ISSN 1476-1580

North West Geography

Volume 15, Number 1, 2015

Sefton Coast's vulnerability to coastal flooding using DEM data

Irene Delgado-Fernandez, Matthew McBride, Rachel Platt, Mark Cameron
Geography Department, Edge Hill University

delgadoi@edgehill.ac.uk

Abstract

A preliminary analysis of the vulnerability of the Sefton coast to coastal flooding was carried out using a high-resolution DEM and census data from 2011. Results indicate that up to 12,500 people live within areas below the significant dune erosion level. Low-lying areas are clustered in two main locations, the South Formby / Hightown and Southport. High dunes from 15 to 35 m high are common in the central part of the Sefton Coast, including Formby Point and Ainsdale. This highlights the significance of the Sefton dune field system as a potential defence mechanism against coastal erosion and flooding, and the need to consider management schemes that would allow the dunes to adapt to sea level rise and climate change.

Keywords

Dunes, sea-level rise, sustainable management, coastal resilience, low-lying areas, Sefton coast

Introduction

Coastal erosion poses significant threats to coastal populations, particularly those living within a few kilometres of the coast. As much as 70% of the world's sandy coastlines were affected by erosion problems in the second half of the 20th century (Bird, 1985), with recent findings suggesting accelerating erosion rates towards the beginning of the 21st century in many coastal locations (Mars and Houseknecht, 2007; Feagin *et al*, 2005). Despite the negative impacts of coastal erosion to human activities and infrastructure, the number of people choosing to settle at the coast is increasing at rates faster than average national populations (Small and Nicholls, 2003).

The vulnerability of coastal populations has been assessed from a variety of perspectives (McGranagan *et al*, 2007), with particular attention to their ability to adapt to sea-level rise (SLR) and climate change (Klein and Nichols, 1999; McCarthy, 2001; McGranahan *et al*, 2007; Nichols *et al*, 2008) and to the social-environmental factors involved in effective coastal sustainability (Eakin and Luers, 2006; Glavovic, 2006). The protective role of coastal dunes is increasingly being recognized in this context. Coastal dunes are depositional sediment stores that act as protective buffers against coastal flooding (Benavente *et al*, 2006). They have the ability of migrating landward during periods of SLR while 'holding back the sea' (Davidson-Arnott, 2005) hence providing a low cost, natural mechanism to defend the shoreline against inundation and saltwater intrusion. Recent research including field measurements and modelling demonstrates that under most circumstances sand moves landward with SLR (Aagaard and Sorensen, 2012; Aagaard, 2014) which maintains the overall coastal profile and may even result in shoreline accretion (Houston and Dean, 2014). It is imperative to conduct a detailed assessment of the geomorphic factors that control shoreline evolution along different coastlines and to determine management strategies that would permit adaptation to a slow migration of the dune field inland to accommodate the effects of SLR.

There is no single, universally accepted model to predict shoreline evolution during SLR. Two-dimensional simple methods ignoring onshore sediment movement such as the Bruun Rule (Bruun, 1962) are not adequate and need to be abandoned (Cooper and Pilkey, 2004) in favour of more comprehensive, conceptually valid approaches including complex linkages between sediment transport exchange units in morphodynamic systems (Davidson-Arnott, 2005; Aagaard and Sorensen, 2012; Ranasinghe *et al*, 2012). The acquisition of airborne scanning laser altimetry (LiDAR) data that can be used to generate digital elevation models (DEM) is used extensively to provide simple flood scenarios under rising sea levels (Brown, 2006; Wang *et al*, 2002; Webster et al, 2004; Demirkesen *et al*, 2007; Murdukhayeva *et al*, 2013). In the absence of well-accepted alternatives to the Bruun Rule there is still a trend towards employing overly-simplified flood models (Cooper and Pilkey, 2004). Despite their significant limitations for appropriate mapping of coastal response GIS and DEMs allow high-quality visualization and handling of three-dimensional terrains hence overcoming many of the difficulties associated to two-dimensional analysis.

This article provides a preliminary examination of a large LiDAR data set acquired along the Sefton Coast, Merseyside, UK. The coast is relatively well populated and subject to a variety of human uses. Several population centres are fronted by the Sefton dune field, the largest dune field in England, which acts as a protective buffer during severe storms. The first part of the article introduces the generation of a high-quality DEM covering up to 65 km^2, and uses this to identify near-coast low-lying areas. The second part of the article uses simple census data to provide an indication of how many people live within low-lying sectors. In agreement with previous authors urging to abandon the Bruun Rule and other simplistic approaches to coastal evolution (Cooper and Pilkey, 2004; Davidson-Arnott, 2005), this article does not use low-lying areas to map the spatial extent of potential flood scenarios (i.e., we cannot predict which areas will be inundated based on a DEM). The article does suggest, however, that low-lying areas are likely to be more vulnerable, and that there is a potential risk to the people living in them. The aim is to present a relatively quick, preliminary spatial analysis of potentially vulnerable hot-spots in Sefton and hence to demonstrate the increasing significance of adequate coastal dune management along this section of the coast.

