



Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

The effectiveness of beach mega-nourishment, assessed over three management epochs

Jennifer M. Brown^{a,*}, Jack J.C. Phelps^{a,b}, Andrew Barkwith^c, Martin D. Hurst^{c,d}, Michael A. Ellis^c, Andrew J. Plater^b^a National Oceanography Centre, Liverpool, L3 5DA, UK^b Department of Geography and Planning, University of Liverpool, Liverpool, L69 7ZT, UK^c British Geological Survey, Nottingham, NG12 5GG, UK^d School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK

ARTICLE INFO

Article history:

Received 18 July 2016

Received in revised form

9 September 2016

Accepted 30 September 2016

Available online 11 October 2016

Keywords:

Beach mega-nourishment

Coastal resilience

Shoreline evolution

Shoreline management planning

Coastal evolution model

Dungeness

ABSTRACT

Resilient coastal protection requires adaptive management strategies that build with nature to maintain long-term sustainability. With increasing pressures on shorelines from urbanisation, industrial growth, sea-level rise and changing storm climates soft approaches to coastal management are implemented to support natural habitats and maintain healthy coastal ecosystems. The impact of a beach mega-nourishment along a frontage of interactive natural and engineered systems that incorporate soft and hard defences is explored. A coastal evolution model is applied to simulate the impact of different hypothetical mega-nourishment interventions to assess their impacts over 3 shoreline management planning epochs: present-day (0–20 years), medium-term (20–50 years) and long-term (50–100 years). The impacts of the smaller interventions when appropriately positioned are found to be as effective as larger schemes, thus making them more cost-effective for present-day management. Over time the benefit from larger interventions becomes more noticeable, with multi-location schemes requiring a smaller initial nourishment to achieve at least the same benefit as that of a single-location scheme. While the longer-term impact of larger schemes reduces erosion across a frontage the short-term impact down drift of the scheme can lead to an increase in erosion as the natural sediment drift becomes interrupted. This research presents a transferable modelling tool to assess the impact of nourishment schemes for a variety of sedimentary shorelines and highlights both the positive and negative impact of beach mega-nourishment.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Climate change and the associated rise in sea level are increasing the vulnerability of coastal communities and industries to flood and erosion risk globally (Nicholls et al., 2007). Small scale frequent beach nourishment is a common practise in locations where beach loss is having a negative impact (Cooke et al., 2012). However, management options that adapt with the natural environment are now used to build long-term resilience into new coastal schemes (Kuklicke and Demeritt, 2016). An innovative approach that uses natural processes to redistribute sediment from a mega-nourishment to adjacent beaches is currently being trialled along

the Dutch coastline (de Schipper et al., 2016). The approach is intended to create a resilient beach that evolves with changing coastal conditions over a 20-year period. To inform decision makers on the possible consequences of such an intervention in other locations, this research aims to assess the potential benefits and adverse impacts of different approaches to beach mega-nourishment. Management frameworks consider impacts on both the ecology of an environmental system and the socio-economic benefits (Schlacher et al., 2014). This research considers the impacts in terms of erosion reduction and creation of beach width and sheltered water, thus informing management needs in relation to flood and erosion risk in addition to the creation of habitat and recreational space.

The dense population of coastlines worldwide puts people and infrastructure at risk of flooding and erosion over varied time and spatial scales. Population and industrial growth combined with the

* Corresponding author.

E-mail address: jebro@noc.ac.uk (J.M. Brown).

consequence of coastal climate change are increasing pressures on coastal habitats and ecosystems (Villatoro et al., 2014). The use of dredged material is thus used where appropriate within harbours for habitat creation, e.g., within New Jersey Harbor, New York (Yozzo et al., 2004). Such practise has been extended to the open coast, where coastal management strategies now consider new and ambitious ‘advance the line’ approaches that use marine aggregate to provide softer interventions that work with the natural environment to increase coastal resilience. Such approaches are intended to supplement existing management schemes to prolong their effective life span in addition to increasing protection in their immediate vicinity, providing economic and/or ecosystem benefits. However, their impact can be both positive (beach widening) and negative (inhibited sediment drift), thus modelling and monitoring studies are important to inform decisions associated with intervention design (Capobianco et al., 2002).

Shoreline management strategies often assess three time periods for the purposes of planning and resource allocation: present-day (Epoch 1, 0–20 years), medium-term (Epoch 2, 20–50 years) and long-term (Epoch 3, 50–100 years). Model simulations are used to explore how the size and position of a single- or multi-location mega-nourishment could evolve to support a coastal system comprising natural barriers and embankments, with seawalls in areas of critical infrastructure, over these epochs. The insight gained from this study site will have wider global impact as hard and soft engineered solutions are used in conjunction at many other locations to mitigate coastal erosion and promote healthy coastal environments (Perkins et al., 2015). The varied impact of different mega-nourishment schemes is illustrated in the context of existing management strategies that vary along the frontage, defending to maintaining the shoreline position, as well as allowing for natural retreat.

The ‘advance the line’ management strategy termed ‘mega-nourishment’ or ‘sandscaping’, largely stems from the Dutch initiative ‘De Zandmotor’; a 21.5 M m³ sand mega-nourishment implemented so that natural wave energy and circulation will redistribute the sand, widening beaches over a 10–20 km stretch over a 20-year period (Stive et al., 2013). The concomitant reduction in the frequency of beach nourishment from typical 3- to 5-year cycles, and the limitation of human intervention to a 128 ha (~1 km²) area of shoreline, reduces the disturbance to the local ecosystem while providing benefits in addition to reduced flood and erosion risk, such as habitat creation and increased amenity for shoreline recreation. This approach has been successful along part of the southern Dutch coast, where a uniform sandy shoreline exists. Implementing a similar strategy for coastlines where the intrinsic dynamics and geomorphology are more complex (e.g., interacting systems of rock coastline, estuaries, sand dune systems, etc.) will require different designs and aggregate sizes (or combinations of aggregates) according to the environmental challenge being addressed (Bishop et al., 2006). To explore the feasibility of mega-nourishment for a complex coast, such as in the UK (French et al., 2016), the Coastal Evolution Model (CEM, Ashton and Murray, 2006a,b) is used calibrated to historic recession rates. The CEM is an exploratory model simulating alongshore sediment transport that can include engineered structures, allowing the exploration of shoreline change in response to alternative management strategies (Barkwith et al., 2014b).

