# 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 4)

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# Executive summary

The proposed Sizewell C Soft Coastal Defence Feature (SCDF) is a maintained and volumetrically enlarged shingle beach[1], seaward of the hard coastal defence feature (HCDF) but distinct from the sandy subtidal beach. Its large sedimentary mass (the combined volume of the existing each and additional sediments from construction is ca. 210,000 m$^3$) 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 (within the native particle size range) 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.

Version 4 of this report updates the Version 3 modelling listed below to include estimates of the Recharge Interval (RI) and SCDF viability for new modelling results of the Beast from the East (BfE) storm sequence modelling within the decommissioning phase.

Version 3 of this report included estimates of the Recharge Interval (RI) and SCDF viability for:

  - The RIs during the operational and early decommissioning phases for the updated permanent HCDF, including the pared back Beach Landing Facility section and extension to include the southern terminus (Section 3.2; numerical values are updated with minor changes to the text in this section, however conclusions are unchanged).

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[1] The SCDF refers to both the additional sediment that will be added as part of the Sizewell C construction process AND the existing beach sediments.

- the full decommissioning phase (until 2140) with the permanent HCDF (new Section 4); and
- the end of the decommissioning phase (2140) with the adapted HCDF and the RCP8.5 sea levels that would have been required to trigger HCDF adaptation (new Section 4).

Version 2 used the standard UKCP18 predictions for sea level rise, which end in 2099, part-way into the planned decommissioning phase.

The SCDF is conceptually divided into two main components (see Figure i). It would consist of a landward safety *buffer* volume, $V_{\text{buffer}}$, 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, $V_{\text{sac}}$, which would be allowed to erode as far back as $V_{\text{buffer}}$ 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 $V_{\text{sac}}$ = 42 $m^3$ per metre of beach (hereafter $m^3/m$) was set in Version 1 of this report based on highly conservative modelling in BEEMS Technical Report TR531. Although model improvements from BEEMS Technical Report TR545 suggest $V_{\text{sac}}$ can be enlarged (and $V_{\text{buffer}}$ decreased), which would lead to less frequent SCDF maintenance, the original value has been retained (i.e., $V_{\text{sac}}$ = 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. Determination of the trigger for beach recharge is part of ongoing work for the Coastal Processes Marine Monitoring Plan (CPMMP, see [REP5-059]) to be consulted on with the Sizewell C Marine Technical Forum and submitted for approval to the Marine Management Organisation (MMO) and East Suffolk Council (ESC) prior to commencement of work

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[2] sequential storms, even along sections where the SCDF is smallest, 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 at Sizewell C, which is substantially greater than predicted sea level rise (SLR) in 2099[3] 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). The modelling also shows no SCDF overtopping for the present day, 2069 and 2099 sea levels (including 1 m storm surge) (BEEMS Technical Report TR545). Under RCP8.5 conditions with the adaptive design, the SCDF crest is predicted to erode in height to 6.0 m ODN with 2140 sea levels using the XBeach 2D sand model.

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, however as the SCDF modelling results presented in this report and BEEMS Technical Report TR545 Rev 3.0 show SCDF viability across the station life is achievable without coarsening sediment, SZC Co have indicated they are comfortable with the default position of working within the native size distribution and not coarsening the sediment. Fine tuning of the defences using further numerical and potentially physical modelling will be undertaken and that the final sediment size would be determined in consultation with the Coastal Geomorphology subgroup of the Marine Technical Forum and require approval from the discharging authorities. BEEMS Technical Report TR545

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[2] Based on a real storm sequence with a 1:12 year storm-energy return interval and highly conservative modelling from BEEMS Technical Report TR531.
[3] 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).

results highlight modest 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 station life. 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[4].

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[5]. 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 and decommissioning phases indicate SCDF viability.

*Operation Phase*

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[6] and would result in 8 – 9 beach maintenance interventions. The total conservative volume estimate for the whole project lifetime of Sizewell C would be 576 000 m$^3$ using peak erosion rates. Recent high resolution beach topography and the preliminary phase 1 modelling suggest up to seven beach maintenance interventions requiring relatively small volumes[7] of sediment (140,000 – 150,000 m$^3$). RI estimates in Version 3 account for changes to the HCDF and are based on storm response modelling using 2D XBeach sand (which overpredicts erosion) and more accurate 1D gravel models. They 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 by estimates presented above. The worst-case predicted SCDF erosion from a single event was for a 1:107 year storm[8] 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 across two localised sections (of 5m and 20m) of the northern SCDF (UKCP18; Lowe et al., 2018).

In the same modelled case, the mean loss along the whole SCDF (43.1 m$^3$/m) exceeded the sacrificial 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

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[4] 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.

[5] This version of the report includes new 2D sand and 1D gravel modelling results (Sections 3.2.2- 3.2.4). The RIs from the new modelling are longer than those derived in Version 1 (Sections 3.1.1 and 3.2.1).

[6] 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.

[7] 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).

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

import of additional sediments to maintain the SCDF volume. In this way, the SCDF would be maintained and disruption to longshore transport avoided.

*Decommissioning phase*

Versions 3 and 4 of this report evaluated the SCDF viability during the decommissioning phase Sizewell C for 2120 and 2140, equating to the mid-point (approximately) and end of decommissioning. The modelling from the more severe 1:107 year (Beast from the East) storm sequence at 2140 showed mean losses increasing to 56. 3 $m^3$/m and maximum losses more than doubling compared to the 1:20 year design storm event to 111.5 $m^3$/m. Although the model showed minor lowering of the SCDF crest height (from 6.4 m ODN to 5.8m ODN), the HCDF was not exposed by the BfE storm. Based upon the modelling outputs, the majority of the frontage could therefore withstand the highly unlikely occurrence of two successive BfE events without exposing the HCDF.

Areas shown to need more immediate recharges are at the northern and southern endpoints of the SCDF. It should be noted that the SCDF designs at the southern endpoint are artificially low due to a localised difference in HCDF – SCDF alignment. Currently minimum sediment values are 105 $m^3$/m but are set to increase by approximately 80 $m^3$/m with updated SCDF designs. Although this will increase volumes locally, the HCDF's most seaward (easterly) point is in this area and so lower SCDF volumes are likely to equate to relatively frequent recharge needs despite the historically low rates of erosion there, especially if the southern shorelines are receded (as per the modelled case).

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 or around the southern endpoint where the smallest initial sediment volumes are situated. The spatially continuous monitoring techniques set out in the CPMMP (BEEMS Technical Report TR523) are designed to detect such localised erosion and would enable targeted recharge.

In the very unlikely event that the UKCP18 RCP 8.5 (95th percentile) climate conditions come to be, the HCDF could be altered to the adaptive design during the decommissioning phase, with a crest height increasing to 16.4 m OD and a 17 m more seaward protrusion of the HCDF (and the SCDF). When modelled under these more extreme conditions and the more severe 1:107 year storm sequence, mean losses exceeded the conservatively set 42 $m^3$/m sacrificial layer by nearly 3 times (erosion of 100.9 $m^3$/m) with the maximum loss of 188.3 $m^3$/m. However, in all cases the HCDF was not exposed – but the northern SCDF's buffer layer and the southern endpoint buffer layer were significantly eroded with volumes as low as 38 $m^3$/m remaining after the storm. Under such conditions immediate recharge would be needed to avoid HCDF exposure by subsequent more moderate storms. Were the adaptive HCDF to be built as a result of high RCP 8.5 (95th percentile) sea levels, it is likely that HCDF exposure would occur following extreme storms unless recharge was rapid. Consequently, an adaptive HCDF should be re-assessed if built in order to understand whether other design features could be employed – such features would include increasing the SCDF volume, using an internal layer of fine cobbles (if not already included in the design) and coarsening the bulk SCDF sediments.

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

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 $V_{\text{recharge}}$ (the threshold volume for SCDF recharge) for the CPMMP, which will form a separate report.
- Closer examination of the gravel model's ground water parameters to determine whether further field and laboratory measurements are needed, to reduce model uncertainty.

This report is specifically for examining SCDF viability and likely recharge intervals. Separate modelling has been conducted for the engineering and safety case included in the Reasonably Foreseeable Design Basis (1:10,000 year conditions acting on an eroded beach due for recharge) in BEEMS Technical Report TR553.

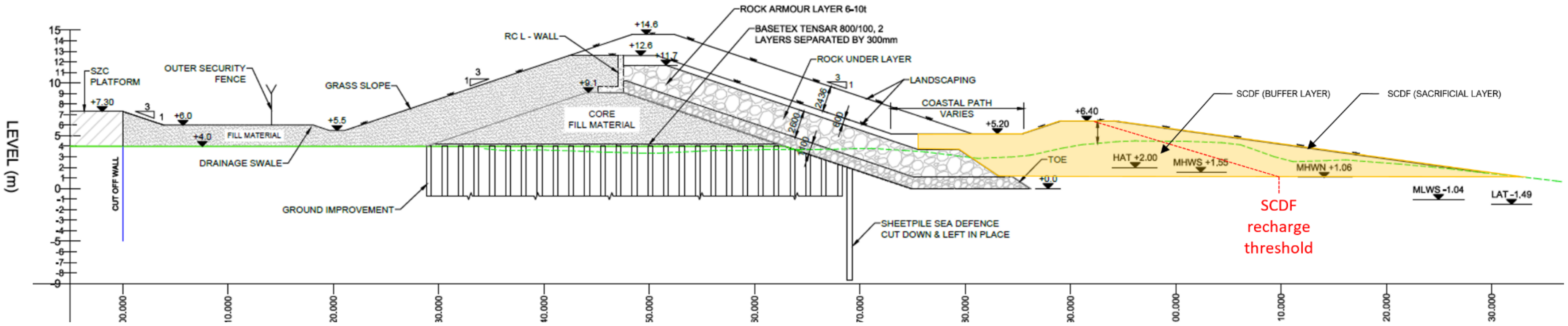

Figure i: Schematic cross-section of the hard and soft coastal defence feature (HCDF and SCDF). The SCDF (yellow) is conceptually divided into two volumes, separated by the dividing SCDF recharge threshold (as the threshold is volumetric, the line is shown for illustrative purposes only, i.e., many different 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[9], seaward of the hard coastal defence feature (HCDF) but distinct from the sandy subtidal beach. Its large sedimentary mass (the combined volume of the existing each and additional sediments from construction is ca. 210,000 $m^3$) 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 operational and decommissioning phases.

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,

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[9] The SCDF refers to both the additional sediment that will be added as part of the Sizewell C construction process AND the existing beach sediments.

- maximise the recharge intervals (RIs) (and minimise disturbance) between SCDF recharge events across the operation and decommissioning phases[10] of Sizewell C, and
- 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[11] 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[12] 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

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[10] 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.

[11] Examples of adaptive approaches include Pevensey Beach (Pentium Coastal Defence Limited, 2001), Lincshore (Environment Agency, 2017), Thames Tideway (HR Wallingford, 2020) and Dungeness.

[12] Flood and Coastal Erosion Risk Management.

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[13] on the immediately neighbouring frontages.

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. Natural England condition surveys (DEFRA MAGIC, 2021) show that annual vegetated drift lines on the Sizewell C to Minsmere Sluice frontage were lost from Unit 113 due to coastal recession around 2010 – 2011, however the surveys noted that the drift line vegetation may have rolled back into the landward Unit 112. Subsequent RSPB surveys in 2015 and 2021 show that drift line vegetation is indeed present in the landward Unit 112, as acknowledged by SZC Co [REP6-025]. The condition survey notes that annual shingle vegetation was evidenced but appeared to be a single species of Atriplex (*Atriplex prostrata*). The condition survey also notes that perennial shingle vegetation was present including *Rumex crispus, Crambe maritime* and *Glaucium flavum*, all of which were abundant or frequent. Bitter stonecrop and sea sandwort are also recorded as being present.

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, the drift line vegetation habitat is likely to remain sparse. 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. Although the whole beach retreat would be slowed as a result of additional shingle, there would be no impact to the cycle of erosion and reconstruction of the beach face and hence to the frontal supra-tidal zone where drift lines form. That is, net environmental forcing remains erosive, so the mixture of natural and imported SCDF sediments would be exposed and shaped by natural wave forces with no adverse effects on their formation or maintenance – periods of faster erosion would remove the drift lines, and periods of slower erosion would allow the drift lines to reform. There may,

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[13] The desired habitat for nesting little tern and annual vegetation of drift lines species.

however, be beneficial effects from a wider (than present-day) supra-tidal zone supporting a greater extent of drift line vegetation.

*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
- Section 1.2 This (new) section
- Section 1.5 Outline (updated)
- Section 2.3.1 SCDF topography and volume (updated)
- Section 2.4.1 SCDF sensitivity to particle size (new section)
- Section 2.4.2 and 2.4.3 (unchanged, formerly 2.4.1 and 2.4.2, respectively)
- Section 3.2 Recharge requirements based on modelled volumetric change (new subsections: 3.2.2 – 3.2.4)
- Section 3.3 Recharge requirements summary (updated)
- Section 5 Conclusions (updated)

## 1.3 Changes in Version 3

Since Version 2 of this report there were a number of design changes to the HCDF (Figure 1). Specifically, these include:

- The southern extents of the BLF that overlap with Sizewell B (an extension of 70 m with a rounded end that was not included in Versions 1 and 2. The most southerly 200 m of the HCDF changes angle from the main frontage of the HCDF, with the most seaward toe position ~26 m more seaward than previously used in this report. The SCDF has not been updated in version 3 of the report as the HCDF designs were not available in time for the commencement of modelling. Therefore, there is an expectation that the lowest initial SCDF volumes will be found here. However, the lowest initial SCDF volumes was measured as 105 $m^3$/m at the southern endpoint, although these volume measurements are artificially low, and will be larger once the SCDF has been fully updated. Historically this is a stable area of shoreline.

- The HCDF at the permanent BLF (beach landing facility) is now in line with rest of the HCDF. The BLF area, which was highlighted in Version 2 as an area with the smallest initial sediment volumes of approximately 162 $m^3$/m, has seen a rise in sediment volume to over 190 $m^3$/m (see updated Figure 8) and therefore reduced risk of HCDF exposure.

As a result of the HCDF design changes since Version 2, the SCDF volumes and RIs have been recalculated for the operation and early decommissioning phases (Section 3.2), however the broad conclusions for this phase remain unchanged and few changes have been made to the text. The volumes remaining after storms and the RIs for the decommissioning phase (Section 4) also use the updated HCDF, as well as the adapted HCDF.

The following sections have been updated or added in Version 3 of this report following new numerical modelling results (BEEMS Technical Report TR545 Rev 2) and changes to the HCDF:

- Executive Summary
- Section 1.3: Changes in Version 3
- Section 1.5: Outline (updated)
- Section 3.2: Updated RIs and volumetric losses considering changes to the HCDF design
- Section 4: Decommissioning phase
    - 4.1 Decommissioning Summary
    - 4.2 XBeach 2D (sand) storm erosion and recharge intervals for the permanent HCDF
- Section 4.3 XBeach2D (sand) storm erosion and recharge intervals for the Adaptive Design
    - 4.3.1 The adaptive HCDF design and modelled conditions
    - 4.3.2 Storm erosion and recharge summary
- Section 5: Conclusions (updated)

The following tables and figures have been updated/added to show the RI calculations in respect to the new HCDF positioning:

- Figure 7
- Figure 8
- Table 1 and Figure 13
- Figure 15
- Table 3
- Table 4

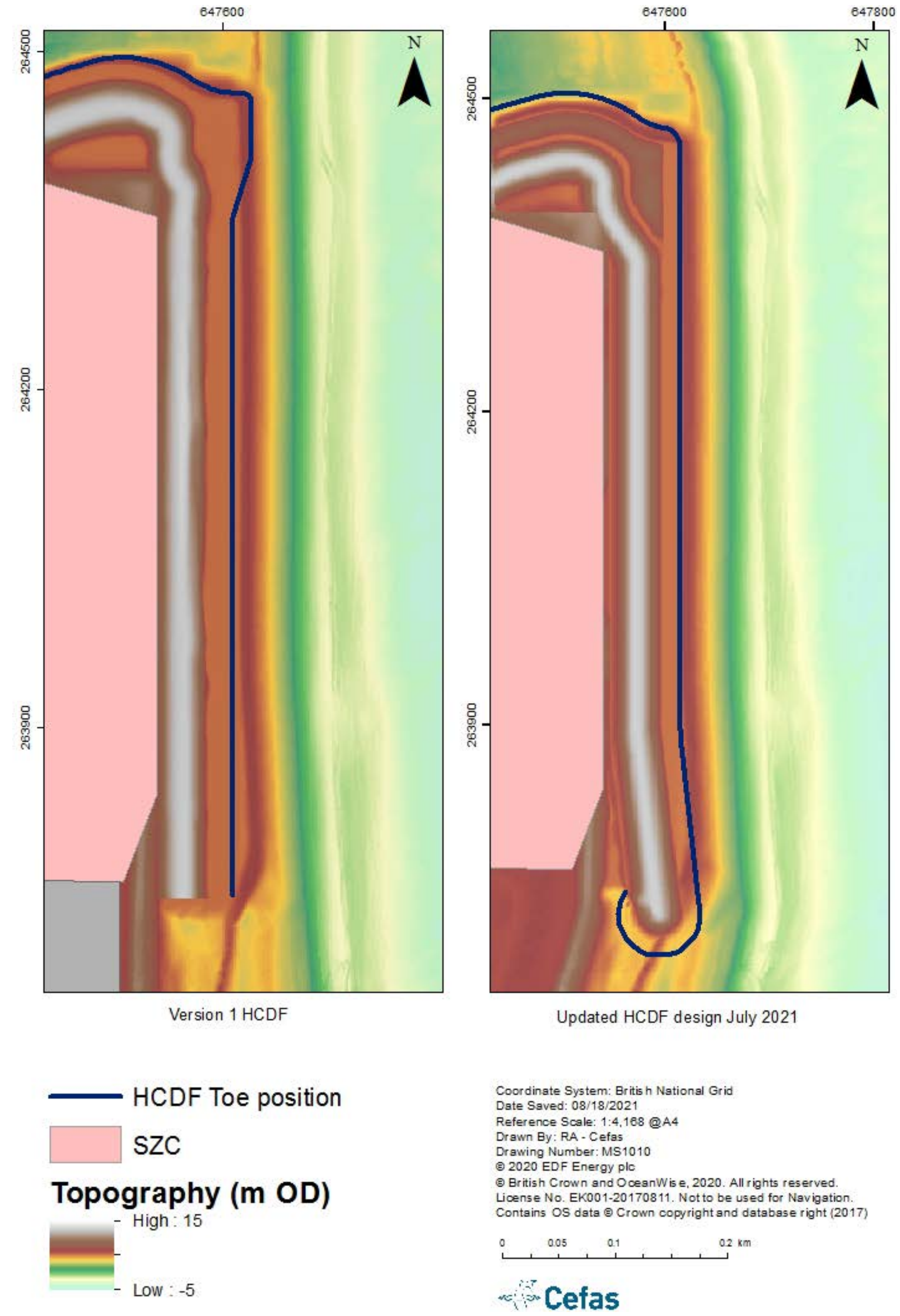

Figure 1: Topographic maps showing the HCDF used in Versions 1 and 2 of this report and the updated HCDF design as received in July 2021 (REP5-015).

