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Quantifying Shoreline Changes along the Sefton Coast (UK) and the Implications for Research-Informed Coastal Management

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ABSTRACT

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The Sefton coast is a 36-km long coastline located between the Mersey and the Ribble estuaries in northwest England. It encompasses the longest coastal dune system in England and Wales, which has been rapidly eroding in the last century. The arcuate shape of this coast favours erosion at the prominent shore of Formby Point from where sediment diverges and is transported longshore promoting accretion northwards and southwards. This study aims to assess how different ways of estimating shoreline change rates (using different proxies and statistical methods) can affect future predictions of shoreline positions. Coastline and high water line positions, dune toe surveys and beach profiles spanning different time frames are analysed. Shoreline change rates are highly dependent on the proxy used to map the shoreline and the statistical methods used to estimate rates of changes. Generic models to predict future positions of the shoreline do not produce good results for this study area. Therefore, the analysis of long-term and a regular monitoring of various shoreline proxies are the best alternative for predicting future shoreline positions. An improved understanding of the past and present patterns of shoreline changes at different spatial and time scales is necessary to support best management practices taking into account scenarios of climate change.

ADITIONAL INDEX WORDS: *dunes, erosion, storms, Formby Point*

INTRODUCTION

Increasingly, local authorities are facing pressure to abide with agenda 21 and the embedded integrated coastal management principles, in which they must consult with stakeholders, use the best knowledge available and incorporate long-term planning to implement the best sustainable management practices (e.g. DUXBURY and DICKINSON, 2007). Furthermore, they need to adapt to climate changes and deal with the uncertainties in predictions related to increasing storminess, accelerated sea level rise, and more frequent floods due to combinations of extreme storm surges and heavy rainfall (e.g. VEGA-LEINERT and NICHOLLS, 2008). Coastal monitoring and research-informed decision-making have a crucial role in assisting local authorities to develop their shoreline management plans. However, the majority of local coastal authorities worldwide are still lacking any regular program of coastal monitoring. In some areas, local authorities have been collecting a variety of data that can be used to qualitatively and quantitatively assess coastal changes through time and space, including: historic maps, aerial photographs, beach profiles, topographic and bathymetric surveys, etc. A number of proxies for shoreline positions can be extracted from these datasets and used to calculate shoreline change rates. In each case the spatial resolution, time frame and uncertainties are dependent on specific data sources and methods of collection and analysis. Both situations challenge coastal managers needing to provide long-term predictions of shoreline positions especially when incorporating the effects of sea-level rise. In the first case, the lack of data can lead managers to adopt the 'remediation approach' (i.e. to deal with problems after they happen) or preferably the conservative approach of planning based on the most pessimistic scenario. These two options can have unacceptably high environmental and socio-economic costs. In the second case, data availability might provide a variety of ways of estimating shoreline change rates based on different proxies or time frames that are not always easily comparable. Irrespective of the situation, the use of the best available knowledge is paramount. In this respect, academic research can play a key role in supporting informed decision-making through collaboration or partnerships with local governments (FLETCHER, 2008).

The Sefton Metropolitan Borough Council (SMBC) is one of the few local authorities in the UK holding an extensive coastal database built upon data collection initiated in early 1900's and a more regular monitoring of beach profiles (since 1979) and dune toe surveys (since 1959). In addition to data collected by SMBC, historic topographic maps (since 1848), aerial photographs (since 1945), lidar surveys (from late 1990's), tidal levels (from 1768) and measurements of oceanographic and meteorologic variables are available from other sources. In 2007, the SMBC produced a report showing predictions of coastline positions for 2055 and 2105 using current rates of change based on dune toe surveys from 1959 to 2005 and accounting for the effects of sea level rise using the Bruun rule (LYMBERY et al., 2007). This study aims to compare predicted shoreline positions obtained using different proxies at a range of time scales and the implications for coastal management using the Sefton coast in NW England (Figure 1) as a case study. It is beyond the scope of this paper to discuss in detail