Figure 1. Location of study site. Aerial mosaic 2010, courtesy of Sefton Council.

Study Site

The Sefton coast extends for 36 km and is influenced by processes in the Irish Sea, the Ribble and Mersey estuaries to north and the south respectively, and the West Lancashire coastal plain (Figure 1).

The coast is macro-tidal with a mean spring tidal range of 8 m. It includes a diversity of coastal environments including salt marshes, beaches, tidal flats, and coastal dunes. Coastal dunes, in particular, extend 16 km alongshore and 4 km inland, covering a total area of 2100 ha and constituting the largest coastal dune field in England, and one of the largest in the UK (Esteves *et al*, 2012). The Sefton Coast has been internationally designated as EU SAC (Special Area of Conservation), RAMSAR, SSSI, and has received multiple national and local recognitions (Worsley *et al*, 2012). The dunes have large conservational and economic value and they are subject of multiple activities and intense human pressure (Pye and Blott, 2010). These include agricultural land, important recreational sites for tourists and local residents, and relatively large conservation areas managed by a number of institutions such as Natural England and the National Trust. Beach and dune sediments consist of uniform, well-sorted, fine to medium quartz sands and predominant winds are from the SW (Plater and Grenville, 2010; Esteves *et al*, 2012).

Methods

DEM

The use of Digital Elevation Models (DEMs) in Geographic Information Systems (GIS) is widely used. Applications include hydrologic modelling (Vieux, 2001), analysis of erosion-deposition processes (Mitasova *et al*, 1996), habitat mapping (Aspinall and Veitch, 1993) and landslide hazards (Olmacher and Davis, 2003) among others. DEMs have also been used to map coastal lowlands (Gambolati *et al*, 2002; Brown, 2006; Wang *et al*, 2002). The procedure often involves in using supervised classifications to identify elevations below a given threshold and the digitalization of low-lying areas into vectors depicting the limits of potential flood-plains (Webster *et al*, 2004).

A total of 79 1x1m spot resolution LiDAR raster files were included in the analysis presented here. The data were collected in 2013. Each raster covered an area of approximately 1.26 km^2 and was referenced into British National Grid. A new raster mosaic was created from the individual raster files. Focal statistics using rectangle as the neighbourhood and mean as the statistic were employed to correct for NoData values in the original LiDAR files. The UK National Oceanography Centre (NERC) works with tidal levels relative to chart datum (CD). The Sefton DEM was corrected from D_OSGB_1936/ODN datum to CD using the values suggested by the National Tidal and Sea Level Facility (NTSLF) at Formby point. (http://www.ntslf.org/tides/datum). This allows comparison of DEM elevation data with tidal ranges at the site. The resulting DEM was extruded in ArcScene (Figure 2) and basic statistics were calculated (see insert in Figure 2).

The average elevation of the dune toe was calculated by analysing the beach-dune boundary (BDB) from Ainsdale to Hightown. Appropriate spatial identification of the dune toe is extremely difficult as this area is characterized by high temporal/spatial variability and the sporadic presence of embryo dunes. As a proxy, the seaward extent of vegetation was used to digitize the beach-dune boundary using common editing procedures. The 3D Analyst toolbox was used to locate outliers and remove them from the beach-dune boundary shapefile prior to calculating statistics. The average elevation of the beach-dune boundary along the Sefton coast was 10.32 ± 0.4 m CD. This is approximately 0.30 m above the average dune toe height reported by Esteves *et al* (2012), who observed a high degree of seasonal variability associated with it.