## 1.4 Changes in Version 4

The following sections have been updated or added in Version 4 of this report following new numerical modelling results (BEEMS Technical Report TR545):

- Executive Summary
- Section 1.4 (this section): Changes in Version 4
- Section 2.4: SCDF sediment composition (updated)
- Section 4.1: Decommissioning Summary
- Section 4.2 XBeach 2D (sand) storm erosion and recharge intervals for the permanent HCDF
    - 4.2.1 1:20 year NE storm sequence
    - 4.2.2 Beast from the East storm sequence
- Section 4.3 XBeach2D (sand) storm erosion and recharge intervals for the Adaptive Design
    - 4.3.3 Beast from the East storm erosion and recharge intervals for the adaptive HCDF
- Section 4.4: X Beach Gravel (1D) storm erosion modelling (updated)
- Section 5: Conclusions (updated)

## 1.5 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[14] 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. Section 4 uses modelled datasets to estimate the SCDF erosion and likely recharge requirements for the midpoint (2120) and end of decommissioning (2140) for the updated HCDF designs and the adaptive HCDF (for sea levels determined using UKCP18 RCP 8.5 climate predictions which would be required to trigger HCDF adaptation). Further detail on sediment sources will be provided in a future version of this report.

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[14] The sediment volumes remaining after modelled storms and the RIs have been updated in this section to reflect changes in the HCDF design such as the paring back at the permanent BLF and inclusion of the southern terminus.

# 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[15]. That is, without the SCDF, shingle moving along the subaerial longshore transport corridor[16] 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[17] 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 2), i.e., across the entire longshore shingle transport corridor. However, its elevation around the Mean High Water Neap contour[18] 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 2 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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[15] Until the Cessation Report and associated actions have been agreed, as per the CPMMP (BEEMS Technical Report TR523).

[16] 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.

[17] Sizewell has a directional bi-modal wave climate (NE and SSE).

[18] 0.69 m ODN

Figure 2: 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.

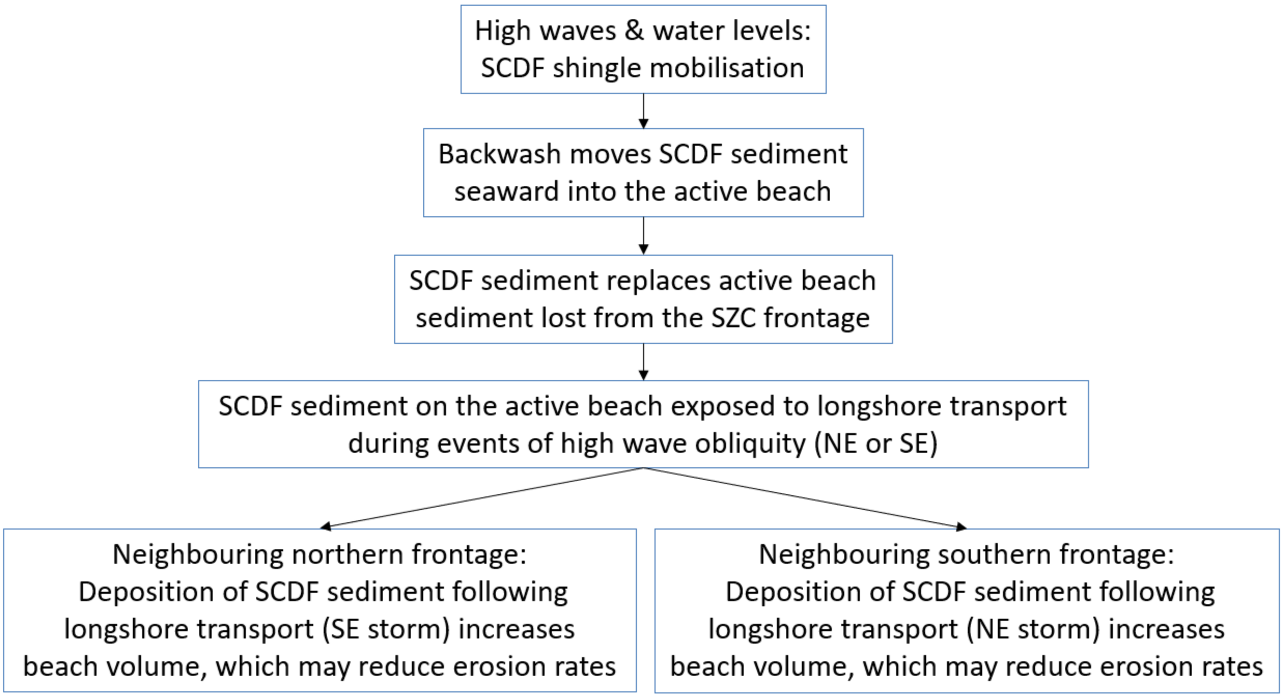

Figure 3: Simple box model describing sediment release from the SCDF and its pathways to neighbouring frontages.

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 or increase in extent (as observed at Sizewell B). This process is shown as a simple box model in Figure 3. 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[19], 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 4).

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[20]. 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[21] 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.

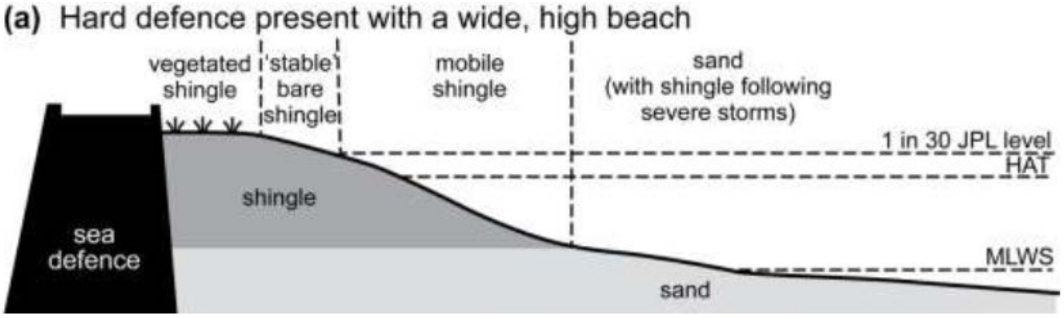

Figure 4: Schematic representation of evolutionary scenarios for hard defences with a fronting shingle beach, comparable to the proposed HCDF/SCDF (Figure 82, Pye and Blott, 2018).

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[19] 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.
[20] 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).
[21] 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[22]. 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[23], 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 increasing the density or extent 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, $V_{\text{buffer}}$, 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, $V_{\text{sac}}$, which would be allowed to erode until $V_{\text{buffer}}$ is reached, and would then be recharged (i.e., restoring the initial $V_{\text{sac}}$[24]). 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 $V_{\text{buffer}}$. For easy recognition, $V_{\text{recharge}}$ is used to describe the threshold for recharge i.e., $V_{\text{recharge}} = V_{\text{buffer}}$. The rationale for the *buffer* component $V_{\text{buffer}}$ 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 5 illustrates these components in cross-section and plots a line to illustrate the $V_{\text{recharge}}$ 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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[22] Although the present 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.

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

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

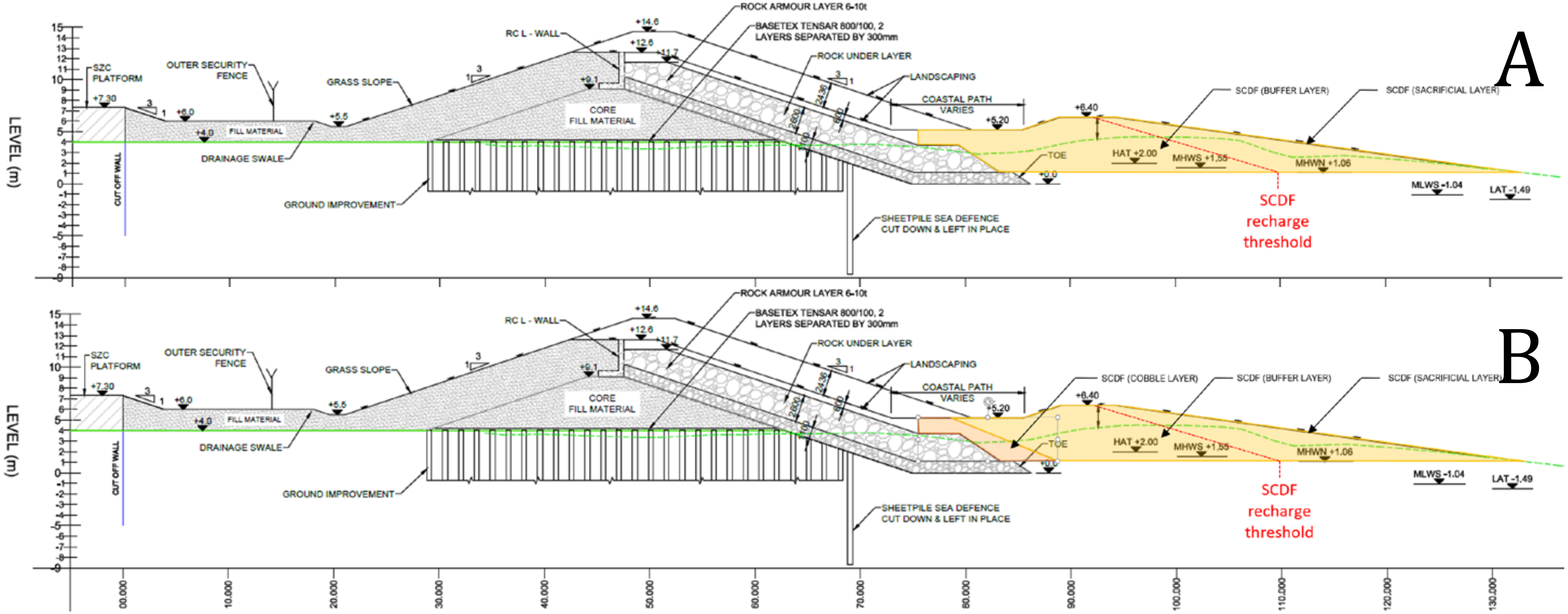


Figure 5: Schematic cross-sections of the hard and soft coastal defence features (HCDF and SCDF). Option **A.** The SCDF (yellow) is conceptually divided into two volumes, separated by the SCDF recharge threshold $V_{recharge}$ (illustrated by a red line). The SCDF *buffer* layer (whose volume is $V_{buffer}$) 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 6). 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 in version 3 is compared with the current topography in Figure 7. The SCDF built with the adaptive design was formed following the methods described above, with the same SCDF crest height of 6.4m ODN following parallel to the adaptive design.

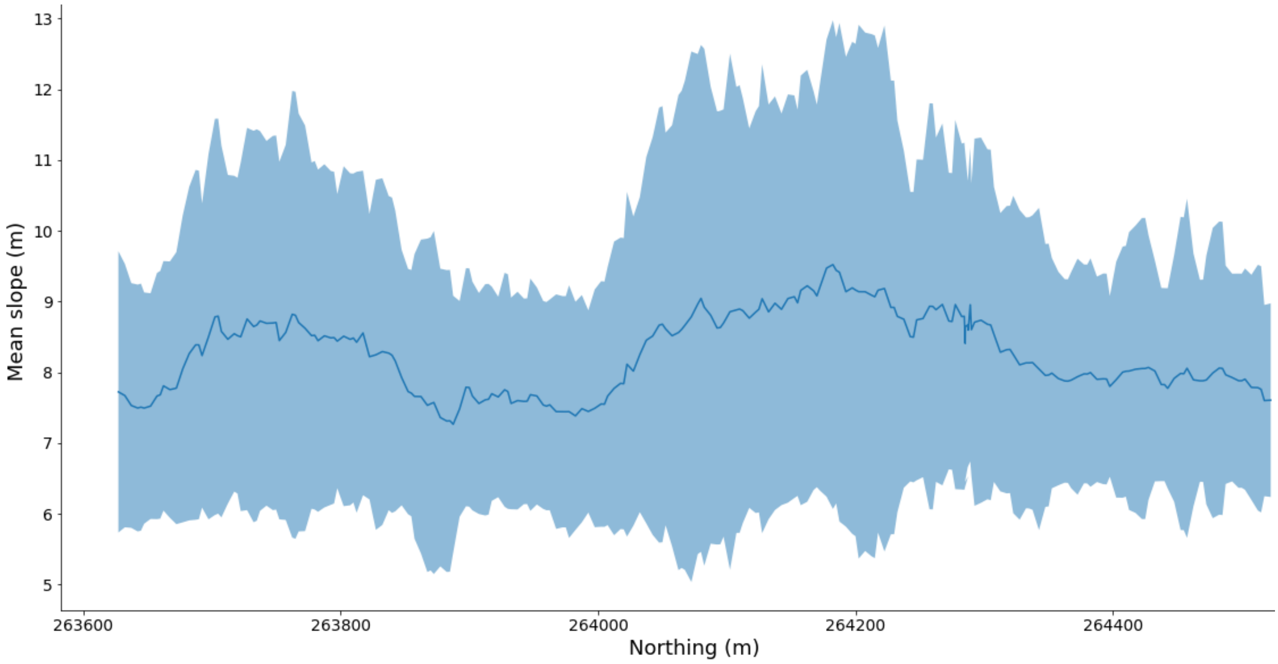
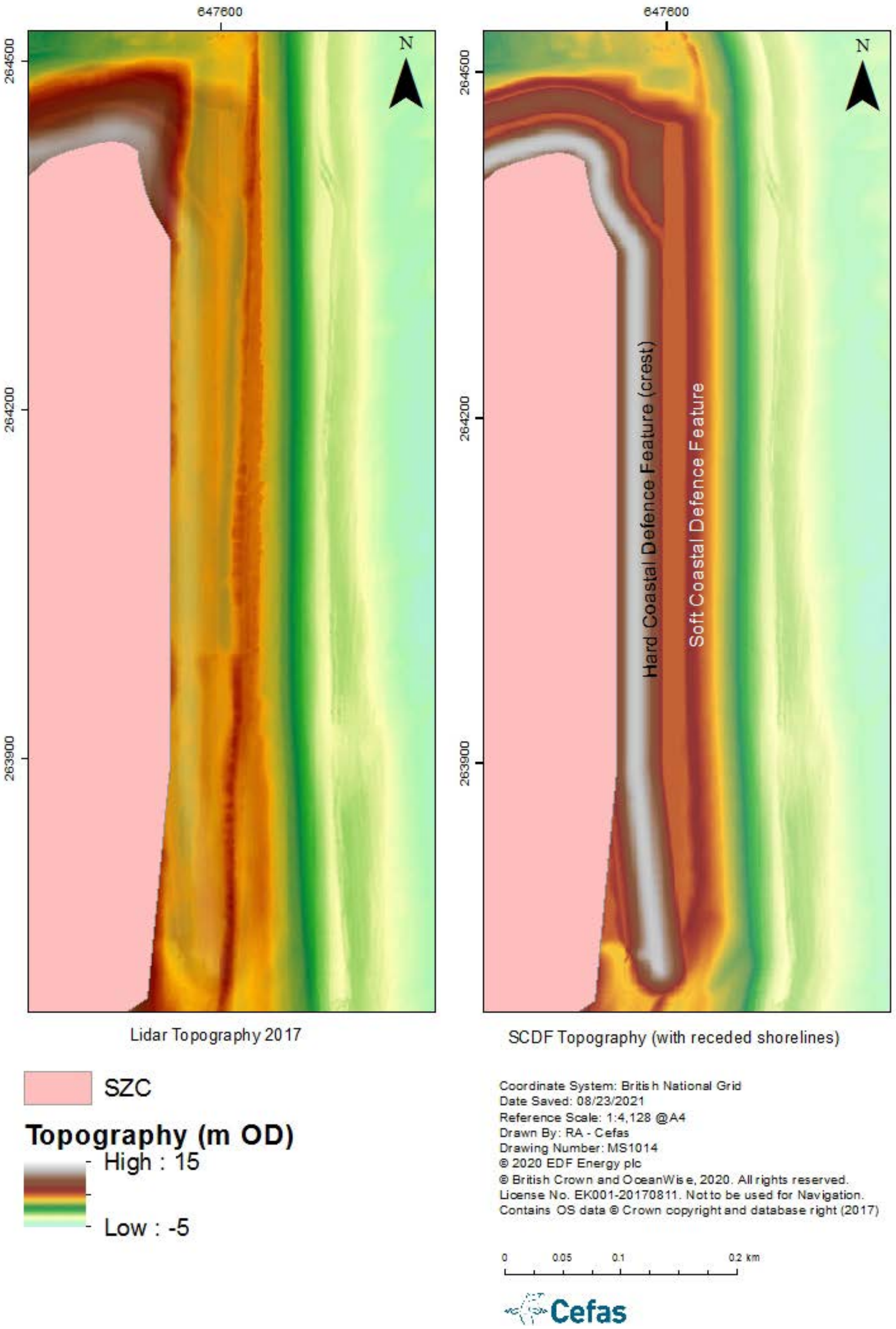


Figure 6: Beach slopes for the Sizewell frontage (°, MSL – HAT) from Sizewell B to just south of the tank traps located just to the north of the proposed Sizewell C site, showing the mean (solid line) and one standard deviation, every five metres.



