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Modeling coastal erosion and sediment transport
on the Dungeness Foreland, UK

J J C Phelps[1,2], J M Brown[1], A J Plater[2]
A Barkwith[3], M D Hurst[3] & M A Ellis[3]

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[1]National Oceanography Centre, Liverpool
6 Brownlow Street
Liverpool
L3 5DA
UK

[2]Department of Geography and Planning
School of Environmental Sciences
University of Liverpool
Roxby Building, Chatham Street
Liverpool L69 7ZT
UK

[3]British Geological Survey
Environmental Science Centre
Nicker Hill
Keyworth
Nottingham NG12 5GG
UK

Author contact details:
Email: JM Brown - jebro@noc.ac.uk
         AJ Plater - gg07@Liverpool.ac.uk

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

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AUTHOR PHELPS, J J C, BROWN, J M, PLATER, A J, BARKWITH, A, HURST, M D & ELLIS, M A	*PUBLICATION DATE* 2015

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ABSTRACT

Ageing coastal defence across the UK is challenging managers to redesign schemes to be resilient, cost-effective and have minimal or beneficial environmental impact. We take Dungeness and Romney Marsh, a region of high value in terms of habitat and energy infrastructure, as a case study that could potentially be a site for a 'sandscaping' project, i.e. an innovative, large-scale beach recharge scheme. At present, this location has both modified gravel barrier defences and engineered structures. We present results for a feasibility study to improve understanding of how 'working with natural processes' to manage coastal flood and erosion risk could provide and support defences protecting this site, ensuring an energy supply that is resilient to climate change. This modelling study investigates the impact of re-engineering the coastline with a series of sandscaping options that mimic the natural shape and former evolution of the Dungeness coastline. Particle tracking is used to show the potential pathways of recharged sediment (fine and medium sand) movement along the coastline in both calm and stormy conditions. A coastal evolution model is also applied to assess the alongshore impact of different intervention designs. It is found that the main sediment drift is likely to be towards the north along the coast and that considering larger interventions could possibly provide increased protection for up to 100 years. Further, a series of three smaller sandscaping interventions offers the greatest immediate reduction in erosion rate. The natural drift within the system causes the initial peninsula-shaped intervention to form a recurve that could potentially create additional areas supporting essential natural habitat within the area.

KEYWORDS:

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   University of Southampton Waterfront Campus
   European Way
   Southampton SO14 3ZH
   UK

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1   Introduction

Dungeness is a large cuspate foreland on the south coast of Great Britain (figure 1), spanning the counties of East Sussex and Kent. The surrounding region encompassing Dungeness, Romney Marsh and Rye Bay contains a diverse range of important habitats including sand dunes, saltmarsh and vegetated shingle, and has been designated as a Site of Special Scientific Interest (Natural England SSSI Citation).

Romney Marsh previously existed as a submerged sandy bay, however alongshore drift and deposition of coarse sediments within the marsh resulted in gradual accretion until c. 2000 BC when a gravel barrier emerged (Long et al., 2006). Archaeological evidence indicates that Romney Marsh was inhabited during the Roman period, and has been inhabited permanently since the Saxon period (Reeves, 1995), however the region was apparently abandoned during the third and fourth centuries, possibly due to a rise in sea level (Cunliffe, 1988).

Despite the coastal protection offered by the gravel beach, Dungeness has been continuously threatened by coastal flooding, and the foreland has been successively inundated and reclaimed by both natural and anthropogenic processes. Early methods used to reclaim and defend the land include the Rumensea and Rhee sea walls, inlet closures and drainage networks (Allen, 1996; Long et al., 2006). More recently the Environment Agency in collaboration with other stakeholders have periodically recycled shingle since the
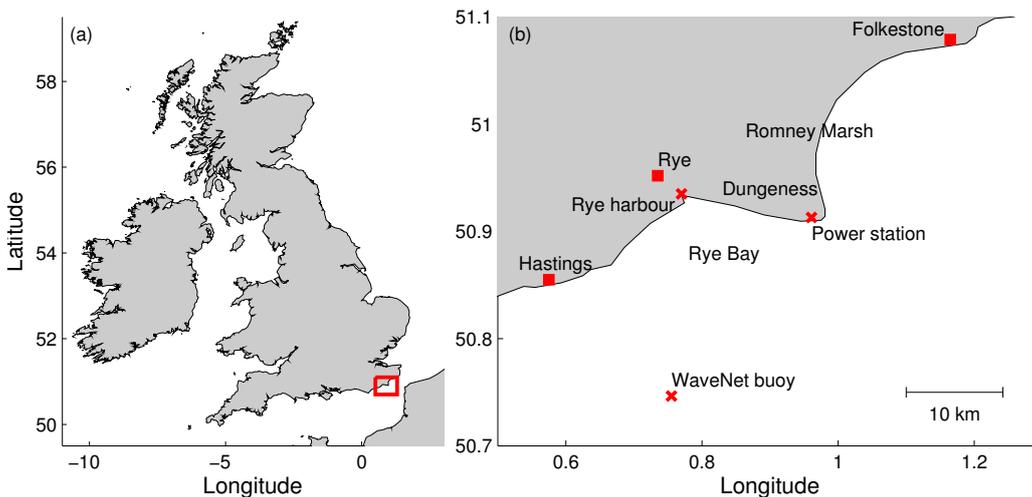
Figure 1: (a) Dungeness shown within Great Britain. (b) Annotated map of Dungeness and surrounding area.

1960s (EA, Dungeness Borrow Pit). This practice involves extracting large volumes of shingle from the eastern side of the foreland, and depositing it on the western side, in order to ensure that the shingle is retained along the Dungeness shoreline.

In this investigation we adopt numerical modelling techniques to study sediment transport in Rye Bay, and assess how this is affected by meteorological forcing and waves. Finally we conduct a preliminary study into the effect of artificially extending the shoreline in a similar manner to the Sand Engine (Zandmotor, www.zandmotor.nl).

The Sand Engine is an innovative coastal engineering intervention in the Netherlands, where 21.5 Mm^3 of sand was introduced to the South Holland coast during 2011. The additional sand formed an artificial peninsula approximately 2 km wide and extending 1 km offshore. The Sand Engine acts as a coastal defence whilst providing additional habitats and recreation areas (Stive et al., 2013). Here we consider a range of potential options, and aim to evaluate the duration of a hypothetical "gravel engine", and assess the coastal protection that it would provide.

2 Sediment Transport

2.1 Methodology

This investigation was conducted using the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) (Holt and James, 2001), a widely documented hydrodynamic model that solves the three-dimensional, hydrostatic, Boussinesq equations of motion. POLCOMS is formulated on an Arakawa B-grid and uses the piecewise parabolic method (PPM) for advection (Colella and Woodward, 1984). The High Resolution Continental Shelf (HRCS) set-up (Holt and Proctor, 2008; Phelps et al., 2015) was adopted here, providing an extensive domain (figure 2a) with approximately 1.8 km horizontal resolution and 32 terrain-following σ-coordinate vertical layers.

The model resolves tidal flow and elevation (which are forced at the open boundaries), along with meteorological and buoyancy driven flow. Meteorological forcing is calculated using atmospheric data (wind velocity, air temperature, pressure, specific heat and low cloud cover) provided by the UK Met Office operational Mesoscale model, which is extended slightly to cover the whole HRCS domain. This atmospheric data has a horizontal resolution of approximately 12 km, wind and pressure data are updated every hour, the remaining data are updated every 3 hours. As the HRCS set-up does not

currently permit wetting and drying (i.e. intertidal grid cells), a minimum 10 m depth is enforced in order to prevent negative depths during low tides. POLCOMS was coupled to the general ocean turbulence model (GOTM) (Umlauf and Burchard, 2003), and the $k - \epsilon$ turbulence closure scheme was selected for this investigation with the stability functions of (Canuto et al., 2001).

Holt and Proctor (2008) validated the HRCS set-up against satellite-tracked drifter measurements in the central North Sea and the Irish Shelf region and found that the model replicates the circulation rather well, although it does tend to underestimate the strength of the mean velocity with an RMS error of 0.08 ms^{-1}. For further technical details about POLCOMS the reader is referred to Holt and James (2001).

