various scenarios of SLR and vertical accretion rates and their impact on inundation zones (and, therefore, vegetative zones) can be explored manually using GIS (see Blackwater Case Study – Appendix A). A number of bespoke models for marsh evolution also exist such as SLAMM (Sea level affecting marshes) model, Clough, 2014.) or MARSED (Long-term marsh sedimentation model), Newcomer et al., 2011) and BTELSS (Baratarina-Terrebonne Ecological Landscape Spatial Simulation), Mcleod et al., 2010).

6.3.6 Evaluation of causes of loss and the role of coastal squeeze

As noted in section 6.3.5, the final judgement on how much of the predicted losses is due to coastal squeeze will require expert geomorphological assessment (EGA). Further explanation of EGA can be found in Defra/Environment Agency (2006, 2009a, b). The central question is: "Will, in the future, there be losses of coastal habitats due to the landward transgression of the habitats being held up?"

The expert judgment should consider the collated data including:

- baseline geomorphological understanding
- measured historical habitat losses and the estimated role of coastal squeeze
- predicted future losses
- likely contributions of other (non-coastal squeeze) causes (see Table 6.13 to Table 6.15)
- uncertainties arising from various causes (see section 6.3.2 on uncertainty)

The assessment of coastal squeeze should exclude losses in the following circumstances:

a) in areas where there are no defences

b) in areas where there is no accommodation space

c) where losses are due to other processes (for example, lateral channel movements, changes in the wind wave climate)

It is recommended that deriving future changes in habitat should not be based just on linear extrapolation alone. Instead, it should consider:

(i) a range of SLR scenarios

(ii) best and worst-case estimates

(iii) expert geomorphological assessment

Assuming the historic trend analysis (HTA) and expert geomorphological analysis (EGA) has been applied, confidence in the assessment should be assigned with the following 'high', 'medium' or 'low' bands using the criteria mentioned in the past habitat losses section (as described in section 6.2.6, see Table 6.16).

Where a frontage is backed by a number of structures owned by different parties, it may be necessary to apportion the coastal squeeze losses and resulting compensatory habitats requirement to the various parties, for example, on the basis of frontage lengths.

6.3.7 Summary of method to determine future habitat losses

In summary, the method consists of 5 main stages:

1. Scoping.
2. Screening
   a) Are there likely to be relevant structure/s and/or management actions over the period of interest?
   b) Is there likely to be an absence of a potential accommodation space landward of the structure over the period of interest?
   c) Are relative sea levels anticipated to rise in the region over the period of interest?
3. Baseline geomorphological assessment.
4. Quantifying future habitat losses and changes in habitat quality.
5. Evaluating causes of loss and the role of coastal squeeze.

6.4 Summary

- This chapter has outlined a method of identifying past and future coastal squeeze losses. The method was initially developed for tidal flats and saltmarshes, but is broadly applicable to other habitats types (see case studies in sections 7.4 and 7.5). The method is summarised in Figure 6.1 and Figure 6.2.
- An initial scoping stage is needed to define the study area, the habitats to be included, and the period of interest.
- A screening stage allows the rapid assessment of whether or not coastal squeeze is a potential contributor to past and future changes in habitats extent.
- For changes in habitat extent or quality that have occurred in the past, or could occur in the future, that could be due to coastal squeeze, the method outlines how to quantify these changes.
- At each step of the method, the relevant data sources and causes of uncertainty that apply are identified.
- The final step of each assessment requires expert judgement to assess whether the observed/predicted changes represent coastal squeeze. Expert judgement is needed since there are multiple causes of changes in coastal habitat, and the physical expression of these changes can be similar.
- The method outlines how an assessment of confidence in the findings - ‘high’, ‘medium’ or ‘low’ - should be made. Where there is low confidence, 2 approaches can be taken:
  - Adopt the precautionary principle, assume that habitat losses result from coastal squeeze, and review the assessment in the future.
  - Carry out further studies to increase confidence in the findings.

7 Summary and discussion

7.1 Problem statement

A number of studies that have been carried out for the Environment Agency around England have highlighted the inconsistencies in the definition of 'coastal squeeze' and demonstrated several problems in quantifying it. This project aimed to improve understanding of coastal squeeze, and also to set out best practice for assessing the historic and future impacts of coastal squeeze at different scales.

7.2 Previous definitions

Chapter 2 shows that the various studies carried out to date have used subtly different definitions for the term 'coastal squeeze'. There were many similarities in terms of elements included/excluded in the definitions, but some significant differences in terms of:

- incorporating the processes driving the landward transgression of habitats
- incorporating habitat quality
- delineation of upper and lower limits of the intertidal zone
- the range of habitats included

7.3 Factors influencing coastal habitat extent

Chapter 3 reviews the various influences on coastal habitat and identifies those that are potentially relevant to coastal squeeze and those that are not. The presence of structures and the impacts of SLR are central to the definition of coastal squeeze.

The review shows that a number of human interventions (both FCERM and non-FCERM) could potentially impede the natural transition of habitats:

- seawalls or revêtments
- flood embankments
- railway/road embankments/quay walls
- reclamations

SLR has the potential to bring about changes to habitats in a number of ways:

- increased wave attack, leading to erosion of seawards edges of habitat
- increased inundation of habitats, leading to changes in habitat zonation (including extent, position and type)
- overtopping/breaching/landward movement of dunes/barrier beaches/barrier islands

An important conclusion is that, in many instances, habitat change is likely to result from multiple causes. A number of these causes do not represent coastal squeeze. In these circumstances, it may be difficult to identify the main cause of change and it may require a range of investigations. Additionally, it is important to consider whether the changes are part of a progressive long-term trend or a shorter cycle. Identifying a progressive long-term trend such as coastal squeeze needs to consider an appropriate time span.

7.4 Stakeholder workshop

Chapter 4 summarises the results of a stakeholder workshop held to consider how best to define 'coastal squeeze' and what methods could be used to assess it. The workshop gained consensus on a number of the main elements to be included in the definition:

- 'the prevention of landward transgression of habitats'
- 'habitat changes driven by SLR'
- 'due to anthropogenic (man-made) structures'

The workshop attendees also agreed on a number of scenarios that did not represent coastal squeeze, such as losses arising from reductions in longshore transport, presence of higher land elevations (preventing transgression of habitats), and losses due to historic land reclamation. Attendees also called for a simple and pragmatic definition and concluded, at the time, that habitat quality was too complex an issue to be included.

7.5 Revised definition

Chapter 5 presents the revised definition of coastal squeeze based on the review of previous work (Chapter 3), the stakeholder workshop (Chapter 4) and extensive discussion between the project boad and project team:

"Coastal squeeze is the loss of natural habitats or deterioration of their quality arising from anthropogenic structures, or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to SLR in conjunction with other coastal processes. Coastal squeeze affects habitat on the seaward side of existing structures."

<u>The definition must be read with the points of clarification relating to what constitutes: anthropogenic (man-made) structures, natural habitats, extent of losses, SLR and coastal processes. The points of clarification also explain those losses of habitat that do not constitute coastal squeeze.</u> After much post-workshop debate, the definition includes reference to deterioration in habitat quality, where such changes result from man-made structures/human actions preventing the landward transgression of habitats, for example, replacing high marsh communities with lower marsh communities.

A review of Annex I and Section 41 priority coastal/intertidal habitats suggests that the following habitats could be subject to coastal squeeze:

- boulder beaches
- shingle beaches and barriers
- intertidal seagrass beds

- intertidal reedbeds
- intertidal rock platforms
- mud and sandflats
- saline lagoons located in front of structures
- saltmarsh
- sand beaches
- sand dunes

The types of habitats that could be affected should be appraised at a site level.

Figure 7.1: The concept of coastal squeeze, although most commonly applied to saltmarshes, can also apply to other coastal habitats such as sand dunes if structures or management actions limit their landward movement.

Photo courtesy of Nigel Pontee, Jacobs.

7.6 Appraisal method

Chapter 6 describes the method that has been developed to appraise the extent of past and future coastal squeeze losses. The method is summarised in 2 flow diagrams. An initial scoping stage defines the study area, the habitats to be included, and the period of interest. A subsequent screening stage allows a rapid assessment of whether or not coastal squeeze is likely to be a potential cause for the habitat change. The method outlines how to quantify these changes, and the relevant data sources and causes of uncertainty that apply to each step of the method are identified. The final stage of the assessment requires expert judgement to assess whether the observed/predicted changes represent coastal squeeze. The method outlines how an assessment of confidence in the findings - ‘high’, ‘medium’, or ‘low’ - should be made. Where there is low confidence, 2 approaches can be taken:

- Adopt the precautionary principle, assume that habitat losses result from coastal squeeze, and review the assessment in the future.
- Carry out further studies to increase confidence in the findings.

The method identifies the data needed to carry out the assessment of coastal squeeze in both the past and future and to:

- identify the presence of defences
- define land levels landward of present day defences (accommodation space)
- document past changes in habitat extents
- assess past and future SLR

7.7 Trial of method

Four case studies were carried out to help develop and refine the method (Appendix A):

- Lymington Estuary, Hampshire, saltmarsh habitats
- Blackwater Estuary, Essex, saltmarsh and mudflat habitats
- Slaughden and Sudbourne, Suffolk, shingle beach habitats
- Dysynni Estuary and adjacent coastal frontage – Gwynedd (Dysynni Estuary habitats and coastal habitats from mouth of the Dysynni to Tywyn)

The main findings from the Lymington case study were:

- Some losses of marsh occur against high land and, therefore, do not represent coastal squeeze. This agrees with the previous assessment by the Solent Dynamic Coastal Project (SDCP) (2008).
- Some losses of marshes do occur against defences. SLR is a possible cause for this marsh loss, but there is a lack of data to prove this conclusively as there are a number of other potential causes (waves, pathogens, pollution). This agrees with the previous assessment by the SDCP (2008). Further studies are needed to assess these various contributory factors and improve confidence in the assessment of coastal squeeze. Without these detailed studies, there is a risk that coastal squeeze is inaccurately identified. This is an important issue and is likely to apply at other sites in the UK.
- Importantly, this case study suggests that the presence of high land a relatively short distance behind the defences, means that the majority of any past losses attributed to SLR may have occurred even without the presence of defences. This suggests that the losses do not represent coastal squeeze. This is a new finding.

- The assessment of coastal squeeze losses requires (i) identification of SLR as the cause of habitat loss and (ii) consideration of a 'hypothetical' baseline – namely the landscape without defences. It is noted that the commonly used diagrams explaining coastal squeeze (for example, Pontee, 2017) suggest that the hypothetical baseline is one in which habitats migrate landward whilst maintaining their extent. The present case study shows that this is not necessarily the case where high land lies relatively close behind the present day defences. This is a new finding and has implications for other sites in the UK.

- A range of further studies are recommended to quantify past losses up to the present day, gather additional data on local rates of past SLR, consider habitat quality, examine the relationships between marsh surface topography/vegetation and local tidal levels, examine the role of waves and other factors for dieback, and consider a range of future climate change scenarios for sediment supply and sea level.

The results of the SDCP (2008) fed into the overall assessment of coastal squeeze for the Solent made in the Solent Shoreline Management Plan (SMP) (SSDRHCP, 2017, 2018). To date, historic losses in the Solent have led to compensatory habitat being provided in the Medmerry Managed Realignment Scheme, Lymington Water Level Management Plan and Manor House Farm. The SMP predicts that additional saltmarsh habitat will be required to compensate for losses arising from coastal squeeze in the future. Several managed realignment schemes are being considered to compensate for these losses.

The main findings from the Blackwater Estuary case study are:

- There have been losses of saltmarsh habitat in front of defences within the Blackwater Estuary but there is weak evidence that SLR is the main cause of these losses.

- The past changes in intertidal habitat extent are likely to have been due mainly to wave action, local channel movements and renewed tidal influence in formerly reclaimed areas, rather than the marsh surfaces not being able to accrete vertically in line with SLR. Such changes would not constitute coastal squeeze. This is a new finding which differs from previous assessments made by English Nature (2006).

- Marshes in the Blackwater Estuary are predicted to be able to accrete vertically and maintain a constant level within the moving tidal frame if future SLR is less than 5mm/yr. This is a new finding which differs from previous assessments made by English Nature (2006). The responses of the marshes to higher rates of SLR is uncertain and so the occurrence of coastal squeeze cannot be ruled out under these scenarios.

- It is possible that the losses on islands at the mouth of Tollesbury Fleet and Salcott Channel are influenced by the presence of defences on the neighbouring mainland shores. Although these impacts would not constitute coastal squeeze under the present definition, they may still require assessment and mitigation/compensation. This is a new finding which was not considered in the previous assessment.

- A number of past estimates of rates of historical saltmarsh loss have been made based on relatively short time periods. These provide a poor basis for the projection of long-term future change.

- A range of further studies are recommended. These include better quantifying past losses, making use of bathymetric data, deriving more specific local information of local sea level changes, examining vertical sedimentation rates, understanding the tidal and wave processes responsible for sediment movements, understanding the mechanisms of internal marsh dissection where defences have breached, modelling water level impacts on wave energy and tidal currents and their impacts on marsh edge morphology, and considering a range of future climate change scenarios.

- There is also a requirement for the direct monitoring of water levels and wave conditions in the outer, middle and inner estuary.

In the Blackwater Estuary, previous assessments of coastal squeeze were made in a number of studies and were incorporated into the SMP for the sub-cell 8 (Royal Haskoning, 2010a, b). Prior to the SMP, past losses arising from coastal squeeze in a number of estuaries, including Blackwater, Colne, Crouch and Roach, led to compensatory habitat being provided in several managed realignments in the Blackwater, including Tollesbury, Abbots Hall and Orplands. In the SMP, past losses (112ha) and predicted losses for epoch 1 (18ha) provided part of the justification for a regional habitat creation programme, which has included managed realignments at Devereux Farm, Wallasea Island, Fingringhoe. A review of actual changes in habitats based on monitoring data versus previous predictions of habitat change is underway at the time of writing this.

The main findings from the Slaughden case study are:

- The defences have had a significant effect on the form and behaviour of the shingle ridge. While rising sea level is not the only, and probably not the main, driver of landward movement of the ridge, it has probably been a minor contributory factor and is likely to become increasingly important in the future. A proportion of the losses of shingle beach are, therefore, believed to be due to coastal squeeze.
- Quantifying the magnitude of historical and future losses is also difficult to achieve with a high degree of confidence due to a number of factors:
    - the limited nature of historical beach morphological data
    - uncertainties regarding past and future rates of SLR, storminess and longshore sediment transport rates
    - uncertainties regarding future management interventions
    - difficulties in estimating the degree to which the beach ridge system would have rolled landwards in the absence of ‘holding’ defences or management actions
- Greater confidence in the assessment of future beach losses could be gained through a better understanding of the factors which influence alongshore and onshore/offshore movement of shingle on this section of coast, particularly in relation to the fate of shingle eroded during storms and its potential to move back onshore during fair weather periods.
- As a general principle, coastal squeeze of shingle beaches, as defined, is likely to occur where fixed defences are present at the back of the beach and if SL rises significantly. Avoiding a reduction in beach area and sediment volume in the face of SLR is only likely where the natural rate of sediment supply is high, where artificial nourishment is carried out, or where the defence line is moved landwards to provide accommodation space for shingle rollover.

The main findings from the Aber Dysynni and Broadwater case study are:

- The method to assess coastal squeeze can be applied both to estuarine habitats such as marshes and open coastal habitats such as sand and shingle beaches.

- There is some evidence to suggest that coastal squeeze could have affected the southern half of the Morfa Gwyllt spit since around 1900. However, a reduction in sediment supply, rather than SLR, is likely to have been the most significant cause of the losses in the south. The northern half of the spit has experienced either no net change or a gain in intertidal and supratidal area.

- In the future, the active storm beach ridge in the north has enough accommodation space to roll back (and, therefore, not experience coastal squeeze), but in the south its capacity to do so is constrained both by rock armour on the upper beach/ridge crest and by the railway line. The southern area is, therefore, likely to experience coastal squeeze.

- Within the Broadwater Estuary there is no evidence of past losses of habitats corresponding to coastal squeeze. It is believed that the marshes will be able to keep pace with the SLR in the range of 3 to 5mm/year in the future and, therefore, no future losses are anticipated under this scenario. However, there is high uncertainty in estimating potential future coastal squeeze losses (or potential intertidal habitat gains) due to underlying uncertainty regarding rates of supply of sediment, future rates of SLR, and future shoreline management policy.

- On the open coast the accuracy of the estimates of habitat loss is limited by the amount and quality of the historical map and aerial photographic evidence available, and by the episodic nature of beach erosion and recovery.

- At the present time, there is a lack of basic physical and biological information relating to the Dysynni Estuary area. A range of further studies could help better understand the causes for habitat changes in the past and allow better prediction of changes that might occur in the future. These studies include the characterisation of sediment budget and transport pathways, wave and currents, and tidal levels.

The SMP for this area of the coast (Royal Haskoning, 2011a) identifies a small predicted loss (8.27ha) associated with the high tide line (HTL) policies. No plans have yet been made to compensate for these anticipated losses. The SMP does not predict any coastal squeeze losses in the estuary.

7.8 Related work on coastal squeeze in the Humber Estuary

In addition to the case studies carried out in the present project, a series of studies investigating coastal habitat change and the influence of defences including coastal squeeze have been carried out in the Humber Estuary as part of the update to the estuary strategy (Humber 2100+; Jacobs, 2019c; KPAL, 2019a, b, c, d). The main findings of these studies were as follows:

- The original flood risk management strategy plan for the Humber made an assessment of past and future coastal squeeze losses and combined this with an assessment of direct losses to develop a programme of compensatory habitat. The method of assessing coastal squeeze losses was refined over time, but an important aspect was the assessment of past changes and using these to estimate future losses. The assessments assumed that any past losses of habitat (excluding direct losses) were due to coastal squeeze and other possible cause of loss were not examined further (apart from the impacts of the 18.6 year lunar nodal tidal cycle). Further details of the past assessments of coastal squeeze are given in Jacobs (2019d).

- The low density of survey data points can make the definition of MHWS and MLWS difficult. This can produce large errors in estimates of intertidal area. If intertidal area is defined between HAT and LAT, then the resulting calculations take advantage of a greater number of data points, which can lead to better assessment of the change in intertidal area over time (Jacobs, 2019; KPAL, 2019a). Intertidal areas measured from HAT to LAT are significantly larger than those measured MHWS to MLWS and trends over time may also differ.

- Trends in intertidal area over time using linear regression analysis are affected by the time period being considered, the number of data points and the region of the estuary (for example, inner, middle, outer) being considered (Jacobs, 2019c; KPAL, 2019b). Whilst a greater number of data points is desirable, the quality of individual data points needs to be carefully considered (KPAL, 2019d). In many instances, the trends identified by linear regression are not statistically significant at the 95% confidence limit.

- An analysis of aerial photographs over the last ~15 years (2003 and 2017) showed that there had been a net gain in vegetated intertidal area at a whole estuary scale (Jacobs, 2019). The expansion of vegetation in the upper intertidal zone had resulted in a slight net reduction in the area of unvegetated intertidal flat (KPAL, 2019a).

- Examination of changes in intertidal profile from 2003 to 2017 (KPAL, 2019a) suggested that there was a relatively small number of locations where coastal squeeze (based on the new definition developed in the present project) could be occurring. The potential locations were scattered around the estuary and a high-level analysis suggested that (i) losses in the rivers, inner estuary and middle estuary were likely to be due to channel and bank movements and not coastal squeeze (ii) losses in the outer estuary may be due to increases in wave height in storm surges. Such effects do not represent coastal squeeze (Jacobs, 2019c).
- After examining changes in intertidal extent from 1946 to 2017 (KPAL, 2019c), it was concluded that the pattern of intertidal change within the Humber did not correlate with mean SLR or variations in the lunar nodal tidal cycle. Variations in the position and size of banks and channels within the estuary are of critical importance, and further investigation of other drivers was recommended including periods of high river discharge, storm-surge induced tidal flows, intrinsic instability in tidal channels, dredging, and sub-decadal to decadal scale variations in wind-wave climate (KPAL, 2019c).

- The work of Horton et al. (2018) suggests that significant losses of UK saltmarshes might be expected when SLR exceeds 7.1mm/yr. In the Humber, according to UKCP18 low and medium emission scenarios, rates of annual SLR are not expected to exceed 7.1mm/yr before 2100 (using median predictions - Palmer et al., 2018), suggesting that widespread coastal squeeze losses might not be expected until after this time (Jacobs, 2019c).

- A range of further studies are being considered for the Humber to better assess past and future changes of coastal habitat extent and the role of flood defences. These studies include using additional historical data and recent survey data on habitat extent, the comparison of observed losses with the expectations of theoretical models for estuary evolution and the consideration of a range of scenarios for sediment supply and SLR.

7.8.1 Monitoring requirements for coastal squeeze

A recent report by Oaten et al. (2018) for National Resources Wales examined the monitoring requirements for coastal squeeze in Wales. Given the difficulty of understanding the causes for habitat losses and the limited available budgets, it was recommended that monitoring in Wales should focus on:

- tracking realised rates of SLR
- monitoring habitat losses that could be due to coastal squeeze (for example, changes to habitat distribution, extent and condition)

The report provides a detailed description of monitoring needed to cover these items including:

- sea level: ODC tide gauges, satellite altimetry (potentially for future use), UKCP18 for future projections
- habitat loss:
    - LiDAR, aerial imagery, bathymetry and ground surveys using GPS systems (RTK GNSS)
    - aerial and satellite imagery (including hyperspectral bands) and field habitat surveys

The present project has identified that understanding the causes of habitat loss is necessary to correctly identify coastal squeeze. Understanding the causes of loss may require additional data arising from fieldwork methods/monitoring techniques, including:

- determining sediment accretion through sediment erosion tables or sediment coring
- installing wave gauges or identifying historical wind patterns (and, therefore, waves) through local weather stations
- identifying water quality parameters, including suspended sediment (if available)

8 Conclusions

The main aim of this project was to better understand the causes of 'coastal squeeze'. This is particularly relevant where there is a legal obligation to compensate for the impacts of maintaining coastal flood management infrastructure or other infrastructure or management activities that could lead to coastal squeeze.

There are, nevertheless, other policy and legislative drivers for positively managing, enhancing and creating coastal priority habitats, which are unrelated to coastal squeeze as defined in this report. It is, nevertheless, anticipated that the present report will be helpful in improving our understanding of the likely rate and scale of impacts of accelerating SLR on coastal habitats in general, and promoting the need to periodically review the evidence available.

The main conclusions from the work are:

- In the past, definitions of coastal squeeze have shown some variations. This project has provided a new definition which clarifies the habitats that it can apply to and the types of habitat loss that do not constitute coastal squeeze. The definition focuses around whether the natural landward movement of habitats under rising sea levels is slowed or prevented by man-made structures or management actions.

- In the past, the way in which coastal squeeze has been assessed has varied across England and Wales. This project has provided a standard method and guidance to allow a consistent assessment. The method has been tested in 4 case studies which were chosen to represent a range of habitats and geographies where coastal squeeze was believed to be occurring. The case studies also illustrate what can be achieved when different amounts/levels of data are available for the assessment.

- The Aber Dysynni and Broadwater case study and the Slaughden and Sudbourne case study demonstrate that the method of assessing coastal squeeze can be applied both to estuarine habitats such as marshes and to open coastal habitats such as sand and shingle beaches, as well as areas where there is limited data availability.

- In the past, the term coastal squeeze was most commonly applied to saltmarshes (following Doody's (2004) original definition), but sometimes to other habitats. This project has reviewed Annex I, Section 41 and Environment Act Section 7 for Wales priority coastal/intertidal habitats and identified those habitats that could potentially be affected by coastal squeeze.
- The project shows that the processes governing the landward extent of habitats differ between habitats. For habitats such as mudflats and saltmarshes, the landward extent is controlled mainly by the limit of tidal inundation. For habitats such as beaches, the landward extent is controlled by both tidal inundation and wave run-up. For sand dunes, the landward extent is controlled by the aeolian (wind) action.

- Identifying coastal squeeze requires an assessment of the impact of the effect of structures, or management actions, in preventing or slowing the ability of a habitat to move landwards in response to SLR (i.e. to transgress). This project has demonstrated that even under natural baselines (without defences), habitat extent may decrease over time if steeply rising land results in there being insufficient room for them to migrate landwards. In these cases, any resulting habitat losses should be considered a form of natural change (accepting that accelerated SLR is not really 'natural').

- The new method provides guidance on how to attribute a confidence score (high, medium, low) to the verdict of whether or not there has been/will be coastal squeeze at a location. Where confidence is 'low', 2 approaches can be taken (i) adopt the precautionary principle, or (ii) carry out further studies to increase the confidence in the findings.
- Previous assessments of coastal squeeze have often lacked basic data with which to scientifically assess the causes of habitat loss. The limitations of past studies (most commonly related to saltmarshes) include the failure to scientifically demonstrate that:

    (i) habitat losses have been due to SLR

    (ii) habitat losses have not been due to other causes (for example, increases in wind waves, lateral channel movements)

  Increasing the level of confidence is vital, using the best available data from scientific studies and other sources. In some cases, additional data sets and/or analysis already exist to improve the scientific understanding.

- Whilst the case studies do not represent full assessments in their own right, they suggest that historic coastal squeeze losses, especially those of saltmarshes, might well be smaller than previous assessments have suggested. This arises for a number of reasons:

    (i) the habitat losses, may have been caused by factors other than SLR against the defences. As noted above, causes of habitat loss, other than SLR and the presence of defences, were commonly overlooked in applying the precautionary principle

    (ii) increases in wave energy were overlooked as causes for the loss of marsh habitats in previous assessments

    (iii) the natural losses of habitats due to steeply rising land may not have been fully accounted for. In some studies, there was an assumption that, in the absence of defences, saltmarsh extents would be maintained through natural migration. It is possible that, in some instances, the presence of steeply rising land further landwards may limit this natural transgression

- Although the role of coastal squeeze as a cause for past habitat losses may have been overstated in some instances, it is important to carefully consider whether coastal squeeze could become more widespread in the future under a scenario of increased SLR. Sediment supply will be an important factor in determining this.

- This project has demonstrated that past changes in habitats may have been caused by a number of factors and has proposed an approach to separate out the losses arising from these causes from those attributable to coastal squeeze.

- The agreed definition excludes a number of causes of change in habitat extent, including downdrift erosion due to defences. However, it is acknowledged that decreases in sediment supply have the potential to increase the susceptibility of downdrift habitats to coastal squeeze. The role of these factors, and the implications for any mitigatory actions, would need to be carefully appraised on a site by site basis.

- Some previous assessments of future coastal squeeze losses have extrapolated past losses. Given that some previous assessments of past losses may have been overestimates, it follows that predictions of future losses may also be overestimates, although this needs to be tempered against anticipated increases in the future rate of SLR.
- The case studies have demonstrated that assessing coastal squeeze on open coast habitats is difficult. Unlike tidally dominated landforms such as marshes and mudflats (whose extent can be estimated by projecting tidal contours inland), determining the degree to which a beach ridge system would have rolled landwards in the absence of structures or management actions is more problematic. Furthermore, assessing the causes of observed changes in beach area requires the roles of changes in wave energy (some of which are unrelated to SLR) and sediment supply. These complexities may result in a low confidence in the final assessment of coastal squeeze and, therefore, the need to either (i) adopt the precautionary principle or (ii) carry out further studies to increase confidence in the findings.
- The case studies demonstrate that full assessments of coastal squeeze need additional data and studies to better understand past changes in habitat extents and the causes of these changes. This understanding is needed to make informed judgements about likely future coastal squeeze losses.
    - For saltmarshes examined in this project, these studies would include: bringing historical gains/loss studies up to date, gathering additional data on local rates of past SLR, considering habitat quality, examining the role of waves/other factors for vegetation loss, and considering a range of future climate change scenarios for sediment supply and sea level.
    - For the shingle beaches at Slaughden and Sudbourne, these studies would include better understanding the factors which influence alongshore and onshore/offshore movement of shingle, particularly in relation to the fate of shingle eroded during storms and its potential to move back onshore during fair weather periods. For the sand and shingle beaches of Aber Dysynni, these studies include the characterisation of sediment budget and transport pathways, wave and currents, and tidal levels.
- Implementing the approach is likely to require collaboration between developers, the Environment Agency (as developer or competent authority), Natural England, National Resources Wales and perhaps others (for example, other competent authorities, including local planning authorities, wildlife groups and research bodies) to both source baseline data and provide expert opinion that secures consensus on the outcome.
- It is recommended that the outcomes of this report are shared and discussed with relevant parties involved with the assessment of future coastal squeeze in England and Wales. The report is relevant to the assessment of losses at SMP, strategy and scheme levels. The report is relevant to FCERM structures such as flood embankments and walls, management actions such as shingle ridge reprofiling, and non-FCERM structures such as road/railway embankments and quay walls.
- It is not anticipated that this guidance will be used to make an immediate wholescale review of coastal squeeze assessments in England and Wales, but

that the new approach be taken at the next scheduled review point for SMPs and strategies. Indeed, the guidance can be used to help shape the operational approaches as compensatory habitat provision and indeed ‘net gain’ restoration progresses into the next 6-year FCERM investment programme and beyond. This will be integral to the wider work arising from the current ‘SMP Refresh’ programme to ensure FCERM remains environmentally sustainable in the long term.

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Abbreviations

AIMS	Asset Information Management System
AMSL	Annual mean sea level
ATT	Admiralty Tide Tables
BTELSS	Barataria-Terrebonne Ecological Landscape Spatial Simulation
CASI	Compact Airborne Spectrographic Imager
CC	County council
CCO	Channel Coastal Observatory
Cefas	Centre for Environment, Fisheries and Aquaculture Science
Defra	Department for Environment, Food & Rural Affairs
DTM	Digital Terrain Model
EGA	Expert geomorphological assessment
EN	English Nature
ENSO	El Niño Southern Oscillation
ESA	European Space Agency
FCERM	Flood and coastal erosion risk management
GIS	Geographic information system
GPS	Global positioning system
HAT	Highest astronomical tide
HTA	Historical trend analysis
HTL	Hold the Line
HW	High water
LAT	Lowest astronomical tide
LiDAR	Light detection and ranging
LWM	Low water mark
MAFF	Ministry of Agriculture, Fisheries and Food
MARSED	Long-term marsh sedimentation model
MCZ	Marine conservation zone
MHW	Mean high water
MHWN	Mean high water neap
MHWS	Mean high water spring
MLW	Mean low water
MLWS	Mean low water spring
MMO	Marine Management Organisation
MR	Managed realignment
MSTR	Mean spring tidal range
MTL	Mean tide level
NAI	No active intervention
NAO	North Atlantic Oscillation
NE	Natural England
NERC	Natural Environment and Rural Communities
NNR	National Nature Reserve
NRW	Natural Resources Wales/Cyfoeth Naturiol Cymru
NTSFL	National Tidal and Sea Level Facility
NVC	National Vegetation Classification
OD / AOD / ODN	Ordnance datum/Above ordnance datum/Ordnance Datum Newlyn – used interchangeably
PSMSL	Permanent Service for Mean Sea Level
RCP	Representative Concentration Pathway
RTK GNSS	Real-time kinematic global navigation satellite system
SAC	Special Area of Conservation
SDCP	Solent Dynamic Coastal Project
SL	Sea level
SLAMM	Sea Level Affecting Marshes Model
SLR	Sea level rise
SMP	Shoreline Management Plan
SPA	Special Protection Areas

SSSI	Site of Special Scientific Interest
TE2100	Thames Estuary 2100
UCL	University College London
UKCP18	UK Climate Projections 2018
USGS	United States Geological Survey
WeBS	Wetland Bird Survey
WEPA	Western Europe Pressure Anomaly
WFD	Water Framework Directive
WICS	What Is Coastal Squeeze

Appendix A: Case studies

A.1 Introduction

This section tests the proposed method using case studies. The case studies provide value in determining whether changes constitute coastal squeeze at the sites, highlighting the approach that can be taken for differing locations/circumstances. They can be considered preliminary assessments, but not fully approved approaches and as such are NOT to be used for any other purpose (such as revising SMP policies, compensation targets or estuary strategies).

The following study sites were chosen in agreement with the project board:

- Lymington Harbour, Hampshire - saltmarsh habitats
- Blackwater Estuary, Essex – for mudflat and saltmarsh
- Slaughden and Sudbourne Beach, Suffolk - mixed sand and shingle beach habitats
- Aber Dysynni and Broadwater Estuary - sand/shingle beach, shingle ridge, saline lagoon in the shingle ridge, mudflats, sandflats, saltmarsh)

The main purpose of the case studies is to:

- test the proposed method that has been developed to see if it can be applied in practice
- identify improvements to the method

The case studies identify:

- how the revised definition and approach differ from previous assessments of coastal squeeze
- the requirement for further studies to clarify coastal squeeze losses at the study site

The case studies draw on existing information contained within reports or readily available data sets such as Environment Agency LiDAR. For the Lymington case study, the main source of previous information is the Solent Dynamic Coast Project (SDCP, 2008). No additional digitisation of historical maps or detailed morphological/ecological modelling of future coastal habitat extents was carried out. For the Blackwater, Slaughden and Aber Dysynni and Broadwater Estuary case studies some additional analysis of historical maps, aerial photographs and LiDAR data, together with some preliminary morphological modelling of future coastal habitat extents, was undertaken by KPAL. LiDAR and aerial photography data for the Blachwater and Slaughden case studies were obtained from the DEFRA Data Services Platform (https://environment.data.gov.uk) and the Channel Coastal Observatory website (https://www.channelcoast.org). Information about designated nature conservation areas in England was obtained from the Natural England Open Data website (https://naturalengland-defra.opendata.arcgis.com). Lidar and nature conservation area data for Wales were obtained from the Lle Geo-portal (https://lle.gov.wales). Aerial photographs were provided by NRW. Tidal data were obtained from the National Tidal and Sea Level Facility website (https://www.ntslf.org) and the Permanent Service for Mean Sea Level website (https://www.psmsl.org).

A.2 Lymington

A.2.1 Overview of method

The Lymington case study tested the first version of the method that was developed. This method is similar to the final version of the method (Chapter 6) and differs only in that it doesn't have a dedicated 'Scoping' stage at the start or a formal assessment of confidence levels. The method that was tested is shown in Box 3.

The following sections show how each of the steps of the method can be applied at Lymington.

Box 3: Method to identify past and future coastal squeeze losses for saltmarshes at Lymington

1. **Determining past coastal squeeze losses**

Screening

- Test 1: Have relevant structure/s and/or management actions been present over the period of interest?
- Test 2: Has there been suitable accommodation space landward of the structure over the period of interest?
- Test 3: Have there been readily observable losses of habitat in front of structures (either LWM retreat or internal erosion) over the period of interest?
- Test 4: Have relative sea levels risen in the region over the period of interest?
    - Baseline geomorphological assessment
    - Quantifying past habitat losses
    - Evaluation of causes of loss and the role of coastal squeeze
    - Identify a shortlist of sites at risk
    - Expert judgment of habitat loss attributable to coastal squeeze

2. **Determining future coastal squeeze losses**

Screening

- Test 1: Are there likely to be relevant structure/s and/or have management actions been present over the period of interest?
- Test 2: Is there likely to be suitable accommodation space landward of the structure over the period of interest?
- Test 3: Are relative sea levels anticipated rise in the region over the period of interest?
    - Baseline geomorphological assessment
    - Quantifying future habitat losses
    - Extrapolate past losses – Historical trend analysis
    - Use of predictive models

3. **Expert judgment of habitat loss attributable to coastal squeeze**

A.2.2 Scoping

Lymington lies approximately 5.5km from the Isle of Wight on the western side of the Solent. The area of interest used for this case study is defined by the Solent Dynamic Coastal Project (SDCP, 2008), which extends from the Solent to the dock used for the Isle of Wight ferry.

The large areas of saltmarsh that exist outside Lymington Harbour are the focus of this assessment, since the SDCP (2008) study did not examine mudflats. The saltmarsh to the east and west of the main navigation channel are analysed separately due to differences in the extent of defences and high land which are relevant to identifying coastal squeeze (Figure 0.1 and 7.2).

The period of interest for the Lymington assessment was taken to be 1946 to 2001 to coincide with the measurements of saltmarsh changes from the SDCP (2008) and the earliest records of historic sea level rise (SLR) from a nearby tidal gauge (Southampton – Haigh et al., 2009, Wahl et al., 2013).

Figure 0.1: The saltmarshes at Lymington are backed by steeply rising land. This image of marshes on the eastern side of the navigation channel was taken in 2017.

Photo courtesy of Nigel Pontee.

A.2.3 Determining past coastal squeeze losses

Screening test 1 - Have relevant structure/s and/or management actions been present over the period of interest?

Method

As part of this assessment, a range of data sets was examined:

- Environment Agency 2m Composite DTM LiDAR (Environment Agency, 2019b)
- SDCP saltmarsh maps (SDCP, 2008)
- Aerial imagery (RGB) captured in 2013 (Environment Agency, 2019c)
- Environment Agency Asset Information Management System (AIMS) data set (Environment Agency, 2019d)
- Google Earth imagery (Google 2019)

The data sets were then analysed on GIS to define:

1. the extent of the saltmarsh. This was done using aerial imagery or SDCP saltmarsh maps
2. whether the landward extent of the saltmarsh lies adjacent to a flood defence asset or other man-made structure that would prevent a natural transgression. The flood defence assets were located using AIMS data and were compared with saltmarsh extent data captured in the previous task
3. whether the landward extent of the saltmarsh lies adjacent to naturally rising land as determined from LiDAR. In GIS, the HAT contour was extracted from the LiDAR and compared with the saltmarsh extent data set captured in Task 1

Results

On the east side of the navigation channel there are no constructed defences and the land rises naturally to high ground. This high ground landward of the marshes lies above HAT (~1.32mOD UKHO, 2015), and reaches approximately 12m ODN. The AIMS defence type also defines the 'defence' as high ground in this area. Large sections of marsh in both the east and west sections also consist of islands with channels on their landward boundaries. In some places, these channels separate the marshes from the defences further landwards. The sinuosity of the channels indicates they are unlikely to be man-made.

The absence of defences on the east side of the navigation channel means that the loss of marshes does not constitute coastal squeeze ('due to defences preventing the landward transgression of habitats'). The east side of Lymington study area will, therefore, be dismissed from the remaining sections of the study. The study area stops short of the Tanners lane in the East, beyond which there are short sections of defences comprised groynes, a timber revêtment, and a concrete wall.

On the west side of the navigation channel, there are a range of man-made structures, including defences such as embankments, walls and breakwaters as well as a harbour. Where the saltmarsh lies against these defences, it could potentially be prevented from naturally transgressing landward. This was determined using AIMS data, LiDAR and aerial imagery (Figure 0.2). The losses of saltmarsh in this area could, therefore, potentially be coastal squeeze.

Figure 0.2: Aerial image of site with dashed line indicating present defence line and HAT from AIMS data and red line indicating potential present day HAT line in the absence of defences.

Screening test 2 - Has there been suitable accommodation space landward of the structure over the period of interest?

Method

As part of this assessment, a range of data sets were used including;

- Environment Agency 2m Composite DTM LiDAR (Environment Agency, 2019b)
- Aerial imagery (Environment Agency, 2019b)
- AIMS data set (Environment Agency, 2019d)

The data sets were then analysed on GIS to answer the following questions:

1. Where does the present-day HAT lie? This was determined using the defence line in AIMS and aerial imagery.
2. Where would the present-day HAT lie in the absence of defences? Is this located landward of the present-day defence line?

Results

On the west side of the navigation channel, the horizontal distance between present day defences/HAT line and the potential location of the HAT line (the ~1.32mOD elevation contour) in the absence of defences extends up to 850m beyond the present defence line and HAT. Aerial imagery indicates that this is agricultural land. Saltmarsh could potentially colonise this area if the defences were absent. This means that any losses of the fronting saltmarsh in this area could potentially be coastal squeeze.

Screening test 3 - Have there been readily observable losses of habitat in front of structures (either LWM retreat or internal erosion) over the period of interest?

Method

This assessment used the saltmarsh extent/change maps produced by SDCP (2008). Only the data presented in SDCP (2008) has been examined.

Result

On the west side, there were significant losses (shown in red) of saltmarsh between 1946 and 2001 as shown by the SDCP (2008) in Figure 0.3. This loss has been composed of frontal retreat and internal fragmentation. Where the marshes lie directly against the defences these losses could potentially represent coastal squeeze.

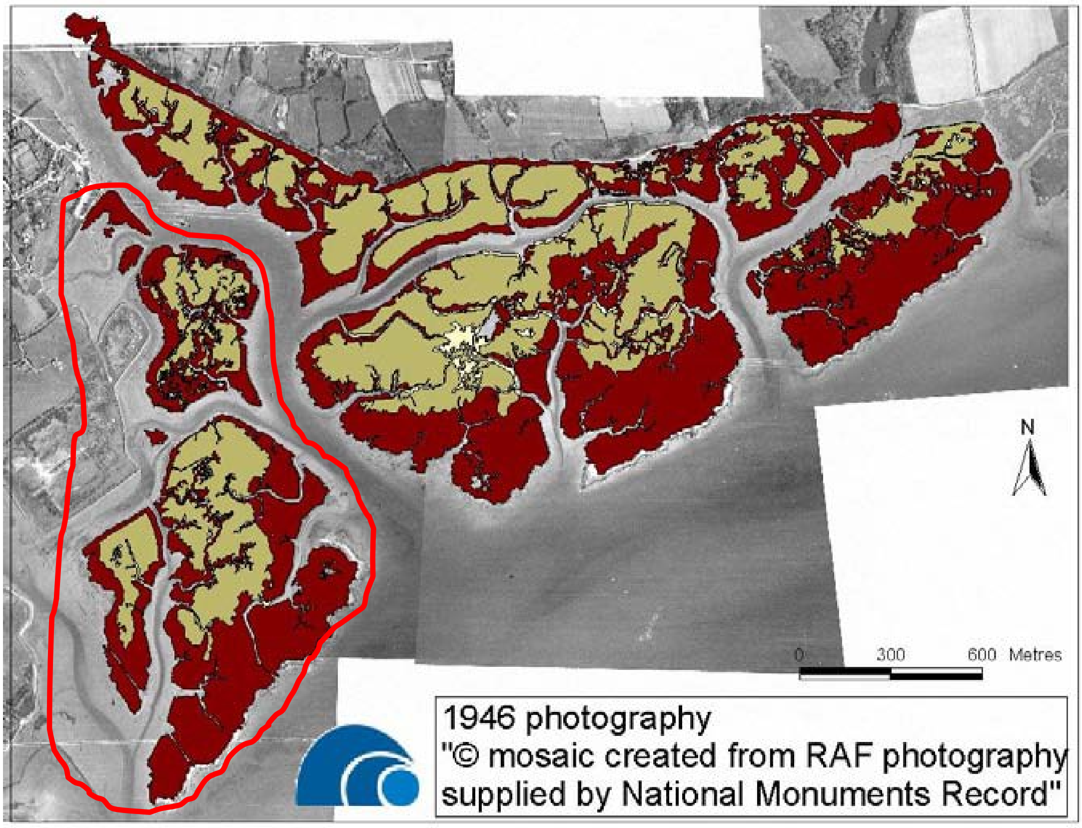

Figure 0.3: Difference in saltmarsh extent between 1946 and 2001. Red line marks losses on west section of study area. Red/brown areas indicate losses, beige areas are stable and areas in white are gains (SDCP, 2008).