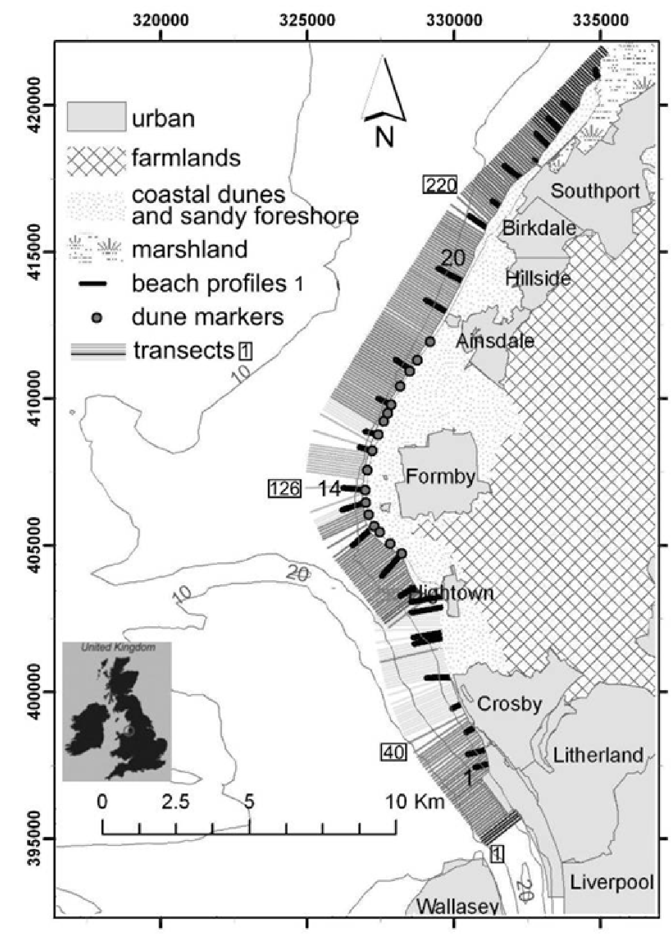

Figure 1. Location of beach profiles, dune markers and transects along which shoreline change rates were estimated. Transects shading indicate trends of stability (light gray), erosion (medium gray), and accretion (darker shades) estimated using WLR and HWL as a proxy for shoreline position.

the validity of different proxies (cf. BOAK and TURNER, 2005) or the application of the Bruun rule (cf. COOPER and PILKEY, 2004).

METHODS

The 36-km long coast of Sefton is located in NW England between the Mersey and the Ribble estuaries and includes a mixture of rapidly eroding sand dunes, accreting marshlands, recreational beaches and rural and urban areas (Figure 1). Coastal monitoring data held by SMBC are analysed here to assess differences in shoreline change rates estimated using different proxies and their influence in predicting future coastline positions. Shoreline change rates are estimated using: (a) dune toe surveys dating from 2001 to 2008, (b) beach profiles collected from 1996 to 2006 and (c) coastline and high water line (HWL) positions from 1848 to 2005. Location of beach profiles and dune markers is shown in Figure 1.

Dune toe surveys were undertaken using kinematic GPS along 10 km from Altcar in the south to Ainsdale in the north and include the frontage of Formby Point and surroundings. Measurements were obtained seasonally and more recently before and after storms. Uncertainties in these data relate to GPS accuracy and the correct identification and mapping of the dune toe and are estimated to be within ± 2m. Beach profiles obtained along 30 cross-shore transects (numbered sequentially from south to north) covering the 36 km of the Sefton coast have been surveyed through time using different methods, including topographic level, total station and more recently GPS. Errors in measurements of vertical changes are estimated to be within ± 0.15 m (cf. PYE and BLOTT, 2008). Positions of the coastline and HWL were digitised from Ordnance Survey topographic maps and are considered in this study to have an error of ± 10 m. Additional coastline positions were digitised from aerial photographs using the vegetation line or hard engineering structures and have an estimated error of ± 15 m.

The Digital Shoreline Analysis System (THIELER et al., 2005) was used to calculate shoreline change rates based on the coastline, HWL and dune toe positions along transects extending seawards from a defined baseline at 100 m intervals along shore (Figure 1). Transects were sequentially numbered from south to north and shoreline change rates were estimated using the end-point (EPR), weighted linear regression (WLR) and least mean squares (LMS) methods for each individual dataset. These were compared subsequently to define patters of change and to analyse differences in rates obtained using different methods. Erosion and accretion are indicated by negative and positive values, respectively. In an attempt to reduce the impact of data outliers, dune toe positions mapped pre and post storms were not used to calculate longer-term rates of change. These were estimated in three different ways using: (a) two seasonal surveys per year (hereafter named Dune), (b) only summer surveys (hereafter named Dune_s) and (c) only winter surveys (hereafter named Dune_w).

