The Sizewell C Project

9.12 Preliminary Design and Maintenance Requirements for the Sizewell C Coastal Defence Feature

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Preliminary design and maintenance requirements for the Sizewell C Soft Coastal Defence Feature (Version 2)

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Executive summary

The proposed Sizewell C Soft Coastal Defence Feature (SCDF) is a maintained and volumetrically enlarged shingle beach, seaward of the hard coastal defence feature (HCDF) but distinct from the sandy subtidal beach. Its large (c. 210,000 m^3) sedimentary mass is designed to avoid disruptions to longshore transport (and the impacts to local beaches) which, in its absence, would occur if the landward HCDF were exposed. Its intended function is akin to a ‘real-time' recharge during storms. The SCDF would be constructed between the HCDF and Mean High Water Spring (MHWS) level and would release sediment into the coastal system when eroded by waves. It provides a large reservoir of shingle designed to release sediment into the coastal system, prevent HCDF exposure, and thereby avoid or minimise disruption to longshore shingle transport and the potential downdrift beach erosion. It uses a “working with nature” approach where the release of sediment into the coastal system, and its re-distribution, are determined by natural coastal processes (erosion by waves).

The SCDF's overall purpose is therefore to ensure continuation of the longshore transport corridor and avoid HCDF exposure, which it will achieve through its key design features: a large volume (sufficient to withstand severe storms) achieved by a profile with a high crest, coarse sediments for erosion resistance, and maintenance (primarily beach recharge) to replace any losses from the Sizewell C frontage.

This technical report, to underpin the Coastal Processes Monitoring and Mitigation Plan (CPMMP), sets out:

- the basic SCDF description,
- how the SCDF would function,
- its erosion resistant properties (to avoid HCDF exposure and minimise recharge frequency), and
- initial estimates of SCDF recharge requirements (frequency and volume).

Throughout the report, inputs have deliberately adopted a worst-case approach to ensure that risk assessments can be considered as precautionary.

The SCDF is conceptually divided into two main components (see Figure i). It would consist of a landward safety *buffer* volume, V_{buffer}, which is not intended to be depleted or frequently exposed but is sufficiently large in itself to avoid HCDF exposure under severe storms, and a seaward *sacrificial* volume, V_{sac}, which would be allowed to erode as far back as V_{buffer} before being recharged. The rationale for the safety *buffer* component is to protect against storms or storm sequences just prior to recharge. A working value of V_{sac} = 42 m^3 per metre of beach (hereafter m^3/m) was set in Version 1 of this report. Although model improvements in this Version suggest V_{sac} can be enlarged (and V_{buffer} decreased), which would lead to less frequent SCDF maintenance, the original value has been retained (i.e., V_{sac} = 42 m^3/m) as it provides a more conservative assessment of the viability of the sacrificial component and serves to highlight the areas of the SCDF that would be most prone to erosion and more frequent interventions.

Preliminary, highly conservative beach-erosion modelling (Phase 1; BEEMS Technical Report TR531) and volumetric analysis of the SCDF design show that it is substantially larger than that required to withstand erosion from 2 – 3 severe[1] sequential storms, even along sections where the SCDF is smallest (adjacent to

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[1] Based on a real storm sequence with a 1:12 year storm-energy return interval and highly conservative modelling from BEEMS Technical Report TR531.

the permanent Beach Landing Facility), throughout the operation phase. The 6.4 m ODN SCDF crest height would be 1 – 2.4 m above the present, unbreached, shingle ridge crest, which is substantially greater than predicted sea level rise (SLR) in 2099[2] under the intermediate climate emissions scenario (RCP4.5) and is similar or greater than SLR under the very unlikely worst-case emissions scenario (RCP8.5, 95th and 50th percentiles, respectively). Modelling also shows no SCDF overtopping for the present day, 2069 and 2099 sea levels (including 1 m storm surge) (BEEMS Technical Report TR545).

Version 1 of this report (submitted at Deadline 2 of the Sizewell C DCO Examination) proposed coarsening the SCDF sediments by using very coarse pebbles (32 – 64 mm diameter; see sediment classification in Appendix A), which is at the larger end of the native particle size distribution, and with a relatively low sand content. This is in line with UK experience and guidance, and is intentionally designed to increase sediment retention and therefore prolong longevity of the SCDF. BEEMS Technical Report TR545 model results support the coarsening of SCDF sediments, highlighting performance improvements (less erosion and therefore reduced maintenance and recharge requirements) of 7 – 23% for very coarse pebbles (modelled as 40 mm diameter) compared to the modal medium pebbles at Sizewell (modelled as 10 mm diameter), over the operation phase. As the relative performance of the coarser particle size improves with increasing sea level rise, the benefits are likely to be even greater for the decommissioning phase. Southern North Sea licensed aggregate sites provide a nearby source of suitable sediment (pebble sizes) for the SCDF, once local supplies from HCDF excavation have been exhausted[3].

The Recharge Interval (RI) and modelled storm erosion predictions have been used to indicate the potential recharge requirements and the viability of the SCDF. Several RI estimates were computed using methods from the Beach Management Manual (Rogers et al., 2010) and based on measured shoreline changes, conservative sand models and more realistic gravel models[4]. Numerous worst-case elements were used in the RI estimations, such as the use of conservative models (that overpredict erosion) and beach volumes at the narrowest part of the SCDF, and application of the Dutch Design Method (increasing the modelled volume lost by a further 40%). Nevertheless, all estimates of the volume losses and notional recharge interval across Sizewell C's operation phase indicate SCDF viability.

Overall, the estimated recharge volumes required over the operation phase are similar to the total SCDF volume (c. 210,000 m^3). The preliminary worst case volume estimate of c. 270,550 m^3 is based on the peak observed 10-year erosion rate on the SZC frontage, applied across the whole frontage for the operation phase[5] and would result in 8 – 9 beach maintenance interventions. Recent high resolution beach topography and the preliminary phase 1 modelling suggest up to seven beach maintenance interventions requiring relatively small volumes[6] of sediment (140,000 – 150,000 m^3). New RI estimates in this Version (Ver 2), based on storm response modelling using 2D XBeach sand (which overpredicts erosion) and more accurate 1D gravel models, suggest that only three (or fewer) beach recharge interventions would be required.

The range of RI estimates is achievable and so demonstrates SCDF viability over the operation phase, even for the worst case. The actual recharge intervals will vary in time (and extent) and are likely to be enveloped

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[2] 2099 marks the end of the UKCP18 climate change predictions and corresponds to the planned decommissioning phase of Sizewell C (assuming a 60-year-long operation phase).

[3] The volume of SCDF grade material in the HCDF excavations has not yet been determined, however boreholes do show there is some pebble-sized material.

[4] This version of the report includes new 2D sand and 1D gravel modelling results (Sections 3.1.2.2 – 3.1.2.4). The RIs from the new modelling are longer than those derived in Version 1 (Sections 3.1.1 and 3.1.2.1).

[5] Measured at beach profile location S1B5, which in reality displays a cyclic decadal erosion-accretion cycle with almost no net change over the past four decades.

[6] Compared to other beach recharge events at high-value frontages in the region e.g., Sea Palling at 1,300,000 m^3 (Dolphin et al., 2012) and 1,500,000 m^3 at Bacton (Gary et al., 2018).

by estimates presented above. The worst-case predicted SCDF erosion from a single event was for a 1:107 year storm[7] with 2099 sea levels and receded lateral shorelines (which exacerbate SCDF erosion at the northern and southern extents) in the 2D sand model, but the high erosion (82 m^3/m) was only across a short (5 m long) localised section at the permanent Beach Landing Facility (BLF) abutment. At that one location approximately half of the SCDF was eroded, meaning that HCDF exposure would require two such rare events with no intervening recharge, which can be considered highly unlikely because of the return intervals, the commitment by SZC Co. to recharge the SCDF and the predicted lack of change in the Sizewell wave climate (UKCP18; Lowe et al., 2018).

In the same modelled case, the mean loss along the whole SCDF (44 m^3/m) exceeded the sacrificial buffer volume (42 m^3/m), implying that most of the SCDF would need to be recharged under the 2099 sea levels with laterally receded shorelines and the 1:107 year storm, should these conditions arise. The results of all other model runs suggest that for much of the operation phase only localised recharge is likely to be required and that until the latter part of the period 2069 to 2099, any recharge events are most likely to arise following gradual erosion of the sacrificial layer. The primary method of replenishment would be beach recharge – the import of additional sediments to maintain the SCDF volume. In this way, the SCDF would be maintained and disruption to longshore transport avoided.

Non-uniformity in erosion across the SCDF suggests that some recharge events will be small (in volume and extent) and potentially more frequent if they are in areas of persistent gradual erosion. Frequent small recharge events are more likely around the permanent BLF frontage, where measured and modelled data show higher rates of erosion and, coincidentally, where the SCDF volume is smallest. The spatially continuous monitoring techniques set out in the Coastal Processes Monitoring and Mitigation Plan (CPMMP) are designed to detect such localised erosion and would enable targeted recharge.

Although the measured and modelled data suggest that the risks of HCDF exposure with the SCDF are very low during the operation phase, those risks will rise with increasing sea levels during the decommissioning phase. The risk of HCDF exposure can be effectively mitigated using a well-designed internal cobble layer (initially proposed in Version 1 (Option B)). The aim of a cobble layer being considered is to increase erosion resistance if the fronting SCDF pebbles were fully removed (unlikely during the operation phase). Model results (and literature) show that exposed cobbles would be very difficult to erode – for example, there was no SCDF volumetric loss for fine cobbles (80 mm) under 2020 and 2069 sea levels and only 2.5 m^3/m loss under the 2099 sea level.

An important benefit of the SCDF design (and soft defences in general) is its adaptability to future pressures and real-world performance – that is, the specifications and triggers in the CPMMP can, and indeed will, be adjusted relatively easily according to environmental conditions and performance, thereby accounting for any uncertainties in SCDF response or future pressures (e.g., sea level rise).

Further work required to refine the SCDF's coastal processes design and finalise the buffer and sacrificial layer volumes includes:

- Setting the $V_{recharge}$ (the threshold volume for SCDF recharge) for the CPMMP.
- Extending the modelling period from the end of the operational phase (2099) to the end of decommissioning for SLR cases.

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[7] Return interval of the cumulative wave power across individual storms.

- Modelling a range of particle sizes between 10 and 80 mm to optimise SCDF particle-size selection and SCDF performance.
- Closer examination of the gravel model’s ground water parameters to determine whether further field and laboratory measurements are needed, to reduce model uncertainty.
- Incorporation of any safety case specific requirements and triggers into the analysis. These may stimulate a shift from Option A to Option B in terms of utilising the cobble layer to reduce the risks of HCDF exposure.

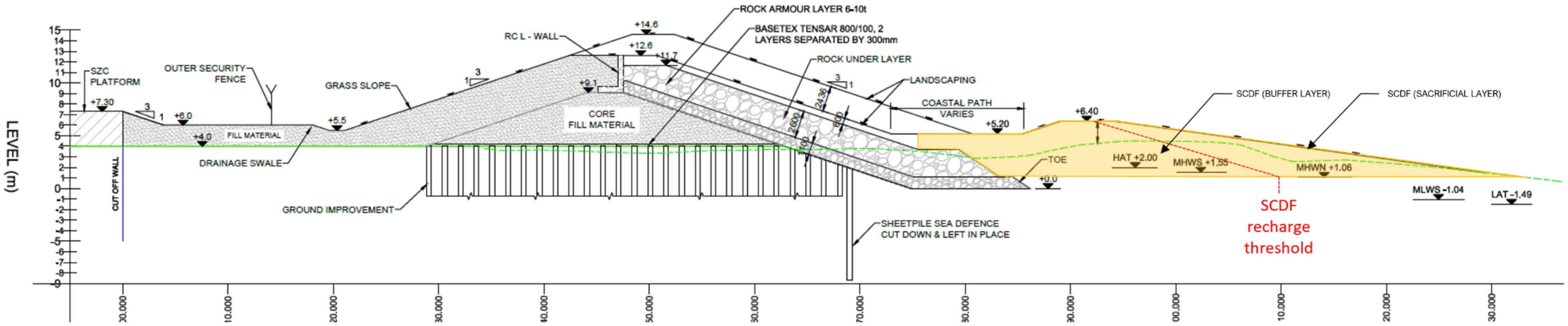

Figure i: Schematic cross-section of the hard and soft coastal defence feature (HCDF and SCDF). The SCDF (yellow) is conceptually divided into two volumes, separated by the dividing SCDF recharge threshold (as the threshold is volumetric, the line is shown for illustrative purposes only, i.e., many different beach profile shapes can produce the threshold volume). The SCDF buffer layer (whose volume is V_{buffer}) sits to landward and is not intended to be exposed, whilst the SCDF sediment to seaward is sacrificial (V_{sac}) and would be replenished once the recharge threshold has been reached. The dashed green line running through the yellow SCDF is the present-day topographic cross-section.

1 Introduction

The proposed Sizewell C Soft Coastal Defence Feature (SCDF) is a maintained and volumetrically enlarged shingle beach, seaward of the hard coastal defence feature (HCDF) but distinct from the sandy subtidal beach. Its large (c. 210,000 m3) sedimentary mass is designed to avoid disruptions to longshore transport and the impacts to local beaches which, in its absence, would eventually occur if the landward Hard Coastal Defence Feature (HCDF) were to be exposed Its intended purpose is to release sediment into the coastal system when eroded by waves. It provides a large reservoir of shingle designed to release sediment into the coastal system, prevent HCDF exposure, and thereby avoid or minimise disruption to longshore shingle transport and the potential downdrift beach erosion. It uses a “working with nature” approach where the release of sediment into the coastal system, and its re-distribution, are determined by natural coastal processes (erosion by waves).

The SCDF’s key coastal processes design features are: a large volume (sufficient to withstand severe storms); coarse sediments for SCDF erosion resistance; a high crest; and maintenance activity (primarily beach recharge) to replace any losses from the Sizewell C frontage.

As the SCDF is designed to avoid the impacts of HCDF exposure during the construction and decommissioning phases, it is defined as embedded (primary) mitigation. SCDF maintenance – the provision of additional sediments to maintain beach volume – is secondary mitigation, as are the other methods (beach recycling and bypassing) listed in the Environmental Statement (NNB Generation Company (SZC) Limited, 2020a) and the Coastal Processes Monitoring and Mitigation Plan (CPMMP; BEEMS Technical Report TR523).

This report sets out:

- the SCDF coastal processes design options,
- how the SCDF would function,
- SCDF erosion resistant properties (to avoid HCDF exposure and minimise recharge frequency), and
- initial estimates for SCDF recharge frequency to demonstrate longevity and viability for the operation phase.

The report draws upon storm erosion modelling at Sizewell (BEEMS Technical Reports TR531 and TR545), BEEMS monitoring data (waves, beach topography), and literature (current best practice and examples). It considers SCDF composition (sediment properties), crest elevation and volume, as these parameters need to be optimised for Sizewell to:

- minimise the erosion rate during severe storms and, therefore, minimise the risk of HCDF exposure,
- maximise the recharge intervals (RIs) (and minimise disturbance) between SCDF recharge events across the operation and decommissioning phases[8] of Sizewell C, and

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[8] The SCDF would be maintained until (at least) around 10 years before the end of the decommissioning phase, when the CPMMP Cessation Report is due. Based on the extensive evidence base at that time and consultation with regulatory stakeholders, any future arrangements for monitoring and mitigation will be set (BEEMS Technical Report TR523). This will require approval of the discharging authority at that time.

- minimise foreshore disturbance associated with recharge events.

Optimisation will consider present day conditions as well as future pressures on the frontage, such as sea level rise (SLR) and receded adjacent shorelines, both of which are likely to increase erosional tendencies on the Sizewell C frontage over time. However, an important benefit of the SCDF (demonstrated by all soft defences in general) is its adaptability to future pressures and real-world performance – that is, the specifications and triggers can be adjusted according to environmental conditions and performance. The trigger for recharge will be set in the CPMMP and monitoring will determine when, and where, any beach recharge is needed, as well as assess its performance. Elements of this structured Adaptive Environmental Assessment and Management process, i.e., using evidence from performance assessment to adjust triggers or mitigation actions over time to account for uncertainties (in this case in how the SCDF responds to future pressures), are applied elsewhere in the UK[9] and will be adopted as best practice as part of the CPMMP.

1.1 Background

Soft shoreline engineering approaches utilise natural processes and sediments (or other natural beach materials or vegetation) to locally reduce erosion. Well-designed soft defences are adaptable, sustainable and provide effective coastal protection (Bayle et al., 2020). Unlike hard defences, which are immobile and tend to reflect wave energy during storms (causing enhanced scour and sediment loss), soft defences work with nature, dissipate energy, supply additional sediment to coastal systems (in the case of the SCDF and beach recharge in general) and therefore benefit local shorelines.

It is generally considered that where the rate of sediment supply is insufficient to maintain beaches in front of high value property and/or infrastructure, hard defences will become the only option in the longer term (Dornbusch, 2017). However, the SCDF (as set out in this report) averts exposure of hard defences by incorporating several proven FCERM[10] design features. Although these features lead to a robust SCDF, they will reduce, but not eliminate, the need for maintenance (SCDF beach recharge) owing to the station's multi-decadal operating life and the pressures of rising sea level. To maintain resilience and minimise the disturbance associated with recharge events, the SCDF will include several erosion resistant features:

- a large volume;
- high crest;
- coarse particle sizes; and
- surface vegetation.

At the point of construction, the SCDF would increase the sediment volume along the SZC beach frontage. Although its maintenance (recharge activity) would imply some disturbance, this would be in naturally eroded areas where sediment and vegetation had been lost, and therefore restoring the supratidal area would allow potential re-colonisation (which doesn't occur where supratidal deposits are lost). Over time, SCDF sediments may also contribute to reducing erosion rates and promoting an increase in supratidal shingle[11] on the immediately neighbouring frontages.

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[9] Examples of adaptive approaches include Pevensey Beach (Pentium Coastal Defence Limited, 2001), Lincshore (Environment Agency, 2017), Thames Tideway (HR Wallingford, 2020) and Dungeness.
[10] Flood and Coastal Erosion Risk Management.
[11] The desired habitat for nesting little tern and annual vegetation of drift lines species.

Along with volume, vegetation and sediment properties are commonly used to enhance the effectiveness of soft engineering solutions (see below).

Vegetation

Natural and planted vegetation in the supratidal backshore (sand dunes and shingle ridges) is considered to reduce erosion rates during storms, although the degree of protection is specific to each site due to sedimentology, the nature (frequency, magnitude, direction) of aeolian and hydrodynamic exposure, and the species present (Feagin et al., 2019). Vegetation influences sediment erodibility by modifying (reducing) water flow and wave run-up above ground, and increasing soil strength below ground (Sigren et al., 2014). For example, Feagin et al. (2019) show that vegetation provides an average ~1.6 factor of safety (erosion resistance) over bare sand for a wide range of northern hemisphere latitudes, whilst Sigren et al. (2014) observed a 30% reduction in the retreat rate of vegetated dune scarps.