Numerical models can be used as tools to provide scientific evidence in support of coastal flood and erosion risk management (Brown et al., 2016). Ensembles of simulations provide a data base of potential impacts capturing the uncertainties of softer management approaches to inform the decisions associated with the design of new coastal schemes. Examples include simulating the influence of vegetated foreshores on the wave loading of defences

(Vuik et al., 2016) and of wetlands on reducing storm tide elevations (Smolders et al., 2015). Here, exploratory modelling of a case study situated in the English Channel (Fig. 1) is used to identify the generic down-drift impact of ‘mega-nourishment’ due to wave driven gravel transport. The site is designated a Site of Scientific Special Interest (SSSI) for international geological and ecological interests, and also supports valuable infrastructure and assets (Maddrell, 1996). This macrotidal location, with an approximately 6.7 m semidiurnal tidal range (Stupples, 2002), experiences large storm surge conditions (Wadey et al., 2015) and a bimodal, bidirectional wave climate (Mason et al., 2009) (Fig. 1). The largest waves exceed 5 m significant wave height with approximately 18 s peak period and come from the southwest (Figs. 1 and 2). Coastal defences comprise a natural gravel barrier and earthen embankments (Prime et al., 2016), supplemented with a seawall in areas of urban infrastructure (Fig. 1). Despite the coastal protection, there is continuous threat of coastal flooding by extreme events (Long et al., 2006). Since the 1960s periodic shingle recycling has been carried out to retain shingle along the frontage. However, the current policy option is ‘no active intervention’ where the natural barrier has formed. The potential erosion reduction offered by a range of hypothetical ‘Gravel Engines’ (Table 1) is explored and the increased coastal protection provided by these mega-nourishments across this frontage over the three shoreline management planning epochs evaluated.

The effectiveness of beach mega-nourishment options ranging in size, number and location (Table 1) are modelled over a 100-year period. The schemes represent novel management approaches to soft intervention that will have time-varying impact over the long-term. By using a simple coastline with multiple management strategies, which interact, this model application aims to identify the possible consequences (both positive and negative) of such an approach to coastal management to inform management decisions. The simulations suggest that a multi-location nourishment scheme provides greater reduction in erosion than a single mega-nourishment of larger size, although the combined impact is less than the sum of the impacts from each component when modelled in isolation. Over 20 years, consistent with the design life of De Zandmotor, smaller scale interventions are as efficient at reducing erosion as a mega-nourishment scheme, making them more cost-effective over shorter management timeframes due to the lower implementation costs. Designing a nourishment scheme such that it works with the natural environment to maintain a high level of resilience ensures long-term costs associated with the intervention are minimised (Stive et al., 2002). The value of larger mega-nourishments is thus more likely to be appreciated beyond a 20-year timeframe.

In Section 2 details of the behavioural modelling approach are provided. The results are described in Section 3 and discussed in Section 4. The concluding remarks stating the benefits of varied approaches to beach mega-nourishment are given in Section 5.

2. Methods

A one-line coastal evolution model (CEM, Ashton and Murray, 2006a,b) has been adapted to investigate the potential evolution of a hypothetical gravel intervention along the Dungeness headland (Fig. 1). The land-sea mask used to represent the headland was obtained from Lidar data collected in August 2014. The model, applied at a 100 m horizontal resolution, can be driven by the observed offshore wave climate (Ashton and Murray, 2006a,b) or a long-term offshore wave climatology to evolve the coastline. In Rye Bay (the southern shore of Dungeness, Fig. 1) a 1.8 km wave model of the English Channel and Southern North Sea was used to provide the local wave climate. The model applied was the 3rd generation

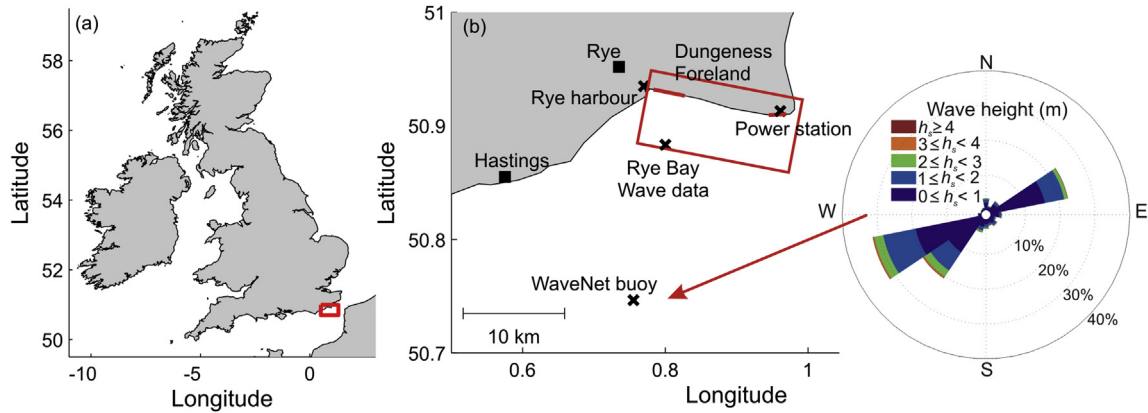


Fig. 1. a) Dungeness headland, southeast UK. b) Modelled shoreline outlined by the box and maintained defence positions indicated by the shoreline sections identified by a thickened coastline, alongside the observed wave climate data (26 November 2002 to 28 July 2014) at the Hastings wave rider buoy (50°44'.79N, 000°45'.30E).

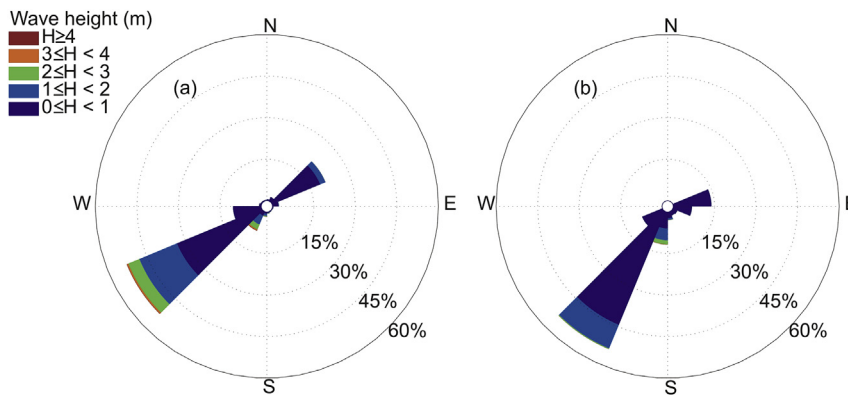


Fig. 2. Modelled wave climate at a) the nearest grid point to the Hastings wave buoy (50.75°N, 0.75°E) and b) centrally in Rye Bay (50.88°N, 0.8°E).

Table 1

Description of the hypothetical nourishment schemes considered within the modelling study.