Sefton beach profile data (Figure 1) were used to investigate two aspects of shoreline change: (a) annual changes in shoreline position, and (b) inter-annual changes in beach volume. In the case of (a), the shoreline location was determined relative to an arbitrary level +3 m above OD (Ordnance Datum). In the case of (b), a cross-shore distance of 400 m from the arbitrary shoreline position defined in (a) were used to determine inter-annual changes in beach volume per metre length of a given beach profile.

ESTIMATES OF SHORELINE CHANGES

This section presents shoreline change rates estimated using dune toe surveys, coastline and HWL positions and analyses their alongshore differences and changes through time. Unless otherwise stated, the rates of change were estimated using the longest time series as described in the methods. As expected, the different statistical methods of estimating rates of change showed the same general trends and differed mainly in their magnitude. For the shoreline proxies used here, the correlation coefficient (R) between the statistical methods of estimating shoreline changes was >0.95; except for HWL when using the LMS method ($0.5 \leq R \leq 0.61$). Table 1 shows the maximum (highest accretion rates) and minimum (highest erosion rates) rates of shoreline change estimated by the different statistical methods and proxies. For all proxies, the highest erosion rates occurred around Formby Point between transects 132 and 141, with the LMS method always showing the highest erosion rates. However, LMS provided the most consistent values across the different proxies (-5.19 to -6.24 m/yr), while the highest rates provided by EPR and WLR varied between -0.71 to -5.39 m/yr and -1.47 to -6.19 m/yr, respectively. In this rapidly eroding area, erosion rates are highest when using coastlines as a proxy and lower when using HWL. The highest accretion rates based on the analysis of dune toe survey data (2.41 to 3.25 m/yr, Table 1) occurred between transects 174 and 181.

Table 1. Maximum, minimum and mean values of shoreline change rates by proxy and statistical method.

		Rates of change (m/yr)			Standard
		Max	Min	Mean	Deviation
Coastline	EPR	15.00	-5.39	2.15	3.59
	WLR	19.29	-6.19	2.62	4.76
	LMS	19.82	-6.24	2.18	4.46
HWL	EPR	11.43	-0.71	2.97	2.62
	WLR	11.48	-1.47	2.76	2.70
	LMS	11.61	-5.20	0.68	3.11
Dune	EPR	2.41	-4.67	-0.58	1.82
	WLR	2.70	-4.25	-0.30	1.89
	LMS	2.89	-5.65	-0.60	2.20
Dune_s	EPR	2.78	-3.61	-0.12	1.79
	WLR	2.89	-4.05	-0.20	1.94
	LMS	3.06	-5.19	-0.31	1.95
Dune_w	EPR	2.52	-4.60	-0.38	1.88
	WLR	2.69	-4.34	-0.36	1.86
	LMS	3.25	-5.73	-0.69	2.15

When using the coastline or HWL, the highest accretion rates (11.48 to 19.82 m/yr) are found at the northernmost end of the study area between transects 284 and 291.

Dune Toe

The correlation coefficient between rates estimated using Dune, Dune_s and Dune_w was ≥ 0.92, indicating that general trends of changes are similar. The lowest correlation (R = 0.92) is found between Dune_s and Dune_w when using the LMS method (Figure 2a). LMS generally results in higher rates of erosion than EPR and WLR (Figure 2b, Table 1), with maximum and mean differences around 2 m/yr and 0.4 m/yr, respectively. Maximum and mean differences in magnitudes of rates between EPR and WLR are 1 m/yr and 0.2 m/yr, respectively, with the lower maximum and mean differences found for Dune_w (0.5 m/yr and 0.14 m/yr). Dune_w also shows better correlation with coastline and HWL (0.62≤ R ≤0.86) than Dune (0.60 ≤ R ≤0.83) and Dune_s (0.58≤ R ≤0.80), except for LMS in which Dune performs slightly better. Dune_w shows better correlation with other proxies and less variation on the magnitudes of rates estimated by different methods. Therefore it will be used thereafter when referring to dune toe rates of changes.