Screening test 4 - Has relative SL risen in the region over the period of interest?

Method

As part of this assessment, a brief literature review found 2 main references which had processed and analysed sea level changes over the past century using data from local tide gauges. These are:

- Haigh ID. 2009 'Extreme sea levels in the English Channel 1900 to 2006' (Doctoral dissertation, University of Southampton)

- Haigh I, Nicholls R and Wells N. 2009 ‘Mean sea level trends around the English Channel over the 20th century and their wider context’ Continental Shelf Research, 29(17), pp.2083-2098

- Wahl T, Haigh ID, Woodworth PL, Albrecht F, Dillingh D, Jensen J, Nicholls RJ, Weisse R and Wöppelmann G. 2013 ‘Observed mean sea level changes around the North Sea coastline from 1800 to present’ Earth-Science Reviews, 124, pp.51-67

Using the identified relevant sources, the following tasks were completed;

1. The nearest tidal gauge stations with measurements of tidal levels over the period of interest were identified.
2. The long-term averaged rates of SLR were found.
3. The occurrence and magnitude of uplift/subsidence was assessed.

Result

Although there is now a tide gauge at Lymington (PSMSL, 2019), it only became operational in 2008. The nearest long-term tide gauge is located at Southampton, approximately 20km away. At Southampton, increases in sea level averaged over different periods have been documented by various authors, including Haigh et al. (2009) and Wahl et al. (2013). The rates of mean sea level rise range from 1.19(+/-0.24)mm/yr between 1935 and 2005 (Haigh et al., 2009) and 1.7(+/- 1.6)mm/yr between 1950 and 2011 (Wahl et al., 2013). It is noted that the error margin in Wahl et al. (2013) is relatively large due to high rates of mean sea level rise observed between 1980 and 2011 of around (3.1 +/- 1.1mm/yr).

There is some uncertainty surrounding measurements of sea level on the south coast due to uncertainties in vertical land motion (Haigh, 2009). Analysis of tide gauge records indicate that south coast subsidence rates are likely to be less than 0.5mm/year, with the potential for some uplift from Portsmouth and Southampton tide records, which would have reduced relative SLR (Haigh, 2009). Land uplift records are unlikely to have exceeded rates of sea level rise such that they offset one another completely. Therefore, based on the evidence outlined above, it is likely that sea levels rose at Lymington over the period 1946 to 2011. This means that any losses of habitats could potentially be coastal squeeze.

Conclusions from screening tests

There have been losses of saltmarsh on both the west and east side of the navigation channel at Lymington in the past and these have been accompanied by a rise in sea level of approximately 7 to 9mm over the period 1946 to 2001. The absence of defences on the eastern side of the channel means that losses here cannot be attributed to defences having held up the landward transgression of saltmarshes. As such, the losses on the eastern side of the channel cannot be considered as coastal squeeze. Some areas of the marshes on the western side are backed by defences and low-lying land. In some areas, the marshes are separated from the defences by channels. In these areas, it appears that the marshes have the potential to move landwards over the mudflat. However, some areas of marsh lie directly against the defences. The losses of saltmarsh have occurred over a period when there has been SLR and, therefore, the losses of the marshes which lie against the defence could potentially be due to coastal squeeze. It is, therefore, necessary to proceed to more detailed assessment of this area to verify whether the losses represent coastal squeeze or not (see below).

A.2.4 Expert geomorphological analysis of historical losses

Baseline geomorphology at Lymington

A number of previous reports and papers describe the geomorphological processes at Lymington. The main aspects of note are:

- **Tidal regime**: The estuary is mesotidal (mean spring tidal range of 2.5m) and ebb-dominant. Tides exhibit a semi-diurnal tidal regime and a double peak at high water.

- **Sediment types/sources**: Clayey silt is found in the inner saltmarshes on the banks of the Lymington River and between Town Quay and Yacht Haven. The intertidal mudflats are composed of sandy, clayey silt and cheniers along south-eastern edges of the saltmarshes are comprised of shells, sand and gravel (Ke and Collins, 2002; SCOPAC, 2004; Hydraulics Research, 1991). The main sediment source is believed to be from the erodible cliffs at Christchurch Bay (Black and Veatch 2008). However, background suspended sediment levels in the area are low (typically <11mg/l). Sediment accumulates within Lymington Harbour which requires annual dredging, but the navigation channel itself does not require maintenance dredging. It is probable that there is a net seaward transport of suspended sediment in the wider estuary due to the ebb dominant tidal regime.

- **Wave conditions:** The prevailing winds are from the south-west (Ke and Collins 2002), which drive waves up the Solent towards Lymington, although Hurst Spit and the Isle of Wight limit the fetch of any waves travelling from the west to south-west direction. Lymington saltmarshes are also exposed (perhaps more so than the west) to storms driven from the east or south-east direction . There is some evidence to suggest that storm waves in the North Atlantic may have increased between 1948 and 2018 and, therefore, there is the potential for waves' height at Lymington to have increased (Castelle et al., 2018). No detailed analyses of changes in the local wind-wave climate at Lymington were carried out as part of this study and further detailed assessment would be required to determine the role of wave erosion in saltmarsh losses at Lymington.

- **Lateral channel movements:** Aerial imagery and saltmarsh losses (SDCP 2008) do not indicate any major or significant lateral movements of the main channel navigation channel (as occurs in other estuaries such as the Humber) between 1946 and 2001. Further analysis of bathymetric data would be needed to carry out a more detailed assessment of the channel evolution over time.

Quantifying past saltmarsh habitat losses

Losses of saltmarsh at Lymington were reported by SDCP (2008) as shown in Table 0.1. The average loss of saltmarsh recorded over the 4 periods was 2.78ha/yr. The rate of annual saltmarsh loss appears to increase over time.

Table 0.1: Losses of saltmarsh reported by SDCP 2008.

Year	Area	Saltmarsh loss (ha)	Saltmarsh loss (ha/yr)
1946	266.3	-	-
1954	248.7	17.6	2.2
1971	207.7	41	2.41
1984	162.2	45.5	3.5
2001	110.9	51.3	3.02

Losses of saltmarsh at Lymington between 1946 and 2001 were quantified by SDCP (2008). However, losses on either side of the navigation channel were not reported separately.

Evaluating causes of saltmarsh loss and the role of coastal squeeze

Identify a shortlist of sites

SDCP (2008) considered that only those losses on the western side of the navigation channel could potentially be coastal squeeze due to the presence of coastal defences in this area. Applying the new method produces the same conclusion. Based on visual inspection of Figure 0.2, the losses on the western side of the navigation channel, which could potentially represent coastal squeeze, constitute approximately 25 to 35% of the overall losses. The total losses over the period from 1984 (date of implementation of the Habitats Directive) to 2001 were 51.3ha, the losses of the western side of the navigation channel are estimated as being between 13 and 18ha. A more detailed assessment of the actual losses could be carried out using GIS.

Expert judgement of habitat losses attributable to coastal squeeze

SDCP (2008) observed that the past rates of marsh loss were greater than would have arisen due to SL submergence alone (assuming no vertical accretion – see section 2.5.2). From this, the SDCP (2008) deduced that other factors such as wave erosion, dredging, Spartina dieback and pollution may also have played a role in past saltmarsh losses in Lymington.

A number of lines of argument can be put forward to support the conclusion that the losses of saltmarsh at Lymington can be attributed to the marsh failing to keep pace with SLR:

- Internal creek dissection has been observed on the Lymington marshes and could be attributed to an increase in tidal currents through the creeks due to the increased sea levels. Further analysis of tidal levels and the magnitude and frequency of storm surges would be needed to evaluate this in more detail.

- Sediment supply rates are low and this could create a situation where vertical accretion rates of the marsh are less than SLR, which could result in the dieback of vegetation and the increased erosion of the marsh platform by waves and tidal currents. However, consideration of this issue is hampered by a lack of information about the present topographic elevations of the marshes relative to the tidal frame, and about modern and historic rates of sedimentation on the marshes. Further studies are needed to investigate these issues.

- It is possible that the rates of marsh loss have been related to the rates of SLR, with the rates of loss increasing over time as the rate of SLR has increased (Wahl et al, 2013). Further investigation of the rates of SLR at Lymington would be needed to verify this.

The role of other causes of vegetation dieback such as pathogens and water quality has not been investigated. The level of the saltmarsh surface and the number of inundations it received had not been investigated. Further studies into these aspects would help clarify the role of these other factors.

The definition that has been developed for coastal squeeze in this project (Chapter 5) is:

“Coastal squeeze is the loss of natural habitats or deterioration of their quality arising from anthropogenic structures, or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to SLR in conjunction with other coastal processes. Coastal squeeze affects habitat on the seaward side of existing structures.”

To summarise, at Lymington there have been observed losses of some marshes that lie against sea defences. It is possible that SLR is a cause for the observed losses, although this is subject to some uncertainty due to (i) the lack of detailed data correlating local SLR and (ii) the existence of a number of other potential contributory factors. In trying to decide: “Have the observed losses of coastal habitats been due to the prevention of the landward transgression”, there are 2 approaches that can be adopted:

Approach A:

- Recognise that the losses on fronting saltmarshes are due to SLR and that without defences the extent of these marshes would have been greater.
- Consider that any losses on the seaward side of the defences should require compensation and, therefore, be termed ‘coastal squeeze’.
- At Lymington, this approach would suggest that some of the marsh losses on the western side of the navigation channel (where the marshes lie against the defences) should be considered as coastal squeeze (if it is assumed that SLR and the presences of the defences are resulting in a loss of marsh).
- The problem with this approach is that it is possible that these losses may have occurred even in the absence of a defence since high land lies only a relatively short distance landward of the defences. A further step is, therefore, required – see Approach B.

Approach B:

- Evaluate baseline conditions to see if the larger extent of marshes that would have existed in the absence of defences would have been maintained by migrating landwards – in other words, construct a ‘hypothetical baseline case’.
- If the marshes could have migrated landwards into accommodation space and maintained their overall extent under SLR, then all of the losses on the fronting marsh would constitute coastal squeeze.

- If the marshes would have been prevented from migrating landwards by rising land, then it is likely that the losses observed on today's marshes would still have occurred. This means that the losses on today's marshes would not constitute coastal squeeze.

Following Approach B at Lymington:

Figure 0.4 shows the theoretical landward extent of marshes based on an estimated 1946 HAT. The 1946 HAT line has been calculated by assuming the worst case of historic SLR of 3.3mm/yr (comprising 1.7mm/yr long-term average 1950 to 2011, including 1.6mm/yr error). The contour was extracted from modern LiDAR assuming no significant changes to land surface have taken place since 1946. For the purposes of this case study, the LiDAR has assumed to be an accurate representation of the ground surface. If a full study was being done, some ground truthing of the LiDAR would be recommended and some sensitivity testing of the results carried out.

The figure (Figure 0.4) suggests that, even without defences, the lack of accommodation space would have meant that SLR rise would have resulted in the position of the HAT being able to move landwards by around 50m in some limited and isolated sections. This would have corresponded to an increase in marsh area of less than 2ha. This is equivalent to around 1% of the total observed losses recorded between 1946 and 2001. This suggests that the majority (99%) of the observed losses at Lymington would have occurred even in the absence of defences. This would also suggest that the majority of the observed losses at Lymington are not coastal squeeze since they would have occurred even without the defences being present.

Figure 0.4: Differences in area between 1946 HAT (shown in pink) and 2018 HAT line (blue) in the absence of defences.

A.2.5 Determining future coastal squeeze losses

Screening test 1 - Are there likely to be relevant structure/s and/or management actions over the period of interest?

Method

The North Solent Shoreline Management Plan (NSSMP 2010) was reviewed to identify the recommended future shoreline management policies in the study area.

Results

For the frontages around Lymington Harbour there is a Hold the Line policy over the next 100 years. Upstream of Lymington Harbour there is a Regulated Tidal Exchange policy in the short term (0 to 20 years). In the east section, there are no man-made defences with natural rises to high ground, therefore, these areas of saltmarsh are not considered further. It is likely that the land to the west of the navigation channel will continue to be defended over the next 100 years and, therefore, some of the losses of saltmarshes here (where they lie up against the defences) could be judged to be at risk from coastal squeeze.

Screening test 2 - Is there likely to be suitable accommodation space landward of the structure over the period of interest?

Method

As part of this assessment, a range of data sets was used, including;

- Environment Agency 2m Composite DTM LiDAR (Environment Agency, 2019b)
- Aerial imagery (Environment Agency, 2019c)
- AIMS data set (Environment Agency, 2019d)
- UKCP18 (2018) rates of SLR under RCP 8.5 (worst emission scenario - 50^{th} percentile) for the $10km^2$ that contains Lymington Harbour and surroundings

Results

In the east section, the land naturally rises to high ground and, therefore, coastal squeeze is not expected to apply here.

To the west of the navigation channel, defences are expected to maintain their current position over the next 100 years. The land that lies behind the defences lies below the present-day HAT mark. As tidal levels increase to approximately 0.68m above present day (2019) by 2100, the accommodation space in this area could increase if HAT rises from 1.32mOD to 2mOD by 2100. The maximum horizontal distance between the defence line and the HAT equivalent contour increases from approximately 850m to 1,100m. The existence of accommodation space landward of the defence means that any future losses of the fronting saltmarsh could potentially be coastal squeeze.

Screening test 3 - Are relative sea levels anticipated to rise in the region over the period of interest?

Method

As part of this assessment, projected SLR data under RCP 8.5 (worst emission scenario - 50th percentile) for the 10km^2 that contains Lymington Harbour and surroundings was extracted from UKCP18 (2018). If a full assessment was being done, then a range of scenarios could be considered.

Results

Using the chosen scenario, projected sea levels are expected to increase to approximately 0.68m above present day (2019) levels. This rise in SLR could potentially lead to the loss of saltmarsh on the west side of the navigation channel by drowning and wave erosion. Depending on the approach adopted (see section 7.2.4 - Expert judgement of habitat losses attributable to coastal squeeze), these changes could be considered as coastal squeeze of saltmarsh.

Conclusions from screening tests

The absence of defences on the eastern side of the channel means that any future losses here cannot be considered as being due to coastal squeeze. Some of the marshes on the western side are backed by defences and low-lying land. Future losses of saltmarshes in this area could potentially be due to coastal squeeze. It is, therefore, necessary to proceed to more detailed assessment of this area.

A.2.6 Future habitat losses

The previous SDCP (2008) report used 2 methods to investigate future changes in marsh extent:

- historical trend analysis
- inundation modelling

Extrapolate past losses based on historical trend analysis

The SDCP (2008) used the historic rates of marsh losses as shown in Table 0.1 to predict future changes in marsh extent relative to the 2001 baseline. Using this data, 3 scenarios were predicted (i) best-case scenario (lowest observed erosion rate), (ii) worst-case scenario (highest observed erosion rate) and (iii) a long-term average.

- The lowest rates of marsh loss were recorded between 1946 and 1954, with a loss rate of 2.2ha per year. The SDCP calculated that if this rate continued, all the saltmarsh would be lost within around 50 years (2051).
- The highest rates of marsh loss were recorded between 1984 and 2001, with a loss rate of 3.0ha per year. The SDCP calculated that if this rate continued, all saltmarsh would be lost within around 37 years (2038).
- The long-term average recorded between 1946 and 2001 had a loss rate of 2.8ha per year. The SDCP calculated that if this rate continued, all saltmarsh would be lost within around 39 years (2040).

- As noted previously, these losses covered both sides of the navigation channel and did not differentiate coastal squeeze losses from other losses (such as pollution, dredging).

Inundation modelling

The SDCP (2008) also did some further modelling using a simple inundation model, which was taken to be an indication of the losses of saltmarsh that could arise due to coastal squeeze in the future.

The model used a linear rate of SLR of 6mm/yr with varying accretion rates of 0mm/yr, 3mm/yr and 6mm/yr (equivalent to modelled SLR). The model predicts saltmarsh area by 2100 according to accretion rates:

- 6mm/yr results in no change of saltmarsh area, since accretion keeps pace with SLR
- 3mm/yr results in around 35ha of saltmarsh remaining
- 0mm/yr results in 0ha saltmarsh remaining

These rates of saltmarsh loss assumed that:

- future SL would rise at a linear rate
- the losses would be governed by the balance between vertical accretion and SLR
- the losses would not be driven by any increases in wave energy
- the losses would not be driven by any additional deterioration in vegetation

Expert geomorphological analysis of future losses

Natural England (2019) states that the SSSI units which encompass both east and west sections (Hurst Castle and Lymington River Estuary SSSI – unit 004 and 005) are in an “unfavourable – recovering” condition. The SSSI assessment concluded that at an estuary wide scale, losses of saltmarsh are attributed to coastal squeeze. Unit 004 to the west was last updated in 2018, while Unit 005 was last updated in 2010 and, therefore, this assessment may be out of date.

Previously, the SDCP (2008) determined that only the losses on the western side of the navigation channel could be considered coastal squeeze.

Applying the new definition and assessment method produces the same conclusions. As indicated in section 7.2.4 (Expert judgement of habitat losses attributable to coastal squeeze), a rough estimate indicates that these losses constitute 13 to 18ha of the total losses that occurred between 1945 and 2001.

As also observed in section 7.2.4, the predicted rates of loss in the 3 scenarios are less than the actual rates that have been observed. SDCP (2008) concluded that factors in addition to submergence have been responsible for the observed losses. The difference between past losses and those predicted by inundation modelling could be due to dieback of vegetation. This dieback could be caused by increased inundation resulting from the marsh surface failing to keep pace with SLR. Dieback could potentially be caused by other factors, although there is currently no evidence to examine other causes at Lymington.

There is no reason to suggest why processes driving historic losses of saltmarsh will not continue into the future. SDCP (2008) predicted the total losses of the marshes would occur between 2038 and 2051.

Much of the past SDCP (2008) work followed the proposed method that has been suggested by the present project. We would recommend that any updated assessment of coastal squeeze considers the following:

- additional data sets for past SLR
- additional data sets to show changes in marsh extent since the SDCP study
- additional assessment of changes to habitat quality
- a range of future SLR scenarios
- an assessment of likely sediment supply to the marshes in the future
- an assessment of the past wind-wave climate to establish whether periods of erosion have coincided with a more energetic wave climate
- quantifying the present topographic variation relative to the tidal frame (not just MSL), vegetation types and health, sediment properties with the remaining marshes
- investigating the marsh surface elevation and past SLs (MSL and extremes) to determine the changes in inundation of the marsh surface
- an assessment of additional causes for Spartina dieback (other than increased inundation)
- revised best- and worst-case scenarios for changes in future marsh extent

A.2.7 Conclusions

This case study has applied the proposed new method to Lymington, drawing upon previous work presented in SDCP (2008). The main conclusions are as follows:

- The absence of defences on the eastern side of the navigation channel means that losses of saltmarsh here cannot be considered as being due to coastal squeeze. This agrees with the previous SDCP (2008) assessment.
- The marshes on the western side are backed by defences and low-lying land. In this area, the losses of saltmarsh have occurred over a period when there has been SLR and, therefore, the losses could potentially be due to coastal squeeze. However, it is noted that some of the marshes appear to be separated from the defences by creeks or mudflats and, therefore, do not appear to be prevented from migrating landwards by the presence of the defences. The proportion of marshes that lie directly against the defence has not been quantified in this case study. Further GIS mapping would be needed to do this.

- SDCP (2008) concluded that there was a range of factors involved in the loss of saltmarsh at Lymington, including wave erosion, dredging, Spartina dieback and pollution. The new assessment concludes that many of the previously identified factors could be interlinked and the main cause of the loss of marshes at Lymington could be the failure of the marsh to accrete vertically in line with SLR. This leads to increased inundation and dieback of vegetation, which means the marsh platform can be more easily eroded by waves and currents.

- It is noted that little is currently understood about the importance of SLR, relative to the other factors (such as pathogens, pollution) in the dieback of vegetation. Further studies are needed to improve understanding. This is an important issue and is likely to apply at other sites in the UK. Without these detailed studies, there is a risk that coastal squeeze is being inaccurately identified.

- In the future, the loss of saltmarsh is likely to continue. A number of recommendations are made with regard to updating the previous SDCP predictions of future coastal squeeze loss.

- Closer investigation of the concept of landward transgression of saltmarsh and considering a hypothetical natural baseline highlights the difficulty in deciding whether or not coastal habitat changes represent coastal squeeze and whether such changes should be compensated for.

- At Lymington, the construction of defences removed an area of former marsh. Following the initial construction of defences, it is likely that there was a phase of marsh expansion in front of the defences. The extent of these newly formed marshes versus the former marshes has not been quantified in this case study. However, there was subsequently a period of extensive loss of these fronting marshes. Two approaches can be proposed to determine whether these losses should be termed coastal squeeze:
    - Approach A – assume that since the original loss of marshes due to reclamation was not compensated for (since it occurred before the Habitats Directive was implemented), the subsequent losses to the marshes in front of the defences should be compensated for. Therefore, marsh losses should be termed 'coastal squeeze' and form part of future compensatory habitat requirements.
    - Approach B – Consider whether the losses of saltmarsh in front of the present-day defences would have occurred without defences. Examining the topography at Lymington shows that even if no defences had been built here, the natural marsh would have extended to the base of high ground in 1946 and there would have been no room for landward retreat under SLR. Therefore, it is likely that there would have been a loss of marsh extent from 1946 to 2001. Following this approach would suggest that any past or future losses of marsh in front of defences do not represent coastal squeeze since they would have occurred anyway.
    - Discussion – although both approaches offer technically correct solutions, in this instance Approach A is recommended given that this recognises the changes relative to a 1992 baseline and provides a sensible balance with respect to the least cost and most environmentally sustainable solutions. This may not be correct in every case and 'expert opinion' or the combined advice of Defra, the

Environment Agency and Natural England, should be used to identify the 'best' answer.

- This case study has demonstrated that it is not possible to comprehensively complete all aspects of the method without more time. As such, the case study cannot give a definitive answer on the amount of habitat loss that could be attributed to coastal squeeze at Lymington. The case study has, however, identified that future studies that would be needed. It has also helped identify some challenging issues that are likely to rise at other sites.

A.3 Blackwater

A.3.1 Overview of proposed assessment method

The proposed method developed in the 'What is coastal squeeze?' (WICS) project is shown in Box 1. The following sections show how each of the steps of the method can be applied to the Blackwater Estuary.

A.3.2 Scoping

The Blackwater Estuary is the largest estuary in Essex, defined in this study as extending between the normal tidal limits at Beeleigh, just west of Maldon, and a line drawn between a point east of Bradwell nuclear power station and West Mersea (Figure 0.5). For the purposes of this study, the limit of the estuary on the north side of Mersea Island is taken to be the B1025 causeway crossing of the Strood Channel. The estuary also includes the subsidiary 'offshoots' of Salcott Channel, Tollesbury Fleet, and Lawling Creek. The total shoreline length is 123.5km and the channel thalweg length is approximately 23.2km. The present tidally active area below HAT (taken to be 3.3AOD) is approximately 5,571ha).

The intertidal areas and land areas surrounding the active estuary lie within the Blackwater Estuary Site of Special Scientific Interest (SSSI), the Blackwater Estuary Special Protection Area (SPA), and the Blackwater Estuary Ramsar site. Part of the intertidal zone and reclaimed marshes also lies with the Blackwater Estuary National Nature Reserve (NNR). The subtidal area and parts of the intertidal zone fall within the Essex Estuaries Special Area of Conservation (SAC), and the whole of the estuary below the level of mean high water (MHW) forms part of the Blackwater, Crouch, Roach and Colne Marine Conservation Zone (MCZ). A number of managed realignment sites have been created in the Blackwater, including at Orplands, Abbotts Hall Farm, Tollesbury and Northey Island. The latter 2 sites have a secondary defence line unlike the former 2 sites, which extend up to high ground and, therefore, do not require a secondary defence line.

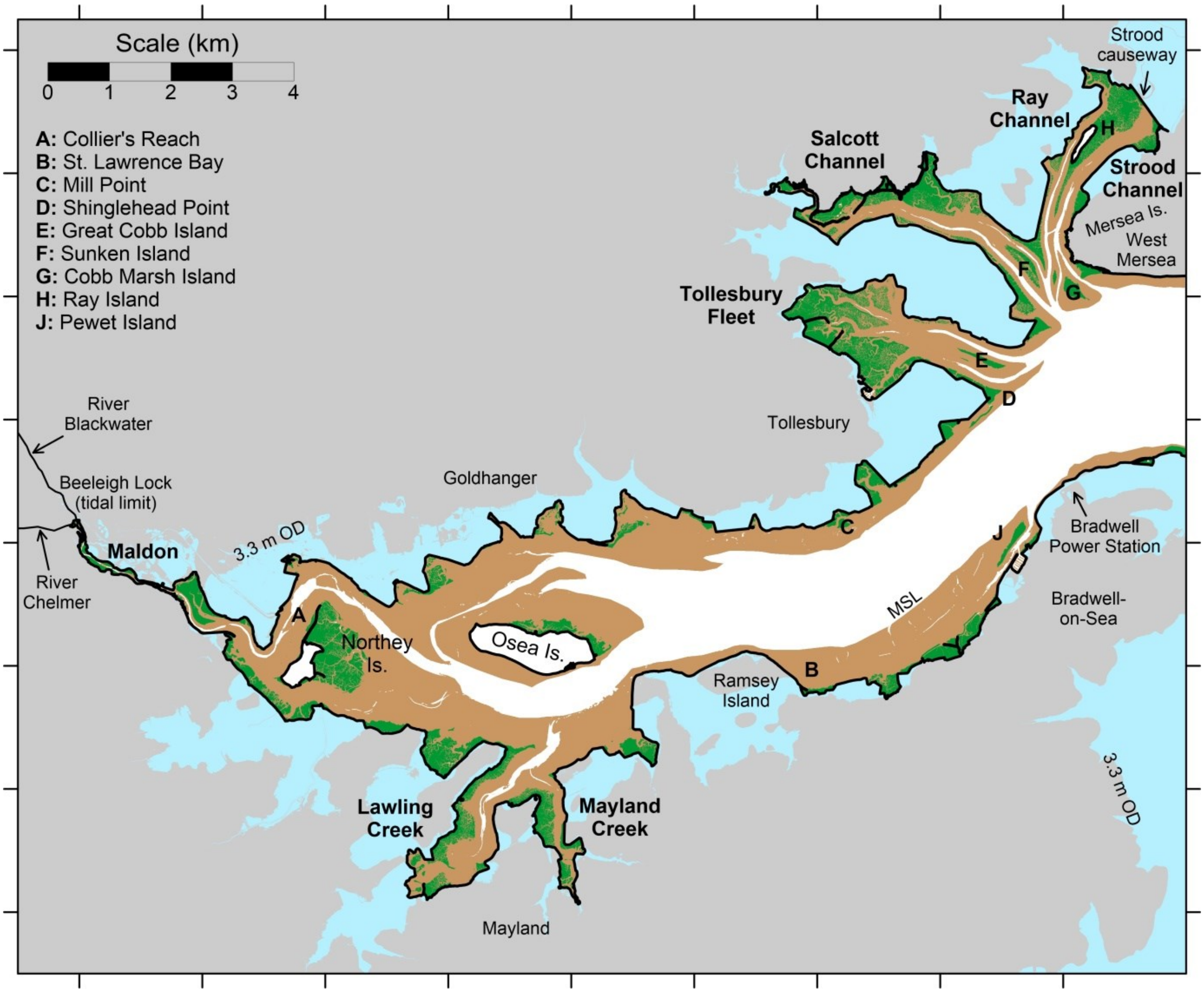

Figure 0.5. Major morphological features of the Blackwater Estuary, showing the main locations mentioned in the text. The area shaded green represents the 'saltmarsh window' defined in this study as lying between 1.6m and 3.3m AOD, while the area shaded brown represents intertidal area below 1.7m AOD and above the lower limit of the 2017 Environment Agency LiDAR surveys (approximately equivalent to mean sea level). Blue areas indicate areas behind the defence line with elevations below 3.3m AOD.

A.3.3 Determining past coastal squeeze losses

Screening test 1 - Have relevant structure/s and/or management actions been present over the period of interest?

Method

This question was approached by referring to published literature, unpublished reports, Ordnance Survey 5m resolution gridded topographic data, aerial photography and LiDAR topographic data sets covering the estuary.

Results

The present tidally active area of the Blackwater Estuary (defined here as the area below HAT) represents approximately half of the maximum area which existed before the beginning of embanking and reclamation. The earliest known embankments were constructed in the early Medieval period, and by the mid-18th century the active estuary plan form was very similar to that seen today (Gramolt, 1960; Pye and French, 1993; van der Wal and Pye, 2000). There have been several embankment failures since the late 19th century, some of which have not been repaired, leading to areas of rejuvenated intertidal habitat, and also a number of managed realignment schemes, including at Northey Island, Tollesbury, Orplands and Abbott's Hall carried out since the early 1990s. At the present time, approximately 75.2km, representing 60.9% of the shoreline of the tidally active estuary, defined as lying west of a line between West Mersea and Bradwell power station, is backed by maintained defences, with potentially tidally floodable land behind (below 3.3m AOD). A total of 15.6km (12.6%) of the estuary margin is defended (for coast protection reasons), but has no potentially floodable land (below 3.3m AOD, approximate HAT level) behind. There are 8.3km of former defences, now breached, which have a surface elevation above 3.3m AOD, but the land behind lies below this level, and 24.4km of shoreline is undefended, with rising land above 3.3m AOD behind (Table 0.2).

Table 0.2. Lengths of defences and undefended shoreline in the Blackwater Estuary.

	Maintained defence with floodable land behind	Maintained defence with no floodable land behind	Former defences, including those breached as part of managed realignment	Undefended with rising ground	Total
Lengths in km					
Shore-attached	72.9	14.3	7.4	19.0	113.5
Islands	2.4	1.3	0.9	5.4	10.0
Total	75.2	15.6	8.3	24.4	123.5
Percentages of whole estuary					
Shore-attached	64.2	12.6	6.5	16.7	100
Islands	23.7	13.3	9.1	54.0	100
Total	60.9	12.6	6.7	19.7	100

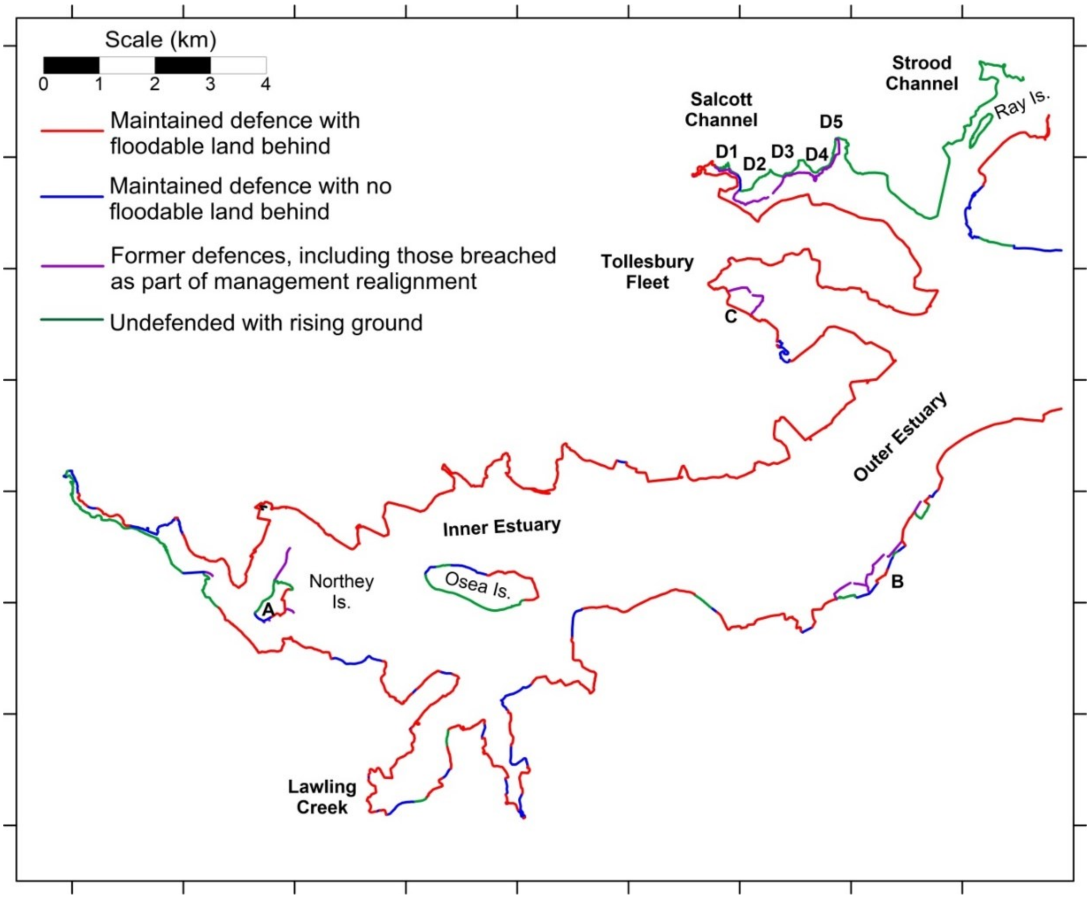

Figure 0.6. Locations of flood defences in the Blackwater Estuary, and sections which are undefended.

Screening test 2 - Has there been suitable accommodation space landward of the structure over the period of interest?

Method

This question was addressed by examining published information, Ordnance Survey maps and 5m resolution gridded data sets, aerial photography and Environment Agency LiDAR data sets. Data were processed using Golden Software GIS software and in-house macros.

Results

The answer to this question is yes. The total area of the potentially active estuary, represented for this purpose by the 3.3m AOD contour, which is the approximate level of the highest astronomical tide (HAT), is 8,616ha. The area of defended, but potentially tidally floodable, land behind the defences is 3,045ha (equivalent to approximately 35% of the total potential tidally active area of the estuary, defined by the 3.3m AOD contour behind the defences). If sea level were to rise by 1m, increasing the average HAT level to 4.3m AOD, the area of potential tidally floodable land behind the defences would increase to 4,282ha, an increase of 1,244ha (44%). Most of the increase in potential tidally floodable area is located around the margins of the inner estuary, including Maldon and Heybridge.

Screening test 3 - Have there been readily observable losses of habitat in front of structures (either LWM retreat or internal erosion) over the period of interest?

Method

Reference has been made to published studies and unpublished reports, notably Burd (1992), Pye and French (1993), van der Wal and Pye (2004), Cooper et al. (2000, 2001), Royal Haskoning (2006), Phelan et al. (2011) and Thomson et al. (2011). Further analysis of changes in the intertidal area between the defences (approximate HAT line) and mean sea level (MSL) has also been carried out for this study using Environment Agency LiDAR data for 2 time periods (1999 to 2002 and 2017). Estimates of changes in the area of the 'saltmarsh window', defined by tidal limits of 1.6m AOD and 3.3.m AOD, have also been made. However, not all of the sediment surface between these levels is covered by saltmarsh vegetation.

Results

GIS analysis of aerial photographs by Burd (1992) identified a net loss of saltmarsh area of 142ha between 1973 and 1988 (an average rate of 9.4ha/yr). By comparing the estimates made by Burd (1992) with the results of further GIS analysis on 1997 and 1998 aerial photographs, Cooper et al. (2000) reported a decline in saltmarsh area for the Blackwater Estuary from 880.2ha in 1973 to 738.5ha in 1988 and 683.6ha in 1998 (an average rate of loss of 5.49ha/yr between 1988 and 1998). They concluded that, owing to differences in the scale of the 1973 and 1988 aerial photographs and in the digitisation methods used, the losses reported by Burd (1992) are likely to have been overestimates. Based on analysis of Ordnance Survey maps, van der Wal and Pye (2000, 2004) estimated an average rate of net saltmarsh loss of 2ha/yr over the longer time period (1874 to 1998). Relatively minor changes in saltmarsh extent were reported by IECS (1993) between 1935 and 1978.

Royal Haskoning (2006) examined change in saltmarsh extent specifically within the Blackwater SPA and estimated a decline from 733.31ha in 1988 to 684.2ha at the time of SPA designation in 1995, to 670.2ha in 1997 and 621.1ha in 2004 (an average annual rate of loss of 7ha/yr from 1997 to 2004).

Thomson et al. (2011) reported a net loss of saltmarsh area in 34 of 78 SSSI management units in the Blackwater Estuary between 1997 and 2008. The largest net loss recorded was -2.59ha in Unit 54 (Northey Island Saltmarsh and Mud), although most units (20) showed a net loss of <0.5ha. A total of 42 units showed net gain (maximum 0.71ha) or no net change, with no data available for one unit and no saltmarsh present in one unit. The total area of saltmarsh in 2008 was reported to be 713.3ha, including the Orplands West managed realignment area, which lies just outside the SSSI boundary.

Phelan et al. (2011) reported a saltmarsh area of 1,373.80ha for the combined Blackwater-Colne estuaries in 2006 to 2009, compared with 1,671.7ha in 1973, 1,482.9ha in 1988 and 1,378.5ha in 1998 reported by Cooper et al. (2001). They suggested that, owing to incomplete aerial photograph coverage, the full extent of saltmarsh may have been underestimated in the Burd (1992) and Cooper et al. (2000, 2001) studies, although evidence was not provided. Taken at face value, a comparison of the Cooper et al. (2000) and Phelan et al. (2011) data would suggest an average rate of loss of only 0.47ha/yr in the combined Blackwater-Colne system between 1998 and 2008.

Since the different studies referred to above used different methods, had different areal coverage, and had varying levels of quality control, the absolute magnitude and rate of saltmarsh loss within the Blackwater Estuary remains open to considerable uncertainty. It is also unclear whether minor fragmentation (less than the detectable error through the analysis) of marsh surfaces has increased. Although the evidence suggests there has been a significant reduction in saltmarsh area within the Blackwater Estuary over the past century, and particularly in the second half of the 20th century, the extent of loss since the date of SSSI notification (12 January 1993) is poorly quantified. Rates of loss appear to have slowed over the past 20 years and, in the same period, there have been gains of around 73ha from managed realignment habitat creation schemes. The Essex and South Suffolk Shoreline Management Plan 2 (Royal Haskoning 2010a, b), while noting the apparent recent reduction in rates of saltmarsh loss, concluded that coastal squeeze has been, and is likely to be, a significant coastal management issue in the Blackwater and neighbouring estuaries. However, no previously published quantitative information is available relating to changes in the areal extent of the intertidal zone as a whole (tidal flats plus saltmarsh), and conclusions about coastal squeeze have been based entirely on perceptions of changes in area and quality of saltmarsh.

Screening test 4 - Has relative SL risen in the region over the period of interest?

Method

Reference has been made to published literature and new analysis of tide gauge records carried out for the Class ‘A tide gauges at Lowestoft and Sheerness, data being obtained from the National Tidal and Sea Level Facility (NTSLF) website.

Results

Previous analyses of UK tide gauge data have provided evidence of SLR over the past century, with some indication of an acceleration over the past 30 years. Woodworth et al. (2009) calculated an average rate of rise of mean sea level (MSL) of +2.54 +/- 0.39mm/yr at Lowestoft for the period 1956 to 2006, and an average rate of rise of +2.23 + 0.13 mm/yr at Sheerness for the period 1901 to 2006 (albeit with a significant gap in the record for the latter station). A later analysis reported by Woodworth (2018) suggested a longer term increase in MSL at Sheerness of 1.680 +/- 0.084mm/yr between 1834 and 2006. Digital data available for both stations have been reanalysed and updated for the purposes of this study in Figure 0.7. Calculated average rates of MSL rise are 3.06 +/- 0.24mm/yr at Lowestoft for the period 1964 to 2018 and 2.14 +/- 0.53 mm/yr at Sheerness for the period 1968 to 2006, consistent with a slight increase in the rate of rise over recent years.

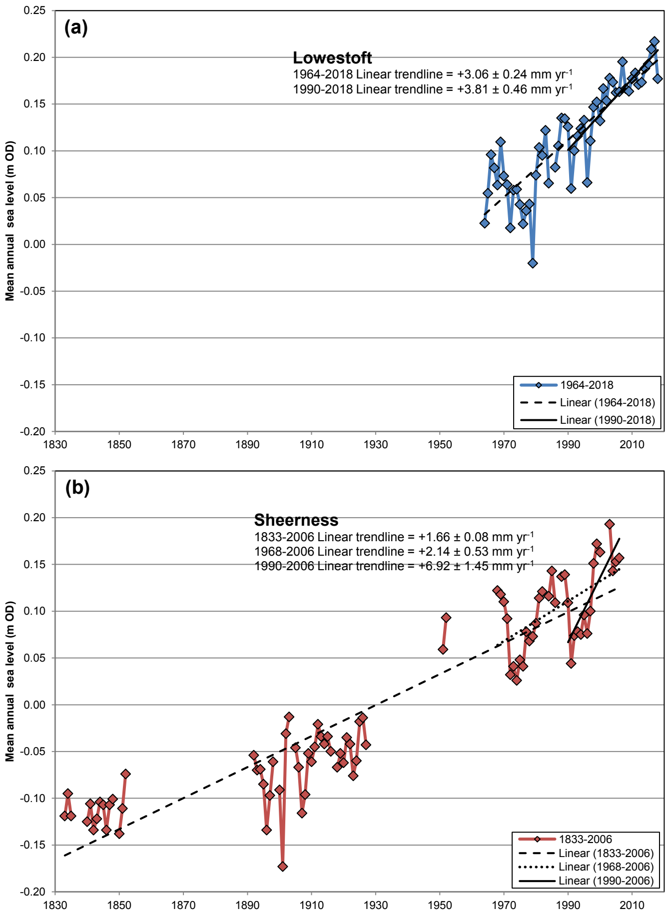

Figure 0.7. Trends in mean annual sea level at Lowestoft and Sheerness, with linear trend lines fitted for the full periods of record, and since 1990 (original data source: NTSLF).

Conclusions from screening tests

It is concluded that all 4 screening tests are met for the Blackwater Estuary as a whole, although not for all parts of the shoreline. Therefore, it is possible that coastal squeeze has occurred in the past.

A.3.4 Expert geomorphological analysis of historical losses

Baseline geomorphology in the Blackwater Estuary

The Blackwater Estuary is relatively large compared with the size of the Rivers Chelmer and Blackwater which flow into it, and geological evidence suggests that the topographic depression within which the estuary lies owes its origin to erosion and downcutting by fluvial and fluvio-glacial meltwaters at times of lower sea level. A buried valley cut largely into London Clay and overlying fluvial and fluvio-glacial gravels is now partly infilled by freshwater, brackish and marine sediments of Late Pleistocene and Holocene age (Greensmith and Tucker, 1971; IECS, 1993). The estuary outline, defined by the 3.3m AOD contour, is highly irregular, reflecting the nature of pre-Holocene fluvial and fluvio-glacial incision and sediment deposition. Outliers of Tertiary rocks (mainly London Clay) create constriction points on the estuary morphology at Bradwell, Tollsebury, Osea Island, Northey Island and Maldon (Figure 0.8).