Suspended sediment transport was simulated using the POLCOMS online Lagrangian particle tracking model described by Lane (2005). Particles are initially located on the seabed, and particle suspension rates are determined by the erosion potential ϵ which is defined as mass of particles that are suspended over a unit area per second (kgm^{-2}s^{-1}). This erosion potential is calculated according to:

$$\epsilon = \gamma u_*{}^2 \tag{1}$$

where γ (kgsm^{-4}) is an erosion constant and u_* is the friction velocity

$$u_* = \tau/\rho \tag{2}$$

where τ represents the combined bed shear stress from currents and waves and ρ is seawater density. In the model the erosion potential is summed within each grid cell over each model time-step until it exceeds a threshold mass, then a particle is suspended into the water column. Suspended particles are advected using the forward Euler method, and are diffused vertically using a random walk model of Fischer et al. (1979).

Brown et al. (2015) adopted an erosion constant of $\gamma = 0.1$ kgm^{-4} and a threshold mass of 50 kg in the 180 m resolution Liverpool Bay POLCOMS set-up, however such values would require a computationally impractical number of particles in the HRCS set-up due to its much coarser resolution. The current study adopted $\gamma = 0.015$ kgm^{-4} and a threshold mass of 100 kg to slow the release of particles (equivalent to using $\gamma = 0.1$ kgm^{-4} as before, but with a threshold mass of 667 kg).

Suspended particles also subject to a vertical settling velocity w_s (ms^{-1}) that is dependent upon grain size, and calculated according to the following
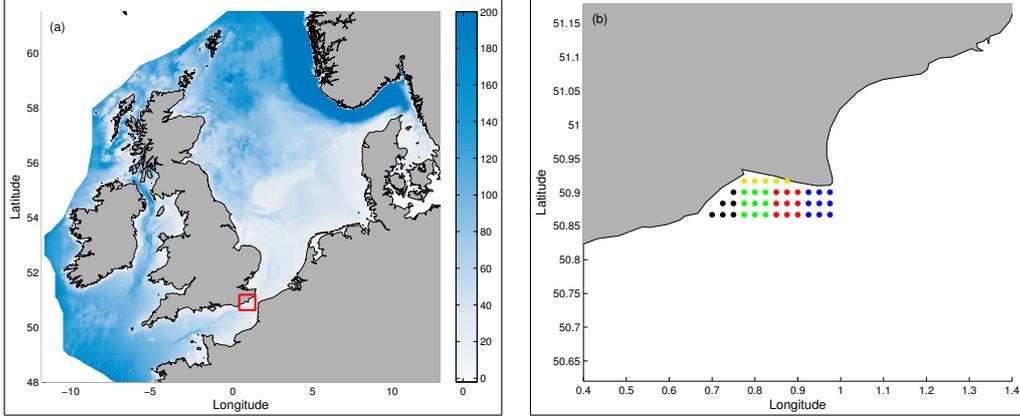
Figure 2: (a) POLCOMS HRCS model bathymetry (m) with the colour axis capped at 200 m depth to show greater detail in the region of interest. Dungeness has been highlighted. (b) Initial particle locations, particles sites are grouped into 5 distinct regions and coloured accordingly.

equation (van Rijn, 1993):

$$
w_s = \begin{cases}
(s-1)gd^2/18\nu & \text{if } d \leq 10^{-4} \text{ m} \\
10\nu(\sqrt{1 + (0.01(s-1)gd^3)/\nu^2} - 1)/d & \text{if } 10^{-4} < d \leq 10^{-3} \\
1.1\sqrt{(s-1)gd} & \text{if } d > 10^{-3}
\end{cases} \tag{3}
$$

where s (gcm^{-3}), ν (m^{2}s^{-1}) and d (m) represent relative density, kinematic viscosity and the sediment grain size respectively. Here we assume $s = 2.65$(gcm^{-3}, $\nu = 10^{-6}$ m^{2}s^{-1} and a range of values are used for d (details below). For further details about the particle tracking model the reader is referred to Lane (2005), Souza and Lane (2013) and Brown et al. (2015).

Particles were initially distributed at 38 coastal grid cells (figure 2), with $2,500$ particles per site. Although the Dungeness beach predominantly consists of gravel, preliminary model testing found that large grain sizes (> 500 μm) returned to the bottom almost immediately after suspension. This suggests that gravel in this region is transported as bed load, which is beyond the current capabilities of the model. It was therefore necessary to reduce the grain size and simulate fine sand ($d = 100$ μm, $w_s = 0.009$ ms^{-1}) and medium sand ($d = 250$ μm, $w_s = 0.035$ ms^{-1}) instead.

Three different model set-ups were used for this study, henceforth referred to as the tide-only, baroclinic and WAM set-ups. In the tide-only set-up POLCOMS is forced by tidal currents and elevations at the open boundaries, however baroclinic forcing due to horizontal density gradients is neglected. In the baroclinic set-up, horizontal density effects are also considered in the

momentum budget. Finally in the WAM set-up the baroclinic POLCOMS model is coupled to the two-dimensional wind-wave model WAM (Bolanos et al., 2014), and a JONSWAP bottom friction is applied. Each simulation was repeated for January 2008 (stormy month) and May 2008 (non-stormy month) (figure 3).

2.2   Results

In the tide-only set-up the mean velocity field at the sea bed was weak and spatially variable during both January and May (figure 4 a, b), and the particle tracking results were similar in both months (figure 5). Across both fine sand simulations ($d = 100$ μm) particles were dispersed a maximum distance of 64 km from their initial site, however 85.5 % of all particles were advected less than 10 km, and the vase majority of those advected greater distances came from the south-eastern group of particles (furthest offshore, coloured blue in figure 2b). Assuming a representative particle mass of 667 kg (see section 2.1), approximately $1,800$ t and $1,400$ t of sediment settled down-drift of the power station site (defined here as east of 0.98°E or north of 50.94°N) in January and May, respectively.

In the medium sand simulations ($d = 250$ μm) suspension rates were unaffected, however the rapid settling velocity ensured that particles generally settled upon the seabed almost immediately after suspension. Over 98 % of particles were advected less than 10 km from their initial location, and 84 % were advected less than 1 km. Clearly the 1.8 km resolution of the HRCS set-up is not well suited to simulating dispersal of such particles, and it would not be appropriate to model larger grain sizes (such as the gravel beach of Dungeness) as the POLCOMS particle tracking model neglects bedload transport. Only 100 t and 120 t of sediment settled down-drift of the power station in January and May, respectively.

In the baroclinic set-up the average bottom velocity field in January was much stronger, approaching 0.2 ms^{-1} and directed to the north-east (figure 4 c). The monthly mean circulation in May remained weak and spatially variable (figure 4 d). In January particles were generally dispersed much further than in the tide-only setup, 39 % of fine sand particles were advected 10 km or greater, and $19,000$ t of sediment was advected beyond the power station (figure 6 a). In reality it is likely that this value is an underestimate as several sites ran out of particles prior to the end of the simulation. The mean circulation during May remained weak (figure 4 d) and there was now a significant drift of particles in the opposite direction (figure 6 b). Altogether 17 % of particles were advected 10 km or greater, and $1,600$ t of sediment settled past the power station. The primary direction of sediment transport in the

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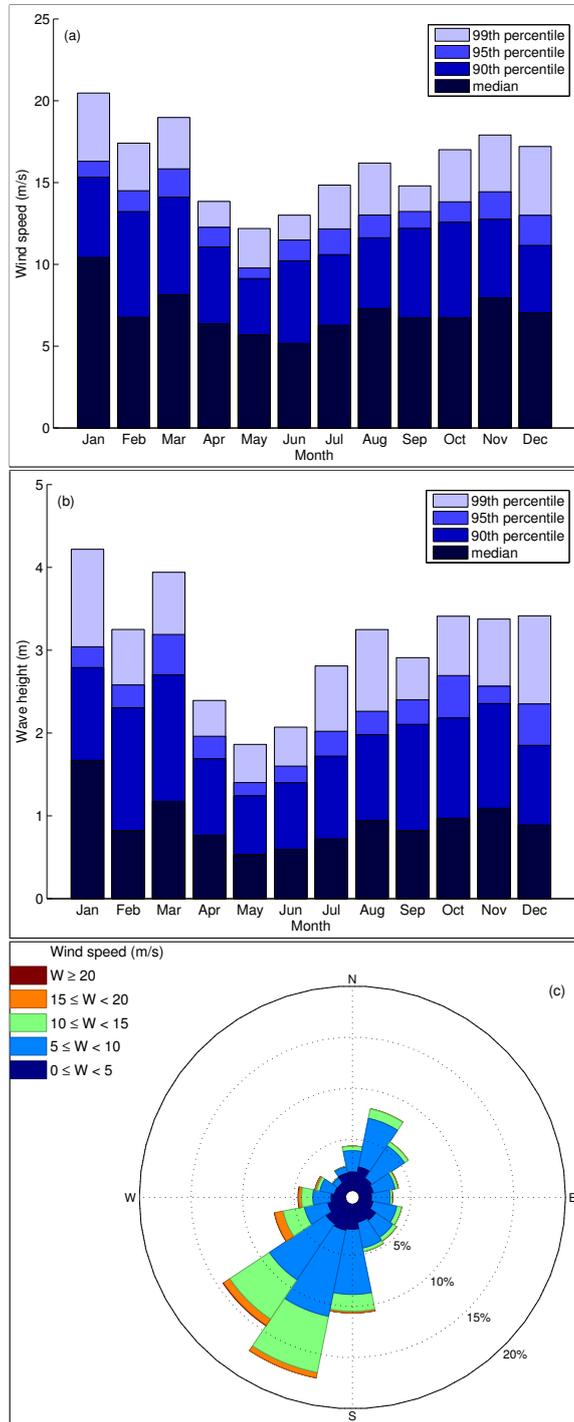
Figure 3: (a) 2008 wind speed percentiles. (b) 2008 significant wave height percentiles. (c) 2008 wind rose. Wind speeds are taken from UK Met Office Mesoscale data at a point in Rye Bay. Wave heights are taken from the nearby CEFAS wavenet buoy at Hastings (see figure 1).

