J Coast Conserv (2007) 11:31–52
DOI 10.1007/s11852-007-0004-5

Implications of sea level rise for coastal dune habitat conservation in Wales, UK

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Received: 15 February 2007 / Revised: 15 April 2007 / Accepted: 31 May 2007 / Published online: 9 August 2007

Abstract The potential impact of future sea level rise and climate change on 15 Welsh coastal dune systems has been investigated. Historical Trend Analysis was undertaken using Ordnance Survey maps to quantify past shoreline change and to permit extrapolation of past trends to predict possible future shoreline positions by 2080–2100. Predictions were also made using the Bruun Rule relationship between sea level rise and shoreline response and an integrated method of assessment, Expert Geomorphological Assessment (EGA), which provides a 'best estimate' of future coastline change, taking into account such factors as geological constraints, the nature of past, present and future environmental forcing factors, and known coastal process–response relationships. The majority of the 15 systems investigated experienced a net increase in dune area over the last 100–120 years. Only one (Whiteford Burrows) experienced significant net area loss (>5 ha). EGA predictions suggest that several systems are likely to experience significant net loss of dune habitat over the next century, whilst continued net gain is likely to occur for systems where sediment supply rates remain high. Little net change is predicted in some systems. Considering the 15 dune systems together, it is considered unlikely that net dune habitat loss will exceed net gain over the next 100 years provided that there are no major disruptions to sediment supply and natural coastal processes.

Keywords Bruun rule · Climate change · Historical trend analysis · SAC · Expert geomorphological assessment · Coastal dunes · Sea level change

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Abbreviations

CD	Chart datum
DP	Drift potential
EGA	Expert geomorphological assessment
FCE	Future change extrapolation
HAT	Highest astronomical tide
HTA	Historical trend analysis
MHW	Mean high water
MHWS	Mean high water spring
MLW	Mean low water
NNR	National nature reserve
cSAC	Candidate special area of conservation
SPA	Special protection area
SSSI	Sites of special scientific interest

Introduction

Many coastal sand dune localities have been designated as nationally and internationally important nature conservation sites due to the unique flora and fauna supported by this habitat. Fundamental to successful long-term sand dune habitat conservation is an adequate understanding of natural geomorphological and ecological processes, and of human activities, which have influenced the past and present character of dune systems. Preparation of suitable management plans to ensure conservation and sustainable use of dune systems also requires that assessments be made of the likely impacts of future changes in climate, sea level, sediment supply and human activities, both within the dune systems themselves and in adjoining onshore and offshore areas. The geomorphological response of sand dune systems to future changes in sea level and climate, and the consequences for their status as ecological habitats, are of key interest for future management strategies.

The effects of past and possible future sea level changes on dune systems have been considered in a number of previous studies. Pye (1984) discussed four conceptual models of coastal dune development associated with different relative sea level scenarios: (1) high sea level, (2) low sea level, (3) falling sea level and (4) rising sea level. In the past, periods of relatively rapid sea level rise in many high and moderate energy settings have been responsible for major transgressive dune development through a process of shoreline erosion, destruction of foredune vegetation, blowout formation and transgressive dune migration. Where wind energy is high, a high proportion of the sediment reworked by coastal erosion is moved landwards as transgressive dunes, rather than moved offshore as predicted by Bruun's (1962) model of shoreline response to sea level rise. Cooper (1958) first suggested a relationship between sea level rise and large-scale transgressive dune development on the coasts of Oregon and Washington. This hypothesis was subsequently supported by detailed morpho-stratigraphic studies of Holocene coastal dune systems on the east coast of Australia (Pye and Bowman 1984).

Rising sea level will have a direct effect on coastal processes by raising the plane of activity from which waves operate (Carter 1991). This may be most evident during storm surges, and their return period will decrease, potentially leading to the magnification of coastal erosion, flooding and avulsion. Carter (1991) suggested that, as dunes are composed of relatively low-strength materials, which respond quickly to perturbations but also reach a new equilibrium in a short time, erosion rates will probably remain proportional to sea level rise. It is likely that foredunes will move both upwards and landwards as sea level rises (Carter 1991). Where the vegetation is absent, or ineffective, due to engulfment, transgressive dunefields or sand sheets may evolve.

The increased frequency and severity of storms which many predict will be associated with future climate change may lead to the formation of new beach ridges which subsequently act as nuclei for further dune growth, although such aeolian accumulations are likely to be short-lived in the face of sustained rising sea level. Alternatively, increased severity and frequency of storms may be expected to enhance the initiation and enlargement of frontal dune blowouts, favouring landward migration of the dune system as a whole. If landward migration of the dunes is not impeded and wind energy is sufficiently high to maintain a high rate of aeolian sand transport, a dune system as a whole has the potential to migrate inland, maintaining a constant area. From a nature conservation point of view such a natural response might be considered favourable, but in many situations there is little space in which to accommodate such movement due to the land uses behind.

The effect of future sea level rise on coastal dunes may be expected to vary spatially and temporally, and will depend on such factors as the rate of rise, local sediment supply and wind energy conditions. Many dune systems occur within coastal process settings where longshore sediment transport is important, and where frontal dune erosion in one area releases sediment for shoreline progradation and new dune development down-drift. Particularly around estuaries, patterns of shoreline and frontal dune erosion and progradation are often complex due to the dynamic behaviour of banks and channels. The presence of coastal protection structures such as sea walls and revetments will also complicate the response of the dunes to sea level rise.

Geomorphological changes to the dune system under conditions of rising sea level will, in turn, affect the groundwater hydrology, which in turn will influence vegetation patterns and aeolian processes in the inland dunes (van der Meulen 1990; Pye 2001). In some situations, coastal erosion due to rising sea level will lead initially to a lowering of the groundwater level in the dune system due to the narrowing of the dune belt. Subsequently, the previously wet-core dunes will become dry and vulnerable to deflation, further altering the dune form. However, the rise in sea level causes a rise in groundwater levels and may offset and reverse the initial decline. The balance between these two effects is likely to be dependent upon the characteristics of the dune area, the amount of erosion and the degree of sea level rise (van der Meulen 1990). Carter (1991) suggested that temporary lagoons may form in inter-dune areas as sea level rises. Changes in groundwater levels will also have an effect upon the vegetation, particularly dune slack species, which have critical maximum and minimum heights of the phreatic level and a 10 cm change can be vital (van der Meulen 1990).

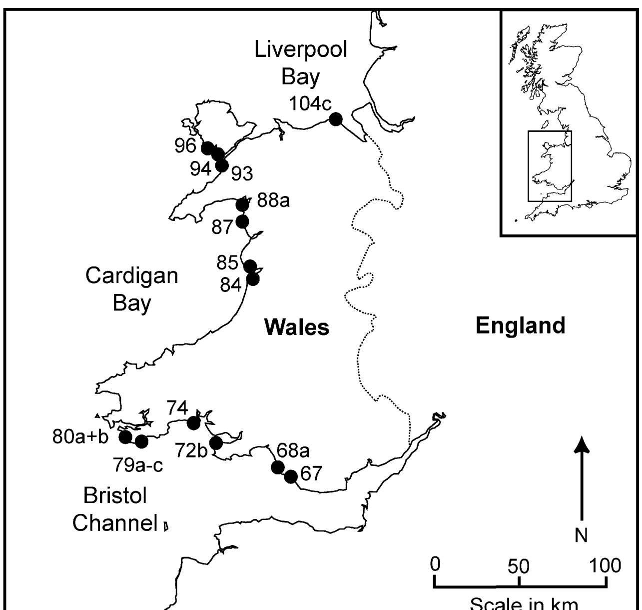
An understanding of the response of the beach/dune systems to recent and past changes in natural and anthropogenic forcing factors is important for the assessment of the likely impact of future changes in climate and human activities. In circumstances where environmental factors remain essentially unchanged, rates of historical change may provide a useful indicator of likely rates of future change. Even where environmental forcing factors are likely to change in the future, rates of historical morphological change can provide a useful benchmark against which to compare predicted future rates of change.

This paper reports the results of a study carried out to quantify historical changes in the areal extent of 15 coastal sand dune systems in Wales, UK, and to assess the likely impact of future changes in sea level on the extent and nature of dune habitats during the next century. The paper describes the methodology used by reference to two of the sites and presents a summary of the results obtained for all 15 sites. Further information can be found in Pye and Saye (2005).

Study sites

Coastal sand dunes occur at 57 sites in Wales and cover a total area of approximately 80 km^2. The majority of these systems have at least one type of conservation designation and 29 systems are Sites of Special Scientific Interest (SSSI), 12 are candidate Special Areas of Conservation (cSAC) and 12 are National Nature Reserves (NNR). Fifteen sites of important conservation value were selected for this study (Fig. 1). Twelve are SAC or cSAC sites, the exceptions being Ynyslas, Aberdovey and Gronant to Talacre. The Annex I habitats and Annex II species that are the primary reason for their recognition of SACs are summarised in Table 1. Several of the cSAC sites which include sand dunes also contain important non-dune Annex I habitats; thus sand dunes and sand dune processes cannot be considered independently of their context and interconnections with other related habitats (Table 2).

Clusters of dune systems occur in Swansea Bay, Pembrokeshire, North Cardigan Bay and Anglesey (Fig. 1). Elsewhere, dune sites are more widely scattered with notably few dune systems in the southern part of Cardigan Bay. The majority of the dune systems are small (<1 km^2), although several systems have areas of 1–4 km^2 and four dune systems are notably larger: Kenfig Burrows(6 km^2), Laugharne and Pendine Burrows (6 km^2), Newborough Warren (12.5 km^2) and Pembrey (16 km^2).



67 Merthyr Mawr (SSSI, cSAC)	84 Ynyslas (SSSI)
68a Kenfig Burrows (SSSI, cSAC)	85 Tywyn to Aberdovey (SSSI)
72b Whiteford Burrows (SSSI, cSAC)	87 Morfa Dyffryn (SSSI, cSAC)
74 Laugharne & Pendine (SSSI, part cSAC)	88a Morfa Harlech (SSSI, cSAC)
79a Barafundle Bay (SSSI, cSAC)	93 Morfa Dinlle (SSSI)
79b Stackpole Warren (SSSI, cSAC)	94 Newborough Warren (SSSI, cSAC)
79c Broad Haven (SSSI, cSAC)	96 Aberffraw (SSSI, cSAC)
80a Linney & Brownslade (SSSI, cSAC)	104c Gronant to Talacre (SSSI)
80b Broomhill (SSSI, cSAC)	

Fig. 1 Location of the dune systems considered in this study. System numbering after Saye (2003)

The great majority of the dunes are of late Holocene age, with most aeolian accumulation occurring within the last 600–1,000 years (e.g. Bailey et al. 2001). On the South Wales coast the dune systems mainly occur in embayment settings. Dune systems in West Wales are mainly occur on single barrier spits in estuarine or open coast settings, although fringing and transgressive systems also occur on the open coast. On the North Wales coast dunes are present both in estuarine and open coast settings and mainly take the form of barrier spit or fringing systems.