Lidar Topography 2017

SCDF Topography (with receded shorelines)

Coordinate System: British National Grid
Date Saved: 08/23/2021
Reference Scale: 1:4,128 @A4
Drawn By: RA - Cefas
Drawing Number: MS1014
© 2020 EDF Energy plc
© British Crown and OceanWise, 2020. All rights reserved.
License No. EK001-20170811. Not to be used for Navigation.
Contains OS data © Crown copyright and database right (2017)

Figure 7: Maps of the current topography and the proposed SCDF. Note only that the topographic surface is shown – the HCDF toe (not shown) is buried beneath the SCDF.

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[25] (BEEMS Technical Report TR531). The SCDF volume[26] based on the previous HCDF design shown in Figure 8 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 were found to be near the permanent BLF (162 $m^3/m$; see Figure 8 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 $m^3/m$.

These initial volumes were used to set the size of the SCDF safety *buffer* volume ($V_{\text{buffer}}$) and the *sacrificial* volume ($V_{\text{sac}}$). An initial suggested working value for $V_{\text{buffer}}$ of 2 – 3 times the conservative storm erosion value gives $V_{\text{buffer}}$ = 80 – 120 $m^3/m$ and, from Version 1 of this report, $V_{\text{sac}}$ in the range 42 – 477 $m^3/m$.

The updated initial volumes (Figure 8), due to changes in the HCDF design, showed minimum values of 162 $m^3/m$ at the BLF but have since been increased to above 190 $m^3/m$ as the BLF abutment has been reduced. This suggests that the sacrificial volume could increase allowing for fewer interventions. The lowest volumes (105 $m^3/m$) are now to be found at the southern endpoint at the SCDF. Due to delivery timescales, the SCDF profile has not yet been adjusted to account for the more seaward HCDF design at the southern terminus in version 3, which means the SCDF volumes in this area are artificially low (and are likely to exceed the previously reported minimum value of 162 $m^3/m$.

Until further modelling and assessment has been completed the initial suggested working values for $V_{\text{buffer}}$ and $V_{\text{sac}}$ 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).

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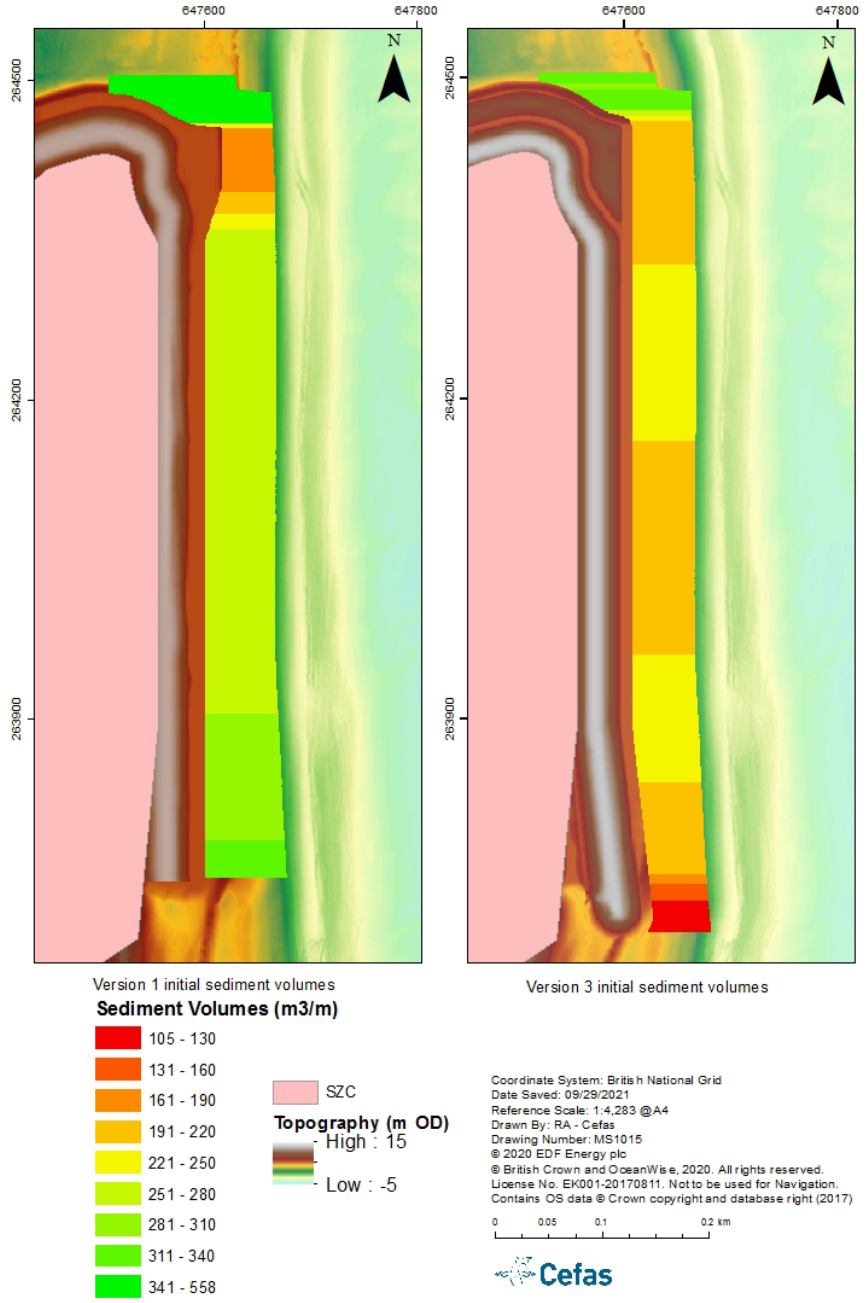
[25] Based on modelling of a 0.4 m sea level rise (relative to 2020), which corresponds to the 95th percentile of the RCP4.5 UKCP18 climate change scenario in 2069. Model results over predict erosion and are highly conservative. 2069 is approximately halfway through the planned operation phase.

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



Version 1 initial sediment volumes

Version 3 initial sediment volumes

Figure 8: SCDF design volumes from version 1 and 3, expressed as $m^3$ per metre of alongshore beach frontage ($m^3/m$) and computed above 0 m ODN. Note that due to delivery timescales, the SCDF has not yet been adjusted to account for the more seaward HCDF design at the southern terminus in version 4, which means the SCDF volumes in this area are artificially low.

Although the shingle ridge is not presently overwashed, it is low in places (especially at the tank traps just north of SZC[27]) 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[28]), which are:

- 0.55 – 0.83 m RCP4.5 (intermediate emissions scenario[29] 50th and 95th percentile respectively) and
- 0.78 – 1.14 m RCP8.5 (worst-case climate emissions scenario[30] 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 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). Whilst Option B is still being considered, SZC Co is comfortable with retaining the native size distribution and not coarsening the pebble sediments as suggested below for Option A. Further fine tuning of the SCDF design will be conducted (numerical and, potentially, physical modelling), and any proposed changes will be consulted on with the Coastal Geomorphology subgroup of the Marine Technical Forum and require approval by the discharging authorities.

The sedimentology used 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 – 4.0 cm; medium to very coarse pebbles). By comparison, sections at Highcliffe with sand and gravel mixtures performed less well and required minor recharges.

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[27] 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.

[28] 2099 would be early in the decommissioning phase, assuming a 60-year-long operation phase.

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

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

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 the 2nd Version, a new section at 3.2.4 examined the modelled SCDF performance for a range of different particle sizes and quantified 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. This 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

As noted above, Option A has been superseded by retention of the native size distribution without coarsening. However, the text on this topic has been retained as all of the evidence in support of the SCDF design, including fine tuning, has yet to be presented.

Option A uses very coarse pebbles (32 – 64 mm diameter; see the modelled 40 mm results in Section 3.2.4), which are at the coarse end of the native particle-size distribution, to prolong the longevity of the SCDF (see Figure 5A). 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[31] within the SCDF (see Figure 5B) 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

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[31] The cobble size class has a diameter of 6.4 – 25.6 cm.

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[32] 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[33] (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 $11^o$ (toward the steeper end of natural beach slopes observed at Sizewell; see Figure 6).

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 * 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).

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[32] The fine cobble sub-fraction has a diameter of 6.4 – 12.8 cm.
[33] Because of their relatively low mobility.

# 3 Recharge Intervals from measurements and operation phase modelling

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), and numerical modelling of sediment loss during large storms (Section 3.2). 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)[34]. The factor of three is chosen to represent the (highly unlikely) occurrence of three sequential BfE style events without opportunity to recharge the SCDF. $V_{\text{buffer}}$ = 3 x 40 $m^3$/m = 120 $m^3$/m. Note that the revised storm erosion modelling (BEEMS Technical Report TR545) suggests that $V_{\text{buffer}}$ = 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).

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[34] 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.

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 $V_{sac,min}$ are highly conservative – the model set up over-predicts erosion and shows losses several times greater than observed.
- 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 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 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 9) 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 10). 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.

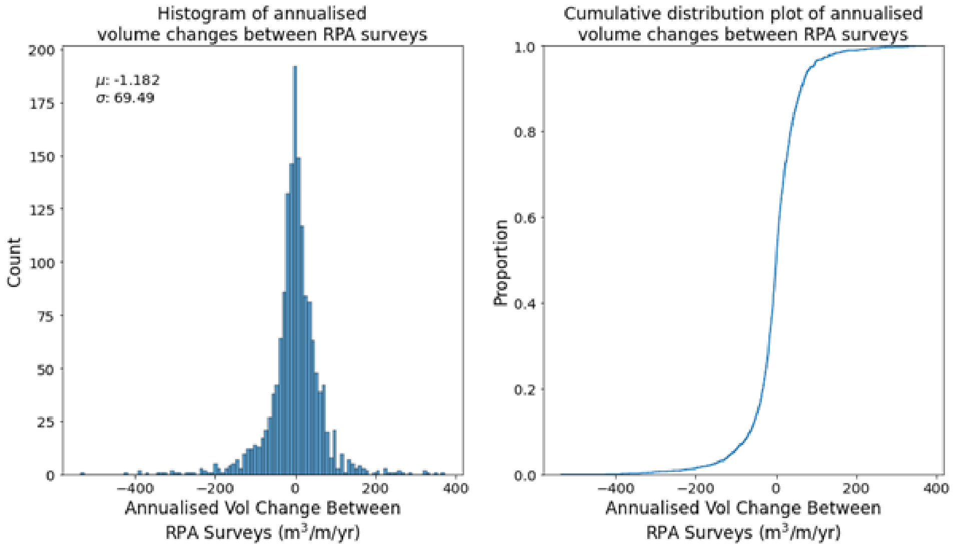

Figure 9: Histogram and CDF plot of aggregated volume changes between all RPA flights for 5 m bins every 50 m between Sizewell Café and the Minsmere Sluice Outfall (262850N and 266500N).

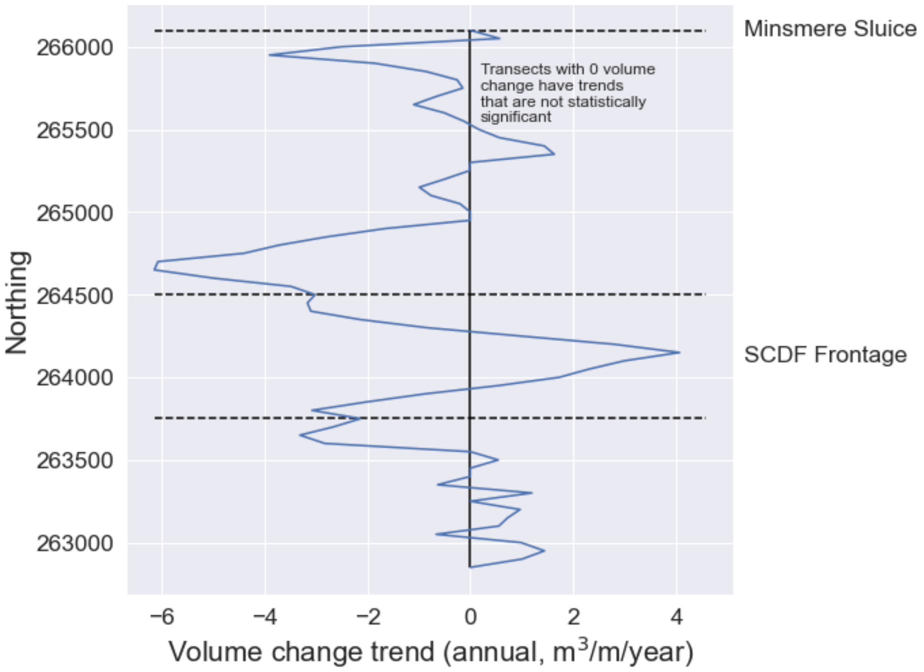

Figure 10: Annual volume change at each northing value derived from a linear regression fit over the time series of all RPA flight volumes for each northing.

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 $V_{sac,min}$ = 42 $m^3$/m, which is near the permanent BLF (Section 2.3.1), for the whole frontage[35] 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 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 3.1.2).

### 3.1.2 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 11 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 12. 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

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[35] 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. Figure 6 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.

Report TR545 is used in Sections 3.2.2 – 3.2.4 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.

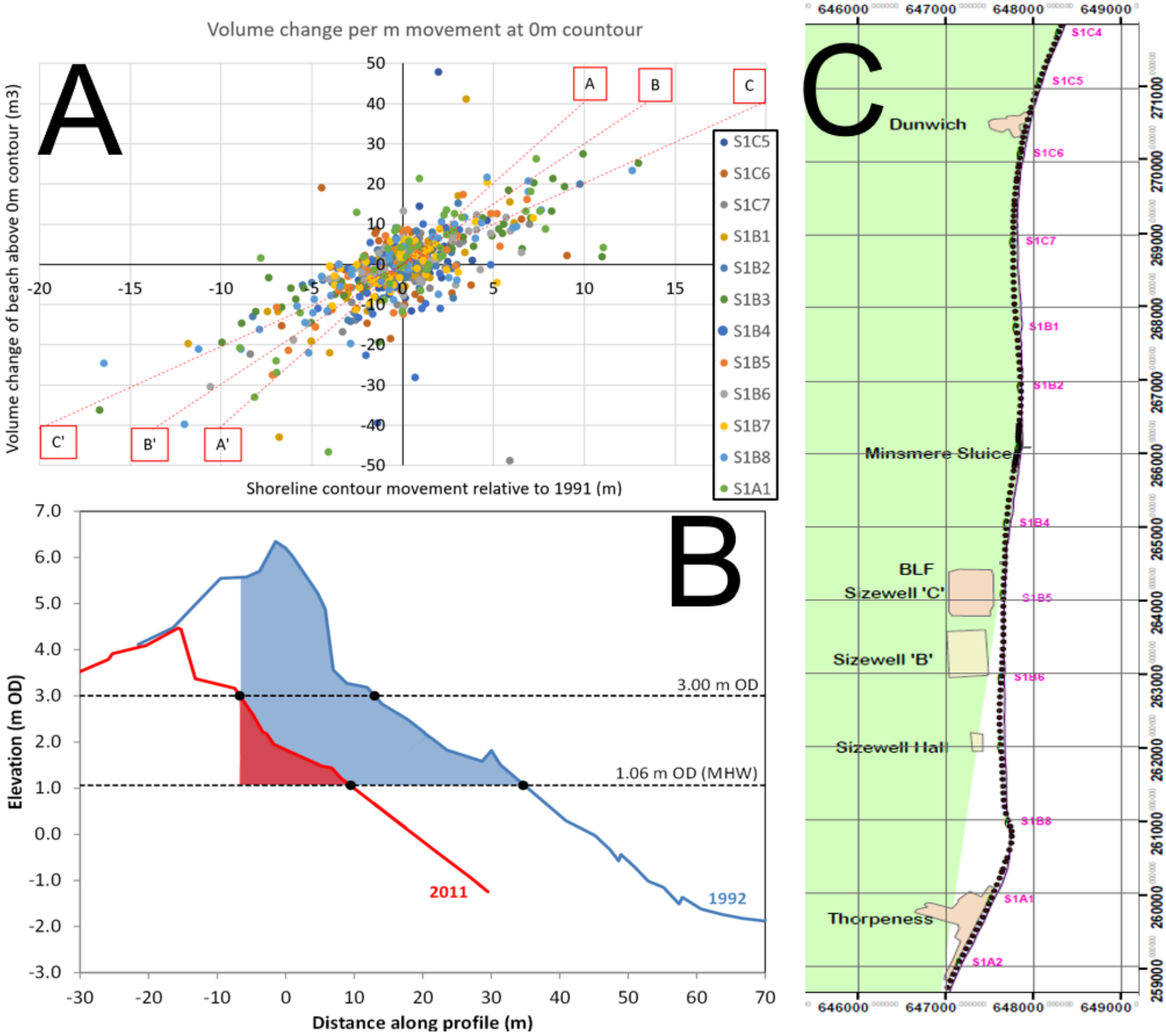

Figure 11: Volume changes as function of shoreline movement for the 0 m ODN contour (A) on Dunwich - Thorpeness frontage for 1991 - 2018, calculated as per (B). Red dashed lines in A represent indicative volume loss of 4 m3/m per metre of retreat (A-A'), 3 m3/m (B-B') and 2 m3/m (C-C'). Panel C shows the locations of each Environment Agency profile corresponding to the legend and coloured points in panel A

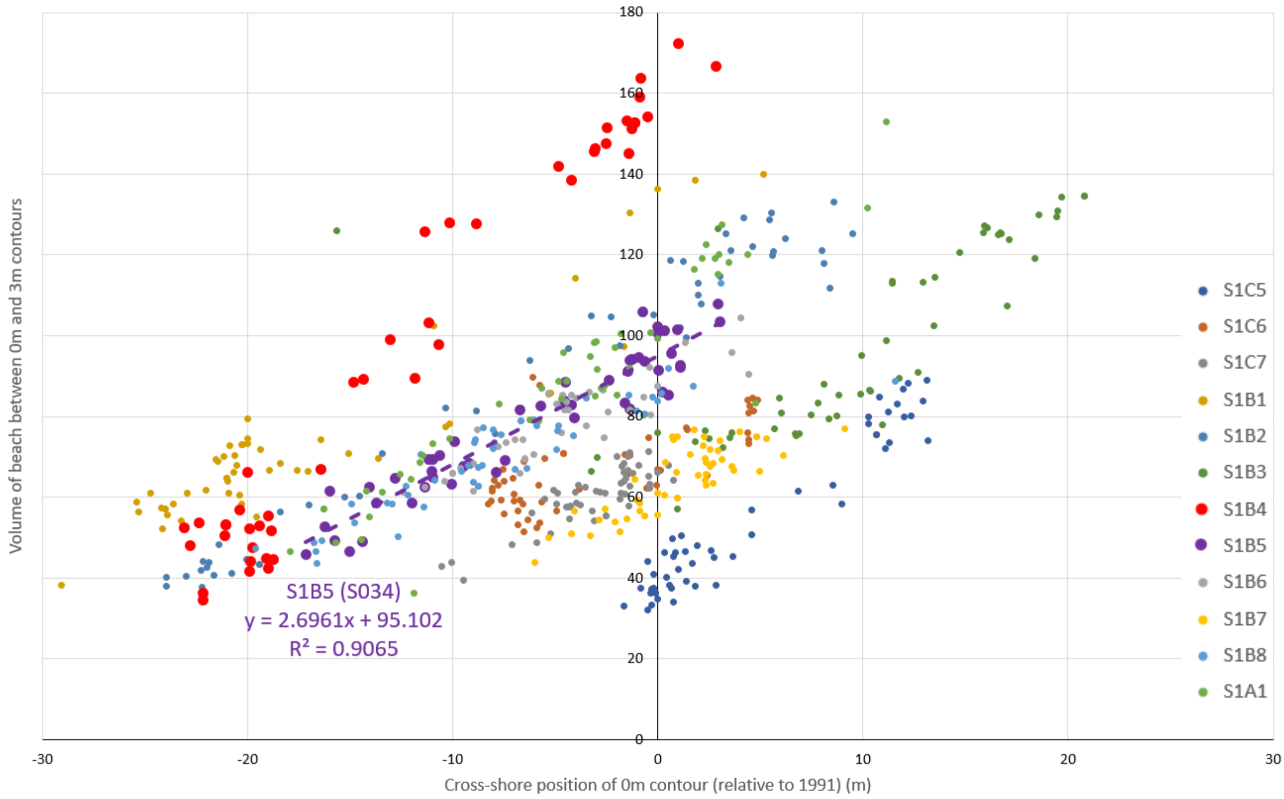

Figure 12: Beach volume changes as function of absolute position for separate EA profiles (1991 – 2018) to illustrate their uniformity, with a statistical best fit line shown for profile S1B5.