The seaward end of the estuary is relatively deep, reaching 20m below chart datum (CD) opposite West Mersea. Between the eastern part of St. Lawrence Bay and the defined seaward limit the intertidal zone is relatively narrow compared with the width of the subtidal zone, but landward of St Lawrence Bay both the depth and width of subtidal zone decrease rapidly. The low water channels bifurcate (divide into two) around Osea Island, with the dominant channel located on the south side where there is a confluence with Lawling Creek. The main channel then extends towards the tip of Northey Island, beyond which it becomes very shallow and almost dries at times of low flow. Northey Island has been linked to the mainland by a tidal causeway at least since Saxon/Viking times. Partly owing to this obstruction, there is now very little flow along Southey Creek on the south side of Northey Island. Osea Island is also linked to the mainland by a causeway across the tidal flats at the head of Goldhanger Creek which can be crossed at low tide.

The inner estuary around Maldon has been heavily modified by construction and drainage diversion, including construction of the Chelmer and Blackwater Canal in the mid-18th century. The construction of a mill and locks effectively limited the influence of tides at the seaward end of the Rivers Blackwater and Chelmer. Dredging on a relatively small scale for navigational purposes has been carried out for decades in the approaches to Maldon and Heybridge Basin. Most of the dredged sediment is deposited at the north-western corner of Northey Island.

A large proportion of the formerly active intertidal area, including saltmarshes, has been embanked and claimed for agriculture since Medieval times (Gramolt, 1960). Many of the tidal creeks were ‘beheaded’ by embankment construction and left ‘over-sized’ with respect to the remaining active intertidal area.

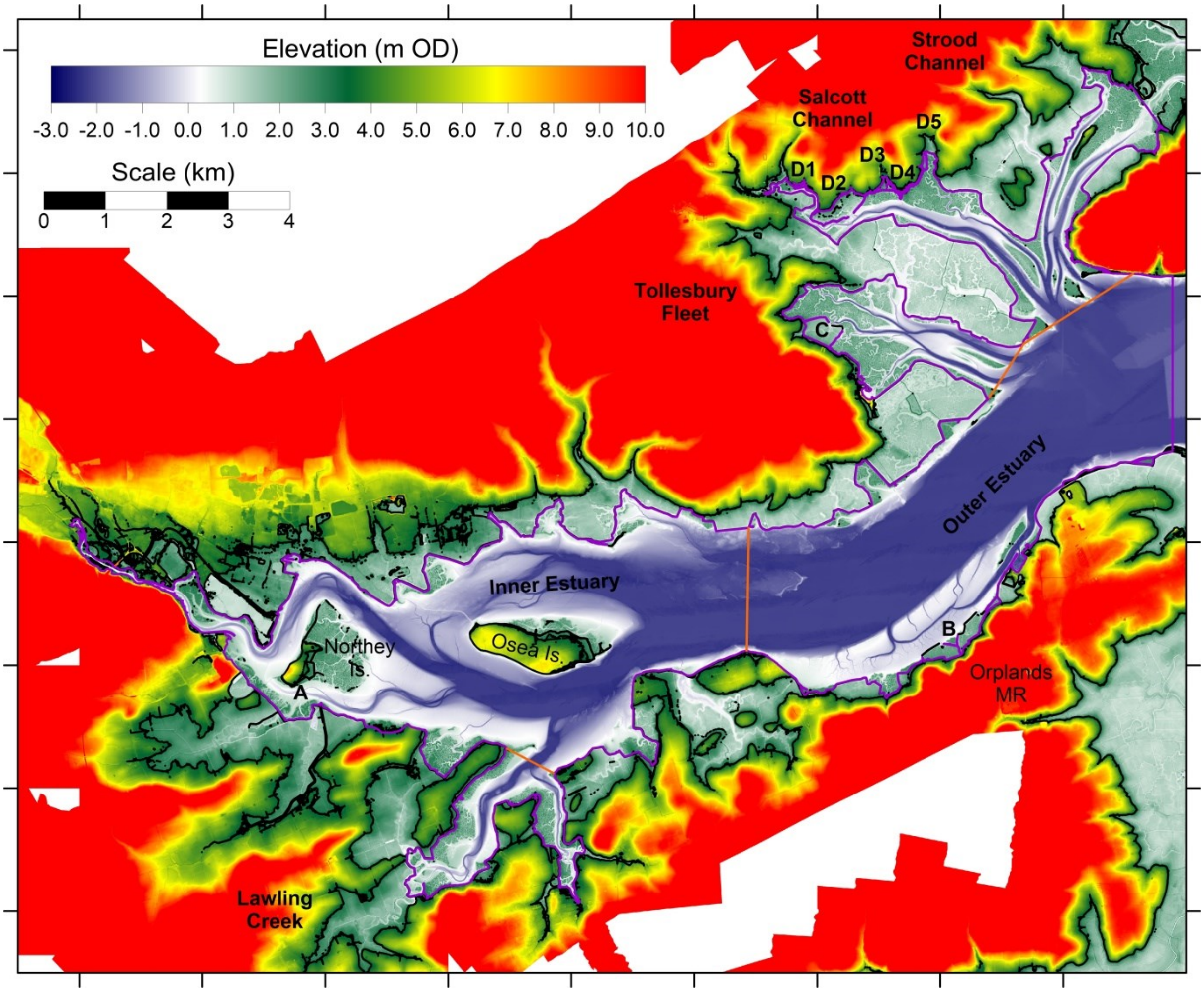

Figure 0.8. Composite LiDAR DTM (from all available surveys, flown 1999 to 2017). The black line shows the 3.3m AOD contour (approximate level of HAT). The purple line shows the HAT line along the toe of the defences and represents the reference boundary line of the estuary. Orange lines divide the main estuary into sectors: Inner Estuary, Outer Estuary, Lawling Creek, Tollesbury Fleet, and Salcott and Strood Channels. Managed realignment sites are indicated as follows: A (Northey Island); B (Orplands); C (Tollesbury); D (Abbotts Hall, of which there are 5 separate compartments).

The present intertidal zone between MSL and HAT represents 31.81% of the present tidally active estuary below HAT level, and 20.6% of the former tidally active estuary before embanking and reclamation (Table 0.4). The saltmarsh 'window' between 1.6m AOD and HAT forms a discontinuous fringe around the main estuary, outside the defences, and along the main estuary represents a relatively small area compared with the area of tidal channel seaward of the 1.6m AOD contour. In the subsidiary estuarine embayments (Tollesbury Fleet, Salcott Channel, the Strood and Mayland Creek) saltmarsh occupies a relatively larger compared with the open water channels.

The estuary experiences a macro-tidal regime with a mean spring tidal range (MSTR) of 4.6 to 4.9m and a mean neap tidal range (MNTR) of 2.6 to 2.9m. The elevation of mean high water spring tides (MHWS) increases up the estuary from c. 2.4m AOD at West Mersea to 2.7m AOD at Osea Island and 2.8m AOD at Maldon (Table 0.3). The elevation of mean high water neap tides (MHWN) also increases up the estuary from 1.1m AOD at West Mersea to 2.2m AOD at Maldon. The levels of HAT reported by UKHO show a more complex pattern, but for present purposes an average of 3.3m AOD has been assumed for the estuary as a whole.

Table 0.3. Tidal levels (m AOD) in the Blackwater Estuary. Source: Admiralty Tide Tables UKHO 2019; nd = no data.

	West Mersea	Bradwell Waterside	Osea Island	Maldon
HAT	3.3	2.9	3.4	3.2
MHWS	2.4	2.5	2.7	2.8
MHWN	1.1	1.5	1.7	2.2
MSL	0.04	0.04	0.05	nd
MLWN	-1.5	-1.4	-1.4	nd
MLWS	-2.2	-2.3	-2.2	nd
LAT	nd	nd	nd	nd
OD	-2.66	-2.68	-2.63	-0.11
MSTR	4.6	4.8	4.9	nd
MNTR	2.6	2.9	3.1	nd

Hydrographic measurements indicate that much of the outer estuary is ebb-dominated (that is the ebb is shorter than the flood, with correspondingly higher maximum tidal current velocities on the ebb tide), while the inner estuary is weakly flood-dominant (West et al., 1988; Pye and French, 1993; IECS, 1993; CCRU, 1996). In Tollesbury Creek, which is a tributary to the outer part of the main estuary, ebb dominance is evident. CCRU (1996) suggested that this spatial variation in tidal asymmetry may be responsible for the change from erosion in the outer estuary to accretion in the inner estuary, but this does not account for the transfer of sediment from the outer to the inner estuary, since ebb-dominance in the outer estuary might be expected to favour export of sediment to the open sea and flood dominance to favour landward transport. As noted by CCRU (1996), the relative magnitudes of maximum ebb and flood velocities do not necessarily give a good indication of long-term net sediment transport directions and retention patterns.

The estuary has a flattened ‘S’ shape in plan, with the inner estuary and entrance areas having an almost W-E orientation and the rest of the outer estuary having a SW-NE orientation. Waves penetrating the estuary mouth from the east can travel up-estuary as far as Mill Point with little impediment, and significant wave heights are relatively large near Bradwell and the entrances to Salcott Channel and Tollesbury Fleet. Refraction and shoaling of these waves leads to loss of energy, but they still have a significant impact on the north bank of the estuary east of Osea island; the remainder of the estuarine shoreline is relatively sheltered from such waves, although under NE wind conditions significant internally-generated waves can impact on the shore of St. Lawrence Bay. Under south-westerly wind conditions, internally generated waves increase in size eastwards of Osea Island towards the estuary entrance, with relatively large significant wave heights impacting on both sides of the estuary (Wolf, 1984).

The bed of the deeper parts of the estuary is largely sandy, with patches of gravel and mud, but the higher tidal flats consist predominantly of muddy sand and mud. A high tide beach composed of sand, shingle and shell is present in some areas, most notably along the fringes of the outer estuary and around Osea Island. The saltmarshes are composed predominantly of fine silt with subsidiary amounts of clay and fine sand; the modal size typically lies in the range 8 to 10μm, the calcium carbonate content is typically 0 to 2% except adjacent to shell cheniers, and the organic matter content (estimated by Loss on Ignition) lies in the range of 5 to 10%. Sediment supply from the rivers is relatively minor compared with that entering the estuary from the sea, and derived from erosion of parts of the estuary bed and short sections of unprotected cliffs.

Geochemical and mineralogical data suggest that the main source of mud is provided by the London Clay (Crooks and Pye, 2000).

The area of the tidally active estuary below assumed HAT level (5,571ha) represents 64.7% of the total area, which could be subject to tidal influence in the absence of defences (Table 0.4). Of the tidally active area, the upper intertidal zone between MSL and HAT represents 1,687ha (12.4%), while the upper intertidal zone above MSL represents 1,845ha (21.0% - sum of upper intertidal zone, natural saltmarsh window and MR sites).

Sea level history in the Outer Thames area is relatively complex, with a number of periods of transgression and minor regressions identified during the Holocene. The post-glacial (Devensian) marine transgression first influenced the outer estuary around 8,500 years BP, and had reached approximately -3m AOD by 5,000 BP. Since that time, there is stratigraphic and lithological evidence that sea level has oscillated but with an overall upward trend (Greensmith and Tucker, 1971, 1973; Devoy, 1977; Long, 1985; Wilkinson and Murphy, 1995). There is evidence of a significant regression between 5,000 and 4,000 BP, with further minor regressions around 3,000 and 1,700 BP, separated by minor transgressions. There may have been a further slight transgression during the Medieval warm period (1,000 to 750 BP), followed by a slight regression during the Little Ice Age (650 – 170 BP) and a return to transgression within the past 170 years. The tendency for average lower mean sea level (perhaps by 15 to 20cm) at times during the Little Ice Age could have been a factor promoting the expansion of saltings and phases of embanking and reclamation during this period, although firm evidence is presently lacking. The onset of marsh erosion in the outer and middle estuary after around 1838 has undoubtedly been favoured by the tendancy to rise in sea level.

Quantifying past saltmarsh habitat losses and habitat quality

Previous studies (for example, Royal Haskoning, 2006) have suggested a major loss of saltmarsh area between 1973 and 2004, amounting to approximately 250ha (29%) within the SPA. No specific assessment of change in habitat quality, as distinct from habitat extent, has previously been made. Furthermore, no detailed assessments have been made of the change in entire intertidal area (for example, between HAT and LAT, MHWS and MLWS or MHW and MLW).

For the purposes of this study, an initial assessment of change in intertidal area between the HAT contour (assumed for this purpose to be 3.3m AOD throughout the estuary) and the MSL contour (assumed to be 0m AOD across the estuary) has been made, based on Environment Agency LiDAR surveys in the periods 1999 to 2002 and 2017. All data processing was carried out by KPAL using GIS procedures applied in numerous previous investigations of estuarine morphological and habitat change. A comparison of elevations of hard surfaces obtained from the 2 surveys indicated a difference of less than +/- 15cm in most areas. Changes in the extent of the saltmarsh ‘elevation window’ taken to extend between 3.3m and 1.6m AOD, were also quantified by KPAL using the LiDAR DEMs. The results for the estuary as a whole are shown in Table 0.4 to Table 0.6, and the spatial distribution of changes are shown in Figure 0.9 to Figure 0.14.

Table 0.4. Intertidal areas within the Blackwater Estuary, both active and potential, based on 2017 LiDAR data, Note that 1.6m AOD (the lower limit of the saltmarsh 'window') is taken to be the average level of MHWN in the estuary, based on predicted vales for Bradwell Waterside and Osea Island given in Admiralty Tide Tables.

	Below 3.3m OD		Below 4.3m OD	
	Area (ha)	Percentage of total floodable area (%)	Area (ha)	Percentage of total floodable area (%)
Total potential tidally floodable area	8,398	100.0	9,642	100.0
of which:				
Total active estuary outside defences	5,571	66.3	5571	57.8
Total inactive estuary inside defences	2,827	33.7	4071	42.2
Of the active estuary:				
Subtidal area below MSL	3,726	43.2		
Upper intertidal zone (1.6m AOD to MSL)	1,068	12.4		
Natural saltmarsh window (HAT to 1.6m AOD)	704	8.2		
Managed realignment sites	73	0.8		

Table 0.5. Areas calculated from LiDAR surveys in 1999 to 2002 and 2017, between HAT and MSL, together with the gains and losses of sediment in that zone.

	Intertidal area (HAT to MSL) (3.3 to 0.0m OD)				
	1999	2017	Gains	Losses	Difference
Inner Estuary	423	475	56	-4	52
Outer Estuary	210	243	44	-12	32
Lawling Creek	186	200	14	0	13
Tollesbury Fleet	221	228	9	-3	7
Salcott and Strood Channels	363	371	14	-7	8
Northey Island	157	179	23	0	22
Osea Island	73	77	4	-1	3
Northey Island MR	1	1	0	0	0
Tollesbury MR	19	19	0	0	0
Orplands MR	26	26	0	0	0
Abbotts Hall MR	27	27	0	0	0
Shore-attached exc. MR	1,405	1517	137	-25	112
Islands exc. MR	230	256	26	-1	26
Whole Estuary exc. MR	1,635	1772	163	-25	138
Shore-attached inc. MR	1,477	1588	137	-26	112
Islands inc. MR	231	257	26	-1	26
Whole Estuary inc. MR	1,707	1845	164	-26	138

Table 0.6. Areas calculated from LiDAR surveys in 1999-2002 and 2017, in the saltmarsh window (HAT to 1.6 m OD) and on the upper mudflat (1.6 m OD to MSL).

	Saltmarsh Window (3.3 to 1.6 m OD)			Upper mudflat (1.6 to 0.0 m OD)		
	1999	2017	Difference	1999	2017	Difference
Inner Estuary	145	161	15	278	314	37
Outer Estuary	71	69	-3	139	174	35
Lawling Creek	88	86	-2	98	114	15
Tollesbury Fleet	104	109	5	117	119	2
Salcott and Strood Channels	181	187	5	182	185	3
Northey Island	66	70	3	90	110	19
Osea Island	19	24	5	55	53	-2
Northey Island MR	1	1	0	0	0	0
Tollesbury MR	4	14	10	15	5	-10
Orplands MR	19	23	4	7	3	-4
Abbotts Hall MR	18	19	1	9	8	-1
Shore-attached exc. MR	590	611	21	814	905	91
Islands exc. MR	85	93	8	145	163	18
Whole Estuary exc. MR	675	704	29	959	1,068	109
Shore-attached inc. MR	631	667	36	845	921	76
Islands inc. MR	86	94	8	145	163	18
Whole Estuary inc. MR	717	761	44	990	1,084	94

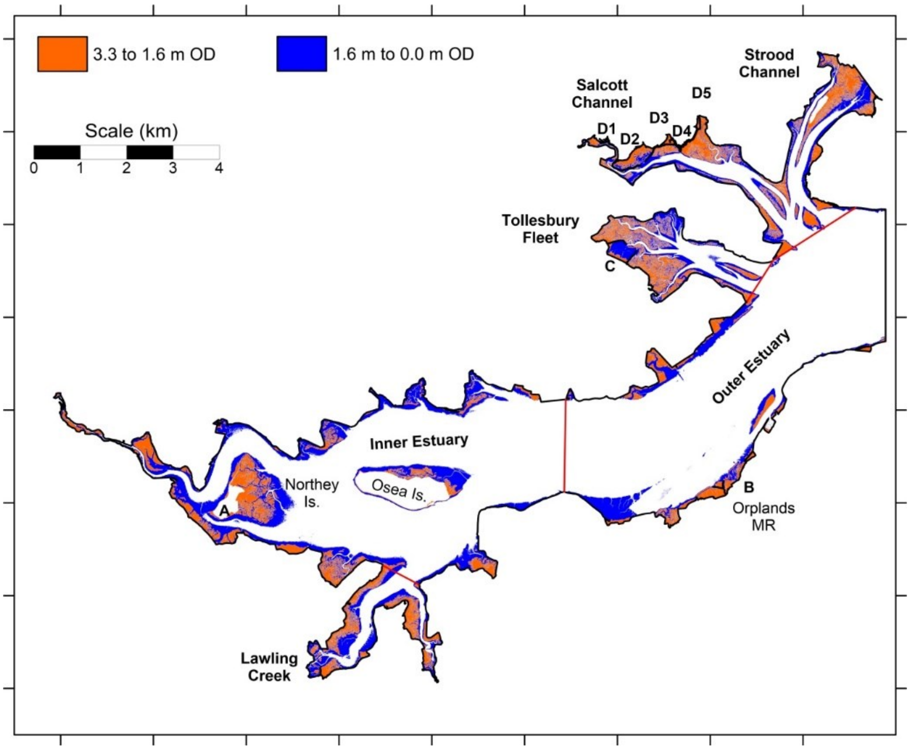

Figure 0.9. Areas within the saltmarsh window (3.3m OD to 1.6m AOD) and on the upper mudflat (1.6m OD to 0.0m OD) in April 1999. Red lines show the boundaries of estuary sub-zones used in the area loss calculations.

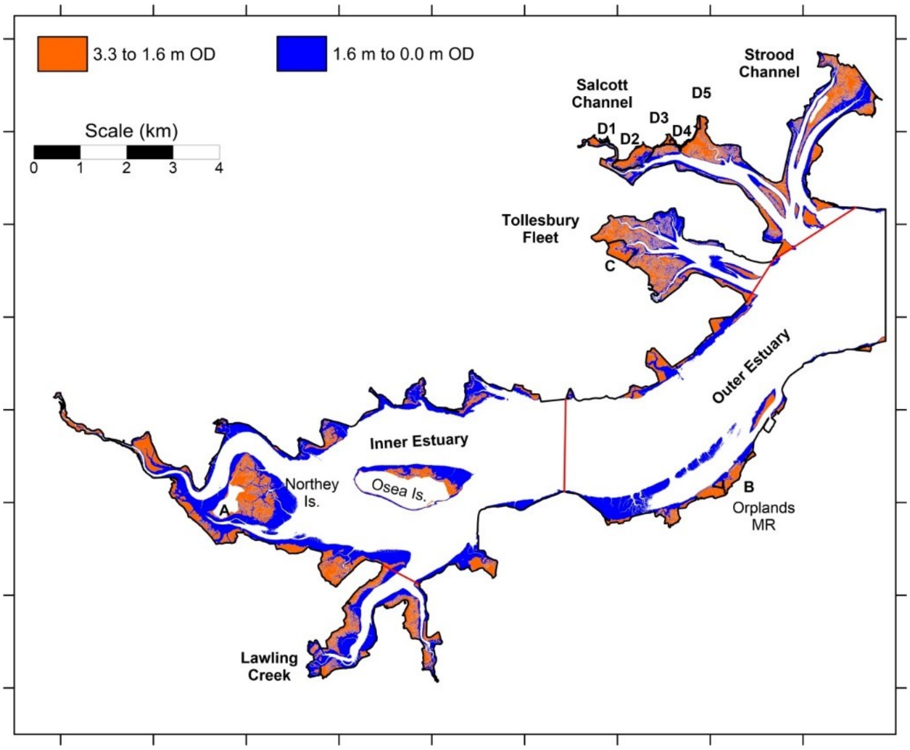

Figure 0.10. Areas within the saltmarsh window (3.3m OD to 1.6m OD) and on the upper mudflat (1.6m AOD to 0.0m OD) in March/April 2017.

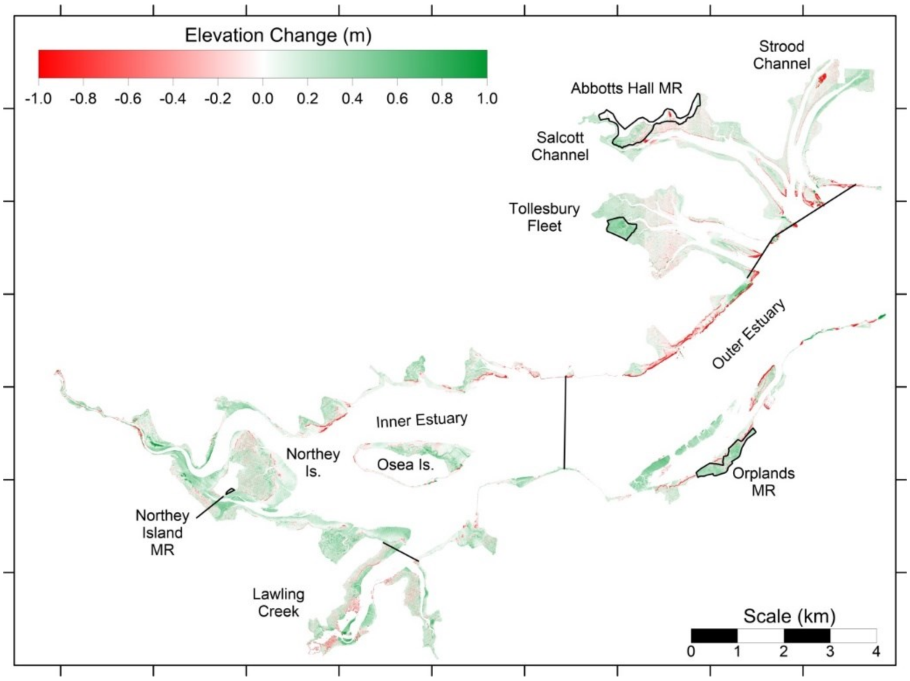

Figure 0.11. Change in elevation between LiDAR surveys in 1999 to 2002 and 2017, for areas above MSL in 2017, or that were above MSL in 1999 and have dropped below MSL in 2017.

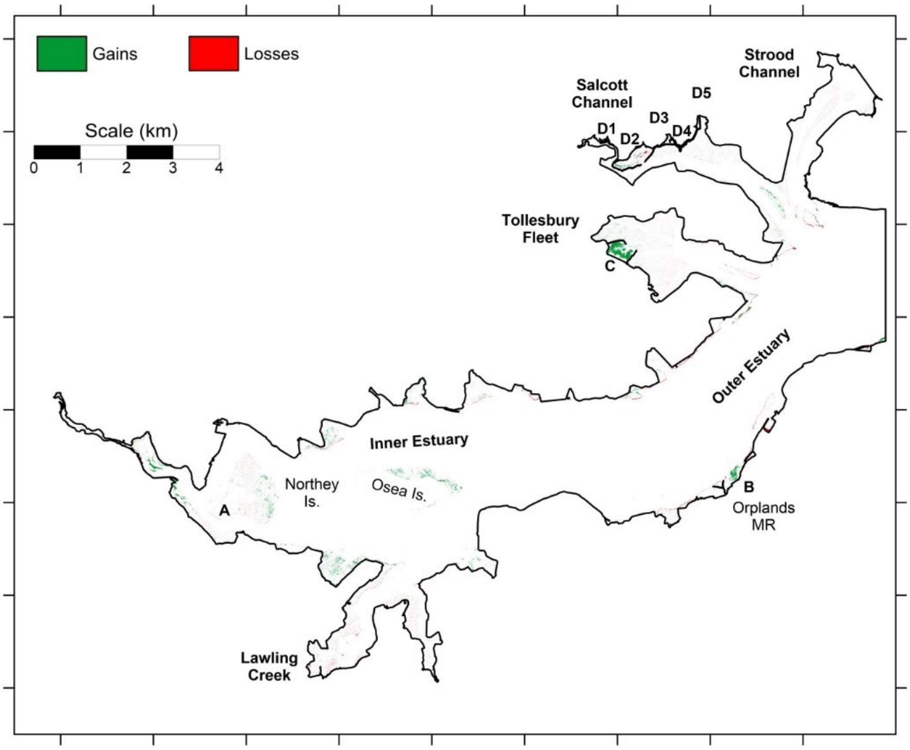

Figure 0.12. Gains and losses of area within the saltmarsh window (3.3m OD to 1.6m OD) between LiDAR surveys in 1999 to 2002 and 2017.

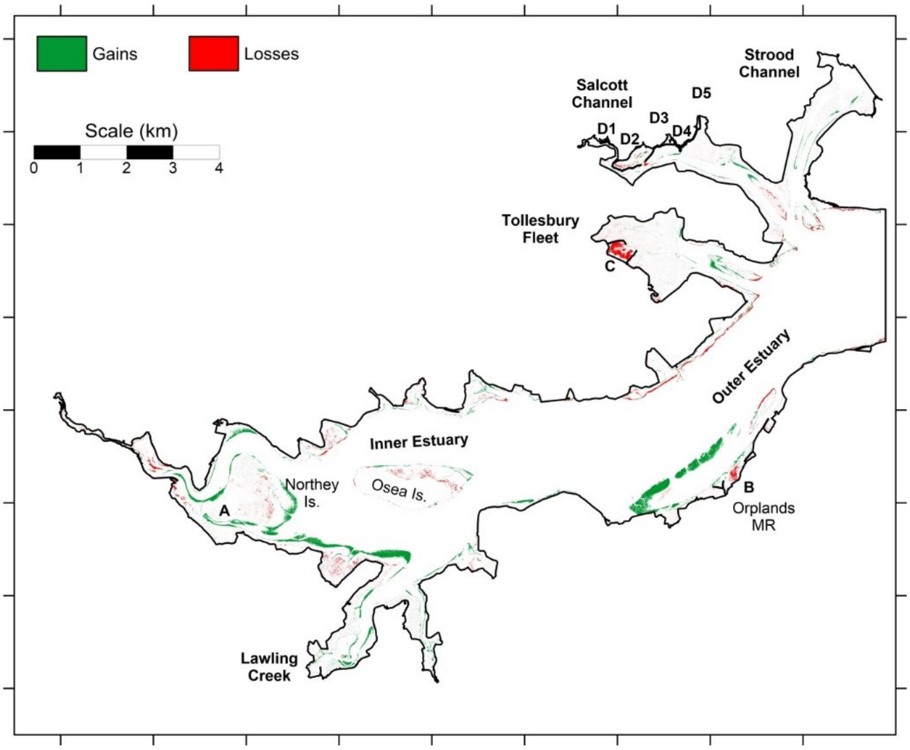

Figure 0.13. Gains and losses of area within the upper mudflat (1.6m OD to 0.0m OD) between 1999 to 2002 and 2017.

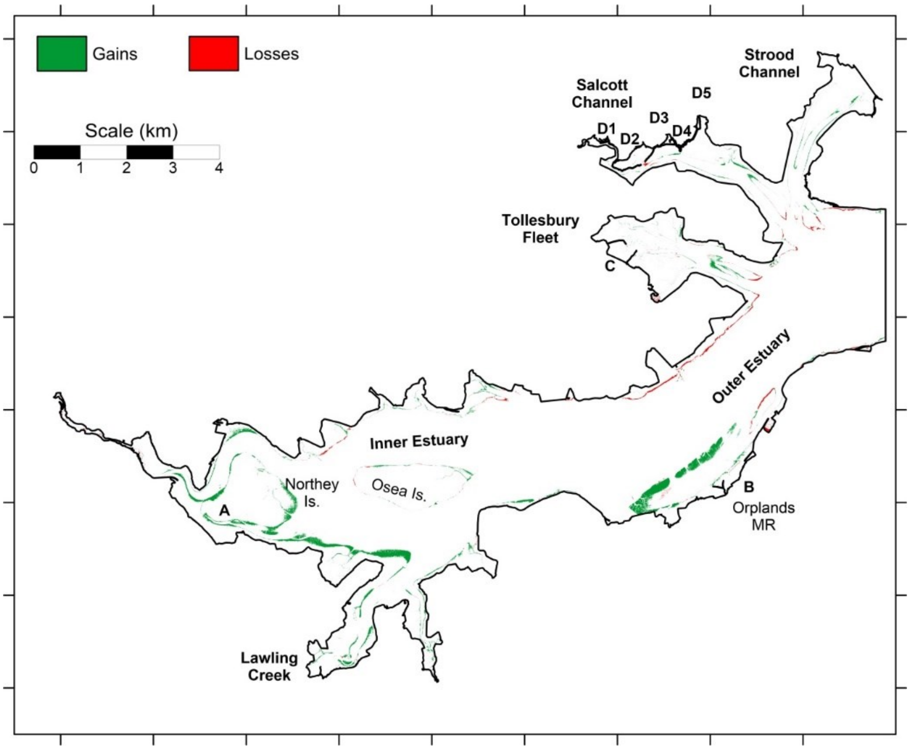

Figure 0.14. Gains and losses of area within the intertidal zone between HAT and MSL (3.3m AOD to 0.0m OD) between 1999 to 2002 and 2017.

The intertidal area above MSL in 2017 was 1,845ha, compared with 1,707ha in 1999 (Table 0.5 and Table 0.6). Although there were localised losses of 26ha, these were more than offset by gains of 164ha, resulting in a net gain of 138ha. The losses were mainly in the outer estuary and subsidiary channels, but even here losses were more than offset by gains. There were net gains both in the ‘saltmarsh window’ (44ha) and on the upper mudflat between 1.6m and 0m AOD (94ha). Most of the gains in the saltmarsh window were either in the inner estuary or within the managed realignment sites at Tollesbury, Orplands and Abbott's Hall. Small net losses within the saltmarsh window occurred only in the outer estuary and within Lawling Creek. Net losses of upper mudflat were recorded only within the managed realignment sites and due to the development of saltmarsh at the expense of mudflat. Within the outer estuary, losses of both saltmarsh and upper mudflat occurred on both sides of the estuary, notably around Tollesbury Wick Marshes, in the northern part of St. Lawrence Bay. However, notable gains of upper mudflat occurred along most of the St. Lawrence Bay frontage. Within the inner estuary, losses of upper mudflat occurred on the northern side of Osea Island and on the opposite mainland shore near the Osea Island causeway. Other apparent losses of upper mudflat between Northey Island and Maldon are due to expansion of saltmarsh.

The main areas affected by loss of both saltmarsh and upper mudflat on the north side of the outer and inner estuary are backed by maintained defences[13] and floodable land, and, therefore, are consistent with the project definition of coastal squeeze. Other areas of loss on the islands at the mouths of Tollesbury Fleet, Salcott Channel and the Strood Channel are not backed by maintained defences and, therefore, fall outside the definition of coastal squeeze.

Evaluating causes of saltmarsh loss and the role of coastal squeeze

Several factors can result in loss of saltmarsh extent and/or quality, and of a wider reduction in intertidal extent. These include:

- relative mean SLR
- decrease in tidal range
- limitation of sediment supply
- change in tidal asymmetry towards greater ebb-dominance, favouring sediment export
- increase in mean wind speeds and wave energy (wave height, period)
- increased wave action due to channel migration and foreshore steepening
- increased frequency of extreme water levels and extreme waves associated with storm surges
- natural vegetation dieback due to fungal infection
- vegetation dieback due to burrowing organisms (worms, crabs)
- vegetation dieback due to waterlogging and excessive sediment anoxia (lack of oxygen)
- vegetation dieback due to pollution (pesticides, nutrients, smothering algal blooms)

[13] This term is introduced to acknowledge that there some defences are maintained, that is, subject to ongoing maintenance, while other defences are no longer maintained and contain some natural breaches.

- damage to vegetation due to physical disturbance (vehicle passage, excessive stock trampling, smothering of vegetation surface)

- channel dredging, leading to deeper water, larger waves and slumping of channels sides

- vessel wash (increased frequency of small waves on channel margins)

- embanking and 'beheading' of tidal creeks, resulting in channel lengthening, meandering and creek-head pan-head formation

Several of these factors may act together or impact on different areas of the same estuary to varying degrees (Pye and French, 1993; Carpenter and Pye, 1997; Pye, 2000). To assess the relative importance of each potential cause the evidence available must be considered.

In a situation of SLR combined with adequate sediment supply, marshes may accrete vertically at a rate sufficient to maintain equilibrium with the moving tidal frame, or to allow normal succession from lower marsh to higher marsh. In these circumstances, the marsh surface may show little morphological change, or on young marshes a reduction in creek and pan density as the surfaces rises relative to the moving tidal frame. The areal extent of marsh may reduce, and low marsh habitats may disappear, but there is unlikely to be a reduction in the surface 'quality' of the remaining marsh (lack of fragmentation, vegetation dieback, appearance of bare mud patches and more water-filled pans). If sediment supply to the fronting tidal flats is high enough, and the balance of hydrodynamic forces does not remove it, saltmarsh extent may actually increase, despite relative SLR.

However, if SLR is accompanied by sediment supply deficiency, the marsh surface level will fall within the moving tidal frame, resulting in reverse succession from higher marsh to lower marsh vegetation communities, an increase in the proportion of bare mud to vegetated surface, dissection of the marsh surface to form complex creek systems and pans, and formation of a fragmented surface composed of mud mounds and intervening depressions. The marsh edge may also recede due to increased water depth and higher breaking wave energy. Depending on the character and level of the fronting tidal flat and exposure to wave energy, the marsh edge may retreat as a distinct cliff, be degraded into a series of erosional furrows and intervening ridges, or be buried by landward-moving wash-over fans composed of sand, shingle and shell. A relict 'pavement' of compacted mud may be left in the upper intertidal zone as the marsh recedes. As the marsh edge retreats the length of tidal creeks is reduced, leading to steepening of the bed gradient, down-cutting and bank collapse, further reducing the marsh surface area.

Where a reduction of saltmarsh area or quality is recorded, and/or a reduction in wider intertidal extent is documented, the definition of coastal squeeze adopted in the present project requires several other criteria be met for the losses/deterioration to be classified as due to coastal squeeze:

- The affected area must be backed by man-made defences.

- There must be potentially floodable/low-lying land behind the defences where salt-marsh or other intertidal habitat could develop in the absence of the defences (accommodation space must exist).

- The occurrence of relative SLR must be demonstrated.

Identify a shortlist of sites

Based on these criteria, the following locations within the Blackwater Estuary have been identified as the main places where coastal squeeze, as defined, could be occurring:

- the shore of the outer estuary on the north side of the entrance to Tollesbury Fleet
- the shore of the outer estuary between Shinglehead Point (west side of the entrance to Tollesbury Fleet) and Mill Point
- the south shore of the outer estuary east of Bradwell power station, extending towards Sales Point
- the shore of the inner estuary between Goldanger and Colliers Reach

Other areas of loss of saltmarsh and upper mudflat exist, mainly in the outer estuary, but do not meet the criteria for coastal squeeze because no maintained defences are present or/and there is no floodable land behind. These areas include:

- Cobmarsh Island
- Sunken Island
- Great Cob Island.
- Pewet Island
- Ray Island
- the marsh between Ray Channel and the Strood Channel

Expert judgement habitat loss attributable to coastal squeeze

Even though intertidal habitat losses might be identified in locations where the above criteria are met, expert judgement is required to assess whether the observed losses/deterioration are actually caused by factors related to SLR (including ‘drowning’ of marsh vegetation due to failure of vertical accretion to keep pace with the rising tidal frame, or stronger tidal currents and larger waves associated with deeper water and a larger estuarine tidal prism).

Since the mid-1980s many investigators have considered SLR to be the main cause of saltmarsh loss and morphological change in the Blackwater Estuary, and in adjoining areas of south-east England. IECS (1993) and CCRU (1996) reported that loss of saltmarsh was associated with a widening of the low water channels in the outer and middle estuary, while in the inner estuary net sediment accretion was associated with narrowing and reduction in depth of the low water channels. These conclusions were based on a comparative analysis of a relatively small number of cross-sections of the outer and middle estuary available for the period 1978 to 1994, while comparable data for the inner estuary were only available for a 12-month period (December 1993 to December 1994). The data were interpreted to show erosional lowering of the intertidal zone, and shallowing of the subtidal zone, in the outer estuary, while the reverse was suggested in the inner estuary where accretion was greater on the upper intertidal flats than on the lower intertidal flats. Within Tollesbury Creek accretion was observed both in the intertidal and subtidal zones, although at a higher rate on the former. This pattern of morphological change was considered by Pethick (2001) and Cooper et al. (2001) to be consistent with a response to SLR, whereby the entire estuary attempts to move landward through a process of 'rollover'. According to this view, the natural tendency for the estuary to widen and disperse sediment over wider area is constrained by the presence of man-made flood defences.

Although the observed pattern of intertidal area change summarised in this report can be considered to be consistent with the rollover hypothesis, the importance of other contributory factors needs to be recognised. In particular, the importance of temporal variations in wind/wave climate and medium to longer term channel movements needs to be considered. Previous work (for example, Carpenter and Pye, 1996; Pye 2000) has demonstrated the occurrence of significant variations in wind speed and direction across south-east England over the past century which had a demonstrable effect on wave regime and patterns of coastal erosion and accretion. The wind record for Shoeburyness shows a significant increase in the duration of winds > 22 knots during the 1960s, 70s and early 1980s when concerns about saltmarsh erosion in the outer Thames Estuary first arose (Pye, 2000). During these decades, anticyclonic conditions with easterly winds were more frequent than during the preceding and succeeding decades, and wave erosion at exposed locations on the coast of south-east England increased. Over the past 30 years these 'easterly' conditions have become less frequent, and south-westerly and westerly conditions more frequent. Over this latter time period, rates of saltmarsh and wider shore erosion had fallen within the Essex and Kent estuaries generally, with a tendency for net sediment accretion to be observed in many locations. Within the Blackwater, upper mudflat and saltmarsh edge erosion has continued along those sections of shore which are most exposed both to south-westerly and easterly waves, notably along the north shore of the outer estuary and on the islands at the entrance to Tollesbury Fleet, Salcott Creek and the Strood. The marshes edges in these locations are characterised in many places by transgressive ridges of sand, shingle and shell, similar to those found along the Dengie Peninsula.

All untrained estuarine channels display natural instability, with a tendency to meander. The position, width and depth of channels may vary considerably on decadal timescales, with direct consequences for patterns of intertidal erosion and accretion. The importance of this process in influencing intertidal changes with the Blackwater has not so far been investigated in detail.

In summary, evaluation of aerial photography and LiDAR data suggests that the main mechanism of saltmarsh loss in the Blackwater Estuary, especially the outer estuary, is recession of the marsh edge. Except along the landward edges of the marshes remote from tidal channels, sediment supply has previously been enough to prevent drowning and fragmentation of the marshes, although in some areas (for example, Northey Island and other unmanaged realignment areas) enlargement of tidal creek systems has brought about such fragmentation. Enlargement of the creek networks in these areas is mainly due to their low elevation of the former reclaimed surfaces within the tidal frame, rather than SLR. The low elevation creates an initially large tidal prism which causes the initial reticulate drainage system, controlled by small agricultural grips and ditches, to evolve to a more natural and higher density dendritic and/or meandering system. Once marsh vegetation is established, rates of vertical sediment accretion increase significantly until the marsh surface level reaches an equilibrium with the moving tidal frame, at which point the size (volume) of the creek network should remain relatively constant. In conclusion, applying the proposed method shows that coastal squeeze, as defined in this project, is not a major process in the Blackwater Estuary. Rates of saltmarsh loss have declined significantly in the past 20 years compared with the 1960 to 80s despite a slight apparent increase in the rate of regional SLR. The available evidence suggests that the observed ongoing erosion is likely to be largely due to wave action, channel movements and creek system reorganisation within unmanaged realignment sites, as opposed to SLR. Further studies are needed to better assess the relative contributions of these factors. Confidence in the assessment is, therefore, judged to be medium/low. Following the proposed method, the choice is to:

- adopt the precautionary principle
- gather more data through further studies

A.3.5 Determining future coastal squeeze losses

Screening test 1 - Are there likely to be relevant structure/s and/or management actions over the period of interest?

Method

Reference has been made to the most recent Shoreline Management Plan covering the Blackwater Estuary (Royal Haskoning, 2011a, b).

Results

The recommended shoreline management policies for management unit F (Blackwater Estuary) identified in the Essex and South Suffolk Management Plan 2 (Royal Haskoning, 2010 a, b) are summarised in Table 0.7 below:

Table 0.7. Summary of recommended policies for coastal management units in the Blackwater Estuary identified in the Essex and South Suffolk SMP2.

Policy development zone	Area	2010-2025	2025-2055	2055-2100
F1	Strood to Salcott – cum-Virley	HTL	HTL	HTL
F2	Salcott Creek	HTL	HTL	HTL
F3	South bank of Salcott Channel to Tollesbury Fleet	HTL	HTL	HTL
F4	Tollesbury	HTL	HTL	HTL
F5	Tollesbury Wick Marshes to Goldanger	HTL	HTL	MR
F6	Goldanger to Heybridge	HTL	HTL	HTL
F7	Heybridge Basin	HTL	HTL	HTL
F8	Maldon Inner Estuary	HTL	HTL	HTL
F9	South Maldon	HTL	HTL	HTL
F10	Maylandsea	HTL	HTL	HTL
F11	Mayland Creek East	HTL	HTL	HTL
F12	Steeple	HTL	HTL	MR
F13	St Lawrence	HTL	HTL	HTL

Policy development zone	Area	2010-2025	2025-2055	2055-2100
F14	St. Lawrence to Bradwell on Sea	HTL	MR	HTL
F15	Bradwell Creek	HTL	HTL	HTL

The implications of these policies, if implemented, are that all existing defences are likely to be maintained and remain in their present position until at least 2025. Local realignment may occur along the St Lawrence to Bradwell frontage in management period 2 (2025 to 2055) and along the Tollesbury Wick to Goldanger frontage in period 3 (2055 to 2100). The potential for defences to contribute to coastal squeeze is, therefore, likely to remain throughout most of the estuary.

Screening test 2 - Is there likely to be suitable accommodation space landward of the structure over the period of interest?

Method

This question has been addressed by reference to the topographic data sets referred to above and also by reference to planning policy documentation relating to this part of Essex.

