The Sizewell C Project

9.12 Preliminary design and maintenance requirements for the Sizewell C Coastal Defence Feature

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Cefas

Preliminary design and maintenance requirements for the Sizewell C Soft Coastal Defence Feature

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Executive summary

The Sizewell C Soft Coastal Defence Feature (SCDF) is a maintained and volumetrically enlarged beach seaward of the hard coastal defence feature (HCDF). Its large (c. 200,000 m^3), supratidal, sedimentary mass is designed to avoid disruptions to longshore transport (and the impacts to local beaches) which, in its absence, would occur if the landward HCDF were exposed. It is akin to a 'real-time' recharge during storms. The SCDF's purpose is therefore to ensure continuation of the longshore transport 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, erosion resistant sediments 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 minimise recharge frequency), and
- initial estimates of SCDF recharge requirements (frequency and volume).

The supratidal SCDF is conceptually divided into two main components (see Figure i). It would consist of a landward safety *buffer* volume, V_{buffer}, which is not intended to be depleted or frequently exposed but is sufficiently large in itself to avoid HCDF exposure under severe storms, and a seaward *sacrificial* volume, V_{sac}, which would be allowed to erode as far back as V_{buffer} before being recharged. The rationale for the safety *buffer* component is to protect against storms or storm sequences just prior to recharge.

Preliminary, highly conservative beach-erosion modelling and volumetric analysis of the SCDF design show that it is substantially larger than that required to withstand erosion from 2 – 3 severe[1] sequential storms, for sections where the SCDF is smallest, for much or all the operation phase. The increase in SCDF crest height of 1 – 2.4 m above the present, unbreached, shingle ridge crest, is substantially greater than predicted sea level rise (SLR) in 2099[2] under the intermediate climate emissions scenario (RCP4.5) and is similar or greater than the very unlikely worst-case emissions scenario (RCP8.5, 95th and 50th percentiles, respectively).

The target SCDF sediments would be in the very coarse pebble size-class (3.2 – 6.4 cm diameter; see Appendix A), which is within the native particle size distribution, and with a relatively low sand content. This is in line with UK experience and guidance and intentionally designed to increase sediment retention and therefore prolong longevity. An option for a cobble-layer[3] deep within the SCDF, to increase erosion resistance in the unlikely event that the SCDF pebbles were fully removed, is also being considered.

[1] Based on a real storm sequence with a 1:12 year storm-energy return interval.
[2] 2099 marks the end of the UKCP18 climate change predictions and corresponds to the planned decommissioning phase of Sizewell C (assuming a 60-year-long operation phase).
[3] Based on the dynamic cobble berm concept.

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].

Conservative estimates of the notional recharge interval across the operational phase (up to seven interventions) and the relatively small volumes[5] (140,000 – 150,000 m^3; preliminary worst case c. 270,550 m^3) indicate strong viability of the SCDF. 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 volumes are similar to the total SCDF volume (c. 203,250 m^3). Of course, recharge events will be triggered when beach volumes reach a certain threshold and so the interval will not be a constant. Nor will it necessarily apply to the whole SZC frontage – spatial patterns in erosion may trigger recharge in some areas (e.g., near the permanent Beach Landing Facility (BLF) where volumes are lowest) and not others. The monitoring set out in the CPMMP is designed to detect such changes, as the monitoring techniques are spatially continuous.

The large SCDF volume, relatively low number of predicted recharge events and relatively small recharge volumes (based on very conservative measures) indicate that the SCDF is viable for at least the operation phase of the station. Longer timescales will be considered in future versions of this report, once modelling results are available.

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).

The preliminary design presented will undergo further refinement including modelling to incorporate longshore sediment transport, SLR at longer timescales and sensitivity to particle size (to refine the target size distribution), and to set the recharge threshold volume in the Coastal Processes Monitoring and Mitigation Plan (BEEMS Technical Report TR523).

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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] 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).