Coastline and HWL

Rates of changes estimated using EPR, WLR and LMS show R ≥0.96 when using coastlines as a proxy, while a poor correlation (0.57 ≤ R ≤0.61) is found between rates estimated by LMS when using HWL as a proxy (Figure 3a). LMS results show higher frequency and larger magnitudes of changes alongshore in HWL rates (Figure 3b), which are not observed in the other methods or proxies (Figure 3c). Additionally, LMS tends to accentuate erosion and reduce accretion in HWL change rates (Figure 3b), while resulting in magnitudes and trends similar to other methods for coastline rates. For HWL, differences between LMS estimated rates and other methods are above 3 m/yr at Formby Point and reach up to 12 m/yr at the northernmost end of the study area (Figure 3b). R values from the correlation between rates of change estimated for coastlines and HWL using EPR, WLR and LMS showed are 0.78, 0.65 and 0.38, respectively. The highest alongshore variability of rates estimated for HWL and coastlines are found at the southern and northern ends of the study area and at Formby Point (Figure 3c). They result from land reclamation, rapid dune erosion and progradation of marshlands, which affect coastline positions more rapidly and intensely than HWL positions. As this uses only the oldest (1848) and the most recent data points (2005), land reclamations conducted in early 1900's affected WLR and LMS estimates to a larger extent than estimates obtained using EPR,. Rates of changes estimated for coastlines using WLR are up to 5 m/yr higher than for EPR at the southern and northern end of the study area. The lowest variations between estimated rates are found between WLR and EPR using HWL as a proxy, showing maximum and mean differences of 1.8 and 0.24 m/yr, respectively.

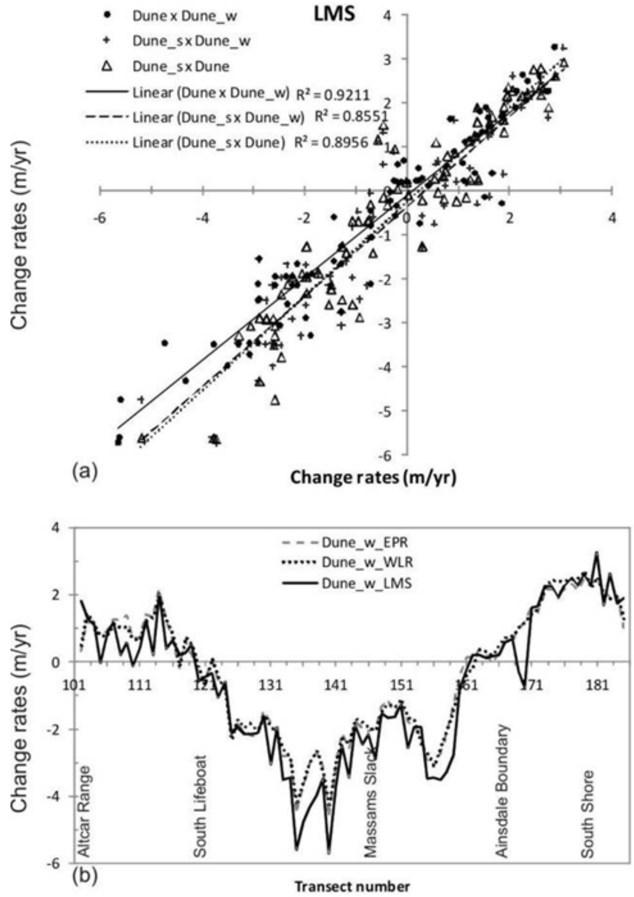

Figure 2. Correlation between rates of change estimated for Dune, Dune_s and Dune_w using LMS (a), and comparison of rates of change estimated using EPR, WLR and LMS for Dune_w (b).

Beach Profiles

The use of beach profiles to determine changes in the dune-fronted sections of the Sefton shoreline is challenging. At some beach profiles, shoreline retreat is accompanied by increases in beach volume and vice-versa (Figure 4). On the other hand, at locations where changes in sediment volume are more variable, the shoreline can be either accreting or eroding. Although the shoreline has obviously retreated at some locations, the amount of