Results

There is no evidence that presently available accommodation space will be significantly reduced or lost due either to natural processes (for example, sedimentation) or human intervention (for example, landfill for major development).

Screening test 3 - Are relative sea levels anticipated to rise in the region over the period of interest?

Method

This question has been addressed by referring to sea level projections contained on the UKCP18 data portal and by considering recent trends evident from measured tide gauge data.

Results

For present purposes, a conservative approach has been adopted and the projected increases in mean sea level for the 50% percentile model output of the RCP 8.5 (high emissions' scenario) are shown in Table 0.8.

Table 0.8. Projected increases in mean sea level (in metres) at the entrance to the Blackwater Estuary, at 10 year intervals up to the year 2100, relative to 2019, under a RCP 8.5 (highest emission) scenario modelled as part of the UKCP18 project.

Year	5%	50%	95%
2029	0.04	0.05	0.07
2039	0.08	0.12	0.16
2049	0.13	0.19	0.26
2059	0.19	0.27	0.38
2069	0.25	0.36	0.52

Year	5%	50%	95%
2079	0.32	0.46	0.67
2089	0.39	0.57	0.83
2099	0.46	0.68	1.01

Considering recent tide gauge data for Lowestoft and Sheerness (Figure 0.7) provides no suggestion that increases in mean sea level are likely to slow or cease in the near future. Indeed, the data suggest that the rate of rise has shown some increase since the 1990s, and this may continue into the future.

Conclusions from screening tests

It is concluded that all 3 screening tests are met for the Blackwater Estuary and, therefore, that coastal squeeze could occur in the future.

A.3.6 Future habitat losses

Extrapolate past losses based on historical trend analysis

A range of estimates of rates of historical saltmarsh loss in the Blackwater Estuary have been made for different time periods and, therefore, a wide range of projected losses is possible based on extrapolating historical rates. A summary is provided in Table 0.9. It should be noted that the Burd et al. (1992) estimates of loss are probably an overestimate due to incomplete assessment of saltmarsh extent in 1973. Both the Burd (1992) and Cooper et al. (2000) estimates relate to a period of high wind-wave energy, while the later studies relate to a period of relatively low wind/wave energy. The later estimates of the rate of apparent saltmarsh loss/gain are influenced by managed realignment schemes at Tollesbury, Orplands and Abbotts Hall. It should also be borne in mind that there are great dangers in making long-term projections based on short-term historical records since conditions are known to change dramatically on decadal to multi-decadal timescales.

Table 0.9. Summary of extrapolated change in saltmarsh area based on estimates of rates of historical loss. NB. Phelan et al. data related to combined Blackwater-Colne system; data from this study relate to the 'saltmarsh window' (elevation range 3.3 to 1.7 m AOD).

Authors	Period	Ave rate of area change (ha/yr)	Data type analysed	Notes	Projected loss/gain by 2050 (ha)	Projected loss/gain by 2100 (ha)
Burd (1992)	1973-1988	-9.4	aerial photographs	saltmarsh only	-582.8	-1052.8
Cooper et al. (2000)	1988-1998	-5.49	aerial photographs	saltmarsh only	-285.48	-505.08
Phelan et al. (2011)	1998-2008	+0.47	aerial photographs	saltmarsh only, including MR	+19.74	+92.48
Royal Haskoning (2006)	1998-2004	-7.0	aerial photographs	saltmarsh only	-322.0	-672.00
This study	1999-2017	+1.61	LiDAR	saltmarsh window	+53.13	+133.63

Authors	Period	Ave rate of area change (ha/yr)	Data type analysed	Notes	Projected loss/gain by 2050 (ha)	Projected loss/gain by 2100 (ha)
				excluding MR sites		
This study	1999-2017	+3.0	LiDAR	saltmarsh window including MR sites	+99.0	+249.00
Thomson et al. (2011)	1998-2008	+3.0	aerial photographs	saltmarsh only, including MR	+126.0	+276.0

Inundation modelling

The risk of 'drowning' of saltmarsh due to SLR depends on the rate of SLR and the rate of surface sediment accretion. For the purposes of this study, a basic inundation modelling assessment has been carried out to estimate how the area of 'saltmarsh window' might change under different combinations of conditions. The results, shown in Table 0.10, show the area change which might occur under 2 scenarios of SLR (3mm/yr and 8.5mm/yr) and 2 assumed rates of vertical accretion due to sedimentation. Under the worst-case scenario, with an average rate of SLR of 8.5mm/yr and no effective sediment accretion, the area of the saltmarsh window is projected to decline by 47% by 2100. Under this scenario, saltmarsh vegetation would be limited to a relatively narrow, discontinuous fringe around the toe of the flood defences. Deeper water across the intertidal zone would lead to increased wave action and might remove saltmarsh altogether except in the most sheltered embayments along the defence line. These modelling projections are for illustration purposes only, and the outputs should not be taken as predictions of the most likely outcomes.

Table 0.10. Example of projected losses (or gains) of saltmarsh in the Blackwater Estuary, assuming a range of SLR estimated and saltmarsh accretion rates. Note that a SLR of 3.0mm/yr is approximately the historically observed rate since the 1960s, while the SLR of 8.5mm/yr is the linear rate projected by UKCP18 under an RCP 8.5 scenario, 50th percentile value. Note that this is an abstract inundation model which considers the balance between sedimentation and SLR as a cause of potential reduction in saltmarsh area; it is timescale-independent.

Assumed rate of saltmarsh accretion (mm/yr)	Assumed rate of SLR (mm/yr)	Area within the saltmarsh window (ha)	Percentage of saltmarsh remaining (%)
0.0	0.0	761	100.0
0.0	3.0	623	81.8
3.0	3.0	761	100.0
6.0	3.0	891	117.1
0.0	8.5	403	53.0
3.0	8.5	520	68.4
6.0	8.5	645	84.7

Expert geomorphological analysis of future losses

Based on current shoreline management and regional planning policies, it is unlikely that very large scale coastal adaptation will take place in the area surrounding the Blackwater Estuary over the next 80 to 100 years. The majority of defences are likely to be maintained, although managed realignment may be carried out in St Lawrence Bay and at Tollesbury Wick marshes. The potential to create a large amount of new intertidal habitat will, therefore, be limited.

It is most likely that sea level will continue to rise throughout the period, although the degree to which the rate will accelerate is highly uncertain. Based on available data, which suggest a recent average rate of mean SLR of around 3mm/yr, an absolute increase in mean sea level of 24cm is possible by 2100, without any further acceleration due to climate change. Based on current UKCP19 projections, a larger total increase in the range of 30 to 40cm may be most likely.

With SLR in the range of 3 to 5mm/yr, it is considered likely, based on historical rates of vertical marsh accretion within the Blackwater Estuary, that the marshes will be able to keep pace with SLR. The main forms of erosion will continue to be erosion of the marsh edge, burial by transgressive sand and gravel lobes, and widening/ reorganisation of creek systems within unmanaged realignment areas. The extent to which this erosion occurs will depend on the magnitude of new sediment supply to the estuary, and the re-distribution of existing sediment between the higher energy outer estuary and lower energy inner estuary. It is likely that greater water depths in the outer estuary will not be matched by sedimentation rates on the upper intertidal flats, which, together with marsh edge cliffs, will continue to erode. It is also likely that the transfer of sediment towards the inner estuary will continue, resulting in further tidal flat accretion and local marsh development. The degree to which a balance between erosion and accretion is maintained is likely to depend to a large degree on the rate of SLR and also on possible future changes in wind/wave climate. A return to increased frequency of ‘easterly’ conditions, as occurred between the late 1950s and 1980s, or a significant increase in westerly wind speeds and the size of internally generated waves, could accelerate the rate of upper intertidal habitat loss, especially in the outer estuary.

In conclusion, the likelihood of future coastal squeeze in the Blackwater Estuary will depend on the balance between the rate of SLR and sediment supply. If SLR is in the range of 3 to 5mm/yr (or less), coastal squeeze, in the form of marsh drowning or surface fragmentation, is unlikely, but erosional retreat of exposed marsh edges, and creek enlargement/low marsh fragmentation within unmanaged realignment areas, could continue.

Erosion of marsh edges is likely to continue to be due wholly or partly to wave action and channel movements. Further studies would be needed to assess the likely contribution of these factors. Given the uncertainty in future SLR rates, wave conditions and channel movements, confidence in assessment of future losses is judged to be medium/low. Following the proposed method, the choice is to:

- adopt a precautionary principle
- gather more data through further studies

Since a large part of the uncertainty relates to SLR, it is recommended that further data is collected on local SLR, sediment supply, hydrodynamic processes and the morphological behaviour of the entire intertidal and subtidal parts of the estuary. Further detailed field studies should be carried out to provide better data relating to the ‘quality’ of marshes throughout the estuary, defined both in terms of morphological and biological criteria.

A.3.7 Conclusions

This case study has demonstrated that the proposed method for assessing coastal squeeze can be applied successfully to an estuary such as the Blackwater.

Applying the method, including a review of the findings of previous studies, has indicated that there have been losses of saltmarsh habitat in front of defences within the Blackwater Estuary, but there is little evidence that these losses are due principally to SLR. The available evidence suggests that the changes in intertidal habitat extent are likely to have been due mainly to wave action, local channel movements and tidal creek network adjustment to renewed tidal influence in formerly reclaimed areas, rather than a failure of the marsh surfaces to accrete vertically in line with SLR. These changes would not constitute coastal squeeze according to the project definition. The confidence in this assessment is judged to be medium.

Greater confidence in the conclusion could be obtained through further studies to determine the rates of recent vertical sedimentation on mature marshes within the estuary, which can be used as a proxy for historical SLR, and by further detailed investigation of the mechanisms and effects of marsh loss/deterioration in different parts of the estuary. The further studies could include modelling the effects of small increments in water levels on wave energy and tidal currents within the estuary, and the respective effects both on marsh edges and marsh surfaces. Further studies are also required to understand the mechanisms of internal marsh dissection within sheltered areas, such as former reclaimed marshes where the defences have been breached (for example, on Northey Island). There is also a requirement for direct monitoring of water levels and wave conditions in the outer, middle and inner estuary.

Applying the method to assessing potential future losses suggests that:

- if SLR accelerates from around 3mm/yr to around 5mm/yr, marshes in the Blackwater Estuary will continue to accrete vertically and maintain a constant level within the moving tidal frame
- it is uncertain if the marshes could keep pace with rates of SLR of > 5mm/yr
- even with SLR of 1m over the next century, raising the average level of HAT from around 3.3m AOD to around 4.3m AOD, there would only be a very small increase in the potentially tidally floodable area behind the defences due to the presence of steeply rising ground around most of the estuary; in other words, there would only be a very small increase in the accommodation space within which saltmarsh might develop behind the defences.

In some parts of the estuary, significant losses of saltmarsh and mudflat habitat have occurred over the past 120 years on islands without maintained flood defences, or on sections of mainland shore which are backed by naturally rising ground (with or without defences). The definition and criteria currently proposed by the method excludes these losses from the definition of coastal squeeze. However, it is possible that the losses on such islands, for example those at the mouth of Tollesbury Fleet and Salcott Channel, are directly influenced by the presence of defences on the neighbouring mainland shores, which act to constrain tidal flows and waves within a narrow entrance corridor. This leads to higher energy levels and potentially enhanced erosion across the intervening marsh island areas. Although these impacts would not constitute coastal squeeze under the present definition, they may still require assessment and mitigation/compensation.

A wide range of estimates of rates of historical saltmarsh loss within the estuary have been made over the past 25 years, all based on relatively short time periods. These provide a poor basis for projecting long-term future change. Early assessments by Burd (1992) and Cooper et al., (2000, 2001) suggested high rates of loss between the early 1970s and late 1990s, but later studies have indicated much lower rates of loss. New analysis carried out for this study has provided additional information regarding wider habitat area change for the upper intertidal zone (upper mudflats and saltmarshes). The results show that significant mud accretion has occurred in the inner Blackwater Estuary, promoting expansion of saltmarsh in some areas. The outer estuary shows a more complex pattern, with significant net loss of upper intertidal area (including saltmarsh) in some areas, notably on the north side of the estuary between Salcott Creek, Tollesbury Wick Marshes and Goldanger, but significant upper intertidal mud accretion in St Lawrence Bay and parts of Tollesbury Fleet, Salcott Creek and the Strood. However, changes in saltmarsh community extent and quality (species composition and vegetation vigour) have not been quantified and require further study.

More reliable estimates of historical saltmarsh extent, and a better estimate of long-term net change, could be obtained by re-analysing the 1973 aerial photography used by Burd, or alternative imagery from the 1970s or 80s, and making comparisons with modern aerial photography from 2018 or 2019.

To understand changes in morphology and habitat extent more fully, there is a requirement to analyse changes across the entire intertidal profile and the subtidal part of the estuary. Further information about such changes could be obtained through analysis of historical charts, bathymetric line surveys and more recent swath surveys, including monitoring data obtained as part of the Anglian strategic coastal monitoring programme. Such monitoring should be continued and expanded into the future to provide a clear understanding of the extent, nature and causes of habitat loss (including intertidal flat as well as saltmarsh).

Estimates of historical SLR in the Blackwater Estuary are currently based on tide gauge data for stations which are located some distance away, and which may not be truly representative of the local area. More specific local information about local sea level changes could be obtained through sedimentological, geochemical and paleo-ecological analysis of sediment cores taken from mature saltmarshes within the estuary.

There is a need to better understand tidal flow and wave conditions in the estuary and their relationship to sediment transport, deposition and potential re-suspension.

Such further studies would provide greater confidence in estimates of historical habitat change and provide a better basis for extrapolation potential future change based on maintaining present conditions.

With regard to alternative means of projecting potential future losses (or gains), more detailed assessment of the potential implications of a wider range of future climate change scenarios is needed.

Many of the existing gaps in data/evidence referred to above could be addressed through further studies, although residual uncertainty will always remain, particularly with respect to future changes in sea level, wave conditions, and the implementation of shoreline management policy.

A.4 Slaughden and Sudbourne

A.4.1 Overview of method

The proposed method developed in the 'What is coastal squeeze?' (WICS) project is shown in Chapter 6. The following sections show how each of the steps of the method can be applied to the Slaughden and Sudbourne Beach area.

A.4.2 Scoping

Slaughden is located on the central Suffolk coast just to the south of Aldeburgh (Figure 0.15). Slaughden was once a small hamlet located on the northern end of the Orford Ness shingle spit, but today is represented only by two yacht clubs and associated businesses located on the estuary side of the ridge between Fort Green and the Martello Tower. This area is included within SMP2 Policy Unit ALB 14.4 (Slaughden). To the south of the Martello Tower lies Sudbourne Beach (SMP2 Policy Unit ORF15.1) and Orford Ness (Policy Unit ORF15.2). The study area includes part of Policy Units ALB14.4 and ORF15.1 and excludes defences within the Alde Estuary.

The habitats included in the assessment are coastal shingle beaches and vegetated shingle ridges. The periods of interest are the mid-1950s to the present, and particularly 1992 to 2018 for which topographic monitoring data are available.

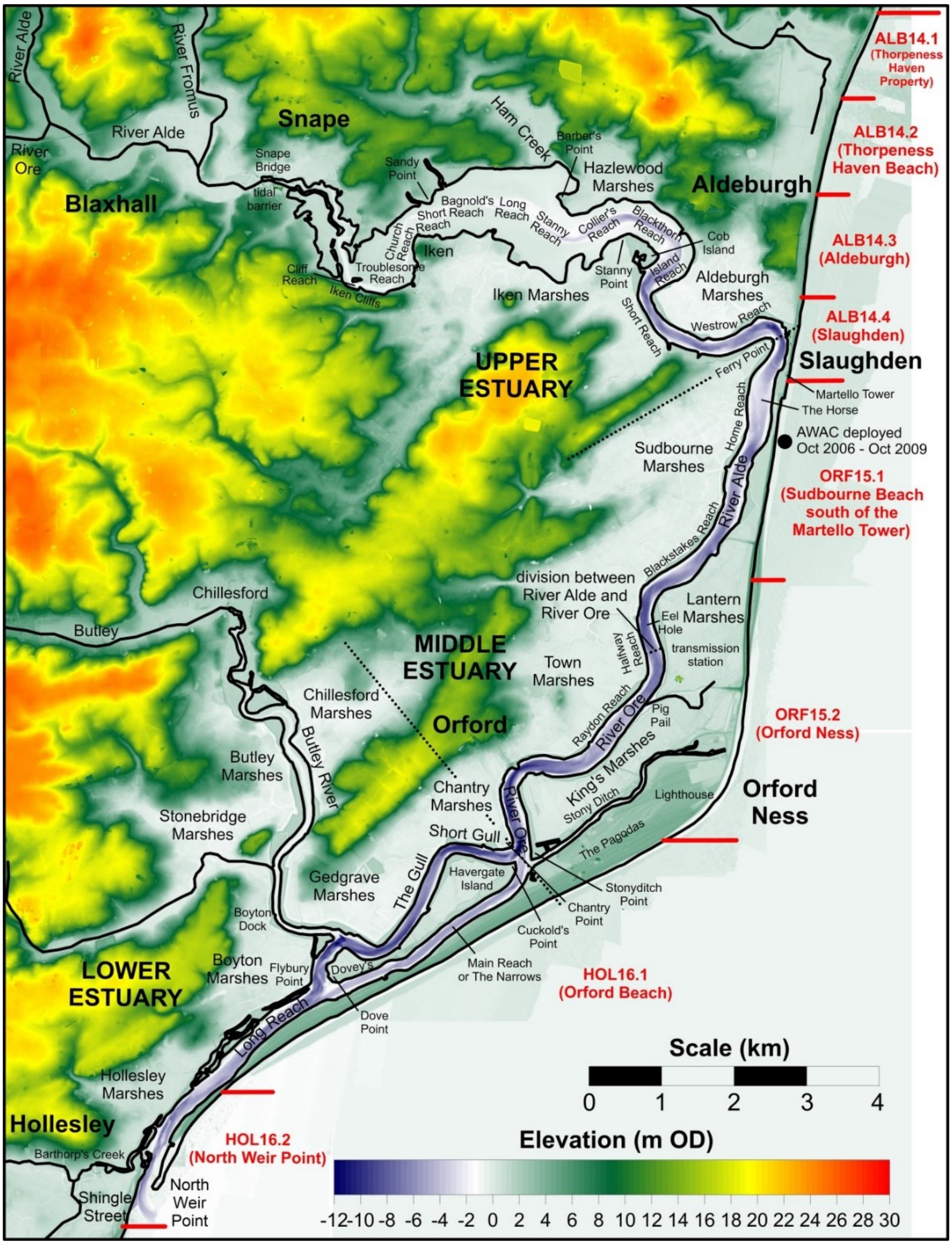

Figure 0.15. Location of Slaughden and Sudbourne Beach within the context of the central Suffolk coast and the Alde-Ore Estuary. SMP2 policy units (red lines and lettering) overlaid on composite DEM derived from LiDAR and bathymetry data (2008 to 2012). Policy units are grouped into Management Area ALB 14 ('Thorpeness Haven to Aldeburgh'), ORF 15 ('Martello Tower to Orford Ness') and HOL 16 ('Orford Ness to Bawdsey Hill'). ALB 14 and ORF 15 in turn comprise Policy Development Zone PDZ 5 ('Thorpeness to Orfordness') and HOL16 comprises part of PDZ6 ('Orford Ness to Cobbold's Point').

A.4.3 Determining past coastal squeeze losses

Screening test 1 - Have relevant structure/s and/or management actions been present over the period of interest?

Method

This question was approached by referring to published literature, unpublished reports, historical Ordnance Survey maps, aerial photography, and LiDAR topographic data sets covering the Slaughden- Orfordness shingle ridge and adjoining parts of the Alde-Ore Estuary.

Results

The position of the beach fronting Aldeburgh has been fixed since the late 19th century using a combination of groynes and concrete walls, and beach levels in front of the town have generally been maintained. However, the retention of sediment in this area has contributed to erosion further south by impeding net southerly longshore sediment drift. In order to counter the tendency of the beach and shingle ridge between Aldeburgh and Slaughden to 'roll back', and to provide adequate defence against sea flooding of the southern part of Aldeburgh and villages surrounding the Alde Estuary, groynes and hard concrete defences have been installed between Fort Green and a point south of the Martello Tower (Figure 0.16) at several different times since the 1940s. In this area, the natural form of the shingle ridge has effectively been destroyed. The early groynes and other defences were overwhelmed during the storm surge of 31 January 1953, after which a new concrete wall and groyne system was constructed. Further major improvements were made between 1989 and 1992, involving the installation of a substantial rock toe apron in front of the northern section of the existing sea wall. Some groynes were replaced and 75,000m^3 of shingle imported to recharge the beach. The southern section was demolished and a new rock armour ‘transition bank’ constructed, realigned slightly between the Martello Tower and the unprotected shingle ridge further south (NRA, 1991). Further improvements to the defences north of the Martello Tower, including placing more rock armour and removing some degraded groynes, were carried out in 2016 (Figure 0.17).

Beyond the end of the present concrete wall south of the Martello Tower the position of the shingle ridge has since been held using a mixture of groynes, rock armour, concrete tetra-pods, concrete H-block mattresses and recycling of shingle brought by dumper trucks form locations further south where natural accretion is occurring (Figure 0.18). However, since early 2013 this area has experienced significant beach lowering and erosional recession of the maintained ridge to the south of the point where the rock armour ends.

The crest level of the shingle ridge in this area has generally been maintained by importing shingle and re-profiling the ridge to provide both a flood defence and a trafficable route south towards Orford Ness. The effect of these interventions has been to retard the natural tendency of the ridge crest to roll landwards and to adopt a more natural profile. However, since 2013 storms have greatly reduced the crest width and caused localised overtopping, leading to natural realignment of the ridge.

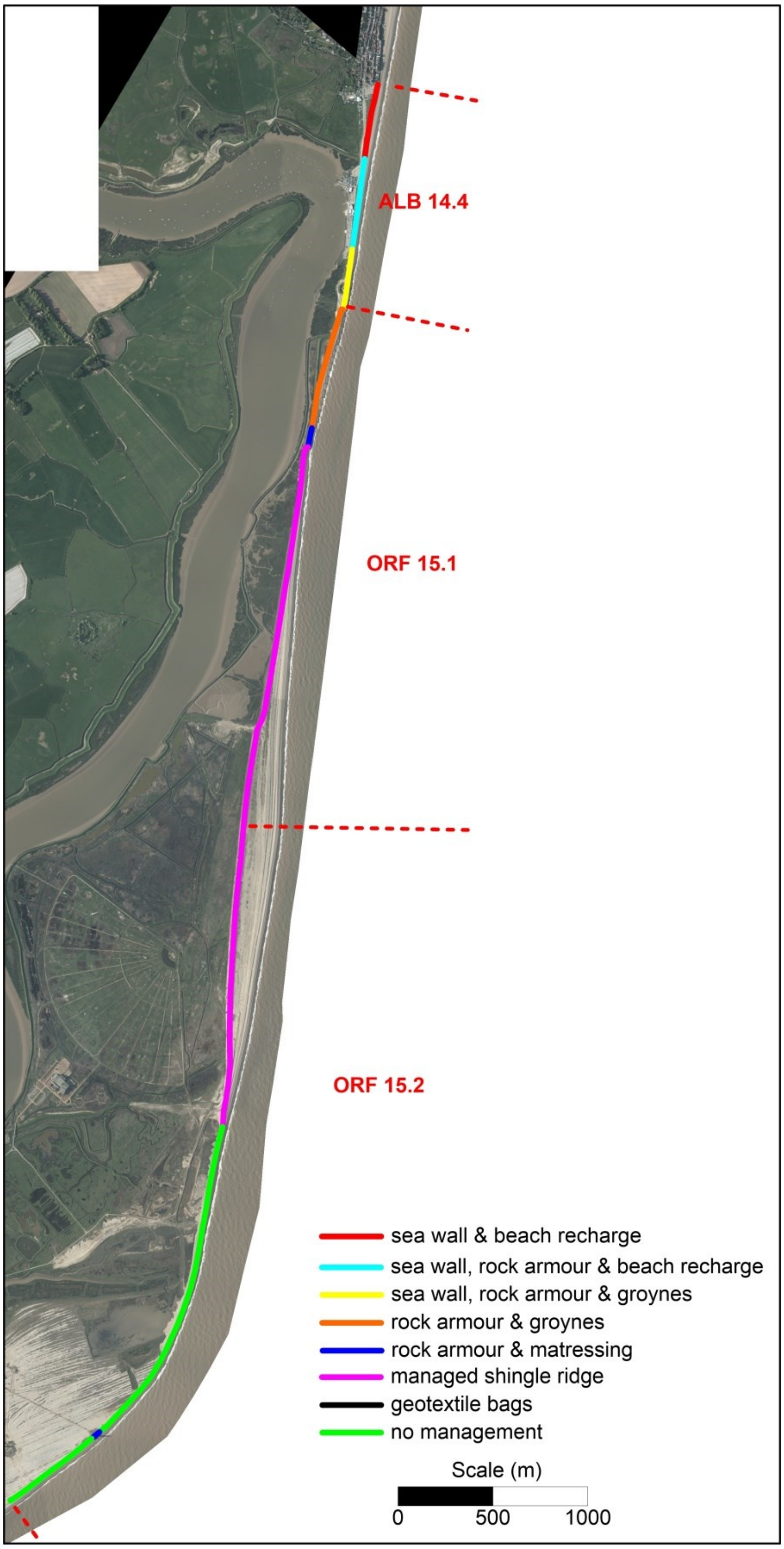

Figure 0.16. Aerial photograph flown 15/05/2018, showing extent of present defences and shingle management.

Figure 0.17. Improvements to the defences in front of the Sailing Club in 2016. (Photo Courtesy of K. Pye).

Figure 0.18. The artificially profiled shingle ridge south of the Martello Tower, showing groynes and rock armour protection (Photo Courtesy of K. Pye).

The length of hard defences south of Fort Green is almost 2km. To the south of this point the position and form of the shingle ridge have been managed for coastal flood risk management and access reasons along a further distance of 3.6km (Table 0.11). Beyond this point the seaward margin of the shingle has not been managed and there are no defences except for a short section of sediment-filled geotextile bags placed to protect Orford Ness Lighthouse. Following further erosion in the 2019 to 2020 winter the lighthouse is unsafe and likely be demolished in the near future (at the time of writing this information was not available and should be confirmed by the readers at a later date).

Table 0.11. Lengths of defences and undefended shoreline along Sudbourne Beach (Fort Green to Orford Ness)

Description	Type	Length (m)	Length (%)
Lantern Marshes	Rock armour	102	1.3
Lantern Marshes to American Wall	Managed shingle ridge	3,626	45.6
Martello Tower	Sea wall, rock armour and groynes	322	4.0
Martello Tower to Lantern Marshes	Rock armour and groynes	655	8.2
Northern limit of ALB 1404 (Fort Green) to Sailing Club	Sea wall and beach recharge	397	5.0
Orford Ness	Unmanaged	1,778	22.3
Orford Ness Lighthouse	Geotextile bags	54	0.7
Orford Ness to southern limit of ORF 15.2	Unmanaged	541	6.8
Sailing club	Sea wall, rock armour and beach recharge	481	6.0
Defended		2,011	25.3
Undefended		5,945	74.7
Total		7,956	100.0

Screening test 2 - Has there been suitable accommodation space landward of the structure over the period of interest?

Method

This question was addressed by examining published information, Ordnance Survey 5m resolution gridded data sets, Ordnance Survey maps, aerial photography and Environment Agency composite LiDAR data sets.

Results

A large area of low-lying land and open water of the Alde-Ore Estuary is present behind the shingle ridge, and it would be able to move landwards and adopt a wider, flatter shape if defences were not present, and the form and position of the shingle ridge not managed.

Screening test 3 - Have there been readily observable losses of habitat in front of structures (either LWM retreat or internal erosion) over the period of interest?

Method

This issue was addressed by referring to evidence from aerial photographs, historical maps, LiDAR, Environment Agency topographic surveys and site inspections carried out by the authors since the late 1990s.

Results

Since 1992 the Environment Agency has monitored changes in the shingle ridge and adjoining beach on a series of transect lines, some of which have been selected for analysis in this study and are shown on Figure 0.20. The selected profiles represent areas where the ridge:

- is fixed by hard defences and where the beach has been nourished with shingle at intervals
- has been artificially managed by re-profiling and introducing imported shingle
- has effectively been unmanaged

The data for selected surveys between 1992 and 2019 are compared in Figure 0.20. Major differences in temporal patterns of erosion (shingle loss) and progradation (shingle accretion) are evident at different profiles.

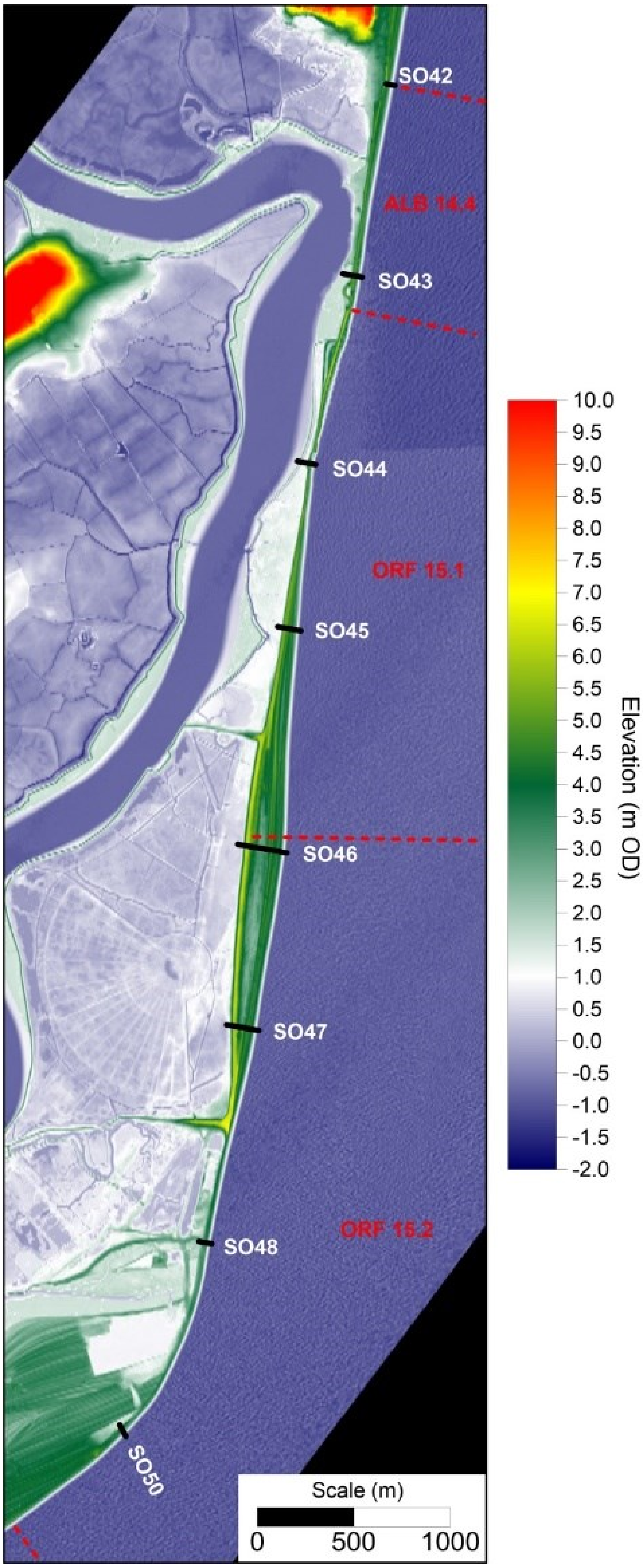

Figure 0.19. LiDAR DTM of the Slaughden and Orford Ness frontage, flown 04/11/2018. Black lines show Environment Agency strategic topographical profile monitoring positions; dashed red lines show SMP2 policy unit boundaries.

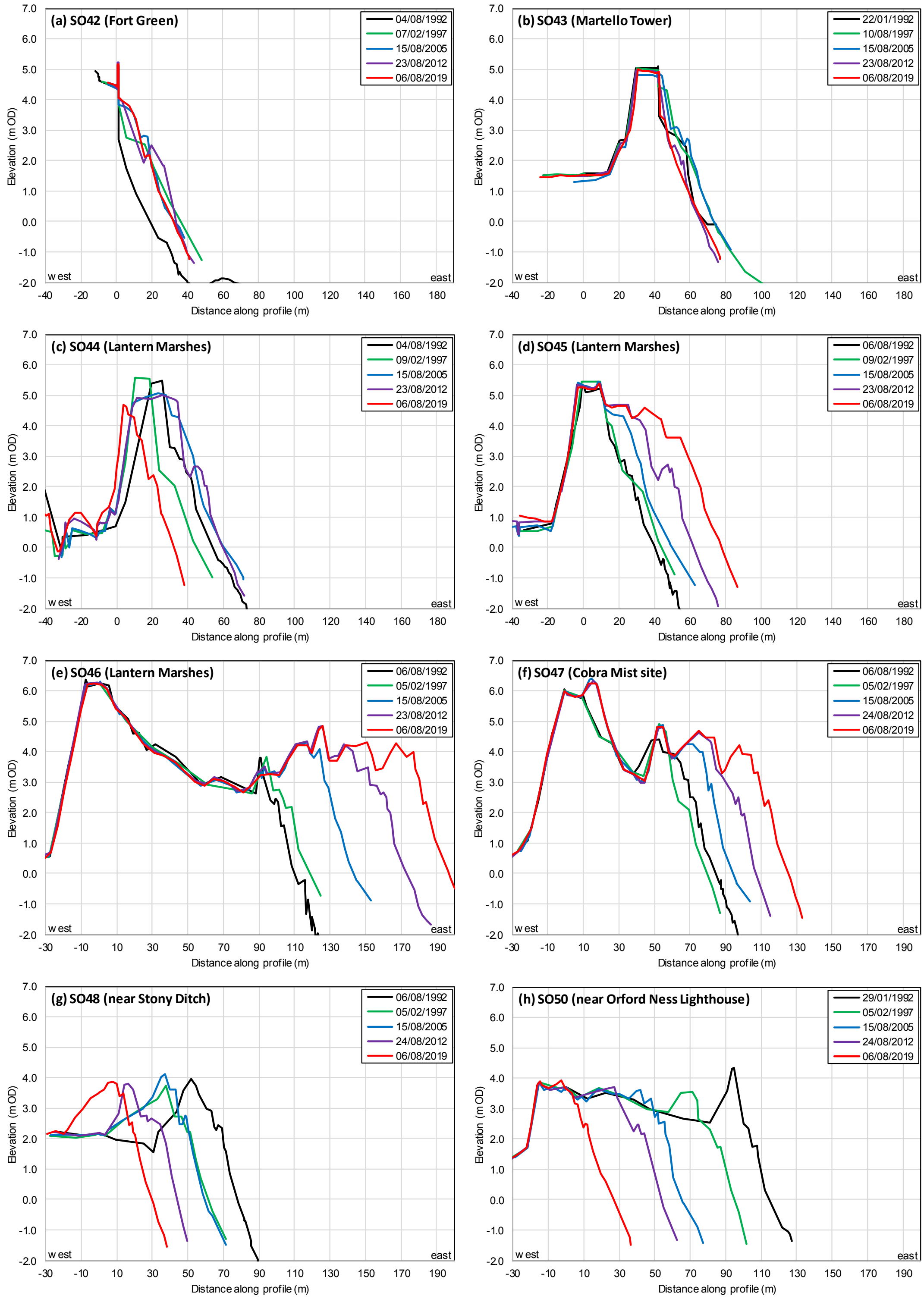

Figure 0.20. Observed changes at selected Environment Agency strategic topographic profiles surveyed 1992-2019.

There is clear evidence that the width and elevation of the shingle beach fronting the defences has experienced a long-term tendency to reduce and has only been maintained through a programme of regular beach nourishment. South of Fort Green (profile SO42), the beach volume was significantly increased following remedial works, including beach nourishment after major erosional losses in 1993. Since that time, the beach level and volume of the upper beach have shown a small overall net gain. However, the natural shingle ridge between Fort Green and the end of the sea wall south of the Martello Tower has been completely obliterated, much of it being flattened to form an artificial bank, which acts as a sea defence and provides an access track to Orford Ness (Figure 0.17 and Figure 0.18). Vegetated shingle habitat in this area is restricted to parts of the artificially steep back-slope of the shingle bank. Near the end of the rock armour, where the ridge has been artificially strengthened using concrete block mattresses and geotextiles, shingle vegetation is also restricted to the landward margin of the ridge.

At profile SO43, near the Martello Tower, the beach has shown a continuing tendency for volume loss, despite regular re-nourishment. This is because the line of the concrete defences lies too far seaward of the equilibrium plan-form alignment.

At profile SO44, just beyond the limit of the rock armour opposite the northern end of Lantern Marshes, the beach has shown a natural tendency to recede since before 1992. Works were carried out between 1997 and 2005, and again between 2005 and 2012, using imported shingle to widen the ridge on the seaward side. However, serious erosion in early 2013 removed much of the placed sediment. Since that time, the beach has continued to erode and the ridge has been reduced greatly in width, leading to localised overwashing during storms since 2016. Currently, there is serious risk of a major breach in this area.

At profiles SO45, SO46 and SO47 there has been a natural net tendency for shingle accretion since 1992, and this area has been used as a donor site for shingle used in beach nourishment further north. However, an artificial shingle bank has been maintained with a crest level of approximately 6.0m AOD on the landward side of the naturally accreting ridges, which have a natural crest level of between 4.2 and 5.0m AOD. Shingle extraction in this area has been consented but may not continue into the future.

To the south of the Cobra Mist Site, where the maintained track to Orford Ness turns inland, there is a transition from shingle accretion to shingle erosion, and at profile SO48 (near Stony Ditch) and profile SO50 (near Orford Ness Lighthouse) there has been progressive erosion since 1992. Where the profile has been unmanaged, as at profile SO48, the shingle ridge behind the beach has rolled back, maintaining a broadly constant cross-section and a crest-elevation of c 4.0m AOD (Figure 0.20g).

Screening test 4 - Has relative SL risen in the region over the period of interest?

Method

Reference has been made to published literature and new analysis of tide gauge records for the Class ‘A tide gauges at Lowestoft and Sheerness carried out, with data being obtained from the National Tidal and Sea Level Facility (NTSLF) website.

Results

Previous analyses of UK tide gauge data have provided evidence of SLR over the past century, with some indication of an acceleration over the past 30 years. Woodworth et al. (2009) calculated an average rate of rise of mean sea level (MSL) of +2.54 +/- 0.39mm/yr at Lowestoft for the period 1956 to 2006, and an average rate of rise of +2.23 + 0.13mm/yr at Sheerness for the period 1901 to 2006. A subsequent analysis (Woodworth, 2018) suggested a longer term increase in MSL at Sheerness of 1.680 +/- 0.084mm/yr between 1834 and 2006. For the purposes of this study, available digital data for both stations have been re-analysed and updated in Figure 0.21. Calculated average rates of MSL rise are 3.06 +/- 0.24 at Lowestoft for the period 1964 to 2018 and 2.14 +/- 0.53 at Sheerness for the period 1968 to 2006.

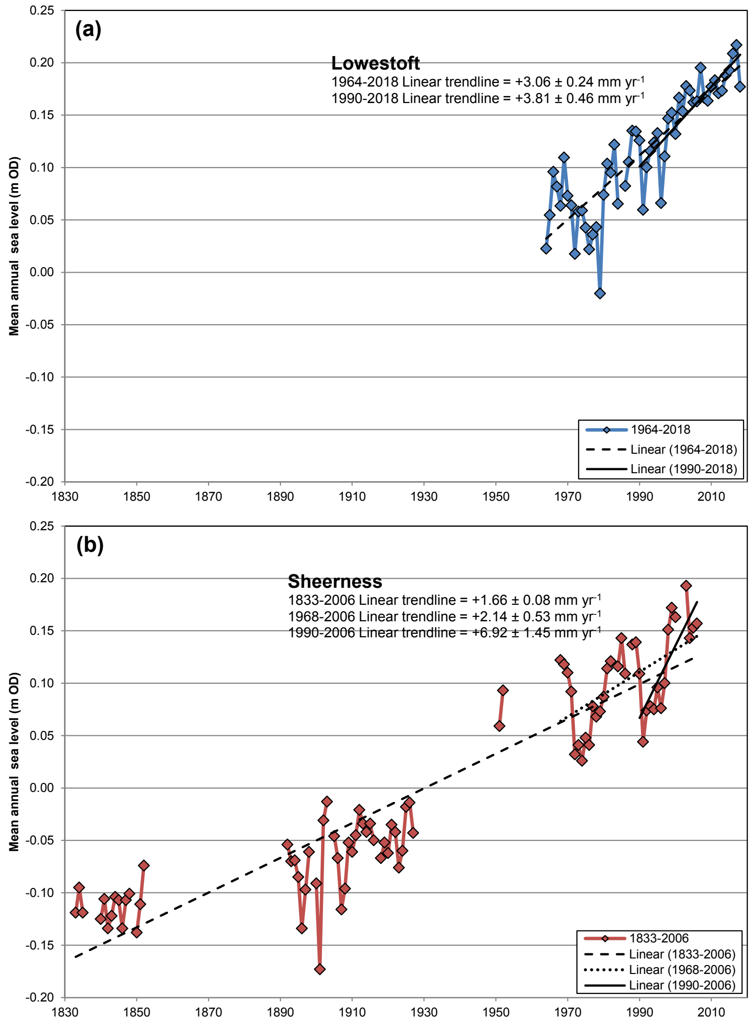

Figure 0.21. Trends in mean annual mean sea level at Lowestoft and Sheerness, with linear trend lines fitted for the full periods of record, and since 1990 (original data source: PSMSL).

Conclusions from screening tests

It is concluded that all 4 screening tests are met for the Slaughden (SMP2 Policy Unit ALB14.4) and northern Sudbourne Beach (ORF15.1) frontages, but not for the southern Sudbourne Beach-Orford Ness) frontage (ORF15.2). It is, therefore, possible that coastal squeeze has occurred in the past at Slaughden and Sudbourne Beach.

A.4.4 Expert geomorphological assessment of historical coastal squeeze losses

Baseline geomorphology

The Aldeburgh to Orfordness area experiences a meso-tidal regime with a mean spring tidal range of 2.3m, the level of MHWS given in Admiralty Tide Tables (ATT) being approximately 1.1 to 1.2m AOD. The mean spring tidal range within the Alde Estuary near Slaughden Quay is also approximately 2.3m, although the elevation of MHWS is slightly greater than on the open coast (1.3m AOD; Table 0.12).

Table 0.12. Predicted tidal levels on the open coast and within the Alde-Ore Estuary from Admiralty Tide Tables (UKHO, 2019).