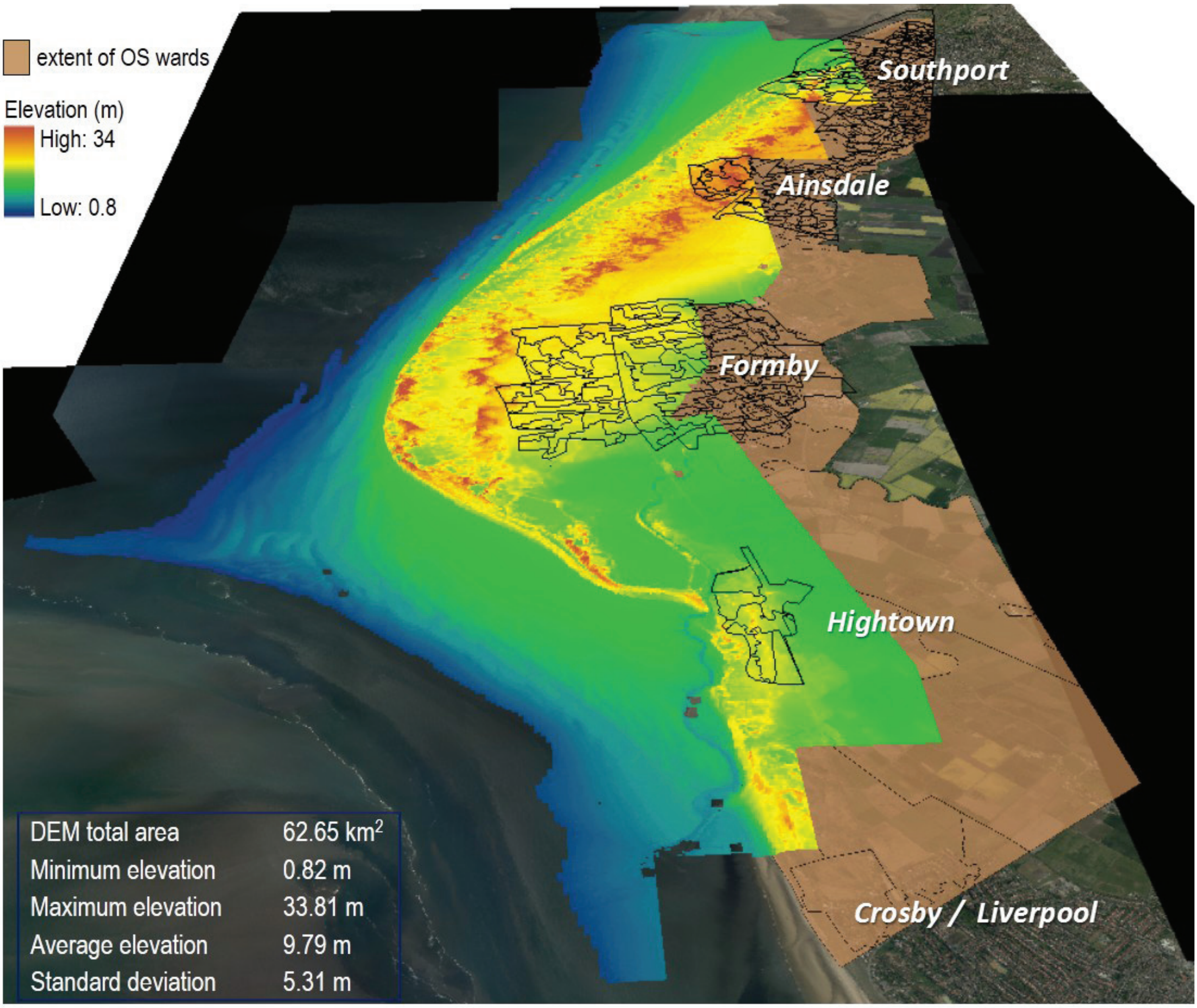

Figure 2. Extent of Sefton DEM and the OS selected wards. Only the seaward sections of Southport, Ainsdale, and Formby fell within the area covered by the LiDAR flight. Hightown was completely within the DEM but none of Crosby's wards could be analysed. Vertical exaggeration x5. Inset includes basic descriptive statistics for the DEM.

Esteves *et al* (2012) classified the type of wave events that result in significant dune erosion (SDE) along the Sefton Coast. Erosion was mainly experienced during periods of peak water levels of 10.2 m (CD) and 2.6 m waves (combined elevation = 12.8 m), rather than during extreme surges and wave heights. The SDE and BDB elevations, alongside tidal elevations provided by the NTSLF for Formby (Table 1), were used to generate binary maps showing the location of low-lying areas in the Sefton DEM.

Table 1. Elevations used to identify low-lying areas in the Sefton coast (based on CD). The significant dune erosion (SDE) value has been adopted from Esteves et al (2012). The beach-dune boundary (BDB) value was estimated in this study. The HAT, MHWS, and MHW values were obtained from the NTSLF at Formby. Water heights are in m.

Elevation	Definition	Height (m)
SDE	Combined effect of 10.2 (water level) + 2.6 wave heights	12.80
BDB	Average height of the Beach-Dune Boundary	10.32
HAT	Highest Astronomical Tide	10.13
MHWS	Mean High Water Spring	9.00
MHW	Mean High Water	8.15

Vulnerability Assessment

Wards boundary data were downloaded from the Office for National Statistics website (http://www.ons.gov.uk/) for 2011. This contains Ordnance Survey boundary line data updated annually for each ward in the UK. Cesus data for the selected wards were downloaded from InFuse 2011, the UK Data Service Census Support (http://infuse2011.mimas.ac.uk/). Analyses were conducted at the Output Areas and Small Areas Local Authorities level, the lowest geographical level at which census estimates are provided. Both files were joined and clipped in ArcMap to get a subset of the study area, with particular interest in the main population centres (Southport, Formby, and Hightown). Additionally, the census shapefile was clipped to match the spatial extent of the LiDAR data. This allowed using intersecting tools to provide an estimate of the number of people and urban zones within low-lying areas identified in the DEM.