medium sand simulations was unaffected (figure 6 c, d), however sediment transport rates were an order of magnitude slower, with approximately $3,200$ t and 140 t of sediment advected past the power station site over January and May, respectively.

The average bottom circulation in the WAM set-up was almost entirely unchanged from the baroclinic set-up in both months (figures 4 e, f). The added bed stress introduced by the wave model ensured that a greater proportion of particles seeded in central areas of Rye Bay were suspended and subsequently advected greater distances (see distribution of red and green particles in figure 7), although this did not generally lead to greater overall transport rates within the model.

In the fine sand simulations approximately $19,000$ t and $1,700$ t of sediment was advected beyond the power station over January and May respectively, whilst the corresponding values in the medium sand simulations were $3,100$ t and 120 t. Finally for completion the WAM set-up was repeated for coarse sand ($d = 1$ mm, $w_s = 0.12$ ms^{-1}), however the results were virtually identical to the medium sand simulations. Clearly such grain sizes are beyond the current capabilities of the model, and it would be necessary to incorporate bedload transport and possibly reduce the model time-step in order to simulate coarse sediments.
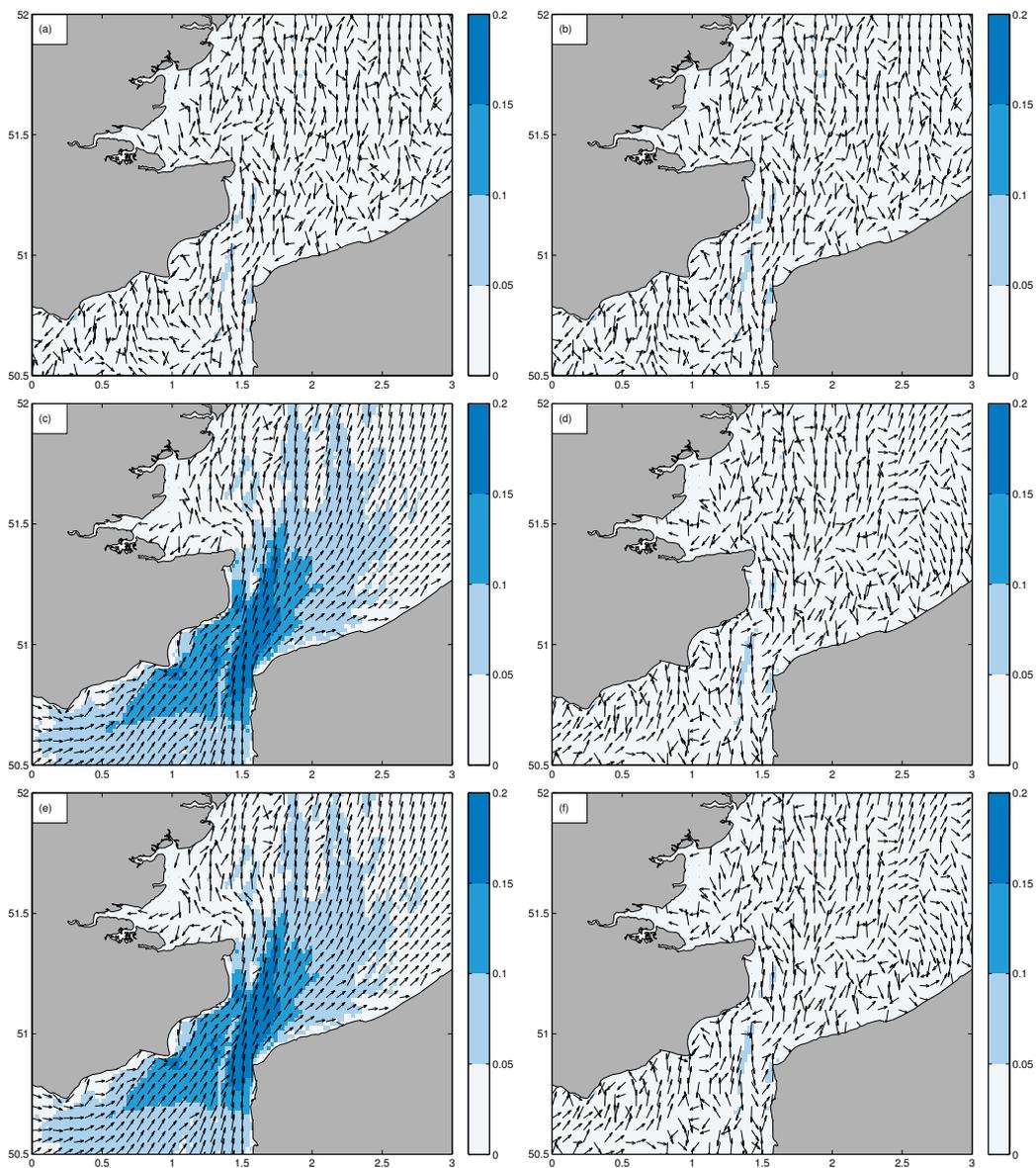
Figure 4: Monthly mean velocity (ms^{-1}) at the sea bed. (a) January 2008
tide-only. (b) May 2008 tide-only. (c) January 2008 baroclinic. (d) May
2008 baroclinic. (e) January 2008 WAM. (f) May 2008 WAM.
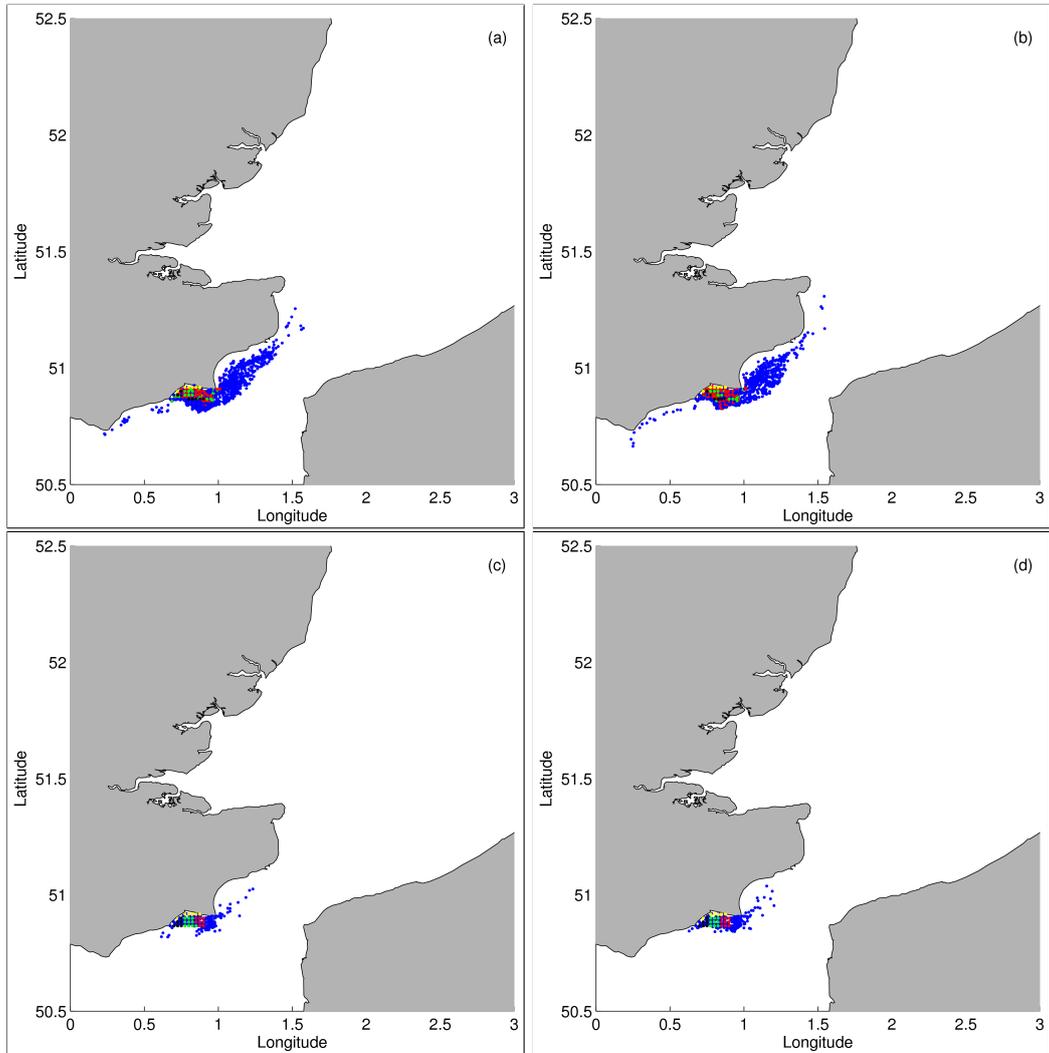
Figure 5: Final particle distributions for each 1 month tide-only simulation. A random sample of 1000 particles are depicted per station, and particles are coloured according to their region of origin (see 2b). (a) January, $w_s = 9$ mm/s; (b) May, $w_s = 9$ mm/s; (c) January, $w_s = 35$ mm/s; (d) May, $w_s = 35$ mm/s