	HAT	MHWS	MHWN	MSL	MLWN	MLWS	LAT	CD	MSTR	MNTR
Open coast, north to south										
Aldeburgh	1.8	1.1	0.7	0.06	-0.7	-1.3	nd	-1.60	2.4	1.4
Bawdsey	2.0	1.6	1.0	0.09	-0.8	-1.5	nd	-1.77	3.1	1.8
Felixstowe	2.3	1.9	1.2	0.13	-1.0	-1.6	-2.1	-1.95	3.4	2.1
Lowestoft	1.4	0.9	0.6	0.16	-0.5	-1.0	-1.4	-1.50	1.9	1.1
Orford Haven Bar	1.9	1.5	0.9	0.13	-0.7	-1.3	nd	-1.66	2.8	1.6
Orford Ness	1.4	1.2	1.1	nd	-0.8	-1.2	nd	-1.65	2.3	1.8
Southwold	1.6	1.1	0.8	0.25	-0.4	-0.8	nd	-1.30	1.9	1.2
Alde-Ore Estuary, mouth to head										
Iken Cliffs	1.6	1.3	0.8	0.20	-0.5	-1.0	nd	-1.60	2.3	1.3
Orford Haven Bar	1.9	1.5	0.9	0.13	-0.7	-1.3	nd	-1.66	2.8	1.6
Orford Quay	1.5	1.2	0.7	0.20	-0.5	-1.0	nd	-1.60	2.2	1.2
Slaughden Quay	1.5	1.3	1.0	0.19	-0.6	-1.0	nd	-1.60	2.3	1.6

Flood tidal currents flow in a southerly direction, while ebb current flow in a northerly direction. There is a slight residual current flow to the south, but this is of little importance in terms of shingle sediment transport.

The nearshore area experiences a bi-directional wave regime, and the direction of net wave-induced sediment transport shows a high degree of variability on monthly, seasonal and inter-annual timescales. However, there is a net long-term drift of shingle size material towards the south (Carr and Baker, 1968; Carr, 1969,1970,1972; May, 2003; Royal Haskoning, 2009).

In the time of Henry VIII and Elizabeth I the 'neck' of land separating the River Alde from the sea was probably more than 500m wide and a quay and storehouses were present on the river side (Steers, 1926; Anon, 1966). By the time of the survey for the First Edition Six Inch Ordnance Survey map in 1881, several piers and a quay were still present on the Alde at Slaughden and a public house was located on the shingle ridge itself, although the width of the ridge was less than 100m in places (Figure 0.22). By 1902, several of the buildings had disappeared, and almost all had gone by 1938 as erosion and landward movement of shingle continued. An aerial photograph taken in 1945 shows a wide and laterally extensive zone of bare shingle with a number of prominent washover lobes (Figure 0.22). During the storm surge of 31 January to 1 February 1953 the ridge was overtopped and shingle spread over a considerable distance landward, some reaching the Alde channel. Following this event, the existing defences (mainly wooden groynes) were replaced by a concrete sea wall and improved groyne system. By the late 1980s, these defences were in a dilapidated state and significant improvements were made between 1989 and 1992. An aerial photograph taken in 1992 (Figure 0.22) shows that the originally straight shoreline had developed a 'bulge' centred on the Martello Tower, with a slight embayment in the beach to the north and a deeper embayment developed in front of Lantern Marshes to the south. After 1992, further recession of the high water mark was prevented as far south as the end of the defences, but erosion has continued immediately to the south of this point, despite periodic beach nourishment and repairs to the ridge behind.

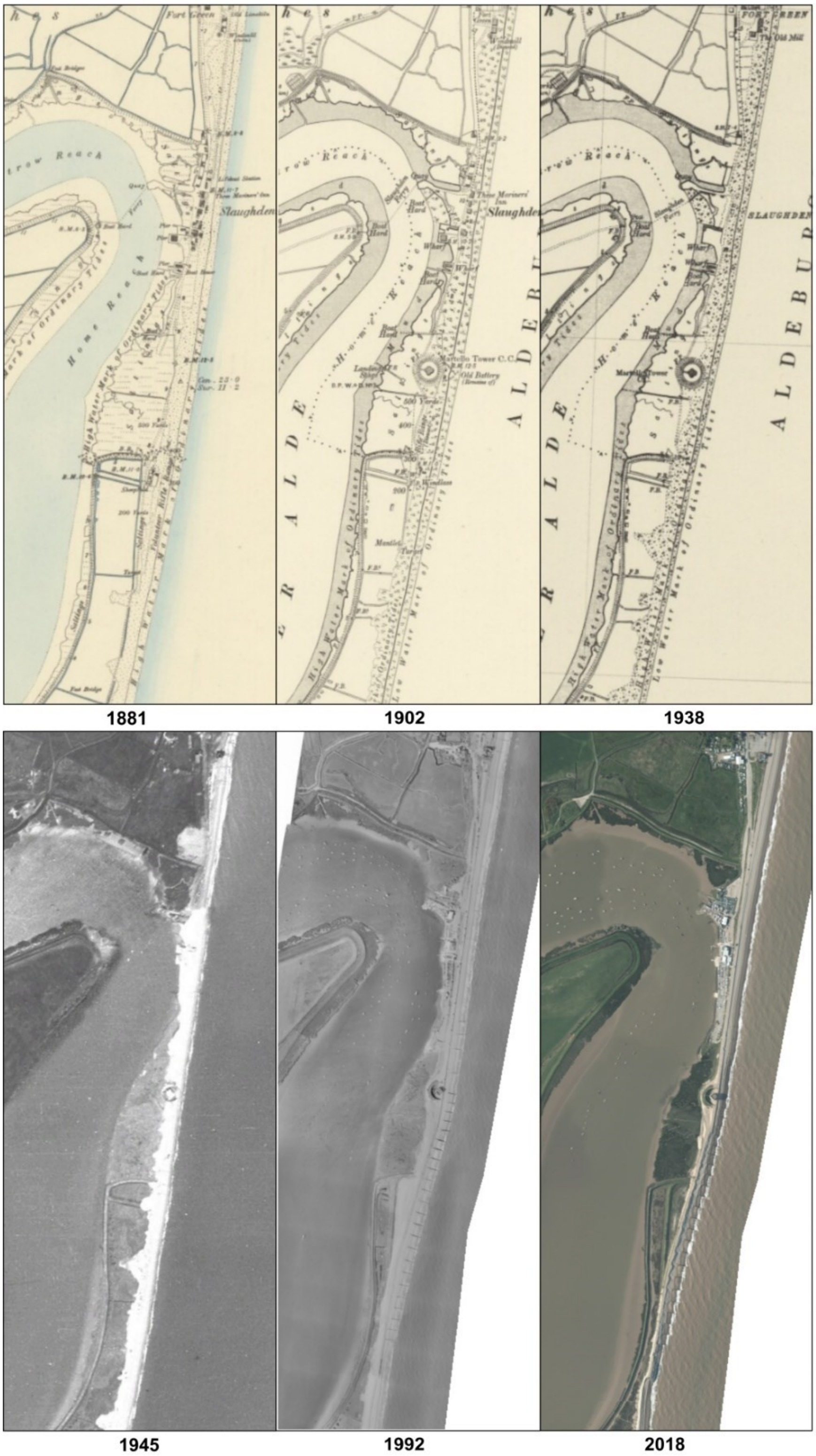

Figure 0.22. The defended frontage between Fort Green and present southern limit of hard defences, shown on historical six-inch Ordnance Survey maps (surveyed 1881, 1902 and 1938) and aerial photographs (flown 1945, 1992 and 2018). Source: Pye and Blott (in prep.).

Figure 0.23 to Figure 0.25 show the pattern of historical shoreline retreat superimposed on 2019 aerial photography of the area between Fort Green and Orford Ness. The map evidence shows that the shoreline between Fort Green and Lantern Marshes has experienced a tendency for landward recession of the mean high water since the mid-19th century. Recession of the northern part was effectively stopped by the constriction of defences between the late 19th century and the mid-1950s. But, following completion of the 1950s works, the adjoining shoreline to the south, fronting the northern end of Lantern Marshes, suffered rapid erosion up to 1976; this has continued at a slower average rate to the present time.

Over the same time period, the shoreline fronting the southern end of Lantern Marshes has experienced sediment accretion and development of a subdued ‘ness’ feature, while the most prominent part of Orford Ness near the Lighthouse has experienced continuous erosion. Evidence provided by analysis of bathymetric charts suggests that the pattern of shoreline change reflects both the effect of construction of the defences and changes in the nearshore bathymetry (Pye and Blott, in prep.). The alongshore-variation in erosion and accretion pattern suggests that an increase in sea level has not been the major driving factor, but it has probably contributed to a long-term increase in storm wave height and erosional tendency along the Suffolk coast as a whole.

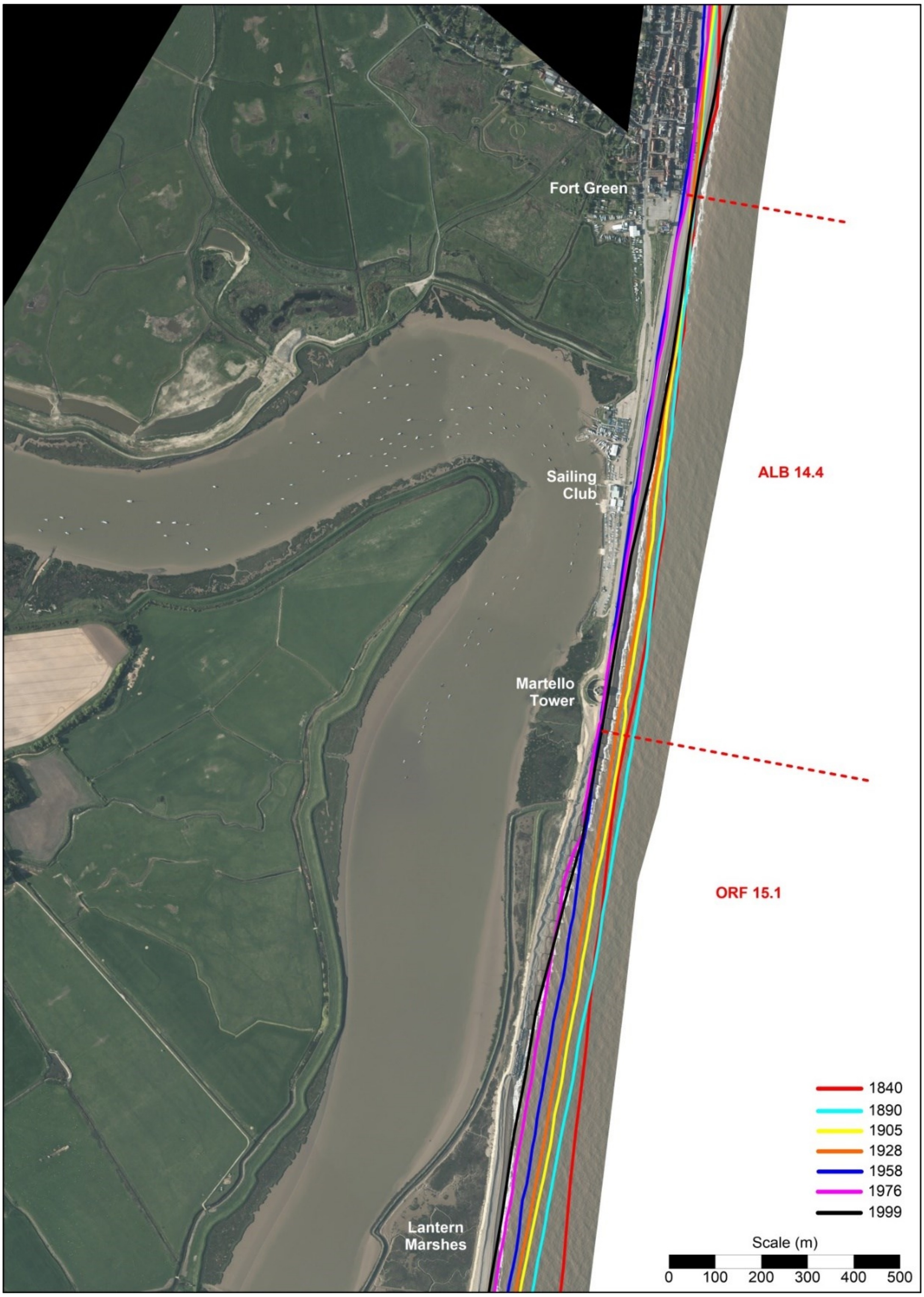

Figure 0.23. Aerial photograph flown 15/05/2018, with historical positions of MHW from OS maps and 1999 LiDAR: Fort Green to Lantern Marshes (after Pye and Blott, in prep.).

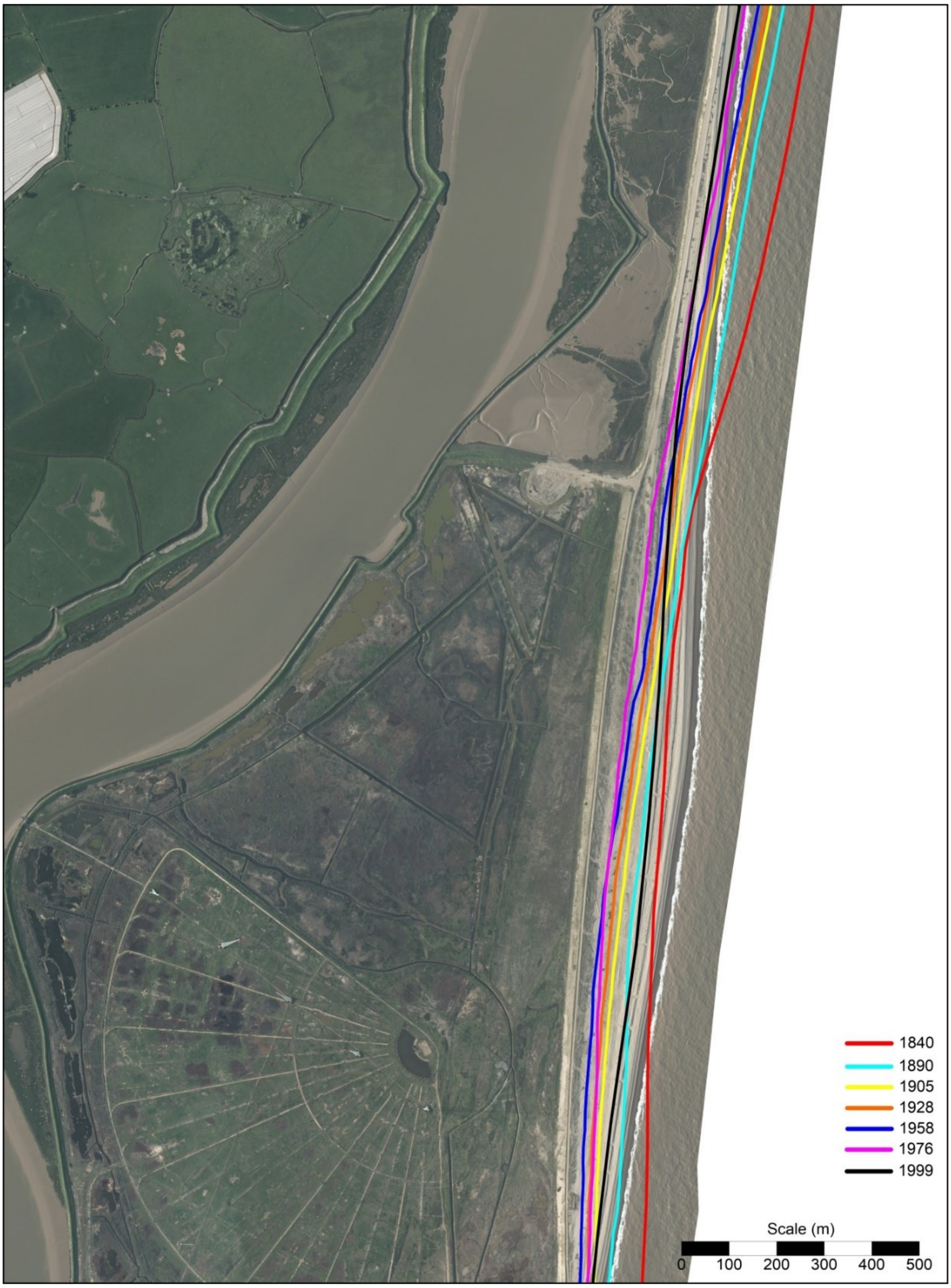

Figure 0.24. Aerial photograph flown 15/05/2018, with historical positions of MHW from OS maps and 1999 LiDAR: Lantern Marshes to Cobra Mist Site (after Pye and Blott, in prep.).

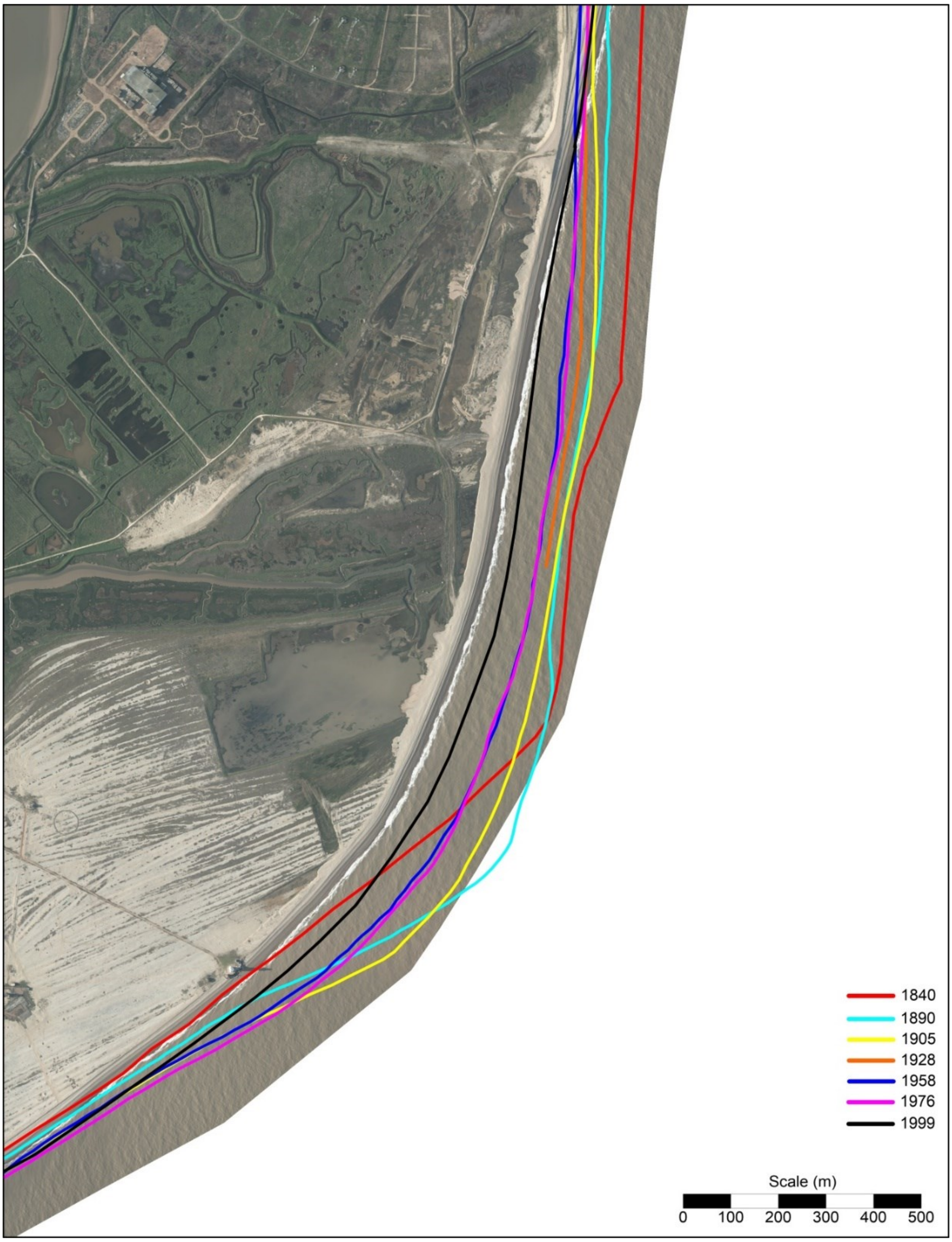

Figure 0.25. Aerial photograph flown 15/05/2018, with historical positions of MHW from OS maps and 1999 LiDAR: Cobra Mist Site to Orford Ness Lighthouse (after Pye and Blott, in prep.).

Quantifying past shingle habitat losses and habitat quality

The effect of the defences constructed since the late 19th century at Slaughden and Sudbourne Beach can be summarised as follows:

- The reduction in shingle beach area as the high water mark has moved landward, while the position of the defences has remained fixed, and, in places, moved seawards.

- The loss of a naturally functioning shingle ridge, including shingle habitat, beneath and behind the defences.

- The destruction of shingle vegetation on the landward side of the ridge due in part to reprofiling of the ridge and movement and re-deposition of shingle by plant.

Based on examining historical maps and aerial photographs, it is estimated that the reduction in area of shingle ridge due to the direct effect of the footprint of the defences and associated access track amounted to around 36,900m^2 between 1945 and 2018 (Table 0.13). Based on a comparison of Environment Agency beach profile data for the period 1992 to 2018, it is estimated that there was a net loss of 11,600m^2 of beach area (15.8%) over the period. This reduction could be interpreted as loss due to possible coastal squeeze.

Table 0.13. Areas affected by beach coastal squeeze and direct footprint losses at Slaughden (Fort Green to end of defences in 2018).

	Area
Area of beach in 1992	73,300m^2
Area of beach in 2018	61,700m^2
Area lost due to erosion	11,600 m^2
Area lost due to erosion 1992 to 2018	15.8% of beach area in 1992
Area lost under hard defences 1945 to 2018	36,900m^2
Area lost under hard defences between 1945 and 2018	c. 50 % of bare shingle area in 1945

A significant reduction in the quality of the remaining shingle habitat in Policy Units ALD14.4 and ORF15.1 due to:

- the lack of natural functioning of the beach due to the presence of groynes and rock armour

- the general absence of a high tide berm where strandline vegetation might develop

- the disturbance to vegetation on the remaining parts of the managed shingle ridge due to plant movement, reprofiling and stockpiling of shingle used for beach nourishment

To the south of the end of the rock armour the quality of the shingle ridge has been reduced by reprofiling to maintain an artificially high and wide ‘bank’.

There has been a relatively minor impact on shingle areas further south (the northern half of Policy Unit ORF15.2) due to plant movements associated with shingle extraction for use in beach nourishment.

Evaluating causes of shingle loss and the role of coastal squeeze

Identify a shortlist of sites

The following locations along the Slaughden to Orford Ness shoreline have been identified as areas where coastal squeeze, as defined, could be occurring:

- Fort Green to the Martello Tower (Slaughden)
- Martello Tower to the end of the rock armour protection (Sudbourne Beach north)
- The managed shingle ridge south of the rock armour fronting Lantern Marshes (Sudbourne Beach central)

Expert judgement of habitat losses attributable to coastal squeeze

There is clear evidence that the presence of hard defences at Slaughden, and artificial management of the shingle bank south of the Martello Tower as far as the northern end of Lantern Marshes, has prevented the beach and ridge system moving landwards as it would otherwise do, and has contributed in a major way to the loss of shingle habitat area and quality. Confidence in this qualified nature of this assessment is judged to be high. Confidence in the quantified assessment of losses due to the direct footprint of defences is also judged to be high, while confidence in the quantified area losses due to coastal squeeze is judged to be low.

The figure for possible coastal squeeze loss shown in Table 0.13 should be treated with great caution since considerable variation in beach area and beach volume occurred within the period, reflecting changes due to natural processes, coastal defence works and the timing of beach nourishment. The available evidence suggests that the role of sea level in influencing the tendency for landward shingle ‘rollover’ appears to be secondary to the effects of changes in nearshore bathymetry and alongshore sediment transport linked to wave climate. The increase in annual mean sea level in the period was small (<7.5cm) over the period 1992 to 2018, and much of the variation in beach area and volume during this period is clearly related to storm-induced wave erosion. Analysis of data for the wider Suffolk coast by Pye and Blott (in prep.) has shown there is no uniform pattern of landward migration of the shoreline in East Anglia over the past 30 years. There is also strong evidence that variations in nearshore bathymetry, wave height, period and direction on multi-year to decadal timescales have played an important role in determining spatial patterns of sediment transport, shoreline erosion and accretion.

A.4.5 Determining future coastal squeeze losses

Screening test 1 - Are there likely to be relevant structure/s and/or management actions over the period of interest?

Method

Reference has been made to the most recent Shoreline Management Plan covering the central Suffolk Coast (Royal Haskoning, 2010a) and a recent review relating to a change in management policy for policy unit ORF15.1 in SMP Epochs 2 and 3 (Coast Partnership East and East Suffolk Council, 2019; Jacobs, 2019a).

Results

The recommended shoreline management policies for shoreline management units ALB14.4, ORF 15.1 and ORF15.2 are summarised in Table 0.14.

Table 0.14. Summary of SMP2 polices for Policy Units ALB14.4, ORF15.1 and ORF 15.2 (from Royal Haskoning, 2010a):HTL = Hold-the-Line; NAI = No-Active Intervention.

SMP2 Policy unit	Name	Epoch 1 (2025)	Epoch 2 (2055)	Epoch 3 (2105)
ALB14.4	Slaughden	HTL	HTL	HTL
ORF15.1	Sudbourne Beach	HTL	NAI	NAI
ORF15.2	Orford Ness	NAI	NAI	NAI

The SMP2 (Royal Haskoning, 2009) identified the potential for squeeze of shingle habitats under a HTL policy, but concluded that there would be no coastal squeeze impact under a policy of no active intervention (NAI). It was suggested that there would be a small positive environmental gain where the policy changes from HTL to NAI. The HTL policy for Policy Unit ALB14.4m might be expected to lead to coastal squeeze in the future. The policy for Policy Unit ORF15.2 is NAI for all 3 epochs, so no coastal squeeze is likely to arise in this area. Following a recent review of the SMP the policy for unit ORF15.1 (Martello Tower to Lantern Marshes) the policy will changes from HTL in the first epoch followed by NAI in the next 2 epochs, to MR in all 3 epochs. It is anticipated that the management measures to achieve MR would include placing shingle at the landward side of the existing ridge in order to maintain its integrity as a flood defence and to reduce the risk of breach formation. The policy of MR will reduce the potential effect of coastal squeeze but will not completely eliminate it.

Screening test 2 - Is there likely to be suitable accommodation space landward of the structure over the period of interest?

Method

This question has been addressed by referring to the topographic data sets mentioned above.

Results

In the short term, there will continue to be accommodation space for the shingle ridge to roll landwards (in the absence of defences or other management to stabilise the position of the ridge). However, the Alde Estuary channel lies only a short distance landward. A significant lowering of the crest during a storm surge event might easily cause the spread of shingle lobes into the channel. If not removed by dredging this would, in the short term, impede the flow of flood and ebb tides within the estuary, but in the longer term might lead to deepening or widening of the channel on its western side. Further studies are required to assess the potential impacts in detail.

Screening Test 3 - Are relative sea levels anticipated to rise in the region over the period of interest?

Method

This question has been addressed by referring to sea level projections contained in the UKCP18 data portal and by considering recent trends evident from measured tide gauge data.

Results

For present purposes, a conservative approach has been adopted and the projected increases in mean sea level for the 50% and 95th percentile model outputs of the RCP 8.5 (high emissions' scenario) are shown in Table 0.15. Under these scenarios, mean sea level in the Slaughden area might rise by between 6 and 7cm by 2030, by between 28 and 39cm by 2060, and by between 69 and 102cm by 2100.

Table 0.15. Projected increases in mean sea level (in metres) at Slaughden, at 10 year intervals up to the year 2100, relative to 2020, under a RCP 8.5 (worst emission) scenario modelled as part of the UKCP18 project.

Year	5%	50%	95%
01/01/2030	0.04	0.06	0.07
01/01/2040	0.09	0.12	0.16
01/01/2050	0.14	0.19	0.27
01/01/2060	0.19	0.28	0.39
01/01/2070	0.26	0.37	0.53
01/01/2080	0.33	0.47	0.68
01/01/2090	0.39	0.58	0.85
01/01/2100	0.47	0.69	1.02

Conclusions from screening tests

It is concluded that all of the screening tests are met for the Slaughden-Sudbourne Beach area.

A.4.6 Future habitat losses

Extrapolate past losses based on historical trend analysis

There are great dangers in making long-term projections based on short-term historical records since conditions are known to change dramatically on decadal to multi-decadal timescales. However, if the current defences are maintained in situ, it may be expected that as MHW continues to rise at an accelerating rate, there will be further loss of shingle beach area (assuming no additional recharge material was added). A simple extrapolation of historical loss of shingle beach area would imply total loss of the remaining beach at Slaughden and Sudbourne Beach north.

Expert geomorphological analysis of future losses

Future changes in the extent of shingle beach at Slaughden and Sudbourne north are likely to be heavily dependent on the degree to which beach nourishment is carried out. With increasing sea level, and in the absence of further nourishment, it is likely that further shingle will be lost and the rock armour toe protection will be increasingly exposed. By 2050, little or no high tide shingle beach is likely to remain unless additional recharge material is added.

It would also likely be very difficult to maintain the position of the shingle ridge in its present position south of the end of the rock armour by 2025 unless a very large-scale beach nourishment scheme is carried out, and/or further rock armour is placed along the shoreline. It currently seems more likely that little or nothing will be done between

2020 and 2025 and a policy of managed realignment will be adopted after that. Placing imported shingle on the landward side of the ridge is already being done. Extending this will lead to an increase in shingle area, together with development of a more natural beach-ridge profile, in the short to medium term. The risk of major washover events during storms will remain, in which case there would probably be a further increase in shingle area as shingle washover lobes extend westwards into the Alde channel.

Unless a policy of strictly managed realignment is adopted, the future occurrence of coastal squeeze is likely to be limited to the hard defences in SMP2 coastal management policy Unit ALB14.4, and to a minor extent in Policy Unit ORF 15.1. However, there are considerable uncertainties in estimating the extent of coastal squeeze, expressed in terms of reduction in shingle area, or habitat quantity, since the degree to which the beach-ridge system would have rolled landwards in the absence of 'holding' defences to the north, or absence of management of the remainder of the ridge, is itself difficult to predict. This is because it would very much depend on the frequency and magnitude of storm events, and the timing and nature of future managed realignment interventions are also unknown. Confidence in this assessment is judged to be medium.

A.4.7 Conclusions

This case study has demonstrated that the proposed method for assessing coastal squeeze can be applied, in principle, to a shingle beach and managed ridge situation such as that found at Slaughden-Sudbourne Beach, although quantifying the size of both historical and potential future losses is difficult to achieve with a high degree of confidence due to the limited nature of historical beach morphological data (especially pre-1992), uncertainties regarding past and future rates of SLR, storminess and longshore sediment transport rates, and uncertainties regarding future management interventions (for example, the frequency and magnitude of beach and/ or shingle ridge nourishment, reprofiling).

Following the proposed method, the choice is to:

- adopt a precautionary principle
- gather more data through further studies

The evidence clearly indicates that for this case study area, the presence of defences, and management of the shingle ridge south of the Martello Tower using reprofiling and sediment nourishment have combined to prevent the natural landward movement of the beach-ridge system. This has completely stopped the natural functioning of the ridge, and effectively destroyed vegetated shingle habitat. While rising sea level is not the only and probably not the main cause of landward movement of the ridge, it has probably been a minor contributory factor and is likely to become increasingly important in the future.

The effect of the defences and maintenance of the associated trackway behind the defences and along the top of the managed shingle ridge has resulted in the almost total loss of shingle habitat beneath the footprint of the defences and track. While bare shingle remains exposed along the length of the track/flood defence bank, it is of low quality from an ecological point of view.

The effect of the defences and management interventions on the adjoining beach has been mixed, with a net increase in shingle beach area following beach nourishment in the north, and little or no net change in the south. The neutral net effect on the beach in the south can only be maintained by further regular re-nourishment, and maintenance of the beach is likely to become increasingly difficult in the future as the rate of SLR increases.

Greater confidence in the assessment of future beach losses could be gained through a better understanding of the factors that influence alongshore and onshore-offshore movement of shingle on this section of coast, particularly in relation to the fate of shingle eroded during storms and its potential to move back onshore during fair weather periods. Further insight into these questions could be gained by further investigating the nearshore bathymetry, sedimentary character of the seabed, nearshore wave climate, currents and resulting sediment transport.

As a general principle, coastal squeeze of shingle beaches (according to the definition) is likely to occur where fixed defences are present at the back of the beach and where SL is rising significantly. Avoiding a reduction in beach area and sediment volume in the face of SLR is only likely to be achieved where the natural rate of sediment supply is high, where artificial nourishment is carried out, or where the defence line is moved landwards to provide accommodation space for shingle rollover.

Assessment of the effect of defences on a shingle beach and/or ridge should not be restricted only to the area immediately seaward of the defences. Erosion rates are often enhanced just beyond the downdrift end of defences, as is the case at the northern end of Sudbourne Beach south of the Martello Tower.

A.5 Aber Dysynni and Broadwater

A.5.1 Overview of method

The proposed method developed in the WICS project is shown in Chapter 6. The following sections show how each of the steps of the method can be applied to the Aber Dysynni and Broadwater assessment area.

A.5.2 Scoping

The case study area is located on the coast of Cardigan Bay, West Wales, and consists of 2 parts:

a) the open coast between Tywyn and the mouth of the Dysynni Estuary, consisting of a shingle and sand spit complex (Morfa Gwyllt spit)

b) the back barrier area, which includes the Broadwater tidal lagoon and the Dysynni Estuary (Figure 0.26)

The open coast consists of a sand-dominated lower beach platform, a shingle-dominated upper beach slope, backshore and active shingle ridge, hummocky windblown sand sheet deposits behind the shingle ridge and sand and gravel former tidal channel deposits, which enclose a small saline percolation lagoon (Morfa Gwyllt Lagoon). The Cambrian Coast Railway line runs across this area from Tywyn towards the Dysynni Railway Bridge. At the northern end of the barrier is a regulated tidal inlet which links the open sea with the Broadwater tidal lagoon and the Afon Dysynni.

The western part of the Broadwater contains a flood tidal delta consisting of sand banks, sand flats, mud flats, areas of pioneer saltmarsh. The eastern part is of lower average elevation and contains small pools of standing water which are fed by flow from the Afon Dysynni at low tide. The Broadwater and tidally active part of the Dysynni are fringed, especially on the southern side, by extensive areas of reclaimed former saltmarsh and brackish marsh. These grade eastwards into freshwater grazing marshes which are protected from flooding by earth embankments. A large part of the former marshland near Tywyn (Morfa Tywyn) was occupied by an RAF station between 1940 and 1945.

The Broadwater was initially declared a Site of Special Scientific Interest in 1958 and was re-notified in 1982, 1983 and 1995. The present extent of the SSSI is shown in Figure 0.27. Defined habitats of biological interest include saltmarsh, shingle spit, mudflats, pools, reed beds, ditches and the river itself. The saltmarsh is dominated by Sea Rush (*Juncus maritimus*) but contains a number of other nationally or locally uncommon species. Sea Campion (*Silene maritima*) and Yellow Horned Poppy (*Glaucum flavum*) are notable plant species found on the shingle spit. Extensive stands of Common Reed (*Phragmites australis*) are found around parts of the tidal lagoon and form islands within the river/estuary. Other notable species found in ditches, pools and in shallow sections of the estuary include Beaked Pondweed (*Ruppia maritima*), Welsh Mudwort (*Limonsella australis*).

Figure 0.26. Location of the Aber Dysynni and Broadwater case study area within their wider regional context. The area in green shows the extent of the Snowdonia National Park.

The Morfa Gwyllt spit and Morfa Gwyllt Saline Lagoon also lie within the Pen Llyn a'r Sarnau/Lleyn Peninsula and the Sarnau Special Area of Conservation (Figure 0.27). Shingle is identified as a site characteristic within the SAC. The Saline Lagoon is a Biodiversity Action Plan Priority Habitat and contains a number of specialist saline/brackish water species (Bamber et al., 2001; Green and Camplin, 2014). The foreshore and subtidal area below the level of mean high water (MHW) are owned by the Crown Estate and currently licensed for wildfowling.

The period of interest is 1887 to 2019, with a focus on the later period 1960 to 2019.

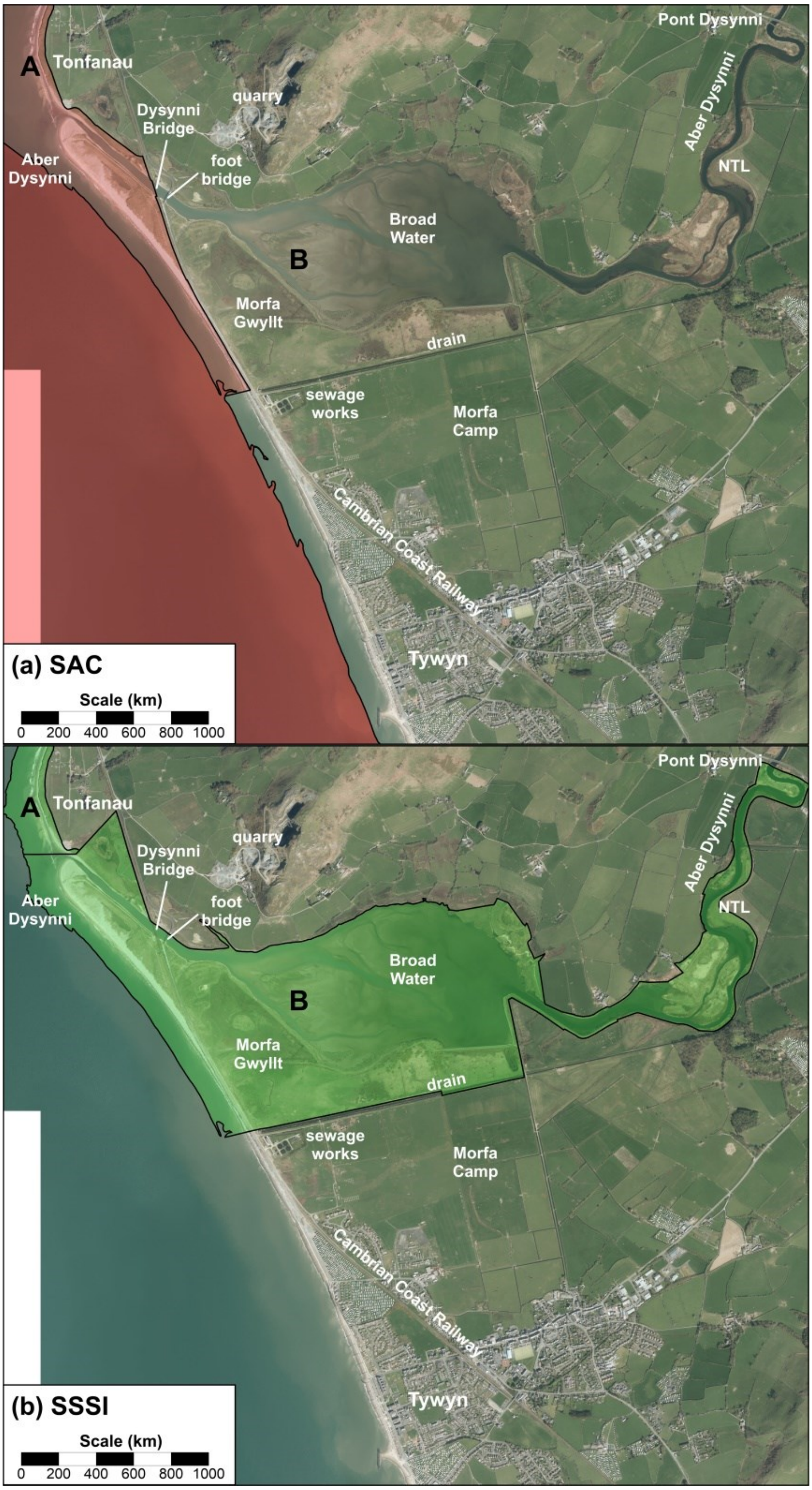

Figure 0.27 (a) Areas designated as SAC (A: Llyn Peninsula and the Sarnau SAC, B: West Wales Marine SAC); (b) Areas designated as SSSI (A: Gannau Tonfanau I Friog SSSI; B: Broadwater SSSI).

A.5.3 Determinating past coastal squeeze losses

Screening test 1 - Have relevant structure/s and/or management actions been present over the period of interest?

Method

This question was approached by referring to published literature, including the West of Wales Shoreline Management Plan (SMP2), unpublished reports, Ordnance Survey maps, aerial photography and LiDAR topographic data sets.

Results

Defences are present along the open coast shoreline between Tywyn and a point approximately halfway along the Morfa Gwylly spit, and around the whole of the southern side of the Broadwater and Afon Dysynni up to Pomnt Dysynni (Figure 0.28). Most of the northern side of the Broadwater is backed by naturally rising ground.

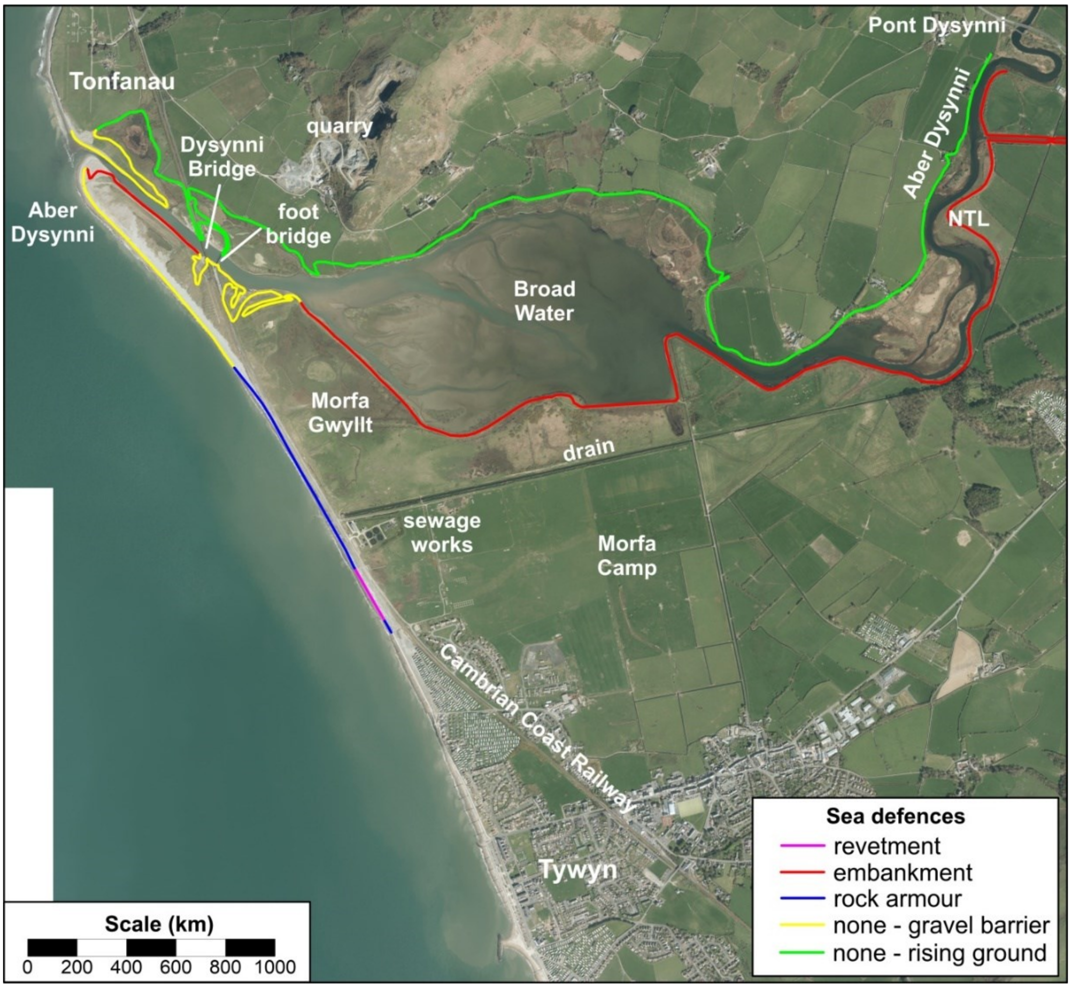

Figure 0.28. Defences on the open coast north of Tywyn and around the Dysynni Estuary.