Certain aspects of the dune systems in Wales have been considered in previous studies. These include regional-scale surveys of the dune vegetation (Dargie 1995), the flood defence status of the dunes (Posford Duvivier Environment 1996), and the morphology, sedimentology and management status of the dune systems (Saye 2003). Detailed ecological and geomorphological studies have been undertaken at a number of sites, notably Newborough Warren (Ranwell 1959; 1960a, b), Pendine Burrows (Walley 1996) and Aberffraw (Bailey et al. 2001; Bailey and Bristow 2004). Assessments of possible future shoreline change are included in some local Shoreline Management Plans and the *Futurecoast* study commissioned by the UK Department of Food, Environment and Rural Affairs (Halcrow 2003; Taylor et al. 2004). However, there have been no previous studies of the possible consequences of future sea level and climate changes on coastal dune habitats.

Influences and constraints on coastal dune development

The scale and rate of coastal dune development in any area is fundamentally dependent on the volume of sand transported from the beach over time. This, in turn, is controlled by the wind climate, the supply of sediment to the beach, beach morphology, sediment size, precipitation and humidity, and the degree of physical disturbance to the sand surface. The mobility/stability of dunes away from the shore is also dependent on wind regime, sand supply, precipitation, type and density of vegetation cover, management practices and dune usage (Table 3).

The accommodation space available for development and movement of a dune system, which can be defined either by natural geological or anthropogenic constraints (such as urban and industrial development), is an important criterion in assessing whether a dune system is likely to 'roll back' under conditions of rising sea level, and whether it can be permitted to do so. In some systems, high ground or developments such as roads, railway lines, housing and industrial buildings constrain natural dune responses and management options.

Table 1 Annex I habitats and Annex II species that are the primary reason for the selection of Welsh cSAC sites

CSAC site	Annex I Habitats							Annex II Species					
	1230 Vegetated sea cliffs of the Atlantic and Baltic coasts	2110 Embryonic shifting dunes	2120 Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)	2130 Fixed dunes with herbaceous vegetation (grey dunes)	2170 Dunes with *salix repens* ssp. *Argentea* (*Salicion arenariae*)	2190 Humid dune slacks	3140 Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.	1014 Narrow-mouthed whorl snail *Vertigo angustior*	1304 Greater horseshoe bat *Rhinolophus ferrumequinum*	1395 Petalwort *Petalophyllum ralfsii*	1441 Shore dock *Rumex rupestris*	1654 Early gentian *Gentianella anglica*	1903 Fen orchid *Liparis loeselii*
Kenfig Burrows and Merthyr Mawr				X	X	X	X			X			X
Carmarthen Bay Dunes (Whiteford Burrows, Pembrey, Pendine and Laugharne Burrows)		X	X	X	X	X		X		X			X
Limestone Coast of South West Wales (Stackpole, Brownslade and Linney Burrows, Broomhill Burrows	X			X					X			X	
Morfa Harlech and Morfa Dyffryn		X	X		X	X				X			
Abermenai to Aberffraw (Morfa Dinlle, Newborough, Aberffraw)		X	X	X	X	X				X	X		

Data from atura 2000 data forms produced by Joint Nature Conservation Council (JNCC)

Table 2 Annex I habitats present at cSAC sites in Wales that include sand dune habitats

Annex I habitat	% Cover of Annex I habitat at each cSAC				
	Kenfig Burrows and Merthyr Mawr	Carmarthen Bay Dunes (Whiteford Burrows, Pembrey, Pendine and Laugharne Burrows)	Limestone Coast of South West Wales (Stackpole, Brownslade and Linney Burrows, Broomhill Burrows)	Morfa Harlech and Morfa Dyffryn	Abermenai to Aberffraw (Morfa Dinlle, Newborough, Aberffraw)
1140 Mudflats and sandflats not covered by seawater at low tide	19.01	n/a	15	n/a	n/a
1230 Vegetated sea cliffs of the Atlantic and Baltic coasts	n/a	n/a	22	n/a	n/a
1320 *Spartina* swards (*Spartinion maritimae*)	0.01	n/a	n/a	n/a	n/a
1330 Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)	1.7	n/a	n/a	n/a	n/a
2110 Embryonic shifting dunes	0.1	1.6	1	0.6	1.5
2120 Shifting dunes along the shoreline with *Ammophila arenaria* (White dune)	3.8	7.1	1	12	4.2
2130 Fixed dunes with herbaceous vegetation ('grey dunes')	45.12	44.3	25	n/a	21.1
2150 Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)	0.05	n/a	n/a	n/a	n/a
2160 Dunes with *Hippophae rhamnoides*	5.1	10.1	n/a	n/a	n/a
2170 Dunes with *Salix repens* ssp. *argentea* (*Salicion arenariae*)	0.4	3.7	n/a	4	6.8
2190 Humid dune slacks	11.21	8.1	1	5	2.4
3140 Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.	2.4	n/a	n/a	n/a	n/a
3150 Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation	n/a	n/a	n/a	n/a	1.6
4030 European dry heaths	n/a	n/a	4	n/a	n/a
6210 Semi-natural dry grasslands and scrubland facies: on calcareous substrates (*Festuco-Brometalia*)	0.1	n/a	2	n/a	n/a
7140 Transition mires and quaking bogs	n/a	n/a	n/a	n/a	0.3
8310 Caves not open to public	n/a	n/a	5	n/a	n/a
8330 Submerged or partially submerged sea caves	n/a	n/a	5	n/a	n/a
91E0 Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion*, *Alnion incanae*, *Salicion alvae*)	0.1	2.7	n/a	n/a	n/a
Total site area (ha)	1,191.67	1,206.32	1,594.53	1,062.57	1,871.03

Data from Natura 2000 data forms produced by Joint Nature Consveration Council (JNCC)

Table 3 Summary of natural and human constraints on the future evolution of the dune systems

Dune system	Accommodation space		Sand supply		Aeolian transport energy		Coastline protected		Management/ Land use
	High hinterland	Hinterland fixed e.g. development	Sand availability	Supply restricted	System orientation	Wind exposure	Natural e.g. shingle ridge	Anthropogenic e.g. sea wall	
Merthyr Mawr	Yes	Part. Urban development	Moderate	No	SSE-SW	High	Rock platform	No	No
Kenfig Burrows	Yes–part	Yes. Infrastructure, Urban and industrial development	Low	No	WSW	High	Shingle ridge part	No	No
Whiteford Burrows	No	No	Moderate	No	WNW–NW	High	No	No	Forestry
Pendine and Laugharne Burrows	Yes–part	Yes. Urban development	Moderate	No	SE–SSW	High	No	Yes. Defences western and eastern ends	MOD
Stackpole	Yes	No	Low	No	E–SE	Moderate	No	No	No
Brownslade and Linney Burrows	Yes	No	Low	No	W	High	Rock platform	No	MOD
Broomhill Burrows	Yes–part	Yes. Infrastructure	Low	No	WSW	High	No	No	No
Ynyslas	No	Yes. Urban development	Moderate	Yes. Groynes	W	High	Shingle ridge, southern end	No	No
Aberdovey	Yes	Yes. Infrastructure, Urban development, Golf course	Moderate	Yes. Groynes	S–WSW	High	Shingle ridge, northern end	No	No
Morfa Dyffryn	No	Yes. Infrastructure, Airfield, Urban development	Moderate	No	SW–W	High	No	Defences southern end	No
Morfa Harlech	Yes	No	High	No	SW–W	High	Sarn	No	No
Morfa Dinlle	No	Airfield (disused). Residential property	Moderate	No	W–N	High	No	Yes. Fort Belan Dock	No
Newborough Warren	Part	Urban development	Moderate	No	SSE–WSW	High	No	No	Forestry
Aberffraw	No	Infrastructure	Moderate	No	SW	High	No	No	No
Gronant and Talacre	No	Yes. Infrastructure, Urban and industrial development	Low	Groynes to west	NNW–N	Moderate	No	Western end	No

Marine reworking of sea floor sediments, combined with longshore drift, is generally the most important natural source of sediment around the coast of Wales, although inputs from rivers and cliff erosion are locally important. The ratio of onshore to longshore sediment supply varies from area to area reflecting the balance of local coastal processes and the nature of the geological framework (e.g. the extent to which the coast is divided into discrete 'compartments'). Modern day fluvial sediment supply is of significance only to a few Welsh dune systems, notably Ynyslas, Aberdovey, Laugharne and Pendine Burrows. The coastal cliffs of Wales are mostly composed of relatively hard, geologically old rocks, and rates of coastal sediment supply from cliff erosion are generally low. Dredging has had an influence on local sediment availability in some areas, notably Swansea Bay, but most Welsh dune systems are virtually unaffected by dredging, and beach nourishment has been carried out only at a relatively small number of locations.

Mean annual rainfall along most of the Welsh coast is <1,000 mm and therefore low by world standards. A spatial trend is evident, with greater average annual rainfall and more rain days in South Wales compared with Mid- and North Wales (Fig. 2). However, the variations in precipitation total and frequency are unlikely to have any significant effect on aeolian sand entrainment thresholds and sand transport rates, although they can significantly influence vegetation growth. Temperature has a direct influence on evaporation and evapo-transpiration and an indirect influence of aeolian sand transport and groundwater levels. Maximum average monthly temperatures occur in July and August and minimum average monthly temperatures occur in January and February (Fig. 2). The temperature is similar at Tenby and Valley (locations shown in Fig. 3) with the maximum monthly average temperature just below 20°C and the minimum average monthly temperature around 3°C.

Wind energy, and orientation of the coastline to the prevailing wind direction, strongly influence dune development. Across Wales, the prevailing winds blow from the southwest, although at a local scale there are variations as a result of coastal orientation and the nature of the surrounding topography. The resultant wind directions for Valley and Pembrey Sands (locations shown in Fig. 3) are directed from the southwest towards the northeast (Fig. 3). The threshold wind velocity for aeolian sand transport is about 11 knots, and above this threshold aeolian sand transport increases as a cubic function of wind speed (Bagnold 1941; Pye and Tsoar 1990). Wind speeds >11 knots represented 52.8% of all winds at Valley during the period 1981–2000 and 47.2% of all winds at Pembrey during the period 1994–2000. Aeolian drift potential (DP) values, calculated using the equation of Fryberger and Dean (1979), are 2,180 vector units (VU) at Valley and 1,935 VU at Pembrey. The calculated Resultant Drift Potential (RDP) values for Valley and Pembrey are 1,465 and 1,435 respectively. The Resultant Drift Directions