The habitats formed by coastal sedimentary deposits and colonising vegetation are also of importance. Supratidal shingle vegetation, indicative of a briefly stable setting which might also benefit nesting birds and other fauna, is rare. Supratidal shingle can feature distinctive, desiccation-tolerant floral species and is one of the five coastal priority habitats listed under the UK Biodiversity Action Plan (JNCC, 2019) with 15 associated UKBAP priority species (Rogers et al., 2010). Drift line vegetation on shingle is sparse and ephemeral; shingle vegetation, including pioneer species at the seaward margin, has the potential to trap wind-blown sands and initiate the processes of dune development and allow more established species to create fixed dunes and grasslands. However, on the SZC to Minsmere Sluice frontage, Natural England condition surveys show that the annual vegetated drift lines were degrading in the early 2000's and were lost by 2010 (DEFRA MAGIC, 2021). This was due to natural coastal squeeze between the relatively static shingle ridge and the landward recession of the intertidal zone.

In the longer term, natural coastal squeeze will continue to reduce the supratidal zone along the Minsmere frontage until regular overwashing and roll back begins. Until that time, unless additional shingle is deposited to widen the supratidal zone, it is unlikely to sustain a drift line vegetation habitat. However, some of the sediment eroded from the SCDF is expected to accumulate and reduce erosion rates along the southernmost extents of the Minsmere frontage. These sediments may contribute to formation of a supra-tidal shingle deposit, which could potentially be colonised by annual vegetated drift line species (as observed at Sizewell B).

Sediments

Sediment size is one of the most important parameters for the design of soft defences and beach recharge schemes (Rogers et. al., 2010). At its most basic level, coarser and/or denser particles are desirable as they are more difficult to mobilise and therefore have a longer residence time before being transported to neighbouring shores (compared to a scheme with finer sediments). In the UK, beach recharge schemes typically use similar or coarser sediments than the native beach. The particle size distribution of sediment is important to longevity and beach behaviour (e.g., Stauble, 2005). For example, decreasing the sand content in gravel beaches increases permeability, slope, and retention. Two options for the SCDF's sedimentary composition are presented in Section 2.4.

1.2 Changes in Version 2

The following sections have been updated or added in Version 2 of this report following new numerical modelling results (BEEMS Technical Report TR545):

- Executive Summary
- 1.2 This (new) section
- 1.3 Outline (updated)
- 2.3.1 SCDF topography and volume (minor updates)
- 2.4.1 SCDF sensitivity to particle size (new explanatory section)
- 2.4.2 and 2.4.3 (unchanged, formerly 2.4.1 and 2.4.2, respectively)
- 3.1.2 Recharge requirements based on modelled volumetric change (subsections 3.1.2.2 – 3.1.2.4 examine erosion and recharge intervals based on new modelling)
- 3.1.3 Recharge requirements summary (updated)
- 4 Conclusions (updated)

1.3 Outline

This report presents preliminary design options for the SCDF, in terms of its key parameters – volume, sediment composition and crest elevation (Section 2), how it would function and its erosion-resistant properties. Section 3 uses measured and modelled datasets to estimate the SCDF recharge requirement (maintenance), consider its viability over the operation phase and examine the benefits of coarser sediments. SCDF sediments are expected to be sourced initially from earth works on the main development site (assuming appropriate sediment properties) and then from already licensed marine aggregate extraction sites, as set out in Section 3.2.2 of NNB Generation Company (SZC) Limited (2020b). There are numerous marine sites within the region that contain suitable sediments. Further detail on sediment sources will be provided in a future version of this report.

2 SCDF design

2.1 Function

The purpose of the SCDF is to avoid disruptions to longshore transport and the impacts to local beaches that would arise if the HCDF were exposed, across the operational and decommissioning phases of the station[12]. That is, without the SCDF, shingle moving along the subaerial longshore transport corridor[13] is likely to eventually encounter a barrier (an exposed HCDF), which would partially or fully block its movement. Consequently, the downdrift beach for each storm direction[14] would experience short-term sediment starvation over a distance of a few hundred metres (NNB Generation Company (SZC) Limited, 2020b). Subject to the duration of the storm or the number of storms in sequence from a single directional sector, measurable beach erosion may occur; however, the process would reverse when the storm and longshore transport directions alternate.

HCDF exposure is not expected as the SCDF would be maintained by SZC Co. over the operation and decommissioning phases. However, in the very unlikely event that the HCDF is exposed as a result of a sequence of very severe storms in rapid succession without the opportunity to recharge, the HCDF would protrude partly or wholly through the beachface and introduce an artificial obstruction to longshore shingle transport until the SCDF was recharged. The obstruction to shingle movement would starve the downdrift beach for short periods of time (the duration of storms) as sediment that accumulates upstream of the blockage would not reach is natural downdrift destination, leading to shoreline retreat there.

The best local analogy for these impacts is the nearby Minsmere Sluice Outfall. The concrete outfall passes underneath the shingle ridge and through the active beachface to a position well beyond the low tide mark (Figure 1), i.e., across the entire longshore shingle transport corridor. However, its elevation around the Mean High Water Neap contour[15] allows some shingle to pass over the outfall during high waves and water levels, amounting to only a partial blockage. As the examples in Figure 1 show, the consequence is alternating patterns of localised erosion and accretion, with little net change. Similar effects might be expected were the HCDF to be exposed (i.e., in the absence of the SCDF) – see Section 7.4.2.2 of Appendix 20A of Volume 2 of the Environmental Statement (NNB Generation Company (SZC) Limited, 2020b).

The SCDF is designed to avoid such impacts by maintaining a blockage-free transport corridor between the HCDF and the sea. Maintenance after large storms (or gradual erosion) would be triggered when the eroded beach reaches a threshold that represents a minimum volumetric buffer sufficient to withstand further large storms.

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[12] Until the Cessation Report and associated actions have been agreed, as per the CPMMP (BEEMS Technical Report TR523).
[13] Shingle is primarily found above the low tide mark at Sizewell, which can thus be considered as the seaward boundary of the SCDF and the shingle transport corridor.
[14] Sizewell has a directional bi-modal wave climate (NE and SSE).
[15] 0.69 m ODN

Figure 1: Downdrift erosion and updrift accretion resulting from the partial blockage to longshore sediment transport caused by the Minsmere Sluice Outfall following NE (top) and SSE (bottom) storm conditions.

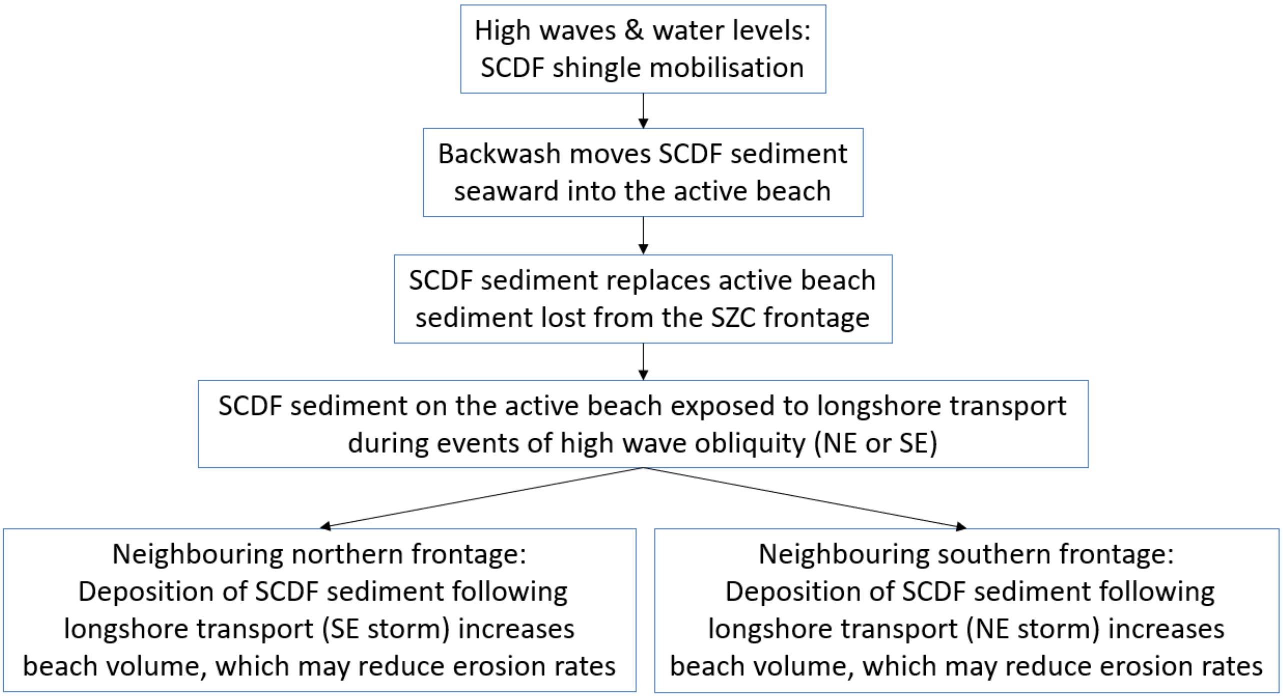

Figure 2: Simple box model describing sediment release from the SCDF and its pathways to neighbouring frontages.

SCDF erosion would occur when water levels are high enough to reach its pebble-sized sediments and wave run-up velocities are sufficient to mobilise them. Mobilisation of SCDF sediment and backwash would build volume on the beachface (as modelled and naturally observed (see BEEMS Technical Report TR545 and Dolphin et al., 2020), replacing sediments moved laterally away from their former resting place under longshore transport (either during the storm, or in subsequent storms if the initial event is an easterly storm). As a result, immediately neighbouring beaches may benefit volumetrically from the additional sediment supplied by the SCDF that would not otherwise be available. Over time, the erosion rates adjacent to the SCDF may be lessened, supratidal shingle may accumulate, and annual vegetated drift line species may colonise (as observed at Sizewell B). This process is shown as a simple box model in Figure 2. The gains in the sediment budgets of the neighbouring beaches are SCDF losses, which would need to be occasionally replenished by way of beach recharge. Note that coarse pebble-sized sediments are largely confined landward of the low tide mark with no losses offshore (NNB Generation Company (SZC) Limited, 2020b, Section 2.3.4.2).

The three primary design parameters used to increase the longevity of the soft defences are volume, crest elevation and particle size. The SCDF design seeks to optimise all three parameters to maintain the SCDF and avoid HCDF exposure whilst minimising intervention across the operation and decommissioning phases. Section 2.3 presents the SCDF topography and examines its volumetric properties whilst Section 2.4 sets out the approach for SCDF sediment composition and gives preliminary details on likely particle size ranges. These factors (volume, crest elevation and composition) are tested further using numerical models in Section 3.

2.2 Guidance and benefits

The SCDF is aligned with Pye and Blott's (2018) guidance that management of shingle features for FCERM purposes does not disrupt regional coastal processes and does not have negative impacts on other shingle feature interests such as vegetation, fauna, geomorphology, landscape quality and visitor appeal. Whilst works to recharge the SCDF may disrupt some local vegetation, any disruption would be temporary, infrequent and localised[16], and without replenishment any local vegetated shingle would be lost due to erosion anyway. That is, SCDF recharge would occur in areas where vegetation is naturally lost, replenishing the sediment there and facilitating potential re-colonisation of the supratidal habitat within the county wildlife site. The SCDF is also analogous to Pye and Blott's 'idealised' shingle beach management for FCERM (see Figure 3).

The SCDF is similar to the commonly used measure of a reprofiled sacrificial 'berm', which requires maintenance if the local sediment budget is negative (Pye and Blott, 2018), except that SCDF reprofiling is not intended[17]. The SCDF would supply sediment accessed, transported and re-profiled by natural coastal processes. Additionally, the beach shingle at Sizewell already experiences low rates of longshore transport and is confined in the Greater Sizewell Bay and above LAT, meaning that shingle losses are very low and that it will be possible to maintain a sufficient sediment supply via the *sacrificial* layer of the SCDF to maintain the beach level (as shown in Section 3).

The relative volume of sand in the SCDF would be kept low, to increase permeability and erosion resistance. This avoids cliffing[18] that can occur in recharge sediments where the sand volumes in mixed sediments are too high. Any cliffing that does occur would be the result of the natural mixing of sand volumes being exchanged between the subtidal and intertidal beach rather than a result of the SCDF. Review of experience on the UK's south coast (McFarland et al, 1994) found that finer material in the sediments used on gravel beaches leads to a more compact and less permeable beach, and a hard vertical face.

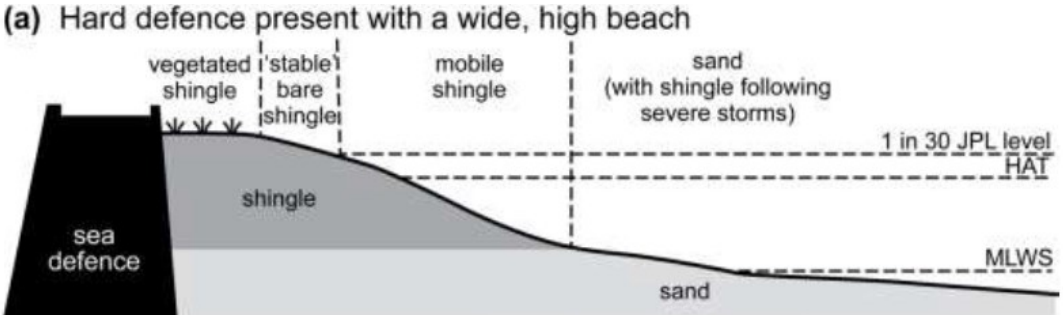

Figure 3: Schematic representation of evolutionary scenarios for hard defences with a fronting shingle beach, comparable to the proposed HCDF/SCDF (Figure 82, Pye and Blott, 2018).

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[16] Whilst the balance of where, when and how much to recharge will be determined by set thresholds and natural events (and is therefore inherently unpredictable), the erosion-resistant design features of the SCDF will function to maximise the interval between recharge events.

[17] Several authors have shown that efforts around reprofiling are ineffective as the beach will reshape itself toward a different equilibrium based in the first storm (Rogers et al., 2010).

[18] The formation of relatively small cliffs in beach sediment

Some of the sediment released from the SCDF will make its way onto the neighbouring shorelines, both north and south of the Sizewell C frontage[19]. Whilst the shoreline immediately to the south is relatively stable, the shoreline to the north is steadily retreating. The mode of retreat on the south Minsmere frontage (south of the Minsmere sluice outfall) is presently scarping[20], as the shingle barrier is presently too high and large for overwashing and barrier roll-back to occur. However, with time and sea level rise, infrequent overtopping can be expected to become more regular and, if unabated retreat continues, temporary breaching may occur, leading to saline intrusion of the freshwater hinterland habitats. Artificially increasing the sediment supply from the SCDF to this area (during south-easterly storms) has the potential to slow erosion rates. With sufficient time, this by-product of the SCDF could delay or avoid breaching on the southern Minsmere frontage (whilst the SCDF is maintained) and may widen the supratidal shingle zone (which is presently very narrow), potentially encouraging the return of drift line vegetation there (which needs a continuing supply of shingle; JNCC, 2019). Hurst Spit (Hampshire, U.K.) provides an example where shingle recharge has promoted colonisation of shingle vegetation (Bradbury (1998) and Bradbury and Kidd (1998)).

2.3 SCDF topography and volume

The SCDF is a reservoir of beach sediment conceptually divided into two main components:

- a landward safety *buffer* volume, V_{buffer}, which is not intended to be depleted or frequently exposed but is sufficiently large in itself to avoid HCDF exposure under severe storms and
- a seaward *sacrificial* volume, V_{sac}, which would be allowed to erode until V_{buffer} is reached, and would then be recharged (i.e., restoring the initial V_{sac}[21]). Effectively it is a ‘real-time’ recharge method for sediment losses that activates when natural swash motion draws SCDF particles onto the active beachface.

Therefore, the trigger to recharge would be V_{buffer}. For easy recognition, V_{recharge} is used to describe the threshold for recharge i.e., $V_{\text{recharge}} = V_{\text{buffer}}$. The rationale for the *buffer* component V_{buffer} is to protect against storms or storm sequences just prior to recharge, to cover uncertainty in performance predictions, and to improve robustness and performance.

Figure 4 illustrates these components in cross-section and plots a line to illustrate the V_{recharge} threshold; however, as the threshold is volumetric, the line is shown for illustrative purposes only. That is, many different beach profile shapes can produce a volume $V = V_{\text{recharge}}$.

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[19] Although the net longshore sediment transport is slowly to the south, it is the sum of gross transport events in opposing directions under individual storms from the NE and SSE. This means there is potential for transport of SCDF sediment during SSE storms onto the southern few hundred metres of the Minsmere frontage, where it may be retained.

[20] The eroding steep / cliffed front face of a dune or shingle ridge is called a scarp.

[21] Subject to the nature of foreshore erosion, restoring V_{sac} may require recharge across the subaerial beach, within the alongshore section where V_{sac} has reached V_{recharge}. The CPMMP will assess the recharge requirements in 50-m-wide alongshore cells across the 750 m SZC frontage.