Results

Figure 3 includes binary maps showing the location of low-lying areas based on elevations in Table 1.

The binary maps show that there are certain areas to the south of Formby and around Hightown where the terrain is below the mean high water (MHW; 8.15 m CD). Most of the beach to the north and south of Formby is above this level but below the mean high water during spring tides (MHWS; 9 m CD). Large areas around Hightown and along the south coast of Southport are at an elevation lower than the highest astronomical tide (HAT; 10.13 m CD) or the beach-dune boundary (BDB; 10.32 m CD). There are multiple sections of the coast below the significant dune erosion level (SDE; 12.8 m CD) including most of the areas south of Formby, a significant amount of frontal dunes in Ainsdale, and the seaward side of Southport. Table 2 includes

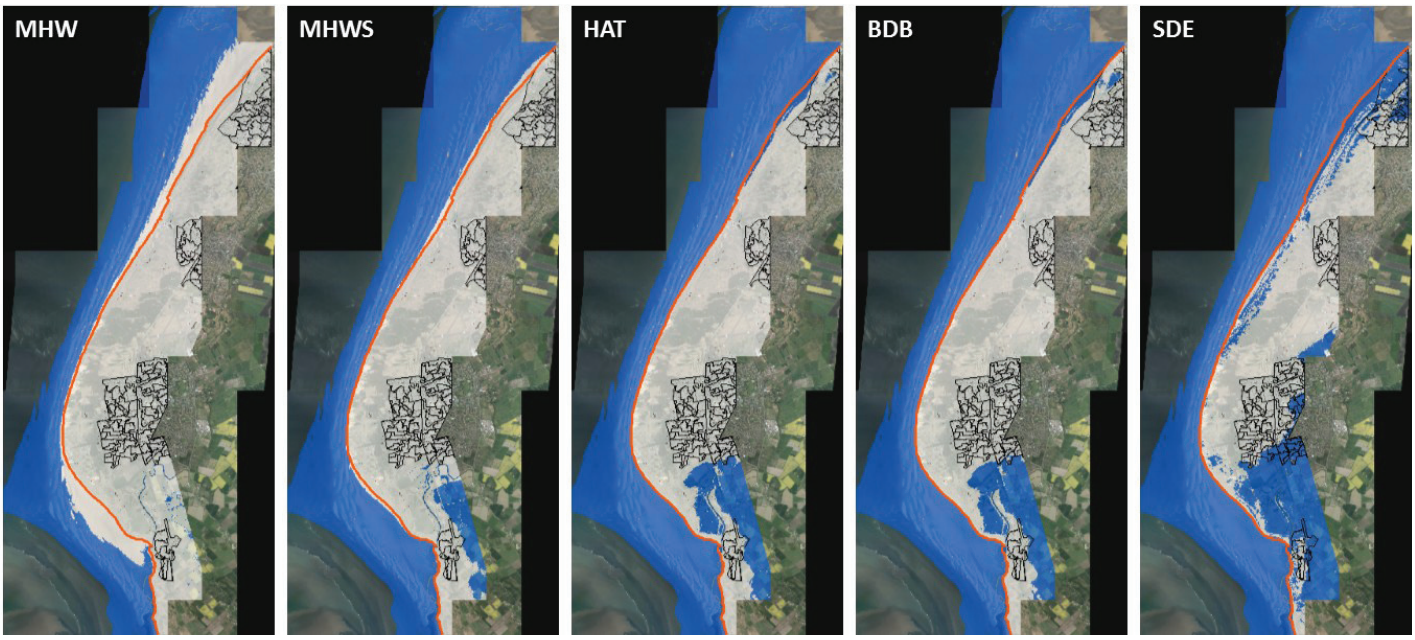

Figure 3. Raster grids showing the location of low-lying areas in Sefton (in blue), defined as areas below the mean high water (MHW), mean high water spring (MHWS), highest astronomical tide (HAT), beach-dune boundary (BDB) and the significant dune erosion (SDE) level identified by Esteves et al. (2011). The spatial location of the BDB used in this study is shown in red.

the areas below and above each elevation and the percent of decrease relative to the MHW map.

Table 2. Areas (km^2) below and above elevations shown in Figure 3. Total area covered by DEM = 62.65 km^2.