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. Extending this throughout the station life of Sizewell C (to 2140), the total recharge requirements would be c. 576 000 $m^3$.

## 3.2 Modelled storm erosion and recharge requirements for the operation and early decommissioning phase (up to 2099)

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[36] 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[37].

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). The modelling 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 3.2.1). Section 3.2.1 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 3.2.2 and 3.2.3). 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 15, 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 3.2.2 and 3.2.3, respectively).

XBeach-G (gravel) 1D (Section 3.2.4). XBeach-G model results are used to examine SCDF performance and RI variation for different SCDF (particle size) compositions (Section 3.2.4). 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[38] 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.

### 3.2.1 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

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[36] 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.

[37] 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.

[38] Called infiltration and exfiltration.

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[39] 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 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.

### 3.2.2 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[40], which is a 1:107 year return interval event in terms of cumulative wave power (see Appendix B of BEEMS Technical Report TR531). 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 volume of 42 $m^3/m$ described in Section 2.3.1 shows that the 1:107 year BfE sequence would not deplete the sacrificial volume at any location for the present day or 2069 sea levels, however in 2099 two sections of approximately 30 m of the SCDF frontage would lose more than 42 $m^3/m$ (up to 45.1 $m^3/m$; see Table 1 and Figure 13). 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 to erosion 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.

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[39] 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] 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.

Table 1: Predicted recharge intervals (RIs) with DDM applied calculated from exponential trendlines fitted in Figure 13, and interpolated every ten 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* | *109 (16.5 $m^3/m$)* | *75 (24.0 $m^3/m$)* | *64 (28.3 $m^3/m$)* |
| 2030 | 103 | 71 | 60 |
| 2040 | 96 | 67 | 56 |
| 2050 | 90 | 63 | 53 |
| 2060 | 85 | 59 | 50 |
| *2069* | *81 (22.3 $m^3/m$)* | *56 (31.9 $m^3/m$)* | *47 (38.0 $m^3/m$)* |
| 2080 | 75 | 53 | 45 |
| 2090 | 70 | 50 | 42 |
| *2099* | *66 (28.3 $m^3/m$)* | *47 (38.4 $m^3/m$)* | *40 (45.1 $m^3/m$)* |
| 2110 | 62 | 44 | 37 |

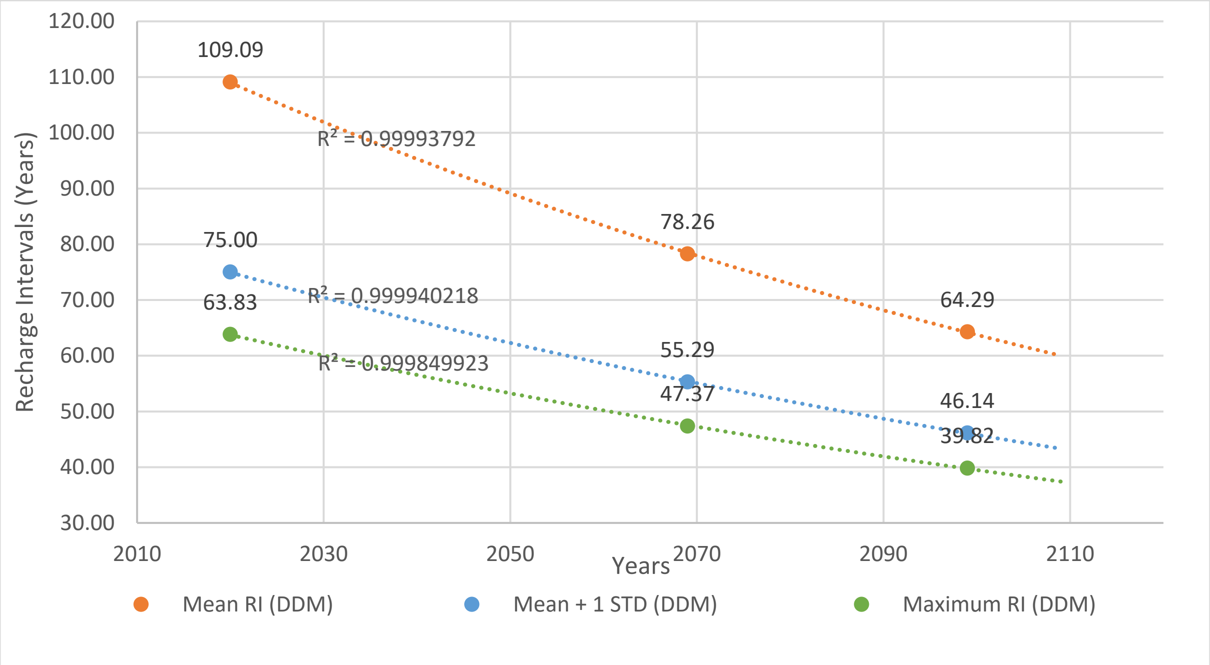

Figure 13: Recharge Interval (RI) in years with the Dutch Design Method (DDM) applied calculated from the mean erosion rate, maximum erosion rate and the mean erosion rate with 1 standard deviation (STD) from XBeach 2D sand model results. Exponential trendlines were fitted to each set of rates.

Using the methods established in Section 3.2.1, the recharge intervals are calculated for a sacrificial volume 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 northern SCDF near the permanent BLF. Therefore, for each sea level case, the RI's are calculated for these three statistics.

At present day sea levels (the 2020 scenario), the 2D model predicted a mean sediment loss of 16.5 $m^3$/m from the BfE storm along the SZC frontage, which is substantially less than the sacrificial volume 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 13, which are a good indicator for the central area 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 81 and 66 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 152 years to 109 years (applying the DDM), and further to 77 years applying the one standard deviation with DDM. Inclusion of the DDM suggests that projected 2069 sea levels may require a recharge as the RI falls to 56 years and 47 years by 2099.

Using the maximum modelled erosion rates, representative of the northern SCDF area near the permanent BLF, 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 38.4 $m^3$/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 45.1 $m^3$/m. This implies that a recharge would be needed after one BfE storm event in 2099, but only in two sections of 30m frontage near the northern SCDF.

Figure 13 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 structured 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 a 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.

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

In addition to the effect of sea level rise (Section 3.2.2), 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[41] 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 southern 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 are shown in Figure 14. The same model conditions used in Section 3.2.2 apply here and include 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 43.1 $m^3$/m with receded lateral shorelines (which just exceeds the sacrificial volume of 42 $m^3$/m), however the erosion is not evenly distributed, as shown in Figure 15. 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 northern endpoint 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 120 $m^3$/m of sediment remaining. It is worth noting too that these results are for the 2D sand model which overpredicts erosion.

For the maximum erosion rates, 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 ~ 66 $m^3$/m, which is below the buffer volume of 120 $m^3$/m. It should be noted that the initial sediment volumes here are set to increase by approximately 80 $m^3$/m which should decrease the vulnerability of this area. However, more frequent localised recharge may be considered in this area if monitoring, as part of the CPMMP's structured Adaptive Environmental Assessment and Management process demonstrates receded lateral shorelines.

The buffer volume of 120 $m^3$/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). These values were specific to an earlier HCDF design where BLF abutment showed the smallest SCDF volumes (Figure 8), however due to the retraction of the HCDF at the BLF area, there is more than 120 $m^3$/m sediment remaining (Figure 15). The smallest remaining volumes of 66 $m^3$/m are now found to be at the southern endpoint and highlight this region as a potential risk area, although the shoreline in this area is very stable and, as noted in Section 2.3.1, the SCDF has not been updated to reflect the seaward southern curvature of the HCDF, as the details were not available when modelling commenced.

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 a conservative estimation. As mentioned in Section 3.2.2, 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 natural coastal processes and the need for recharge will be assessed by continuous monitoring.

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

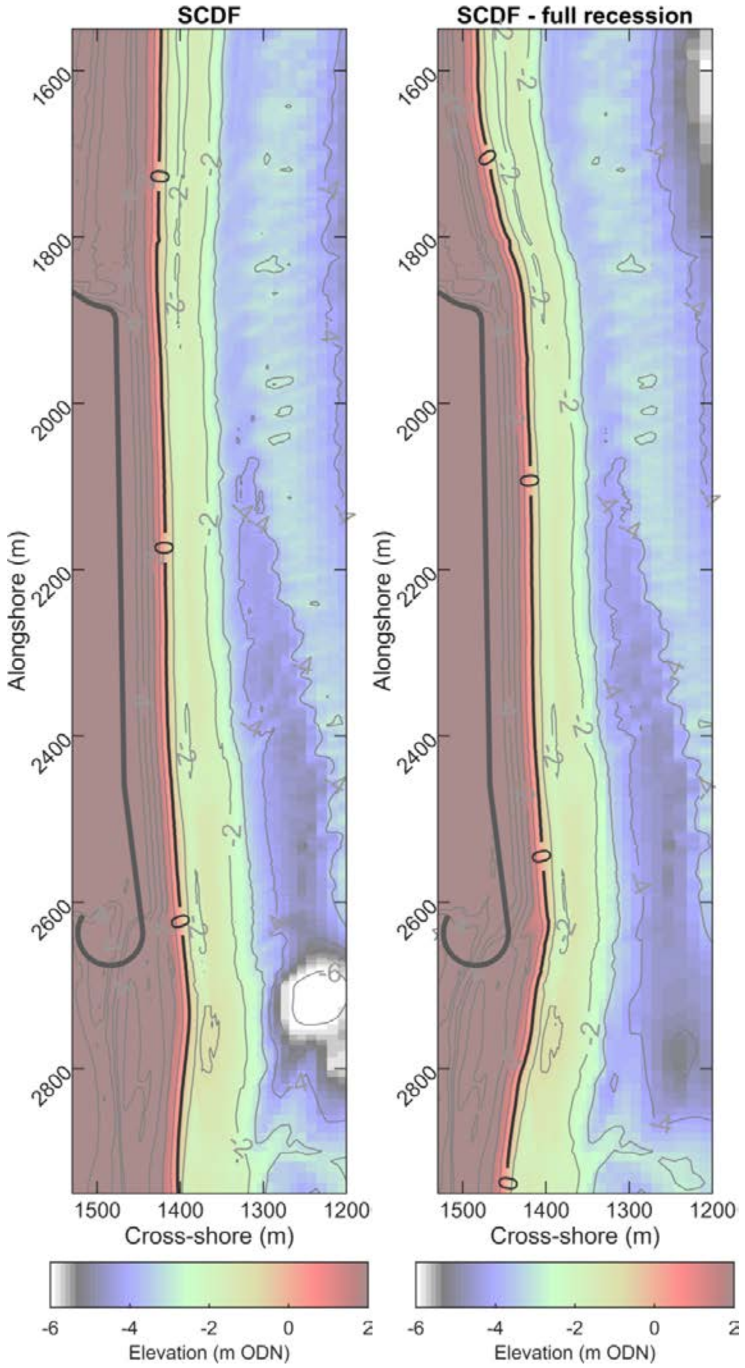

Figure 14: The Beast from the East storm, 2099 Sea Level – Post-storm bed elevation for the SCDF with present-day shoreline (left) and SCDF-future shoreline position (right) cases. (BEEMS Technical Report TR545 Version 2.0).

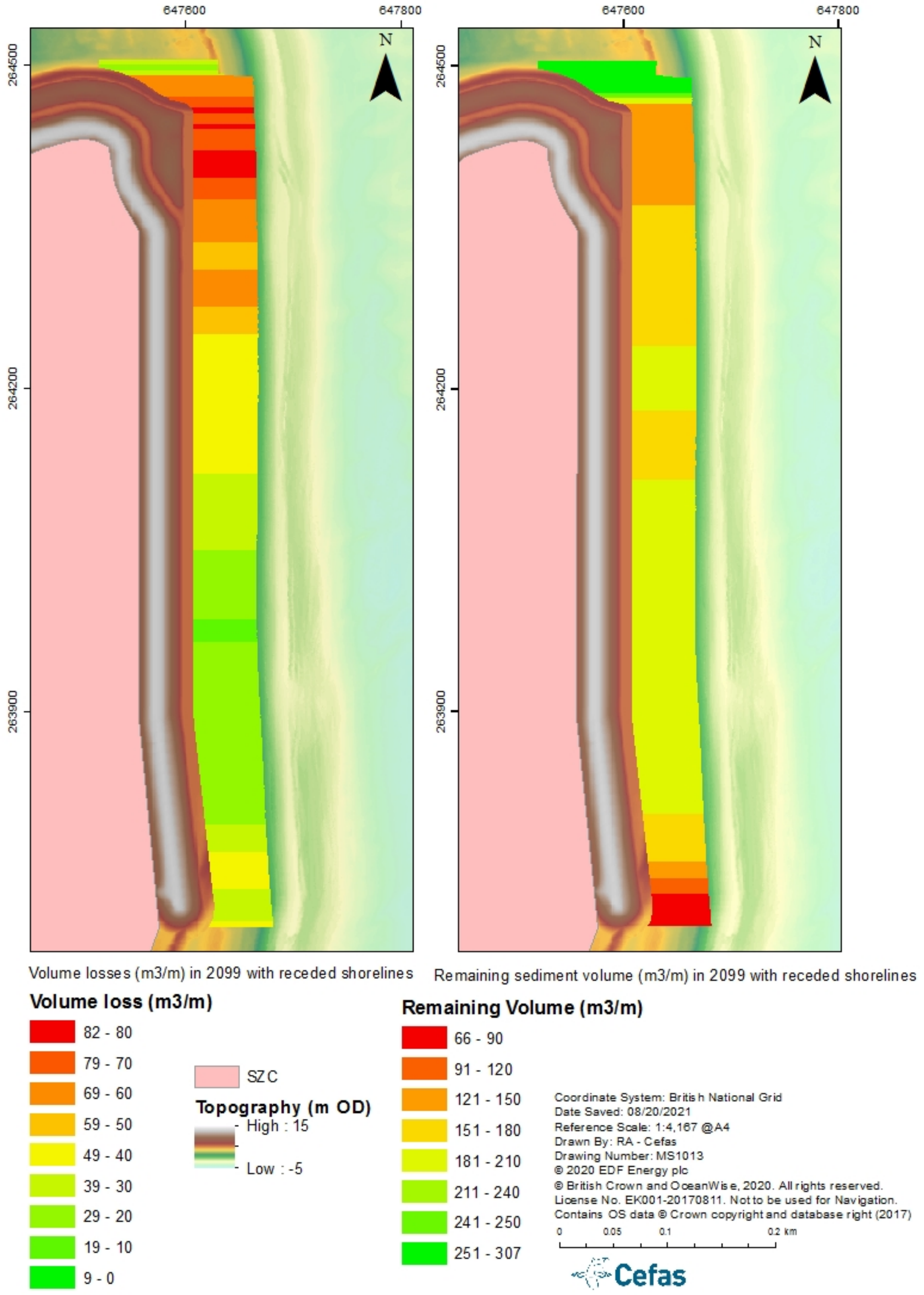

Figure 15: The loss of sediment volume in XBeach 2D sand model runs from the BfE storm in 2099 with receded lateral shorelines (left) and the remaining sediment volume of the SCDF after the BfE storm (right).

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

Whilst the XBeach2D modelling used in Section 3.2.2 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. This is in contrast to XBeach-G which can simulate the dominant pebbles at Sizewell, accounting for the larger particle mass and the swash infiltration and exfiltration[42] 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 3.2.1 – 3.2.3). 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.

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 16.

Within the XBeach-G results (green and brown lines in Figure 16), 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

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[42] 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.

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.

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.