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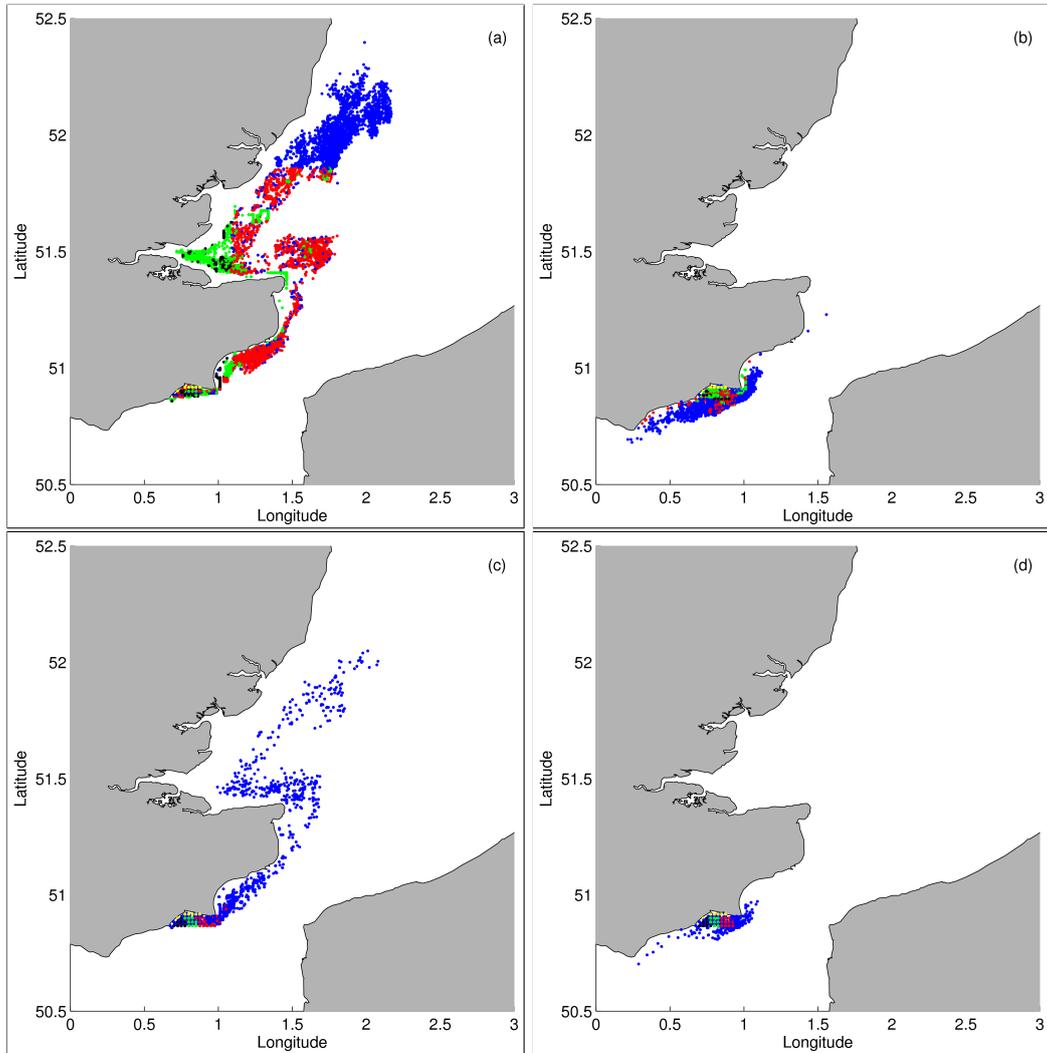
Figure 6: Final particle distributions for each 1 month baroclinic simulation. A random sample of 1000 particles are depicted per station, and particles are coloured according to their region of origin (see 2b). (a) January, $w_s = 9$ mm/s; (b) May, $w_s = 9$ mm/s; (c) January, $w_s = 35$ mm/s; (d) May, $w_s = 35$ mm/s

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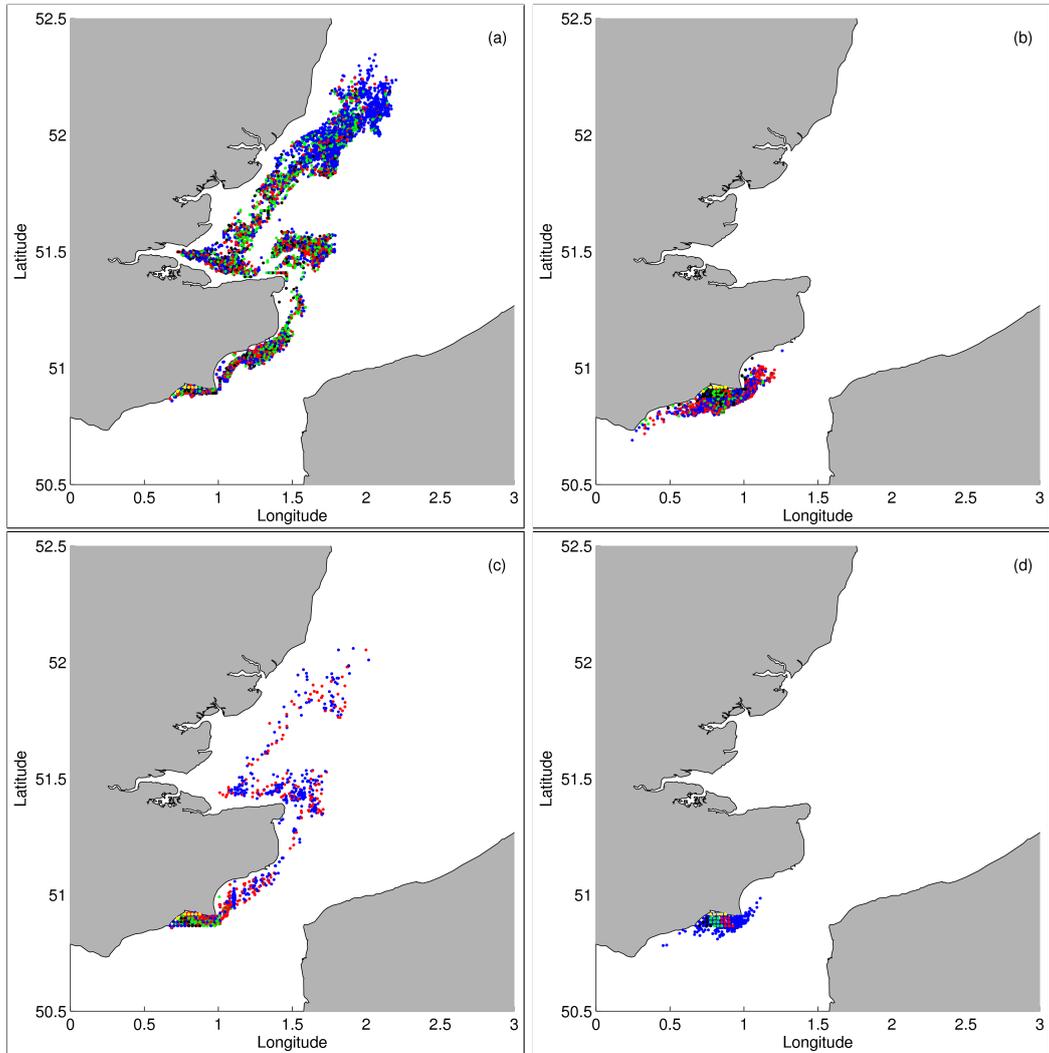
Figure 7: Final particle distributions for each 1 month WAM simulation. A random sample of 1000 particles are depicted per station, and particles are coloured according to their region of origin (see 2b). (a) January, $w_s = 9$ mm/s; (b) May, $w_s = 9$ mm/s; (c) January, $w_s = 35$ mm/s; (d) May, $w_s = 35$ mm/s