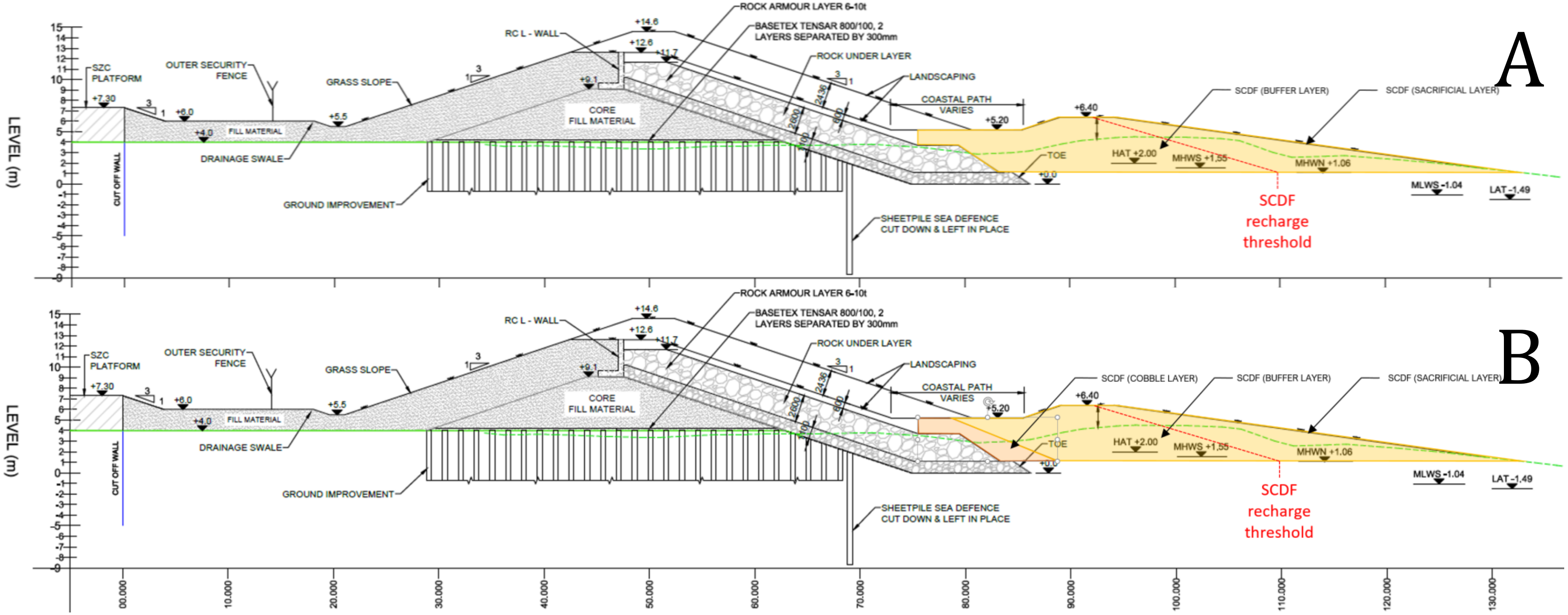


Figure 4: Schematic cross-sections of the hard and soft coastal defence features (HCDF and SCDF). Option **A.** The SCDF (yellow) is conceptually divided into two volumes, separated by the SCDF recharge threshold $V_{recharge}$ (illustrated by a red line). The SCDF *buffer* layer (whose volume is V_{buffer}) is not intended to be exposed, whilst the SCDF sediment to seaward is *sacrificial* (V_{sac}) and would be replenished once $V = V_{rechange}$. Option **B** is identical to Option **A** except it features a band of fine cobbles at the SCDFs landward extent (see Section 2.4.3). The dashed green line running through the SCDF is the present-day topographic cross-section.

2.3.1 SCDF topography and volume

The SCDF topography was developed in ArcGIS as a digital elevation model (DEM). Its primary features along the 750 m Sizewell C frontage are, approximately:

- A horizontal surface extending from the HCDF at 5.2 m (ODN);
- a 6.4 m (ODN) crest, which is similar to the present-day shingle ridge, albeit 1 – 2.4 m higher; and
- an initial seaward slope of approximately 8.3° (1:7) down to the active beach face (the slope is expected to change as coastal processes naturally rework the beach profile).

The 8.3° seaward slope of the DEM was based on a four-year record of natural beach slopes measured between mean sea level and highest astronomical tide, every 5 m along the Sizewell frontage (Figure 5). Contour lines were projected landward at 8.3° to the 6.4 m ODN crest to create the DEM. The northern side of the SCDF was modelled following a similar contouring process but respecting the SZC Main Development Site boundary; therefore, the slope of the SCDF was adjusted to gradually meet the natural topography before the property boundary. The contours were then rasterised and merged with the lower and subtidal beach topographic data. The SCDF topography is compared with the current topography in Figure 6.

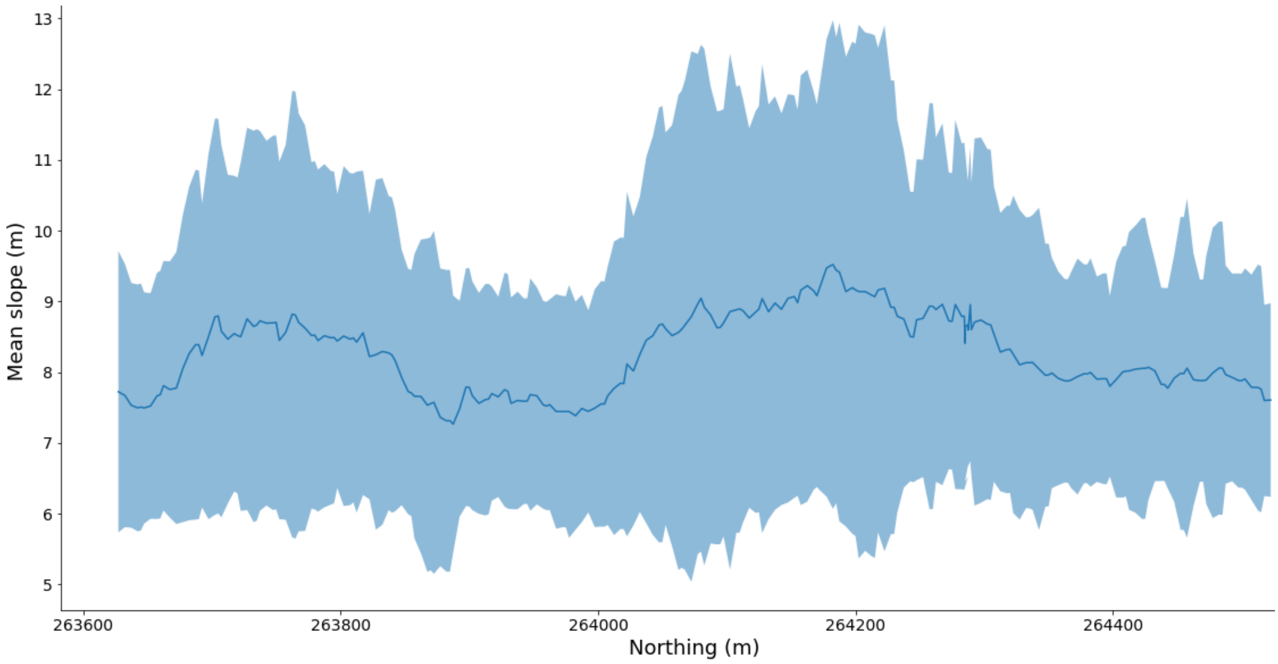
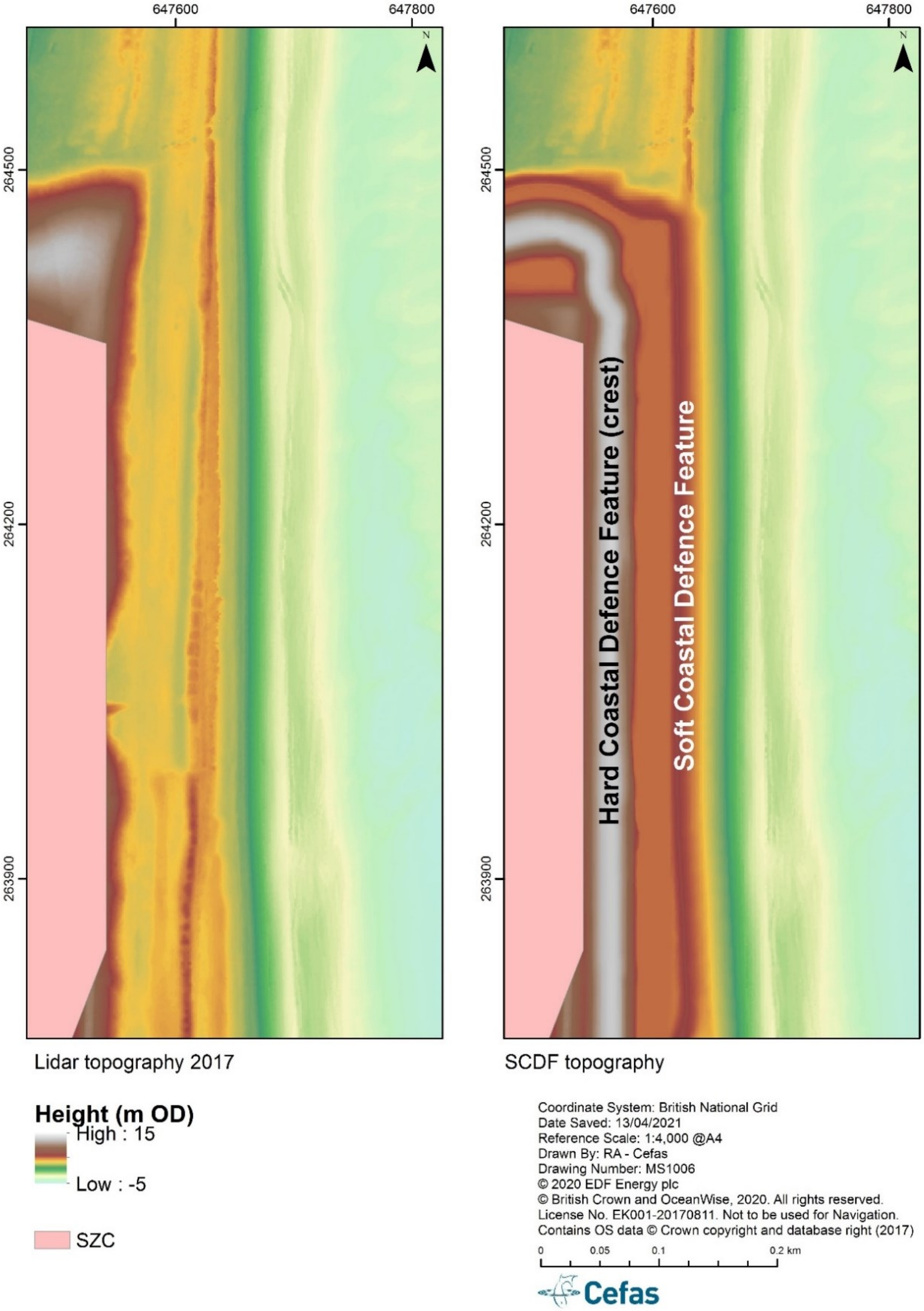


Figure 5: Beach slopes for the Sizewell frontage (°, MSL – HAT) from Sizewell B to just south of the tank traps located just to the north of the proposed Sizewell C site, showing the mean (solid line) and one standard deviation, every five metres.



Lidar topography 2017

SCDF topography

Coordinate System: British National Grid
Date Saved: 13/04/2021
Reference Scale: 1:4,000 @A4
Drawn By: RA - Cefas
Drawing Number: MS1006
© 2020 EDF Energy plc
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Figure 6: Topographic maps of the current and proposed SCDF topography.

Preliminary 1D storm erosion modelling has conservatively shown that a beach volume of 30 – 40 m^3/m would be sufficient to protect against a 1:12 year storm condition (defined using storms E1 and E2 in the 'Beast from the East' (BfE) storm sequence) for the predicted SLR in 2069[22] (BEEMS Technical Report TR531). The SCDF volume[23] shown in Figure 7 is substantially larger than the volume of sediment conservatively eroded by the modelled storm, indicating its viability. The proposed SCDF volume is 4 to 14 times larger than the modelled erosion of 40 m^3/m (2069 SLR case). The smallest volumes would be near the permanent BLF (162 m^3/m; see Figure 7 for location), rising to 260 – 300 m^3/m along the central and southern SZC frontage, whilst the maximum volumes just north of the north-east corner of the permanent BLF would be up to 557 m^3/m.

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[22] Based on modelling of a 0.4 m sea level rise (relative to 2020), which corresponds to the 95th percentile of the RCP4.5 UKCP18 climate change scenario in 2069. Model results over predict erosion and are highly conservative. 2069 is approximately halfway through the planned operation phase.

[23] Volumes were calculated above 0 m ODN and between the HCDF and the 0 m ODN contour.

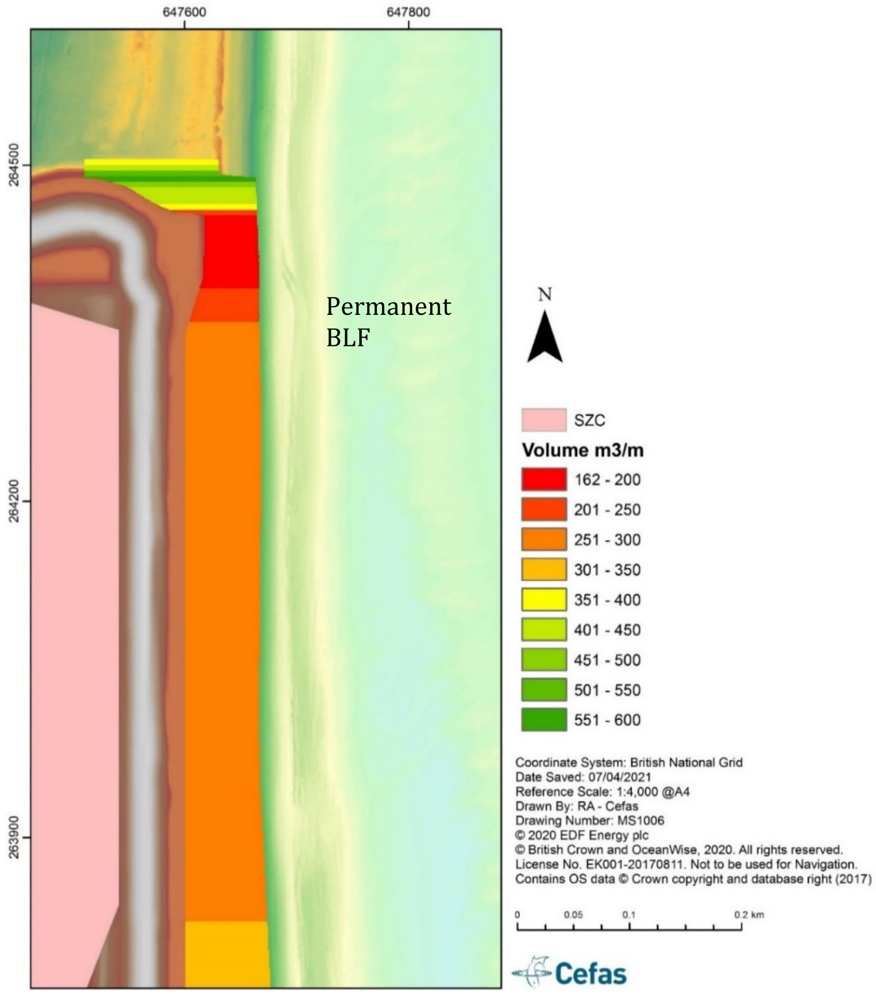

Figure 7: SCDF design volumes, expressed as m^3 per metre of alongshore beach frontage (m^3/m) and computed above 0 m ODN.

These volumes will be used to set the size of the SCDF safety *buffer* volume (V_{buffer}) and the *sacrificial* volume (V_{sac}). An initial suggested working value for V_{buffer} is 2 – 3 times the conservative storm erosion value of 40 m^3/m. At V_{buffer} = 80 – 120 m^3/m, V_{sac} would be in the range 42 – 477 m^3/m. The recent improvements in model performance (BEEMS Technical Report TR545 and Section 3 of this report) suggests that this value is larger than it needs to be and should be refined to a lower value, which would allow for a larger sacrificial volume and fewer interventions. However, until further modelling has completed (e.g., decommissioning phase), the initial suggested working values for V_{buffer} and V_{sac} have been retained in this report version.

2.3.2 SCDF crest elevation

The SCDF crest elevation has been set by SZC engineers at approximately 6.4 m ODN, which is 1 – 2.4 m higher than the standard of protection offered by the present-day shingle ridge on the SZC frontage (4 – 5.4 m ODN). Recent X-Beach G modelling of severe storms and sea levels up to 2099 has demonstrated that this SCDF is not overtopped (BEEMS Technical Report TR545). Overtopping per se is not of direct concern for the functioning of the SCDF, since its purpose of avoiding disruption to longshore shingle transport due to HCDF exposure will not be affected. However, overwashing of quantities of sediment sufficient to alter or mobilise the crest could lead to breaching and affect the integrity and maintenance frequency of the SCDF. To mitigate this, the crest elevation should be high enough to avoid heavy overwashing. It is worth noting any natural event mobilising or overtopping the 6.4 m ODN SCDF crest would also be expected to cause severe overwashing, roll-back and breaching across the Minsmere frontage, owing to the lower shingle ridge crest there – 85% of the natural Minsmere ridge is lower than the SCDF crest would be.

The present-day SZC shingle ridge is not presently overwashed and there is only limited evidence of overtopping, suggesting it is sufficiently high to defend against severe storms at the present sea level. For example, the BfE storm sequence (February – March 2018) did not breach or overwash the barrier at SZC, despite substantial reworking of the beach profile, barrier scarping and limited erosion of the shingle ridge toe (1 m retreat at 3 m ODN, no erosion at or above 3.5 m ODN; BEEMS Scientific Position Paper SPP094).

Although the shingle ridge is not presently overwashed, it is low in places (especially at the tank traps just north of SZC[24]) and with rising sea levels and no intervention (i.e., no SCDF), overwashing would be inevitable within the operation or decommissioning phases of the station. However, raising the current SZC ridge by 1 – 2.4 m means that the SCDF crest would be similar to, or substantially exceed, the sea level rise (SLR) predictions early in the SZC's decommissioning phase (2099[25]), which are:

- 0.55 – 0.83 m RCP4.5 (intermediate emissions scenario[26] 50th and 95th percentile respectively) and
- 0.78 – 1.14 m RCP8.5 (worst-case climate emissions scenario[27] 50th and 95th percentile respectively).

In 2099 (end of UKCP18 predictions and early in the SZC decommissioning phase[20]), the SCDF crest would still substantially exceed SLR associated with the intermediate emissions RCP4.5 UKCP18 scenario, and would exceed or be similar to the worst-case climate emissions scenario (RCP8.5). As the wave conditions are predicted to be similar or less than the present day for Sizewell (Lowe et al., 2018), it is reasonable to

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[24] BEEMS Technical Report TR545 shows that a breach would form at the tank traps under 2099 sea levels with high waves and a 1 m storm surge. The breach occurs with and without the SCDF but does not account for sediment supply from the SCDF to this area, which may over the intervening decades provide sufficient sediment to avoid a breach under the stated conditions.

[25] 2099 would be early in the decommissioning phase, assuming a 60-year-long operation phase.

[26] CO2 emissions continue rising until 2040 – 2045 and half the 2050 levels by 2100.

[27] RCP8.5 is considered to be very unlikely and has rising CO_2 emissions throughout the 21st century.

consider that the overtopping or overwashing potential will be significantly lessened at the start of SZC operation due to the SCDF crest height and would be similar to or less than that of the present day by early decommissioning (around 2099).

As the SCDF would be maintained through-out, gradual erosion would not lead to crest lowering.