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.  $D_{50}$ = 10 mm is the modal size for the native particles and is the default size intended for the SCDF. 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) (SCDF default) | 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 $m^3/m$) |

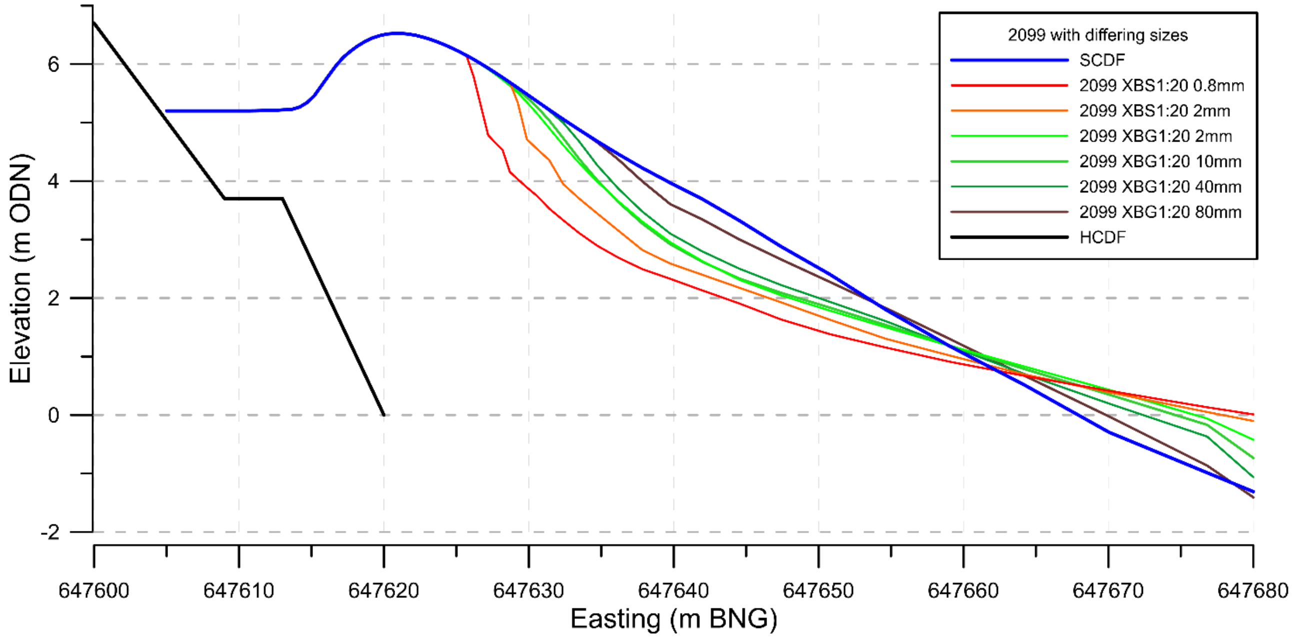

Figure 16: Pre and post storm beach profiles for a range of particle sizes using the 1D sand and gravel versions of XBeach for 2099 sea levels. The section shown is in the centre of the Sizewell C frontage. XBS = XBeach sand and XBG = XBeach gravel. The legend shows the sediment diameter used.

## 3.3 Storm erosion and recharge summary (operation and early decommissioning phases, to 2099)

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 operational life of the station of c. 270,550 m$^3$ (increasing to 576 000 m$^3$ for the whole station life)

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 central region 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, where the largest sediment losses were found.

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 75-47 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 volume 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.

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.

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 | 16.5 (109 years) | 22.3 (81 years) | 28.3 (66 years) | 43.1 (42 years) |
| | Mean and 1 STD Loss | 24.0 (75 years) | 31.9 (56 years) | 38.4 (47 years) | 61.7 (29 years) |
| | Maximum Loss | 28.3 (64 years) | 38.0 (47 years) | 45.1 (40 years) | 82.1 (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 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 3.2.4), and represent 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 its 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 are 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 secured. Large variances in RIs due to changing SLR’s highlight the need for regular monitoring and revision of not only how actual 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 Decommissioning Phase

As with the operation phase modelling (Section 3.2), the XBeach 2D sand and 1D gravel models for sea level rise at 2120 and 2140 (RCP4.5 95th percentile) were used to envelope the storm scale change for the middle and end of decommissioning and consider RIs and SCDF viability. Three storm conditions were modelled within the BEEMS Technical Report TR545 Version 3.0 for this updated report; the 1:20 year NE and SE storm and the 1:107 year BfE storm. The 1:20 year SE storm has a smaller impact on SCDF erosion and does not change the overall conclusions within this report. A 1D XBeach G model with a $D_{50}$ particle size of 10 mm was also run as this is modal pebble size and the default intended for the SCDF composition. The 2D sand model was also used as it recognises longshore transport and envelopes the likely storm response under modelled conditions owing to its conservative use of more mobile sands.

The UKCP18 predictions suggest varying degrees of decreasing wave climate at Sizewell (subject to the RCP scenario), however no reductions have been applied.

Recharge intervals for the decommissioning runs were calculated using the methods established in Section 3.2.1 and using the same sacrificial volume of 42 $m^3/m$ for consistency. This still assumes the working buffer volume and recharge trigger of three BfE storms ($V_{buffer}$ = 3 x 40 $m^3/m$ = 120 $m^3/m$). Determination of the trigger for beach recharge is part of ongoing work for the CPMMP to be consulted on with the Sizewell C Marine Technical Forum and submitted for approval to the MMO and ESC prior to commencement of work on the permanent HCDF and the SCDF.

## 4.1 Decommissioning Summary

Several 1D gravel and 2D sand XBeach model runs were used to establish storm erosion sediment losses ($m^3/m$) for the decommissioning phase up to 2140, with the detailed results presented in Sections 4.2 to 4.4. The results have been summarised in Table 4 and highlight that the northern SCDF would be at greatest risk of HCDF exposure when under the 1:20 year NE storm and would be the area which would most likely need more frequent recharges. This is in agreement with the modelling for the operation phase (Section 3.2) that also suggests the northern frontage is likely to be the most vulnerable area in general. The southern SCDF is a secondary area that is likely to require more frequent recharge owing to its lower sediment volumes.

*1:20 NE model simulation*

Erosive losses with the 1D XBeach gravel model (with a particle size of $D_{50}$= 10mm, which is considered more representative of the native subaerial beach) were less than 16.5 $m^3/m$, up to 1/3rd of the rates in the conservative XBeach 2D sand model (where sediment size is $D_{50}$= 0.8 mm). These losses stayed relatively low within the native particle range (the $D_{50}$ = 40 mm model lost 16.0 $m^3/m$) but reduced significantly for the larger particle size (the $D_{50}$ = 80 mm model had losses as little as 1.0 $m^3/m$). Therefore the $D_{50}$ = 80 mm fine cobbles could be highly beneficial in reducing erosion of the SCDF if used as a potential SCDF internal layer.

The losses and recharge values using the 2D sand model are likely to be overpredicting sediment losses and therefore imply that the recharges needed in the decommissioning phase are likely to be less than suggested by the sand model.

Table 4: 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 throughout the decommissioning phase with receded shorelines. $D_{50}$ = 10 mm is the modal size for the native particles and is the default particle size intended for the SCDF. The calibrated XBeach2D sand model used a grainsize of $D_{50}$ = 0.8 mm. The 2140 Adaptive design used UKCP18 RCP 8.5 (95th percentile) sea level conditions whereas all other models were run with UKCP18 RCP4.5 (95th percentile) sea levels.

| **Model Conditions** | | **2099 SLR sediment losses ($m^3/m$)** | **2120 SLR sediment losses ($m^3/m$)** | **2140 SLR sediment losses ($m^3/m$)** | **2140 SLR, Adaptive Design sediment losses ($m^3/m$)** |
|---|---|---|---|---|---|
| 2D 1:20 year Hs storm | Mean Loss | 24.3 (25 years) | 26.2 (23 years) | 27.3 (22 years) | 44.5 (13 years) |
| | Mean and 1 STD Loss | 31.4 (19 years) | 33.6 (18 years) | 36.6 (16 years) | 66.4 (9 years) |
| | Maximum Loss | 38.3 (16 years) | 41.0 (15 years) | 51.4 (12 years) | 140.9 (4 years) |
| 1D 1:20 year Hs storm | $D_{50}$= 10mm (XBG) | 14.3 (42 years) | 15.0 (40 years) | 16.5 (36 years) | 13.1 (46 years) |
| | $D_{50}$= 40mm (XBG) | 11.6 (52 years) | (not modelled) | 16.0 (38 years) | (not modelled) |
| | $D_{50}$= 80mm (XBG) | 2.5 (240 years) | (not modelled) | 1.0 (588 years) | (not modelled) |
| 2D 1:107 year BfE storm | Mean Loss | 43.1 (42 years) | 50.9 (35 years) | 56.3 (32 years) | 100.8 (18 years) |
| | Mean and 1 STD Loss | 61.7 (29 years) | 72.3 (25 years) | 79.0 (23 years) | 135.0 (13 years) |
| | Maximum Loss | 82.1 (22 years) | 103.1 (17 years) | 111.5 (16 years) | 188.3 (10 years) |

The sand model results are applied as a precautionary approach to the assessment of recharge intervals and SCDF viability. The results show that the SCDF is viable through Sizewell C's decommissioning phase. The maximum modelled erosion rates across the SCDF frontage at 2140 with RCP 4.5 (95th percentile) climate conditions predict sediment losses of 51.4 $m^3/m$. With the initial buffer volume of 120 $m^3/m$, this implies that a recharge would be needed after one 1:20 year storm, but these maximum losses are focused on 45 m of the northern SCDF frontage where remaining sediment volumes were greater than 160 $m^3/m$ i.e., the sacrificial volume would not be depleted.

*Beast from the East model simulation*

The SCDF remains viable when tested against more extreme BfE storm sequence. Whilst mean sediment losses increased to 56.3 $m^3/m$ and maximum losses more than doubled compared to the 1:20 year storm event to 111.5 $m^3$/m, the SCDF still prevented HCDF exposure. A 10 m section within the northern frontage of the SCDF would require immediate recharge to prevent HCDF exposure by a second sequential BfE storm prior to recharge. However, the rest of the frontage would withstand even this highly unlikely occurrence.

*Adaptive HCDF with 1:20 NE model simulation*

In the unlikely event that the UKCP18 RCP 8.5 (95th percentile) climate conditions come to be, the HCDF would be altered to an adaptive design, with a crest height increasing to 16.4 m ODN and a more seaward protrusion of the HCDF. Using the XBeach 2D sand model, Version 2 of BEEMS Technical Report TR545 predicted no lowering of the SCDF crest up to 2140 under RCP4.5 sea levels, but with the adaptive design in 2140 the SCDF crest height was reduced by 0.2 m to approximately 6 m ODN under RCP8.5 conditions[43].

When modelled in these more extreme conditions, mean losses exceeded the 42 $m^3$/m sacrificial volume at 45.4 $m^3$/m with the maximum loss reaching 141 $m^3$/m (on the northern SCDF; Figure 18). However, the HCDF is not exposed by the modelled storm and the lowest remaining sediment volumes of 99 $m^3$ (while suggesting an immediate recharge would be needed) is still twice that eroded by a storm of this magnitude.

Recharge intervals decrease from 19 to 16 years (DDM applied) between 2099 and 2140 when conservatively using the mean erosion rate plus one STD (Table 4). Using this conservative rate, the losses from a 1:20 year storm event do not exceed the sacrificial volume of 42 $m^3$/m, suggesting that no immediate recharge would be needed.

*Adaptive HCDF with Beast from the East model simulation*

The adaptive design showed that it would withstand a BfE storm sequence, however losses would be significantly higher compared to the 1:20 year storm sequence. Mean sediment losses of 100.8 $m^3$/m were predicted with the highest losses reaching 188.3 $m^3$/m at the northern endpoint of the HCDF. Remaining sediment volumes would be reduced at the two endpoints and would need immediate recharge after a storm event in order to avoid potential exposure under moderate storms. Were the adaptive HCDF to be built as a result of high RCP 8.5 (95th percentile) sea levels, it is likely that HCDF exposure would occur following extreme storms unless recharge was rapid. Consequently, an adaptive HCDF should be re-assessed if built in order to understand whether other design features could be employed – such features would include increasing the SCDF volume, using an internal layer of fine cobbles (if not already included in the design) and coarsening the bulk SCDF sediments

Further work is expected to refine the recharge intervals, including updates to buffer volumes and trigger levels. Despite the 2D sand models highly conservative nature, these results suggest that storms may trigger recharge mitigation during the decommissioning phase if the SCDF is at or near full capacity. Net erosion over decades, most likely due to storm events with partial volumetric recovery, would make some areas more at risk over time to HCDF exposure. Volumetric assessment of monitoring results will identify any localised erosion hot-spots that may trigger smaller, more frequent intervention in some areas and very little or none in others. Monitoring will also provide a useful early marker for the location of future recharge and likely volumes and the methods proposed in the CPMMP will also be capable of detecting areas

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[43] No crest lowering occurred when modelling the same scenario in XBeach-G using medium pebbles (D50 = 10 mm).

accumulating sediments, which may be suitable for transfer to areas requiring maintenance – that is, the application of bypassing or beach recycling.

The estimated erosion rates as predicted from the modelling of the decommissioning phase in this report have been incorporated into the CPMMP to determine the trigger values for the recharge intervals. The sand model overpredictions of erosion volumes contribute to a conservative estimation, with Version 4 of this report (this Version) demonstrating the potential benefits of fine cobbles as an internal layer, but only marginal benefits of increasing the SCDF bulk material particle size from 10 to 40 mm (within the native particle size range). Whilst the BfE storm sequence resulted in larger sediment losses throughout the decommissioning phase, the broad conclusions of SCDF viability remains the same.

## 4.2 XBeach 2D (sand) storm erosion and recharge intervals for the permanent HCDF

The two models runs (2120 and 2140) used the future receded shorelines topography[44] as introduced in section 3.2.3 above and shown in Figure 14 because:

- the receded shoreline case is more likely at this timeframe and
- the approach is conservative as naturally receded adjacent shorelines increase SCDF erosion (BEEMS Technical Report TR545 Version 3.0).

Sedimentary volumes have been calculated with respect to the updated HCDF (as discussed in Section 1.3), however the SCDF topography (crest height and location) used within the modelling was not altered as the designs were not available before the commencement of modelling. As a result, the SCDF was not remodelled to run parallel with the updated HCDF and does not extend as far south – the consequence is that the results presented in this section have a lesser volume than they should over the southern 70 m and therefore are volumetrically conservative. Effectively, the SCDF in the model is smaller than it should be with volumes in the southernmost 70 m as low as 105 m$^3$/m (see Figure 8). From provisional redesigns of the SCDF, this minimum volume is set to increase by approximately 80 m$^3$.

The recharge intervals were calculated for a sacrificial volume of 42 m$^3$/m, as per Section 3.2.1. The RI’s were based on the design storm occurring within a 20-year period and spatial statistics of the modelled SCDF erosion across the Sizewell C frontage: the mean, the mean with one standard deviation (STD) and the maximum erosion along the SCDF.

### 4.2.1 1:20 year NE storm

The notional minimum sacrificial volume of 42 m$^3$/m shows that the modelled 1:20 year NE storm would not deplete the sacrificial volume under 2120 sea level. However, storm erosion under the higher sea levels by 2140 would exceed the working trigger value of 42 m$^3$/m (see Table 5, Figure 17 and Figure 18) along 45 m of the northern SCDF frontage. The 1:20 year NE conditions have been calculated for 2020 and for future sea levels (2099, 2120 and 2140) with receded lateral shorelines for comparison in Table 5 and Figure 17.

In 2140 (end of decommissioning), the mean RI has been reduced (i.e., requiring more frequent recharges) by a third from the present-day RI of 33 years to 22 years (DDM applied). However, within the decommissioning phase alone there was only a reduction of 12% from the calculated RI of 25 years in 2099.

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

This was equal to an increase in mean sediment loss of approximately 0.08 $m^3/m$ per year within the decommissioning phase up to 27.3 $m^3/m$ in 2140, which is well within the sacrificial volume of 42 $m^3/m$.

Table 5: Predicted recharge intervals (RIs) with DDM applied calculated from modelled sediment losses (shown in brackets) from a 1:20 year NE storm scenario from 2020 to end of decommissioning phase in 2140. Years 2099-2140 include receded lateral shorelines, whereas 2020 uses present day shoreline.

| | Predicted RI's (years) | | |
|---|---|---|---|
| **Year** | **Mean** | **Mean + 1STD** | **Maximum** |
| 2020 | 33 (18.2 $m^3/m$) | 26 (22.7 $m^3/m$) | 23 (25.9 $m^3/m$) |
| 2099 | 25 (24.3 $m^3/m$) | 19 (31.4 $m^3/m$) | 16 (38.3 $m^3/m$) |
| 2120 | 23 (26.2 $m^3/m$) | 18 (33.6 $m^3/m$) | 15 (41.0 $m^3/m$) |
| 2140 | 22 (27.3 $m^3/m$) | 16 (36.6 $m^3/m$) | 12 (51.4 $m^3/m$) |

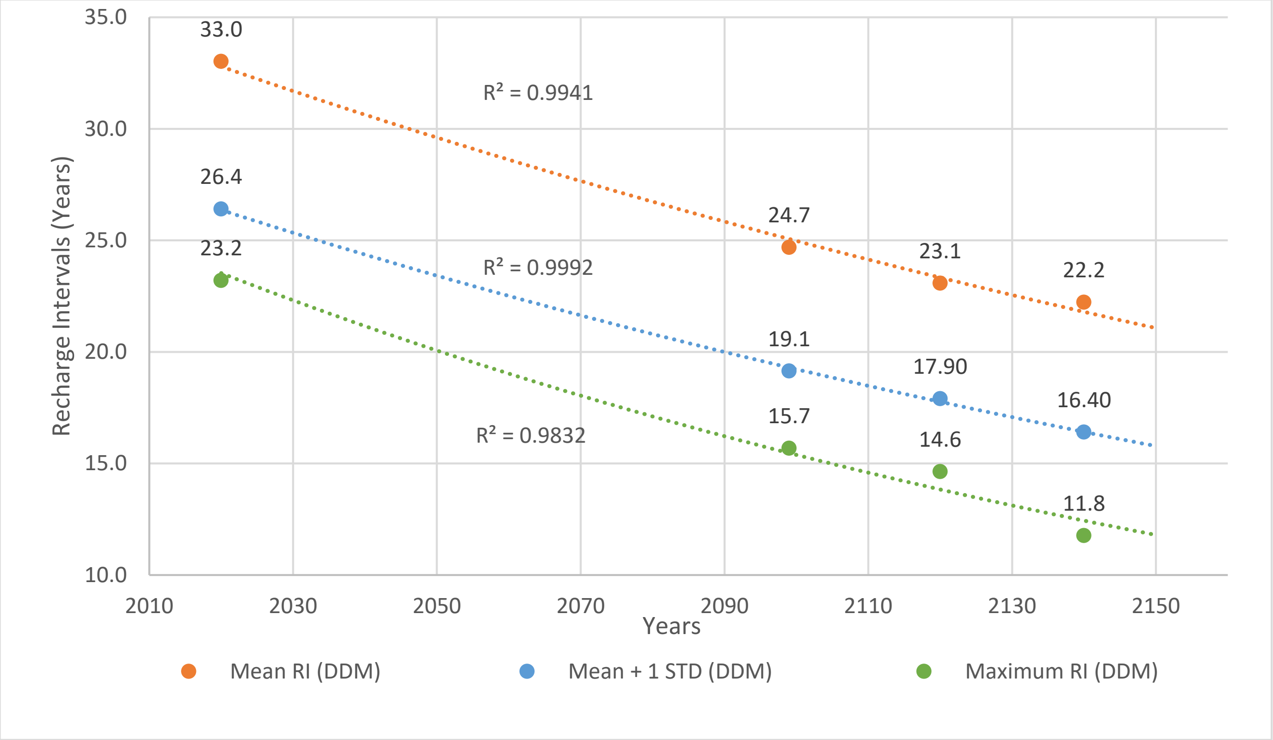


Figure 17: Recharge Interval (RI) in years with the Dutch Design Method (DDM) applied calculated from the mean erosion rate, maximum erosion rate and the mean erosion rate with 1 STD throughout the operational and decommissioning phase for the NE 1:20 storm. Exponential trendlines were fitted to each set of rates.