3 Coastal Evolution

3.1 Methodology

The coastal evolution model (CEM) of Ashton and Murray (2006a,b) was adapted to investigate the potential evolution of a sandscaping intervention along the Dungeness headland. The changes made to the model for this study are summarised below.

Volumetric alongshore sediment transport Q_s (m^{3}s^{-1}) is calculated as a function of significant breaking wave height H_b (m) and the angle ϕ between the breaking wave crest and the shoreline using the CERC equation,

$$Q_s = K \left(\frac{\rho_w g^{\frac{1}{2}}}{16 \gamma_b^{\frac{1}{2}} (\rho_s - \rho_w)(1 - n)} \right) H_b^{\frac{5}{2}} \sin(2\phi) \qquad (4)$$

where ρ_w and ρ_s represent the density of seawater and the sediment grains respectively (kgm^{-3}), $g = 9.81$ ms^{-2} is gravitational acceleration, $\gamma_b = 0.78$ is the breaker index, $n = 0.4$ is the porosity factor and K is a dimensionless empirical constant. USACE (1984) recommends using $K = 0.39$ (assuming H_b represents significant wave height), however this value is typically used to calculate alongshore transport of quartz density sand, and the appropriate value for coarse grain sizes (> 1 mm) such as those found in Dungeness is the subject of much discussion (Van Wellen et al., 2000). Here we adopt $K = 0.054$ following 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 (see Ashton and Murray, 2006a, their figures 5, 6). For the current study this aspect of wave shadowing was extended to prevent land erosion within any shadowed region, allowing recurved gravel spits to completely eliminate coastal erosion in the affected area.

Whilst this model was initially designed as an exploratory model to investigate the influence of the idealised wave climates on flat coastlines, Barkwith et al. (2014a,b) adapted the model to read in observational wave data and coastline masks that represent real coastlines. These modifications were retained for the present investigation. A land-sea mask representing Dungeness was developed using LIDAR data at 25 m resolution. The Hastings Wavenet buoy (figure 1) provides a reliable time series of significant wave height, direction and period, and demonstrates that the local wave climate is dominated by high angle waves ($\phi > 45°$) and almost entirely asymmetrical. This extreme wave climate led to instabilities in the model during
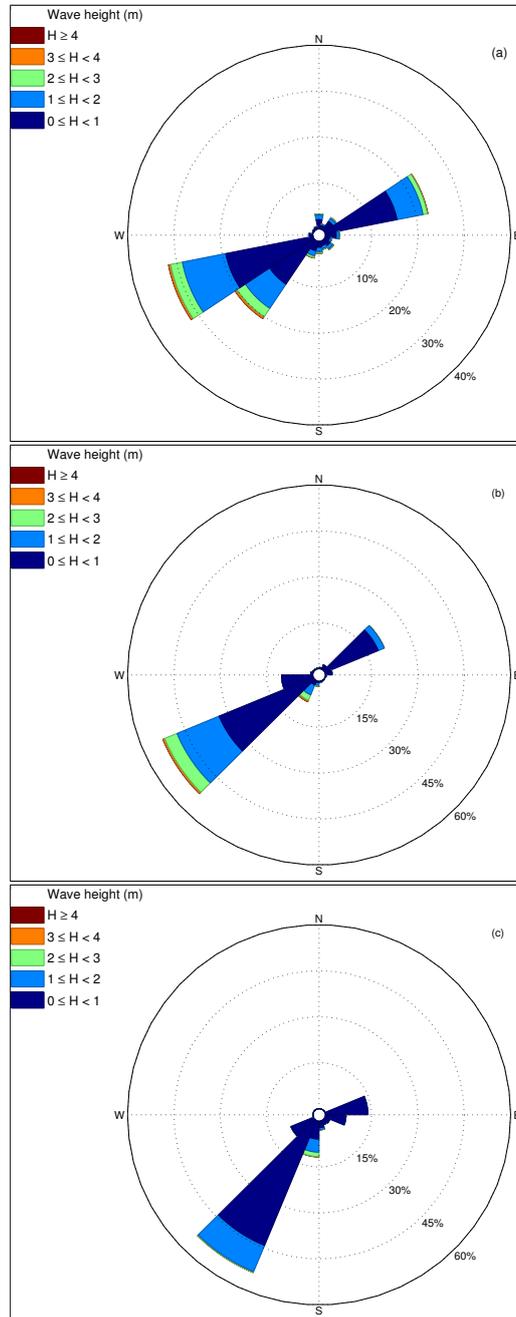
Figure 8: Significant wave height roses for 2008. (a) Observational data at Hastings Wavenet buoy. (b) POLCOMS-WAM output at Hastings Wavenet buoy site. (c) POLCOMS-WAM output at Rye Bay station (see figure 1). Note that all offshore (i.e. Northerly) waves are neglected by the CEM.

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Scenario	Description	Added gravel area (ha)
B	Baseline scenario	0
S1	Recurved spit 1	55
S2	Recurved spit 2	55
S3	Recurved spit 3	55
SS	Simultaneous recurved spits 1 to 3	165
S4	Recurved spit 4	270
P	Parabolic gravel addition	300

Table 1: Details of the seven CEM scenarios.

preliminary testing. A ten year time series of POLCOMS-WAM output suggests that the wave climate at the Hastings Wavenet buoy site (highness = 0.86, asymmetry = 0.017) is significantly different to the wave climate within Rye Bay (highness = 0.19, asymmetry = 0.15), therefore POLCOMS-WAM output data within Rye Bay was used to force the CEM (figure 8).

It should be highlighted that the CEM does not consider elevation, and there is no way of implementing an inter-tidal region, as Dungeness is macrotidal this is a significant simplification. Tidally-induced sediment transport is also neglected. At present the model does not permit different 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 value K.

Seven different scenarios were simulated with the CEM. Firstly a baseline scenario was investigated, focusing upon a stretch of the Dungeness coast between Rye Harbour and the power station site at 100 m resolution. In all subsequent simulations additional gravel was introduced to extend the beach in a similar manner to the Sand Engine in the Netherlands. Between 55 ha and 300 ha of gravel was added in each scenario (summarised in table 1, and depicted in figures 9a and 11 to 16). For comparison, the Sand Engine initially expanded the South Holland shoreline by approximately 128 ha (Zandmotor, www.zandmotor.nl), however simulations suggest that it may result in a beach area gain of 200 ha over a 20-year period (Stive et al., 2013). Each simulation was run for 100 years, and parameters were calibrated to the historic coastal erosion rate of 1 m per year approximated from Google Earth historic images. Two stretches of the coastline are protected by reinforced coastal defences, collectively covering approximately 5 km of the coastline, and erosion is negated within this region (figure 9a).

3.2 Results

In the baseline scenario the Dungeness coastline eroded an average distance of 46 m over 100 years, ranging from 0 m at the coastal defences to almost 100 m to the east of the power station site (figures 9, 10). The total area of lost land was 68 ha. Of all the subsequent scenarios, the simultaneous recurved gravel spit SS run reduced the land erosion rate by the greatest amount by a factor of 2.6 to 26 ha, therefore saving approximately 42 ha of land. The CEM predicts that each gravel spit would reconnect to the coastline after approximately 10 years to form coastal lagoons, which would ultimately survive for roughly another 10 years (figure 14). The two eastern spits merge into one another after 5 years. The SS scenario was closely followed by S4 in terms of land protection, which protected 37 ha of land in comparison to the baseline run. In the S4 scenario the large gravel spit reconnected to the coast after approximately 50 years and the resulting coastal lagoon survived the entire 100 year simulation (figure 15).