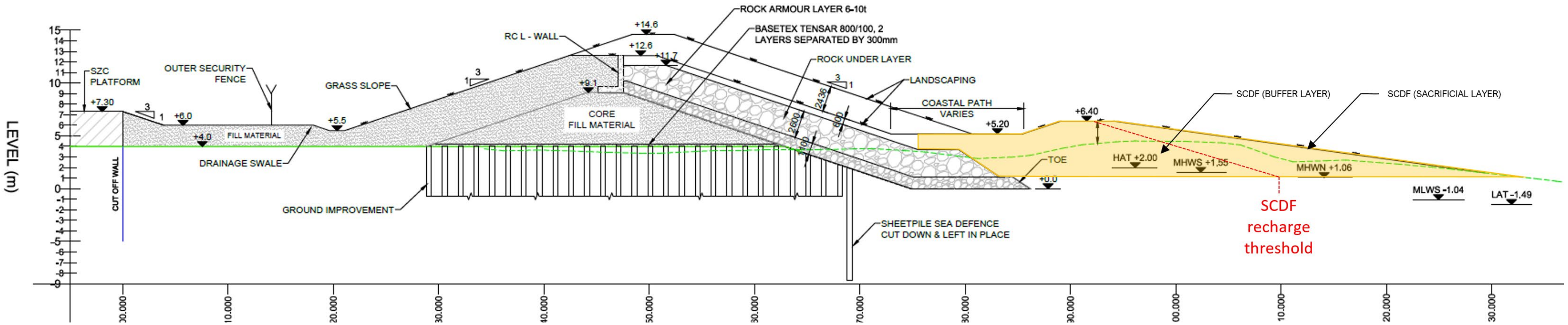

Figure i: Schematic cross-section of the hard and soft coastal defence feature (HCDF and SCDF). The SCDF (yellow) is conceptually divided into two volumes, separated by the dividing SCDF recharge threshold (as the threshold is volumetric, the line is shown for illustrative purposes only, i.e., many different 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 Sizewell C Soft Coastal Defence Feature (SCDF) is a maintained and volumetrically enlarged beach seaward of the hard coastal defence feature (HCDF). Its large (c. 200,000 m^3), supratidal, sedimentary mass is designed to avoid disruptions to longshore transport and the impacts to local beaches which, in its absence, would eventually occur if the landward Hard Coastal Defence Feature (HCDF) were to be exposed. It is akin to a 'real-time' recharge during storms. The SCDF's key design features are: a large volume (sufficient to withstand severe storms), erosion resistant sediments, a high crest and maintenance (primarily by beach recharge) to replace any losses from the Sizewell C frontage.

As the SCDF is designed to avoid impacts of HCDF exposure during the construction and decommissioning phases, it is embedded (primary) mitigation. SCDF maintenance – the provision of additional sediments into the beach to maintain a threshold 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:

- preliminary SCDF 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 (longevity).

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

- minimise the erosion rate during severe storms and, therefore, minimise the risk of HCDF exposure,
- maximise the recharge intervals (RIs) (and minimise disturbance) between SCDF recharge events across the operation and decommissioning phases[6] 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 relatively easily 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 adaptive management approach, using evidence from performance assessment to adjust triggers or mitigation actions

[6] 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.

over time and account for uncertainties (in this case in how the SCDF responds to future pressures), are applied elsewhere in the UK[7].

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[8] design features. Although these features lead to a robust SCDF, they will reduce, but not eliminate, the need for maintenance (SCDF 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 supratidal sediment volume along the SZC beach frontage. Although its maintenance (recharge activity) would imply some disturbance, this would be in naturally eroded areas where sediment and vegetation had been lost, and therefore restoring the supratidal area would allow potential re-colonisation (which doesn't occur where supratidal deposits are lost). Over time, SCDF sediments may also contribute to reducing erosion rates and promoting an increase in supratidal shingle[9] on the immediately neighbouring frontages.

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

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

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

resistance) over bare sand for a wide range of northern hemisphere latitudes, whilst Sigren et al. (2014) observed a 30% reduction in the retreat rate of vegetated dune scarps.

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

In the longer term, natural coastal squeeze will continue to reduce the supratidal zone along the Minsmere frontage until regular overwashing and roll back begins. Until that time, unless there is additional shingle deposited to widen the supratidal zone, it is unlikely to sustain a drift line vegetation habitat.