Elevation	Area below	Area above	Decrease (%) of land over particular elevations (relative to MHW)
MHW	24.94	37.70	–
MHWS	31.07	31.57	9.78
HAT	34.73	27.92	15.62
BDB	35.12	27.53	16.24
SDE	41.15	21.50	25.87

Results from overlaying topography and census data indicate that a relatively large number of people live within the low-lying areas (Table 3). The total amount of urban area below the MHW is only 0.65 x 10^{-3} km^2 including approximately 929 people (2.87% of the total population analysed in this study) in 2011. The total urban area and number of residents within low-lying areas based on MHWS, HAT, and BDB levels gradually increase up to 0.19 km^2 and 2679 people (8.27% of residents) for the latter case. There is a dramatic increase in the area and amount of people living below SDE elevations, with almost 2.20 km^2 of urban zones and 12,500 people (38.56% of the population).

Table 3. Urban areas classified as low-lying areas and number of people living within them. Percentages have been calculated with respect to the total amount of population considered in this study (32,393 residents) as given by the OS census data clipped to the spatial extent of the Sefton DEM (see Figure 2).

Elevation	Urban area (km^2)	Number of people	% population below particular elevations
MHW	0.65 x 10^{-3}	929	2.87
MHWS	7.72 x 10^{-3}	1,248	3.85
HAT	95.31 x 10^{-3}	1,923	5.94
BDB	0.19	2,679	8.27
SDE	2.20	12,492	38.56

Discussion

Potential risks coastal populations and sea level rise

It is worth stressing that maps shown in Figure 3 do not depict modelled flood scenarios. Water levels have been used here to identify relative low-lying areas, not necessarily areas that will be flooded during high water periods. Flooding and coastal morphological changes resulting from increases in sea level strongly depend on time and location, and are regulated by complex mechanisms and non-linear relations between many factors not considered here (e.g., presence of vegetation, sediment transport paths, wave and wind action, duration and timing of storm events, etc.) (Esteves *et al*, 2012). The existence of low-lying areas is a strong indication, however, of the potential vulnerability of sections of the Sefton Coast to future SLR and climate change. The latest 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) suggests a number of sea level rise projections depending on different gas emissions scenarios. Predictions include increases in average sea level of approximately 0.2 m (best case scenario) and 0.25 m (worst case scenario) by 2050, and 0.44 m (best case scenario) or 0.73 m (worst case scenario) by 2100. Because of the levels of uncertainty considered by the IPCC sea level could in fact rise even more by up to 1m towards 2100, posing real challenges for the Sefton Coast.

The importance of dune mobility and implications for management

Figure 4 shows the location of large dune areas along the Sefton Coast. While Ainsdale village partially sits over one of the areas including some of the highest dunes in the system, Formby town is almost entirely fronted by very large dunes seaward. This provides in principle a very significant buffer against coastal erosion and flooding. However, the effectiveness of coastal dunes as a defence mechanism strongly depends on a number of variables, including their ability to move and respond to environmental changes (Pye *et al*, 2014).

As in many other locations worldwide (Jackson and Cooper, 2011; Miot da Silva, 2013; Provoost *et al*, 2009) the Sefton dunes have undergone progressive over-growth of vegetation and re-sealing (Smith, 2012). The loss of bare sand has significant consequences for associated habitats and ecosystems diversity (Smith, 2012). Hence dune regeneration programs are now seeing vegetation stripping and dune remobilization as necessary elements for sustainable dune management (Terlouw and Slings, 2005; Walker *et al*, 2013; Houston and Dargie, 2010; Pye *et al*, 2014). The reduction of dune mobility as a result of the over-growth of vegetation also has consequences for dune morphodynamics (Saye and Pye, 2007). However, the potential effects of sea level rise at Sefton should be assessed in the context of the littoral sediment budgets and coastal evolution, particularly in the extent and location of sediment sinks.

Dune erosion may be accentuated in sections of the Sefton dunes prone to wave undercutting during high water levels (Pye and Blott, 2008; Halcrow, 2009; Brown *et al*, 2010; Esteves *et al*, 2012). Complications may arise in areas that were subject to sand mining before and after the Second