The individual smaller recurved spits S1 to S3 are certainly more practical and financially feasible, and these each offered different levels of coastal protection. The least effective of these three scenarios was S1 as the area of land initially covered by the gravel spit was already protected by the sea wall (figure 11). Interestingly the erosion rates on the eastern half of the model domain were actually marginally greater in the S1 scenario than the baseline simulation (figure 10) as the recurved spit grew in size and essentially blocked eastward gravel transport. The S2 and S3 scenarios were similarly effective, reducing land erosion by 25 ha and 22 ha respectively compared to the baseline simulation over the 100 year period (figures 12, 13).

Finally the parabolic addition of gravel at Rye harbour was by far the least

Scenario	5 years	10 years	25 years	50 years	100 years
B	1.7, 2.5	3.5, 5.1	9.5, 14.0	20.7, 30.5	46.0, 67.6
S1	1.7, 2.5	3.5, 5.1	9.6, 14.2	20.2, 30.0	42.0, 61.8
S2	1.4, 2.1	2.9, 4.2	7.0, 10.2	13.5, 19.9	28.9, 42.6
S3	1.4, 2.1	2.8, 4.2	7.2, 10.6	14.4, 21.2	30.9, 45.5
SS	1.0, 1.5	2.1, 3.1	5.1, 7.6	9.2, 13.6	17.5, 25.9
S4	1.1, 1.6	2.3, 3.4	6.5, 9.5	12.5, 18.4	21.1, 31.2
P	1.7, 2.4	3.4, 4.9	9.8, 14.4	23.1, 34.0	47.2, 69.4

Table 2: Summary of land erosion rates in the seven CEM scenarios. Each cell gives the average distance eroded in m (left), and the total area eroded in ha (right).
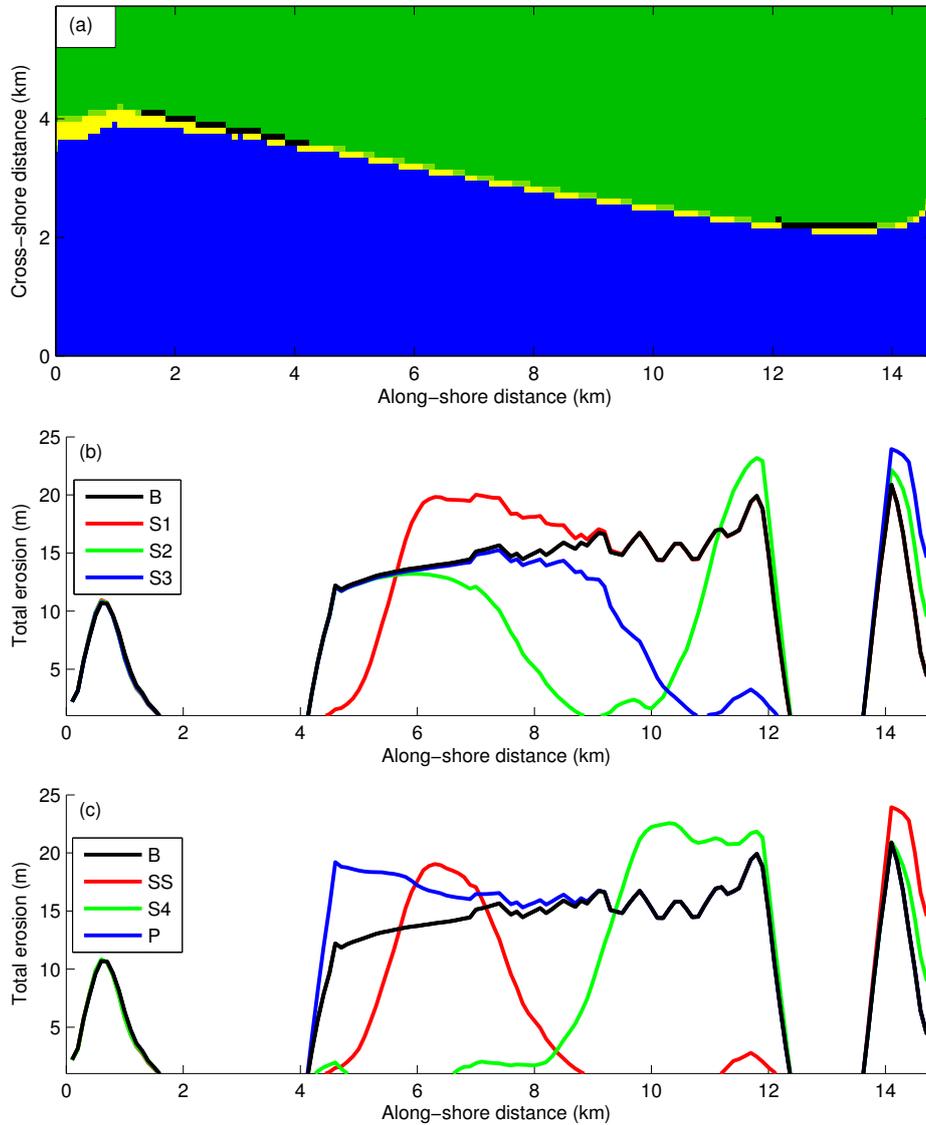
Figure 9: (a) Contour plot of the baseline Dungeness CEM set-up. Green, yellow, blue and black regions represent land, gravel beach, sea and coastal defences respectively. (b,c) Meters eroded after 25 years for each scenario. Erosion distances has been passed through a moving average filter (500 m width) to reduce the noise introduced by the coarse 100 m resolution.