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 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). SCDF sediments are expected to be sourced initially from earth works on the main development site (assuming appropriate sediment properties) and then from already licenced aggregate extraction sites, as set out in Section 3.2.2 of NNB Generation Company (SZC) Limited (2020b). There are numerous marine sites within the region that contain suitable sediments. Further detail on sediment sources will be provided in a future version of this report.

2 SCDF design

2.1 Function

The purpose of the SCDF is to avoid disruptions to longshore transport and the impacts to local beaches that are likely to arise if the HCDF were exposed, across the operational and decommissioning phases of the station until the Cessation Report and associated actions have been agreed, as per the CPMMP (BEEMS Technical Report TR523). That is, without the SCDF, shingle moving along the subaerial longshore transport corridor[10] 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[11] would experience short-term starvation over a distance of a few hundred metres (BEEMS Technical Report TR420). 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.

The best local analogy for these impacts is the nearby Minsmere Sluice Outfall. The concrete outfall passes underneath the shingle ridge and through the active beachface to a position well beyond the low tide mark (Figure 1), thereby acting as a blockage across the entire longshore shingle transport corridor. However, its elevation around the Mean High Water Neap contour[12] allows some shingle to pass over the outfall during high waves and water levels, equating to a partial blockage. As the examples in Figure 1 show, the consequence is alternating patterns of localised erosion and accretion, with little net change. Similar effects might be expected were the HCDF to be exposed (i.e., in the absence of the SCDF) – see Section 7.4.2.2 of Appendix 20A of Volume 2 of the Environmental Statement (NNB Generation Company (SZC) Limited, 2020b).

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

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 drawdown onto the beachface by backwash would build volume there, 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). As a result, immediately neighbouring beaches may benefit volumetrically from the additional sediment supplied by the SCDF that would not otherwise be apparent. Over time, the erosion rates there may be lessened, supratidal shingle may accumulate and annual vegetated drift line species may colonise (as observed at Sizewell B). This process is shown as a simple box model in Figure 2. The gains in the neighbouring beaches' sediment budget 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).

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[10] Shingle is primarily found above the low tide mark at Sizewell, which can thus be considered as the seaward boundary of the shingle transport corridor.
[11] Sizewell has a directional bi-modal wave climate (NE and SSE).
[12] 0.69 m ODN (BEEMS Technical Report TR462)