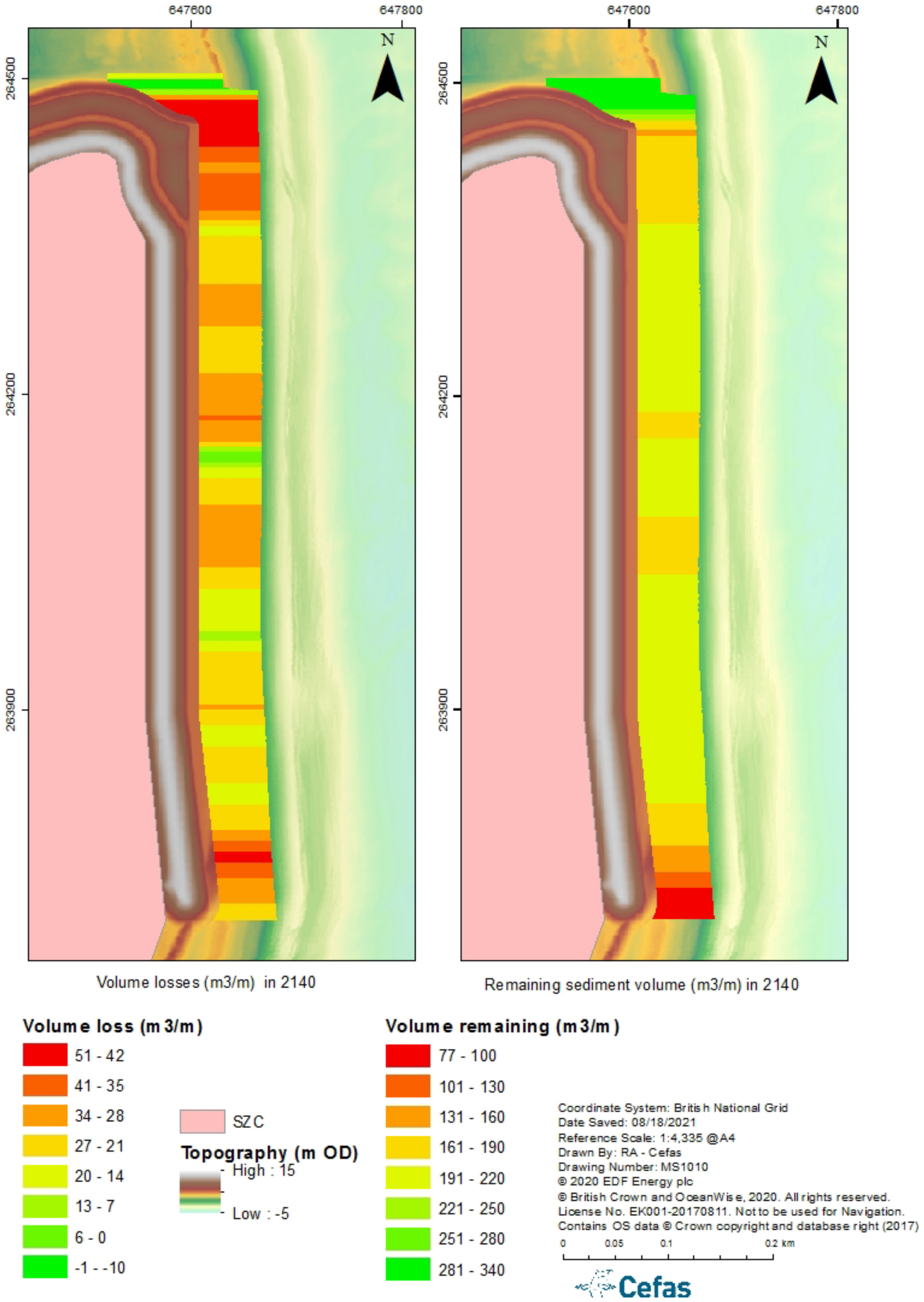


Figure 18: The loss of sediment volume in XBeach 2D sand model runs from a 1:20 year NE storm RCP4.5 scenario in 2140 with receded lateral shorelines (left) and the remaining sediment volume of the SCDF after the 1:20 year storm (right).

A more conservative approach of adding one standard deviation to the mean reduces the initial RIs by 22 – 27% between 2120 and 2140 for the mean RIs respectively. The additional increase of one standard deviation increases the sediment losses in 2140 to 36.6 $m^3$/m, which again is not large enough to trigger a recharge and creates a RI of 16 years (DDM applied).

The maximum modelled erosion rate found anywhere along the SCDF frontage is used to assess the lowest RIs (i.e., for a modelled erosion hot spot). In 2140 the maximum erosion rate was at the northern end of the SCDF and had an RI = 12 years (with DDM applied). This is a reduction of 45% compared to the mean erosion rate in 2140 and it is the only case that produces a sediment loss larger than the $V_{sac,min}$; sediment losses are 51.4 $m^3$/m, which implies that a recharge would be needed after just one 1:20 year storm over a short section of the beach (45 m of the northern SCDF; Figure 18). However, importantly, the HCDF was not exposed and the remaining buffer volume of 160 $m^3$/m would be sufficient to withstand a similar amount of erosion prior to recharge also without exposing the HCDF.

The volumes that were predicted to be lost at 2120 were less than the sacrificial volume of 42 $m^3$/m, with the smallest RI calculated at 15 years (DDM applied).

Relatively high maximum losses (up to 45.4 $m^3$/m) were found on a 10 m section of the southern SCDF. This area leaves a remaining volume of 146 $m^3$/m, which again would suggest there would be no need for an immediate recharge. However, currently the most southerly 45m section of the beach volumes have an artificially low remaining volume below the 120 $m^3$ buffer volume (since the SCDF has not yet been remodelled as the HCDF comes out to meet it; see Section 1.3), ranging in volume from 77-112 $m^3$/m. The remaining modelled volume is sufficient to withstand the unlikely event of at least two further 1:20 year storms without any recharge intervention before HCDF exposure. It should be noted that the SCDF volumes will increase once the southern SCDF is remodelled (by approximately 80 $m^3$/m), and therefore these results can be considered as conservative.

Table 5 is an updated version of Table 1 and can be used to compare volume change and RIs assessed on a decadal basis against the actual progression of sea level rise and the levels of SCDF erosion. This can be used to ascertain whether the demand for recharge is greater or less than that predicted and the likely future demands. They will also be used to revise forward looking plans, such as whether the very unlikely adaptive HCDF design is required for the decommissioning phase (see Section 4.3.1). This will be part of the structured Adaptive Environmental Assessment and Management process described in the CPMMP.

### 4.2.2 Beast from the East storm sequence

To examine erosion from a more severe (erosive) storm throughout the decommissioning phase, the 2D modelling considered the full Beast from the East (BfE) storm sequence, which has a 1:107 year return interval in terms of cumulative wave power (see Appendix B of BEEMS Technical Report TR531 Rev 2). Statistically speaking, such a storm may be expected to occur once or twice within the whole project lifetime of Sizewell C. To reflect this, the BfE storm sequence is assumed to occur once within a 60-year period when determining recharge intervals throughout the lifetime of Sizewell C. This is an additional conservative measure, with the reduced return interval creating larger erosive rates and smaller recharge intervals. The modelled runs (at 2120 and 2140) used the future receded shorelines topography in line within the previous section.

Using the notional minimum sacrificial volume of 42 $m^3$/m, the modelled BfE storm sequence would deplete the sacrificial volume under both the 2120 and 2140 sea level scenarios, with mean losses of 50.9 $m^3$/m and 56.3 $m^3$/m respectively (Table 6 and Figure 19). This results in recharge intervals of 35 and 32 years respectively (with DDM applied) over a 60 year period. Compared to 2099, this results in reduction in the recharge interval by 24% for mean losses and a 27% reduction for areas vulnerable to maximum losses.

The majority of the frontage is predicted to be able to withstand the unlikely occurrence of a sequential event of the same magnitude prior to recharge without HCDF exposure at 2140 (with the whole frontage able to withstand such an event at 2120). Therefore, immediate recharge would not need to occur over the vast majority of the SCDF. The remaining sediment volumes show that the HCDF would not be exposed from a single BfE storm event, with the SCDF retaining 67 - 303 m3/m of sediment (Figure 20).

The maximum sediment losses in 2140 are located within a 70 m area of the northern SCDF and reach 111.5 $m^3$/m. The remaining volumes in this 70 m area are less than the initial buffer volume of 120 $m^3$/m, indicating that immediate recharge would be required, although the HCDF is not exposed. The HCDF could be exposed by an unlikely second sequential BfE storm across a short 10m sub-section where the volumes remaining after one BfE storm were predicted to be very low (99 $m^3$/m).

The pre-storm volumes for the most southerly 50m section of the beach volumes are artificially low (where the SCDF has not yet been remodelled; see Section 1.3). In this area, the remaining volumes are also lower as a result, and range from 67-101 $m^3$/m. Nonetheless, the eroded volumes (73.1 $m^3$/m) exceed the sacrificial volume in this area, which would be expected to trigger beach recharge. It should be noted that the initial SCDF sediment volumes are expected to increase by approximately 80 $m^3$/m once the southern SCDF is remodelled and therefore the results shown here are considered to be conservative. Even with these conservative results, the southern endpoint contains sufficient sediment to withstand a further BfE storm without intervening recharge and would not be expected to expose the HCDF.

Erosion of the SCDF crest was predicted to occur during the BfE storm with RCP4.5 SLR during both of the modelled storm events at 2120 and 2140 sea levels (BEEMS TR545). At 2140, the crest height was reduced from 6.4 m ODN to approximately 5.8 m ODN, but would still be higher than the elevation of the coastal path behind the SCDF crest.

## 4.3 XBeach 2D (sand) storm erosion and recharge intervals for the adaptive HCDF

### 4.3.1 The adaptive HCDF and modelled conditions

The HCDF has been designed for 1 in 10,000 year water level and wave height conditions with a sea level rise taken from RCP 8.5 (95th percentile) at the end of design life in 2140 (the Reasonably Foreseeable Design Basis) (Sizewell C Coastal Defences Design Report [REP2-116]). As the design conditions also increase the wave heights and periods by a further 10%, the approach is considered conservative in light of UKCP18 predictions for decreasing wave conditions at Sizewell. It is recognised that the RCP 8.5 (95th percentile) sea levels, the Design Basis and the 1:10,000 year conditions may exceed the initial HCDF design and require future adaptation to accommodate worse climate scenarios, if they develop. These conditions are not expected to occur during the decommissioning phase as the RCP8.5 scenario is significantly worse than the current RCP trajectory and, even were RCP8.5 to be realised, the condition for HCDF adaptation would not be met until the end of decommissioning. However, the adaptive HCDF design is a requirement of the safety case and so has been assessed here in terms of SCDF viability.

The adaptive HCDF revetment would be overlaid on the previous revetment, and the toe section extended seaward by 17 m to a lower (-1.5 m ODN) level (Figure 21) as stated in Sizewell C Coastal Defences Design Report ([REP2-116]) The adaptive design would increase the HCDF crest height by placing additional armour and a wave wall on the top of the initial HCDF to attain a crest level of 16.4 m OD (from the previous height of 12.6 m OD).

Table 6: Predicted recharge intervals (RIs) with DDM applied calculated from modelled sediment losses (shown in brackets) from the BfE storm scenario within the decommissioning phase up to 2140 with receded lateral shorelines.

| | Predicted RI's (years) | | |
|---|---|---|---|
| **Year** | **Mean** | **Mean + 1STD** | **Maximum** |
| 2020 | 109 (16.5 $m^3/m$) | 75 (24.0 $m^3/m$) | 64 (28.3 $m^3/m$) |
| 2099 | 42 (43.1 $m^3/m$) | 29 (61.7 $m^3/m$) | 22 (82.1 $m^3/m$) |
| 2120 | 35 (50.9 $m^3/m$) | 25 (72.3 $m^3/m$) | 17 (103.1 $m^3/m$) |
| 2140 | 32 (56.3 $m^3/m$) | 23 (79.0 $m^3/m$) | 16 (111.5 $m^3/m$) |

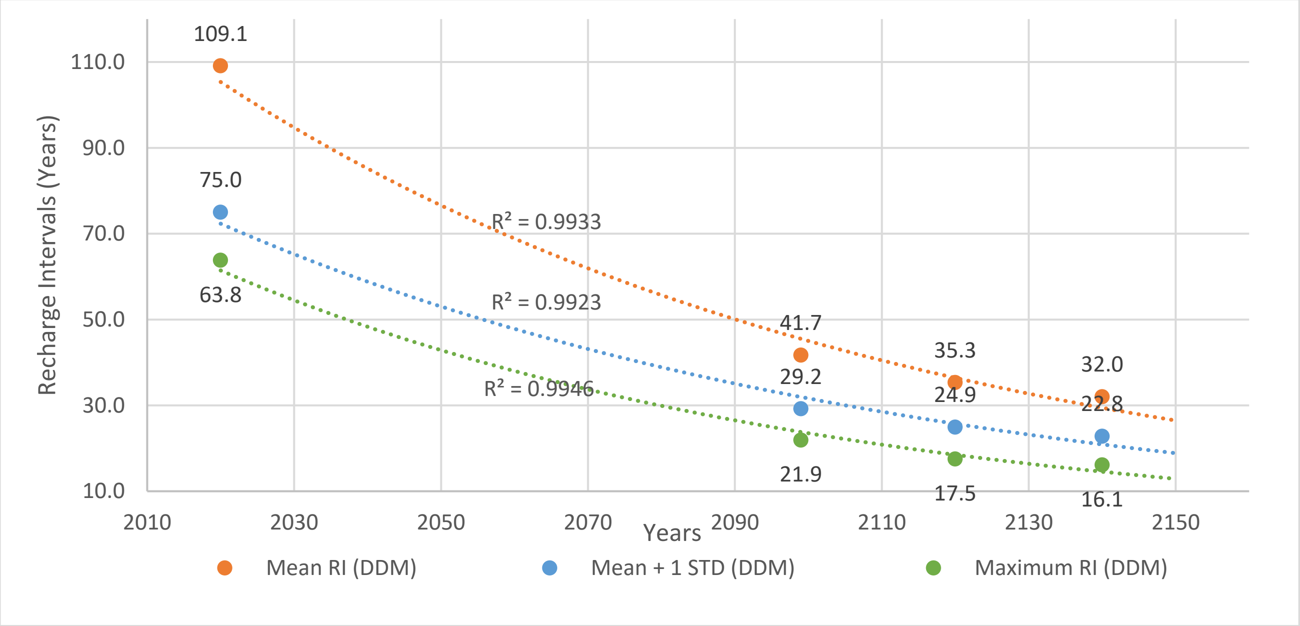


Figure 19: Recharge Interval (RI) in years with the Dutch Design Method (DDM) applied calculated from the mean erosion rate, maximum erosion rate and the mean erosion rate with 1 STD throughout the operational and decommissioning phase from a BfE storm sequence. Exponential trendlines were fitted to each set of rates.