The Tywyn frontage has been defended using a variety of hard structures, including concrete walls, groynes and, more recently, a detached offshore breakwater and beach nourishment, for more than a century. The first short section of defences was constructed around 1900 for coast protection and to create a promenade. The promenade and sea walls were subsequently extended northwards and southwards, supplemented by a groyne system, which is now largely in a state of disrepair. In 2009, a detached breakwater was constructed opposite the central part of the promenade and sand and gravel imported to widen the beach and encourage the development of a tombolo in the lee of the breakwater (Figure 0.28). The effect of these structures has been to hold the position of the shoreline at Tywyn, to eliminate the supply of new sediment from cliff erosion in this area, and to retain sediment on the beach fronting Tywyn, thereby reducing the supply of sediment to the frontage immediately to the north.

A breakwater and rock armour protection were installed in the mid-19th century at the outfall of the Morfa Gwyllt drain, later also used for discharge from the Tywyn sewage works. The Cambrian Coast Railway line was built in the 1860s along a route which took it very close to the sea along the shingle ridge to the north of the outfalls (Rear and Williams, 1978). The ridge was partially modified to create an incline leading up to the Dysynni Bridge River crossing, which itself was stabilised by breakwaters. The original railway bridge was re-built in 1911 and rock abutments were subsequently constructed on either side of the river to the east of the railway bridge to support a road bridge. The bridge was demolished in the 1960s but was replaced by a footbridge in 2012 to 2013.

Figure 0.29. Oblique aerial view from Tywyn towards Morfa Gwyllt and the Broadwater (source: Cherish project archive, reproduced under Open Government Licence).

The northern end of Morfa Gwyllt spit has been modified on a number of occasions. New training walls and a breakwater extension were built in the 1960s when the course of the river was diverted further to the east and the north in order to widen the end of the spit to use as an Army firing range (Bamber et al, 2001). The Morfa Gwyllt percolation saline lagoon subsequently developed in part of an abandoned tidal channel. The present entrance channel to the Dysynni is, in effect, a canal, controlled by training walls built in the 1960s.

Reclamation of parts of the saltmarshes and tidal flats around the Broadwater began more than 200 years ago. A major drain and embankment across Morfa Gwyllt was constructed in the mid-19th century. Embankments to provide protection against combined tidal and riverine flooding now extend for several kilometres upstream from the Pont Dysynni road crossing. The lengths of different types of defences now present below Pont Dysynni (the limit of the area covered by the West of Wales SMP2) are summarised in Table 0.16.

Table 0.16. Lengths of defences and undefended shoreline between Tywyn and Aber Dysynni, and around the Broadwater.

	Length (m)	Percentage
Open coast		
Rock armour	1,008	44.2
Revêtment	238	10.4
Gravel/shingle barrier	1,032	45.3
Total	2,278	100.0
Estuary		
Embankment	6,269	40.8
Gravel/shingle barrier	2,624	17.1
Rising ground	6,467	42.1
Total	15,360	100.0
Open coast and estuary		
Embankment	6,269	35.5
Rock armour	1,008	5.7
Revêtment	238	1.3
Gravel/shingle barrier	3,656	20.7
Rising ground	6,467	36.7
Total	**17,638**	**100.0**

Screening test 2 - Has there been suitable accommodation space landward of the structure over the period of interest?

Method

This question was addressed by examining Ordnance Survey maps and Environment Agency LiDAR data sets.

Results

There is clear evidence that accommodation space for movement/landward expansion of both the shingle ridge and the Broadwater tidal lagoon exists. A digital terrain model of the estuary, compiled using Environment Agency LiDAR data, is shown in Figure 0.30. The Afon Dysynni is a misfit stream which sits within a relatively wide trough created by glacial action during the Pleistocene. Near its seaward end the valley below an elevation of around 3.0mOD is approximately 2.5 to 3km wide, decreasing upstream to about 1.3km near Pont Dysynni.

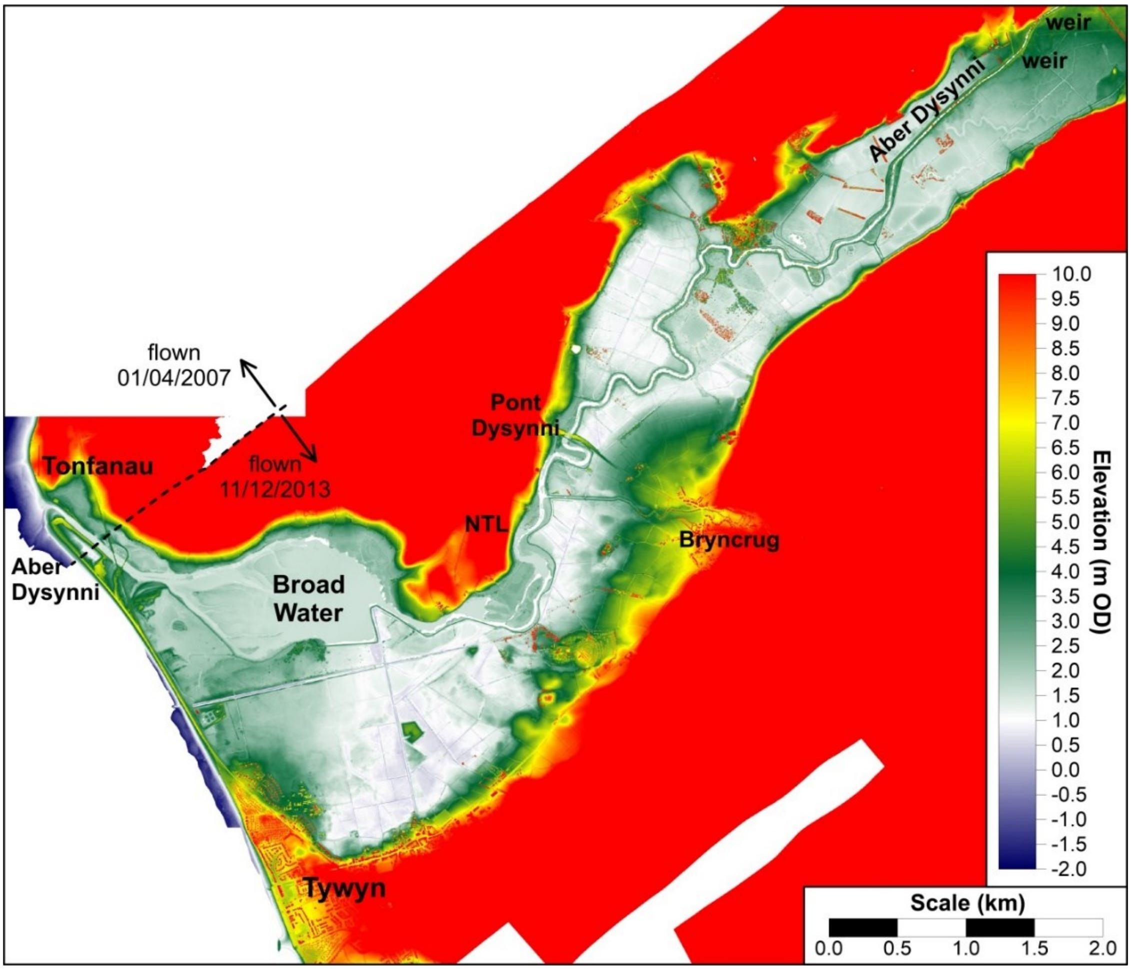

Figure 0.30. LiDAR DSM flown mostly on 11/12/2013, with a small section at Aber Dysynni flown on 01/04/2007. The black line shows the current estuary outline (the HAT contour on the seaward side of the defence line or rising ground throughout the estuary).

Figure 0.31 shows the extent of potentially floodable land below an elevation of 2.96m OD (that is, below the approximate level of MHWS at the estuary entrance), while Figure 0.32 shows the extent of potentially floodable land below a level of 3.18m OD (the approximate HAT level at the entrance). It is evident that, even allowing for differences in tidal elevations along the estuary, and the restricted inflow of tidal water through the artificially constrained estuary mouth, intertidal habitats could occupy a significantly larger area within the estuary if defences were not present. Above the 3.18m contour land levels rise rapidly.

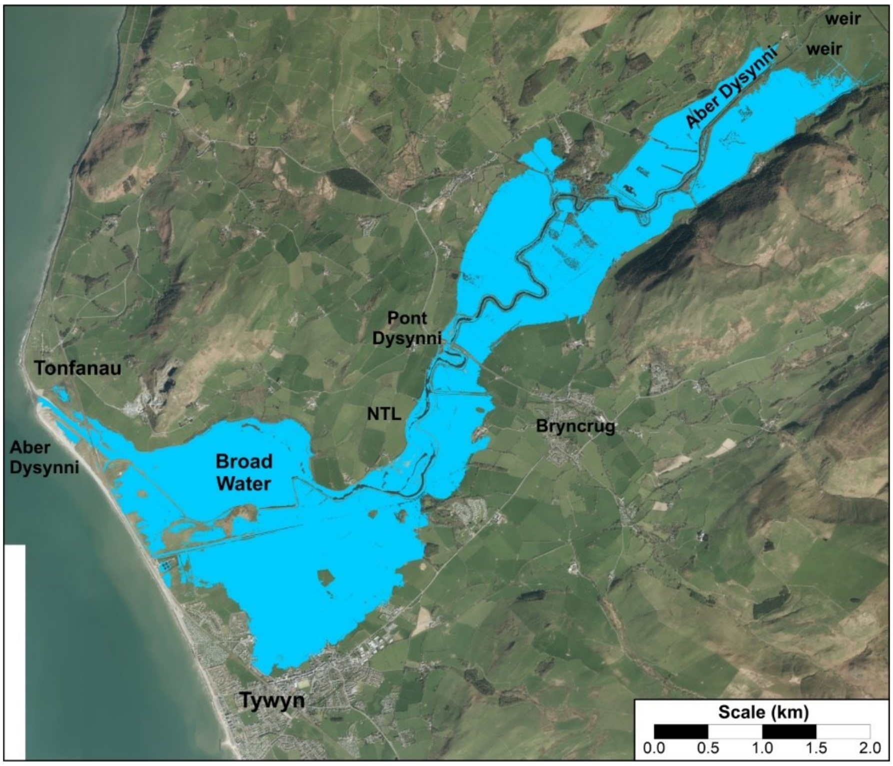

Figure 0.31. Potentially floodable areas of the estuary (166.8ha) below 2.56m AOD (approx. level of MHWS at the entrance). The black line shows the current estuary outline (the HAT contour on the seaward side of the defence line or rising ground throughout the estuary). Base aerial photography flown in 2013.

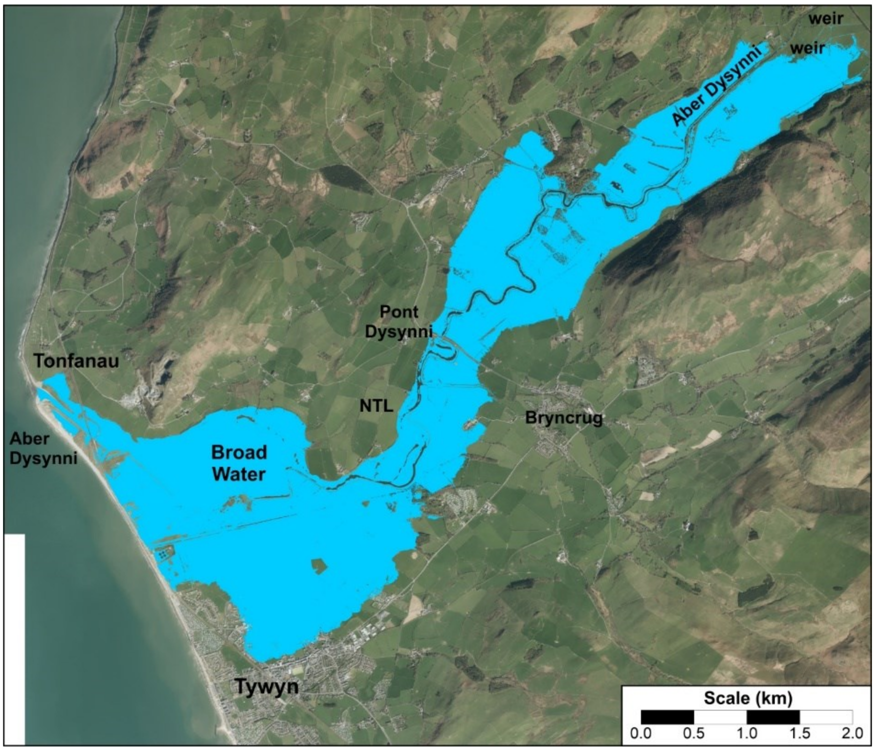

Figure 0.32. Potentially floodable area below 3.18m AOD (approx. level of HAT at the entrance), both in front (192.6ha) and behind (687ha) the defences. The black line shows the current estuary outline (the HAT contour on the seaward side of the defence line or rising ground throughout the estuary). Base aerial photography flown in 2013. In the absence of defences the area of floodable land at 2.56m OD would be 761ha and at 3.18ha would be 880ha.

Screening test 3 - Have there been readily observable losses of habitat in front of structures (either LWM retreat or internal erosion) over the period of interest?

Method

Reference has been made to published studies and unpublished reports, historical maps, aerial photography and LiDAR data.

Results

The evidence indicates that there has been a reduction in beach width, including the upper beach, in the area north of Tywyn, and especially around the Morfa Gywllt Outfall since around 1900. The mean high water mark has been fixed more or less in the same position by the outfall and later rock armour placed to defend the railway, sewage works and other neighbouring infrastructure. However, the mean low water mark has moved landwards, mainly between 1900 and 1948, resulting in a narrowing of the beach. This is consistent with the concept of 'beach coastal squeeze'. Further north from this point the mean high water mark has shown little net change since 1900 and the low water mark has retreated landwards to a much lesser degree. The northern end of the Morfa Gwyllt spit has grown northwards by around 600m since 1821, and the ebb tidal delta of the Dysynni has continued to act as an area of sediment accumulation up to the present, fed mainly by alongshore drift of sand and gravel from the south. Consequently, there is no evidence of possible coastal squeeze in this area.

The extent of the tidally active area of the Broadwater decreased significantly between 1820 and 1900, due to a combination of natural siltation and land reclamation, but has changed little since 1900. No detailed quantitative information exists regarding changes in the extent of individual habitats within the estuary, but qualitative evidence from maps and aerial photographs suggests that losses have been very largely due to engineering works at the entrance to the estuary and to associated land claim rather than to erosion of habitat on the seaward side of the defence line. Localised changes in channel position have occurred in some parts of the estuary, but appear to be due to the natural meandering behaviour of the channels. This process has produced localised gains and losses of intertidal area immediately in front of individual lengths of defences (mainly flood embankments).

Screening test 4 - Has relative SL risen in the region over the period of interest?

Method

Reference has been made to new analysis of tide gauge records carried out for the Class 'A tide gauges at Holyhead, Barmouth and Fishguard, with data being obtained from the Permanent Service for Mean Sea Level (PSMSL) website.

Results

All 3 records examined suffer from significant gaps in the data and large numbers of values flagged as 'improbable', particularly in recent years. The period of record for Barmouth is very short (1993 to 2013). Therefore, estimates of average rates of sea level trend are subject to large uncertainties, larger than those indicated by the SE values associated with the mean of the trend. However, the records for all 3 stations indicate an increasing sea level tendency. Calculated average rates of change in annual mean sea level (AMSL) are +2.77 +/- 0.23 at Holyhead for the period 1938 to

2018, +4.97 +/- 1.91 at Barmouth for the period 1993 to 2013, and +5.83 +/-1.02 at Fishguard for the period 1969 to 2014 (Figure 0.33). Based on the length and quality of record, the trend for Holyhead is probably more reliable than those for Barmouth and Fishguard.

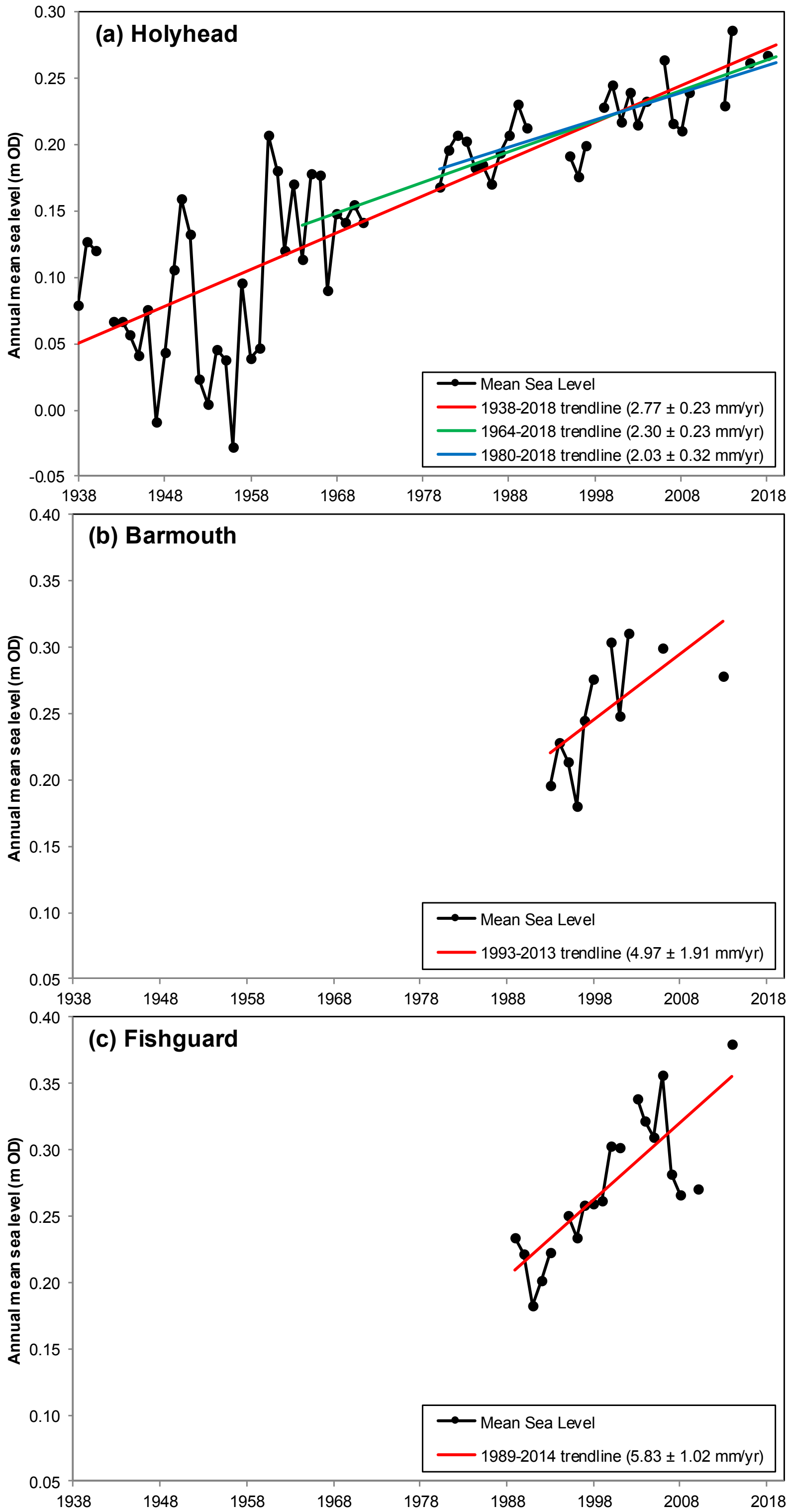

Figure 0.33. Annual mean sea levels recorded at (a) Holyhead; (b) Barmouth; and (c) Fishguard. Linear regression lines are shown for different time periods. Original data source: PSMSL.

Conclusions from screening tests

It is concluded that all 4 screening tests are met for part of the Tywyn to Aber Dysynni open coast (the southern section) but not for the northern section where there is no evidence of intertidal narrowing and no defences present. Three of the 4 tests are met for the Dysynni Estuary (Broadwater), with no clear evidence of a reduction in intertidal habitat area or quality in front of the flood embankments. It is, therefore, possible that coastal squeeze has occurred in the past on the southern part of the Tywyn to Aber Dysynni frontage, but there is no indication of it elsewhere.

A.5.4 Expert geomorphological analysis of historical losses

Baseline geomorphology

There is only limited detailed information available relating to the geomorphological features and habitats in the Aber Dysynni-Broadwater area.

Brief descriptions of the Aber Dysynni (or Morfa Gwylt) shingle ridge between Tywyn and Aber Dysynni were provided by Sneddon and Randall (1993) and Stapleton (1996) as part of national assessments of shingle vegetation and landforms in Wales. Sneddon and Randall (1993) considered the Aber Dysynni spit to be a complex coastal system and noted the presence of complex transitions between shingle, blown sand and saltmarsh on the landward side, with a saline lagoon trapped between the sand and shingle ridges. Stapleton (1996) reported a small number of surveyed profiles across the upper beach and most seaward shingle ridge and provided limited data relating to the size, shape and composition of the shingle.

A regional overview of coastal processes, coastal erosion and flood risk and the nature of defence works was provided in the North Cardigan Bay Shoreline Management Plan (Gwynedd Council, 1998), and an updated overview provided in the West of Wales Shoreline Management Plan 2 (Royal Haskoning, 2011a).

Bamber et al. (2000, 2001) made a brief assessment of the saline lagoon (Morfa Gwyllt Lagoon) trapped within the shingle area, and the faunal assemblages (animal fossils) present have been monitored by CCW/NRW since that time (for example, Green and Camplin, 2014).

Pye and Blott (2018) carried out a preliminary investigation of the historical evolution of the shingle ridge and provided a summary of current management activity to keep the estuary mouth clear of shingle. Very brief summaries of the physical characteristics of the Dysynni Estuary (including Broadwater) were provided in the Nature Conservancy Council’s Estuaries Review (Davidson et al., 1991), and as part of the Defra-funded Estuaries Research Programme (summarised at http://www.estuary-guide.net/search/estuaries/details.asp?fileid=20). The latter programme classified the Dysynni as a Spit Enclosed Estuary with a shoreline length of 9.9km and a channel length of 4.4km. The ‘Core area’ was defined as 116.5ha and the intertidal area 69ha.

The area experiences a macro tidal regime, with a mean spring tidal range of approximately 4.3m (Table 0.17). The estimated levels of mean high water spring tides (MHWS) and the highest astronomical tide (HAT) are 2.56m AOD and 3.18m AOD, respectively. Owing to the present restricted nature of the estuary entrance the high water levels inside the tidal lagoon and estuary are slightly lower than those on the open coast, although in the past, when the estuary entrance was wider, the tidal levels in the estuary may have been relatively higher than today.

Table 0.17. Tidal levels at the secondary ports of Barmouth and Aberdovey, and estimated at Aber Dysynni, based on Admiralty Tide Tables (UKHO, 2019). Where levels are the same at Barmouth and Aberdovey, Aber Dysynni is also assumed to be the same. For HAT, the level estimated by the Environment Agency (2018) Coastal Boundary Study database for Aber Dysynni has been taken, which is approximately in proportion to the relative distances to Barmouth and Aberdovey.

	Barmouth	Aber Dysynni	Aberdovey
HAT	3.26	3.18*	3.06
MHWS	2.56	2.56	2.56
MHW	1.81	1.81	1.81
MHWN	1.06	1.06	1.06
CD	-2.44	-2.44	-2.44
MSTR	4.30	4.30	4.30

The 1 in 1 year water level for Aber Dysynni estimated in the Environment Agency's Coastal Boundary Study for England and Wales (Environment Agency, 2018) is 3.26 to 3.1mAOD, while the 1 in 100-year level is estimated to be 3.80 to 4.06mAOD (Table 0.18).

Table 0.18. Return period of extreme water levels for offshore point 818 located approximately 2.0km SW of Aber Dysynni. Data from the Coastal Flood Boundary Conditions Update (Environment Agency, 2018).

Return period (years)	Level (m OD)	95% confidence interval (m OD)
1	3.27	3.26 to 3.31
2	3.37	3.35 to 3.41
5	3.50	3.47 to 3.54
10	3.59	3.55 to 3.65
20	3.69	3.63 to 3.76
25	3.72	3.66 to 3.80
50	3.81	3.73 to 3.93
75	3.87	3.77 to 4.01
100	3.91	3.80 to 4.06
150	3.96	3.83 to 4.15
200	4.00	3.86 to 4.22
250	4.03	3.88 to 4.27
300	4.06	3.90 to 4.31
500	4.13	3.95 to 4.44
1,000	4.25	4.03 to 4.61
10,000	4.63	4.26 to 5.37

No long-term measured wave data are available for Cardigan Bay, but hindcast data for the period 1980 to 2016 for a point 5km west of Tywyn, available from Cefas Wavenet website, indicate a dominance of waves from the west to south-west (Figure 0.34) The dominant waves approach the Tywyn to Aber Dysynni shore at an oblique angle, inducing alongshore sediment transport towards the north. Owing to the nature of the coastal orientation, there is a local alongshore drift reversal towards the south-east along the southern part of Tonfanau. These processes have been responsible for the formation of asymmetric paired spits at the entrance to the Dysynni Estuary, the southern (Morfa Gwyllt spit) being far the larger.

Sediment accumulation at the mouth of the Dysynni continues today, and National Resources Wales has, for several years, removed shingle from the southern side of the Dysynni channel and placed it on the northern (Tonfanau side) in order to maintain ebb drainage and reduce the flood risk within the Dysynni Valley (Pye and Blott, 2018).

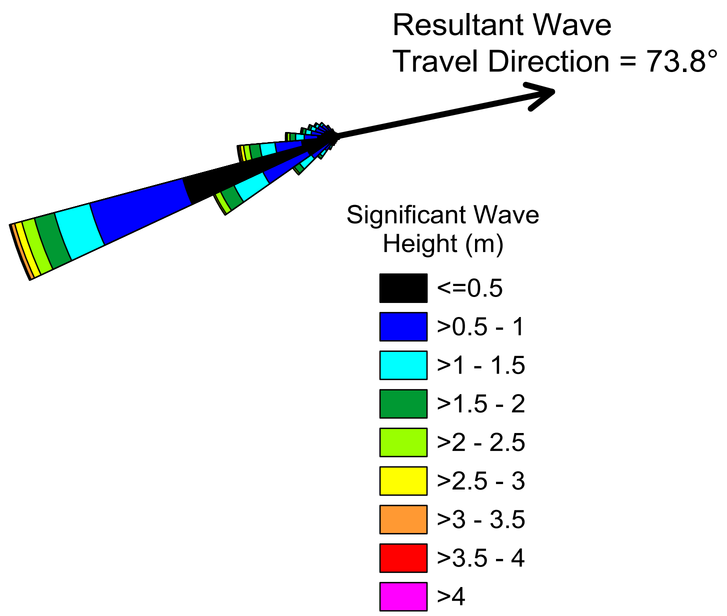

Figure 0.34. Wave rose calculated from Met Office hindcast data at an offshore point 5km west of Tywyn for the period 1980 to 2016. Raw data source: Cefas Wavenet website, original analysis by Pye and Blott, 2018).

Historical documentary evidence and the earliest maps indicate that the entrance to the estuary was formerly much wider, and the Broadwater much more open, than at present (Figure 0.37). A local shipbuilding industry once existed, and the estuary may have acted as a minor port of passage between Ireland and the English Midlands.

Before the construction of defences at Tywyn the outcrops of glacial till in the area provided an important local source of sediment. As the Morfa Gwyllt spit extended northwards from Tywyn a series of recurves formed, some of which (those closer to Tywyn) had low covering of sand dunes. Erosion of glacial deposits at Tonfanau also provided a second source of sediment which was partly transported southwards to build spits on the northern side of the estuary entrance. At the time of the 1887 survey, a significant shallow embayment existed on the Tonfanau side of the entrance, with a second small embayment to what is now the Dysynni footbridge crossing. These embayments became progressively cut off from the estuary due to spit growth during the late 19th and early 20th centuries. Both areas were reported by Bamber et al. (2000, 2001) to contain freshwater pools. The North Pool (nearest to Tonfanau) has become almost filled by terrestrial and aquatic vegetation over the past 20 years, but the eastern pool (‘Farm Pool’) continues to experience tidal influence today, although it is not formally identified as a saline lagoon.

When the Cambrian Coast Railway line was built in the mid-19th century, training walls were constructed to control flow and movement of the main estuarine channel beneath the railway bridge. Later, in the 1960s additional breakwaters were built around the northern end of the spit to give it a wider, blunter form, reportedly as part of a plan to create a firing practice area (Bamber et al., 2001). Since that time, the form of the end of the spit has been subject to natural change, becoming narrower and extending towards the Tonfanau side. Build-up of shingle against the southern side of the entrance breakwater continues, and incursion into the entrance channel presents an ongoing problem for the maintenance of land drainage (Pye and Blott, 2018).

Figure 0.35 provides a comparison of the coastal features of the area in 2013 with the shoreline indicated on the First Edition Ordnance Survey One-inch map, originally surveyed in the 1820s and published after revision in 1837. Although the 1837 map contains survey inaccuracies, 3 major differences are evident:

1. a major increase in length and width of the Morfa Gwyllt spit
2. significant accretion of a smaller shingle spit complex on the northern side of the estuary mouth
3. large-scale accretion and land-claim at Morfa Gwyllt on the western side of the Broadwater

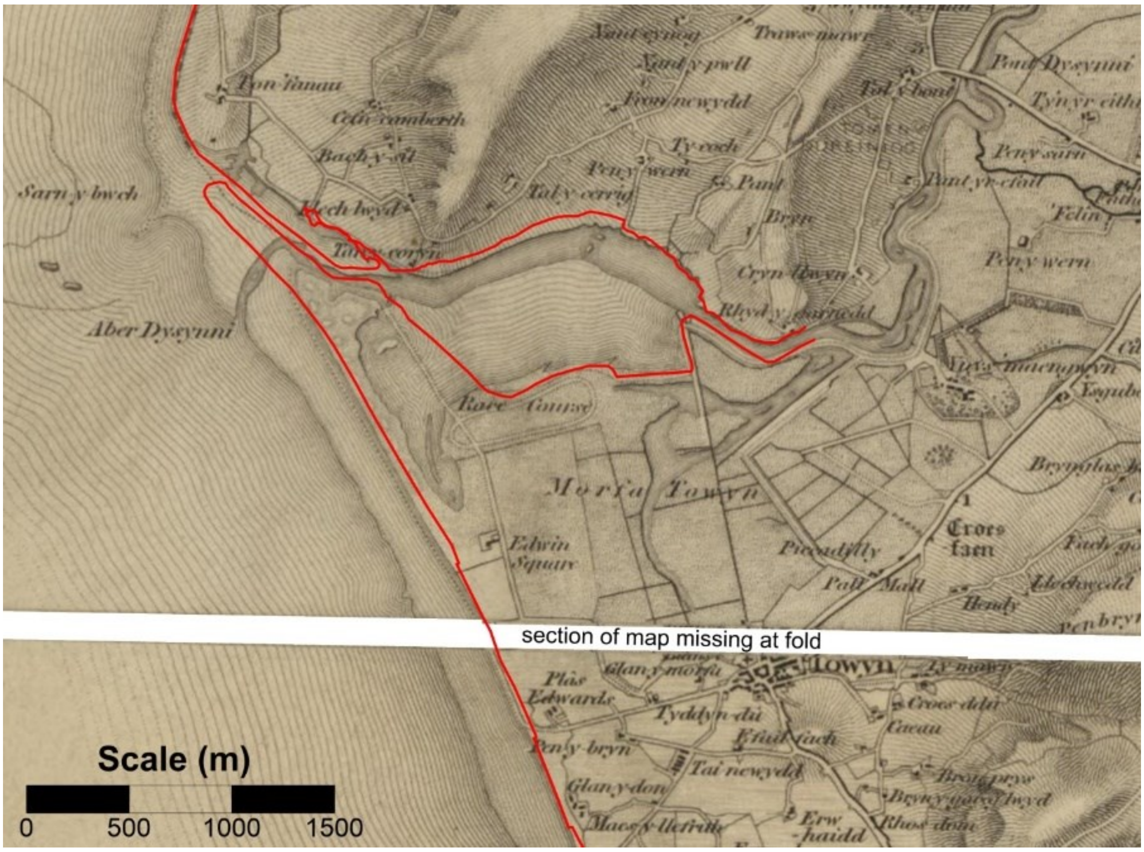

Figure 0.35. Extract from the First Edition one-inch map, originally surveyed in the 1820s, revised in the 1830s and published in 1837. The red line indicates the position of the 2.36m OD contour (approx. MHWS line) based on 2015 LiDAR. Note that there are limitations to survey the accuracy of the 1837 edition One-inch map.

The glacial till shoreline at Tywyn has been protected by wooden groynes and a concrete promenade for over a century, and in more recent years, rock groynes and a headland breakwater have been constructed. This has eliminated the sediment supply provided by cliff erosion in this area and contributed to a sediment deficit on the beaches fronting the southern part of the Aber Dysynni ridge. A shallow embayment has formed with its centre located to the north of the sewage works, placing additional stress on the ridge in this area. The natural recession of the ridge immediately to the north of this point is prevented by rock armour placed on the back-beach and ridge crest, but beyond the northern limit of the shore protection the ridge has a relatively natural form, with storm washover fans in several places.

Figure 0.37 to Figure 0.40 and Figure 0.45 to Figure 0.48 provide aerial photographic and LiDAR DTM enlargements of the 4 areas labelled 'A', 'B', 'C' and 'D' shown on Figure 0.36. Figure 0.41 shows an extract from the 1953 edition Six-inches to the Mile Ordnance Survey Map of the northern area (revised in 1948, with mean low water re-surveyed in 1952), which illustrates the former meandering nature of the low water channel within which the Morfa Gwyllt saline lagoon later developed.

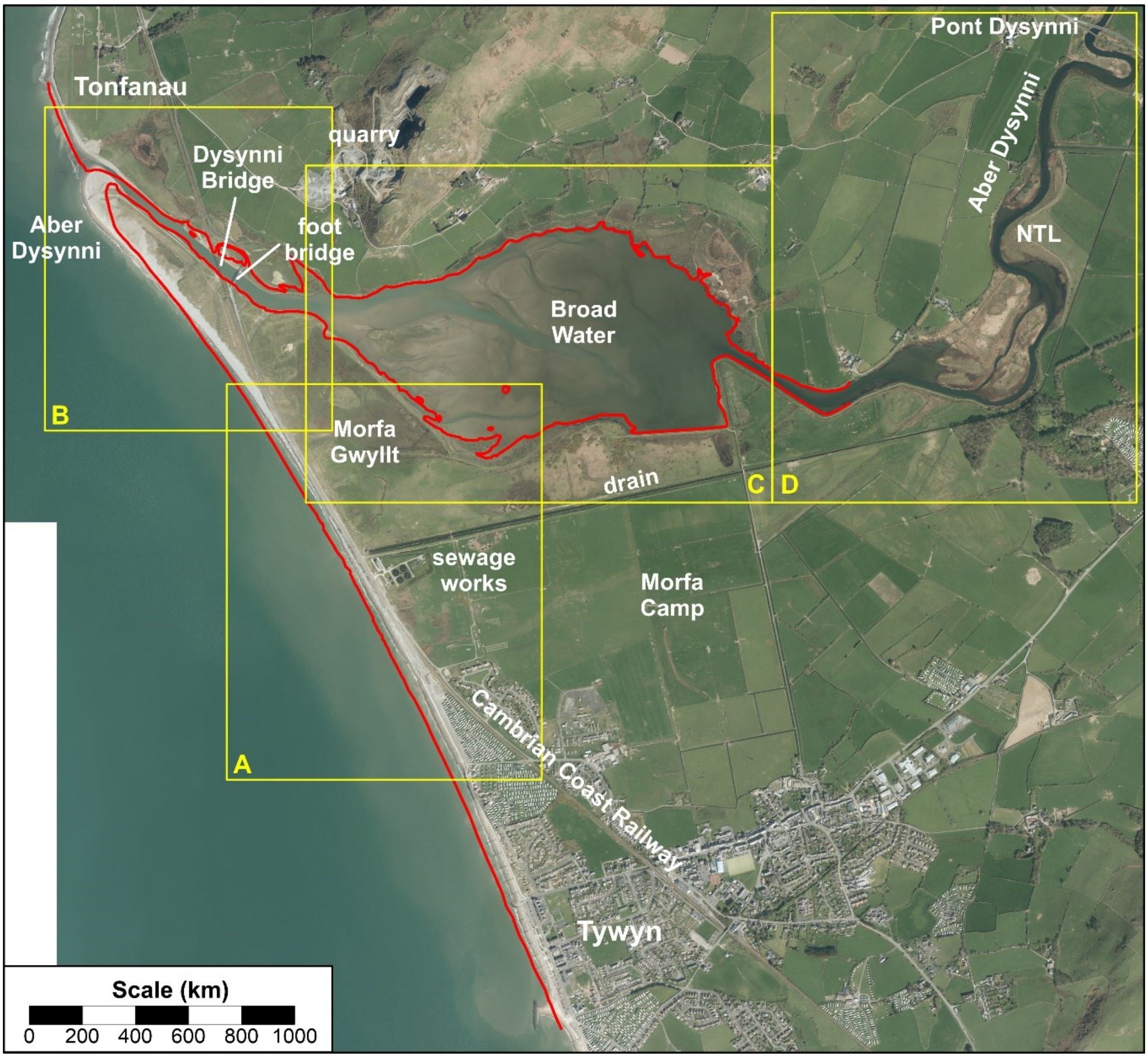

Figure 0.36. Major features of the Tonfanau to Tywyn frontage and Dysynni Estuary. The red line shows the MHW line indicated on the First Edition Six-inch Ordnance Survey map surveyed in 1887. The yellow boxes indicate the coverage shown on following enlargements.

Figure 0.37. Enlargement A showing the section of the Cambrian Coastal Railway which is defended with rock armour and sea walls. Lines show positions of MHW from historical maps (1887, 1952 and 1972) and LiDAR (2005). Note that the MHW line around Broad Water was not revised in 1952. Base aerial photograph flown in 2013.

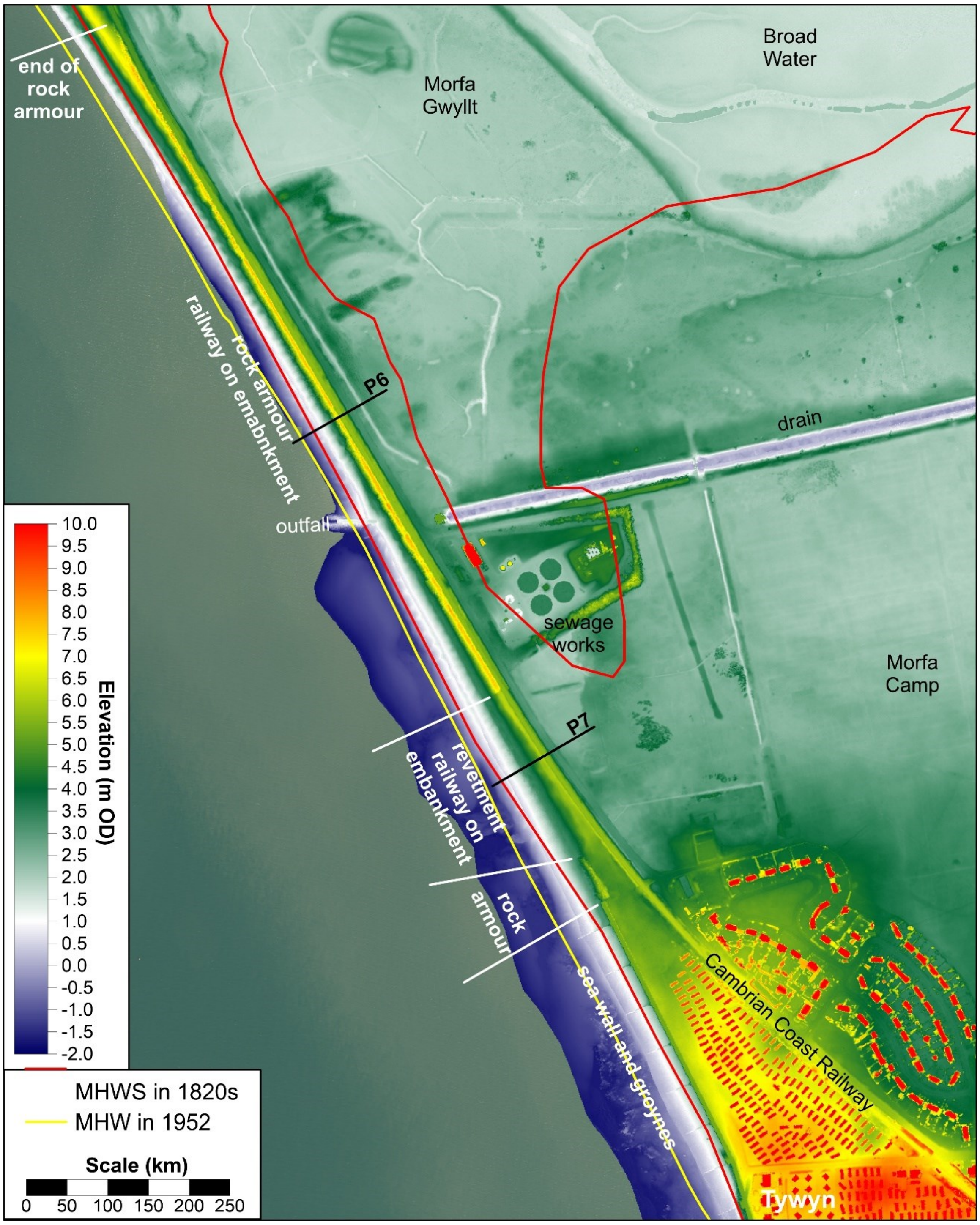

Figure 0.38. Enlargement A showing the section of the Cambrian Coastal Railway which is defended with rock armour and sea walls. Lines show positions of MHW from historical maps (1820s and 1952). Base LiDAR DSM flown on 11/12/2013.