effective of all scenarios investigated here, despite covering the largest area. The overall land erosion rate was actually greater than the baseline scenario as the large block of gravel reduced eastward gravel transport significantly (figure 16).
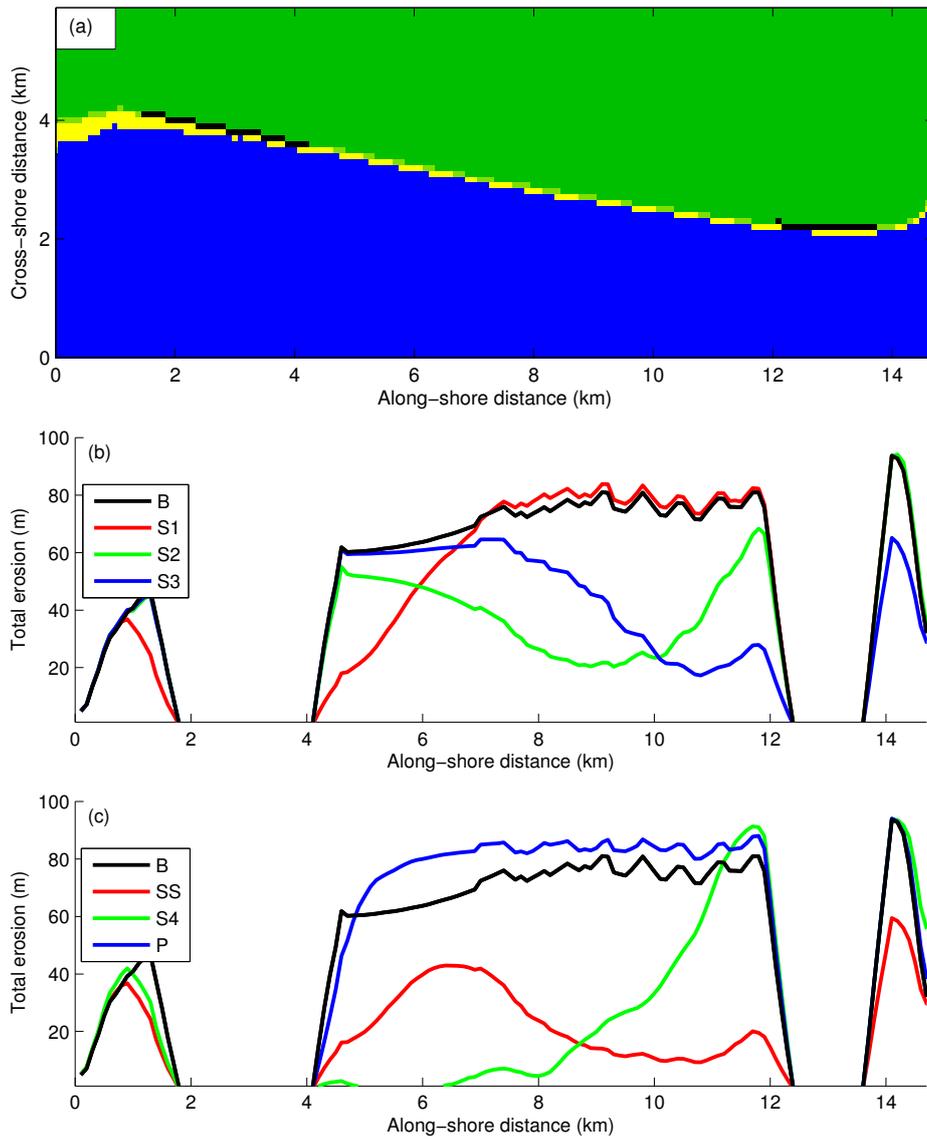
Figure 10: As figure 9 but after 100 years
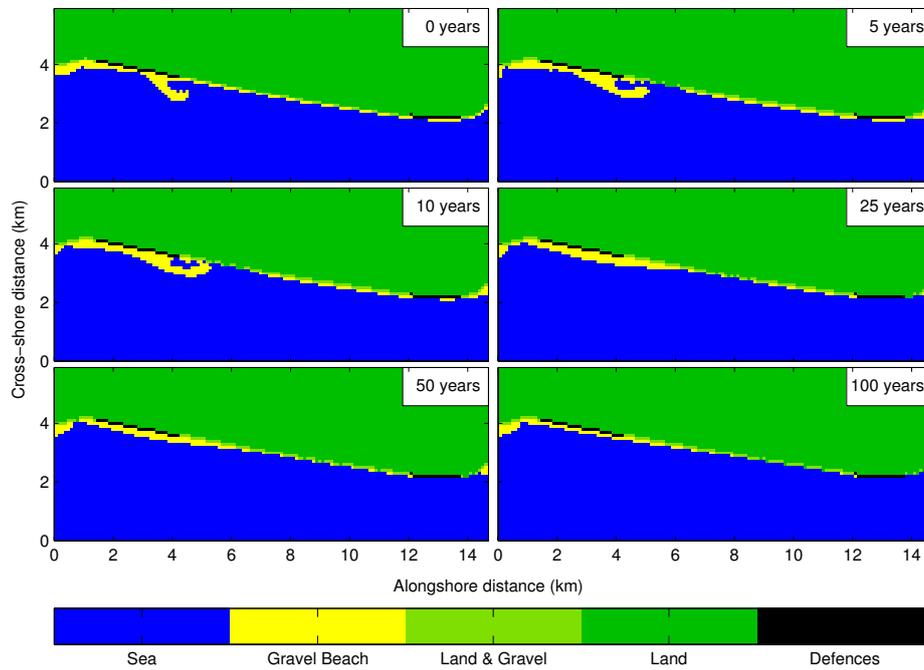
Figure 11: Snapshots of the CEM output for the S1 scenario after 0, 5 10, 25, 50 and 100 years.
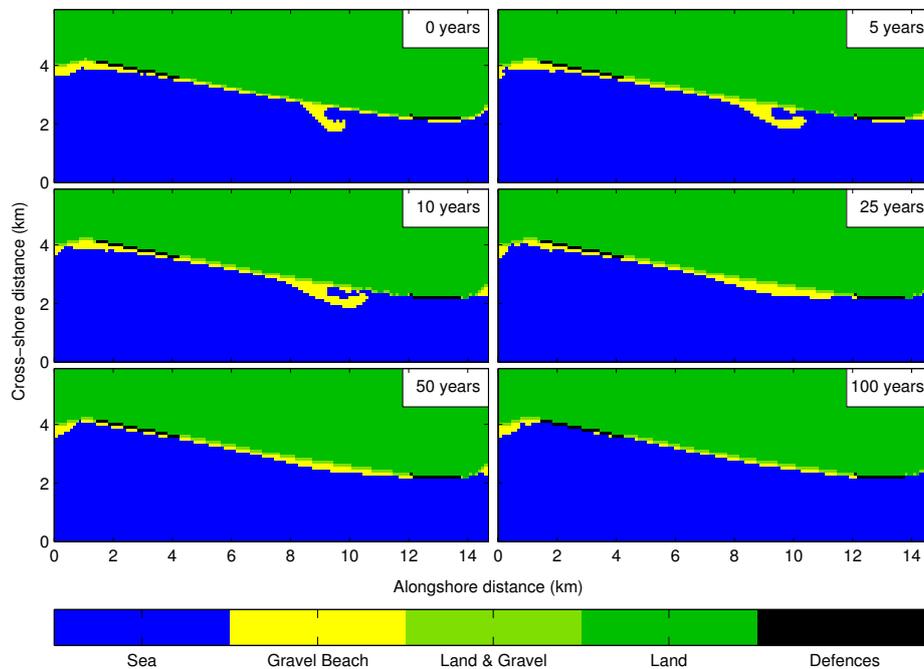
Figure 12: As figure 11 but for the S2 scenario.
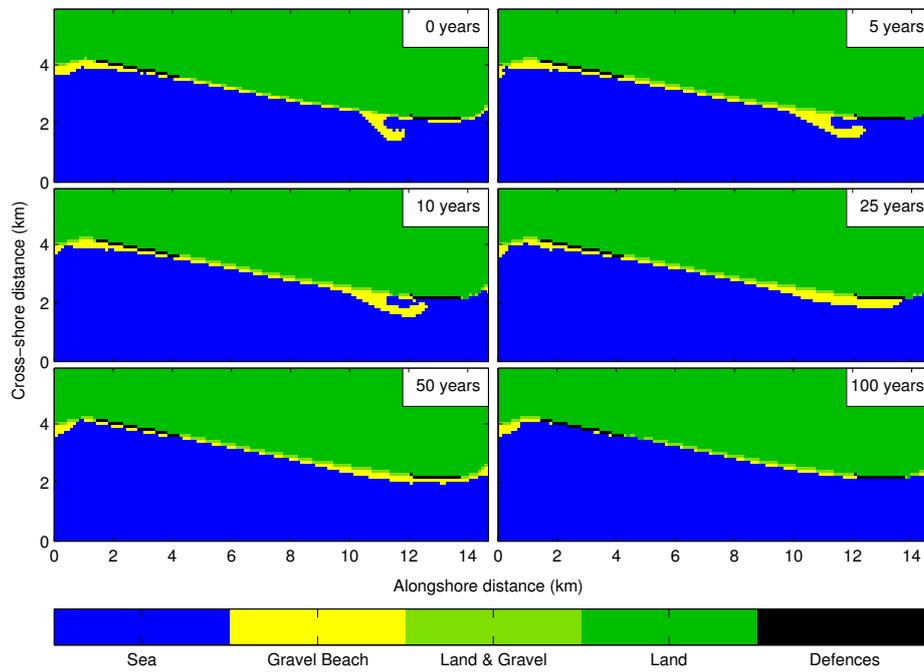
Figure 13: As figure 11 but for the S3 scenario.
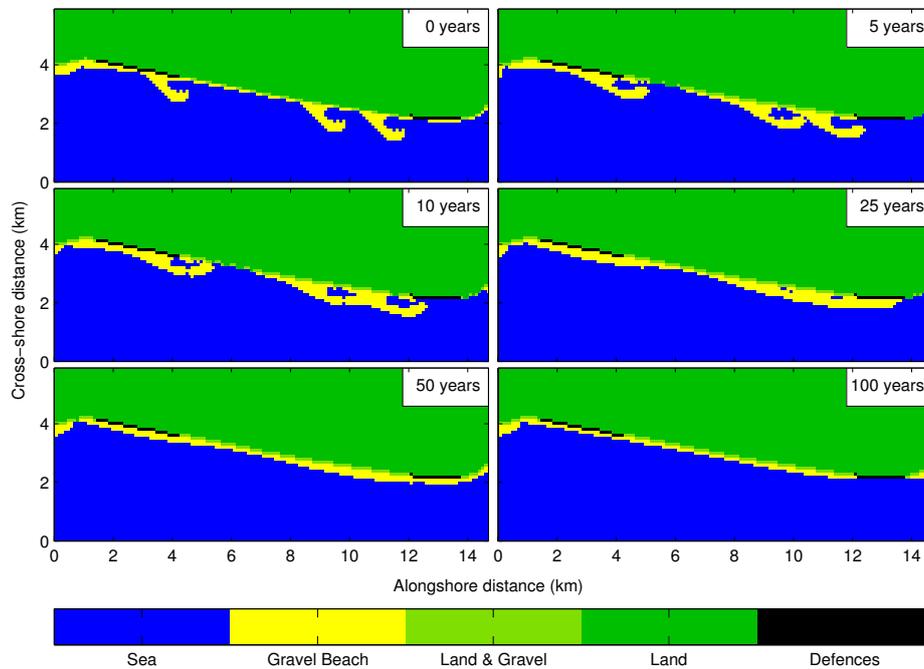
Figure 14: As figure 11 but for the SS scenario.
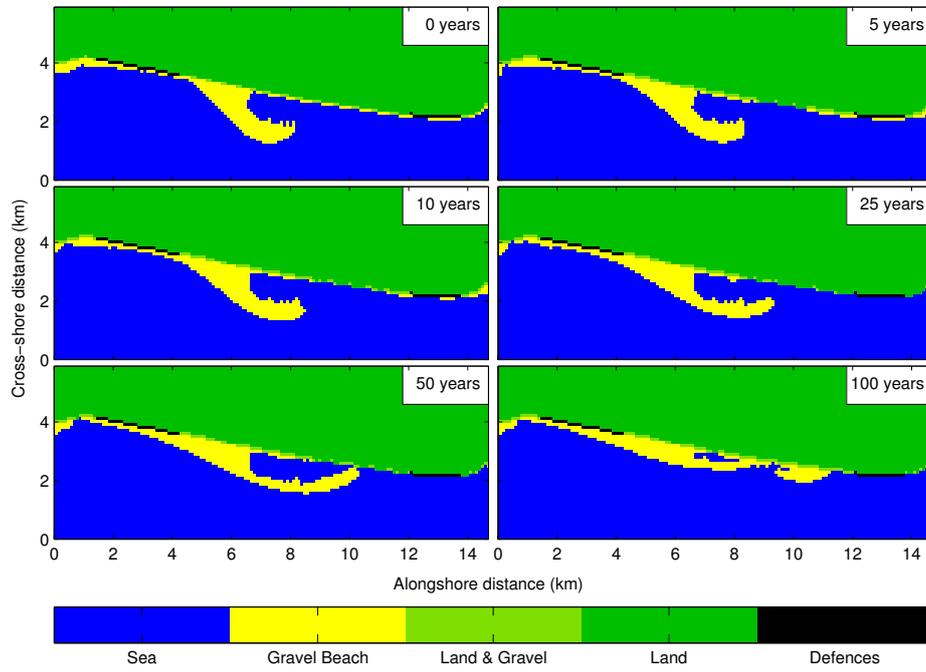
Figure 15: As figure 11 but for the S4 scenario.
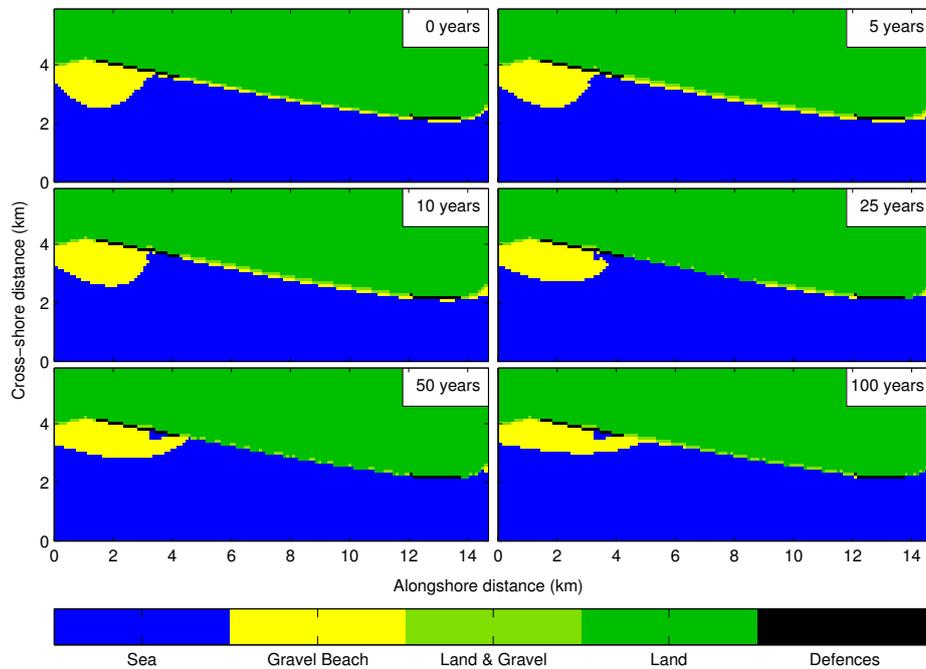
Figure 16: As figure 11 but for the P scenario.