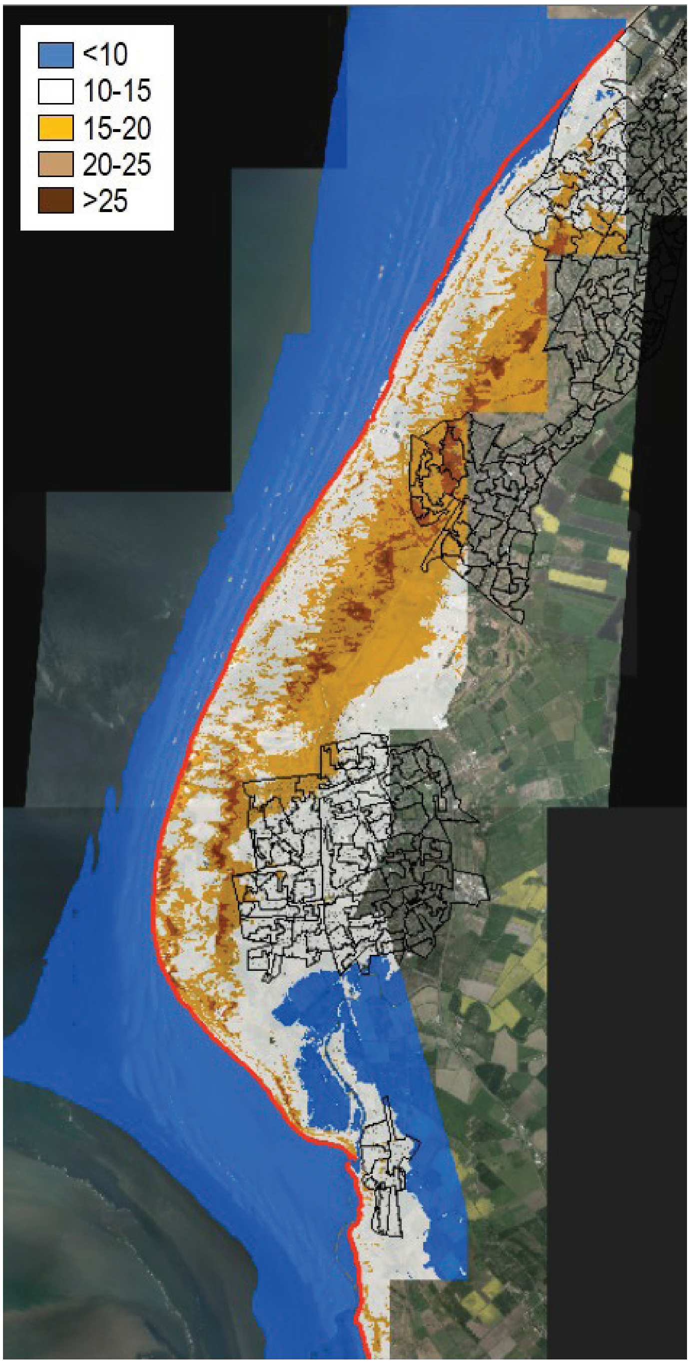

Figure 4. Location of Sefton highest dunes. Elevation is in metres.

War World and/or where sea defenses exist (Smith, 2012). Dune erosion during a storm may not be a problem if there is no dune breaching. In fact, cliffing of the foredune may increase the opportunity for landward transfer of eroded material over the dune crest and hence inland migration of the dune to keep pace with rising sea level (Davidson-Arnott, 2005). Recent studies suggest that under most conditions coastal profiles migrate landward with increasing sea-level (Aagaard and Sorensen, 2012; Aagaard, 2014; Houston and Dean, 2014). Higher water levels at Sefton will likely lead to dune erosion but this may facilitate sand transport inland and thus landward migration of the protective dune system. Appropriate analysis of the Sefton coast dynamics at a variety of scales is necessary to investigate sustainable long-term management including strategies that call for managed retreat with preservation of dunes as a response to sea level rise and climate change.

Conclusions

This study presents a DEM that permits some preliminary assessment of the problem of coastal vulnerability at the Sefton Coast. Further studies are required to assess in detail the geomorphic factors that control shoreline evolution and determination of a management strategy that would permit adaptation to a slow migration of the dune field inland to accommodate the effects of the geomorphic evolution and SLR, except in those areas where the littoral budget is sufficiently positive to allow stability of the shoreline or even progradation despite higher water levels. Current understanding of shoreline evolution suggests that there is no need for sand from the dunes to be used to build up the nearshore under rising sea levels (as the Bruun model calls for) (Aagaard and Sorensen, 2012; Houston and Dean, 2014). Contrary to this the volume of dunes can be maintained as they move inland and may be even increased through the addition of some eroded material (Davidson-Arnott, 2005). Hence both dune mobility and space for the coastal dune field to adjust to new conditions are key aspects contributing to the resilience of the coastal dune field, and its ability to act as a sustainable coastal defence.

The Sefton DEM shows that while some of the largest dunes are now completely stabilized below urban centres (e.g., Ainsdale) with sections of the coast prone to coastal squeeze, considerable areas of the dune field have the potential to act as significant buffers against coastal flooding (e.g., Formby point). The existence of low-lying areas clustered around Hightown/South Formby and Southport needs to be further investigated. In particular there is a need to understand what geomorphic factors control the actual vulnerability of these areas in relation to the dune field. Analysis should be conducted to distinguish between areas that are vulnerable to flooding under existing conditions from those that are potentially vulnerable in the absence of high dunes. This could provide the rational to guide dune management and long-term actions designed to enhance dune growth and long-term sustainability of the Sefton dune field.