2.4 SCDF sediment composition

This section sets out and justifies the general approach for SCDF composition (sedimentology). It uses the modified Udden-Wentworth particle-size classification shown in Appendix A. Two very similar particle-size options are presented that utilise coarse sediment particles to increase erosion resistance, beach stability and therefore longevity. This approach – using sediment coarser than the native size distribution – is commonly used for beach recharge schemes in the UK (Rogers et al., 2010). The SCDF uses a similar approach, although the SCDF's very coarse pebbles (Option A; Section 2.4.2) would be within, but at the coarse end of, the Sizewell particle size distribution. A second option would comprise a high percentage of very coarse pebbles but also include an internal layer of fine cobbles (Option B; see Section 2.4.3). In both cases, the aim is to increase beach stability and longevity of the placed sediments. Beach coarsening is considered suitable for the steepening intertidal zones of the East Coast of England (Rogers et al., 2010, p. 730). The scheme at Highcliffe (Dorset) is also highlighted by Rogers et al. (2010) as a successful example of shingle beach coarsening that showed good longevity, especially where the sediment had a narrow grading (1.5 – 4 cm; medium – very coarse pebbles). By comparison, sections at Highcliffe with sand and gravel mixtures performed less well and required minor recharges.

The SCDF composition would have a low sand volume to enhance its erosion resistant properties (by increasing permeability and hydraulic conductivity) and avoid more rapid sediment losses observed in mixed sediments. It would also avoid cliffing effects that can arise in mixed sand-gravel beach recharges.

2.4.1 SCDF sensitivity to particle size

Sand and gravel beaches respond to storms in fundamentally different ways. As sediment is coarsened, beaches tend to become more erosion resistant because of increased particle mass, making them more difficult to move. Additionally, the larger interstitial spaces between gravel sediments (compared to sand) interact with the wave swash motions running up and down the beach, reducing the energy available to move particles and affecting the sediment transport direction storms (often onshore, compared to sandy beaches that move sediment offshore).

The following two sections examine SCDF composition options. They were originally formulated (Version 1 of this report) based on literature and first principles of beach morphodynamics. They utilise the 'beach coarsening' approach to improve SCDF erosion resistance and longevity, thereby decreasing the maintenance and intervention requirements. In this 2nd Version, a new section at 3.1.2.4 examines modelled SCDF performance for a range of different particle sizes and quantifies the benefits of using medium to very coarse pebbles (10 mm and 40 mm particles are modelled) as described in Sections 2.4.2 and 2.4.3 below, for SCDF construction and maintenance. The new modelling also supports the use of an internal layer of fine cobbles (Section 2.4.3) which would effectively arrest erosion if exposed – the model results show no erosion under present and 2069 sea levels and minimal erosion at 2099 sea levels for an exposed cobble surface.

2.4.2 SCDF Option A: Very coarse pebbles

Option A uses very coarse pebbles (32 – 64 mm diameter; see the modelled 40 mm results in Section 3.1.2.4), which are at the coarse end of the native particle-size distribution, to prolong the longevity of the SCDF (see Figure 4A). Its function as a supratidal reservoir of sediment can be directly compared with the successful Sand Bay scheme (Weston-super-Mare, UK), which created a steep mixed sand-gravel berm on a sandy-muddy foreshore in 1983-4 (Rogers et al., 2010) and which has only recently (January 2021) needed maintenance.

The SCDF *sacrificial* layer is effectively a 'real-time' recharge method for sediment losses that occur during storms. That is, natural swash motion during storms is the mechanism by which SCDF particles would arrive on the active beachface from the supratidal. The use of sediments coarser than the native grain sizes on the active beach is well-established practice – Rogers et al. (2010) and Pye and Blott (2018) provide multiple examples from around the UK.

2.4.3 SCDF Option B: Very coarse pebbles with recessed cobble layer

Option B also uses very coarse pebbles across the majority of the SCDF, to prolong longevity. However, it features a band of cobbles[28] within the SCDF (see Figure 4B) to further restrict erosion in the unlikely event that the pebble *buffer* and *sacrificial* SCDF layers had been fully removed. It would further strengthen the SCDFs erosion resistance and reduce the risk of HCDF exposure. The cobble-sized sediments would have a degree of mobility (albeit less than coarse pebbles), constitute a beach morphology and facilitate continued longshore shingle transport due to its relatively smooth, mobile and dissipative sedimentary surface (compared to immobile and reflective rock armour of an exposed HCDF).

The rationale for using cobbles is drawn from the literature on artificial cobble composite beaches, which have been successfully deployed on high energy coastal systems and typically show low mobility. Cobble sediments (often fine cobbles[29] e.g., Allan and Gabel 2016) can be placed on the upper beachface for erosion prevention and are referred to as *cobble berms* or cobble revetments[30] (Lorang, 1991; Komar and Allan, 2010; and Weiner et al., 2019). Dynamic *cobble berms* are an effective form of soft coastal defence because the sloping, porous cobble beach is able to dissipate the wave energy by adjusting its morphology in response to the prevailing wave conditions.

Evidence shows that if the cobble berm mass and height are sufficient, only minor changes to morphology are observed, even in the face of very severe storms. However, key design parameters need to be correctly determined on a case-by-case basis. These include the sizes and types of cobble-sized sediment to be used, crest elevation and volume, as shown by Allan et al. (2005) for the very high energy coast of Oregon (USA). In an extensive examination of naturally occurring cobble beaches, they concluded that beaches containing larger volumes of cobble sediments (> 50 m^3/m) and larger widths were the most stable. For artificial cobble berms, they recommended a crest elevation of ~7.0 m (above low tide), mean grain-size not less than 6.4 cm (i.e., slightly larger than the very coarse pebbles proposed for the SCDF), and a beach slope of 11° (toward the steeper end of natural beach slopes observed at Sizewell; see Figure 5).

Similar conclusions on the importance of volume and widths are also provided by Allan and Gabel (2016) and Newkirk et al. (2018). Overall, the guidelines for high-energy Oregon/California (Pacific) coasts suggest that a stable cobble berm requires a crest width of c. 5 m, a volume of >50 m^3/m and a crest height ~ 0.8 *

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[28] The cobble size class has a diameter of 6.4 – 25.6 cm.
[29] The fine cobble sub-fraction has a diameter of 6.4 – 12.8 cm.
[30] Because of their relatively low mobility.

annual maximum water level (m). These parameters are a useful initial guide for the buried SCDF cobble layer design, but they (in particular, particle size, volume, width) are likely to be larger than required for Sizewell, due to the very large differences in wave climate. That is, Oregon experiences significant wave heights (H_s) of 10 – 14 m on a regular basis during winter months compared to Sizewell's maximum recorded H_s in 12 years and nine months of 4.72 m ($H_{s,mean}$ = 0.77 m).

Were the SCDF's cobble sediment layer to be exposed, it would still function as mitigation, allowing native pebbles to pass over it and to dissipate wave energy into its porous matrix. It would prevent HCDF exposure and thereby avoid wave reflection, turbulence and scour from the HCDF. During severe storm, cobble beaches tend to steepen and undergo landward transport, increasing the ridge height, which means that the SCDF cobbles would remain local and would not need to be recharged as volume loss is not expected.

It is important to emphasise that Option B's cobble layer draws upon the properties of cobble berms to provide increased erosion resistance were it to be exposed; however, unlike cobble berms it would be buried deep within the SCDF and so would only come in use if the pebble *buffer* and *sacrificial* layers were fully eroded. The use of a cobble berm would facilitate longshore transport of shingle (compared to an exposed HCDF) and aligns with UK beach recharge practices in which particles are often coarser than native sediments (see Rogers et al., 2010 and Pye and Blott, 2018).

3 Recharge interval

The Beach Management Manual (Rogers et al., 2010) suggests three broad categories of methods for calculating recharge volume requirements:

- simple methods based on historical beach volumes;
- calculations based on the beach profile response to design storms (the 'profile design method'), and
- detailed computational and physical modelling.

SCDF recharge frequency is considered in this report using two variations on the historical beach volume method (Section 3.1.1), and numerical modelling of sediment loss during large storms (Section 3.1.2). The profile design method (Powell, 1993) assumes placement directly into the active beach, rather than as a supratidal reservoir like the SCDF, and so is not considered here.

To estimate the interval between recharges the following steps are taken:

- Assume reasonable worst-case from the parameters available in this report.
- Set preliminary values for the *buffer* and *sacrificial* volumes:
    - Set the *buffer* volume as three times the conservatively modelled BfE storm with 0.4 m of SLR (2069)[31]. The factor of three is chosen to represent the (highly unlikely) occurrence of three sequential BfE style events without opportunity to recharge the SCDF. V_{buffer} = 3 x 40 m^3/m = 120 m^3/m. Note that the revised storm erosion modelling (BEEMS Technical Report TR545) suggests that V_{buffer} = 120 m^3/m is much larger than it needs to be, however it is presently retained as a conservative value and will be investigated further and revised accordingly as part of the developing Coastal Processes Monitoring and Mitigation Plan (BEEMS Technical Report TR523).
    - To ensure a conservative estimate, the *sacrificial* volume was set for the smallest SCDF volume on the SZC frontage (162 m^3/m; near the permanent BLF). $V_{\text{sac,min}}$ = 162 - 120 = 42 m^3/m.
- For each method, the loss from the *sacrificial* volume for a 60-year operation phase, expressed as a per year average rate of loss ($\bar{V}_{loss}$) was calculated.
- The recharge interval in years as RI = $V_{\text{sac,min}} / \bar{V}_{loss}$ was calculated
- Apply the Dutch Design Method (DDM) by assuming a further 40% on the loss rate (Verhagen et al., 1992 and Rogers et al., 2010).

Several layers of conservatism have been applied in these calculations to account for uncertainty:

- Calculations are based on the narrowest, lowest volume section of the SZC frontage.
- The model results used to set $V_{\text{sac,min}}$ are highly conservative – the model set up over-predicts erosion and shows losses several times greater than observed.

---

[31] The modelled 0.4 m SLR corresponds to the RCP4.5 95th percentile in 2069 (BEEMS Technical Report TR531). This intermediate date (2069) was chosen based on previous work in NNB Generation Company (SZC) Limited (2020b) and is approximately halfway through the operation phase. Further runs will be conducted to envelope the range of SLR expected over operation and decommissioning phases.

- A factor of three has been used to represent three sequential severe storms without SCDF recharge intervention. Note that there is no evidence to suggest the future wave climate would make such an event more likely, in fact UKCP18 predictions for Sizewell show similar or reduced wave conditions to the end of predictions (2099) (Lowe et al., 2018).
- Assessment of recharge requirements uses the narrowest frontage and specifies recharge once the small *sacrificial* volume is lost. HCDF exposure would also require loss of the *buffer* volume.
- The predicted volume lost is increased by a further 40% following the Dutch Design Method.

It should be noted that this method produces a broad estimate for the sediment losses and the recharge intervals. The actual losses will be determined by coastal processes and the need for recharge will be assessed by continuous monitoring throughout the operational period as a part of a structured Adaptive Environmental Assessment and Management process under the CPMMP.

3.1.1 Recharge requirements based on measured volumetric change

Sizewell Beach has been monitored by ground survey since 1991 and by spatially continuous Remotely Piloted Aircraft (RPA) survey available since 2016. These datasets allow estimates of future volume change and expected recharge requirements to be made from estimated and measured historical volume change.

3.1.1.1 Beach volume change based on RPA derived digital surface models

RPA surveys flown approximately monthly at Sizewell during 2016, and from 2019 onwards, were used to create digital surface models (DSMs). The coast between 262850N and 266100N (Sizewell Café to Minsmere Sluice Outfall) was divided into 5-m-wide bins at northings every 50 m, extending from the line of vegetation to the 0.71 m (Mean High Water Neaps) contour. Volumes for each bin were calculated for each DSM and used to derive annual equivalent volume changes between each bin in each RPA flight.

The histogram of volumetric changes between surveys (expressed per year) for all bins (Figure 8) shows that erosion and accretion are fairly balanced across the survey area i.e., the distribution is near symmetrical. This reflects the results of previous studies that show no net seaward loss of shingle, cross-shore exchange of sand in and out of the subaerial beach (subtidal sand is abundant), low longshore transport rates, and very low longshore shingle loss in the Minsmere to Thorpeness embayment (NNB Generation Company (SZC) Limited, 2020b).

Trend analysis of all RPA flights between 2016 and present, for each bin, shows that the beach has distinct zones of erosion and accretion (Figure 9). For the SZC frontage (263750N – 264500N), recent annualised rates (computed between sequential surveys) vary between -3.1 and +4.1 m^3/m per year.

Applying the most erosive rate observed on the Sizewell frontage of 3.1 m^3/m/year equates to 186 m^3/m or 139,500 m^3 across the frontage, for the station's 60-year operation phase. Considering the smallest sacrificial SCDF volume $V_{\text{sac,min}}$ = 42 m^3/m, which is near the permanent BLF (Section 2.3.1), for the whole frontage[32] gives a worst-case recharge interval of 13.5 years $= 42\frac{m^3}{m}/3.1\frac{m^3}{m.yr}$ or 4.43 recharge events over the operation phase. Applying the DDM (i.e., increasing the annual loss rate by 40%) reduces the RI to 9.7

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[32] Setting V_{sac} = 42 m^3/m for the whole frontage is a substantial underestimate as V_{sac} is much larger across most of the frontage. SCDF design volumes, expressed as m^3 per metre of alongshore beach frontage (m^3/m) and computed above 0 m ODN.Figure 7 shows that 85% of the SCDF's 750-m-length would have a volume > 250 m^3/m, which gives V_{sac} > 120 m^3/m, almost three times greater than the 42 m^3/m used here for worst case.

years. These results suggest that the permanent BLF frontage (where V_{sac} is smallest) would require SCDF recharge up to 6 – 7 times over the operation phase. The estimated recharge interval should be considered as an average – the actual RIs are likely to be longer at the start of the operation phase and shorter by the end, due to sea level rise.

It is important to acknowledge that the worst case 3.1 m^3/m rate of change was for one survey pair (i.e., the volume change between one pair of sequential surveys) and at one location only. Applying this rate from one location and one moment in time to the whole SZC frontage is highly conservative. Nonetheless, the RI is based on the greatest erosion observed over a relatively short (but spatially comprehensive) record (2016 – present). Therefore, a longer record is also considered to make a second RI estimate based on historical shoreline recession (Section 3.1.1.2).

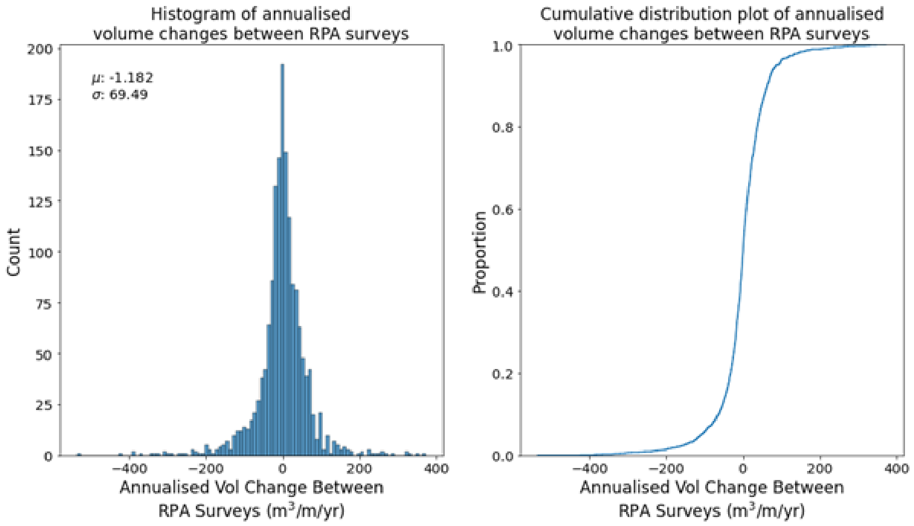

Figure 8: Histogram and CDF plot of aggregated volume changes between all RPA flights for 5 m bins every 50 m between Sizewell Café and the Minsmere Sluice Outfall (262850N and 266500N).

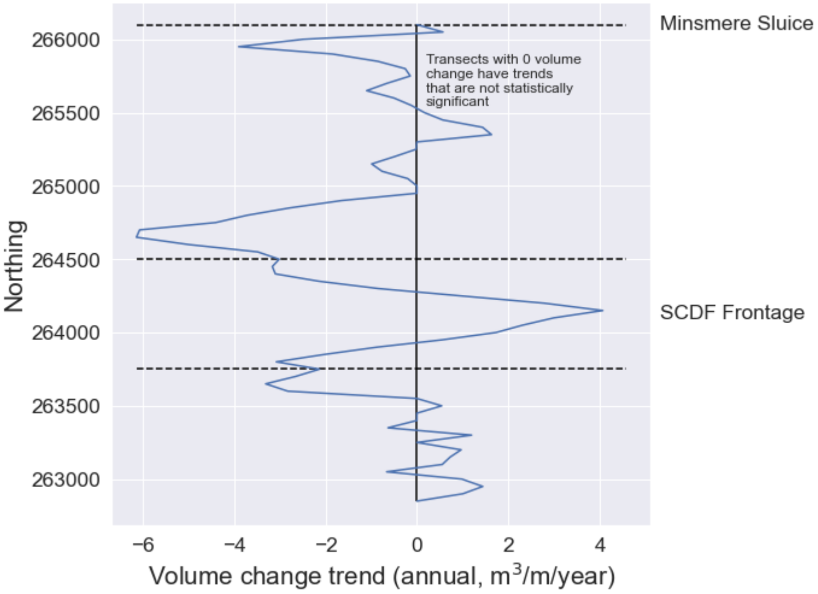

Figure 9: Annual volume change at each northing value derived from a linear regression fit over the time series of all RPA flight volumes for each northing.

3.1.1.2 Historical beach volume change based on shoreline movement

Data presented in BEEMS Technical Report TR223 suggest that change in beach volume above mean sea level (0.11 m) is strongly correlated with movement landward or seaward of the beach contours. This is not unexpected as the shingle barrier has not begun to roll-back, so incremental shoreline recession should equate to a proportionate decrease in volume. Farris and List (2007) also observed a strong correlation between shoreline and beach volume change – their analysis of 54 profiles, each surveyed 48 times, gave a mean $r^2 = 0.84$ and led to their conclusion that shoreline change is a useful proxy for subaerial beach volume change.

Figure 10 shows a clear correlation between changes in the beach volume and the position of the mean sea level shoreline between Dunwich and Thorpeness (based on almost 30 years of data). It suggests a relatively uniform rate of volume loss or gain (between 2 and 4 m^3/m) per metre of shoreline retreat or advance for the whole coastline.