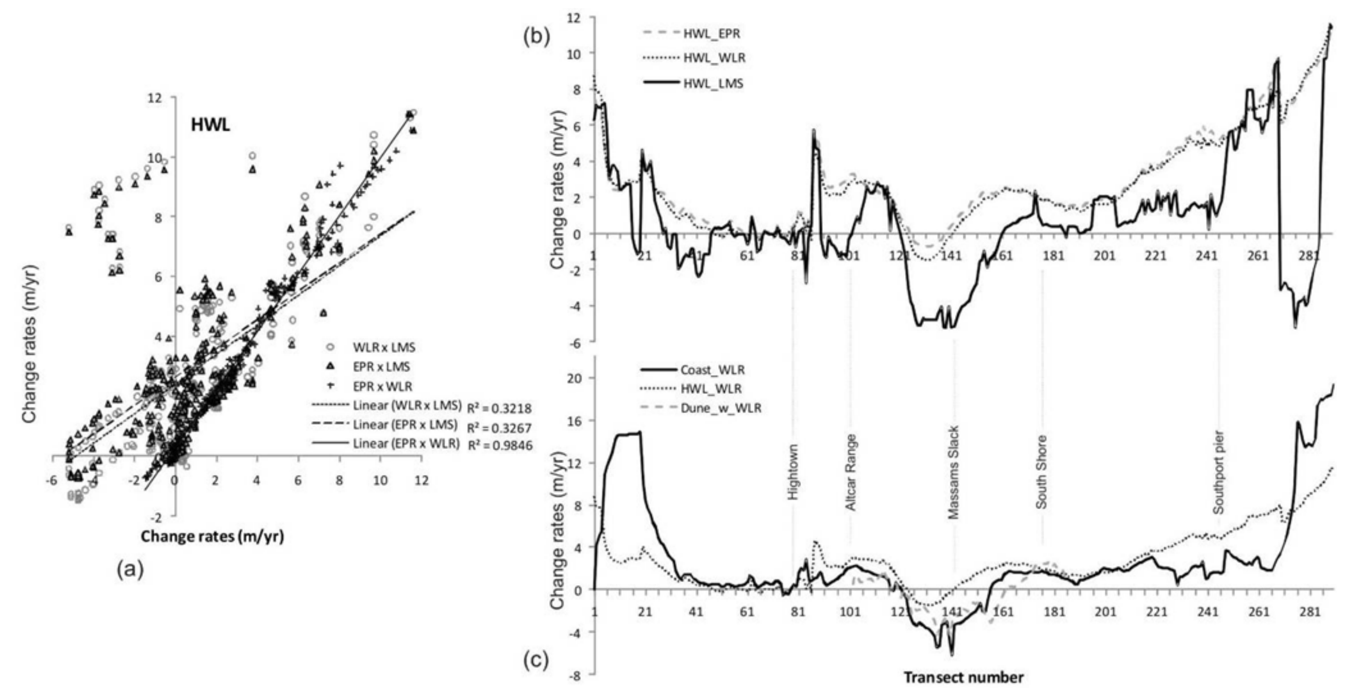

Figure 3. Scatter plot showing that HWL change rates using EPR, WLR and LMS and their linear regression factor (a). HWL change rates along the Sefton coast evidencing that LMS accentuate erosion when compared to EPR and WLR (b). Comparison between change rates estimated for coastlines, HWL and Dune_w using WLR (c) showing greater differences at the southern and northern ends.

retreat depends on the reference datum used. In areas such as Formby Point, analysis of beach profiles indicated shoreline retreat in accordance with other proxies. However, changes in sediment volume are slightly positive, probably due to erosion of dunes/upper beach acting as sediment source for the lower sections of the profile. In general, areas where accretion has been observed, changes in sediment volume are negligible and do not indicate positive or negative trends. Due to the variability in the results obtained through the analysis of beach profiles, they are not used here to quantify rates of changes.