Acknowledgements

Funding for this research was generously provided by the Manchester Geographical Society. The LiDAR data used in this study was collected by Sefton Council and kindly provided Paul Wisse. The data was distributed under the Open Government Licence for Public Information copyright. Robin Davidson-Arnott is thanked for his review and contributions to earlier drafts. We also thank Phil Smith for valuable comments on the final version.

References

Aagaard, T., 2014. Sediment supply to beaches: cross-shore sand transport on the lower shoreface. *Journal of Geophysical Research: Earth Surface* 119, doi:10.1002/2013JF003041.

Aagaard, T. and Sørensen, P., 2012. Coastal profile response to sea level rise: a process-based approach. *Earth Surface Processes and Landforms* 37: 354–362.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Aldre, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Scholmer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.). Cambridge University Press, Cambridge, UK and New York, USA.

Aspinall, R. and Veitch, N., 1993, Habitat mapping from satellite imagery and wildlife survey data using a Bayesian modeling procedure in a GIS. *Photogrammetric Engineering and Remote Sensing* 59, 537-543.

Benavente, J., del Río, L., Gracia, F.J., Martínez-del-Pozo, J.A., 2006. Coastal flooding hazard related to storms and coastal evolution in Valdelagrana spit (Cadiz Bay Natural Park, SW Spain). *Continental Shelf Research* 26, 1061-1076.

Bird, E.C.F., 1985. *Coastline Changes: a global review*. Chichester: Wiley.

Brown, I., 2006. Modelling future landscape change on coastal floodplains using a rule-based GIS. *Environmental Modelling & Software* 21, 1479-1490.

Brown, J.M., Souza, A.J., Wolf, J., 2010. An 11-year validation of wave-surge modelling in the Irish Sea, using a nested POLCOMS-WAM modelling system. *Ocean Modelling* 33, 118–128.

Bruun P., 1962. Sea-level rise as a cause of shore erosion. *Journal Waterways Harbors Division, ASCE*88, 117–130.

Cooper, J. A. G., and Pilkey, O. H. (2004). Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change* 43, 157-171.

Davidson-Arnott, R.G.D., 2005. Conceptual model of the effects of sea level rise on sandy coasts. *Journal of Coastal Research* 21, 1166-1172.

Demirkesen, A.C., Evrendilek, F., Berberoglu, S., and Kilic, S., 2007. Coastal flood risk analysis using Landsat-7 ETM+ imagery and SRTM DEM: A case study of Izmir, Turkey. *Environmental Monitoring and Assessment* 131, 293-300.

Eakin, H. and Luers, A.L., 2006. Assessing the vulnerability of social-environmental systems. *Annual Review of Environment and Resources* 31, 365.

Esteves, L.S., Brown, J.M., Williams, J.J., and Lymbery, G., 2012. Quantifying thresholds for signicant dune erosion along the Sefton Coast, Northwest England. *Geomorphology* 43, 52-61.

Feagin, R.A., Sherman, D.J., and Grant, W.E., 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Frontiers in Ecology and the Environment* 3, 359–364.

Gambolati, G., Teatini, P., & Gonella, M., 2002. GIS simulations of the inundation risk in the coastal lowlands of the Northern Adriatic Sea. *Mathematical and Computer Modelling* 35, 963-972.

Glavovic, B., 2006. Coastal Sustainability–An Elusive Pursuit?: Reflections on South Africa's Coastal Policy Experience. *Coastal Management* 34, 111-132.

Halcrow, 2009. *North West England and North Wales Shoreline Management Plan 2* (Consultation Draft, Revision 1 Oct. 2009), Appendix C: Baseline Processes, 40 pp. Available online from http://mycoastline.org/documents/AppendixC-C.4F_Seftoncoast.pdf (accessed on 5 Jan 2015).

Houston, J. A. and Dargie, T.C.D., 2010. *A study to assess stakeholder support for implementing a programme of dune re-mobilization on selected dune systems in Wales*. CCW Contract Science Report No: 936, 124pp, Liverpool Hope University Press, Liverpool.

Houston, J.R., and Dean, R.G., 2014. Shoreline change on the East Coast of Florida. *Journal of Coastal Research* 30, 647-660.

Jackson, D.W.T, and Cooper, J.A.G., 2011. Coastal dune fields in Ireland: rapid regional response to climatic Change. *Journal of Coastal Research* SI 64, 293-297.