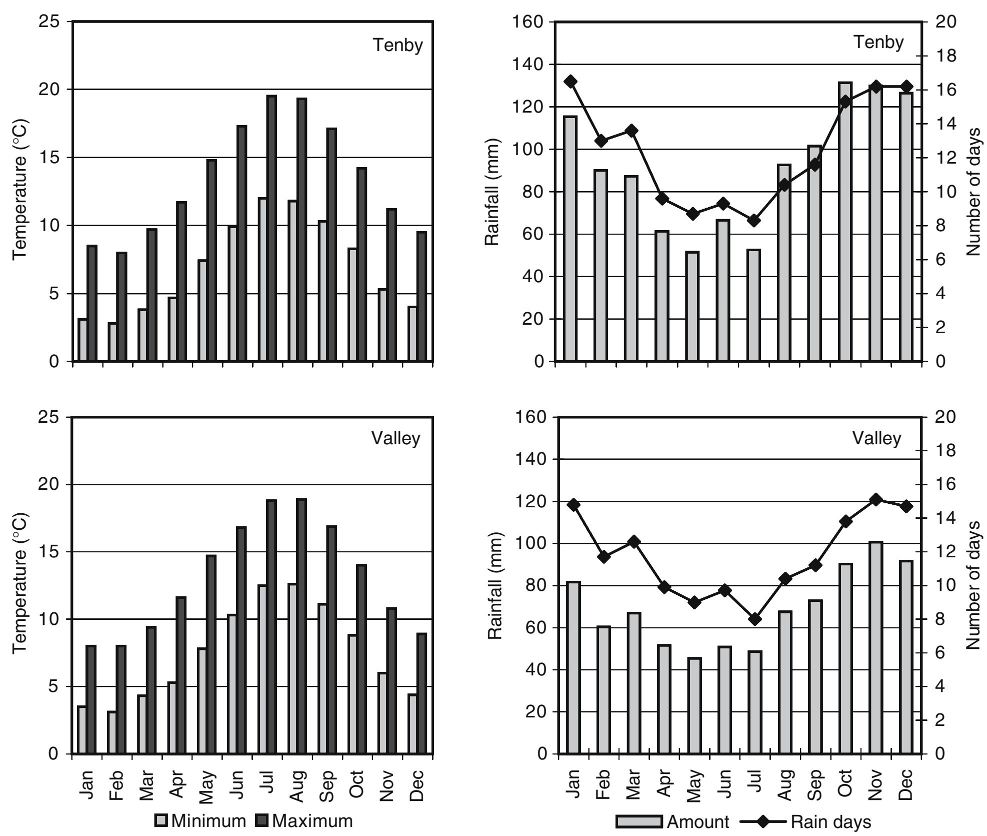


Fig. 2 Average monthly minimum and maximum temperatures, rainfall, and number of rain days for the period 1971–2000 at Tenby and Valley. Data source: the UK Meteorological Office

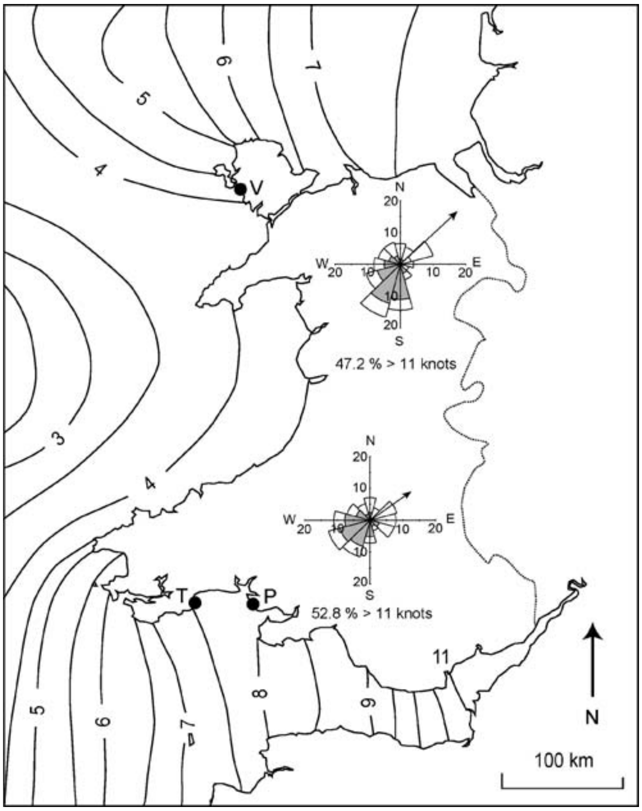


Fig. 3 Mean spring tidal range (m) around the coast of Wales and wind roses for Pembrey and Valley calculated from Meteorological Office data. *Unshaded segments* refer to all winds, *shaded segments* refer to winds >11 knots. *Arrows* indicate the resultant wind direction for all winds. *P* Pembrey, *T* Tenby, *V* Valley

(RDD) of 33° and 53°, respectively, are essentially from the southwest towards the northeast. However, on the North Wales coast south-westerly winds have relatively less influence than in South Wales and West Wales.

Tidal range is an important factor controlling the intertidal area from which sand can be deflated. The entire Welsh coast is macro-tidal, with a mean spring tidal range of >4 m (Fig. 3). Tidal range is smallest on the west coast (4–5 m) and increases eastwards along the South Wales coast, exceeding 8.9 m at Porthcawl. Similarly, tidal range increases eastwards along the North Wales coast towards the Dee estuary.

Coast protection works can strongly affect dune evolution. Sea defences anchor sections of coast, limiting the amount, rate and pattern of shoreline recession. However, only a few systems have been affected by large-scale coast protection works. Recreational activities, including walking, cycling, off-road vehicle driving, motorcycling, horse riding and golfing, can destroy vegetation cover and/or alter the plant species present, thereby affecting sand mobility and dune morphology. Military activities have caused substantial erosion to some dune systems in Wales, particularly during and following both World Wars. Grazing by domestic cattle, sheep and horses, and by wild animals (predominantly rabbits), influences sand stability and the structure of vegetation communities. However, only a few of the systems have land uses, such as forestry and military training, that strongly influence dune dynamics.

Methods

Historical trend analysis

Historical Trend Analysis (HTA) involves the interrogation of time-series data to identify directional trends and rates of processes and morphological change over varying time periods (Blott et al. 2006). HTA can be performed on many different types of data, including ground survey profiles, topographic maps, bathymetric charts and aerial photographs. In this study Ordnance Survey maps and Admiralty Charts provided the principal sources of morphological information. The Ordnance Survey first carried out mapping at a scale of 6 in. to the mile (1:10,560) in 1840. The map sheets covered individual counties and became known as the County Series. The maps were subsequently revised several times prior to 1945. In 1944/1945 mapping was transferred to the National Grid projection and the scale changed to 1:10,000. Further revisions and partial resurveys have been carried out at various dates up to the present, although the last major survey of shoreline positions was undertaken in the 1970s.

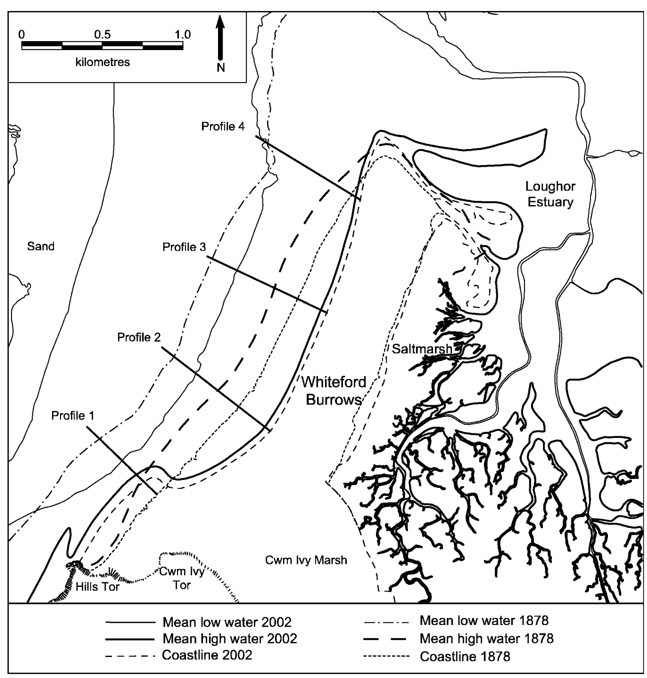


Fig. 4 Changes in position of the coastline, mean high water and mean low water at Whiteford Burrows as shown by 1878 and 2002 edition Ordnance Survey maps. The locations of shore-normal profile lines used to calculate foreshore and backshore widths are also shown

Several map editions for each dune area were obtained in paper format and digitised. The most recent available ‘Landline’ data, relating to 2001/2002 but based on surveys in the 1970s, were obtained in digital format from the Ordnance Survey. Historical maps were geo-referenced using a minimum of four control points and MapInfo Professional GIS software. Four to six historical map editions were used for each area, depending on availability.

In order to represent the rate of shoreline movement as accurately as possible, the year of survey was used as opposed to the year of map publication. Particularly with earlier editions, a degree of uncertainty surrounds the extent of resurvey included in each edition. Map editions since the 1950s generally specify the year(s) that the mean high water (MHW) and mean low water (MLW) were surveyed. Where the survey was conducted over more than 1 year, an

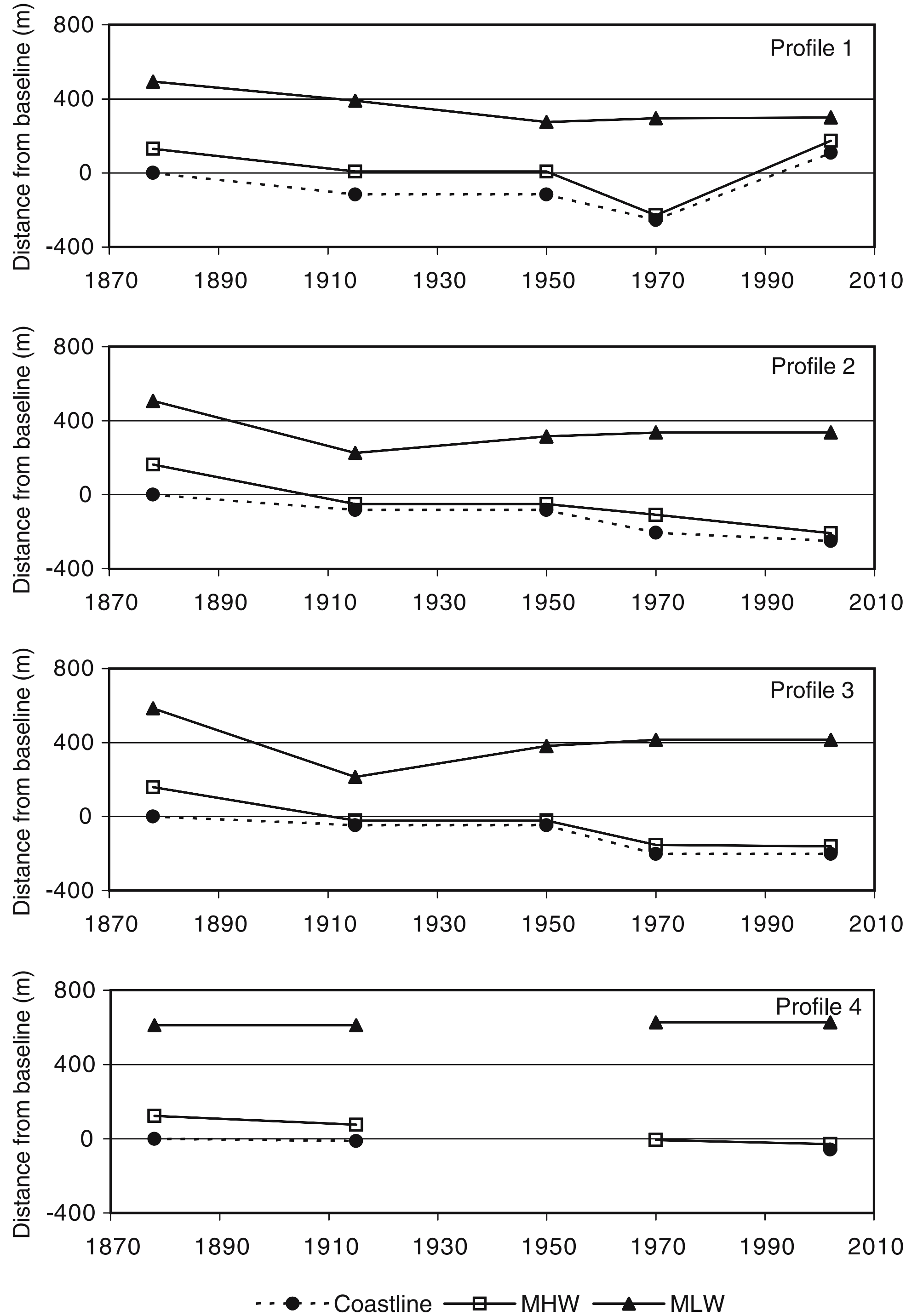


Fig. 5 Changes in the position of the coastline, mean high water (*MHW*) and mean low water (*MLW*), relative to the 1878 baseline, at Whiteford Burrows

Fig. 6 Cliffed frontal dunes along the central section of Whiteford Burrows, looking east-northeast (taken in 2004)

average was taken. Where a dune system is covered by two or more adjacent maps surveyed at different dates, the individual survey years were used for each map section.