Scenario	Description	Size of intervention (ha)
B	No additional intervention	0
S1	Recurved spit positioned to the west	55
S2	Recurved spit positioned off centre towards the east	55
S3	Recurved spit positioned to the east	55
M	Multi-location recurved spits located as in S1-S3	165
L	Large recurved spit positioned off centre towards the east	270

spectral WAve Model (WAM, Komen et al., 1994) adapted for shallow water (Monbaliu et al., 2000). The decadal model output (Fig. 2) suggests that the wave climate within Rye Bay (highness = 0.19, asymmetry = 0.15) is noticeably different to the wave climate at the Hastings Wavenet buoy site (highness = 0.86, asymmetry = 0.02). Available observations (from 26 November 2002) at Hastings to the southwest of Dungeness (Fig. 1, highness = 0.89, asymmetry = 0.06) suggest there is underestimation of waves from the northeast. For application within the CEM, waves with an onshore (southerly) component only are used as the offshore boundary conditions, thus the model derived wave climate at Rye Bay is considered to be acceptable. Both datasets confirm the local wave climate is almost entirely asymmetrical and dominated by high angle waves (>45°) relative to the shore. Subsequent wave transformation to breaking conditions follows linear wave theory (Hurst et al., 2015).

Volumetric alongshore sediment transport Q_s (m^3s^{-1}) driven by

wave energy is calculated as a function of significant wave height H_s (m) at the break line position (b) and the angle φ (radians) between the breaking wave crest and the shoreline using the CERC equation (Ashton and Murray, 2006a; USACE, 1984):

$$Q_s = K \left(\frac{\rho H_{s,b}^{2.5} \sin(2\varphi)}{2^{3.5} g^{1/2} (\rho_s - \rho)(1-p)} \right)$$

where ρ and ρ_s represent the density of seawater and the sediment grains respectively (kg m^{-3}), $g = 9.81 \text{ ms}^{-2}$ is gravitational acceleration, $p = 0.45$ is the porosity factor for gravel (van Rijn, 2014) and K is a dimensionless empirical constant. A value of $K = 0.054$ is applied, appropriate for gravel transport (van Wellen et al., 2000; Chadwick et al., 2005).

The CEM incorporates “wave shadowing”, whereby sediment transport is neglected in a given grid cell if a shoreline protuberance directly prevents an incoming wave from reaching that grid cell

(Ashton et al., 2001). For the current study this aspect of wave shadowing was extended to prevent land erosion within any shadowed region, allowing the recurved gravel spits to completely eliminate coastal erosion in the affected area. Although not required in this application the model can also account for the sediment supply and localised reduction in erosion rates by cliffs (Barkwith et al., 2014a,b).

It is emphasized that CEM is an exploratory, behavioural model derived from a complexity approach to the modelling of natural environments (Murray, 2007). The model has an excellent track record of generating and explaining the variable morphologies of sandy coastlines in many parts of the world (e.g., Carolina (Ashton et al., 2001), the UK (Barkwith et al., 2014a,b), the Netherlands (Ashton et al., 2003), Massachusetts, New Jersey, Ukraine, Alaska, Russia and Spain (Ashton et al., 2016)). It draws its power from the ability to rapidly explore alternative scenarios that would otherwise be prohibitively computationally too expensive. In particular, the CEM does not consider elevation, tides or tidal currents. The model operates at coarse timescales, integrating sediment transport across the short-term timescales such as tidal cycles. By using nearshore wave observations or in this case a coupled wave-circulation model, the influence of the tides (and other short-term processes) on the wave field is implicitly accounted for. In Rye Bay waves are considered the main driver for sediment transport as bedload due to the coarse grain sizes. At present the model does not permit spatially variable grain sizes such as those found in Dungeness, and all sediments are assumed to be transported using the CERC equation with an identical K value. Although this value has been chosen to be representative of Rye Bay, different sediment compositions could lead to faster or slower evolution rates than projected here. It is advised that a sensitivity analysis of the K value should be performed when assessing potential mega-nourishment schemes to determine the uncertainty in long-term evolution.

Six different scenarios are simulated with the CEM (Table 1). A baseline scenario was simulated with only the current management policy being applied along the frontage between Rye Harbour

and the power station site. Two stretches of the coastline, where there is critical infrastructure, are protected by reinforced (maintained) coastal defences (Fig. 1), collectively covering approximately 5 km of the coastline, erosion is negated within these regions. Using this simulation the model was calibrated to the historic coastal erosion rate along the natural coastline of 1 m per year, approximated from Google Earth historic images. This approach is becoming more commonly used where there is a lack of spatial recession data as it provides a growing data set of annual shoreline photography (Boardman, 2016). In all subsequent simulations additional gravel was introduced within the model grid cells to extend the beach in a similar manner to the Sand Engine in the Netherlands. Each simulation was run for 100 years.

3. Results

The hypothetical interventions (Table 1) are situated immediately down-drift of the western seawall and up-drift of the eastern maintained gravel and earthen barriers (Figs. 3–7). The aim of these nourishments is to focus beach widening in front of the maintained defences, to reduce abrasive wave impact and scour risk, while also providing support to the adjacent naturally evolving barrier coastline, prolonging the defence effectiveness along the full frontage with minimal intervention. Scenarios S1, S2 and S3 are just less than half the area of the Dutch Zandmotor. After 5–10 years (Figs. 3–5) they evolve to form a sheltered intertidal lagoon and by 25 years the initial feature collapses and only a widened beach frontage remains. S1 (Fig. 3) is positioned close to the western seawall. Beach widening over the 100-year period is limited to in front of the seawall and the western edge of the natural barrier. S2 (Fig. 4) and S3 (Fig. 5) are positioned up-drift of the eastern maintained defences. S2 widens the beach along the natural frontage, but has limited impact in front of the maintained defences. S3 increases beach volume in the east, with reducing width increase towards the west across the natural frontage, but also supports the full length of the eastern maintained defences and the beach just beyond. When the interventions (S1, S2 and S3)