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4 Discussion

This document presented a series of preliminary investigations into sediment transport and potential coastal engineering projects along Dungeness, a dynamic and vulnerable headland on the south coast of Great Britain that is of significant ecological and economical importance. The particle tracking simulations demonstrated that transport of suspended sediments in this region is highly variable according to grain size and meteorological conditions.

The major pathway of sediment transport was north-eastwards, which reflects the long-term mean wind-driven circulation and wave direction. As much as 19,000 t fine sand was advected from Rye Bay to the east of the power station site during a single stormy month, however this value decreased significantly when grain size was increased and wind and wave forcing calmed. The results suggest that some south-westward transport of suspended sediments may be possible during calm months, however transport is almost entirely north-eastwards during stormy periods. Over the timescales investigated here, suspended sediments remain trapped within the strong coastal circulation, and do not enter the North Sea during the first month of transport.

The results were also strongly dependant upon model set-up. The introduction of baroclinic forcing affected the results dramatically, changing the residual circulation and leading to significantly enhanced sediment transport rates. The wave model also increased suspension rates due to the wave-generated bed stress, particularly closer to the coastline. Clearly tide-only models are insufficient for such an investigation and would significantly underestimate the rate of sediment transport.

Whilst the particle tracking simulations have elucidated the rate of sediment transport and the primary influences, they have also revealed some deficiencies within the model. Firstly there was little difference between the medium sand and coarse sand results, even with baroclinic and wave forcing, because the large settling velocities caused particles to return to the seabed almost immediately after suspension. Such coarse grain sizes will therefore be primarily transported as bedload. In reality Dungeness beach largely consists of very coarse sediments (gravel), therefore future versions of the POLCOMS particle tracking model should incorporate bedload transport in order to give a more realistic representation of sediment transport in this region. It may also be helpful (but computationally expensive) to reduce the internal model time step, allowing particles to be suspended for multiple time steps.

It should also be highlighted that very few of the coastal particles (coloured yellow in figure 2b) were suspended into the water column as the bed stress along the coastline was too weak. This may be partially due to the enforced

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10 m minimum depth. It would appear sensible for future studies to create a local, high resolution model domain of Dungeness that permits intertidal grid cells (wetting and drying), similar to the Liverpool Bay set-up (Souza and Lane, 2013; Brown et al., 2015).

The CEM revealed that if a "gravel engine" was constructed on the Dungneness coast, it could potentially lead to a significant reduction in coastal erosion rates. Such a project should be considered carefully however, as the simulations suggest that any coastal protection offered by an artificial gravel recurved spit would depend upon its size, shape and location. Furthermore, poor design could actually lead to an acceleration in coastal erosion along part of the coastline. The results demonstrate that a greater addition of gravel will not necessarily lead to superior coastal protection. Indeed the S2 scenario protected almost 27 ha of land more than the P scenario over a 100 year period, despite the gravel installation being almost six times smaller. In each simulation the added gravel spit reconnected to the coastline prior to collapsing, creating a protected coastal lagoon.

It should be noted that there is some uncertainty about the appropriate equation for calculating longshore transport for gravel beaches such as Dungeness. Furthermore the CEM is only forced by wave data, and does not take account of tidal circulation. Whilst coastal evolution in many areas is primarily driven by wave forcing, Rye Bay is macro tidal, and the energetic tidal circulation would certainly affect longshore sediment transport. The results should therefore be treated with some caution.

The CEM has sucessfully provided some insight into the evolution of a gravel engine on the Dungeness coastline. These initial results suggest that Dungeness may benefit from such an installation. The S2 and S3 scenarios would appear to be the most promising options based upon these simulations, as they offer a good degree of coastal protection and create additional habitat, whilst surely being more practical and affordable than the S4 and SS scenarios. Further research is required to confirm these results, and to investigate the cost and feasibility of a range of gravel engines, and attempt to quantify the economic and ecological benefits.

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