Three datum lines were digitised: (1) the ‘coastline’, which was taken to represent the dune toe, and which in most cases is approximately equivalent to the elevation of the highest astronomical tide (HAT), (2) mean high water (MHW) and (3) mean low water (MLW). In order to assess shoreline movement, the positions of the coastline, MHW and MLW were measured along profiles perpendicular to the coastline shown on the first edition map. The number of profiles selected varied between dune systems depending on the length of coastline and the degree of spatial variation evident in shoreline movement. On average, profiles were located at 0.5 to 1 km intervals. Two measures of change were determined: (1) change between successive surveys, and (2) the overall net change between the first available survey and the most recent survey. Rates of change were calculated by dividing the magnitude of change by the number of years between surveys. An average rate of change was calculated by averaging all the profiles in each system. The backshore width, defined as the distance between the coastline and MHW, and the foreshore width, defined as the distance between MHW and MLW, were also calculated for each year of survey. The foreshore exerts an important influence on wave energy dissipation, while the backshore acts both as a buffer zone which absorbs storm wave energy and acts as a reservoir of sand for aeolian transport to the frontal dunes.

Prediction of future coastline change based on results of Historical Trend Analysis

Simple predictions of the position of the coastline and tidal levels in 100 years can be made by extrapolating the results of the HTA analysis, a procedure referred to as *Future Change Extrapolation* (FCE). This was conducted for the survey record as a whole in the case of all 15 sites, and also for the interval between the last and penultimate surveys at some sites. An average error of ±10 m was incorporated into the calculations to reflect uncertainty in method precision. The linear regression predictions assume that conditions remain constant over the next 100 years. However, historical change at most sites has not been linear over the last 120 years, and HTA/FCE predictions therefore represent a theoretical scenario. Actual shoreline changes will clearly depend on the nature and magnitude of any future changes in the process regime and sediment supply.

Prediction of future changes using the Bruun Rule

Bruun’s (1962) simple two-dimensional cross-shore model predicts the amount of erosion which may result from rising sea level, based on certain assumptions. The model uses the principle that adjustment to sea level rise will be achieved by dispersal of eroded sediment across the nearshore zone to maintain an equilibrium profile. Mathematically this can be expressed by:

$$W = \frac{XS}{Y} \tag{1}$$

where W is the width of beach erosion, X is the horizontal length from shore to limited depth of sediment transport (closure depth), S is sea level rise, and Y is the vertical dimension of the profile between the closure depth and sea level datum (all expressed in metres).

The distance between Mean High Water Spring (MHWS) and the closure depth was determined from Admiralty Charts. In order to standardise the calculation procedure, in most cases the closure depth was taken to be 10 m below Chart Datum (CD). However, in some instances this was not possible since the shore-normal profiles did not cross the −10 m isobath. This problem arises most frequently with dune systems located near estuary mouths, where sandbanks and tidal channels are present. In such cases the −5 or −2 m CD isobaths were

Fig. 7 Coastal progradation at the southern end of Whiteford Burrows, looking northeast (taken in 2004)

used instead. The vertical distance between the closure depth and MHWS was used for the value of Y in Eq. 1.

The UK Climate Impacts Programme (UKCIP) was established in 1997 to oversee the development of studies into climate change impacts in the UK. Under this programme initial national level climate change scenarios (known as UKCIP98) were established for the UK (Hulme and Jenkins 1998). These scenarios were based on findings of the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and experimental results generated by the Hadley Centre HadCM2 model. Four alternative climate change scenarios, Low, Medium-Low, Medium-High and High, were developed covering a range of emission scenarios and different climate sensitivities.

Predicted relative sea level rise (with respect to the 1961–1990 average) around the coast of Wales by 2070–2100 ranges from 0.11 for the UKCIP02 Low Emissions scenario to 0.71 m for the High Emissions scenario (Hulme et al. 2002). These estimates include an adjustment for regional land movement of −0.2 mm/year (based on Shennan 1989). An assumed sea level rise of 0.41 m, intermediate between the minimum and maximum estimates, was used in this study to predict future coastline change using the Bruun Rule model. The predictions also make the assumption that the nearshore profile is linear and in equilibrium. Actual shoreline recession is likely to be less than predicted by the Bruun model where sandbanks or moraine ridges are present in the nearshore profile since such features provide protection from wave activity. Where alongshore sediment transport, as well as onshore–offshore transport, is involved, the pattern of shoreline changes is also likely to be more complex than predicted by the simple 2D Bruun model.

Predicted future coastline change based on Expert Geomorphological Assessment

Expert Geomorphological Assessment (EGA) involves integration of the results of Historical Trend Analysis (HTA), short-term process model outputs and background information about physical, chemical and biological processes, geological constraints, sediment properties and process–form interactions determined through field and laboratory experiments (Blott et al. 2006). EGA predictions can be considered as a 'best estimate' of future coastline change over the next century, taking into account all available information.

Calculation of historical and predicted future loss of dune system area

Historical loss, gain and net changes in dune area, as a result of changes in the position of the coastline, were calculated for each dune system using a polygon function in *MapInfo*. Predictions of future area change were then made using the FCE/HTA, Bruun Rule and EGA methods. The calculated area changes only reflect movements of the coastline position, and do not take into account any possible movement of the landward margin. The Bruun Rule was used only to predicts changes in the coastline position along the seaward margin of the dune systems; the

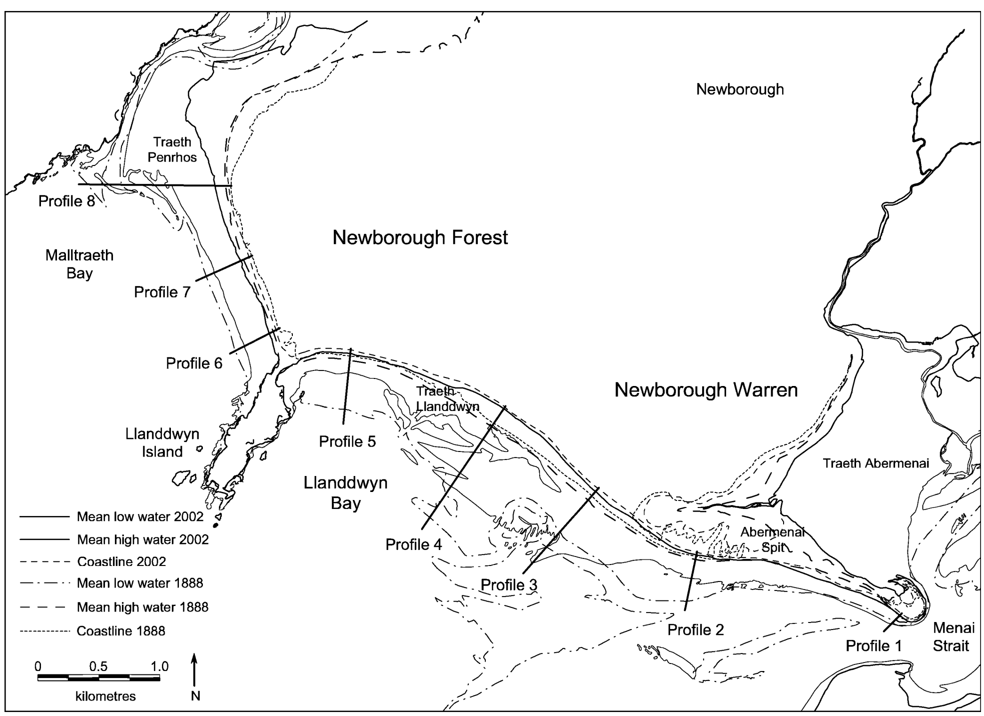


Fig. 8 Changes in the position of the coastline, mean high water and mean low water at Newborough Warren based on the 1878 and 2002 edition Ordnance Survey maps. The locations of the shore-normal profiles lines used to calculate foreshore and backshore widths are also shown

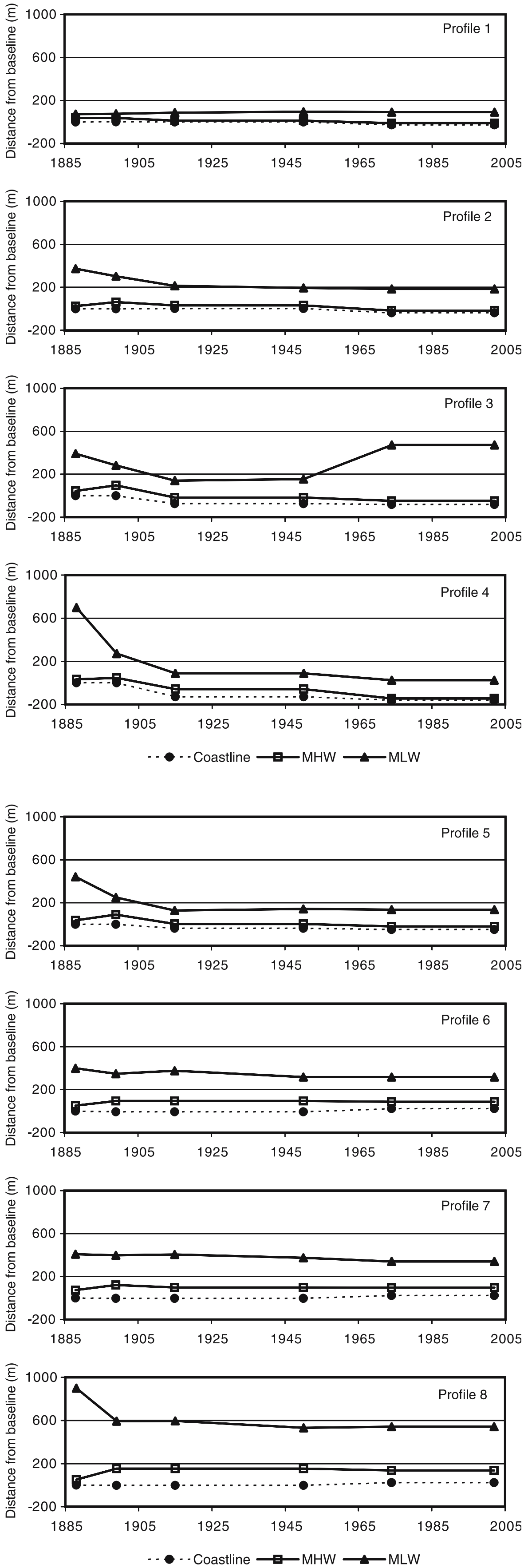


Fig. 9 Changes in the position of the coastline, *MHW* and *MLW*, relative to the 1888 baseline, at Newborough Warren

inner sides of spit systems were assumed to remain unchanged for the purposes of the area calculations.