The relationship between shoreline change and volume change varies from location to location, as shown in Figure 11. With the exception of profile S1B4, all profiles between Dunwich and Thorpeness produce a volume of around 2 - 3 m^3/m per metre of shoreline change. At Sizewell C, profile S1B5 is toward the upper end of the typical range at 2.7 m^3 for each metre of shoreline retreat and has a shoreline retreat rate for the 1991 – 2018 record of 0.11 m/yr (NNB Generation Company (SZC) Limited, 2020b).

The near zero rate at profile S1B5 over almost three decades is due to cyclical shoreline behaviour. In volumetric terms, the 0.11 m/yr retreat equates to a loss of 0.3 $m^3/m/yr$ or 18 m^3/m when extrapolated across the 60-year operation phase (13,500 m^3 for the whole SCDF). Were the beach to retain the same cyclical behaviour, SCDF recharge would not be required because the loss of 18 m^3/m is less than the conservative $V_{sac,min} = 42\ m^3/m$. Although this estimate includes a component of SLR (that which occurred between 1991 and 2018) and several conservative factors (listed at the start of this section), it does not account for accelerating future SLR, and so may be an under-estimate. Storm erosion modelling from BEEMS Technical Report TR545 is used in Sections 3.1.2.2 – 3.1.2.4 to fully consider the erosion and maintenance requirements for the SCDF under future sea level rise cases (2069 and 2099).

The peak erosion rate over a 10-year period, which captured a phase of more rapid shoreline change at S1B5 (SZC). The fastest retreat rate observed was 2.23 m/yr (6 m^3/m per year), which is higher than the persistent erosion hotspot between SZC and Minsmere Sluice Outfall (S1B5: average and peak (10-year) retreat rates of 1.01 and 2.07 m/yr respectively). During the erosive phase of a cycle, recharge may be triggered, only to be followed by a natural recovery phase resulting in larger volumes and little or no further recharge.

Using the peak 10-year retreat rate (2.23 m/yr) as a preliminary worst case by assuming it persists across the station life rather than cyclical behaviour, and applying Vsac,mon = 42 m^3/m as before, gives a recharge interval (RI) of 7 years $= 42\frac{m^3}{m}/6\frac{m^3}{m.yr}$. Although there is no persistent historical trend at SZC, and noting the 2.23 m/yr rate is worse than the average and peak rates of erosion at the S1B5 erosion hot spot (between SZC and Minsmere Sluice; 1.01 and 2.07 m/yr respectively), the total recharge requirement would be c. 270,550 m^3 across the operation phase.

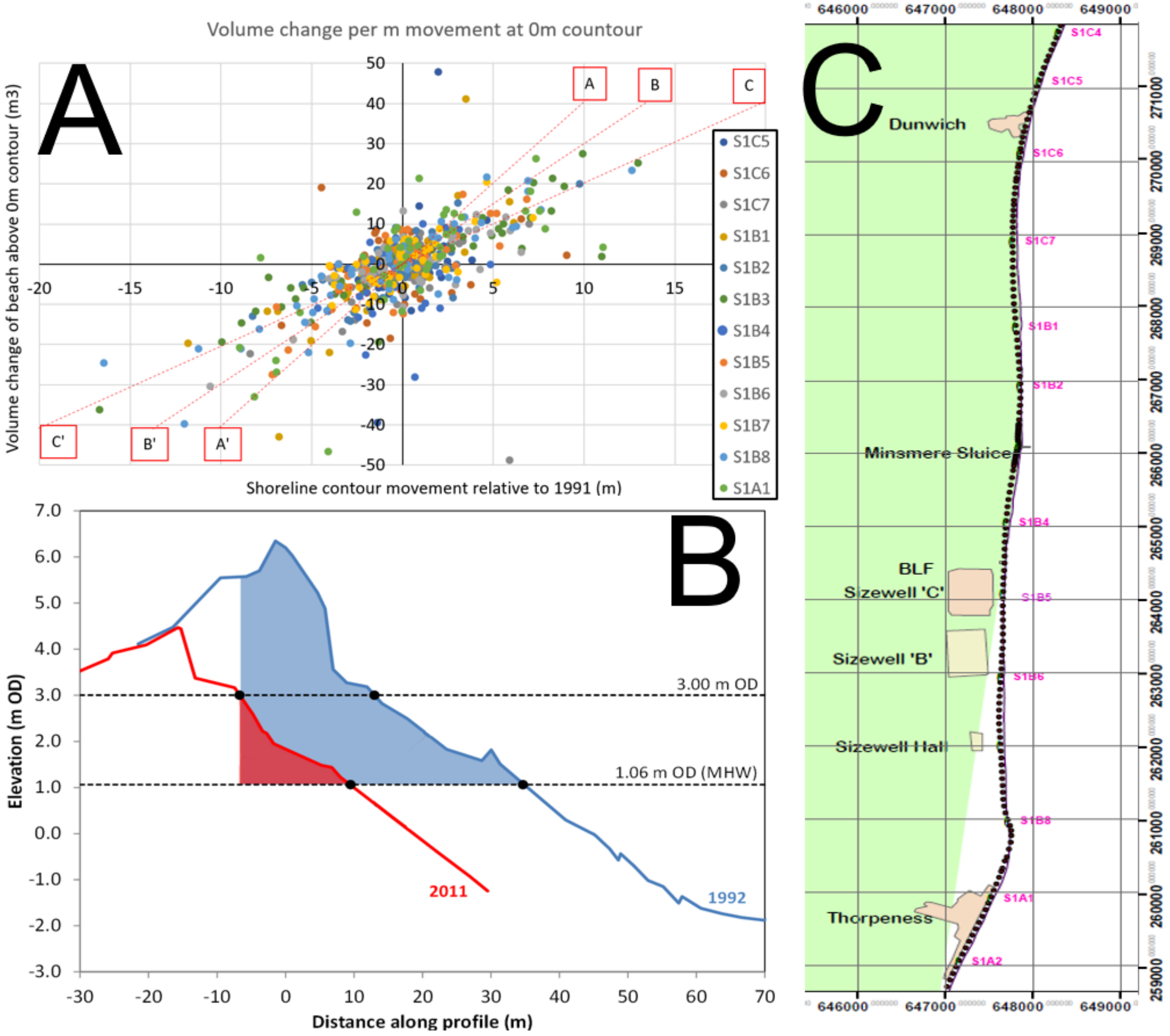

Figure 10. Volume changes as function of shoreline movement for the 0 m ODN contour (**A**) on Dunwich - Thorpeness frontage for 1991 - 2018, calculated as per (**B**). Red dashed lines in **A** represent indicative volume loss of 4 m^3/m per metre of retreat (A-A'), 3 m^3/m (B-B') and 2 m^3/m (C-C'). Panel **C** shows the locations of each Environment Agency profile corresponding to the legend and coloured points in panel **A**.

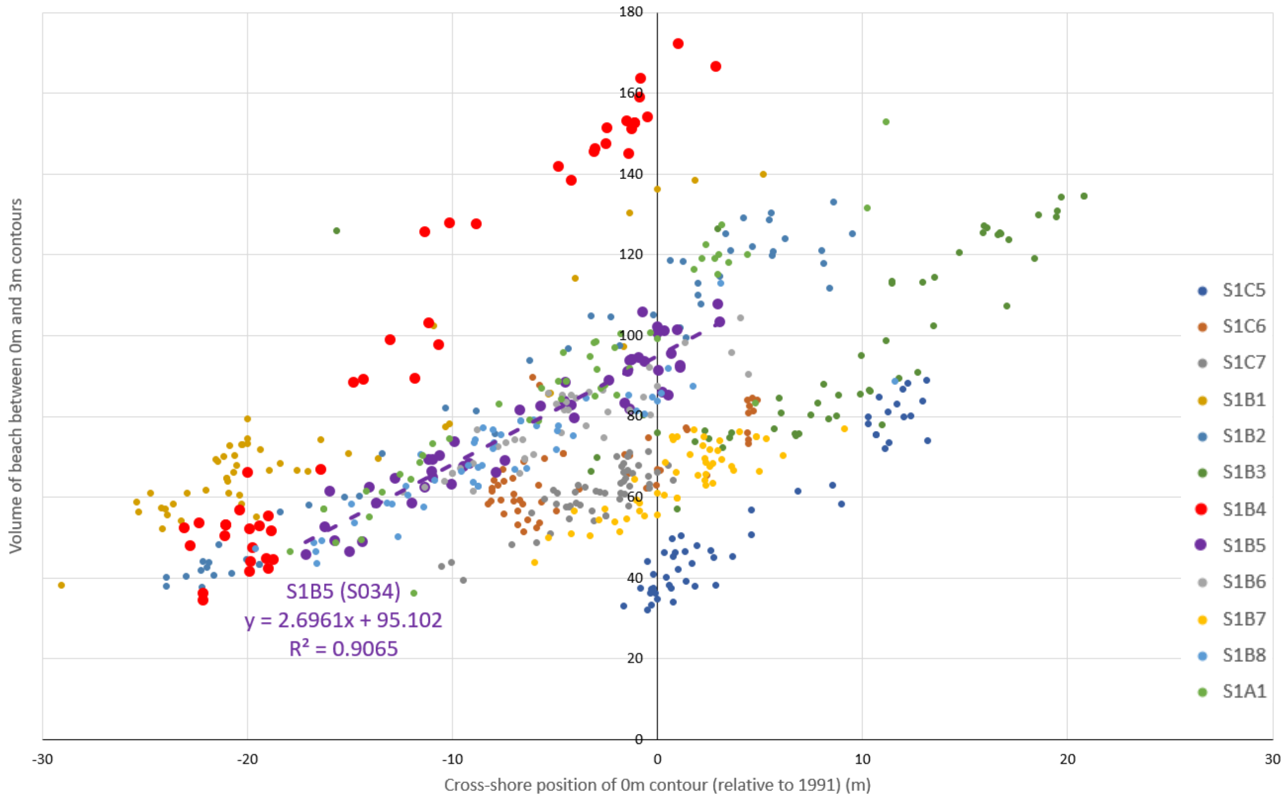

Figure 11. Beach volume changes as function of absolute position for separate EA profiles (1991 – 2018) to illustrate their uniformity, with a statistical best fit line shown for profile S1B5.

3.1.2 Modelled storm erosion and recharge requirements

Sizewell Beach is a complex composite beach consisting of a sandy subtidal, a mixed sand and gravel intertidal and a gravel (pebble class) supra-tidal. Numerical models have not yet been developed to account for this level of complexity, as discussed in Section 2.1 of BEEMS Technical Report TR545. Therefore, the XBeach modelling suite[33] was selected to consider storm erosion for a range of sediment sizes at Sizewell – this modelling is detailed in BEEMS Technical Reports TR531 and TR545. The separate sand and gravel models envelope the range of likely responses, with a high degree of conservatism due to the erosion over prediction from the sand models (for Sizewell Beach). The likely sediment demands to maintain the SCDF over time are expected to be closer to the XBeach-G (gravel) results, owing to its more accurate representation of the processes that shape gravel beaches. However, the XBeach-G model used is not currently fully calibrated[34].

The modelled storm erosion results are used to examine the performance of the SCDF under severe storms and to make further estimates of the RI (in addition to those made in Section 3.1.1). The modelling

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[33] XBeach sand can model sand sizes up to 2mm grain size and has 1D (cross-shore profile) and 2D (areal) versions, the latter allowing consideration of longshore transport. XBeach-G is a 1D model for gravel sized sediments, ranging from 2 – 80 mm.

[34] Whilst the XBeach-S model is calibrated to observations of the existing beach at Sizewell, the XBeach-G model is not strictly calibrated to Sizewell or the SCDF as data does not exist, for example for hydraulic conductivity (the ability of water to infiltrate and exfiltrate through the gravel beach). However, the model is parameterised based on suitable published calibration studies.

conservatively considers the erosion phase of storms only, not recovery. In most cases, a fully recharged SCDF is sufficiently large that the volumetric trigger for mitigation would not be activated, following which natural recovery would occur. Therefore, the need to mitigate is most likely to arise from a combination of episodic storm events and gradual erosion (e.g., partial recovery from storms).

The following three sub-sections explore volumetric erosion and the potential requirements to maintain the SCDF – recharge intervals:

XBeach sand 1D (Section 3.1.2.1). Section 3.1.2.1 is based on the preliminary XBeach 1D storm modelling for sands reported in BEEMS Technical Report TR531 – this section has not changed since Version 1, Version 2.

XBeach sand 2D (Sections 3.1.2.2 and 3.1.2.3). Subsequent to BEEMS Technical Report TR531, the XBeach model calibration was refined to give more accurate results (though still conservatively over-predicting erosion) and run using the 2D (sand) version of the model (see BEEMS Technical Report TR545). Unlike XBeach 1D (sand), XBeach 2D incorporates longshore sediment transport, allowing sediment to be moved from one coastal section to another under storms with oblique waves. This means that spatial patterns can be examined to identify the location and magnitude of the worst-case erosion along the Sizewell C frontage (see Figure 14, for example). The demand for sediment during storms is investigated using the XBeach 2D outputs for three sea level scenarios and present day and future (severely receded) shorelines (Sections 3.1.2.2 and 3.1.2.3, respectively).

XBeach-G (gravel) 1D (Section 3.1.2.4). XBeach-G model results are used to examine SCDF performance and RI variation for different SCDF (particle size) compositions (Section 3.1.2.4). Unlike the 1D and 2D sandy versions of XBeach, the XBeach-G model can account for water movement into and out of the larger interstitial spaces[35] between gravel beach particles. Accounting for this is important as, on real-world gravel beaches, swash and ground water processes exert strong controls on sediment transport and beach evolution, and make gravel beaches more difficult to erode compared to their sandy counterparts.

3.1.2.1 XBeach 1D storm erosion modelling (sand) – BEEMS Technical Report TR531

Section 2.3.1 described the preliminary modelling undertaken to estimate storm erosion during the first two storms in the BfE storm sequence, which together equate to a 1:12 year storm energy return interval (see BEEMS Technical Report TR531 for details). The modelling results are highly conservative (i.e., they overpredict erosion) but are used instead of measurements as the BfE post-storm survey was 2.5 months after the storms (during which some recovery is likely to have occurred). The UKCP18 predictions for reductions in Sizewell's wave climate[36] suggest no increase of wave climate or storms.

The modelling predicted 30 – 40 m^3/m of storm -event erosion for a 0 – 0.4 m SLR, whereas the observed worst-case loss along the SZC frontage was less than 1 m^3/m (a net sediment gain was observed for the whole profile after 2.5 months). Bearing in mind that (i) sand supply is expected to remain similar or increase (Brooks and Spencer, 2012), (ii) shingle is effectively confined to the system (and is also likely to increase once Dunwich Cliffs begin to erode) and (iii) the model result is conservative and preliminary, a conservative

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[35] Called infiltration and exfiltration.

[36] Lowe et al.'s (2018) regional analysis gives small reductions in mean significant wave height at Sizewell (RCP4.5 = -1.7% and RCP8.5 = -3.3%) but larger reductions in the annual maximum significant wave height, which are more representative of the storm wave climate (RCP4.5 = -2.6% and RCP8.5 = -12.3%).

40 m^3/m net loss every 12 years applied across the 60-year operation phase would equate to a volume required for recharge of 200 m^3/m (150,000 m^3 or 3.33 m^3/m per year, for the SCDF frontage).

Using $V_{sac,min}$ = 42 m^3/m for the whole frontage gives a worst-case recharge interval of $42\frac{m^3}{m}/3.3\dot{3}\frac{m^3}{m.yr}$ = 12.6 years (5 recharge events). Applying the DDM reduces the interval to 9 years. This result suggests that the permanent BLF frontage (where V_{sac} is smallest) may require SCDF recharge 6 – 7 times during the operation phase. The estimated recharge interval should be considered as an average – the actual RIs are likely to be longer at the start of the operation phase and shorter by the end, due to sea level rise.

This approach assumes only the BfE style events lead to net loss, the sea level is 0.4 m higher than present (2020) and unchanging for the SZC operational phase, and that the model is accurate. It is therefore approximate.

3.1.2.2 XBeach 2D storm erosion modelling (sand) – sea level rise cases

XBeach 2D sand modelling simulates cross-shore and alongshore hydrodynamic and morphodynamic processes to estimate the storm erosion during storms. The model was run for sea level rise cases (RCP4.5 95th percentile) in 2069 and 2099, representing the middle and end of the Sizewell C operation phase. By 2099 this also marks the end of the UKCP18 RCP4.5 climate change predictions. The UKCP18 predictions suggest no increase of wave climate or storms at Sizewell. However, in order to examine erosion from a more severe storm, the 2D modelling considered all three storms in the Beast from the East (BfE) storm sequence[37], which is a 1:107 year return interval event in terms of cumulative wave power (see Appendix B of BEEMS Technical Report TR543). Statistically speaking, such a storm would not be expected more than once within the operational phase of Sizewell C.

Comparison of the modelled erosion with the notional minimum sacrificial buffer of 42 m^3/m described in Section 2.3.1 shows that the 1:107 year BfE sequence would not deplete the sacrificial buffer at any location for the present day or 2069 sea levels, however in 2099 up to 45 m of the SCDF frontage would lose slightly more than 42 m^3/m (up to 45.2 m^3/m; see Table 1 and Figure 14). Bearing in mind the conservative nature of the 2D sand model, these results suggest that storms are unlikely to trigger recharge mitigation during the operation phase if the SCDF is at or near full capacity. However, net erosion over years to decades, most likely due to storm events with partial volumetric recovery, would make some areas more prone over time. Assuming basic erosion trends remain consistent, monitored gradual erosion will provide a useful early marker for the location of future recharge and likely volumes.

Using the methods established in Section 3.1.2.1, the recharge intervals are calculated for a sacrificial buffer of 42 m^3/m. The RI's were calculated from the assumption of one BfE event occurring throughout the 60-year operational period and are based on spatial statistics of the modelled erosion: the mean, the mean with one standard deviation (STD) and the maximum erosion modelled along the SCDF (Table 1). These three different erosive rates encompass spatial differences along the SCDF frontage. The mean erosion rate is largely a good representative of the southern half of the SCDF frontage whilst using the mean with one STD allows a more conservative approach (over-estimation of erosion). The maximum erosion rate is representative of the SCDF at the permanent BLF abutment, which is also where the SCDF volumes are lowest (owing to the more seaward position of the HCDF). Therefore, for each sea level case, the RI's are calculated for these three statistics.

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[37] Whereas the preliminary modelling only considered the first two storms – a 1:12 year return interval for cumulative wave power, as described in Section 3.1.2.1.