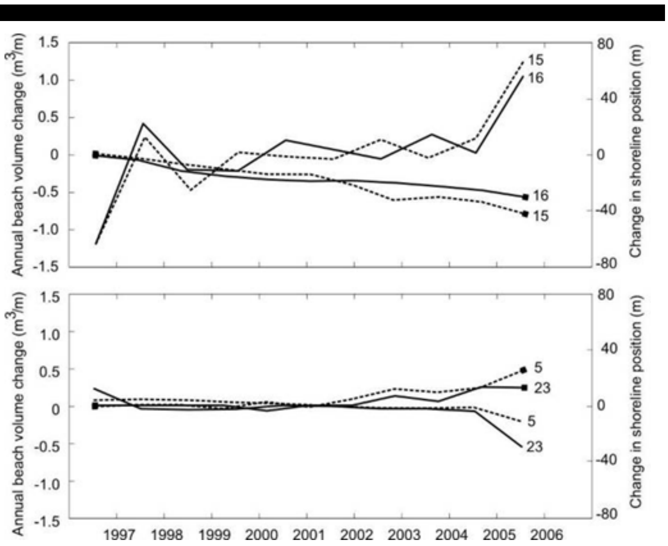

Figure 4. Annual variations in beach volume and changes in shoreline position (lines with markers) obtained from the analysis of beach profiles showing that, at some locations, increasing beach volumes are associated with shoreline retreat (top) and reduction in beach volumes are associated with accretion (bottom).

PREDICTIONS OF FUTURE SHORELINE POSITIONS

Predictions of future positions of the shoreline were made by the Sefton Council using current rates of change based on dune toe survey data and the Bruun rule to account for impacts of sea level rise (Figure 5). The validity of the Bruun rule for the study site is tested here by comparing the observed changes in coastline position from 1955 to 2005 with the retreat predicted by the rule along selected profiles. The sea level rise used was the revised mean sea level trend of 1.60±1.7 mm/yr estimated for the period 1901-2004 for Liverpool (WOODWORTH et al., 2009). For some locations, the Bruun rule overestimates the retreat and others it underestimate the retreat (Table 2). Therefore, predictions relying on measured shoreline changes are preferable especially in areas where variation in sediment volume is apparent.

At present, there is no reliable method of predicting future coastal retreat rates taking into account accelerated rise in sea level. It is suggested here that the best predictions of shoreline positions are provided by the analysis of data obtained locally through regular and long-term monitoring of different shoreline proxies. Figure 5 shows the position of the coastline in 2055 predicted using WLR. In the accreting areas south of Albert Road, all the predicted shorelines lie at similar locations. North of Albert Road to Wicks Lane, WLR predictions are seawards of SMBC predictions, suggesting that dune toe data used by SMBC result in eroding rates while data used in this study indicate accretion. From Wicks Lane to Freshfield, the predicted position of the 2055

Table 2. Comparison of observed shore retreat measured from 1955 to 2005 with predictions using the Bruun rule for a sea level rise of 1.60±0.17 mm/yr.

		Bruun Rule	
Location	Observed	1.43 mm/yr	1.77 mm/yr
Range Lane	+157	+40	+50
Lifeboat Rd	-184	-85	-106
Wicks Lane	-322	-112	-138
Victoria Rd	-123	-143	-177
Fisherman's Path	-111	-129	-160
Ainsdale	-19	-23	-28

coastline is landwards of the SMBC predictions, indicating that the coastline has been eroding faster than the dune toe in this area. North of Fisherman's Path, this studies prediction for the location of the 2055 coastline lies seaward of the SMBC predictions, indicating that, in the long-term, this area is accreting rather than eroding. However, the analysis of dune toe surveys also indicates an accretion trend. Therefore, a more detail analysis of change rates through time is required to better understand differences in predicted shoreline positions based on various shoreline position proxies. For coastal management purposes, it is recommended that the most conservative (e.g. pessimistic) rates of change are used (i.e. the highest rates of erosion), unless the variations between rates estimated using different methods and proxies are understood. As seen in this study, the LMS method usually accentuates erosion trends and might be a more conservative method to estimate future shoreline positions.

CONCLUSIONS

The availability of a wide range of coastal data can be as troublesome as the lack of data for coastal managers attempting to predict future positions of the coastline. An extensive coastal dataset is available for the Sefton coast and this is used here to analyse rates of changes and to predict future shoreline positions. Regular and long-term monitoring of shoreline positions using different proxies is essential for understanding variability of shoreline changes in space and time. The indiscriminate use of general models might not be the best option for coastal managers to predict future shoreline positions. The use of the highest rates of change obtained using different proxies and statistical methods might provide the best way to predict shoreline positions in the future. It is expected that the rationale of estimating rates of change and predicting future shoreline positions suggested here can be applied in other areas.

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Figure 5. Shoreline positions predicted for 2055 and 2105 using the current rate of change based on dune toe surveys and the Bruun rule (SMBC) and the position of the coastline in 2055 using WRL (white circles).