Data errors and uncertainties

There a number of sources of uncertainty which affect the quality of the data used:

(1) inaccuracies in the original survey measurements and data plotting
(2) map distortions during storage
(3) incomplete resurveys between map editions
(4) errors in map digitisation and computerised data handling
(5) errors in defining the ‘coastline’ which is sometimes not shown as a clear line on published maps

Of these, (1) and (3) are potentially the most serious. Errors in the original survey are difficult to quantify, but are likely to be greater for older map editions and for the mean low and mean high water marks, which are sometimes arbitrarily defined by the surveyors with little reference to changes in tidal elevations over the lunar-nodal tidal cycle. Type (3) errors are clearly evident on some map sheets where the area extent of re-survey is shown. This is not always the case, but a lack of resurvey can be inferred from an absence of any recorded change between different map editions and discontinuities between adjoining map sheets. Type (2) errors can be minimized, if not entirely eliminated, if appropriate measures are taken to geo-reference different map sheets. Type (4) errors are also inevitable but are considered unlikely to exceed ±5 m when working with 1:10,000 scale maps. Type 5 errors are also inevitable but probably do not exceed ±20 m in most cases.

Fig. 10 Cliffed frontal dunes along Traeth Penrhos, Newborough Warren, looking northeast (taken 2000)

Fig. 11 Frontal dune accretion aided by fencing, Traeth Llanddwyn, Newborough, looking west-northwest (taken in 2000)

Results

Historical change

Maps illustrating historical changes in the position of the coastline, MHW and MLW at all 15 dune systems are contained in Pye and Saye (2005). For the purposes of illustration in this paper, historical changes for only two dune systems, Whiteford Burrows and Newborough Warren, are presented. At both systems there has been net retreat of the coastline at most profile locations.

The coastline along the central part of Whiteford Burrows has retreated consistently during the survey period at rates of −0.5 m/year to −2.0 m/year, with the greatest retreat rates between 1950 and 1970 (−6.1 to −7.8 m/year; Figs. 4, 5 and 6). At the southern end of the system,

Table 4 Summary of trends obtained from historical trend analysis at dune systems

Dune system	Survey period	Coastline			MHW			MLW		
		Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Overall retreat/advance (m)										
Whiteford Burrows	1878–2002	−101	−250	109	−199	−370	42	−130	−194	16
Newborough Warren	1888–2002	−36	−162	23	−34	−179	87	−197	−672	82
Merthyr Mawr	1877–2001	−18	−35	7	6	−12	38	−323	−345	−313
Morfa Dyffryn	1887–2002	−10	−38	19	−13	−53	14	14	−35	53
Broomhill Burrows	1906–2002	−4	−7	0	20	17	22	−167	−176	−158
Brownslade and Linney	1906–2002	1	−2	5	1	−1	3	−152	−184	−73
Kenfig Burrows	1876–2002	9	0	20	28	13	45	−18	−51	17
Morfa Dinlle	1888–2002	28	−8	66	−1	−31	18	11	−28	62
Aberdovey	1887–2002	52	−23	189	29	−33	168	20	−60	235
Ynyslas	1887–2002	33	−5	118	35	7	111	−15	−63	13
Stackpole	1906–2002	59	−21	245	60	−5	220	−47	−70	−4
Gronant to Talacre	1871–2002	82	−24	443	145	−19	467	−22	−326	149
Aberffraw	1888–2002	159	138	176	148	129	168	−93	−108	−77
Morfa Harlech	1887–2002	197	6	629	241	−1	801	86	−23	187
Laugharne and Pendine	1887–2002	214	73	694	214	62	688	−167	−473	501
Overall retreat/advance rate (m/year)										
Whiteford Burrows	1878–2002	−0.8	−2.0	0.9	−1.6	−3.0	0.3	−1.0	−1.6	0.1
Newborough Warren	1888–2002	−0.3	−1.4	0.2	−0.3	−1.6	0.8	−1.7	−5.9	0.7
Merthyr Mawr	1877–2001	−0.1	−0.3	0.0	0.1	−0.1	0.3	−2.3	−2.6	−2.0
Morfa Dyffryn	1887–2002	−0.1	−0.3	0.2	−0.1	−0.5	0.1	0.1	−0.3	0.5
Broomhill Burrows	1906–2002	0.0	−0.1	0.0	0.2	0.2	0.2	−1.7	−1.8	−1.6
Brownslade and Linney	1906–2002	0.0	0.0	0.1	0.0	0.0	0.0	−1.6	−1.9	−0.8
Kenfig Burrows	1876–2002	0.1	0.0	0.2	0.2	0.1	0.4	−0.1	−0.3	0.1
Morfa Dinlle	1888–2002	0.2	−0.1	0.6	0.0	−0.3	0.2	0.1	−0.2	0.5
Aberdovey	1887–2002	0.5	−0.2	1.6	0.3	−0.3	1.5	0.2	−0.5	2.0
Ynyslas	1887–2002	0.3	0.0	1.0	0.3	0.1	1.0	−0.1	−0.6	0.1
Stackpole	1906–2002	0.6	−0.2	2.6	0.6	0.0	2.3	−0.5	−0.7	0.0
Gronant to Talacre	1871–2002	0.6	−0.2	3.4	1.1	−0.1	3.6	−0.2	−2.5	1.1
Aberffraw	1888–2002	1.4	1.2	1.5	1.3	1.1	1.5	−0.8	−0.9	−0.7
Morfa Harlech	1887–2002	1.7	0.1	5.5	2.1	0.0	7.0	0.7	−0.2	1.6
Laugharne and Pendine	1887–2002	1.9	0.6	6.0	1.9	0.5	6.0	−1.5	−4.1	4.4

Presented are average, minimum and maximum overall retreat/advance distances and rates between the first survey and the most recent survey for the coastline, MHW and MLW. Negative values indicate retreat, whilst positive values indicate an advance. Note dune systems are ordered from greatest average retreat rate to greatest average advance rate of the coastline progradation has occurred since the 1970s with the development of low shore-parallel ridges which incorporate a brackish wet slack area (profile 1 in Fig. 5; Fig. 7). Little net change has occurred on the seaward margin at the northern end of the system, although the spit has extended northwards. MHW and MLW have also retreated landwards, with the exception of an advance in the MHW near the neck of the spit (profile 1) and the relatively unchanged MLW position at profile 4. Overall retreat of the MHW position has occurred at rates of −1.2 m/year to −3.0 m/year. Although MLW generally retreated over the entire study period, the inter-survey trends are more complex at profiles 2 and 3, where retreat between 1878 and 1915 was followed by advance.

Distinctly different trends occur at the two beaches, Traeth Llanddwyn and Traeth Penrhos, which front the Newborough Warren dune system (Fig. 8). Overall, the coastline has retreated consistently along Traeth Llanddwyn and Abermenai Spit by between 29 and 162 m, or at −0.3 to −1.4 m/year on

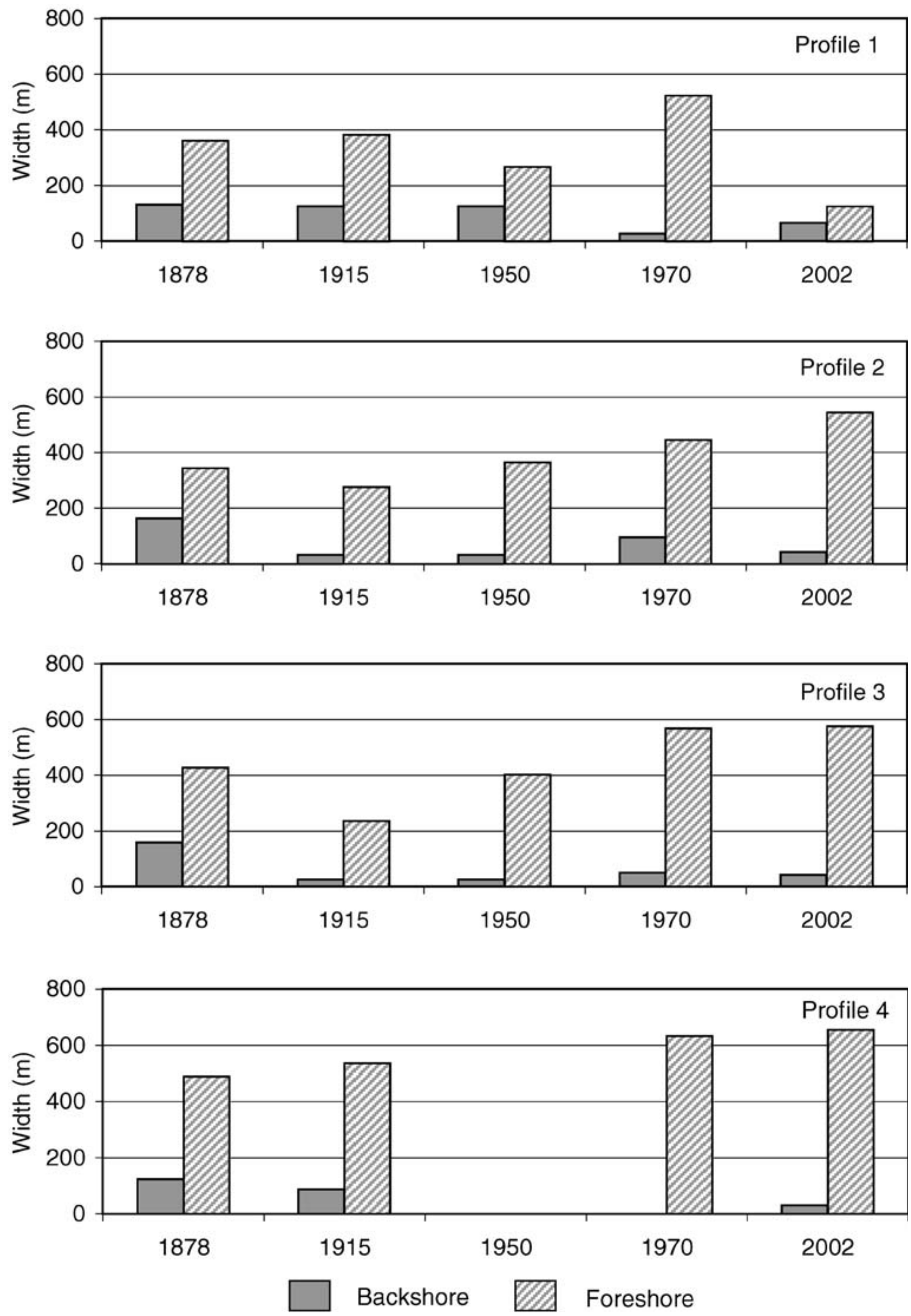


Fig. 12 Variation in backshore and foreshore widths at Whiteford Burrows

average, at profiles 1 to 5 (Fig. 9). Retreat has been greatest in the vicinity of profiles 3 and 4. Coastline retreat is undermining the roots of the pine trees within the forested area causing them to fall (Fig. 10). However, lateral dune accretion has recently occurred in the central section of Traeth Llanddwyn, near to the main beach access, aided by stake fencing (Fig. 11). Despite changes on both the seaward and landward sides of Abermenai Spit, it has essentially retained its form and position. Along Traeth Penrhos the coastline has advanced by about 20 to 30 m overall, mainly since the 1950s (profiles 6 to 8 in Fig. 9).