At present day sea levels (the 2020 scenario), the 2D model predicted a mean sediment loss of 17 m^3/m from the BfE storm along the SZC frontage, which is substantially less than the sacrificial buffer as $V_{sac,min}$ = 42 m^3/m. Like all of the 2D model results, the erosion is substantially less than the preliminary modelling owing to refined model calibration. The mean results in Table 1 and Figure 12, which are a good indicator for the southern half of the SCDF, suggest that recharge may not be needed there across the operation phase (i.e., for all three sea levels modelled). Even with the DDM applied, the RI's were only 78 and 64 years for 2069 and 2099 sea levels respectively.

The more conservative approach of adding a standard deviation to the mean reduces the initial RIs by approximately 40% compared to the mean. The initial RI in 2020 reduces from 148 years to 107 years, and further to 77 years applying the DDM. Inclusion of the DDM suggests that projected 2069 sea levels may require a recharge as the RI falls to 55 years and 46 years by 2099.

Using the maximum modelled erosion rates, representative of the permanent BLF abutment area, produces the lowest RIs with only the 2020 scenario suggesting that no recharge would be needed (RI = 64 years). By 2069 there is a maximum loss of 38 m^3/m but a recharge is still implied within the operational period if applying DDM (RI of 47 years). The only scenario that produces a sediment loss larger than the $V_{sac,min}$ is in 2099 when the sediment loss is 45.2 m^3/m. This implies that a recharge would be needed after one BfE storm event in 2099, but only across the c. 100 m long BLF abutment frontage.

Figure 12 highlights the rising pressure of SLR on the SCDF, extrapolating the points every ten years through to 2110, which is approximately ten years after the scheduled end of operation. In its tabular form (Table 1), this will form part of the Coastal Processes Monitoring and Mitigation Plan, and be assessed on a decadal basis alongside the actual progression of sea level rise to ascertain whether sea level rise and the likely demand for recharge is greater or less than that predicted, and to revise plans and expectations accordingly as part of a structed Adaptive Environmental Assessment and Management process under the CPMMP.

These predictions assume only the BfE style events lead to net loss, the sea level rates are as per the UKCP18 climate predictions for the respective years of 2069 and 2099 (RCP4.5, 95th percentile), and that the model is accurate. It is therefore an approximate guide but the sand model overpredictions of erosion contribute to conservative estimation, as do the other factors listed at the start of Section 3. Any actual losses will be determined by coastal processes and the need for recharge will be assessed by continuous monitoring.

Table 1: Predicted recharge intervals (RIs) with DDM applied calculated from exponential trendlines fitted in Figure 12, and interpolated every 10 years. 2020, 2069 and 2099 RIs are calculated from the modelled sediment losses (shown in brackets).

	Predicted RI's (years)		
Year	**Mean**	**Mean + 1STD**	**Maximum**
2020	*106 (17 m³/m)*	*77 (23.5 m³/m)*	*64 (28.2 m³/m)*
2030	100	72	60
2040	94	67	57
2050	88	63	53
2060	82	59	50
2069	*78 (23 m³/m)*	*55 (32.6 m³/m)*	*47 (38.0 m³/m)*
2080	73	52	45
2090	68	49	42
2099	*64 (28 m³/m)*	*46 (39.0 m³/m)*	*40 (45.2 m³/m)*
2110	60	43	37

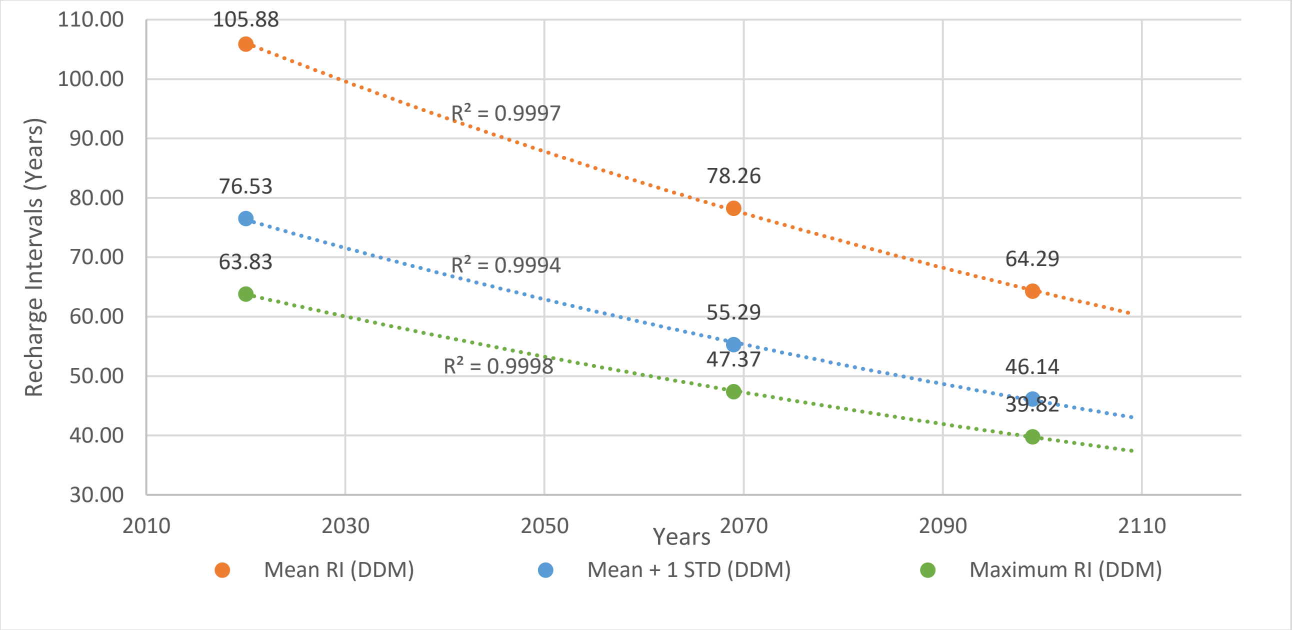

Figure 12: Recharge Interval (RI) in years with the Dutch Design Method (DDM) applied calculated from the mean erosion rate, maximum erosion rate and the mean erosion rate with 1 STD. Exponential trendlines were fitted to each set of rates.

3.1.2.3 XBeach 2D storm erosion modelling (sand) – receded lateral shorelines

In addition to the effect of sea level rise (Section 3.1.2.2), misalignment between the maintained SCDF shoreline and a future, naturally eroded, adjacent coast could further increase erosion pressure on the SCDF. To consider the effects of such lateral shoreline recession on the SCDF, a potential post-decommissioning shoreline[38] was converted into digital bathymetry for XBeach 2D modelling (see BEEMS Technical Report TR545). The expectation was that gradients in longshore transport during storms would preferentially erode the SCDF at its north and / or south extents, increasing the likelihood of localised recharge.

The modelled case for sea level rise case in 2099 is considered with the receded lateral shorelines bathymetry to examine worst case effects for the operation phase. The modelled bed elevations for the present day and receded lateral shorelines are shown in Figure 13. The same model conditions used in Section 3.1.2.2 apply here including the Beast from the East storm sequence.

In 2099 with a receded future shoreline, the rates of erosion rose significantly compared to the scenario with a present-day shoreline. The mean volume of sediment loss almost doubled from 23 m^3/m to 44 m^3/m with receded lateral shorelines (which just exceeds the sacrificial buffer of 42 m^3/m), however the erosion is not evenly distributed, as shown in Figure 14. Instead, the erosion is preferentially on the northern half of the SCDF with losses ranging from 40 – 82 m^3/m. The maximum erosion rate of 82 m^3/m at the BLF abutment is more than double the sacrificial volume and so would trigger mitigation, however, it is not sufficient to deplete the SCDF buffer layer, with at least a further 82 m^3/m between the sea and the HCDF. It is worth noting too that these results are for the 2D sand model which overpredicts erosion.

For the BLF abutment area, the resultant RI is 31 years in 2099 with laterally receded shorelines, reducing to 22 years when applying the DDM.

The southern endpoint of the SCDF may also become more prone to erosion if laterally receded shorelines arise, although to a lesser degree than in the northern endpoint. After one BfE storm event there is a 10 m section at the southern SCDF where sediment volume remaining is as low as ~ 124 m^3/m, which is very close to the buffer volume of 120 m^3/m. Therefore, more frequent localised recharge may be needed in this area if monitoring, as part of the structured Adaptive Environmental Assessment and Management process within the CPMMP, demonstrates receded lateral shorelines.

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[38] See Section 7.7 of Chapter 20, Volume 2 of the Environmental Statement (NNB Generation Company (SZC) Limited, 2020a).

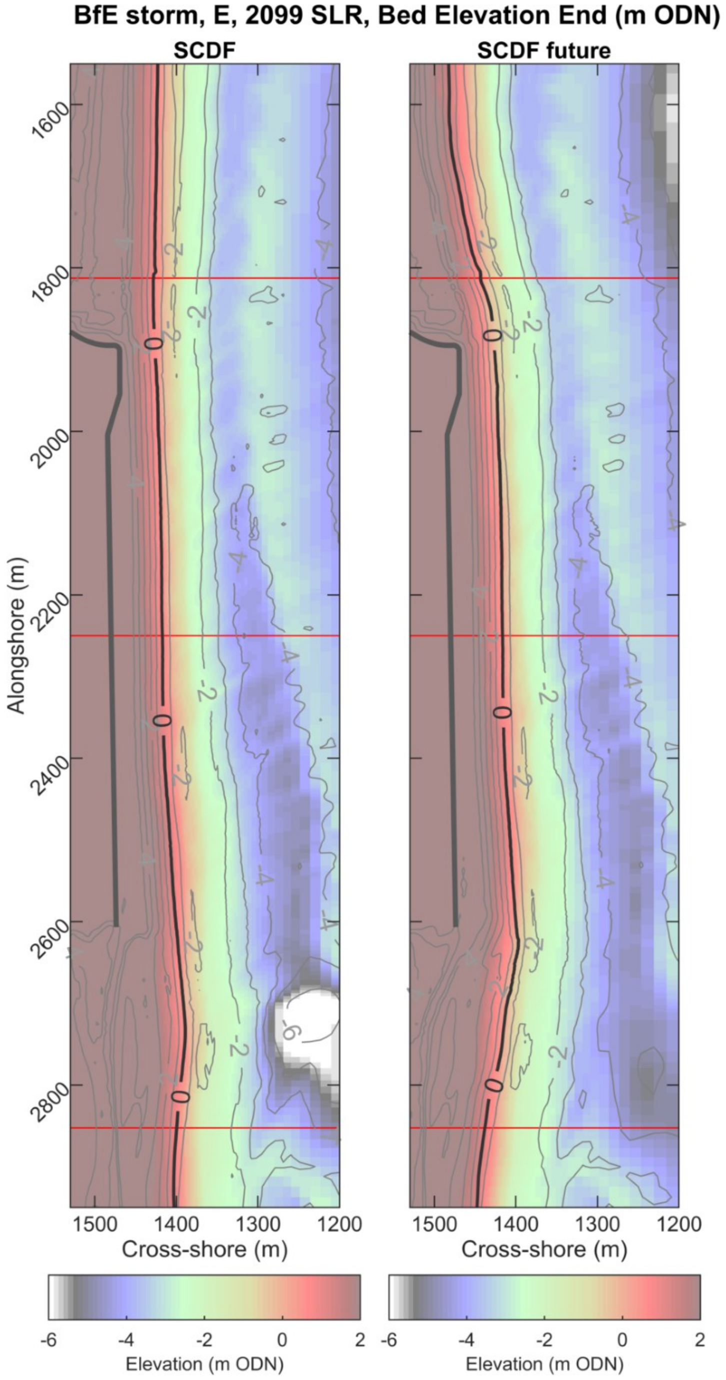

Figure 13: The Beast from the East storm, 2099 Sea Level – Post-storm bed elevation for the SCDF with present-day shoreline (left) and SCDF-future shoreline position (right) cases. (BEEMS Technical Report TR545)

The buffer volume of 120 m³/m was chosen in Section 3 to represent a highly unlikely occurrence of three sequential BfE style events occurring before the SCDF could be recharged (which is considered to be precautionary). However, in this scenario, which is specific to the BLF abutment where SCDF volumes are smallest, the potential maximum loss of 82 m³/m would leave only enough sediment within the buffer volume for one sequential event of the magnitude of the BfE (Figure 14). However, the return interval of such an event makes this an unlikely occurrence and the modelling used in these calculations is conservative, overpredicting erosion. These results highlight that the permanent BLF abutment area is prone to erosion and at greatest risk of HCDF exposure. Therefore, rapidly recharging this relatively short section of coast will be important to prevent erosion following an unlikely second BfE style storm sequence.

These predictions assume only the BfE style events lead to net loss, the sea level rates are as per the UKCP18 climate predictions for the respective years of 2069 and 2099 (RCP4.5, 95th percentile), and that the model is accurate. It is therefore an approximate guide but the overprediction of erosion by the sand model leads to conservative estimation. As mentioned in Section 3.1.2.2, a proposed re-evaluation of the 2D models every ten years would include this scenario, with updated SLR information. Any actual losses will be determined by coastal processes and the need for recharge will be assessed by continuous monitoring.

3.1.2.4 XBeach-Gravel and the effect of particle size on recharge intervals – BEEMS Technical Report TR545

Whilst the XBeach2D modelling used in Section 3.1.2.2 can simulate sediment transport in any direction, importantly capturing longshore transport behaviours during storms, it is only available as a sand model. This means that, even with calibration, it overpredicts the erosion for Sizewell's pebble dominated intertidal and supra-tidal zones whereas XBeach-G can simulate the dominant pebbles at Sizewell, accounting for the larger particle mass and the swash infiltration and exfiltration[39] that is important for sediment transport and erosion/accretion. In correctly accounting for these two factors, XBeach-G provides a more realistic account of storm evolution, albeit without longshore transport (as the model is 1D). The 1D model is considered appropriate for understanding SCDF erosion potential as all the storm energy is focussed on beach erosion and cross-shore transport (offshore, from the subaerial SCDF beach).

The behavioural differences between the sand and gravel models are illustrated by erosion rates of 159 - 464% times greater in the sand model (D_{50} = 0.8 mm) compared to the smallest particle size used in the gravel model (D_{50} = 2mm). The sand model was deliberately used in order to account for longshore transport and to provide conservative results as a test of SCDF performance and viability (examined by way of the recharge intervals in Sections 3.1.2.1 – 3.1.2.3). However, as the SCDF will be dominated by gravel sediments (most likely medium – very coarse pebbles), the recharge intervals are likely to increase with the increasing SCDF particle size, as the remainder of this section shows.

As noted above, the hydrodynamics in XBeach-G account for swash-groundwater interactions, which are not included in the sand model. As swash-by-swash interactions need to be accounted for in XBeach-G, the model run times are extremely long compared to the more efficient 'surfbeat' approach used in the XBeach sand models. As a result, it is not currently possible to run the BfE storms in XBeach-G (although this will be investigated further). Instead, BEEMS Technical Report TR545 used 1:20 year instantaneous NE wave height of 3.18 m, with a peak spectral period of 10.71 s over a tidal cycle (13 hours) with a 1 m storm surge. To allow model comparison, this storm condition was run in both 1D XBeach sand and gravel models.

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[39] Infiltration and exfiltration refer to movement of water into and out of the beach face (typically gravel beaches) with each swash motion up and down the beach.

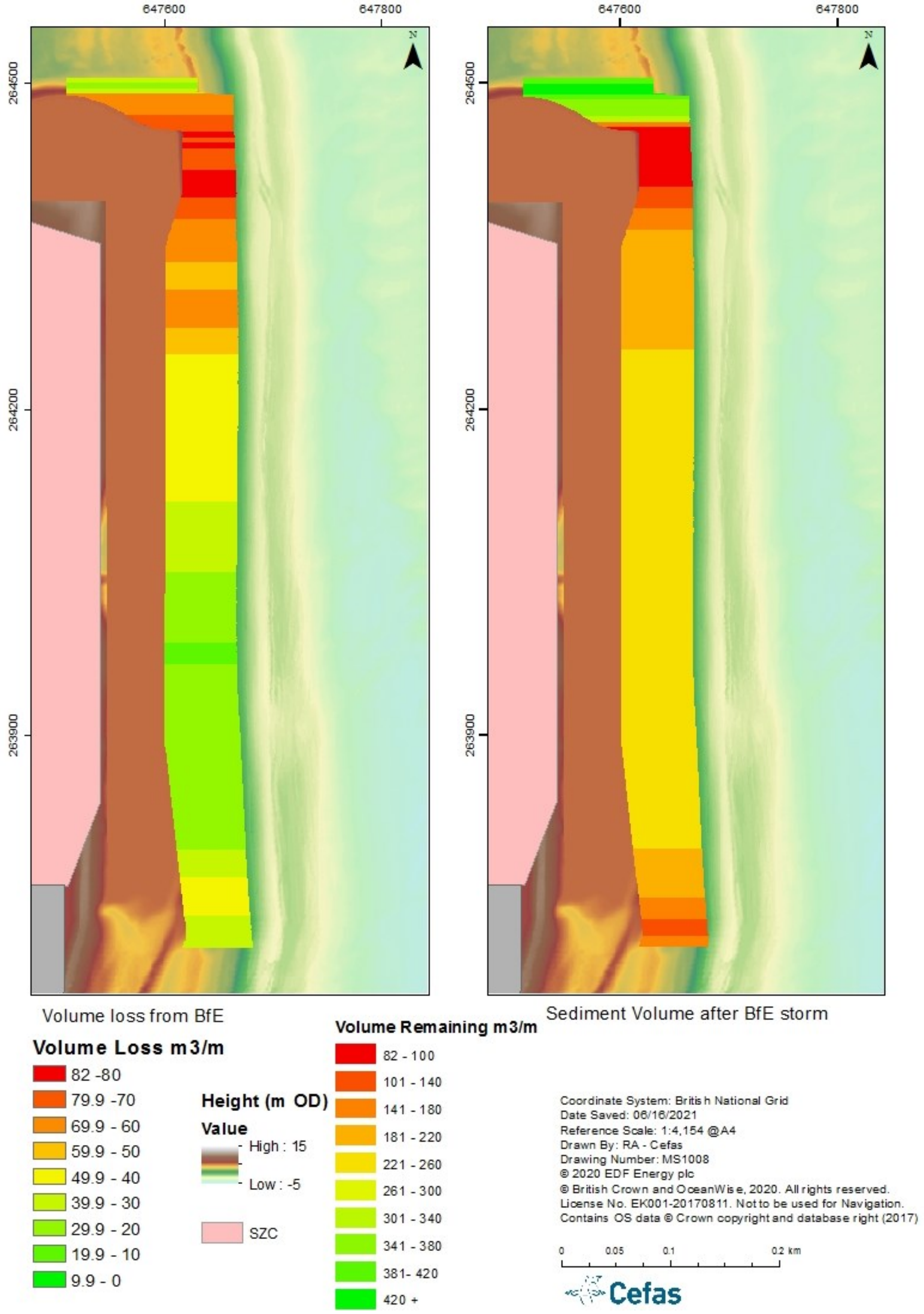

Figure 14 The loss of sediment volume from the BfE storm in 2099 with receded lateral shorelines (left) and the remaining sediment volume of the SCDF after the BfE storm (right).