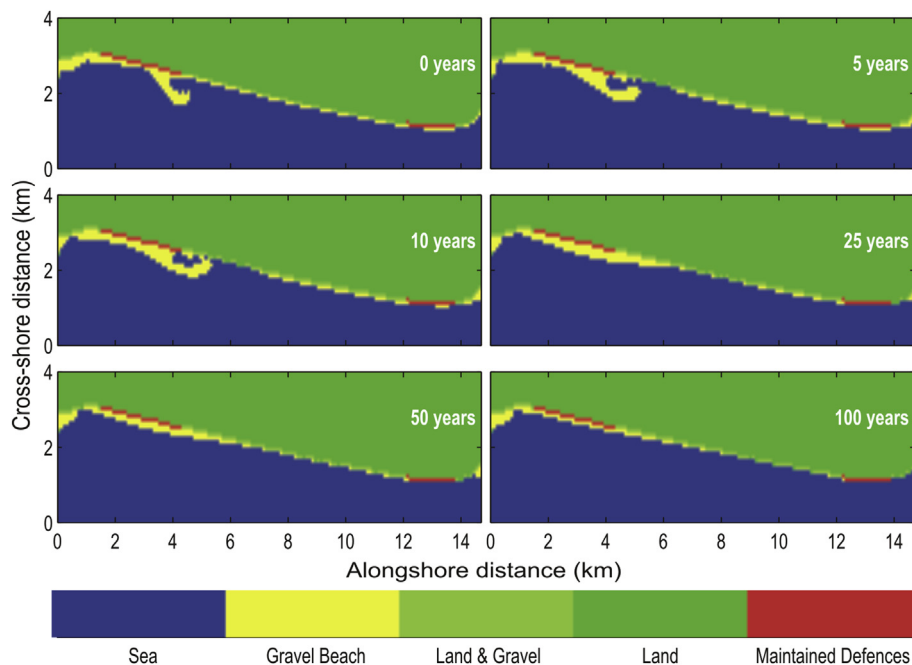


Fig. 3. Projected evolution of the Rye Bay shoreline for the region highlighted in Fig. 1 for the hypothetical intervention scenario S1, as described in Table 1.

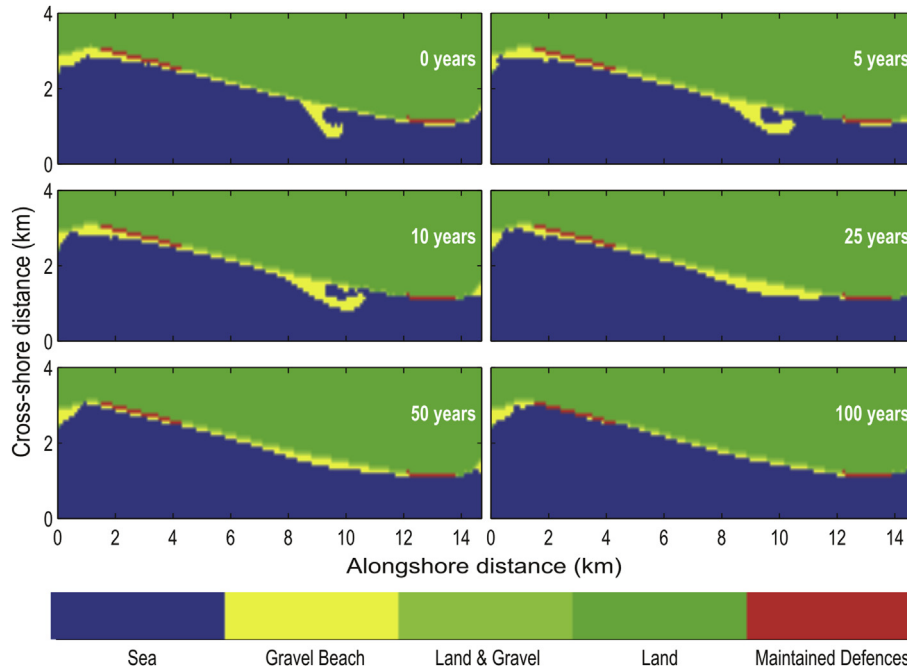


Fig. 4. Projected evolution of the Rye Bay shoreline for the region highlighted in Fig. 1 for the hypothetical intervention scenario S2, as described in Table 1.

are combined to form a multi-location mega-nourishment, M, the three smaller features still disperse after c.25 years (Fig. 6), but the intertidal lagoons generated by the two recurved spits in the east persist, albeit they are relatively small. After approximately 5 years the eastern spits within this multi-location approach (Fig. 6) act to support each other, increasing the local reduction in erosion compared with their isolated impact (S2 and S3, Figs. 4 and 5, respectively). The single mega-nourishment, L, is positioned

similarly to S2 to maximise the length of impacted shoreline (Fig. 7). The recurved spit grows in the down-drift direction, forming a region of sheltered water, reconnecting with the coast after ~50 years. The feature starts to dissipate after 100 years.

The impact of the hypothetical interventions is compared with the baseline scenario a combination of ‘hold the line’, maintaining the existing sections of maintained defences, and ‘do nothing’ in between the maintained defences along the evolving barrier and

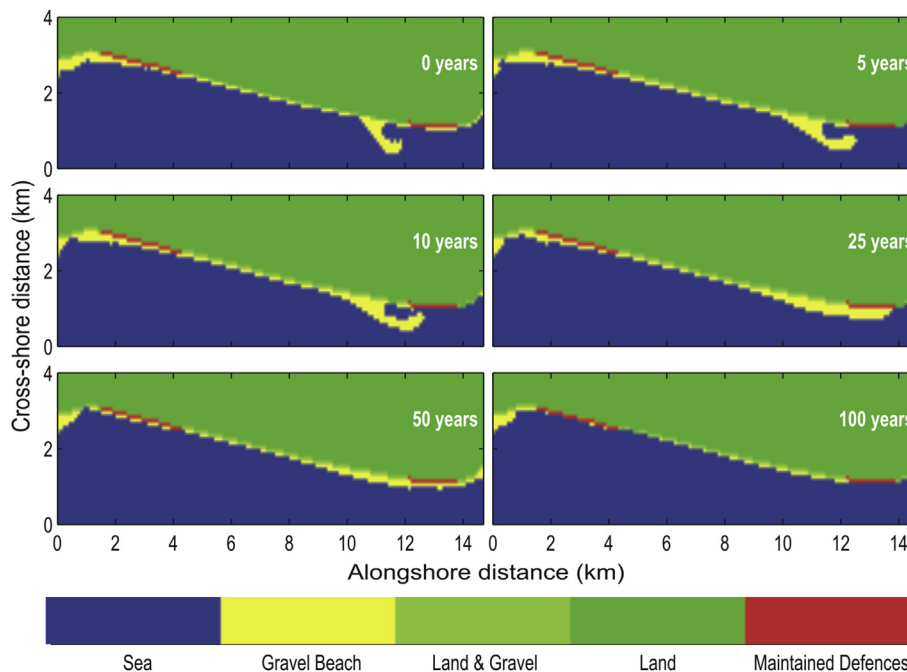


Fig. 5. Projected evolution of the Rye Bay shoreline for the region highlighted in Fig. 1 for the hypothetical intervention scenario S3, as described in Table 1.