MHW and MLW have retreated along Traeth Llanddwyn and Abermenai Spit (profiles 1 to 5), although advance of MLW occurred at profiles 1 and 3. Trends in MLW are complicated by the presence of sand banks which have altered significantly in size, form and position since the first survey, particularly in the vicinity of profiles 3 and 4. MHW advanced along Traeth Penrhos, whilst MLW retreated overall. Most change occurred at profile 8 where changes in the sand banks near the mouth of the River Cefni and fluctuations in the course of the river itself, have influenced the position of MLW. The dune system has extended towards the River Cefni at the north eastern corner with advance of both the coastline and MHW.

Net average retreat of the coastline was recorded at three other dune systems, Merthyr Mawr, Morfa Dyffryn and Broomhill Burrows (Table 4). However, at all of these sites there was also net advance at some profiles. The greatest average coastal advance occurred at Laugharne and Pendine, Morfa Harlech and Aberffraw, where no profiles experienced net erosion over the period of survey.

Average rates of coastline erosion were highest at Whiteford Burrows (−0.8 m/year), while average rates of coastal progradation were highest at Laugharne and Pendine (1.9 m/year), Morfa Harlech (1.7 m/year) and Aberffraw (1.4 m/year; Table 4). The maximum overall retreat rate at any profile was also recorded at Whiteford Burrows (−2.0 m/year), while the highest overall rate of progradation at any profile was recorded at Laugharne and Pendine (6.0 m/year).

In general, there is a fairly close correlation between the pattern of movement of MHW and that of the coastline. However, only Whiteford Burrows and Newborough Warren showed average retreat of MHW of >20 m. Nine of the sites showed average advance of >20 m, while the largest average advances (>200 m) were at Laugharne and Pendine and Morfa Harlech. By contrast, only one site (Morfa Harlech) showed net average advance of the MLW of >20 m. At most sites there was considerable longshore variation in the trend of MLW, with some profiles showing

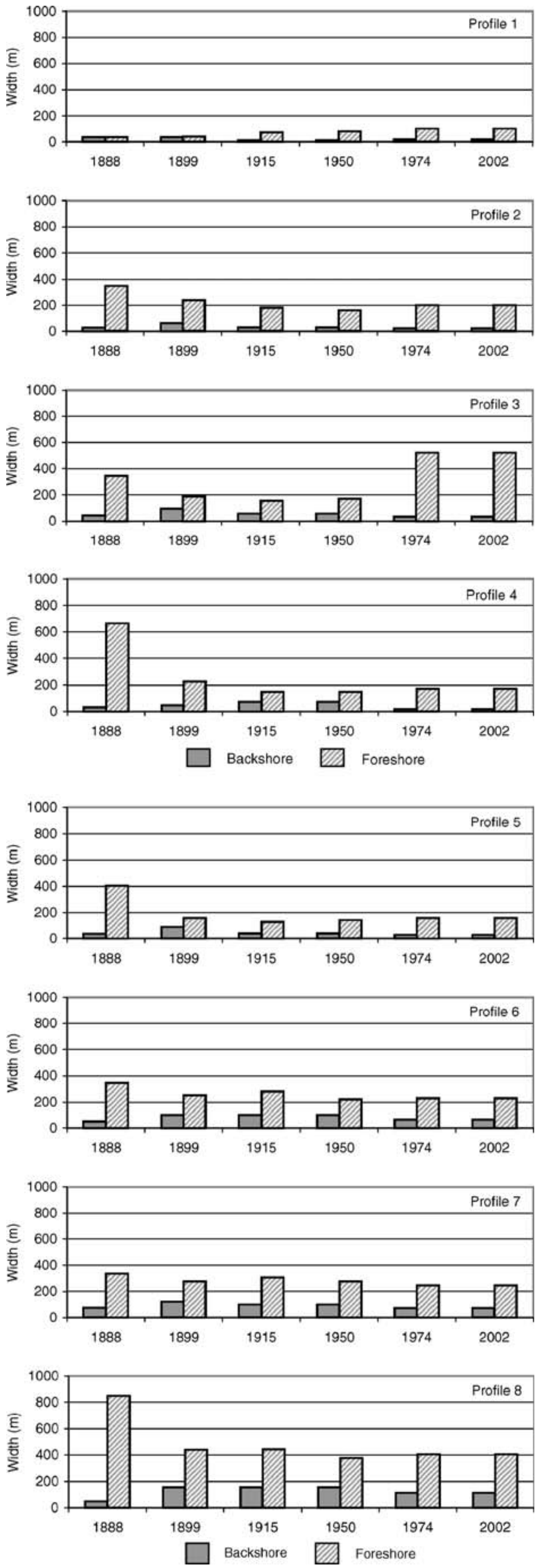


Fig. 13 Variation in foreshore and backshore widths at Newbrough Warren

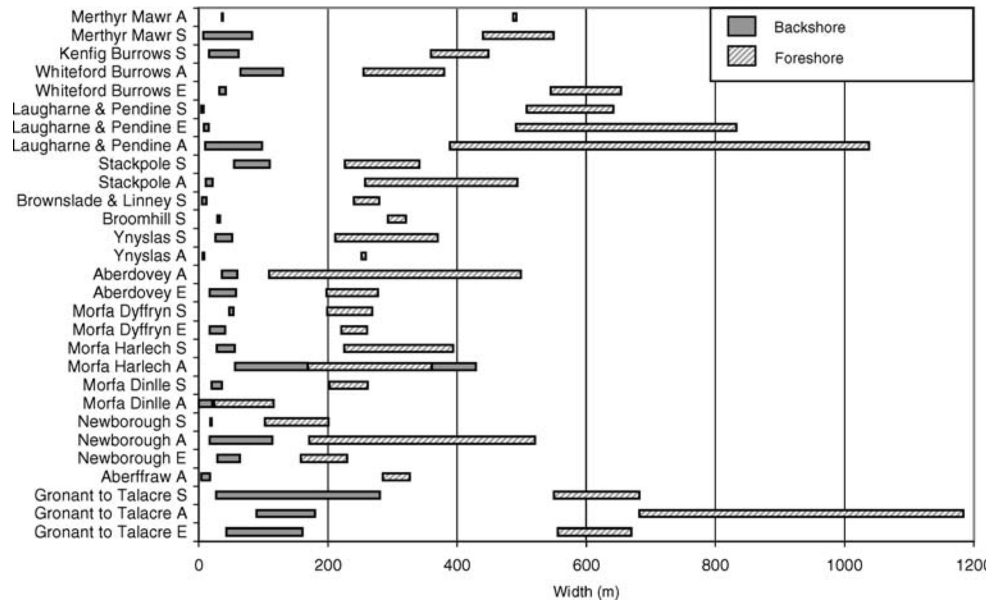


Fig. 14 Range of backshore and foreshore widths indicated by the latest edition Ordnance Survey maps for different frontal dune erosion/accretion status types at the 15 dune systems considered. *A* Accretion, *E* erosion

seaward advance and others showing landward retreat. However, at Merthyr Mawr, Broomhill Burrows, Brownslade and Linney Burrows, Stackpole and Aberffraw, all profiles showed net retreat. The overall effect of a landward movement of MLW, combined with a seaward movement of MHW, at most sites has been a steepening of the intertidal profile.

As a consequence of coastline movement, the backshore zone has narrowed overall since the 1878 survey at Whiteford Burrows while the foreshore has widened, although at profile 1 both parts of the beach have narrowed (Fig. 12). Along Traeth Llanddwyn at Newborugh Warren, MHW retreat has been more rapid than coastline retreat, leading to narrowing of the backshore by 5 to 20 m. At the time of the latest survey the backshore ranged in width from 17 m at profile 4 to 34 m at profile 3 (Fig. 13). The foreshore along Traeth Llanddwyn narrowed significantly (between 148 and 494 m) during the survey period, although it widened at profiles 1 and 3 by 66 m and 176 m, respectively. At the time of the latest survey the foreshore was generally 100 to 200 m wide, except at profile 3 where it was 521 m wide. Along Traeth Penrhos the backshore has generally widened since the first survey, although there has been little net change at profile 7. The foreshore has narrowed by 90 to 450 m, accompanied by retreat of MLW.

In general, steepening of the intertidal profile reflects an adjustment to an increase in energy conditions, and is often a precursor to the onset of frontal dune erosion. Average foreshore narrowing was recorded at 12 of the 15 sites, and average backshore narrowing at five sites. This indicates that, at most sites, steepening of the intertidal profile had not yet had a negative effect on the backshore (and frontal dune stability). A general relationship is evident between the recent backshore and foreshore width and erosion/accretion status of the frontal dunes (Fig. 14). In any given system, accreting dunes are associated with wider foreshores, while eroding dune are generally associated with narrower foreshores. However, there is no simple relationship between historical dune recession/accretion and foreshore width, owing to differences in the process regimes between beach and dune systems.