The recharge intervals and eroded volumes for different particles sizes from the sand and gravel models are shown in Table 2. These should be considered in a comparative sense and as metrics of the relative performance. The RIs have been calculated using the methods outlined in Section 3.

The well-known effect of including swash-groundwater processes in modelling gravel beaches is obvious in the reduced volumes and increased RIs for XBeach-G. This is highlighted by the step change between the 2 mm particles for the sand and gravel models (rows two and three in Table 2). The sand model shows 63 – 253% more volumetric erosion (depending on the SLR scenario) than the gravel model for the same (2 mm) sediment. These differences are also obvious in the post-storm sand (reds) and gravel (greens) beach profiles, shown in Figure 15.

Within the XBeach-G results (green and brown lines in Figure 15), erosion resistance is 7 – 23% greater for the 40 mm (coarse end of native size range) than the 10 mm particles (typical mode of the native size range). Erosion performance improves with rising sea levels for the 40 mm sediment, indicating that coarsening SCDF sediments within the native size distribution may be an effective means of reducing future SCDF losses (and increasing intervals between recharge events). However, the largest step change is from the very coarse pebbles (40 mm) to the fine cobbles (80 mm). The fine cobbles show no erosion for the present day and 2069 sea levels, and only very minor losses (2.5 m^3/m) for the 2099 sea level. The model indicates substantial erosion resistance benefits across the 40 - 80 mm range, and is aligned with the literature (described in Section 2.4.3) that also shows that cobble beaches are highly resistant to erosion.

As expected, erosion generally increases with SLR and accordingly the intervals between recharge events decrease (Table 2). However, the pebble model runs (10mm and 40 mm) suggest very long intervals between recharge, highlighting the viability of the SCDF. That said, the methods used are general guides – although they demonstrate SCDF viability across the operation phase, the actual recharge intervals will differ and may be less than those computed. Overall the conclusions from this modelling indicate that , the coarser SCDF composition proposed in Sections 2.4.2 and 2.4.3 will increase the longevity of the SCDF and reduce recharge frequency.

Table 2. The Recharge Intervals and eroded volumes calculated from the X-Beach sand surfbeat 'XB-S' and XBeach gravel non-hydrostatic 'XB-G' models with varying sediment sizes (D_{50}) and the Dutch Design Method (DDM) applied. Years have been rounded up.

Particle diameter (& model)	**Present day RI (& volume)**	**2099 RI (& volume)**
0.8 mm (XB-S)	20 years (29.9 m^3/m)	16 years (37.0 m^3/m)
2 mm (XB-S)	32 years (18.7 m^3/m)	26 years (23.3 m^3/m)
2 mm (XB-G)	113 years (5.3 m^3/m)	42 years (14.3 m^3/m)
10 mm (XB-G)	130 years (4.6 m^3/m)	42 years (14.3 m^3/m)
40 mm (XB-G)	140 years (4.3 m^3/m)	52 years (11.6 m^3/m)
80 mm (XB-G)	– (no volumetric loss)	240 years (2.5 m^3/m)

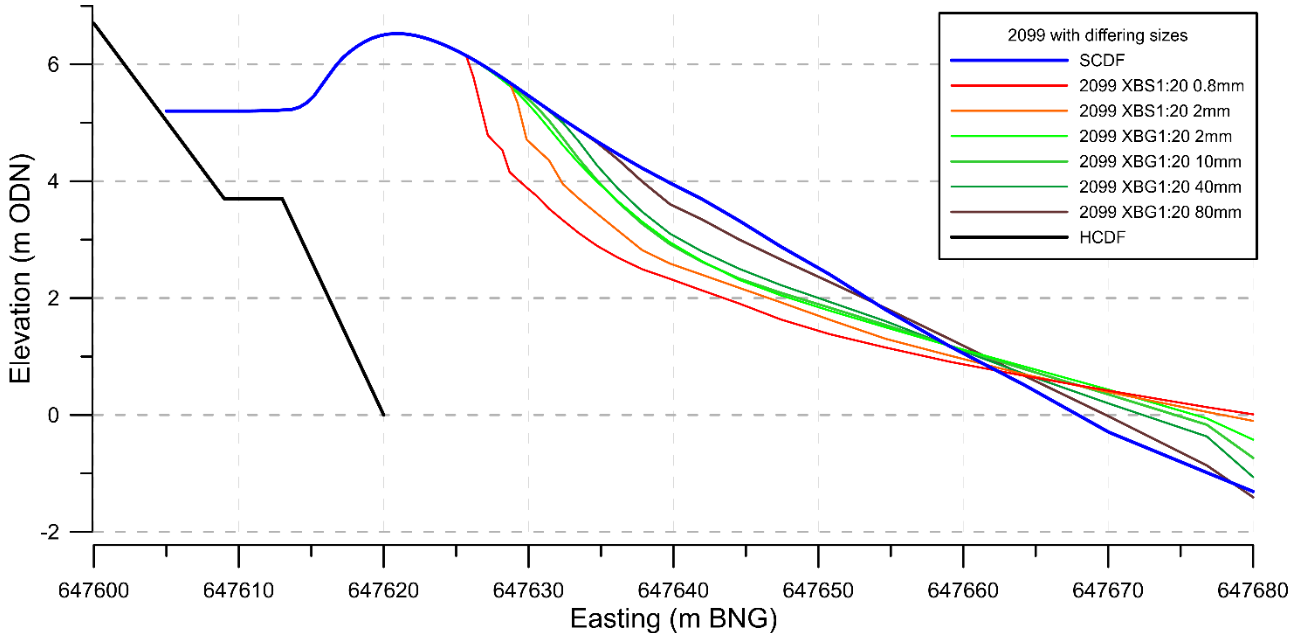

Figure 15. Pre and post storm beach profiles for a range of particle sizes using the 1D sand and gravel versions of XBeach for 2099 sea levels. The section shown is in the centre of the Sizewell C frontage. XBS = XBeach sand and XBG = XBeach gravel. The legend shows the sediment diameter used.

The modelled cobble behaviour and the literature on cobble berms both show significant benefits of an internal cobble layer, as suggested in Section 2.4.3, which would be highly resistant to erosion if uncovered and, if well designed, would avoid HCDF exposure.

The modelled cobble behaviour and the literature on cobble berms both show a significant benefits of an internal cobble layer, as suggested in Section 2.4.3, which would be highly resistant to erosion if uncovered and, if well designed, would avoid HCDF exposure.

3.1.3 Recharge Summary

Several approaches have been employed to indicate and envelope the possible recharge requirements over SZC's operational life. These can be broadly separated into estimates based on extrapolation of single (storm) event-based rates of sediment loss, or estimates based on measured beach volume changes over time. Of the two methods, the storm event-based estimates yield far longer RIs, but are based on the assumption that only major storms contribute to net volume change. This method also appears to neglect the smaller (but continual) contributions of lesser storm events year-in, year-out, which contribute to the observed trends over periods of years or decades. However, such estimates are based on observed changes in the volume of the active beach face, which is sub-tidal for at least part of every day – the SCDF, by contrast, is expected to be supra-tidal for the majority of the time, particularly the early part of the operational period, and is also expected to be more erosion resistant due to a coarser particle size (and potentially increasingly so over time). Nevertheless, storm modelling shows that erosion events will increase in severity and the net effect may be to increase the rate of beach volume loss over time, possibly at specific locations along the SCDF. The spectrum of estimates should therefore be considered indicative of the likely performance of the SCDF while providing a reliable worst-case estimate of the volume requirements.

The RPA measurements and the preliminary storm-erosion model gave similar recharge intervals of 12 – 13 years (9 – 10 years if applying DDM). The near 30-year shoreline change record at Sizewell shows a cyclical pattern superimposed on a very low background rate of retreat (0.11 m/yr) – were that behaviour to dominate the SZC frontage, SCDF recharge may not be required. However, the peak 10-year retreat rate within the SZC cycle gave an estimated recharge interval of 7 years and a total recharge requirement across the life of the station of c. 270,550 m^3.

Several 1D and 2D XBeach model runs were used to establish sediment losses (m^3/m) and the resultant RIs, which are summarised in Table 3. Throughout the 2D modelling, three different erosive rates were analysed to encompass spatial differences along the SCDF frontage. The mean erosion rate is a good representation of the southern half of the SCDF frontage whilst using the mean with one STD allows a more conservative approach (over-estimation of erosion). The maximum erosion rate was representative of the permanent BLF abutment, which is also where the SCDF volumes are lowest (owing to the more seaward position of the HCDF).

The recharge intervals from 2D modelling were shown to have a large variance when SLRs are considered throughout the operational phase. Recharge intervals range from 77- 46 years (DDM applied) when conservatively using the mean erosion rate plus one STD (2020 to 2099 SLR). The losses from a BfE event do not exceed the sacrificial buffer of 42 m^3 using this rate. However, using the conservative DDM approach in which predicted volume lost is increased by a further 40%, recharge would be needed within the operation phase.

Table 3: The results from the XBeach sand 2D and X-Beach G 1D modelling, showing the sediment losses (and resultant RIs DDM applied in brackets in years) under different conditions. The particle sizes D_{50} = 10mm and 40mm were chosen to represent the mode and coarser end of the native sediment size at SZC respectively. The D_{50}= 0.8mm used XBeach 2D sand modelling is the recommended maximum particle size.

Model Conditions		**Present Day SLR sediment losses (m^3/m)**	**2069 SLR sediment losses (m^3/m)**	**2099 SLR sediment losses (m^3/m)**	**2099 SLR, Receded Shoreline sediment losses (m^3/m)**
2D BfE storm	Mean Loss	17.0 (106 years)	23.0 (78 years)	28.0 (64 years)	44.0 (40 years)
	Mean and 1 STD Loss	23.5 (77 years)	32.6 (55 years)	39.0 (46 years)	62.8 (28 years)
	Maximum Loss	28.2 (64 years)	38.0 (47 years)	45.2 (40 years)	82.0 (22 years)
1D 1:20 year Hs storm	D_{50}= 0.8mm (XBS)	29.9 (20 years)	(not modelled)	37.0 (16 years)	(not modelled)
	D_{50} = 10 mm (XBG)	4.6 (130 years)	(not modelled)	14.3 (42 years)	(not modelled)
	D_{50} = 40 mm (XBG)	4.3 (140 years)	(not modelled)	11.6 (52 years)	(not modelled)

The coarsening of particle size has been shown to reduce sediment losses and increase RIs with rising sea levels. The coarse end of the native particle size range (modelled D_{50} = 40 mm) shows volumetric performance improvements (less erosion) of 7 – 23% compared to the modal 10 mm size. The difference in erosion performance increases with rising sea levels, indicating that coarsening SCDF sediments within the native size distribution may be an effective means of reducing future SCDF losses and recharge intervention. Furthermore, the modelling shows fine cobble surfaces are very difficult to erode and therefore the inclusion of a cobble layer into the SCDF would reduce the risk of HCDF exposure.

The sediment volume losses predicted throughout modelling are at the end of a 1:107 year BfE sequence (or 1-in-20 year storm sequence for 1D modelling in Section 3.1.2.4), representing severe storm conditions. The modelled volume changes do not account for natural beach recovery, and so they represent a more severe case than would be experienced most of the time. The modelling also assumes that extreme storms are the drivers of net change away from a dynamic equilibrium. This is reasonable because beach pebbles are retained in the subaerial beach and whilst the beach can undergo dramatic changes in response to severe storms, it tends to retain is overall volume and recover naturally.

The worst-case scenario is likely to be for a severe storm occurring when the beach volumes were naturally nearing the $V_{recharge}$ threshold and in an area where the *buffer* volume is low, such as the permanent BLF abutment). As seen in the modelled storm scenario for 2099 SLR with receded lateral shorelines, there is only enough sediment volume to withstand two consecutive BfE events at the BLF before the HCDF would be exposed (though as noted, two such events in sequence is unlikely).

Using the particle size D_{50}=0.8mm in 2D XBeach-S modelling is highly conservative and actual volumetric losses are likely to be lower than modelled. The buffer layer is approximately three times or more the modelled sediment losses from a single BfE storm event up to 2099, indicating that there is sufficient sediment to avoid HCDF exposure across the rest of the SCDF. The sacrificial and buffer volumes are adequate so long as the SCDF is well monitored and maintained.

The estimates in this report will be refined and incorporated into the Coastal Processes Monitoring and Mitigation Plan following more detailed modelling (longer time scales, more sea level cases, more particle size cases) and model improvements once additional calibration datasets have been secure. Large variances in RIs due to changing SLR's highlight the need for regular monitoring and revision of not only how sea level rise progresses, but also how the SCDF frontage responds. An examination of real-world performance every decade against the predicted SLRs, SCDF volume changes and RIs should allow improved forecasting and, if needed, adaptation.

It is worth noting that the volumetric assessment for recharge will be made in 50-m longshore cells, which would capture any localised erosion that might mean smaller, more frequent intervention in some areas and very little or none in others. The monitoring methods proposed in the CPMMP will also be capable of detecting areas accumulating sediments, which may be suitable for transfer to areas requiring maintenance – that is, the application of bypassing or beach recycling.

4 Conclusions

The main coastal processes design parameters (volume, crest height and composition) of the SCDF have been set out. They show that the SCDF volume would be substantially larger than that required to withstand 2 – 3 severe[40] sequential storms, even along sections where the SCDF would be relatively smaller, near the permanent BLF (264,390 N – 264,455 N, Figure 7). The increased crest height (compared to the present shingle ridge at SZC, is substantially larger than the SLR predicted under the intermediate climate emissions scenario (RCP4.5) and is larger or similar to the SLR under the very unlikely worst-case emissions scenario (RCP8.5). This is supported by the BEEMS Technical Report TR545 modelling that shows no SCDF overtopping for the present day, or indeed for 2069 and 2099 sea levels (including 1 m storm surge).

Version 1 of this report proposed the use of very coarse pebbles (with a relatively low sand content), amounting to beach coarsening within the native particle size distribution, which is in line with UK experience and best practice guidance (Rogers et al., 2010), and intentionally designed to increase shingle retention and therefore prolong longevity. The SCDF is conceptualised as a sedimentary feature comprising a large inner safety *buffer* volume, V_{buffer}, and an outer *sacrificial* volume, V_{sac}. An option for a cobble-layer deep within the SCDF, based on the dynamic cobble berm concept, is also being considered and, if adopted, would further increase erosion resistance in the unlikely event that the SCDF pebbles were fully removed. The variation in SCDF performance has been investigated in BEEMS Technical Report TR545 and this Version (2) report.

The results from the preliminary phase 1 modelling (BEEMS Technical Report TR531) took a precautionary approach with respect to model calibration and as a result significantly overpredicted erosion. The phase 2 modelling (BEEMS Technical Report TR545) refined the calibration parameters and produced more realistic storm erosion, albeit still consistently overpredicting. The modelling suggests that the volumes of the buffer and sacrificial layers should be reconsidered taking into account the phase 2 results – specifically, the *buffer* volume appears to be larger than needed, which means that the *sacrificial* layer could be increased in size and accordingly RIs would rise, in practice reducing the frequency of disruptions arising from beach maintenance. However, for this Version of the report the original value has been retained ($V_{\text{sac}} = 42\ \text{m}^3/\text{m}$) as it provides a more conservative assessment of the viability of the sacrificial component and serves to highlight the areas of the SCDF that would be most prone to erosion and more frequent interventions.

Several RI estimates have been computed using methods from the Beach Management Manual (Rogers et al., 2010) – specifically, measured shoreline changes, sand models and more realistic gravel models. The RIs (along with modelled storm erosion predictions) indicate the potential recharge requirements and viability of a scheme. Using this guidance, the results of this study have been interpreted with respect to their input data, the layers of conservatism applied and deficiencies in the method. RIs derived from modelling are longer (suggesting a lower maintenance requirement) than those derived in Version 1 (see Sections 3.1.1 and 3.1.2.1) and presented in BEEMS Technical Report TR531, which should therefore continue to be viewed as indicative worst-case estimates. As the Sizewell C project has a relatively long timeline, changes in future coastal processes have been factored into future RI estimates by way of modelling two sea level cases (midway, and shortly after the end, of the planned operation phase) and potential severe erosion of

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[40] Storm return interval of 1:12 years, based on the first two storms in the BfE sequence using preliminary modelling (which has not been shown to be highly conservative, prompting future consideration of rebalancing the buffer and sacrificial volumes).

the adjacent shorelines. In doing so, future viability has been tested and proven to the end of the operation phase.

The most conservative estimates of the notional recharge interval[41] (up to seven interventions) and the relatively small volumes[42] (140,000 – 150,000 m^3 (Sections 3.1.1.1 and 3.1.2.1); worst case c. 270,550 m^3 (Section 3.1.1.2)) indicate SCDF viability for the operation phase. The conservative 2D sand and more accurate 1D gravel model results suggest that recharge events may be even less frequently required. Several worst-case elements were used in the recharge interval estimations, including conservative modelling (i.e., erosion is overpredicted), use of beach volumes at the narrowest part of the SZC frontage and application of the Dutch Design Method (increasing the volume lost by a further 40%). The projected recharge volume requirements are similar to the total SCDF volume (c. 210,000 m^3).

The worst-case single SCDF erosion event is predicted to be localised at the permanent BLF abutment (82 m^3/m across five metres of frontage) and arises from the modelled 2099 sea levels with receded lateral shorelines case. However, this combination of erosive conditions still only erodes half of the SCDF volume at this location, meaning that HCDF exposure would require a second 1:107 year event prior to recharge – this is considered unlikely because of the return intervals, the commitment to recharge by SZC Co. and the predicted lack of change in the Sizewell wave climate (UKCP18; Lowe et al., 2018).

The same case also showed that the spatial mean loss of sediment along the full length of the SCDF (44 m^3/m) exceeded the sacrificial buffer volume (42 m^3/m), implying that much of the frontage would require recharge, were these conditions to arise. These results suggest that for much of the operation phase only localised recharge is likely to be required and that until the latter part of the period 2069 to 2099, any recharge events are most likely to arise following gradual erosion of the sacrificial layer.

Non-uniformity in erosion across the SCDF suggests that some recharge events will be small (in volume and extent) and potentially more frequent if they are in areas of persistent gradual erosion. Measured and modelled data indicates that the northern half of the SCDF frontage is likely to require more frequent recharge, specifically at the permanent BLF where SCDF volumes are also the lowest due to the restricted area available. The monitoring set out in the Coastal Processes Monitoring and Mitigation Plan (CPMMP) is designed to detect localised erosion, as the monitoring techniques are spatially continuous, enabling targeted recharge to be undertaken.