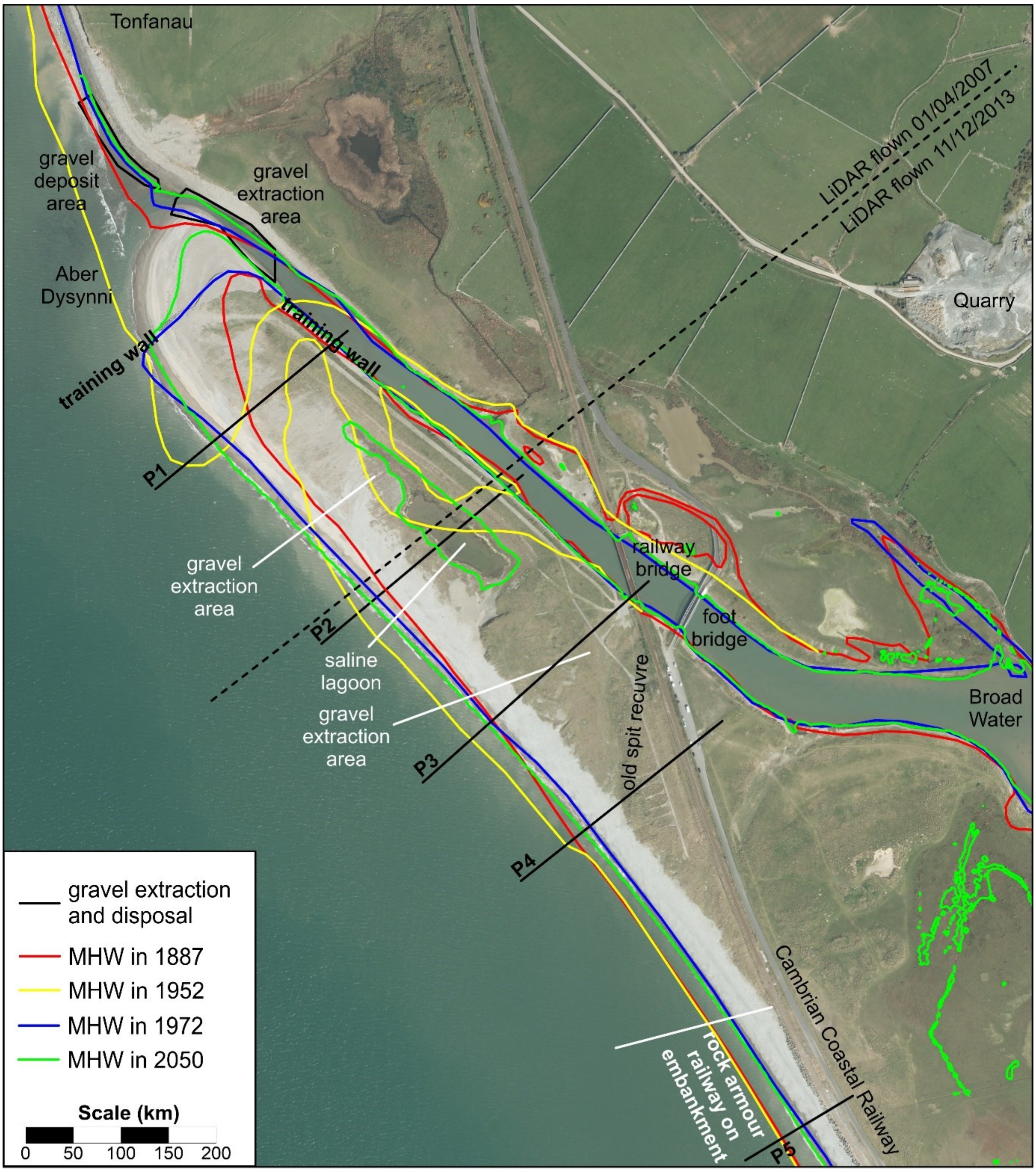

Figure 0.39. Enlargement B showing the section between Tonfanau and the northern limit of rock armour. Base aerial photograph flown in 2013. The historical positions of MHW take from rectified historical OS Six-inch maps are also shown.

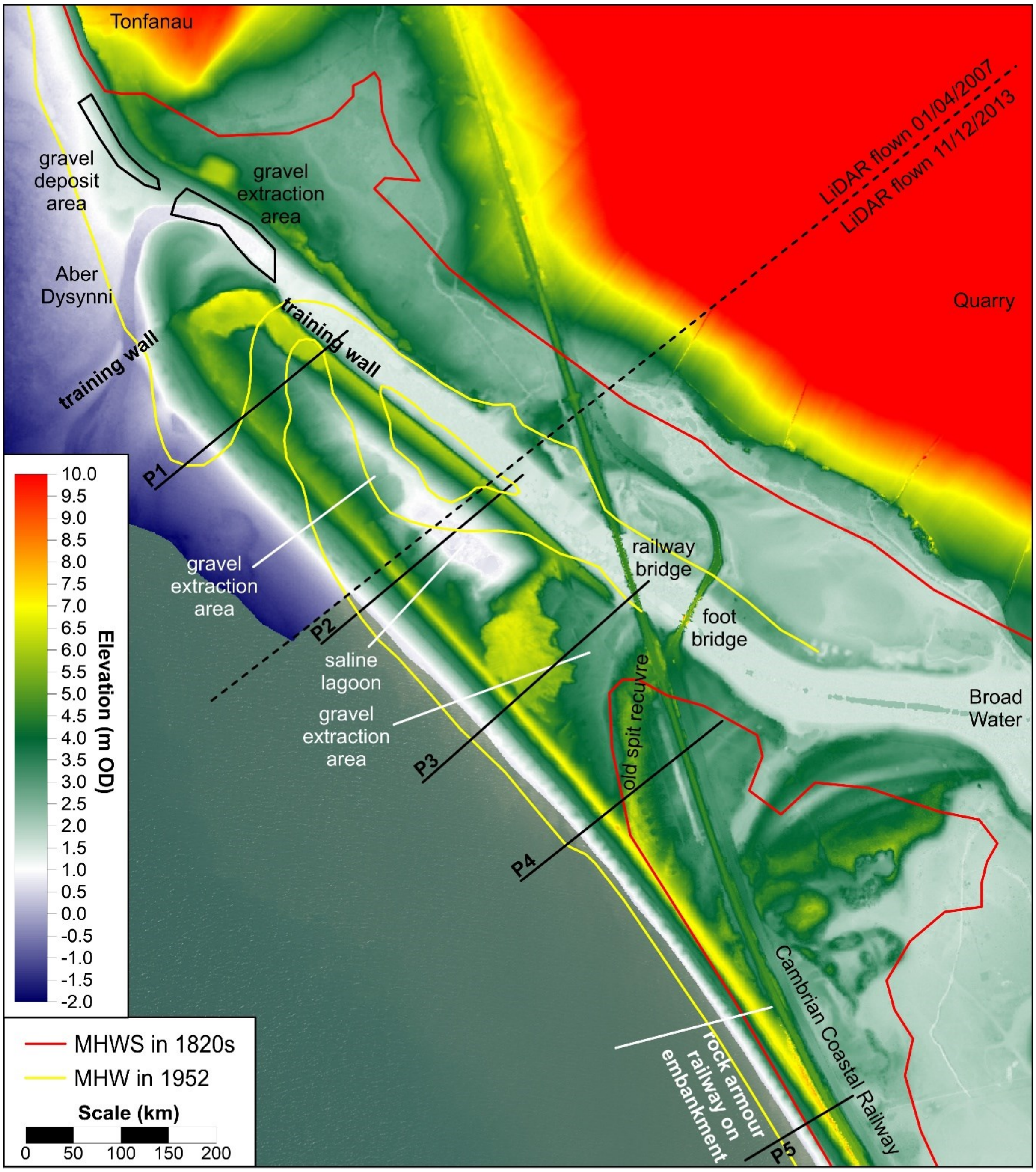

Figure 0.40. Enlargement B showing the section between Tonfanau and the northern limit of rock armour. Lines show positions of MHW from historical maps (1820s and 1952). Base LiDAR DSM flown on 11/12/2013 (SE area) and 01/04/2007 (NW area).

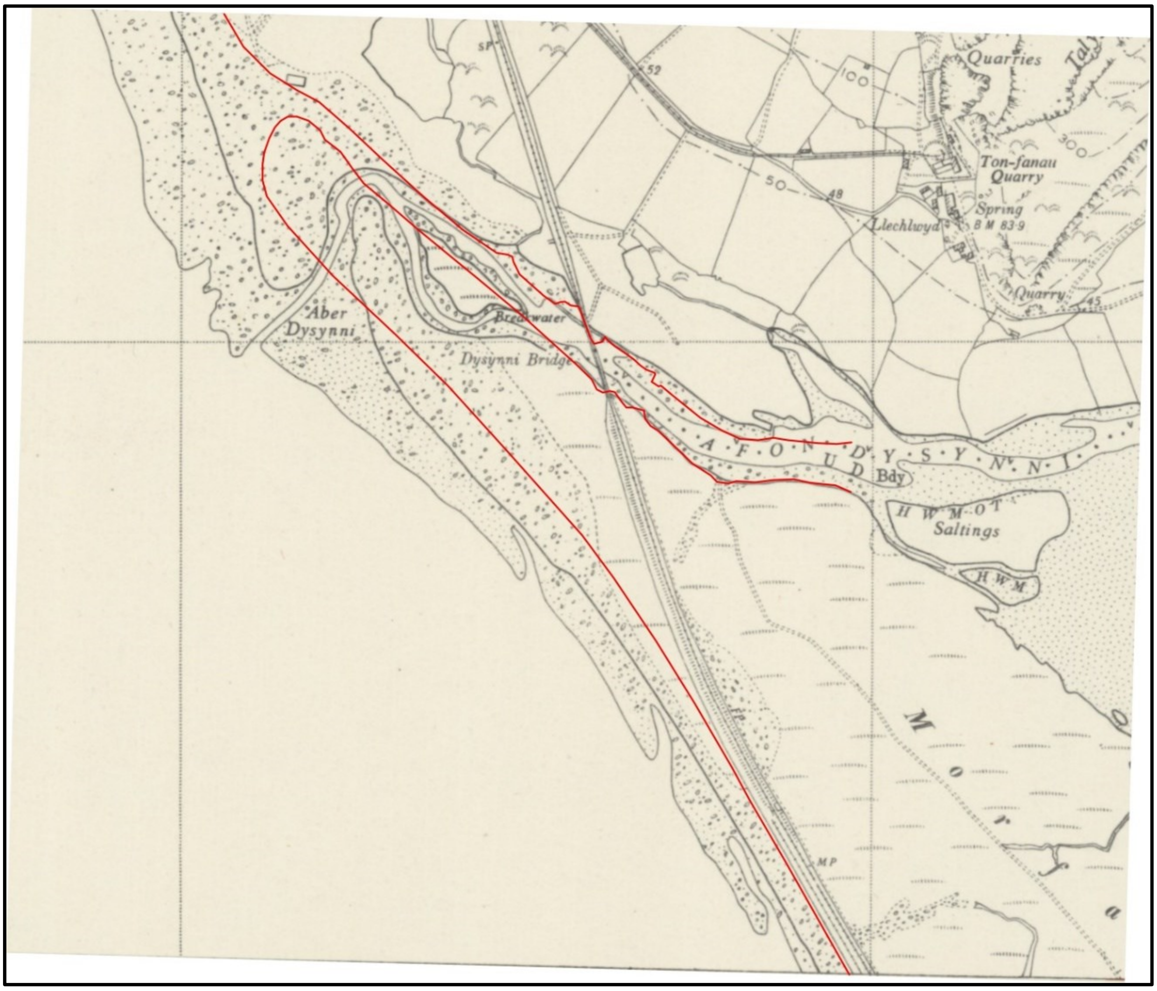

Figure 0.41. Six-inch Ordnance Survey map surveyed 1948 to 1952 and published in 1953 (showing LWMOT re-surveyed in 1952). The red lines indicate the approximate position of MHW estimated from 2013 and 2015 LiDAR. Note the old course of the main channel within which the Morfa Gwyllt saline lagoon has developed.

Figure 0.42 provides a comparison of selected cross-section extracted from 2005, 2013 and 2015 LiDAR DTMs, while Figure 0.45 provides a graphical representation of the changes in MHW position since 1887 on each of the profiles P1 to P7 (summarised numerically in Table 0.19).

At profiles P1 to P3 there has been a long-term seaward movement, while at the southern end of the spit (P4 to P7), where defences are present, there has been net landward movement, particularly since the early 1960s. The cross-profiles from the LiDAR (Figure 0.42, Figure 0.43) show relatively little change over the period of available data (2005 to 2015) except at profile P6, where a high ridge has been formed immediately west of the railway line, and at P6 and P7 where shingle overwashed the line in the stormy winter of 2013 to 2014. It can be concluded that, where the elevation of the railway is low, it does not act as a total barrier to the landward movement of shingle under storm conditions.

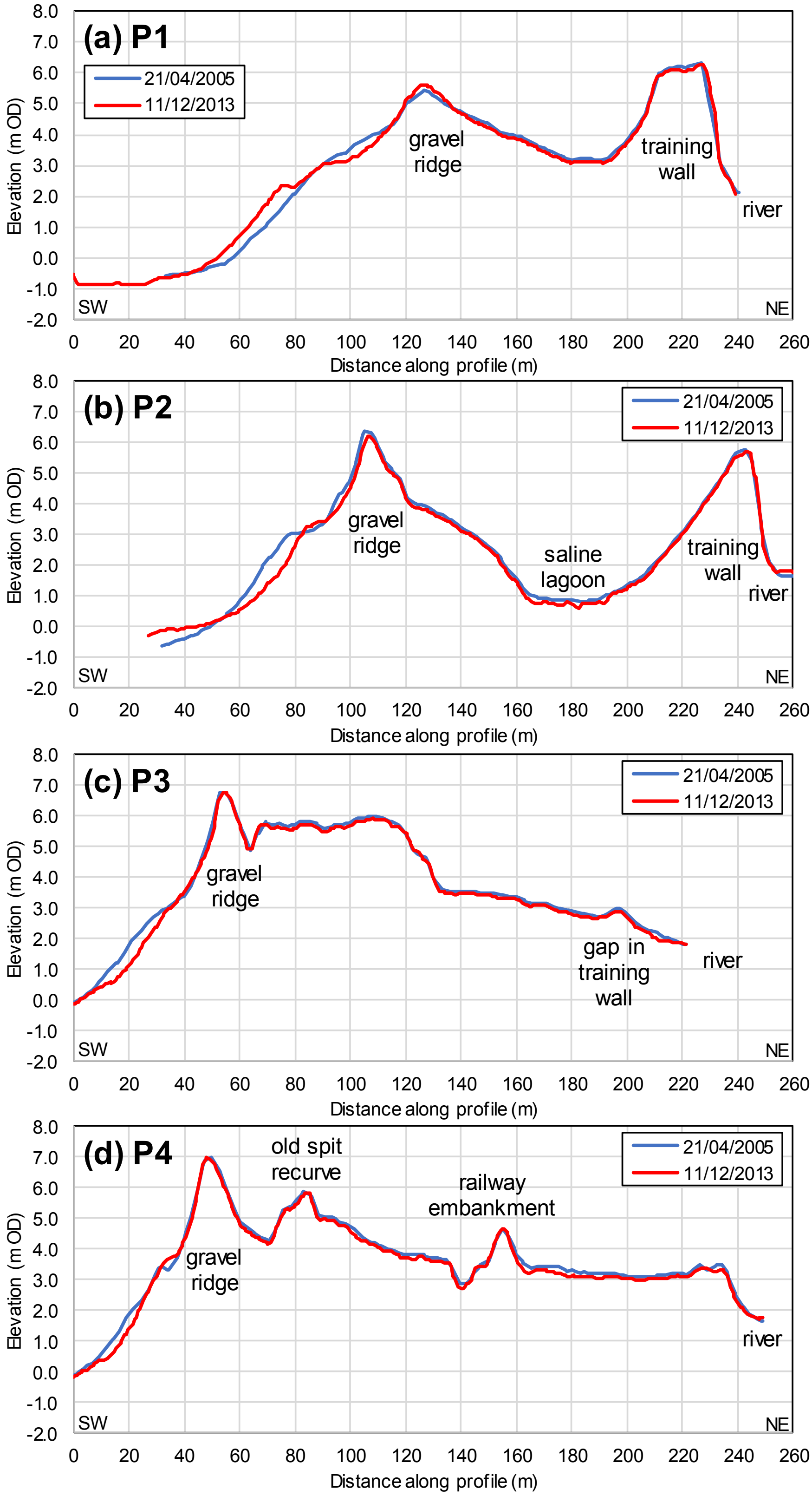

Figure 0.42. Profiles P1 to P7 taken across available LiDAR surveys.

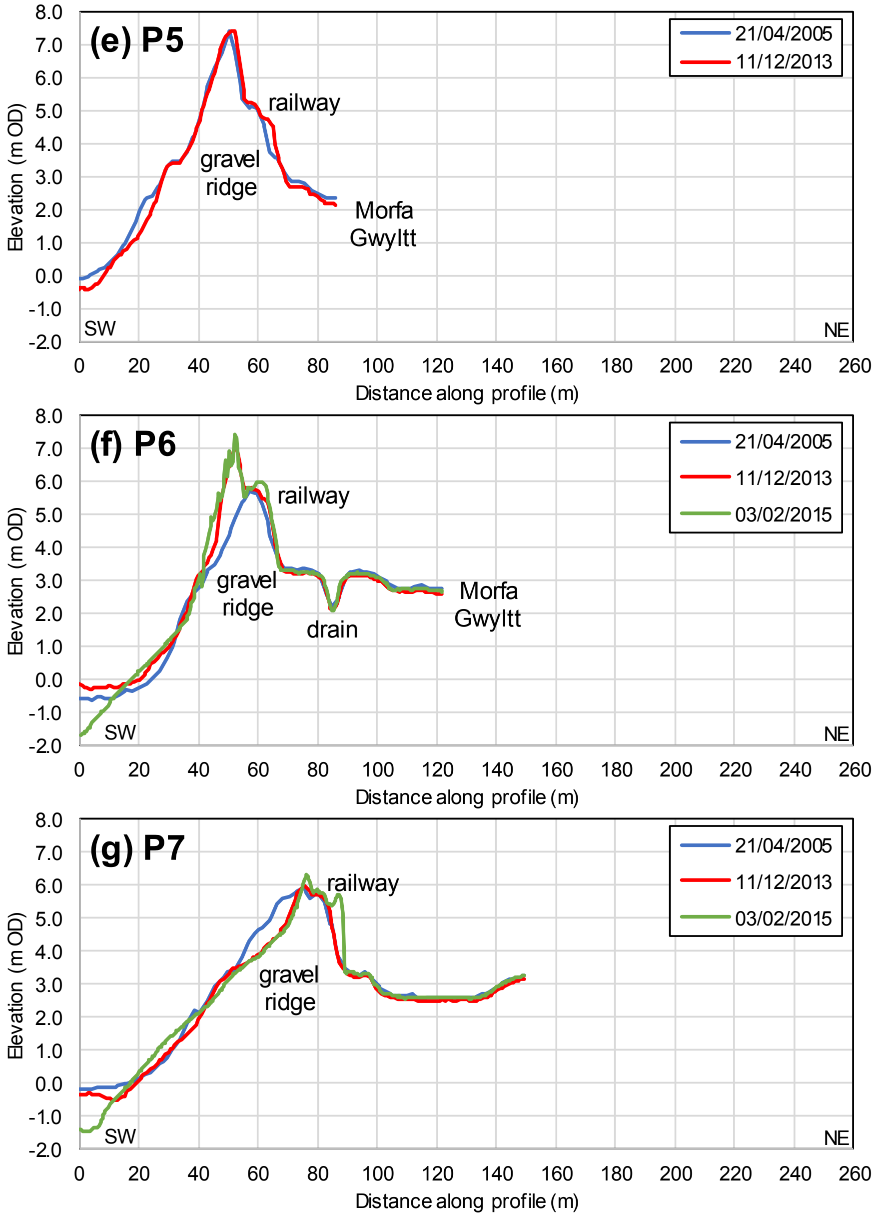

Figure 0.43. continued

Table 0.19. Movement of the MHW contour at the 7 open coast profiles, relative to the year 1887. Contours taken from Ordnance Survey maps surveyed in 1887, 1952 and 1972, and LiDAR surveys flown 21/04/2005 and 11/12/2013 (MHW assumed to be 1.81m OD).

	1887	1952	1972	2005	2013
P1	0	-50.5	37.7	48.3	55.2
P2	0	38.2	12.2	20.4	13.7
P3	0	30.1	1.9	7.0	2.6
P4	0	10.2	-20.4	-11.7	-14.0
P5	0	3.0	-25.4	-21.2	-24.7
P6	0	3.4	-26.8	-28.8	-29.9
P7	0	2.0	-35.1	-36.7	-39.3

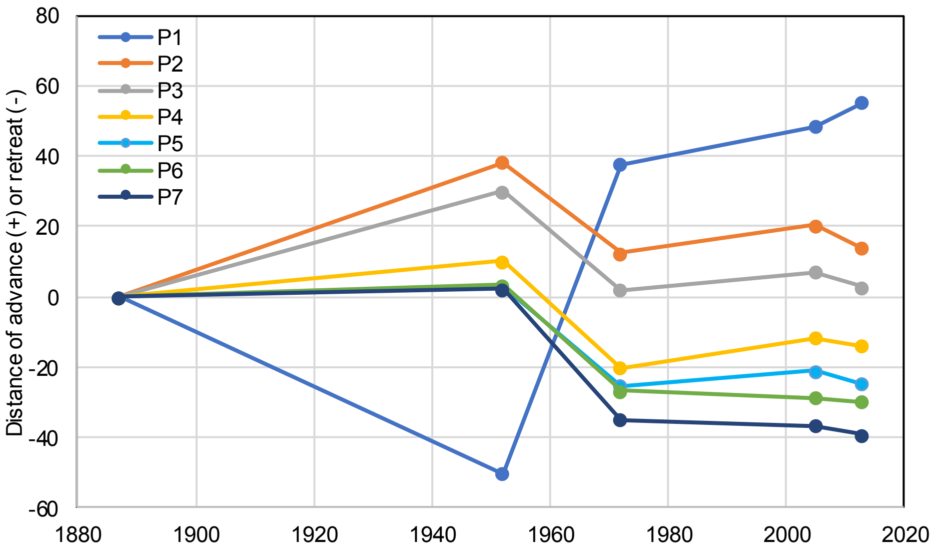

Figure 0.44. Movement of the MHW contour at the 7 open coast profiles, relative to the year 1887. Contours taken from Ordnance Survey maps surveyed in 1887, 1952 and 1972, and LiDAR surveys flown 21/04/2005 and 11/12/2013 (MHW assumed to be 1.81 m OD).

Table 0.20 provides a summary of the area of beach (MLW – MHW) and beach above MHW which was lost to erosion or direct placement of rock armour in the period 1887 to 2013. The total net loss of beach/ridge, excluding direct 'footprint' losses, was 6.83ha.

Table 0.20. Areas of beach and under the defences along the frontage defended by rock armour north of the Tywyn sea wall and in front of the railway (in hectares), measured from historical Ordnance Survey maps (1887, 1952 and 1972) and LiDAR (2015).

	1887	1952	1972	2013
MHW-MLW	17.14	6.16	14.52	4.85
Beach above MHW	4.38	5.03	2.32	1.98
Area under defence (rock armour)	0.00	0.00	0.00	0.82

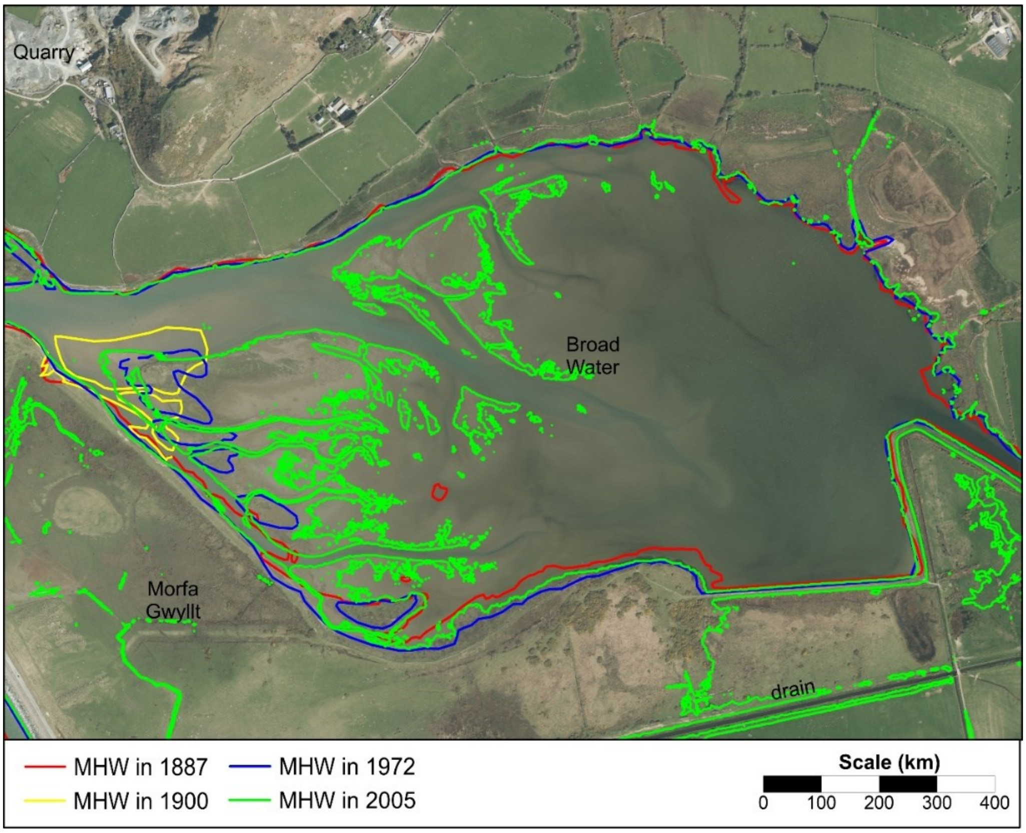

Figure 0.45. Enlargement C: Broadwater. Lines show positions of MHW from historical maps (1887, 1900 and 1972) and LiDAR (2005). Base aerial photograph flown in 2013.

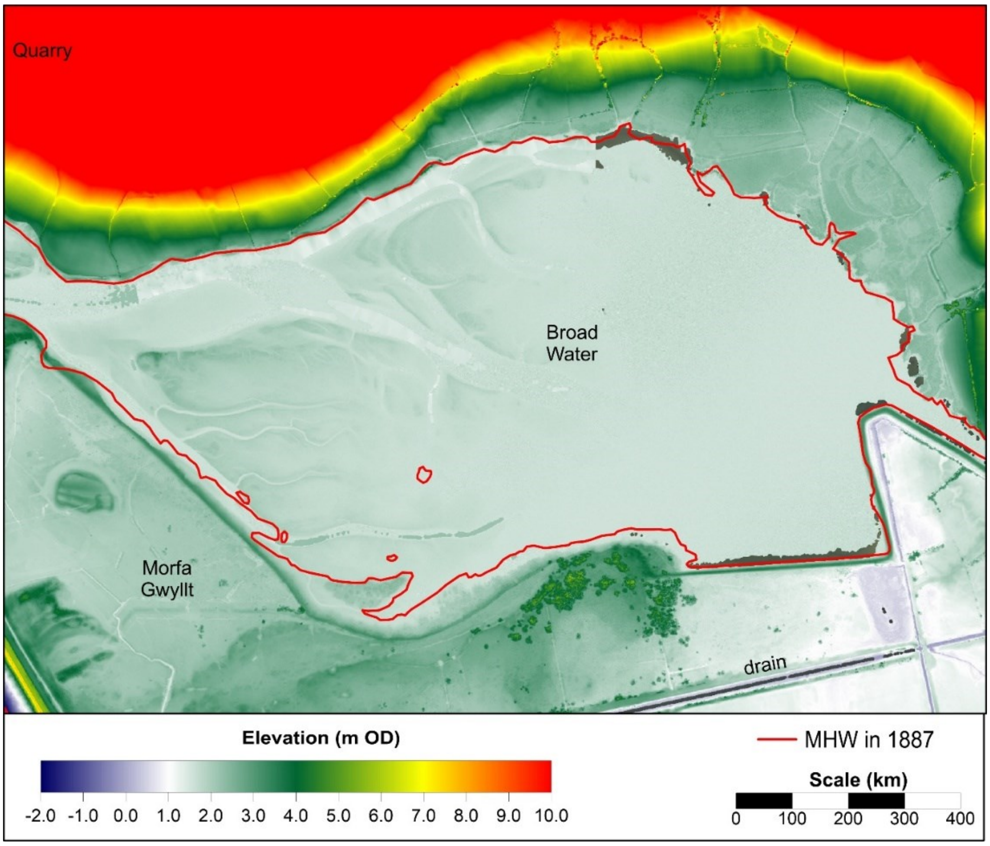

Figure 0.46. Enlargement C: Broadwater. Lines show positions of MHW from historical map in 1887. Base LiDAR DSM flown on 11/12/2013.

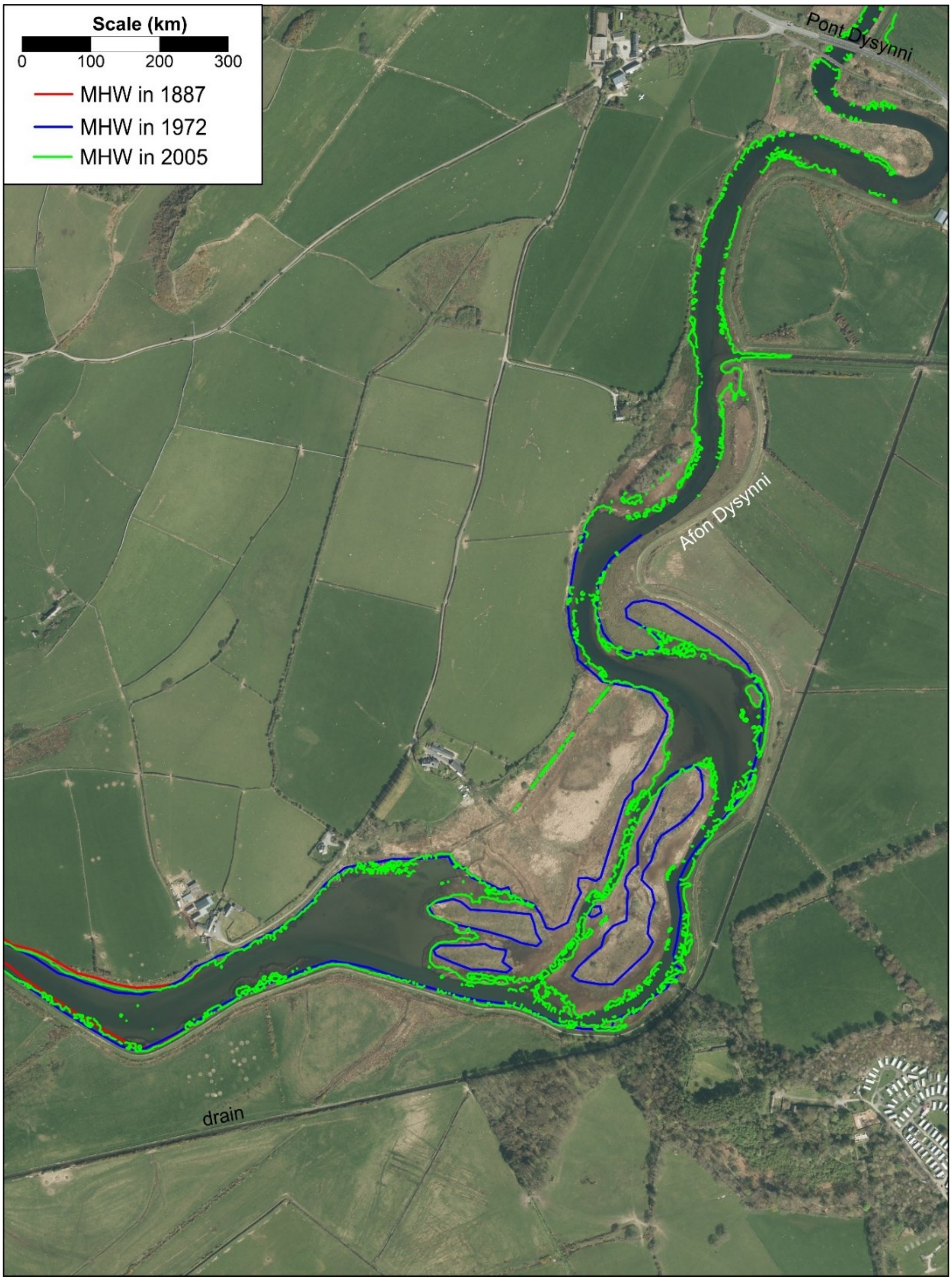

Figure 0.47. Enlargement D: the Afon Dysynni east of Broadwater. Lines show positions of MHW from historical maps (1887 and 1972) and LiDAR (2005). Note that the normal tidal limit did not extend as far up the river in 1887. Base aerial photograph flown in 2013.

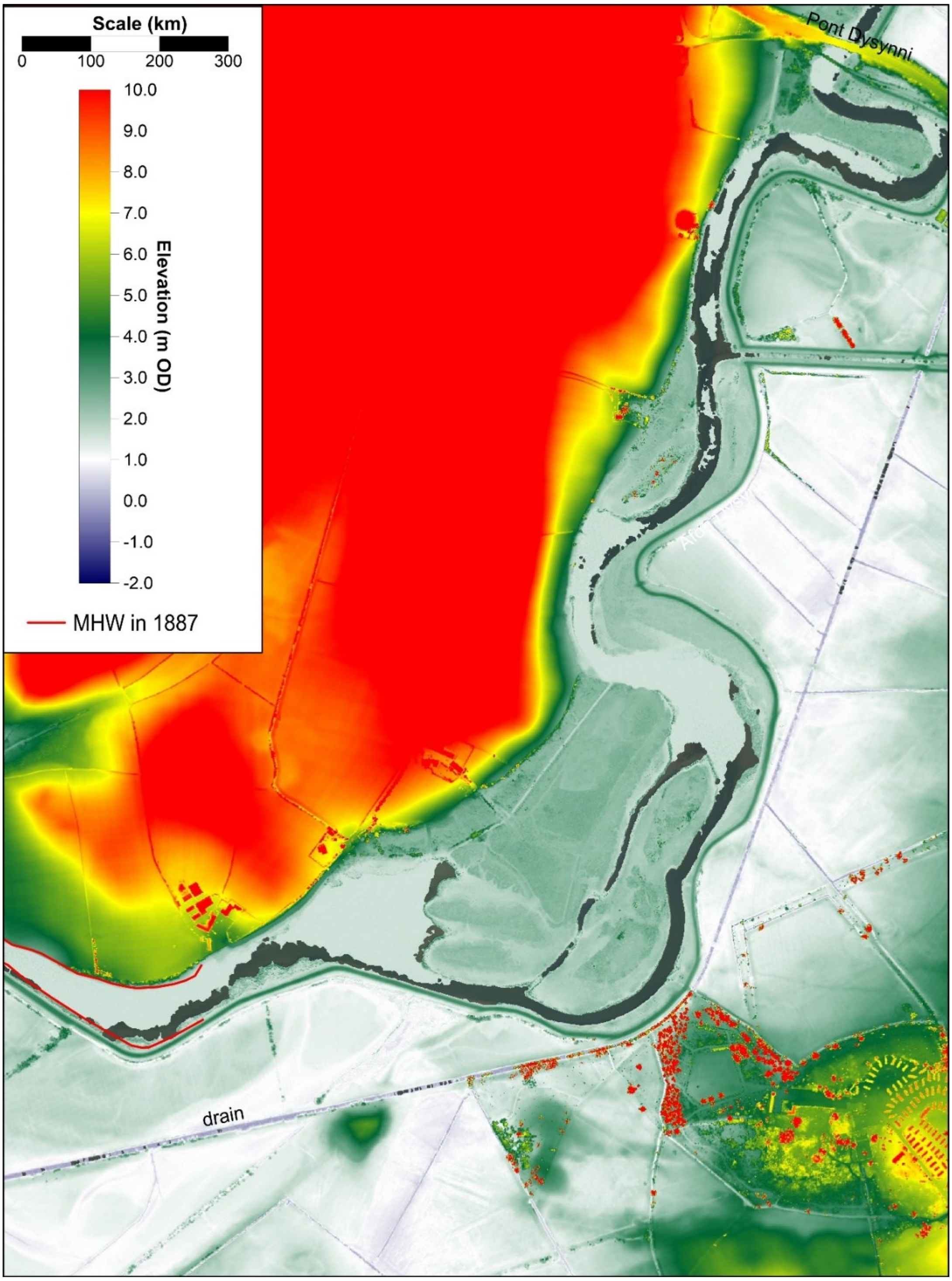

Figure 0.48. Enlargement D: the Afon Dysynni east of Broadwater. Lines show positions of MHW from historical map in 1887. Base LiDAR DSM flown on 11/12/2013.

Quantifying past saltmarsh and related intertidal habitat losses

There is currently no reliable quantitative evidence to indicate any loss of intertidal habitat area, or quality, outside the defences within the Broadwater and adjoining parts of the Dysynni Estuary.

Evaluating causes of shingle loss and the role of coastal squeeze

Identify a shortlist of sites

Based on the evidence available, the only location within the study area where there is significant evidence for possible coastal squeeze is the southern part of the Aber Dysynni (Morfa Gwyllt) spit (open coast frontage).

Expert judgement habitat loss attributable to coastal squeeze

There is a tendency for shoreline erosion along the southern part of the Morfa Gwyllt spit, which has been driven by a reduction in sediment supply from the south. This formerly included erosion of glacial till cliff exposures at Tywyn, which are now cut off from the sea by defences.

In this area, the beach sediment budget has become progressively negative over the past 120 years and the average level of the beach has fallen, resulting in a landward movement of the mean low water mark. However, the position of the mean high water mark has not changed greatly, being fixed in position by a combination of structures, including the concrete revêtment and groynes at the northern end of the Tywyn frontage, the outfalls of the Morfa Gwyllt Drain and Sewage Works, and the rock armour placed to defend the railway line and other infrastructure.

Although the quality of tide gauge data for stations on the west coast of Wales is poor, it is likely that mean sea level has been rising at a rate of 2.0 to 3.0mm/yr in recent decades. However, the cumulative effect on average water levels over the past 70 years is unlikely to exceed 20cm and is more likely to be in the range of 10 to 15cm. While this can be considered to be a contributing factor to possible coastal squeeze on the beach and shingle ridge, its effect is judged to be minor compared with the reduction in sediment supply at the southern end of the shingle ridge (mainly due to the effect of defences). It is concluded that there could have been coastal squeeze in this area.

At the northern end of the Morfa Gwyllt spit, where the sediment budget is positive due to alongshore transport, the high water mark has remained stable and locally has moved seawards, in part due to engineering works to widen the end of the spit in the 1960s, indicating that historical SLR has had no significant impact. It is concluded that there has been no coastal squeeze in this area.

The Morfa Gwyllt saline percolation lagoon is a relatively recent feature formed as a result of human interventions in the estuary. It has not been affected by coastal squeeze.

The available evidence indicates that the Broadwater-Dysynni Estuary had experienced long-term sediment accretion since at least the early 19th century. It is likely that the main source of sediment has been supplied from marine sources, with a subsidiary contribution from rivers. Sedimentation within the estuary is likely have been enhanced by narrowing of the estuary entrance, initially associated with natural spit growth on both sides, and later by man-made training of the entrance channel and by embanking and land claim within the estuary, which had the effect of reducing the tidal prism and tidal flow velocities. Based on map evidence, the tidal prism of the estuary has decreased over time due both to natural processes and land claim, rather than increasing as might be expected with significant SLR. At present, the entrance to the Dysynni continues to experience shoaling, and regular dredging is required to maintain current flows and reduce flood risk within the estuary and in upstream areas. These conditions have favoured sedimentation and the development/preservation of intertidal habitats around the margins of the estuary, and on islands located within it. It is concluded that there has been no coastal squeeze in this area.

A.5.5 Determinating future coastal squeeze losses

Screening test 1 - Are there likely to be relevant structure/s and/or management actions over the period of interest?

Method

Reference has been made to the most recent Shoreline Management Plan covering the area (Royal Haskoning, 2011a).

Results

The recommended shoreline management policies for the Aber Dysynni-Broadwater area identified in the West of Wales Shoreline Management Plan 2 are summarised in Figure 0.51 below.

The policy for the open coast Tywyn to Aber Dysynni frontage is Hold-the Line (HTL) in all 3 management epochs, so existing defences are likely to be maintained and possible enhanced.

The preferred policy for the Broadwater is HTL in Epoch 1 followed by managed realignment in Epochs 2 and 3. Under these policies, defences around the Broadwater are unlikely to be maintained in their present form beyond 2025, and new defences may be created on a more landward alignment in some areas.

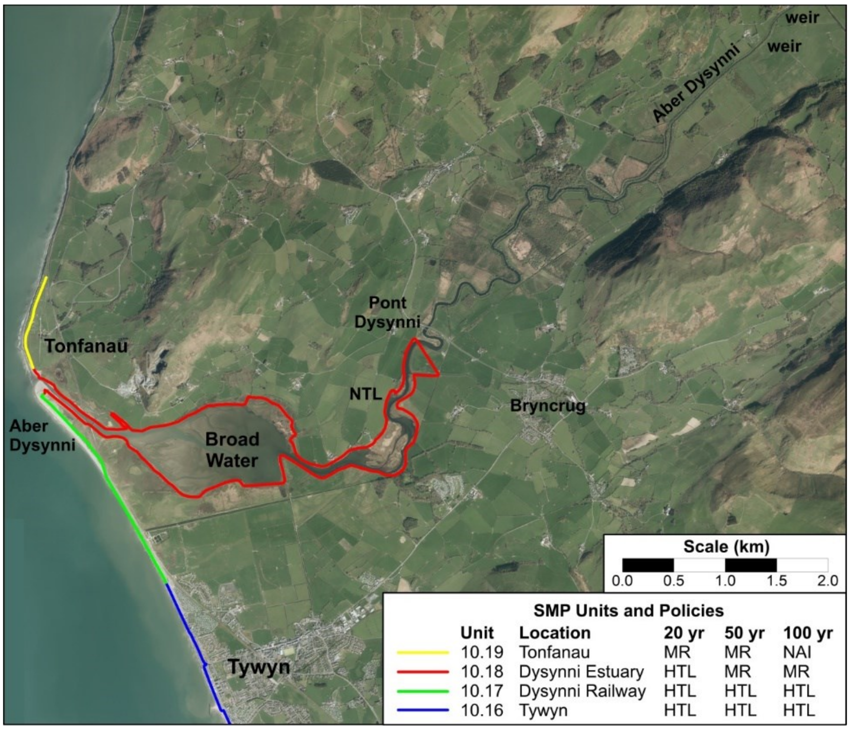

Figure 0.49. The Tonfanau to Tywyn frontage, including Broadwater and the valley of the Afon Dysynni. The SMP2 units and policies are also shown in the box on the bottom right. Base aerial photography flown in 2013.

Screening test 2 - Is there likely to be suitable accommodation space landward of the structure over the period of interest?

Method

This question has been addressed by referring to the topographic data sets mentioned above and also by referring to planning policy documentation relating to this part of the Welsh coast.

Results

In the Broadwater, there will continue to be accommodation space for possible intertidal expansion, particularly behind the flood defence embankments along the south side of the estuary (on Morfa Gwyllt and Morfa Tywyn).

The potential accommodation space for intertidal habitats, landwards of the present-day defences is shown in Figure 0.32 above.