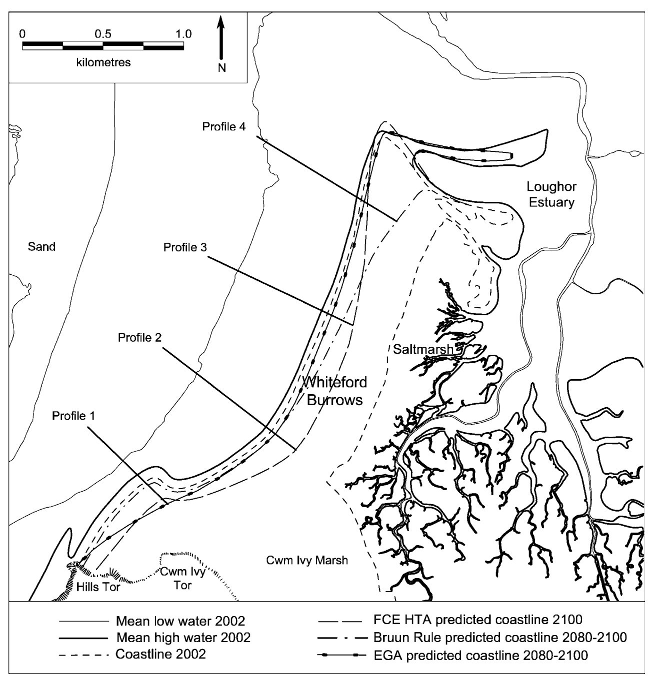


Fig. 15 Predicted positions of the coastline by 2080–2100 at Whiteford Burrows based on HTA/FCE, the Bruun Rule and EGA

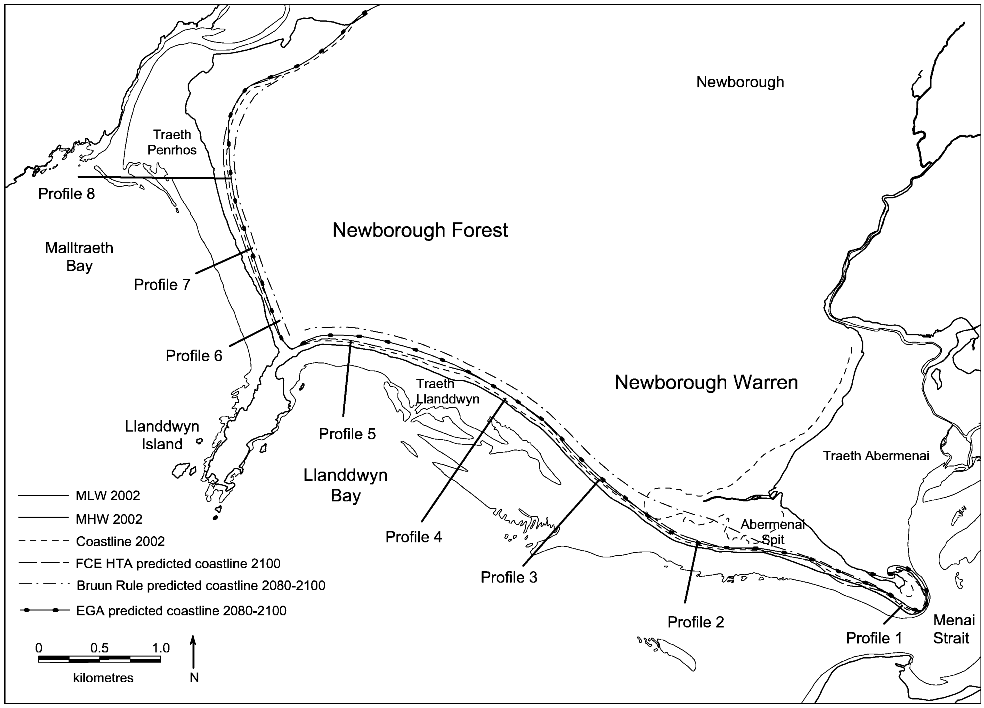


Fig. 16 Predicted positions of the coastline by 2080–2100 at Newborough Warren based on HTA/FCE, the Bruun Rule and EGA

Future change

Figures 15 and 16 show the predicted coastline positions at Whiteford Burrows and Newborough Warren using the three methods, HTA/FCE, Bruun Rule and EGA. As would be expected, the pattern of HTA/FCE prediction closely mirrors that of historical change. For most sites, the predicted position of the coastline in 2080–2100 using the Bruun Rule lies some considerable distance inland of the FCE/HTA predicted shoreline position. However, an exception is provided by much of the Whiteford Burrows frontage where historical rates of coastline recession have been particularly high.

At some dune systems the Bruun Rule predicted shoreline positions are clearly unrealistic, notably where there is a very gentle offshore gradient or where high land occurs close to the coast (e.g. near Aberdovey). Nevertheless, in most cases the Bruun Rule predictions provide an informative 'worst case' prediction of future shoreline position.

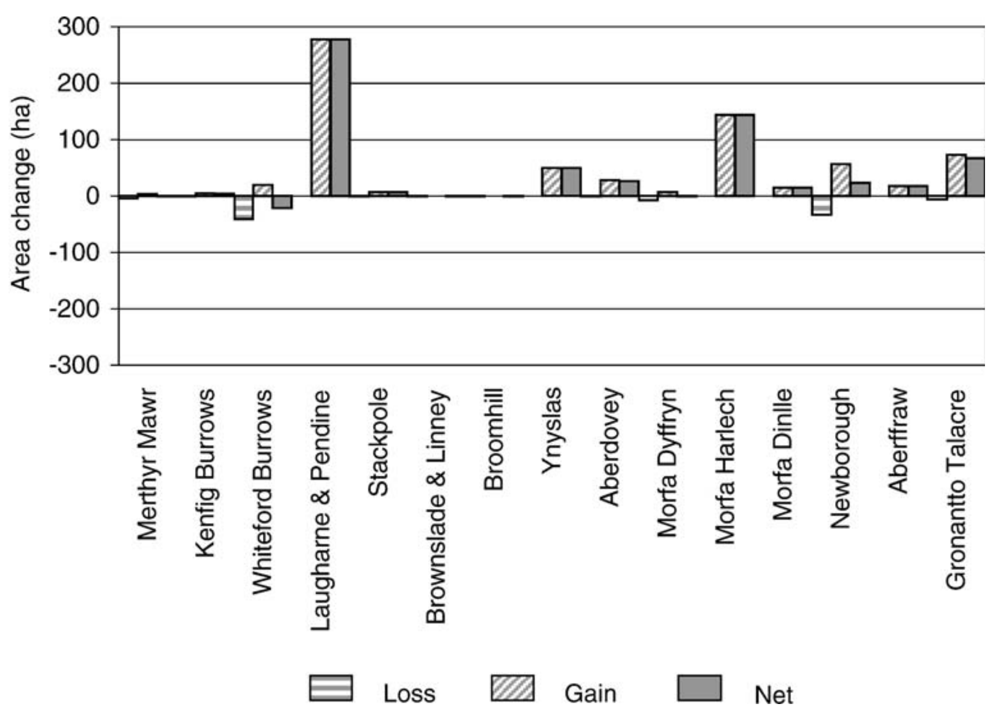


Fig. 17 Change in area of the 15 dune systems based on a comparison of the first edition and most recent edition Ordnance Survey maps

However, as noted above, actual shoreline change over the next century is unlikely to follow a simple Bruun-Rule type pattern, for several reasons. Firstly, the Bruun Rule predictions made in this report only consider onshore–offshore sediment exchange, whereas in many areas longshore sediment transport is also important. In areas which receive significant sediment by longshore drift, or from river discharge to the coast, coastal recession is unlikely to occur on the scale predicted by the Bruun Rule, and in extreme cases progradation may continue. Other situations in which the

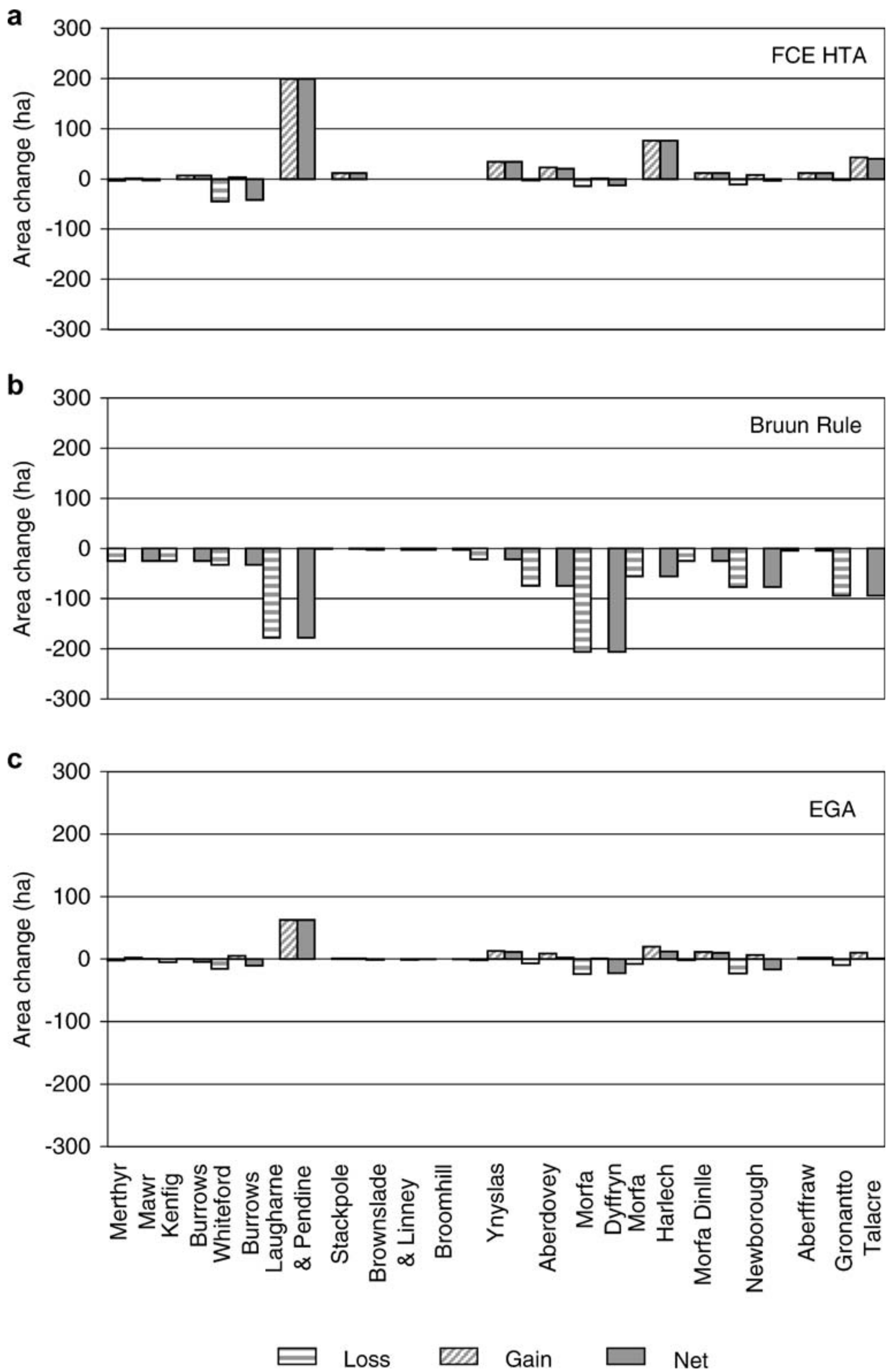


Fig. 18 Predicted change in dune area based on **a** HTA/FCE, **b** the Bruun Rule and **c** EGA

amount and rates of coastal recession are likely to be limited include sections of coast which are 'anchored' by natural rock outcrops or artificial sea defences.

The EGA predictions take account of such processes and constraints. In most cases the EGA predicted coastline positions lie between those predicted by the HTA/FCE method and the Bruun Rule, although there are exceptions. These include areas of high sediment supply, for example the ends of spit systems (e.g. Point of Air and Laugharne and Pendine Burrows), where it is anticipated that the sediment budget will remain sufficiently favourable to maintain lateral progradation in the face of rising sea level.