Klein, R.J.T. and Nicholls, R.J., 1999. Assessment of coastal vulnerability to climate change. *Ambio*, 182-187.

Mars, J. C. and Houseknecht, D. W., 2007. Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska. *Geology* 35, 583-586.

McCarthy, J.J. (Ed), 2001. *Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization* 19, 17-37.

Miot da Silva, G., Hesp, P., Keim, B., Martinho, C.T. and Ferligoj, Y., 2013. Changes in dunefield geomorphology and vegetation cover as a response to local and regional climate variations. *Journal of Coastal Research*, Special Issue 65, 1307-1312.

Mitasova, H., Hofierka, J., Zlocha, M., and Iverson, L.R., 1996. Modelling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Systems* 10, 629-641.

Murdukhayeva, A., August, P., Bradley, M., LaBash, C., and Shaw, N., 2013. Assessment of Inundation Risk from Sea Level Rise and Storm Surge in Northeastern Coastal National Parks. *Journal of Coastal Research* 29, 1 – 16.

Nicholls, R.J., Wong, P.P., Burkett, V., Woodroffe, C.D., and Hay, J., 2008. Climate change and coastal vulnerability assessment: scenarios for integrated assessment. *Sustainability Science* 3, 89-102.

Ohlmacher, G.C., and Davis, J.C., 2003. Using multiple logistic regression and GIS technology to predict landslide hazard in northeast Kansas, USA. *Engineering Geology* 69, 331-343.

Plater, A.J. and Grenville, J., 2010. Liverpool Bay: Linking the eastern Irish Sea to the Sefton Coast. In: A.T. Worsley, G. Lymbery, V.J.C. Holden and M. Newton (Eds). *Sefton's Dynamic Coast*. Proceedings of the Conference on Coastal Geomorphology, Biogeography and Management, 28-54.

Provoost, S., Jones, M.L.M. and Edmondson, S.E., 2009. Changes in landscape and vegetation of coastal dunes in northwest Europe: a review. *Journal of Coastal Conservation*. doi: 10.1007/s11852-009-0068-5.

Pye, K., Blott, S.J., 2008. Decadal-scale variation in dune erosion and accretion rates: an investigation of the significance of changing storm tide frequency and magnitude on the Sefton Coast, UK. *Geomorphology* 102, 652–666.

Pye, K. and Blott, S.J., 2010. Geomorphology of the Sefton Coast sand dunes. In: A.T. Worsley, G. Lymbery, V.J.C. Holden and M. Newton (Eds). *Sefton's Dynamic Coast*. Proceedings of the Conference on Coastal Geomorphology, Biogeography and Management. 131-160.

Pye, K, Blott, S.J., Howe, M.A., 2014. Coastal dune stabilization in Wales and requirements for rejuvenation. *Journal of Coastal Conservation* 18, 27-54.

Ranasinghe, R., Duong, T.M., Uhlenbrook, S., Roelvink, D., Stive, M., 2012. Climate-change impact assessment for inlet-interrupted coastlines. *Nature Climate Change*, DOI: 10.1038/nclimate1664.

Saye, S.E. and Pye, K., 2007. Implications of sea level rise for coastal dune habitat conservation in Wales. *Journal of Coastal Conservation* 11, 31-52.

Small, C., and Nicholls, R., 2003. A global analysis of human settlement in coastal zones. *Journal of Coastal Research* 19, 584-599.

Smith, P.H., 2012. Reserve focus: Cabin Hill NNR, Merseyside. *British Wildlife* 23, 343-347.

Terlouw, L., and Slings, R., 2005. Dynamic dune management in practice–remobilization of coastal dunes in the National Park Zuid-Kennemerland in the Netherlands. *Proceedings: Dunes and Estuaries* 19, 211-217.

Vieux, B.E., 2001. *Distributed hydrologic modeling using GIS*. Springer Netherlands.

Walker, I.J., Eamer, J.B.R., Darke, I.B., 2013. Assessing significant geomorphic changes and effectiveness of dynamic restoration in a coastal dune ecosystem. *Geomorphology* 199, 192-204.

Wang, Y., Colby, J.D., Mulcahy, K.A., 2002. An efficient method for mapping flood extent in a coastal floodplain using Landsat TM and DEM data. *International Journal of Remote Sensing* 23, 3681-3696.

Webster, T.L., Forbes, D.L., Dickie, S., Shreenan,R., 2004. Using topographic lidar to map flood risk from storm-surge events for Charlottetown, Prince Edward Island, Canada. *Canadian Journal of Remote Sensing* 30, 64-76.

Worsley, A.T., Lymbery, G., Holden, V.J.C., Newton, M., 2012. *Sefton's Dynamic Coast*. Proceedings of the Conference on Coastal Geomorphology, Biogeography and Management, 2008.