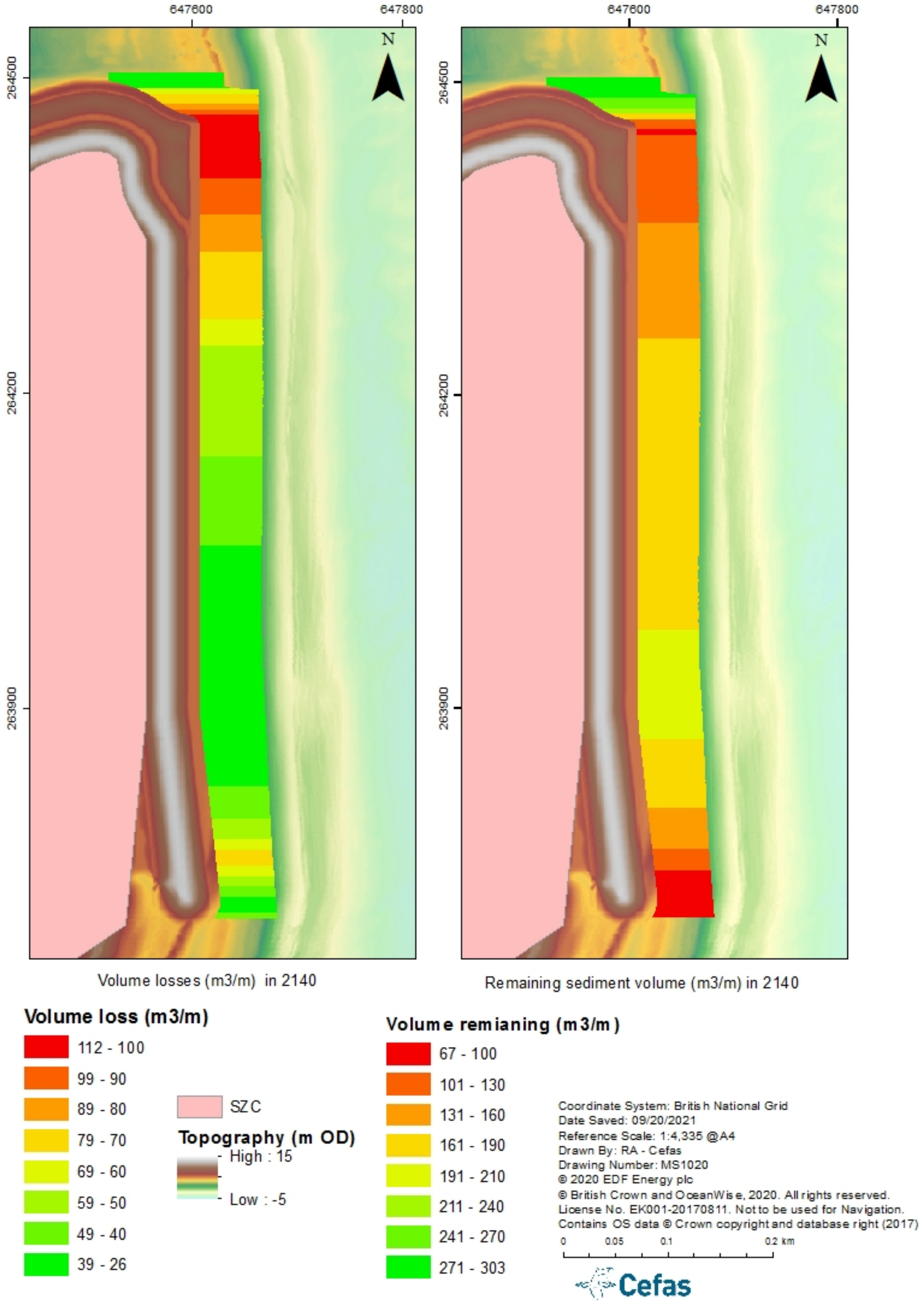


Figure 20: The loss of sediment volume in XBeach 2D sand model runs from the BfE storm sequence with RCP4.5 sea levels in 2140 with receded lateral shorelines (left) and the remaining sediment volume of the SCDF after the BfE storm (right).

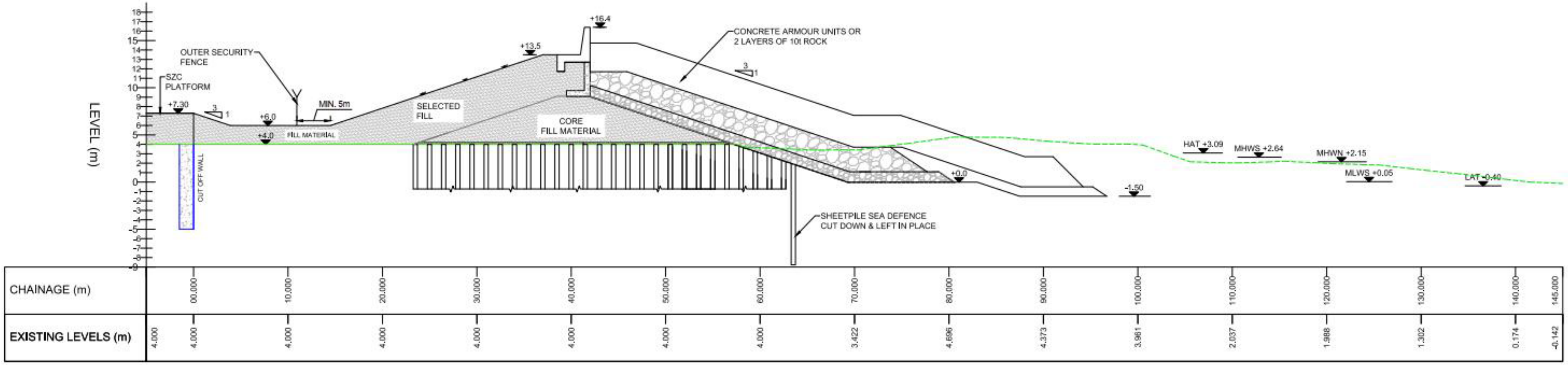


Figure 21: Schematic cross-section of the hard coastal defence feature (HCDF) with the adaptive design provision (black outline). The adaptive design will increase the crest height to 16.4 m OD and will change the toe position seaward by approximately 16 m and buried to a depth of -1.5 m. The dashed green line running through the cross-section is the present-day topographic cross-section. Source: Sizewell C Coastal Defences Design Report [REP2-116]

To construct the adaptive HCDF, excavation would occur within the beach/ SCDF to permit the extension and lowering of the HCDF toe, including placement of armourstone units to form the new revetment on the seaward side of the initial HCDF. There would be no enhancements to the foundations or the core of the HCDF as these will be installed initially as part of the original HCDF. The SCDF would be reinstated following construction.

Should the observed trend of sea level rise exceed the UKCP18 RCP8.5 (95th percentile) predictions then the adaptive design would be implemented. Therefore, 2D XBeach sand and 1D XBeach gravel models have been developed for the adaptive HCDF with the matching RCP 8.5 (95th percentile) 2140 sea levels required to trigger construction of the adaptive HCDF. The SCDF has also been remodelled 17 m seaward of its initial position, corresponding to the same horizontal seaward shift in the adapted HCDF toe, but it retains the same cross-section and slope dynamics as modelled previously. It includes the full southern extents where the SCDF volume is approximately 186 $m^3$/m. The bathymetry is unchanged, with the sand bars remaining in the same position they have been throughout modelling, which results in less wave energy dissipation owing to the increased sea level as the modelled bars are not modified to keep pace with sea level, even though this is likely to occur (so long as there is sufficient sand supply).

The storm conditions and future receded shoreline are those set out in Section 4.2.

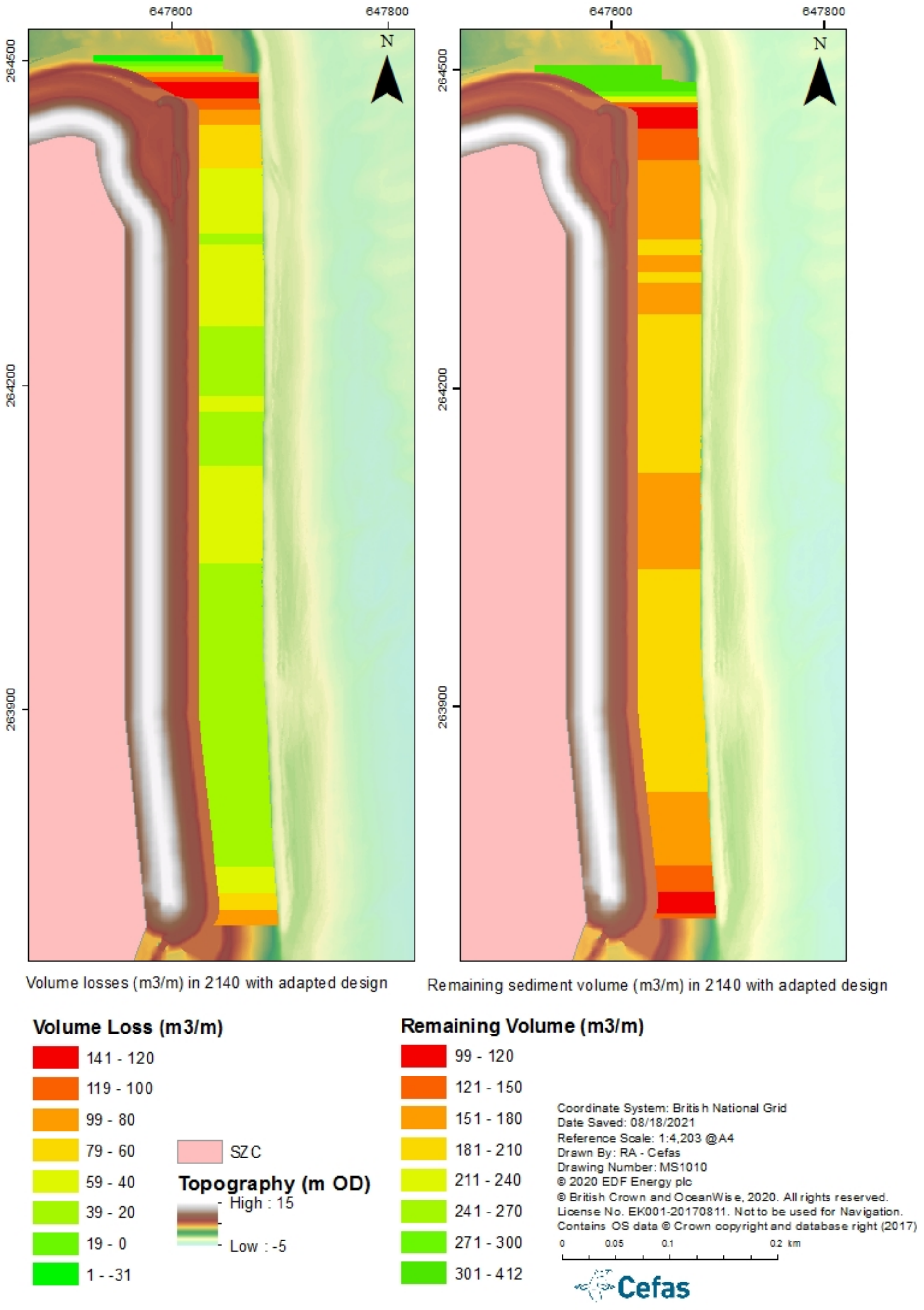
### 4.3.2 1:20 year NE storm erosion and recharge intervals for the adaptive HCDF

In 2140 with the adaptive HCDF and UKCP18 RCP8.5 95th percentile sea level rise, the rates of SCDF erosion rise significantly due to higher sea levels and the 17 m seaward translation of the SCDF. The mean volume of sediment loss with the XBeach 2D Sand model was 44.5 $m^3$/m, which just exceeds the sacrificial volume of 42 $m^3$/m, suggesting that the modelled 1:20 year storm would trigger a recharge along the SCDF. These losses are of a similar quantity to the mean losses at the receded lateral shoreline in 2099 after a BfE storm event (see Section 3.2.3). This results in an RI of 13 years (DDM applied), reducing to 9 years by adding one standard deviation to the losses (for a more conservative approach).

The maximum sedimentary loss across the SCDF (141 $m^3$/m) is significantly higher than the unadapted HCDF (51.4 $m^3$/m). This would cause a recharge to be triggered as it over triple the sacrificial volume of 42 $m^3$/m and gives a recharge interval of 4 years (DDM applied). These losses (over 100 $m^3$/m) occur over a localised area of 35m that does not exceed the total SCDF volume and so would not expose the HCDF.

The maximum losses occur again on the northern SCDF (Figure 22), due to the modelled NE storm direction and the curvature of the receded shoreline, putting this area under higher erosion pressure (compared to the rest of the SCDF). The lowest remaining sediment volume across the frontage was 99 $m^3$/m, which would not be sufficient to avoid HCDF exposure if a second storm of similar magnitude occurred prior to recharge. However, the return interval of such an event and the extreme sea levels used makes this an unlikely occurrence and the modelling used in these calculations is conservative. The XBG 10 mm models estimate sediment losses to be at least 40% lower than the losses calculated from 2D sand modelling of 10 mm sediment particle size These results reiterate that the northern endpoint would be at greatest risk of HCDF exposure and the need for responsive recharge were the modelled situation to arise.

The main frontage of the SCDF (i.e., in between the northern and southern pressure points), whilst facing losses up to 60 $m^3$/m, still had sediment volumes remaining of at least 150 $m^3$/m (Figure 22), suggesting that most of the SCDF could withstand the unlikely scenario of two more storms of this magnitude with no recharge before HCDF exposure.



Volume losses (m3/m) in 2140 with adapted design

Remaining sediment volume (m3/m) in 2140 with adapted design

Figure 22: The loss of sediment volume in XBeach 2D sand model runs for a 1:20 year NE storm scenario in 2140 with adaptive HCDF design and RCP 8.5 (95th percentile) sea levels (left) and the remaining sediment volume of the SCDF after the 1:20 year storm (right).

The southern SCDF also experiences high levels of erosion, although to a lesser degree than in the northern endpoint, with losses reaching a maximum of 91 $m^3$/m. A 15 m section in the southern area had a remaining sediment volume of ~ 110 $m^3$/m, which is slightly less than the suggested buffer volume of 120 $m^3$/m. However, a further modelled 1:20 year storm would not fully deplete the SCDF buffer volume or expose the HCDF, but lead to more frequent localised recharge at the southern SCDF to restore the sacrificial volume.

### 4.3.3 Beast from the East storm erosion and recharge intervals for the adaptive HCDF

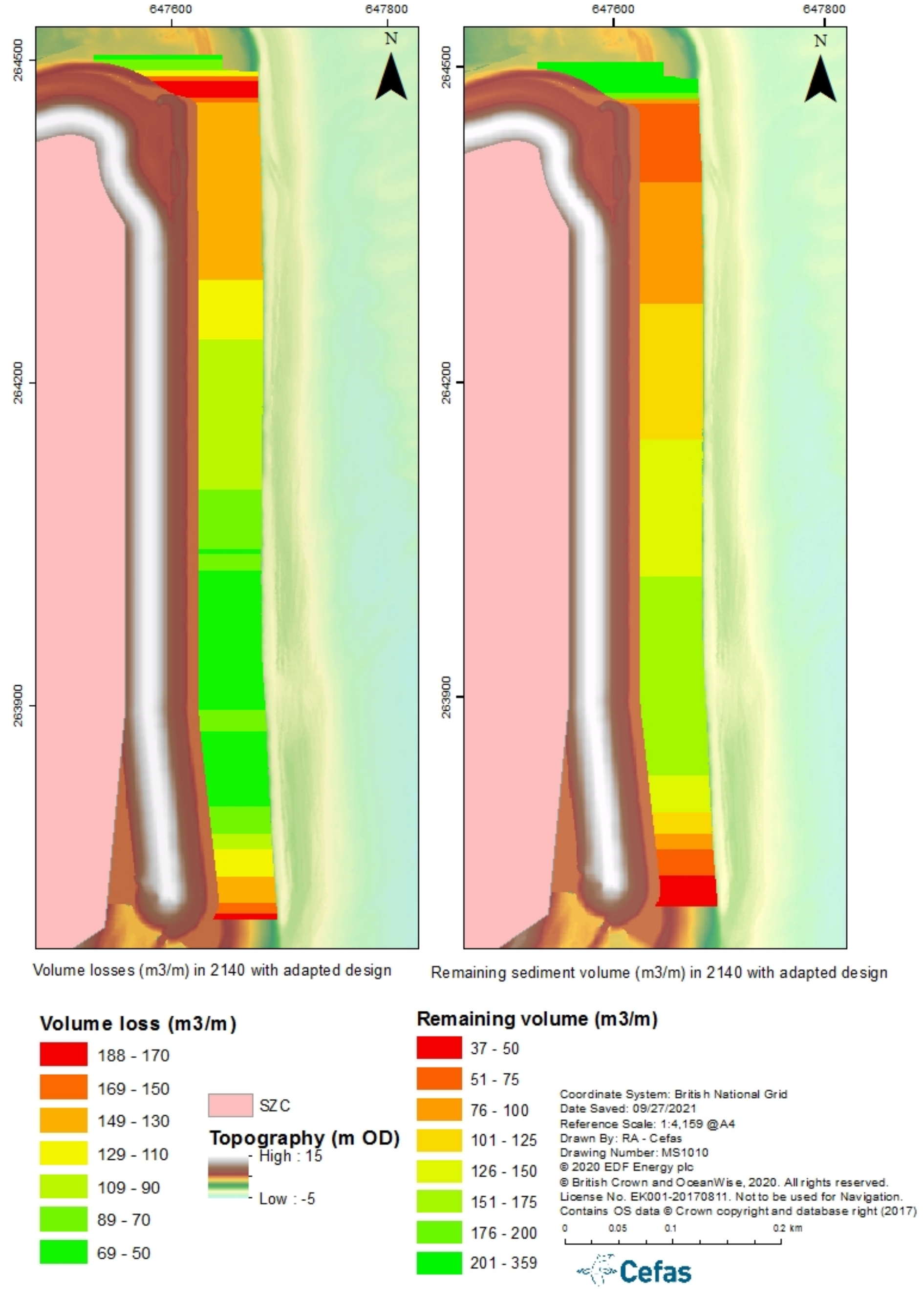
To examine erosive losses of the adaptive design at 2140 (approximate end of the decommissioning phase), the 2D XBeach sand modelling considered the Beast from the East (BfE) storm sequence, which has a 1:107 year storm return interval in terms of cumulative wave power (see Appendix B of BEEMS Technical Report TR531). This model run used the future receded shorelines topography as well as extreme RCP8.5 sea level conditions.

The mean sediment losses from the BfE storm event were 100.9 $m^3$/m and a more conservative approach of adding one standard deviation resulted in losses 135.0 $m^3$/m, which is 2-4 times larger than the sacrificial volume in this report of 42 $m^3$/m, as shown in Figure 23.

Along two SCDF sections the sediment volumes are lowered more than 50%; i.e., the 70m southern endpoint of the HCDF and a 225 m section at the northern SZC frontage. Both areas experience high losses (up to 188.3 $m^3$/m), and the southern endpoint has the lowest initial sediment volumes (186 $m^3$/m), increasing its vulnerability to HCDF exposure. Neither region experiences total HCDF exposure from the BfE storm sequence but localised recharges would be needed to prevent exposure in an extremely unlikely event of a second BfE storm sequence or indeed from lesser storms.

The SCDF crest height was reduced by the BfE storm sequence from 6.4 m ODN to approximately 5.2 m ODN, eroding back towards the edge of the coastal path. However, even with substantial sediment losses, the vast majority (510 m) of the SCDF frontage had over 50% of initial sediment remaining and would still exceed the initial 120 $m^3$/m buffer volume. Therefore, an immediate recharge would not be needed in these areas.