Removing the present-day defences would lead to a larger overall extent of the intertidal area and the landward extent would lie against or close to high land forming the valley's margins. There is no evidence that presently available accommodation space will be significantly reduced or lost due either to natural processes (for example, sedimentation) or human intervention (for example, landfill for major development). However, given the rapid rise in land levels beyond the 3.18m contour there is limited scope for the landward migration of HAT contour under future SLR.

On the open coast, there is accommodation space landward of the current beach, and in the absence of defences and the railway line, the shingle ridge would be able to migrate landward either as a high storm ridge or as a series of washover lobes. These features could eventually migrate to the western edge of Morfa Gwylt, and could lead to the infilling and burial of the Morfa Gwyllt Lagoon (loss of saline lagoon habitat through natural shingle rollover).

Screening test 3 - Are relative sea levels anticipated to rise in the region over the period of interest?

Method

This question has been addressed by referring to sea level projections contained on the UKCP18 data portal and by considering recent trends evident from measured tide gauge data.

Results

Table 0.21 shows the projected changes in mean sea level for Aber Dysynni relative to the year 2020 under each of the 3 atmospheric emissions scenarios considered by UKCP18. Under these scenarios, mean sea level could increase by between 0.17m and 0.96m by 2100, with a 50th percentile model output value for the higher emissions scenario (RCP8.5) of 0.62m.

Table 0.21. Projected changes in mean sea level relative to the year 2020 at Aber Dysynni (in metres) according to UKCP18 under the RCP2.6, RCP4.5 and RCP8.5 scenarios. The values shown are 5th, 50th and 95th percentile modelled outputs.

Date	RCP2.6 scenario			RCP4.5 scenario			RCP8.5 scenario		
01/01/2030	0.03	0.04	0.06	0.03	0.04	0.06	0.03	0.05	0.07
01/01/2040	0.05	0.08	0.12	0.06	0.09	0.13	0.07	0.11	0.15
01/01/2050	0.08	0.12	0.18	0.09	0.14	0.20	0.11	0.17	0.25
01/01/2060	0.10	0.16	0.25	0.12	0.19	0.28	0.16	0.25	0.36
01/01/2070	0.12	0.20	0.31	0.16	0.24	0.37	0.22	0.33	0.49
01/01/2080	0.14	0.23	0.38	0.19	0.30	0.46	0.27	0.42	0.63
01/01/2090	0.15	0.27	0.45	0.22	0.35	0.55	0.33	0.52	0.79
01/01/2100	0.17	0.30	0.53	0.24	0.40	0.65	0.40	0.62	0.96

Figure 0.50 and Figure 0.51 show the projected increases in sea level suggested by UKCP18 relative to the year 2007 compared with recorded trends in mean sea level at Holyhead and Barmouth, respectively. A significant increase in the future rate of SLR, compared with extrapolations based on measured historical rates, is projected under all 3 UKCP18 emissions scenarios.

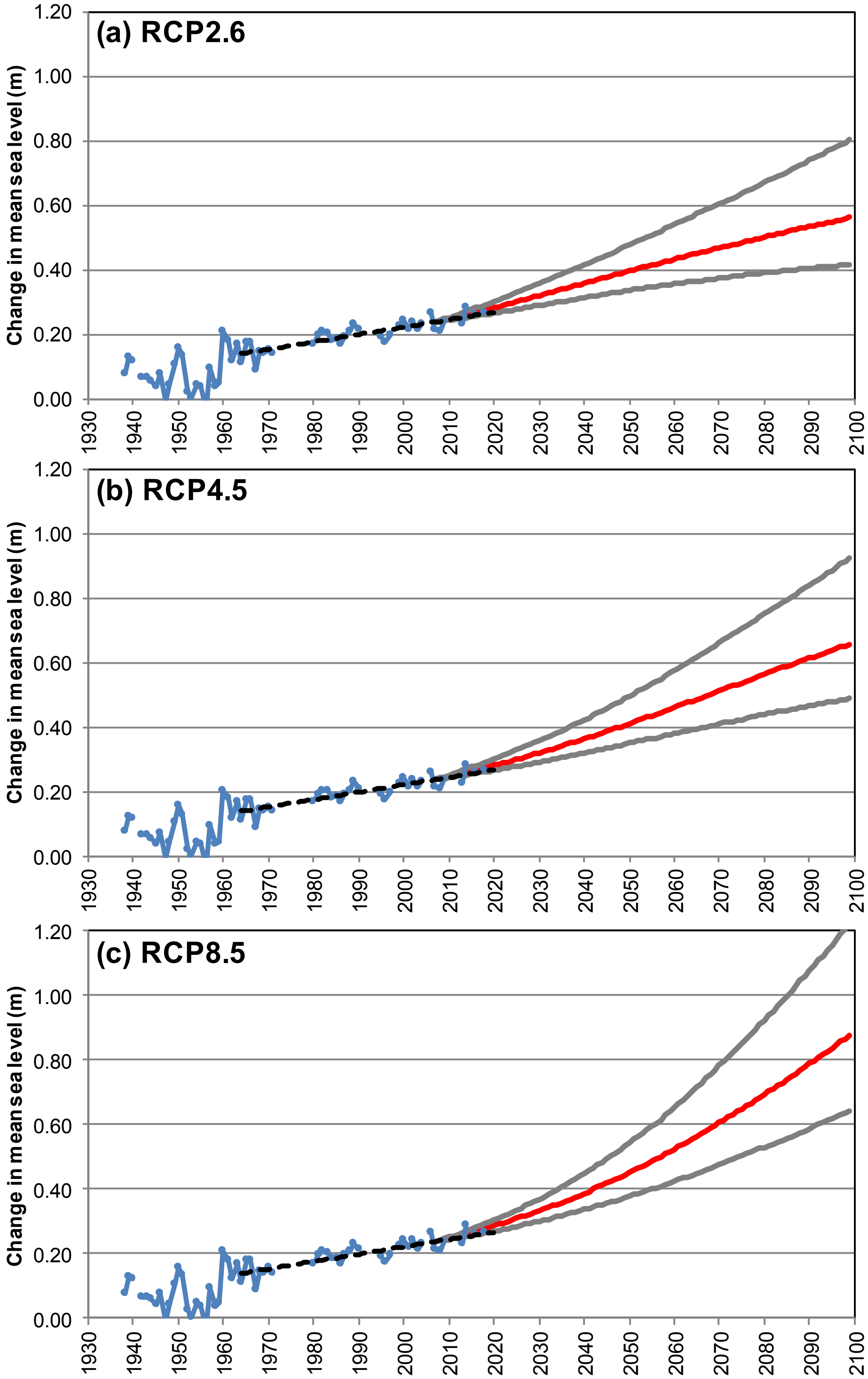

Figure 0.50. Annual mean sea levels recorded at Holyhead between 1938 and 2018 (blue line, with linear regression line shown as a black dashed line), and projected mean sea level in the future according to UKCP18 for the period 2007 to 2099 for 3 scenarios: (a) RCP2.6; (b) RCP4.5; and (c) RCP 8.5. The red lines show the 50th percentile model output, while the grey lines show the 5th and 95th percentiles.

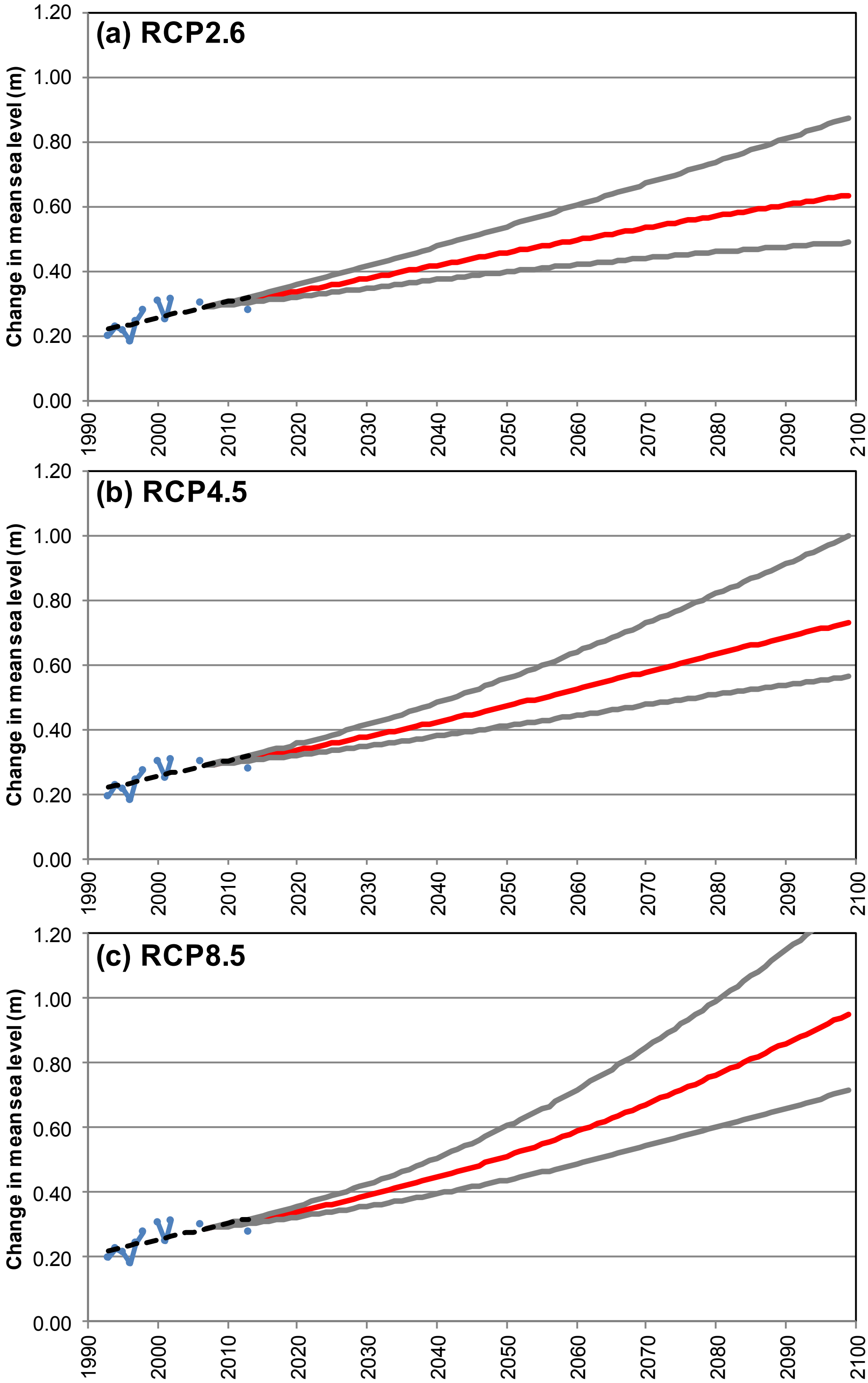

Figure 0.51. Annual mean sea levels recorded at Barmouth between 1993 and 2013 (blue line, with linear regression line shown as a black dashed line), and projected mean sea level in the future according to UKCP18 at Aber Dysynni for the period 2007 to 2099 for 3 scenarios: (a) RCP2.6; (b) RCP4.5; and (c) RCP 8.5. The red lines show the 50th percentile model output, while the grey lines show the 5th and 95th percentiles.

Conclusions from screening tests

It is concluded that all 3 screening tests are met for the southern part of the Tywyn to Aber Dysynni open coast. Therefore, there could potentially be coastal squeeze losses in the future in this area. Further assessment of this is made in the next section.

In the case of the Broadwater (Dysynni Estuary) a policy of managed realignment is proposed in SMP2 epochs 2 and 3, such that there is the potential to create additional intertidal habitat, and coastal squeeze is unlikely. At the present time, however, the extent and timing of removing defences or realignment are unknown, and it is, therefore, impossible to assess the amount of intertidal habitat that might be created or lost in the future.

A.5.6 Future habitat losses

Extrapolate past losses based on historical trend analysis

The maximum historical losses of intertidal area (shingle and sand beach) along the southern part of Morfa Gwyllt spit since 1900 are estimated to be around 50,000m^2, due mainly to landward movement of the mean low water mark while the mean high water mark has been fixed. To this should be added a further small area of direct losses of around 3,000 m^2 below the footprint of the defences themselves. However, there has been an increase in intertidal area along the largely undefended northern half of the spit of at least 30,000m^2. If average historical rates of potential loss due to coastal squeeze are extrapolated to 2050, a further net loss of around 125,000m^2 would be projected. However, this is likely to be a maximum figure since there is a finite limit to the degree the low water mark can move landwards, and it is already very close to the defences close to the Morfa Gwyllt Drain.

Since no evidence of net habitat loss due to possible coastal squeeze has been found within the Broadwater, extrapolation of future change would indicate either no change or a small net gain over the next 30 years.

Expert geomorphological analysis of future losses

Based on current shoreline management and regional planning policies, it is possible, though by no means certain, that large scale coastal adaptation will take place in the area surrounding the Dysynni Estuary over the next 80 to 100 years. Some defences are likely to be maintained or realigned close to their present positions, but others may be set back a considerable distance, possibly in stages.

It is most likely that sea level will continue to rise throughout the period, although the degree to which the rate will accelerate is highly uncertain. Based on available data, which suggests a recent average rate of rise in mean sea level of around 3mm/yr, an absolute increase in mean sea level of around 9cm is possible by 2050 and 24cm by 2100, without any further acceleration due to climate change. However, based on current UKCP18 projections, a larger increase in the range of 65 to 96 cm might occur by 2100.

With SLR in the range of 3 to 5mm/ yr, it is considered likely that the marshes will be able to keep pace with SLR, and the main forms of erosion will be localised erosion of the marsh edge in areas where channel migration occurs, or where there is a large fetch for internally-generated wind-waves. These losses are likely to be substantially offset in areas where the channel moves away from the shore, or where additional sediment is deposited.

As in other estuaries, the possibility of future coastal squeeze in the Broadwater will depend on the rate of SLR versus sediment supply. If SLR is in the range of 3 to 5mm/yr, then coastal squeeze, in the form of marsh drowning or surface fragmentation, is unlikely. A further major uncertainty relates to the managing existing defences within the estuary in the future.

A.5.7 Conclusions

This case study has demonstrated that the proposed method for assessing coastal squeeze can, in principle, be applied successfully to a combined open coast-barrier lagoon/estuary situation as found at Aber Dysynni and the Broadwater.

It is concluded that there is some evidence to suggest that coastal squeeze could have affected the southern half of the Morfa Gwyllt spit since around 1900, although the northern half of the spit has experienced either no net change or a gain in intertidal and supratidal area. However, a reduction in sediment supply is likely to have been the most significant cause of the losses in the south. Maximum net losses of intertidal sand and shingle are estimated to be no more than 12.3ha, and direct losses of (mainly) shingle ridge due to placement of defences are estimated to be around 0.82ha. The accuracy of these estimates is limited by the amount and quality of the historical map and aerial photographic evidence available, and by the episodic nature of beach erosion and recovery. Confidence in the values for estimated past losses are, therefore, considered to be low to medium. Greater confidence in the assessment of historical losses could be gained by more detailed analysis of a greater number of maps, maritime charts, aerial photographs, LiDAR DTMs and ground survey data.

Most of the historical loss in intertidal areas has been from the lower beach platform, which is predominantly sandy, while the width of the upper shingle beach face has been reduced to a much less extent. At present, the active storm beach ridge in the north has enough accommodation space to roll back, but in the south its capacity to do so is constrained both by rock armour on the upper beach/ridge crest and by the railway line. The area is, therefore, likely to experience coastal squeeze. If average historical rates of potential net loss due to coastal squeeze are extrapolated to 2050, a further net loss of beach area of around 3.3ha might be projected. However, confidence in the accuracy of this estimate is low. Unless there is an unexpected increase in sediment supply, erosional pressures will increase at the southern end of the spit, but the effect of the defences will be to constrain the capacity of both the low and high water marks to move landward, thereby limiting the reduction in intertidal area.

Within the Broadwater there is no evidence of past losses of habitats corresponding to coastal squeeze. With SLR in the range of 3 to 5mm/yr, it is considered likely that the marshes will be able to keep pace with SLR and, therefore, no future losses are anticipated if these rates of SLR are realised. There is great uncertainty in estimating potential future coastal squeeze losses (or potential intertidal habitat gains). This is due to underlying uncertainty about:

- the sources and rates of supply of sediment to this part of Cardigan Bay and to the Dysynni Estuary

- future rates of SLR, and future shoreline management policy, particularly within the estuary where managed realignment is currently proposed in SMP2 epochs 2 and 3

Further insight into the sediment budget and sediment transport pathways could be gained by further investigating nearshore bathymetry, sedimentary character of the sea bed, nearshore wave climate, currents and resulting sediment transport patterns. A better framework for coastal and estuarine monitoring, including measuring tidal levels inside and outside the estuary, would help gain a better understanding of the present coastal landforms and sediments, and of their likely response to future changes in forcing factors. At present, there is a lack of basic physical and biological information relating to the Dysynni Estuary area.

Assessing possible future changes in habitat extent would also be improved by greater clarity on the likely implementation of recommended shoreline management policy, and by improved monitoring as recommended by Oaten et al. (2018).

Appendix B: Summary notes from coastal squeeze workshop 9 July 2018

Agenda

Time	Agenda
11:00 to 11:15	***Arrival, registration and coffee*** Ask people to sign in.
11:25 – 11:40	***Brief overview of project*** Project aims, process, timelines etc, building on the info contained in the workshop briefing.
11:40 – 12:10	***Thought provoker*** 2 minutes from each on key issues/how assessed to date/ how are predictions being verified by monitoring/how do targets get set. People stand up where they are sat (rather than come to front) – no need for context or intro, just outline key issues. Topics: 1. Geomorphological considerations 2. Ecological considerations 3. View from Wales 4. Where project started 5. Practicalities of assessing and compensating for coastal squeeze 6. Healthy estuaries and coastal squeeze 7. High level governmental view
12:10 – 12:20	**Questions of clarification**
12:30 – 12:35	**Introduction to group exercise 1** Explain that the purpose of this session is to explore the aspects that need to be included in a definition of coastal squeeze. Quick reminder of the aspects that are typically included in traditional definitions and other aspects that could be considered in a broader definition. Leave a slide up on the projector during the session as a prompt.
12:35 – 1:15	**Group exercise 1 - Identifying the challenges to defining coastal squeeze?** To focus on identifying the issues that should be captured in a definition of coastal squeeze. Facilitators will have a prompt sheet listing all the possible factors we have identified and will record where the group agrees these should/should not be included and where there is debate. Facilitators will encourage identification of issues/topics we have not already considered. Record on flip charts. Each group to prioritise the three most important issues that the definition should capture/clarify. (we will use this info to structure group exercise 2). For example, issues may be: • Which habitats are included? • Which structures are included? • Which processes are included? (SLR, waves, sediment supply)
1:15 – 1:30	**Feedback from group exercise 1** Groups each highlight priority issues and note areas where there was disagreement.

Time	Agenda
	Brief intro to exercise 2 – we would like people to join the group that best suits their knowledge/experience. Sign up for these over lunch.
1:30 – 2:00	**LUNCH** *(if running behind, reduce to 20 minutes)* During lunch the Jacobs team will review the key issues/questions for group exercise 2 in the light of the feedback from exercise 1.
2:00 – 2:15	**Reflection/questions** Opportunity for questions relating to morning session/lunchtime discussions.
2:15 – 2:25	**Introduction to group exercise 2 – exploring methods to assess coastal squeeze** Explain that the focus of this exercise is on exploring methods to assess coastal squeeze.
2:25– 3:10	**Group exercise 2 – Develop action plans** Each group to tackle one of the topics, with a view to moving us towards a more precise definition and agreed methods for assessing coastal squeeze. People choose which group to join. Currently expect these to be as follows (but we may add/edit topics to pick up feedback from the morning session): • How should past losses be assessed? • How should future coastal squeeze losses be estimated? What types of habitat loss are not coastal squeeze and how can they be distinguished? • What data do we need to estimate past losses and future losses? Where can such data be obtained? What approaches could be adopted in estuaries with little data? • What methods exist to capture uncertainty? • How should the limits of various habitats be defined, for example, tidal contours, species type?
3:10 – 3:30	**Feedback from group exercise** Groups each highlight key issues.
3:30 – 3:45	**Open discussion/questions**
3:45 – 4pm	**Next steps** Couple of slides on process and opportunities for further engagement Request for points of contact etc.
4pm	**Thanks and close**

Attendance and groups

Group and facilitator	Attendance/organisation
Group 1 – Environment Agency representative	Environment Agency representative, (Thames)
Group 1	University College, London (UCL) representative
Group 1	Network Rail representative
Group 1	Denbighshire County Council representative
Group 2– Jacobs representative	Natural Resources Wales (NRW) representative
Group 2	Marine Management Organisation (MMO) representative
Group 2	Environment Agency (Severn) representative
Group 2	JBA representative
Group 2	ABPmer representative
Group 3– Jacobs representative	Defra representative
Group 3	Environment Agency (Evaluation) representative
Group 3	Environment Agency (Humber) representative

Group 4– Environment Agency representative	Natural England representative
Group 4	Environment Agency (Geomorphology) representative
Group 4	Environment Agency (East Anglia) representative
Group 4	Ken Pye Associates representative
Group 4	NRW representative
Group 5– Environment Agency/ Jacobs representatives	Natural England representative
Group 5	Network Rail representative
Group 5	former Environment Agency representative

Initial thoughts

A number of individuals gave short 2 to 3 minute presentations on a number of topics related to coastal squeeze.

Environment Agency representative - Where the project started

- Experience in the Humber.
- National consistency.
- Implications of scale of compensation required.
- Wanted to be transparent and understandable.
- Would like a coastal squeeze definition that is scalable and easily applicable.

Defra representative – High level government view

- In 2004, a target was set to bring 95% by area of SSSIs into favourable or recovering condition by 2010. Defra's 25 Year Environment Plan sets an ambition target of 75% of SSSIs in favourable condition by 2042.
- Legally required to prevent and compensate losses of intertidal habitats under EU Habitats Directive.
- Defra's 25 Year Environment Plan aims to result in a net gain in spatial area and quality of habitat.

Natural Resources Wales (NRW) representative - View from Wales

- In Wales, the biggest predicted coastal squeeze losses are in the Severn Estuary, and this is also the area where we think habitat losses may be occurring already.
- Concerned about whether a one size fits all definition and method will work due to differences in approach/policy between Wales and England. In Wales compensatory targets are driven by assessments at the scheme stage rather than the strategic level SMP assessments.
- Trying to identify who is responsible for which anthropogenic (man-made) coastal squeeze losses and, separating natural losses from anthropogenic (man-made) losses is difficult but needed for project level assessments.
- NRW (Permitting Service) needs to consider coastal squeeze impacts in project level HRAs when determining marine licences.

Natural England representative – Ecological considerations

- Intertidal habitats.
- Saltmarsh.
- Impact of accelerated SLR and other climate change-related issues.
- Better understanding of the ecological relationships and their management needed.
- Habitat quality is important. We need to evaluate intertidal habitat loss not only in terms of area but also quality.

Environment Agency representative – Healthy estuaries

- Healthy Estuaries 2020.
- The project output is a ‘tool’ (a simple GIS based model) which generates an equilibrium channel planform relative to tidal prism.
- May be possible to use the tool or the technique of applying regime theory more generally, to assess coastal squeeze on an estuary scale.

Environment Agency representative - Assessing coastal squeeze

- How precise do we need to be in our assessment of change?
- What metrics should we be using?
- How do we determine the cause of change?

Environment Agency representative - Compensating for coastal squeeze

- Is bigger better?
- Is like for like really necessary?
- Practicalities of delivery.
- Running out of potential MR sites and raised concerns about increasing costs.

Ken Pye Associates representative

- Important to look at past studies. Issues raised on coastal squeeze were highlighted by MAFF in the 1980s and relevant today – don’t need to reinvent the wheel.
- It is important to consider features and natural processes. We need to have a strong evidence base to assess future risk and develop appropriate management strategies due to increasing public scrutiny and the threat of legal battles.
- It is also important to improve our understanding of physical processes in estuarine systems.

Further discussion

Jacobs representative

- Difficult to quantify habitat quality.
- Compensation of habitat losses is straightforward when using areas, but habitat quality losses associated with coastal squeeze is hard to quantify.

UCL representative

- Jim Titus produced a paper outlining coastal squeeze in 1991 as an early reference of these problems. Sometimes coastal squeeze is termed ‘geological squeeze’.
- Physical processes underpin natural characteristics.
- SLR cannot be single driver of marsh loss.

Natural England representative

- Cost of realignment is becoming an inhibiting factor.
- Need to consider unmanaged realignment.
- We can’t predict coastal squeeze losses – we need more monitoring.

Network Rail representative

- Predictions of coastal squeeze and SLR don’t include details of physical processes.
- Where can we make choices to realign? Some difficulties including site suitability, including presence of freshwater habitats, legal obligations to maintain defences.
- Need a secondary compensation programme.
- Network Rail funds habitat creation and needs an accurate assessment of coastal squeeze losses.

Environment Agency representative

- Most defences built in 1953, which we can’t maintain.
- Problem is private funding, we are not in control.

Environment Agency representative

- Justification for more spending on managed realignment.
- Quality and quantity of saltmarshes. What do we need to monitor?

Former Environment Agency representative

- Unmanaged realignment can’t work because former land is not suitable.

Remote Environment Agency representative (NB did not attend workshop, sent response via email)

- “My take on coastal squeeze is that it is a concept to describe a man-made problem. I would define coastal squeeze not simply by the intertidal habitat that is being lost to the seaward of defences (and hard coast), but by the extent to which the presence of the defences prevents the creation of new intertidal habitat. This pushes the emphasis onto the area and elevation of the land to the hinterland. The more land that is protected from flooding, the more severe the coastal squeeze as that is a lot of potential intertidal habitat lost.”
- “Unfortunately, the many diagrams that are produced usually depict the issue in two dimensions as a x-section through a piece of coast. This completely ignores some of the critical longshore sediment processes that are occurring. So, the coastal squeeze concept does not just apply to the intertidal habitat that is located on a horizontal line running perpendicular to the defence line. Sediment processes could be affected for some distance longshore as well. So, the

intertidal habitat element of coastal squeeze related loss needs to take physical processes into account as well."

Session 1 – Definitions

The purpose of session 1 was to explore the aspects that need to be included in terms of the definition. Attendees were asked to discuss the merits of including various elements within a definition of coastal squeeze:

- SLR.
- Flood defences preventing landward movement of habitats.
- Decreases in intertidal habitat area.
- Saltmarsh and mudflat loss in estuary environments.
- Internationally designated habitats SPA/SAC.
- Supratidal habitats, for example, aeolian dunes.
- Causes other than SLR that can give rise to landward movement of the low water marks (for example, channel migration, increases in wind-wave climate).
- Changes in habitat quality (for example, marsh being replaced by mudflat, changing species composition).
- Internal erosion of saltmarshes (for example, creek expansion).
- Other impacts of defences (for example, reduction in longshore sediment supply).
- Other anthropogenic (man-made) structures.
- Natural squeeze against rising land.
- Reclamation losses.

Main points raised in session 1

Group 1

- Definition needs to be simple.
- Do not include habitat quality.
- Need to consider timescales.
- Should be evidence based and include processes.
- Should include natural topography as well as man-made structures.
- SLR as a driver.

Group 2

- Definition needs to be simple, narrow intertidal zone with no physical features (exclude natural rising land from definition).
- Man-made and natural barriers need to be separated.
- Needs to consider transgression potential behind defences (previous reclamation).

- Need for consistency.
- Habitat quality is too complex to be incorporated into definition at present.

Group 3

- Definition needs to be simple and consistently defined.
- Any coastal habitat included in the Annex 1 NERC priority habitats (for example, shingle ridges, saltmarshes) that are affected by coastal squeeze should be included.
- Coastal squeeze is only one part of habitat loss that needs to be considered in habitat compensation schemes. Therefore, definition is not important as we are interested in all losses not just those attributed to coastal squeeze. If we keep coastal squeeze separate, then we need to consider other impacts.
- Our understanding is limited, and we cannot accurately determine habitat losses attributable to coastal squeeze only.

Group 4

- Definition needs to be simple.
- Man-made structures should be included, natural rising land should be excluded.
- SLR should be considered as sole driver.
- Only anthropogenic (man-made) changes should be considered.
- Habitat quality should not be considered at the moment but may need to be considered for future monitoring.
- If using tidal range modified by defences, consider changes in water level not SLR as a driver and losses attributable.

Group 5

- Definition needs to be simple.
- Only anthropogenic (man-made) changes should be considered.
- Needs to be pragmatic to help managers and coastal planners.
- Exclude habitat quality.
- Should consider saltmarsh and mudflats only.

Session 2 - Explore methods to assess coastal squeeze

The purpose of session 2 was to explore methods to assess coastal squeeze. Attendees were organised into groups to help develop methods for assessing a number of aspects of coastal squeeze.

Main points raised in session 2

Topic 1 – How should past losses be assessed?

- Extrapolate from the past for now but in the future, build up new data sets (for example, LiDAR) using improved data sources (for example, increased resolution).

- Automation could also be used to reduce errors.
- Extrapolation could be achieved using physical and numerical modelling.
- These approaches could be picked up nationally as part of a consistent assessment.

Topic 2 – How should future coastal squeeze losses be estimated?

- Disentangling what is directly attributable to human activity.
- Baseline data is key.
- Use historical data (Defra 2010) – saltmarsh survey there were some issues around the method but these are now resolved. This could be used as a baseline.
- Going back further to the 1990s there is enough data to interpret past losses.
- Could incorporate habitat quality such as number of birds supported by habitat.
- Mudflats are difficult to interpret, and losses are harder to quantify.
- Past and future what do they mean to one another?

Topic 3 – What methods exist to capture uncertainty?

- Baseline data is key – where do you make it because the data has changed so much over time.
- It is important to ensure the public has confidence, previous problems with uncertainty resulted in public engagement issues.
- Modelling issues – invest in more modelling.
- Looking at the system as a whole and compensating individual areas.
- Use of qualitative data to support findings.
- Standards to ensure data is collected with right resolution and metadata that we can use in the future.
- When do we consider the effect of coastal squeeze on realignment sites?

Topic 4 – What types of habitat loss are not coastal squeeze and how can they be distinguished?

- Short-term processes are not coastal squeeze such as coastal processes and short-term ecological changes (Spartina dieback).
- Long-term changes in sea level water level monitoring combined with Digital Terrain Model (DTM) elevation monitoring.
- Need long-term (at least 25 years) data to extract long-term changes in sea level and land change against short-term noise.

Topic 5 – Data?

- Depends on definition of coastal squeeze – that is, if defined as purely SLR and constrained of intertidal areas due to defences, need data sets that record changes in elevation such as DTM or aerial imagery to calculate loss and water level tide gauges.
- Many data sets available including geospatial.

- Hydrodynamic modelling.
- NVC data.
- Satellite data – CASSI and Sentinel 2.
- Common standards for all SSSI sites began in the early 1990s and can see trend over time. Also, included for each estuary pressures and threats and actions to be carried out.
- Site improvement plans IPENS or SIPS.
- Invertebrate surveys – JNCC have all data sources.
- Annex 1 NERC priority habitats.
- Natural Resources Wales have more comprehensive data sets and range of baseline data.

Topic 6 – How should limits of various habitats be defined?

- Consistent baseline.
- Predictors should be used rather than observations.
- Now is the time – past data has inaccuracies.
- JNCC website has extent of habitat recorded – where habitat is likely, overall trend, future prospect sites – Available for each habitat type and where data comes from.
- Annex 1 NERC priority habitats available on MAGIC.
- Common standards for all SSSI.
- Saltmarsh surveys covered for WFD assessments.

Topic 7 – What might a flow chart to define coastal squeeze look like?

- Issues with current flowchart.
- When do we start assessing past losses?
- Need clarity over 'do existing targets look realistic' - is this related to funding or intuition?
- Need to define response options and targets.
- Two possible approaches to determine baseline; time since regulations came into force, but the habitat may not be in peak condition OR go for the healthy estuaries approach.
- A wish list may include FCERM and what habitats we need to restore.

Closing thoughts

- To calculate costs of monitoring different techniques and cost benefit analysis against not doing any form of monitoring.
- Integrity of Natura 2000 network is important.
- How can we sustain these into the future?

- Need to change over time not just coastal squeeze – look at inventory of habitat and determine loss.
- All organisations to consider this further.
- SMPs – technical review nationally to see if they can be determined.
- Methods that come out of this project to review all other SMPs.

Appendix C: Relevant coastal habitats

Table B 1: Annex I Coastal Habitats.

Note this table excludes the following Annex 1 habitats - Freshwater habitats, temperate heath and scrub, natural and semi-natural grassland formations, raised bogs and mires and fens, forests. The correspondence with the simplified habitat naming convention adopted in the present study has also been listed in the final column. It should be noted that there may be some site-specific variations around the UK. For example, in some areas estuaries (EU code 1130) may contain mudflats and sandflats, whilst in others they contain mudflat and intertidal rock platforms. Habitat types, therefore, need to be identified at a local level.

Source: JNCC, 2018

Habitat type	Habitat sub type	EU code	Habitat name as adopted in Directive	Simplified habitat type used in present study
1. Coastal and halophytic habitats	11. Open sea and tidal areas	1110	Sandbanks which are slightly covered by sea water all the time	Sandflats
		1130	Estuaries	Saltmarsh, intertidal reedbeds, Intertidal rock platforms, mud and sandflats
		1140	Mudflats and sandflats not covered by seawater at low tide	Mud and sand flats
		1150	* Coastal lagoons	Saline lagoons
		1160	Large shallow inlets and bays	Intertidal seagrass beds, intertidal rock platforms, sand beaches, boulder beaches, gravel beaches and barriers, sand dunes, mud and sand flats
		1170	Reefs	**Excluded**
	12. Sea cliffs and shingle or stony beaches	1210	Annual vegetation of drift lines	Shingle beaches and barriers, sand beaches
		1220	Perennial vegetation of stony banks	Shingle beaches and barriers
		1230	Vegetated sea cliffs of the Atlantic and Baltic coasts	**Excluded**
	13. Atlantic and continental saltmarshes and salt meadows	1310	Salicornia and other annuals colonising mud and sand	Mud and sandflats, saltmarsh
		1320	Spartina swards (Spartinion maritimae)	Mud and sandflats, saltmarsh
		1330	Atlantic salt meadows (Glauco-Puccinellietalia maritimae)	Saltmarsh

Habitat type	Habitat sub type	EU code	Habitat name as adopted in Directive	Simplified habitat type used in present study
	14. Mediterranean and thermos – Atlantic saltmarshes and salt meadows	1420	Mediterranean and thermo-Atlantic halophilous scrubs (Sarcocornetea fruticosi)	Saltmarsh
2. Coastal sand dunes and inland dunes	21. Sea dunes of the Atlantic, North Sea and Baltic coasts	2110	Embryonic shifting dunes	Sand dunes
		2120	Shifting dunes along the shoreline with Ammophila arenaria (`white dunes`)	Sand dunes
		2130	* Fixed dunes with herbaceous vegetation (`grey dunes`)	Sand dunes
		2140	* Decalcified fixed dunes with Empetrum nigrum	Sand dunes
		2150	* Atlantic decalcified fixed dunes (Calluno-Ulicetea)	Sand dunes
		2160	Dunes with Hippophae rhamnoides	Sand dunes
		2170	Dunes with Salix repens ssp. argentea (Salicion arenariae)	Sand dunes
		2190	Humid dune slacks	Sand dunes
		21A0	Machairs *Scotland only	Mud and sandflats, saltmarsh, sand dunes and sand beaches
		2250	Coastal dunes Juniperus spp. *Scotland only	Sand dunes
		2330	Inland dunes with open Corynephorusa Agrostis grasslands	Sand dunes
8. Rocky habitats and caves	83. Other rocky habitats	8830	Submerged or partially submerged sea caves	**Excluded**

Table B 2: Section 41 (S41) Habitats of Principal Importance in England.

Excludes arable and horticultural, freshwater, grassland, heathland, inland rock, some wetland and woodland habitats. The correspondence with the simplified habitat naming convention adopted in the present study has also been listed in the final column. It should be noted that there may be some site-specific variations around the UK. Habitat types therefore need to be identified at a local level.

Source Natural England 2008.

Broad habitat	Habitat name	Simplified habitat type used in present study
Coastal	Coastal saltmarsh	Saltmarsh
Coastal	Coastal sand dunes	Sand dunes
Coastal	Coastal vegetated shingle	Shingle beaches and barriers
Coastal	Intertidal mudflats	Mudflats and sandflats
Coastal	Maritime cliff and slopes	**Excluded**
Coastal	Saline lagoons	Saline lagoons located in front of structures
Marine	Blue mussel beds	Intertidal rock platforms, mud or sandflats
Marine	Estuarine rocky habitats	Intertidal rock platforms
Marine	Fragile sponge and anthozoan communities on subtidal rocky habitats	**Excluded**
Marine	Horse mussel beds	**Excluded**
Marine	Intertidal boulder communities	Boulder beaches
Marine	Intertidal chalk	Intertidal rock platforms
Marine	Maërl beds	**Excluded**
Marine	Mud habitats in deep water	**Excluded**
Marine	Peat and clay exposures	Mud and sandflats
Marine	Sabellaria alveolata reefs	Intertidal rock platforms
Marine	Sabellaria spinulosa reefs	Intertidal rock platforms
Marine	Seagrass beds	Intertidal seagrass beds
Marine	Sheltered muddy gravels	Mud and sandflats
Marine	Subtidal chalk	**Excluded**
Marine	Subtidal sands and gravels	**Excluded**
Marine	Tide-swept channels	Mud and sandflats
Wetland	Coastal and flood plain grazing marsh	**Excluded**
Wetland	Reedbeds	Intertidal reedbeds

Table B 3: Marine habitats classified of Principal Importance under the Environment (Wales) Act Section 7. The correspondence with the simplified habitat naming convention adopted in the present study has also been listed in the final column. It should be noted that there may be some site-specific variations around the UK. Habitat types therefore need to be identified at a local level.

Source National Resources Wales 2020 available through the LLE Geoportal
https://lle.gov.wales/catalogue/item/MarineBAPOSPARHabitats/?lang=en

Habitat name	Simplified habitat type used in present study
Blue mussel beds	Intertidal rock platforms, mud or sandflats
Carbonate reefs	**Excluded**
Estuarine rock	Intertidal rock platforms
Fragile sponge and anthozoans	**Excluded**
Honeycomb worm (Sabellaria alveolata)	**Excluded**
Horse mussel modiolus bed	**Excluded**
Intertidal mudflats	Mud and sandflats
Intertidal underboulder	Boulder beaches
Maerl beds live and dead	**Excluded**
Mud habitats in deep water	**Excluded**
Musculus discors green crenella beds	**Excluded**
Oyster beds	Intertidal rock platforms
Peat clay exposures	Saltmarsh
Sabellaria spinulosa reef	Intertidal rock platforms
Saline lagoons	Saline lagoons located in front of structures
Saltmarsh	Saltmarsh
Seagrass beds	Intertidal seagrass beds
Seapens and burrowing megafauna	**Excluded**
Sheltered muddy gravel	Mud and sandflats
Subtidal mix mud sediments	Mud and sandflats
Tide swept channels	Mud and sandflats

Other useful documents

Additional supporting habitats descriptions (SPA and SAC):
https://www.gov.uk/government/publications/sac-features-and-spa-supporting-habitats-general-descriptions

Table B 4: Adapted list of relevant UK BAP coastal and marine habitats that may be subject to coastal squeeze.

Habitat	Description
Boulder beaches	This habitat incorporates substrata types such as bedrock and stable boulders (JNCC 2011).
Gravel beaches and barriers	Gravel or ‘shingle’ is defined as sediment with particle sizes in the range 2 to 200mm which occur in high energy environments and can take the form either of spits, barriers or barrier islands formed by longshore drift, or of cuspate forelands where a series of parallel ridges piles up against the coastline (JNCC 2011).
Grazing marsh	Grazing marsh is defined as periodically inundated pasture, or meadow with ditches which maintain the water levels, containing standing brackish or fresh water (JNCC 2011).
Intertidal seagrass beds	Seagrass beds develop in intertidal and shallow subtidal areas on sands and muds. They may be found in marine inlets and bays but also in other areas, such as lagoons and channels, which are sheltered from significant wave action (JNCC 2011).
Intertidal reedbeds	Reedbeds are wetlands dominated by stands of the common reed Phragmites australis, wherein the water table is at or above ground level for most of the year (JNCC 2011).
Intertidal rock platforms	Gently sloping intertidal platforms that consist of bedrock exposures that are regularly tide swept.

Habitat	Description
Mud and sand flats	Mud and sand flats are sedimentary intertidal habitats created by deposition in low energy coastal environments, particularly estuaries and other sheltered areas (JNCC 2011).
Saline lagoons located in front of structures	Lagoons in the UK are essentially bodies, natural or artificial, of saline water partially separated from the adjacent sea. They retain a proportion of their seawater at low tide and may develop as brackish, full saline or hyper-saline water bodies (JNCC 2011).
Saltmarsh	Coastal saltmarshes in the UK (also known as 'merse' in Scotland) comprise the upper, vegetated portions of intertidal mudflats, lying approximately between mean high water neap tides and mean high water spring tides (JNCC 2011). In some estuaries saltmarsh can extend up to HAT.

Appendix D: SLR data for UK capitals

	London			Cardiff			Edinburgh			Belfast		
YEAR	R2.6	R4.5	R8.5	R2.6	R4.5	R8.5	R2.6	R4.5	R8.5	R2.6	R4.5	R8.5
2020	0.07 – 0.13	0.07 – 0.13	0.07 – 0.13	0.06 – 0.12	0.06 – 0.12	0.07 – 0.13	0.01 – 0.07	0.01 – 0.07	0.02 – 0.07	0.02 – 0.08	0.02 – 0.08	0.03 – 0.08
2040	0.13 – 0.26	0.14 – 0.27	0.16 – 0.29	0.12 – 0.25	0.13 – 0.26	0.15 – 0.28	0.04 – 0.16	0.05 – 0.17	0.06 – 0.20	0.05 – 0.18	0.06 – 0.18	0.08 – 0.21
2060	0.19 – 0.40	0.22 – 0.44	0.26 – 0.52	0.18 – 0.39	0.21 – 0.43	0.25 – 0.51	0.06 – 0.27	0.08 – 0.30	0.13 – 0.38	0.08 – 0.29	0.10 – 0.32	0.15 – 0.40
2080	0.24 – 0.55	0.30 – 0.63	0.39 – 0.80	0.23 – 0.53	0.28 – 0.62	0.38 – 0.79	0.07 – 0.37	0.12 – 0.45	0.21 – 0.62	0.10 – 0.40	0.15 – 0.48	0.23 – 0.65
2100	0.29 – 0.70	0.37 – 0.83	0.53 – 1.15	0.27 – 0.69	0.35 – 0.81	0.51 – 1.13	0.08 – 0.49	0.15 – 0.61	0.30 – 0.90	0.11 – 0.52	0.18 – 0.64	0.33 – 0.94

Figure C 1: Projected ranges of sea-level at U.K. capital cities under three climate projection scenarios. Source: Palmer et al., 2018.

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