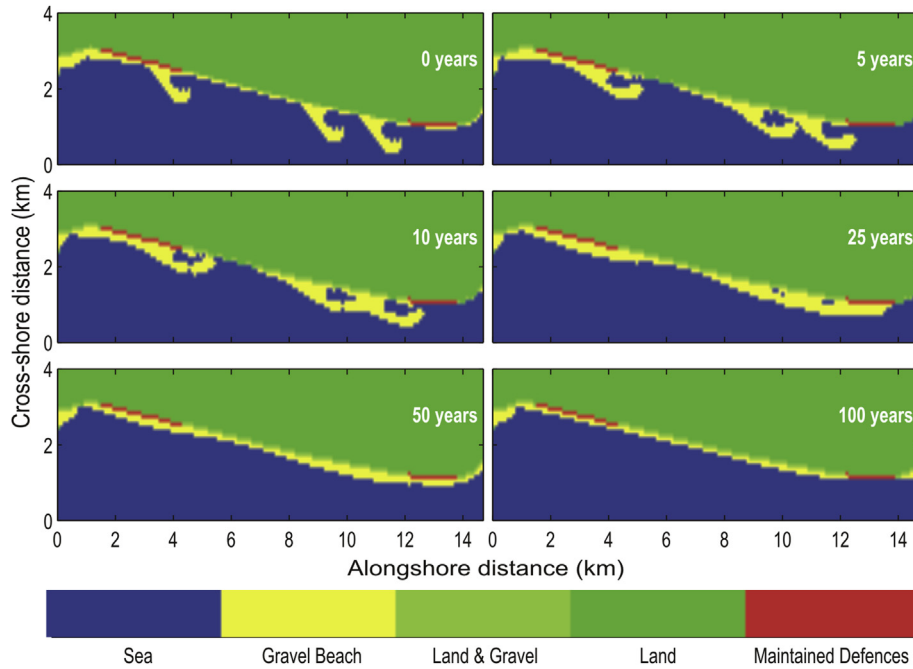


Fig. 6. Projected evolution of the Rye Bay shoreline for the region highlighted in Fig. 1 for the hypothetical intervention scenario M, as described in Table 1.

immediately to either side of the maintained defences (Fig. 8). During the first 25 years (Fig. 8a) due to the size of the interventions the natural alongshore sediment drift is inhibited. Although a large reduction in erosion (and in some cases prevention, e.g., L) occurs locally around the intervention, erosion is increased farther down-drift due to reduced sediment supply. Over a 25-year period (Fig. 8a) the erosion of the central frontage in scenario M is less than in S1 due to the sediment supply from the eastern interventions.

However, the increased erosion to the east of the eastern maintained defence section remains the same as in S3. Although beach widening occurs along the majority of the frontage under scenario L, the natural sediment drift to the east is inhibited, enhancing erosion either side of the eastern defence over both the 25-year and 100-year timeframes. Over the longer 100-year timeframe (Fig. 8b) the extent of erosion reduction spreads eastward along the frontage, counteracting the initial acceleration in erosion as the features

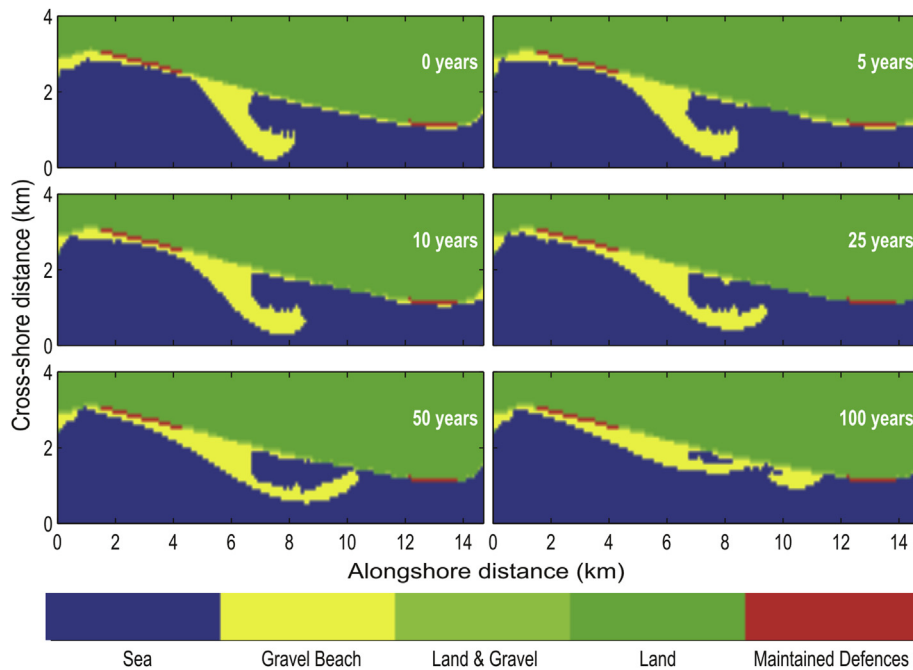


Fig. 7. Projected evolution of the Rye Bay shoreline for the region highlighted in Fig. 1 for the hypothetical intervention scenario L, as described in Table 1.