It should be noted that these highly conservative sand model results represent a worst-case scenario as it does not consider the effects of coarser particle sizes (medium pebbles) that would dominate the SCDF and natural beaches, which are more resistant to erosion than the sandy sediment modelled (see Section 3.2.4). Furthermore, the predictions are for erosion only and do not model the natural process of recovery and return of sediments moved seaward during the storm. Overall, this modelling provides an approximate guide and provides a conservative estimation of storm erosion rates and expected recharge intervals.



Volume losses (m3/m) in 2140 with adapted design

Remaining sediment volume (m3/m) in 2140 with adapted design

Figure 23: The loss of sediment volume in XBeach 2D sand model BfE storm scenario in 2140 with adaptive HCDF design and RCP 8.5 (95th percentile) sea levels (left) and the remaining sediment volume of the SCDF after the BfE storm sequence (right).

## 4.4 XBeach Gravel (1D) storm erosion modelling

XBeach 2D modelling used in Sections 4.2 and 4.3 is only available for sandy-sized sediments, which overpredict erosion for Sizewell's pebble dominated intertidal and supra-tidal zones as discussed in Section 3.2.4. XBeach G can provide a more realistic account of storm evolution albeit only in a 1D scenario (without longshore transport). It can account for the larger particle mass and the swash infiltration and exfiltration[45] that is important for gravel transport and erosion/accretion. 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 two models envelope the likely response of the SCDF to storms, which is the best approach available given models for composite, mixed sand and gravel beaches are yet to be developed.

Section 3.2.4 used the scenario of a 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 for XBeach G and S with Table 2 showing the results of the mean losses and resultant RI's. This section presents the results from the XBeach G $D_{50}$ = 10 mm (typical mode of the native sediment particle size range) model runs for the three scenarios discussed in Sections 4.2 and 4.3:

- 2120 and 2140 under RCP 4.5 (95th percentile) sea levels for the permanent HCDF and
- 2140 under RCP 8.5 (95th percentiles) sea levels for the adaptive HCDF.

The results are summarised in Table 7.

The 10 mm gravel model for the permanent HCDF with 2120 and 2140 (RCP4.5, 95th percentile) sea levels, reduced the recharge intervals to 40 and 39 years respectively compared to 23 and 22 years predicted by the XBeach 2D sand model (mean losses). The gravel model volumetric losses did not exceed 16.5 $m^3$/m throughout the decommissioning phase for the RCP4.5 climate conditions.

The effect of sea level rise is more complex under RCP8.5 conditions with the adaptive HCDF, due to changes in the cross-shore distribution of erosion and accretion under higher sea levels and the present-day MSL datum above which volumetric change is calculated, specifically eroded sediment is deposited higher up the profile and therefore reduces the net loss calculated. The result is a smaller volume loss of 13.1 $m^3$/m at 2140 above 0 m ODN resulting in a higher RI value of 46 years. In reality, the volume of sediment eroded from the subaerial beach (i.e. above *mean sea level*) is approximately 18.8 $m^3$/m (which would create a smaller RI of 32 years) with 5 $m^3$ of sediment being deposited above 0 m ODN. Therefore, subaerial beach erosion is still expected to steadily increase with sea level rise.

XBeach G demonstrates the effect of including swash-groundwater processes in modelling for gravel produces reduced volumes and increased RIs. As it is likely the SCDF will be dominated by gravel sediments (at or close to the native modal size range), these results demonstrate that the recharge intervals shown in Sections 4.2 and 4.3 are likely to increase when SCDF particle size is considered within the SCDF design.

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[45] 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.

Version 4 of this report modelled the volumetric losses from varying sediment sizes throughout the decommissioning phase (Table 8). Within the native particle range ($D_{50}$ = 10mm and 40mm), losses had a small variation (between 16.5 – 16.0 $m^3/m$) in 2140 compared to 2099 results (between 14.3 -11.6 $m^3/m$).

This suggests that the benefits of 40 mm diameter sediments over 10 mm are marginal and retention of the native distribution without intentional coarsening is, initially at least, the best and least disruptive approach. In contrast, particles slightly larger than the native sediments (80 mm fine cobbles compared to the 40 mm very coarse pebbles) highlighted drastic reductions in volumetric erosion – as little as 1.0 $m^3/m$ under 2140 RCP4.5 sea levels. The 80 mm sediments were specifically used to test whether a layer of fine cobbles embedded within the SCDF's buffer layer would provide an additional effective layer of protection to avoid HCDF exposure, as has been described from examples in the literature (see Section 2.4.3). The modelling is in agreement with the literature that a relatively thin layer would significantly reduce the risk of HCDF exposure.

The methods used here are general guides – although they demonstrate clear SCDF viability across the decommissioning phase, the actual recharge intervals will differ and may be less than those computed. The XBeach-G modelling provides a closer match to the native sediments and their dynamics (than the conservative XBeach sand model), suggesting greater longevity and reduced recharge frequency.

Table 7: The Recharge Intervals and eroded volumes calculated from the XBeach gravel non-hydrostatic 'XB-G' models with sediment size $D_{50}$= 10 mm and the Dutch Design Method (DDM) applied for the decommissioning phase.  RIs have been rounded up to total years.

| **Model Scenario** | **Grain size (mm)** | **Net volume change ($m^3/m$)** | **Recharge Interval (DDM applied)** |
|---|---|---|---|
| 1-in-20 year storm, NE, RCP4.5 2120 SLR, SCDF | $D_{50}$ = 10 $D_{90}$ = 15 | 15.0 | 40 years |
| 1-in-20 year storm, NE, RCP4.5 2140 SLR, SCDF | $D_{50}$ = 10 $D_{90}$ = 15 | 16.5 | 36 years |
| 1-in-20 year storm, NE, RCP8.5 2140 SLR, adaptive design SCDF | $D_{50}$ = 10 $D_{90}$ = 15 | 13.1 | 46 years |

Table 8: The volumetric losses calculated from the XBeach gravel non-hydrostatic ‘XB-G’ models with various sediment sizes from a 1:20 year NE storm scenario within the decommissioning phase.

| **Model Conditions** | | **2099 SLR sediment losses ($m^3/m$)** | **2140 SLR sediment losses ($m^3/m$)** |
|---|---|---|---|
| 1-in-20 year storm, NE, RCP4.5 2140 SLR, SCDF | $D_{50}$ = 10 mm | 14.3 (42 years) | 16.5 (36 years) |
| | $D_{50}$ = 20 mm | 12.2 (49 years) | 16.3 (37 years) |
| | $D_{50}$ = 40 mm | 11.6 (52 years) | 16.0 (38 years) |
| | $D_{50}$ = 50 mm | 9.7 (62 years) | 14.5 (41 years) |
| | $D_{50}$ = 60 mm | 5.6 (107 years) | 5.8 (104 years) |
| | $D_{50}$ = 70 mm | 3.1 (194 years) | 3.5 (173 years) |
| | $D_{50}$ = 80 mm | 2.5 (240 years) | 1.0 (588 years) |

# 5 Conclusions

The main coastal processes design parameters (volume, crest height and composition) of the SCDF have been set out and together with the numerical modelling show that the SCDF volume would be substantially larger than that required to withstand 2 – 3 severe[46] sequential storms, even along sections where the SCDF would be relatively small such as near the permanent BLF (264,390 N – 264,455 N, Figure 8). The increased crest height (compared to the present-day shingle ridge at SZC, is 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 for the middle and end of the operation phase (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, $V_{\mathrm{buffer}}$, and an outer *sacrificial* volume, $V_{\mathrm{sac}}$. An option for a layer of fine cobbles (modelled as 80 mm diameter) 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 within sections 3.2.4 and 4.4.

The phase 2 modelling (BEEMS Technical Report TR545) produced realistic storm erosion, albeit consistently overpredicting by a factor of two to three. 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 necessary, 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 ($V_{\mathrm{sac}} = 42\ \mathrm{m^3/m}$) 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.

Several RI estimates have been computed using methods from the Beach Management Manual (Rogers et al., 2010) – specifically, measured shoreline changes, conservative 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. Measured shoreline changes (see Sections 3.1 and 3.2.1) and presented in BEEMS Technical Report TR531 produced the highest erosive rates 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 four future sea level cases through the operational and decommissioning phases (2069, 2099, 2120 and 2140) and potential severe erosion of the adjacent shorelines, which increases erosion pressure. In doing so, future viability has been tested and proven to the end of the decommissioning phase.

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[46] 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).

*Operation phase*

The projected recharge volume requirements across the operation phase are similar to the total SCDF volume (combined volume of the existing each and additional sediments from construction is 210,000 m$^3$). The most conservative estimates of the notional recharge interval[47] (up to seven interventions) and the relatively small volumes[48] across the operation phase(140,000 – 150,000 m$^3$ (Sections 3.1.1 and 3.2.1); worst case c. 270,550 m$^3$ (Section 3.1.2)) indicate SCDF viability. The predicted worst-case volume required for recharge over the project lifetime of Sizewell C would be c. 576 000 m$^3$. However, 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 results of the XBeach 2D sand model showed the worst-case single SCDF erosion event (BfE storm conditions) within the operational phase 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 (RCP 4.5). However, this combination of erosive conditions still leaves a minimum remaining sediment volume of 120 m$^3$/m, meaning that HCDF exposure would require two further 1:107 year events 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 BfE storm scenario also showed that the spatial mean loss of sediment along the full length of the SCDF (43.1 m$^3$/m) slightly exceeded the sacrificial 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 (specifically at the northern and southern endpoints of the SCDF) 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.

Erosive losses with the 1D XBeach gravel model (with a particle size of $D_{50}$= 10mm, which is considered more representative of the native subaerial beach) were less than 16.5 m$^3$/m throughout the operation (and decommissioning) phase, ranging between 15 - 60% of the loss rates from the XBeach 2D sand model (where sediment size is $D_{50}$= 0.8mm). The XBeach-G modelling provides a closer match to the native sediments and their dynamics, suggesting greater longevity and reduced recharge frequency compared to the conservative XBeach 2D sand model.

*Decommissioning phase*

When extending sea level rise (RCP 4.5) into the decommissioning phase, higher mean losses of 51.4 m$^3$/m were modelled in 2140 for a 1:20 year NE storm scenario. As with the operation phase, erosion pressure was highest on the northern endpoint of the SCDF, although the remaining sediment volume (~160 m$^3$/m) is sufficient to withstand two or more unmitigated storms before HCDF exposure. The more erosive Beast from the East (BfE) storm sequence increased the mean sediment loss to 56.3 m$^3$/m whilst the area of maximum erosion more than doubled to 111.5 m$^3$/m, however the SCDF prevented HCDF exposure. A 70 m stretch of coast with the greatest erosion would be prone to subsequent HCDF exposure if a second BfE storm

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[47] Based on historical shoreline trends (see Section 3.2.1).

[48] 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).

occurred prior to beach recharge. However, the rest of the frontage would withstand this highly unlikely occurrence, with sediment volumes exceeding the 120 $m^3$/m buffer volume.

The southern endpoint was also identified as an area where more localised recharges may be needed due to low initial sediment volumes, however this is partly due to an incomplete SCDF model, which shows lower volumes than would be found in the full SCDF for this southern area. However, despite having a lower volume than intended, the HCDF was not exposed. The SCDF topography will be updated in the next version of this report, which should increase these sedimentary volumes from the stated 105 $m^3$/m to approximately 185 $m^3$/m.

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 indicate that the northern half of the SCDF frontage is likely to require more frequent recharge, specifically at the permanent BLF where losses are higher and at the southern endpoint where SCDF initial volumes are expected to be lowest. The monitoring set out in the 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 both the operational and decommissioning phases of the station under RCP 4.5 climate conditions and that the risk of HCDF exposure is low if the SCDF is well maintained.

In the unlikely event that the UKCP18 RCP 8.5 (95th percentile) climate conditions come to be, the HCDF would be altered to its adaptive design, with a crest height of 16.4 m ODN and a more seaward protrusion of the HCDF. The 1:20 NE storm model showed mean losses slightly in excess of the 42 $m^3$/m sacrificial volume at 45.4 $m^3$/m with the maximum loss reaching 141 $m^3$/m. The losses are substantially higher for the BfE storm sequence, with mean losses rising to 100.8 $m^3$/m and most of the SCDF eroded on some sections of the northern and the southern SCDF frontages experiencing low post-storm sediment volumes (38 $m^3$/m). Localised recharges would be needed to prevent HCDF exposure from occurring from a secondary storm of a similar magnitude or smaller magnitude. As the average erosion is substantially larger than the current threshold, recharge over the whole frontage would be likely. However, further work is required on the mitigation thresholds and the results to date suggest $V_{recharge}$ may be more appropriately set at a higher value. This is considered the worst- case scenario and is being included within the report as a safety case.

*Particle size, triggers and further work*

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. The performance of the 40 mm diameter sediment (relative to 10 mm sediments) showed modest performance improvements of up to 23%, suggesting that coarsening particle size may be a useful design factor for fine tuning of the SCDF. However, altering the particle size increases uncertainty in terms of how the SCDF would interact with the adjacent coast by way of longshore transport. As the benefits of 40 mm sediments as modelled are not substantial and the SCDF viability has been comfortably shown across the station life by the envelope of sand (0.8 mm) and medium pebble (10 mm), the recommended default position is to retain the native particle size distribution and not to coarsen the sediment. The modelling that best represents the native sediments is the 10 mm XBeach-G modelling, as 10 mm corresponds to the modal pebble size.

A well-designed layer of fine-cobbles embedded deep within the SCDF could also effectively counter the increased risk of HCDF exposure during the decommissioning phase, as shown by the modelled lower loss rates of fine cobbles. For example, modelling results indicate that there was no volumetric loss of cobbles under 2020 and 2069 sea level predictions and only 1.0 – 2.5 $m^3/m$ under the forecast 2099 – 2140 sea levels. This result is in agreement with the scientific literature which also show that natural and artificial cobble beaches are resistant to erosion if the volume, crest height and beach thickness are sufficient for the incident wave conditions (see Section 2.4.3).

An important benefit of the SCDF design is its adaptability to future pressures and real-world performance. The SCDF would be constructed seaward of the HCDF 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 avoids or minimises 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 through:
    - 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.

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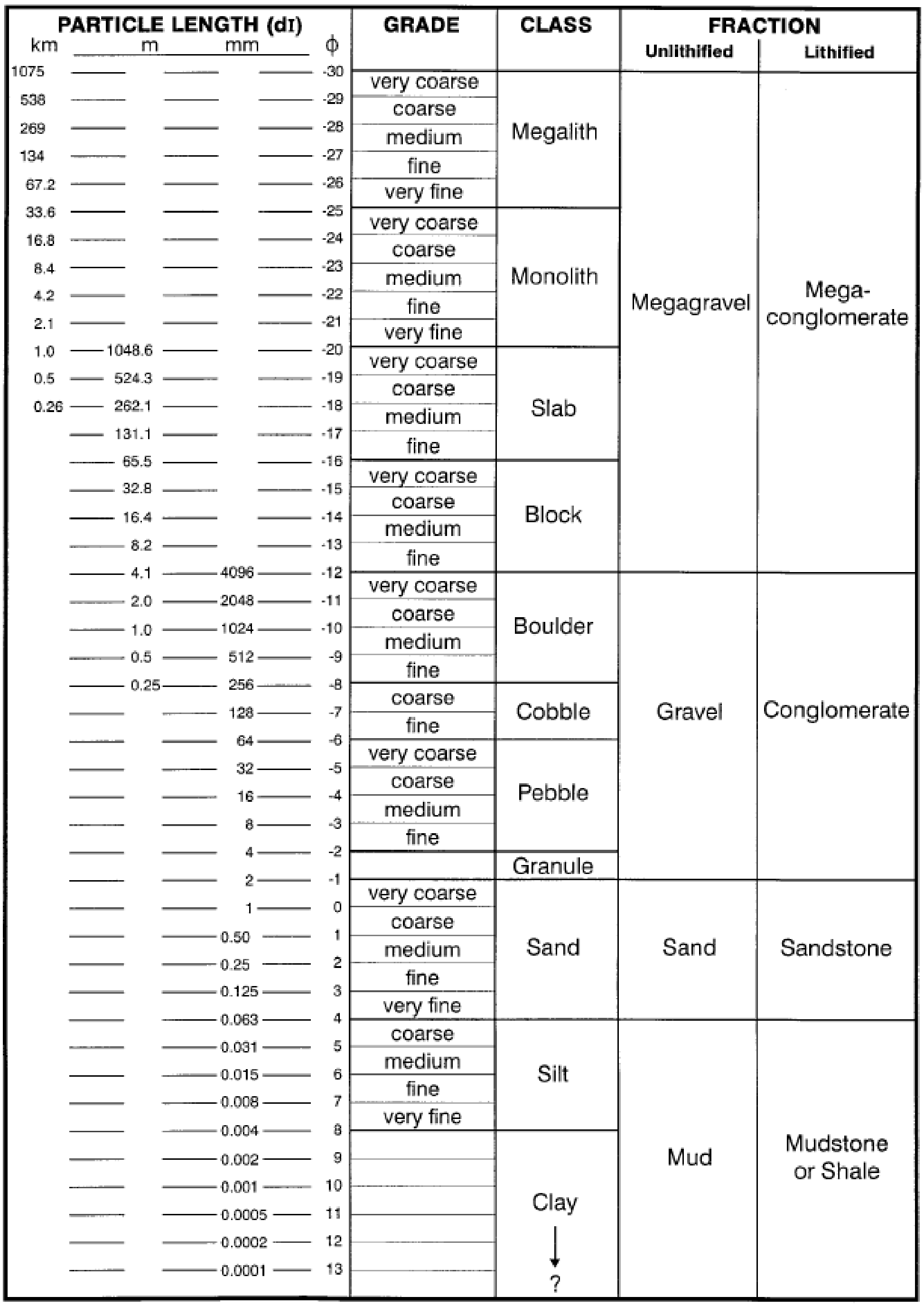
# Appendix A Modified Udden-Wentworth classification



| 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<br>↓<br>? | | |
| | | 0.002 | 9 | | | | |
| | | 0.001 | 10 | | | | |
| | | 0.0005 | 11 | | | | |
| | | 0.0002 | 12 | | | | |
| | | 0.0001 | 13 | | | | |

Source: Blair and McPherson (1999).