Dune area change

Historically, Whiteford Burrows, Merthyr Mawr and Morfa Dyffryn experienced the largest net loss of dune area, while Laugharne and Pendine Burrows, Morfa Harlech and Gronant to Talacre experienced the largest net gains (Fig. 17). Expressed as a percentage of the 'present' dune area, Whiteford Burrows, Merthyr Mawr and Morfa Dyffryn showed the largest loss, but Ynyslas showed the highest percentage net gain. Significant area loss has also occurred at Newborough, but has been offset by area gain.

As might be expected, a similar trend was found for predicted future area loss derived from HTA/FCE (Fig. 18a). At most of the dune systems considered, future area loss predicted using the Bruun Rule is substantial, with Laugharne and Pendine Burrows and Morfa Dyffryn predicted to incur the largest losses (Fig. 18b). Taking all factors into account, Morfa Dyffryn, Newborough and Whiteford Burrows are predicted to experience the largest total areas losses (Fig. 18c). However, significant net gains are predicted at Laugharne and Pendine Burrows, Morfa Harlech and Ynyslas.

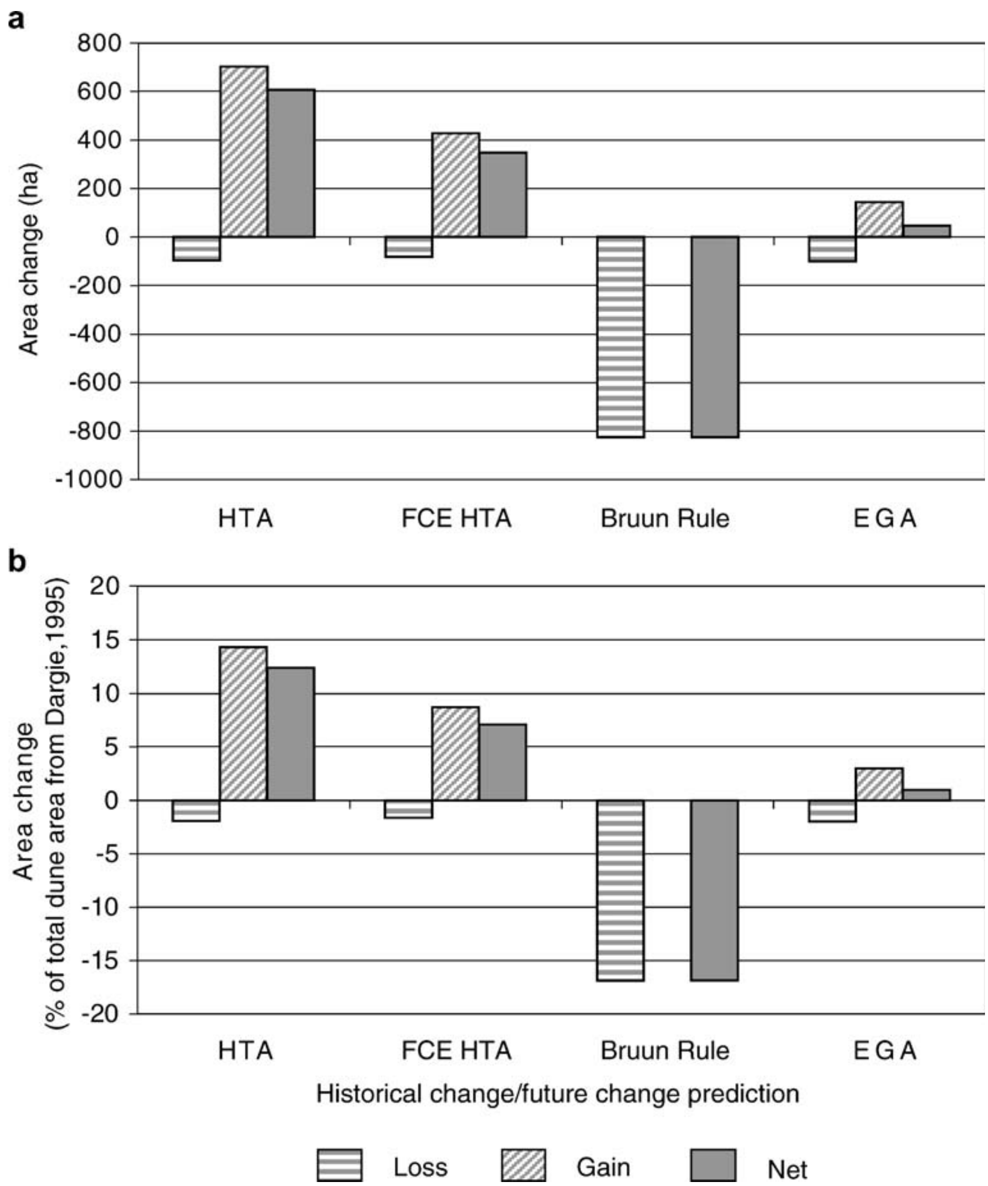


Fig. 19 Aggregate historical area change and three future change predictions by 2080–2100 for all 15 dune systems expressed **a** in terms of hectares and **b** as a percentage of the total dune area reported by Dargie (1995)

Considering all 15 systems together, there was a net dune area increase of 607 ha ±10% over the period of historical record, representing approximately 12% of the total area of the 15 systems quoted by Dargie (1995). Predictions using HTA/FCE suggest a possible further increase in area of 348 ha (about 7%) over the next century (Fig. 19), assuming little or no change in the environmental forcing factors which have operated over the last century. Taking into account the effects of sea level rise as predicted by the Bruun Rule, an overall loss of area of 826 ha (about 17%) is predicted. However, the Bruun model almost certainly overestimates the actual loss which is likely to occur owing to the complexity of coastal morphology–sediment transport interactions and geological framework constraints. The EGA predictions, suggest that there will, in fact, be very little net change in total area, and possibly a slight net gain. There will, however, be significant variations between dune sites and even between different parts of individual sites.

Habitat change

Future changes in coastline position and dune system area are likely to affect sand stability, dune mobility and groundwater levels, which in turn will affect biological habitats. The possible implications of future shoreline change, and its possible effects on dune area and habitat loss/gain are summarised in Table 5. Coastline erosion normally results in a loss, or prevents the development of, embryo and 'yellow' dunes. Except in dune systems which have experienced very long term coastal erosion, fixed ('grey') dune habitats and slacks are affected only to a limited degree. In such circumstances fixed dunes can be reactivated by blowouts, buried by younger mobile dunes and sand sheets, or may simply be eroded without burial by new sand. Dune slacks within fixed dune landscapes may, however, be adversely affected by changing groundwater levels linked to coastline change.

Table 5 Summary of past and projected major habitat change at the dune systems, based on the spatial pattern of changes in dune area

	Past habitat change (first to recent survey)							Future habitat change (EGA)						
	Loss				Gain			Loss				Gain		
	Embryo dune	Shifting dune	Fixed dune	Fixed dune (forested)	Embryo dune	Shifting dune	Fixed dune	Embryo dune	Shifting dune	Fixed dune	Fixed dune (forested)	Embryo dune	Shifting dune	Fixed dune
Merthyr Mawr	X	X		–	X			X	X		–	X		
Kenfig Burrows		X		–	X			X	X		–	X		
Whiteford Burrows		X			X	X		X	X	X		X		
Laugharne and Pendine Burrows	–	–	–	–	X	X	X	–	–	–	–	X	X	
Stackpole	X	X		–	X	X	X	X	X	X	–	X		
Brownslade and Linney Burrows		X		–	X				X	X	–	–	–	–
Broomhill Burrows		X		–	–	–	–		X		–	–	–	–
Ynyslas	–	–	–	–	X	X		–	–	–	–	X	X	
Aberdovey		X		–	X	X			X	X	–	X	X	
Morfa Dyffryn		X		–	X	X	X		X		–	X		
Morfa Harlech	–	–	–	–	X	X			X		–	X	X	
Morfa Dinlle	–	–	–	–	X	X			X		–	X	X	
Newborough Warren	X	X		X	X	X		X	X	X	X	X	X	
Aberffraw	–	–	–	–	X	X					–	X		
Gronant and Talacre	X	X	X	–	X	X		X	X	X	–	X	X	

Hyphen denotes no loss or gain of dune area calculated or no forested fixed dune present

The EGA predictions of shoreline change suggest that there is likely to be significant loss of embryo dune and shifting dune habitat at some sites, notably Merthyr Mawr, Kenfig, Whiteford Burrows, Stackpole, Newborough and Gronant to Talacre, but in the majority of systems there will be development of new embryo and shifting dunes. Only at Brownslade and Linney and Broomhill Burrows is there likely to be (limited) loss of shifting dune and little or no compensating development of new dunes. At Laugharne and Pendine Burrows, Ynyslas and Aberffraw, losses of all dune habitat types are likely to be relatively small scale, and more than offset by the development of new embryo and/or shifting dunes. Uncompensated loss of fixed dune is likely at Whiteford Burrows, Stackpole, Brownslade and Linney Burrows, Aberdovey, Newborough and Gronant to Talacre.

Conclusions

Historical Trend Analysis based on Ordnance Survey maps provides a practical method of assessing past coastal change and allows extrapolation and prediction of future coastal change assuming no change in environmental forcing factors or human intervention. However, the accuracy of the data obtained is dependent on the quality of the survey information available. For a number of reasons, future change is unlikely to mirror historical change exactly owing to changes in the rate of mean sea level rise, wind/wave climate and patterns of sediment supply. Models such as the Bruun Rule allow an estimate of the effects of sea level rise to be made, but the accuracy of the predictions is likely to be dependent on several factors, including the nature of the geological framework, coastal morphology, sediment transport patterns, and management practices. Based on available knowledge of such factors and their interactions, a 'best estimate' of future change can be made; a process referred to as expert geomorphological assessment. The accuracy of EGA predictions will always depend on the quality and relevance of available survey information relating to morphology, coastal processes and sediment supply, the nature and magnitude of any future changes in these factors, and future coastal management policies.

Based on the results of this study, no major net loss of dune habitat is predicted, although significant losses are likely to occur at some individual systems. There will be some loss of frontal dune area at such sites and there is likely to be an increase in dune sand mobility near the shore, leading to greater habitat diversity and dynamism. Marine erosion of sand from some frontal dune areas will result in accumulation in other areas down-drift, notably within estuary mouth spit complexes, leading to the creation of embryo dunes and partially mobile 'yellow' dunes. In most dune systems, shoreline erosion alone is unlikely to have a major impact on dune habitats at distances of more than 1 km from the shore. However, changes in temperature, precipitation and wind regime may have a significant effect on ground water level fluctuations and hence on vegetation communities. Further work is required to evaluate the potential effects of such changes on individual dune systems.

Acknowledgements This paper is based largely on research commissioned by the Countryside Council for Wales. We thank Dr. Rod Jones and other CCW staff for data provision and helpful comments at various stages of the work. Thanks are also due to Dr. Simon Blott for assistance with preparation of some of the figures.

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