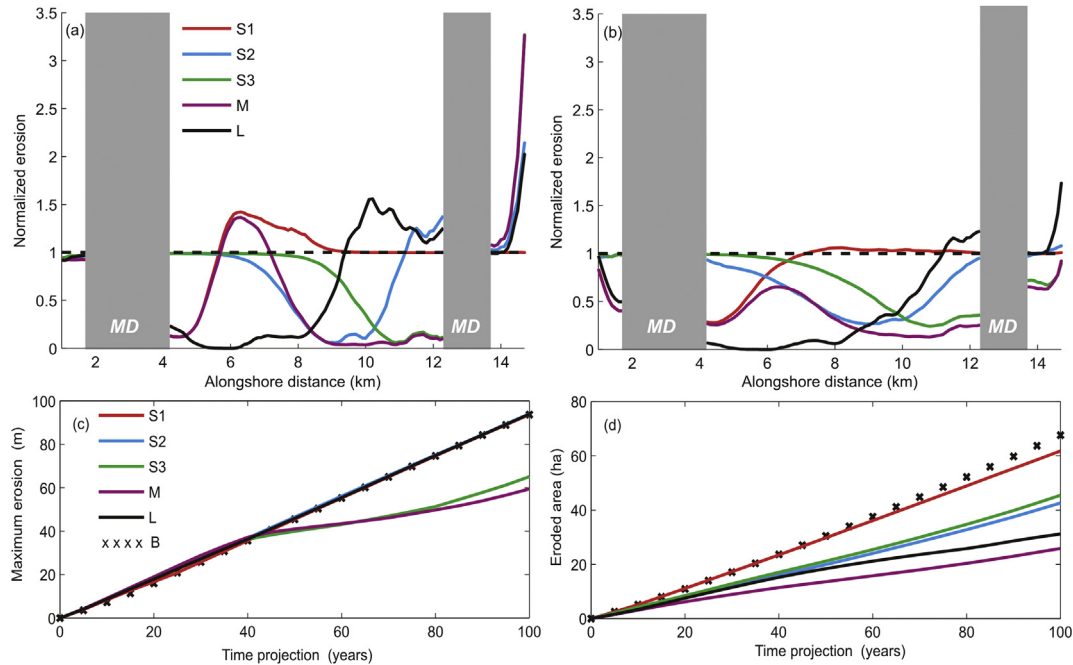


Fig. 8. The projected erosion of Rye Bay frontage normalised by the 'no additional intervention' scenario (B) after a) 25 year and b) 100 years for each management option. The shaded areas represent the position of the maintained defences (MD). The c) maximum erosion along the frontage, and d) the area eroded over a 100 year period. The projected simulations represent scenarios with no additional intervention (B) and each hypothetical intervention (S1, S2, S3, M & L) considered in Table 1.

dissipate. The position of S2 reduces erosion along the majority of the frontage, while S1 has minimal reduction compared with 'no additional intervention' (Fig. 8b). The reduction in frontage erosion by M (~1/3 greater than the area of the Zandmotor) is greater than that generated by L (~twice the area of the Zandmotor), which is positioned in the most beneficial location of S2 (Fig. 8b). The combined impact of all three spits in M reduces erosion across the full frontage over a 100-year period (Fig. 8b). Although the large recurved spit (L) has a long-term impact reducing the area eroded, the maximum erosion rate towards the east is greater than that of the other interventions. With time the extent of accelerated erosion is reduced for the larger interventions, suggesting the greatest benefit from L is likely to occur beyond 100 years.

Over time (Fig. 8 c–d) the impact of the interventions across the frontage is variable. Over present-day timescales (<20 years), equivalent to the design life of De Zandmotor, all of the interventions cause increased maximum erosion rates compared with the baseline (B) of 'no additional intervention'. However, all but the single recurved spit, positioned to the west (S1) reduce the area eroded. In the first 20 years there is little variability in the erosion reduction between all hypothetical interventions (S1, S2, S3, M and L) and the baseline simulation with 'no additional intervention' (B). The smaller interventions can achieve a similar benefit to that gained from the larger interventions if positioned appropriately, thus creating more cost-effective solutions over management epoch 1. A clear step change in maximum erosion rates occurs at ~40 years for S3 and M (Fig. 8c). This is attributed to the change in erosion down-drift of the eastern maintained defence. S3, alone and as a component of M, inhibits natural sediment drift initially, causing rapid erosion rates at the tip of the foreland (Fig. 8a). Following the dispersion of the intervention (at ~20 years) the local sediment supply slowly restores and after 40 years the thinning beach starts to diffuse beyond the maintained defences limiting erosion (Fig. 8b). Over 100 years the multi-location intervention (M) generates greatest reduction in

maximum erosion rates and area lost to erosion (Fig. 8 c–d).

4. Discussion

Coastal evolution varies over a range of spatial and temporal scales (Cowell and Thom, 1994; Stive et al., 2002). The need for coastal models to inform decisions surrounding the design of nourishment schemes and assess their potential impacts has been identified as essential (Hamm et al., 2002). Here, the time-varying impact of different approaches to beach mega-nourishment on a shoreline frontage for 3 management epochs is assessed. The modelling approach chosen is capable of simulating a range of coastal environments and clearly demonstrates both positive and negative impacts of beach mega-nourishment. From the results presented it is clear that in the short-term there is immediate benefit locally, while down drift of the intervention the coast can become sediment starved as the natural alongshore drift is inhibited. Over longer periods (>40 years) any increase in erosion rate down-drift starts to become mitigated as the alongshore drift is restored and enhanced with the redistribution of sediment from the nourishment.

These results have been analysed to show the change in maximum erosion rate and area eroded. The area of erosion enables analysis of the spatial impact of an intervention, whereas the maximum erosion rates are important to identify future areas of higher risk from erosion. The results presented show how the different hypothetical designs considered have variable influence on the area eroded, while the maximum rates only differ noticeably from the Baseline scenario (B) after the collapse of a nourishment feature when it is positioned close to the location of maximum erosion (e.g., S3 in this case positioned close to the eastern tip of the Dungeness foreland). For local management needs this model allows the (time-varying) alongshore extent of the impact, the position at which the maximum erosion rates occur and locations where erosion rates become accelerated, due to inhibited

alongshore sediment transport, to be identified. To gain confidence in these future projections it is, of course, necessary to assess the model capability against historic observations and current understanding of the local sediment movement.

For this case study the erosion rates in the baseline simulation increase towards the east. The closer a small intervention is to the location of maximum erosion the greater the impact on maximum shoreline retreat, but this does not necessarily relate to a reduced loss in coastal area. It is suggested that having minimal overlap with areas of maintained defence, which hold the line, enables greater reduction in the area of coast lost. For example, S2 (positioned between the maintained defences but towards the east where erosion rates are higher) has greatest impact reducing the loss of area, while S3 (in the most easterly position close to the maximum rates of erosion) has greatest impact at reducing the maximum rate of erosion. The most beneficial position will thus depend on the management need, either reducing a localised area of rapid erosion (e.g., in front of an asset) or having wide spread impact to reduce the frontage area lost (e.g., to protect habitat). The implementation of larger schemes increases the width of alongshore impact, reducing the need for such precise positioning and enabling both the maximum erosion rates and area lost to be reduced with time (within 20–50 years for M and L).

The simulations also allow projections of the life expectancy of the shallow water lagoons and barrier estuaries, as well as localised increase in beach volume, to assess the time-evolving environmental, ecological and societal benefits. This information, when combined with the costs of the initial new-build, flood and erosion event response and recovery, and defence maintenance, can then be used as the basis for cost-benefit analyses of alternative coastal planning options over different epochs. It therefore offers an important scoping tool to help managers explore the physical, ecological and socio-economic impacts when making decisions associated with new and ambitious approaches to coastal management adaptation.