The large SCDF volume, relatively low number of calculated recharge events and relatively small recharge volumes (based on conservative measures) indicate that the SCDF is viable across the operation phase of the station and that the risk of HCDF exposure during this phase is very low. Coarsening of the SCDF sediments would further improve the performance of the SCDF (either from the outset or subject to examination of real-world performance) by increasing erosion resistance. In particular, the performance of the 40 mm diameter sediment (relative to 10 mm sediments) improved performance by up to 23% with increasing sea level, suggesting that coarsening particle size may be an important design factor when considering the higher sea levels associated with the decommissioning phase. A well-designed cobble layer could also effectively counter the increased risk of HCDF exposure during the decommissioning phase. An examination of current literature combined with the modelling show that the cobble layer would be very

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[41] Based on historical shoreline trends (see Section 3.1.1.2).

[42] Compared to other beach recharge events at high-value frontages in the region e.g., Sea Palling at 1,300,000 m^3 (Dolphin et al., 2012) and 1,500,000 m^3 at Bacton (Gary et al., 2018).

difficult to erode if exposed. For example, modelling results indicate that there was no volumetric loss of cobbles under 2020 and 2069 sea level predictions and only 2.5 m^3/m under the forecast 2099 sea level.

An important benefit of the SCDF design is its adaptability to future pressures and real-world performance. The SCDF would be constructed between the HCDF and Mean High Water Spring (MHWS) level and would release sediment into the coastal system when eroded by waves. It provides a large reservoir of shingle designed to release sediment into the coastal system, prevent HCDF exposure, and thereby avoid or minimise disruption to longshore shingle transport and the potential downdrift beach erosion. It uses a "working with nature" approach where the release of sediment into the coastal system, and its re-distribution, are determined by natural coastal processes (erosion by waves).

The specifications and triggers in the CPMMP can be adjusted to reflect environmental conditions and performance, thereby accounting for any uncertainties in SCDF response or future pressures (e.g., sea level rise) as part of a structured Adaptive Environmental Assessment and Management process. Decadal consideration of SLR predictions, erosion and RIs is recommended as part of the CPMMP 10-year review. This would track the SCDF performance in detail, improve understanding of the SLR pressures and responses, and allow reforecasting if conditions change or take account of the results from models (should there be substantial improvements in such techniques).

Further work required to refine the SCDF's coastal processes design and finalise the buffer and sacrificial layer volumes includes:

- Setting the V_{recharge} (the threshold volume for SCDF recharge) for the CPMMP.
- Extending the modelling period from the end of the operational phase (2099) to the end of decommissioning for SLR cases.
- Modelling a range of particle sizes between 10 and 80 mm to optimise SCDF particle-size selection and SCDF performance.
- Consideration of whether gravel model calibration work should be undertaken to reduce model uncertainty, specifically measurements of the groundwater properties (hydraulic conductivity) for Sizewell's supra-tidal sediments, which are the closest analogy to the SCDF available. Full-scale physical modelling may also be required to finalise the design prior to SCDF construction.

Incorporation of any safety case specific requirements and triggers into the analysis. These may stimulate a shift from Option A to Option B in terms of utilising the cobble layer to prevent HCDF exposure.

References

Allan, J. C., R. Hart, and R. Geitgey, 2005, Dynamic revetments for coastal erosion stabilization: A feasibility analysis for application on the Oregon Coast, Special Paper Rep. SP-037, 71 pp, Oregon Department of Geology and Mineral Industries, Portland, Oregon.

Allan, J.C. and Gabel, L.L., 2016. Monitoring the Response and Efficacy of a Dynamic Revetment Constructed Adjacent to the Columbia River South Jetty, Clatsop County, Oregon. Oregon Department of Geology and Mineral Industries. Technical Report O- 16-07.

Attal, M., and J. Lave´ 2009. Pebble abrasion during fluvial transport: Experimental results and implications for the evolution of the sediment load along rivers, J. *Geophys. Res.*, 114, F04023, doi:10.1029/2009JF001328.

Bayle P., Blenkinsopp C., Conley D., Masselink G., Beuzen T., Almar R., 2020. Performance of a dynamic cobble berm revetment for coastal protection under increasing water level. *Coastal Engineering* 159, 103712.

BEEMS Scientific Position Paper SPP094. The ‘Emma’ storm sequence (February – March 2018) and its effect on Sizewell Beach. Cefas, Lowestoft.

BEEMS Technical Report TR523. 2020. Sizewell C Coastal Processes Monitoring and Mitigation Plan. Cefas, Lowestoft.

BEEMS Technical Report TR531. 2020. Storm Response Modelling – Preliminary evidence toward setting volumetric thresholds for SCDF recharge. Cefas, Lowestoft.

Blair, T.C. and McPherson, J.G., 1999. Grain-size and textural classification of coarse sedimentary particles. *Journal of Sedimentary Research* (1999) 69 (1): 6–19. https://doi.org/10.2110/jsr.69.6

Bradbury, A. P., 1998. Response of shingle barrier beaches to extreme hydrodynamic conditions. Unpublished PhD thesis, School of Ocean and Earth Science, University of Southampton

Bradbury, A. P. and Kidd, R., 1998. Hurst Spit stabilisation scheme. Design and construction of beach recharge. In: Proc of the 33rd MAFF conference of river and coastal engineers, Keele University, July 1998, pp 1.1.1 to 1.1.14

DEFRA MAGIC (accessed April 2021). Designated Sites View, Minsmere-Walberswick Heaths and Marshes SSSI - MINSMERE HAVEN SHINGLE (PSRT UNIT 56 PRE-FEB 02) (113). https://designatedsites.naturalengland.org.uk/UnitDetail.aspx?UnitId=1027095

Dolphin, T.J., Vincent, C.E., Bacon, J.C., Dumont, E. and Terentjeva, A., 2012. Decadal-scale impacts of a segmented, shore-parallel breakwater system. *Coastal Engineering* 66 (2012) 24 – 34.

Dolphin, T., Burningham, H., Sifnioti, D., Manning, W., Wallbridge, S. and Farcas, A., 2020. Mixed Sand/Gravel Beach Response to the Beast from the East Storms. Journal of Coastal Research, 95, 463 – 467.

Dornbusch, U., Robinson, D.A., Williams, R.B.G. and Moses, C.A., 2003. Estimation of Abrasion on Flint Shingle Beaches in East Sussex, UK Proceedings of the International Conference on Coastal Sediments 2003, Clearwater Beach, Florida, pp. 18-23.

Dornbusch, U., 2017. Design requirement for mixed sand and gravel beach defences under scenarios of sea level rise. *Coastal Engineering* 124 (2017) 12–24.

EMU. 2012. Anglian Marine Aggregate Regional Environmental Assessment.

Environmental Resources Management (ERM). 2010. Marine Aggregate Regional Environmental Assessment of the Outer Thames Estuary.

Farris, A.S. and List, J.H., 2007. Shoreline Change as a Proxy for Subaerial Beach Volume Change. *Journal of Coastal Research*, 23(3), 740 – 748.

Feagin, R.A., Furman, M., Salgado, K., Martinez, M.L., Innocenti, R.A., Eubanks, K., Figlus, J., Huff, T.P., Signen, J. and Silva, R., 2019. The role of beach and sand dune vegetation in mediating wave run up erosion. *Estuarine, Coastal and Shelf Science*, 219 (2019) 97–106. https://doi.org/10.1016/j.ecss.2019.01.018

Gary, A., Gilchrist, C., Smith, C., Taylor, S., Donohue, D., Learmonth, J., Page, C., Brew, D. and Rodgers, C., 2018. Bacton to Walcott Coastal Management Scheme Environmental Statement. Report for North Norfolk District Council, Shell U.K. Ltd. And Perenco.

HR Wallingford, 2020. Tideway. Central Region Permanent Works – Scour and accretion monitoring and mitigation plan. Document reference: 4610-FLOJV-TTCEN-151-TZ-PQ-000001.

JNCC, 2019. Coastal habitat descriptions: UK Terrestrial & Freshwater Habitat Types (jncc.gov.uk). https://data.jncc.gov.uk/data/b0b5e833-7300-4234-8ae5-bdbf326e854c/habitat-types-coastal.pdf

Komar, P. D., and J. C. Allan, 2010. “Design with Nature” strategies for shore protection—The construction of a cobble berm and artificial dune in an Oregon State Park Rep., 117-126 pp, U.S. Geological Survey Scientific Investigations Report 2010-5254.

Lorang, M.S., 1991. An artificial perch-gravel beach as a shore protection structure. In: *Coastal Sediments* ’91, vol. 2. American Society of Civil Engineers, Reston, pp. 1916–1925.

Lowe, J.A., Bernie, D., Bett, P.E., Bricheno, L., Brown, S., Calvert, D., Clark, R.T., Eagle, K.E., Edwards, T., Fosser, G., Fung, F., Gohar, L., Good, P., Gregory, J., Harris, G.R., Howard, T., Kaye, N., Kendon, E.J., Krijnen, J., Maisey, P., McDonald, R.E., McInnes, R.N., McSweeney, C.F., Mitchell, J.F.B., Murphy, J.M., Palmer, M., Roberts, C., Rostron, J.W., Sexton, D.M.H., Thornton, H.E., Tinker, J., Tucker, S., Yamazaki, K., and Belcher, S. 2018. *UKCP18 Science Overview report*. Met Office, Exeter.

Mankelow, J.M., Bide, T.P., Sen, M.A., Raycraft, E. and Cameron, D.G. 2016. Collation of the results of the 2014 Aggregate Minerals Survey for England and Wales. British Geological Survey Commissioned Report, OR/16/005. 160pp.

McFarland, S., Whitcombe, L. and Collins, M.B., 1994. Recent shingle beach renourishment schemes in the UK – some preliminary observations. *Ocean & Coastal Management*, Volume 25 Issue 2 p143-149.

Newkirk, S., Veloz, S., Hayden, M., Battalio, B., Cheng, T., Judge, J., Heady, W., Leo, K., and Small, M., (The Nature Conservancy and Point Blue Conservation Science), 2018. Toward Natural Shoreline Infrastructure to Manage Coastal Change in California. California Natural Resources Agency. Publication number: CNRA-CCC4A-2018-XXX.

NNB Generation Company (SZC) Limited, 2020a. *The Sizewell C Project, 6.3 Volume 2 Main Development Site, Chapter 20 Coastal Geomorphology and Hydrodynamics*. PINS Reference Number EN010012.

NNB Generation Company (SZC) Limited, 2020b. *Sizewell Coastal Geomorphology and Hydrodynamics: Synthesis for Environmental Impact Assessment (MSR1 – Edition 4)*. PINS Reference Number EN010012.

Pentium Coastal Defence Limited, 2001. Pevensey Bay Sea Defence Scheme, Environmental Statement.

Pye, K. and Blott, S. J., 2018. *Advice on Sustainable Management of Coastal Shingle Resources*. NRW Report No: 273, 167pp, NRW, Cardiff.

Randall, R.E., 1977a. Shingle foreshores. In: Barnes, R.S.K. (ed.) *The Coastline*, pp. 49-61. Wiley, London, UK

Randall, R.E., 1977b. Shingle formations. In: Barnes, R.S.K. (ed.) *The Coastline*, pp. 199– 213. Wiley, London, UK

Randall, R.E., 2004. Management of coastal vegetated shingle in the United Kingdom. *Journal of Coastal Conservation*, 10, 159– 168.

Rodwell, J.S., 2006. NVC Users' Handbook. Joint Nature Conservation Committee. JNCC.

Rogers, J., Hamer, B., Brampton, A., Challinor, S., Glennerster, M., Brenton, P., and Bradbury, A., 2010. *Beach management manual* (second edition). CIRIA C685 RP787 © CIRIA 2010 ISBN: 978-0-86017-682-4-3.

Scott, G.A.M., 1963. The ecology of shingle beach plants. *J. Ecol*. 51: 517-527.

Sigren J.M., Figlus, J. and Armitage, A.R., 2014. Coastal sand dunes and dune vegetation: Restoration, erosion, and storm protection. *Shore & Beach*, 82(4), 5 – 12.

Sneddon, P.E. & Randall, R.E., 1993. Coastal vegetated shingle structures of Great Britain: Main Report and Appendices, JNCC, Peterborough

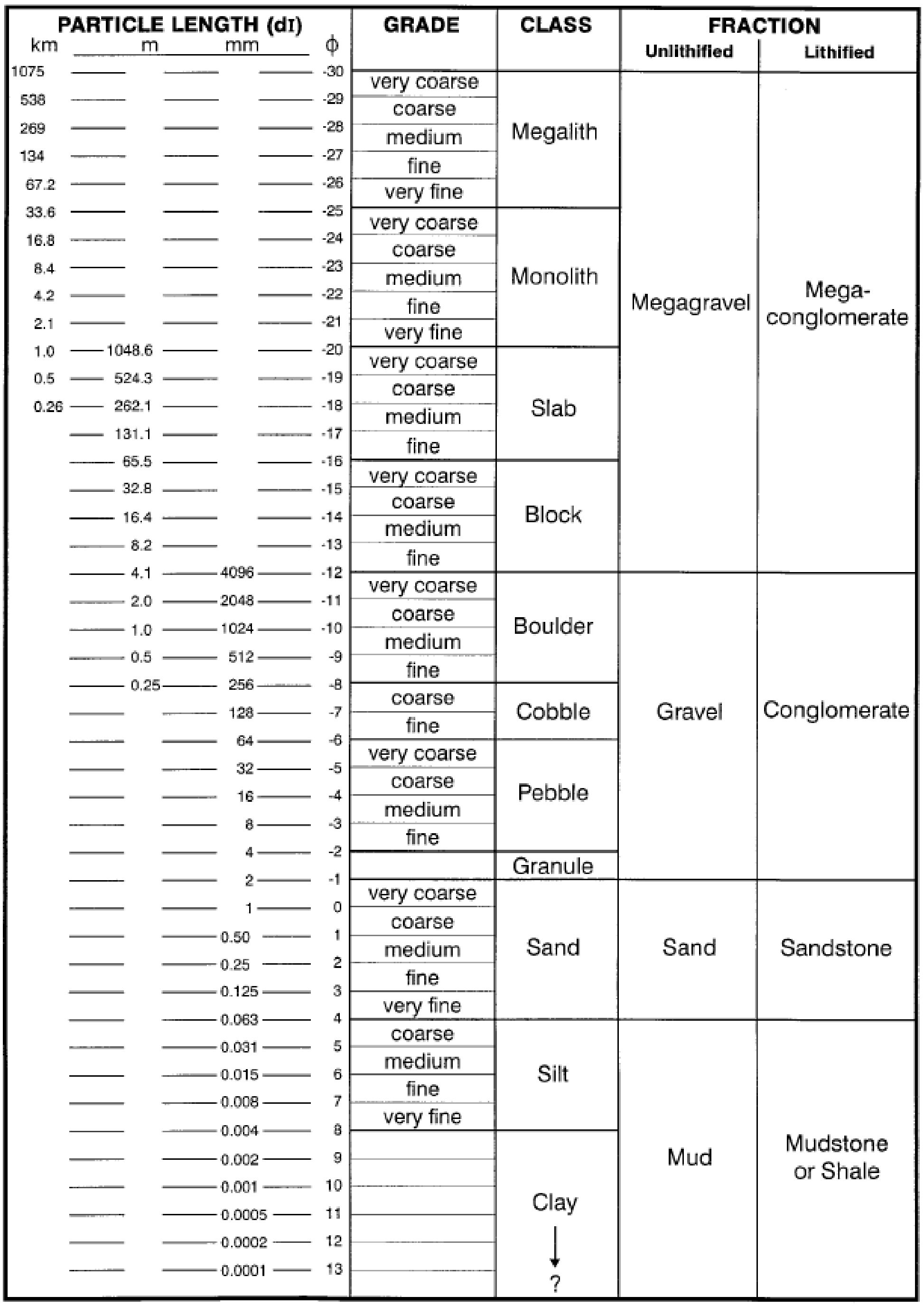
Stauble, D. K., 2005. A review of the role of grain size in beach nourishment projects. In: *Proceedings of the National Conference on Beach Preservation Technology, Florida Shore & Beach*. Preservation Association, Destin Florida.

The Crown Estate (TCE) and British Marine Aggregate Producers Association (BMAPA). 2020. The area involved: 22nd annual report. ISBN: 978-1-906410-79-7.

Verhagen, H J., 1992. Method for artificial beach nourishment. In: *Proc 23rd int conf on coastal engineering*, Venice, Italy, October 1992, B L Edge (ed), ASCE (ISBN: 0-87262-933-3), pp 2474–2485

Weiner, H.M., Kaminsky, G.M., Hacking, A., McCandless, D., 2019. North Cove Dynamic Revetment Monitoring: Winter 2018-2019, Technical Report 19-06-008, Shorelands and Environmental Assistance Program. Washington State Department of Ecology, Olympia, WA.

Appendix A Modified Udden-Wentworth classification



PARTICLE LENGTH (dI)				GRADE	CLASS	FRACTION	
km	m	mm	ϕ			Unlithified	Lithified
1075			-30	very coarse	Megalith	Megagravel	Mega-conglomerate
538			-29	coarse			
269			-28	medium			
134			-27	fine			
67.2			-26	very fine			
33.6			-25	very coarse	Monolith		
16.8			-24	coarse			
8.4			-23	medium			
4.2			-22	fine			
2.1			-21	very fine			
1.0	1048.6		-20	very coarse	Slab		
0.5	524.3		-19	coarse			
0.26	262.1		-18	medium			
	131.1		-17	fine			
	65.5		-16	very coarse	Block		
	32.8		-15	coarse			
	16.4		-14	medium			
	8.2		-13	fine			
	4.1	4096	-12	very coarse	Boulder	Gravel	Conglomerate
	2.0	2048	-11	coarse			
	1.0	1024	-10	medium			
	0.5	512	-9	fine			
	0.25	256	-8	coarse	Cobble		
		128	-7	fine			
		64	-6	very coarse	Pebble		
		32	-5	coarse			
		16	-4	medium			
		8	-3	fine			
		4	-2		Granule		
		2	-1	very coarse	Sand	Sand	Sandstone
		1	0	coarse			
		0.50	1	medium			
		0.25	2	fine			
		0.125	3	very fine			
		0.063	4	coarse	Silt	Mud	Mudstone or Shale
		0.031	5	medium			
		0.015	6	fine			
		0.008	7	very fine			
		0.004	8		Clay ↓ ?		
		0.002	9				
		0.001	10				
		0.0005	11				
		0.0002	12				
		0.0001	13				

Source: Blair and McPherson (1999).