Over time different costs are associated with coastal schemes (Firth et al., 2014). Initially there is the build cost, which is followed by monitoring and maintenance costs (Jones et al., 2015). The frequency of maintenance will vary over the life of a scheme due to long-term degradation and/or changing storm impact. Where beaches are nourished recharge is often on an annual or 2–3 year timescale. With a changing climate the nourishment frequency (Cooke et al., 2012) and the need for defence (Firth et al., 2014) is increasing. Hard engineered structures can be built and raised in response to changing conditions, but they are environmentally and financially unsustainable (Jones et al., 2015). Mega-nourishment has the potential to maintain resilient beach levels as it evolves over time with the natural conditions, reducing wave impact on existing or new hard structures. However, the initial build cost will depend on the availability of large volumes of appropriate material. In locations where the appropriate material can be sourced this approach has the potential to be more cost-effective than hard engineering, with minimal maintenance costs as natural energy is used to redistribute the sediments. With beaches becoming squeezed softer interventions are also valuable in terms of socio economics (Cooke et al., 2012) and ecosystem services (Cooper, In Press). With a low public 'willingness to pay' cost-effective solutions are required by local authorities, as found in the study area (Jones et al., 2015). Thus there is a need to explore new alternative approaches to flood and erosion risk management that build with nature.

5. Conclusion

This study exemplifies the importance of exploratory modelling

to understand the potential impact of human intervention on shoreline evolution and the consequences for down-drift ecosystems, habitats and infrastructure. Beach mega-nourishment is shown to limit alongshore sediment drift causing increased down-drift erosion over the short-term (<25 years), with the longer-term (>25 years) impact being mostly beneficial across the frontage or at least negligible. The effectiveness of the smaller schemes depends strongly on their positioning. The more extensive schemes, M and L, have more noticeable impact beyond 50 years and require a smaller initial nourishment if implemented at multiple locations, e.g., M. For present-day considerations (<20 years) there is little difference in the impact of the interventions, however, beyond 50 years there is clearer variability in impact. A smaller scheme is thus considered to be more cost-effective for management epoch 1 (<20 years), while larger schemes are considered more cost-effective for management epoch 3.

Acknowledgements

This research was funded through the NERC Environmental Risks to Infrastructure Innovation, Research Grant: "Sandscaping for Mitigating Coastal Flood and Erosion Risk to Energy Infrastructure on Gravel Shorelines: a case study approach" (grant no. NE/M008061/1) and the NERC highlight topic "Physical and biological dynamic coastal processes and their role in coastal recovery" (BLUE-coast, grant no. NE/N015614/1). The authors would also like to acknowledge that this interdisciplinary collaboration emerged from the EPSRC-funded C project: Adaptation and Resilience of Coastal Energy Supply (ARCoES) (EP/I035390/1). The Aggregate Levy Sustainability Fund (ALSF), contract MEPP 09-P114, is thanked for the provision of the decadal wave hindcast. Model calibration and scenario design was achieved through communications with Tom Dauben (Environment Agency). The model set up required the provision of LiDAR data from the Environment Agency (<https://data.gov.uk/publisher/environment-agency>), the British Geological Survey digital geological map of Great Britain from Edina digimap (<http://digimap.edina.ac.uk/geology>) and wave data from the offshore wave rider at Hastings, which is part of the UK wave buoy network (WaveNet) delivered by the Centre for Environment Fisheries and Aquaculture Science (<https://www.cefas.co.uk/cefas-data-hub/wavenet/>). M.H., A.B. and M.E. publish with the permission of the Director of the British Geological Survey.

References

- Ashton, A.D., Murray, A.B., 2006a. High-age wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. *J. Geophys. Res. Earth Surf.* 111 (F04011), 19pp.
- Ashton, A.D., Murray, A.B., 2006b. High-age wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature. *J. Geophys. Res. Earth Surf.* 111 (F04012), 17pp.
- Ashton, A., Murray, A.B., Arnould, O., 2001. Formation of coastline features by large-scale instabilities induced by high-angle waves. *Nature* 414, 296–300.
- Ashton, A., Murray, A.B., Ruessink, G.B., 2003. Initial tests of a possible explanation for alongshore sandwaves on the Dutch coast. In: Sánchez-Arcilla, A., Bateman, A. (Eds.), *Proc. 3rd IAHR Symposium on River, Coastal and Estuarine Morphodynamics*, vol. 1, pp. 320–330.
- Ashton, A.D., Nienhuis, J., Ellis, K., 2016. On a neck, on a spit: controls on the shape of free spits. *Earth Surf. Dyn.* 4, 193–210.
- Barkwith, A., Thomas, C.W., Limber, P.W., Ellis, M.A., Murray, A.B., 2014a. Coastal vulnerability of a pinned, soft-cliff coastline, I: assessing the natural sensitivity to wave climate. *Earth Surf. Dyn.* 2, 295–308.
- Barkwith, A., Hurst, M.D., Thomas, C.W., Ellis, M.A., Limber, P.L., Murray, A.B., 2014b. Coastal vulnerability of a pinned, soft-cliff coastline, II: assessing the influence of sea walls on future morphology. *Earth Surf. Dyn.* 2, 233–242.
- Bishop, M.J., Peterson, C.H., Summerson, H.C., Lenihan, H.S., Grabowski, J.H., 2006. Deposition and long-shore transport of dredge spoils to nourish beaches: impacts on benthic infauna of an Ebb-tidal delta. *J. Coast. Res.* 22, 530–546.
- Boardman, J., 2016. The value of Google Earth™ for erosion mapping. *Catena* 143, 123–127.
- Brown, J.M., Ciavola, P., Masselink, G., McCall, R., Plater, A.J., 2016. Preface:

- monitoring and modelling to guide coastal adaptation to extreme storm events in a changing climate. *Nat. Hazards Earth Syst. Sci.* 16, 463–467.
- Capobianco, M., Hanson, H., Larson, M., Steetzel, H., Stive, M.J.F., Chatelus, Y., Aarninkhof, S., Karambas, T., 2002. Nourishment design and evaluation: applicability of model concepts. *Coast. Eng.* 47, 113–135.
- Chadwick, A.J., Karunaratna, H., Gehrels, W.R., O'Brien, D., Dales, D., 2005. A new analysis of the Slapton barrier beach system, UK. *Proc. ICE Marit. Eng.* 158, 147–161.
- Cooke, B.C., Jones, A.R., Goodwin, I.D., Bishop, M.J., 2012. Nourishment practices on Australian sandy beaches: a review. *J. Environ. Manage* 113, 319–327.
- Cooper, J.A.G., O'Connor, M.C., McIvor, S., 2016. Coastal defences versus coastal ecosystems: a regional appraisal. *Mar. Policy*. Available online 2 March 2016 (in press).
- Cowell, P.J., Thom, B.G., 1994. Morphodynamics of Coastal Evolution. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), *Coastal Evolution: Late Quaternary Shoreline Morphodynamics*. Cambridge University Press, Cambridge, pp. 33–86.
- de Schipper, M.A., de Vries, S., Ruessink, G., de Zeeuw, R.C., Rutten, J., van Gelder-Maas, C., Stive, M.J.F., 2016. Initial spreading of a mega feeder nourishment: observations of the Sand Engine pilot project. *Coast. Eng.* 111, 23–38.
- Firth, L.B., Thompson, R.C., Bohn, K., Abbiati, M., Airoldi, L., Bouma, T.J., Bozzeda, F., Ceccherelli, V.U., Colangelo, M.A., Evans, A., Ferrario, F., Hanley, M.E., Hinz, H., Hoggart, S.P.G., Jackson, J.E., Moore, P., Morgan, E.H., Perkol-Finkel, S., Skov, M.W., Strain, E.M., van Belzen, J., Hawkins, S.J., 2014. Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. *Coast. Eng.* 87, 122–135.
- French, J., Burningham, H., Thornhill, G., Whitehouse, R., Nicholls, R.J., 2016. Conceptualising and mapping coupled estuary, coast and inner shelf sediment systems. *Geomorphology* 256, 17–35.
- Hamm, L., Capobianco, M., Dette, H.H., Lechuga, A., Spanhoff, R., Stive, M.J.F., 2002. A summary of European experience with shore nourishment. *Coast. Eng.* 47, 237–264.
- Hurst, M.D., Barkwith, A., Ellis, M.A., Thomas, C.W., Murray, B.A., 2015. Exploring the sensitivities of crenulate bay shorelines to wave climates using a new vector-based one-line model. *J. Geophys. Res. Earth Surf.* 120, 2586–2608.
- Jones, N., Clark, J.R.A., Malesios, C., 2015. Social capital and willingness-to-pay for coastal defences in south-east England. *Ecol. Econ.* 119, 74–82.
- Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M., 1994. *Dynamics and Modelling of Ocean Waves*. Cambridge Univ. Press, Cambridge, U.K., 532 pp.
- Kuklicke, C., Demeritt, D., 2016. Adaptive and risk-based approaches to climate change and the management of uncertainty and institutional risk: the case of future flooding in England. *Glob. Environ. Chang.* 37, 56–68.
- Long, A.J., Waller, M.P., Plater, A.J., 2006. Coastal resilience and late Holocene tidal inlet history: the evolution of Dungeness Foreland and the Romney Marsh depositional complex (U.K.). *Geomorphology* 82, 309–330.
- Maddrell, R.J., 1996. Managed coastal retreat, reducing flood risks and protection costs, Dungeness Nuclear Power Station, UK. *Coast. Eng.* 28, 1–15.
- Mason, T., Bradbury, A., Poate, T., Newman, R., 2009. Nearshore wave climate of the English Channel - evidence for bi-modal seas. In: *Proceedings of the 31st International Conference on Coast. Eng.*, pp. 605–616.
- Monbaliu, J., Padilla-Hernández, R., Hargreaves, J.C., Carretero-Albiach, J.C., Luo, W., Sclavo, M., Günther, H., 2000. The spectral wave model WAM adapted for applications with high spatial resolution. *Coast. Eng.* 41, 41–62.
- Murray, B., 2007. Reducing model complexity for explanation and prediction. *Geomorphology* 90, 178–191.
- Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. *Climate change 2007: impacts, adaptation and vulnerability*. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp. 315–356.
- Perkins, M.J., Ng, T.P.T., Dudgeon, D., Bonebrake, T.C., Leung, K.M.Y., 2015. Conserving intertidal habitats: what is the potential of ecological engineering to mitigate impacts of coastal structures? *Estuar. Shelf S* 167, 504–515.
- Prime, T., Brown, J.M., Plater, A.J., 2016. Flood inundation uncertainty: the case of a 0.5% annual probability flood event. *Environ. Sci. Policy* 59, 1–9.
- Schlacher, T.A., Schoeman, D.S., Jones, A.R., Dugan, J.E., Hubbard, D.M., Defeo, O., Peterson, C.H., Weston, M.A., Maslo, B., Olds, A.D., Scapini, F., Nel, R., Harris, L.R., Lucrezi, S., Lastra, M., Huijbers, C.M., Connolly, R.M., 2014. Metrics to assess ecological condition, change, and impacts in sandy beach ecosystems. *J. Environ. Manage* 144, 322–335.
- Smolders, S., Plancke, Y., Ides, S., Meire, P., Temmerman, S., 2015. Role of intertidal wetlands for tidal and storm tide attenuation along a confined estuary: a model study. *Nat. Hazards Earth Syst. Sci.* 15, 1659–1675.
- Stive, J.J.F., Aarninkhof, S.G.J., Hamm, L., Hanson, H., Larson, M., Wijnberg, K.M., Nicholls, R.J., Capobianco, M., 2002. Variability of shore and shoreline evolution. *Coast. Eng.* 47, 211–235.
- Stive, M.J.F., de Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G.J., van Gelder-Maas, C., van Thiel de Vries, J.S.M., de Vries, S., Henriquez, M., Marx, S., Ranasinghe, R., 2013. A new alternative to saving our beaches from sea-level rise: the sand engine. *J. Coast. Res.* 29, 1001–1008.
- Stupples, P., 2002. Tidal cycles preserved in late holocene tidal rhythmites, the wainway channel, Romney Marsh, southeast England. *Mar. Geol.* 182, 231–246.
- USACE (U.S. Army Corp of Engineers), 1984. *Shore Protection Manual*. Coastal Engineering Research Center.
- van Rijn, L.C., 2014. A simple general expression for longshore transport of sand, gravel and shingle. *Coast. Eng.* 90, 23–39.
- van Wellen, E., Chadwick, A.J., Mason, T., 2000. A review and assessment of long-shore sediment transport equations for coarse-grained beaches. *Coast. Eng.* 40, 243–275.
- Villatoro, M., Silva, R., Méndez, F.J., Zanuttigh, B., Pan, S., Trifonova, E., Losada, I.J., Izaguirre, C., Simmonds, D., Reeve, D.E., Mendoza, E., Martinelli, L., Formentin, S.M., Galiatsatou, P., Eftimova, P., 2014. An approach to assess flooding and erosion risk for open beaches in a changing climate. *Coast. Eng.* 87, 50–76.
- Vuik, V., Jonkman, S.N., Borsje, B.W., Suzuki, T., 2016. Nature-based flood protection: the efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coast. Eng.* 116, 42–56.
- Wadey, M.P., Haigh, I.D., Nicholls, R.J., Brown, J.M., Horsburgh, K., Carroll, B., Gallop, S.L., Mason, T., Bradshaw, E., 2015. A comparison of the 31 January–February 1953 and 5–6 December 2013 coastal flood events around the UK. *Front. Mar. Sci.* 2, 27pp.
- Yozzo, D.J., Wilber, P., Will, R.J., 2004. Beneficial use of dredged material for habitat creation, enhancement, and restoration in New York–New Jersey Harbor. *J. Environ. Manage* 73, 39–52.