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

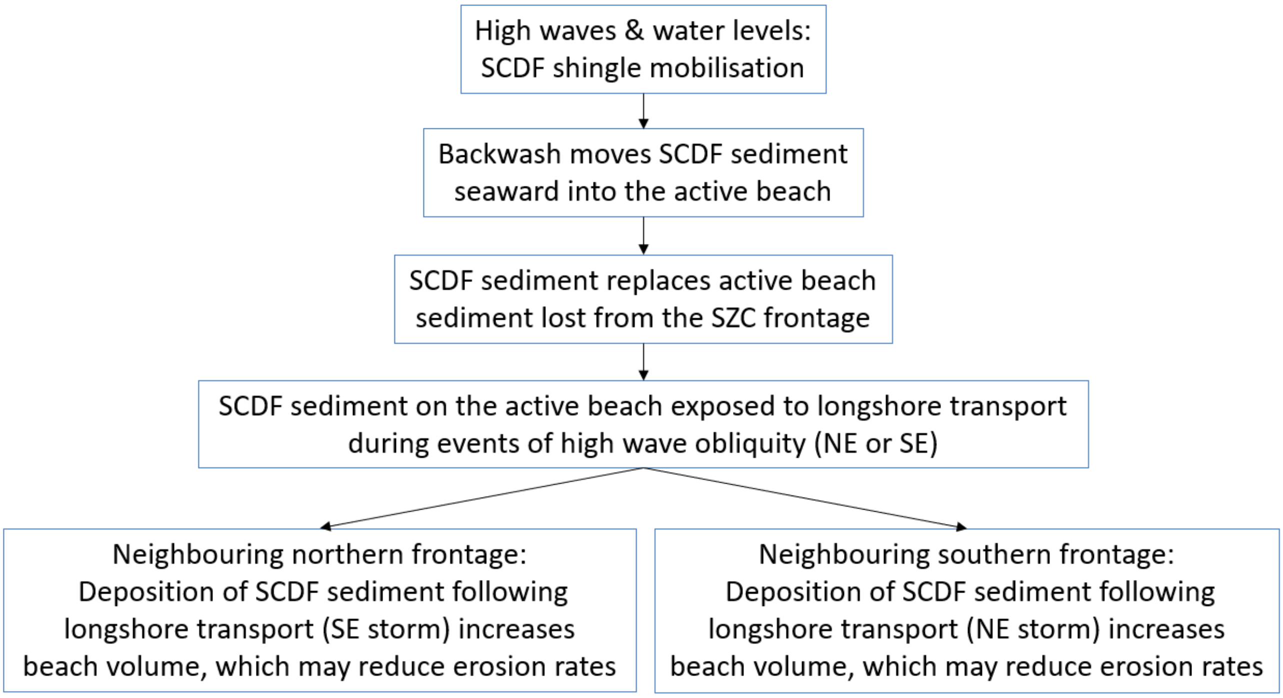

Figure 2: Simple box model describing sediment release from the SCDF and its pathways to neighbouring frontages.

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 both parameters to maintain the SCDF and avoid HCDF exposure whilst minimising intervention across the life of the station. Section 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, will be tested further using numerical models (see Section 4).

2.2 Guidance and benefits

The SCDF respects 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[13], and without replenishment any local vegetated shingle would be lost due to erosion anyway. That is, SCDF recharge would occur in areas where vegetation is naturally lost, replenishing the sediment there and facilitating potential re-colonisation of the supratidal habitat within the county wildlife site. The SCDF is also analogous to Pye and Blott's 'idealised' shingle beach management for FCERM (see Figure 3).

[13] 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.

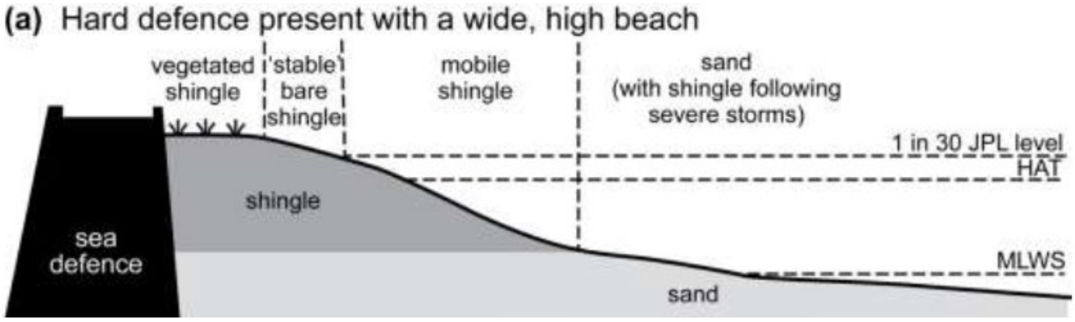

Figure 3: Schematic representation of evolutionary scenarios for hard defences with a fronting shingle beach, comparable to the proposed HCDF/SCDF (Figure 82, Pye and Blott, 2018).

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[14]. The SCDF would supply sediment accessed, transported and re-profiled by natural coastal processes. Additionally, the beach shingle at Sizewell 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.

The relative volume of sand in the SCDF would be kept low, to increase permeability and erosion resistance. This avoids cliffing 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.

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

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[14] 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).
[15] Although the net longshore sediment transport is slowly to the south, it is the sum of gross transport events in opposing directions under individual storms from the NE and SSE. This means there is potential for transport of SCDF sediment during SSE storms onto the southern few hundred metres of the Minsmere frontage, where it may be retained.

2.3 SCDF topography and volume

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

- a landward safety *buffer* volume, V_{buffer}, which is not intended to be depleted or frequently exposed but is sufficiently large in itself to avoid HCDF exposure under severe storms and
- a seaward *sacrificial* volume, V_{sac}, which would be allowed to erode until V_{buffer} is reached, and would then be recharged (i.e., restoring the initial V_{sac}[16]). Effectively it is a 'real-time' recharge method for sediment losses that activates when natural swash motion draws SCDF particles onto the active beachface.

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

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

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 5.2 m (ODN) surface extending from the HCDF,
- 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 (which is expected to change as coastal processes naturally rework the beach profile).

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

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

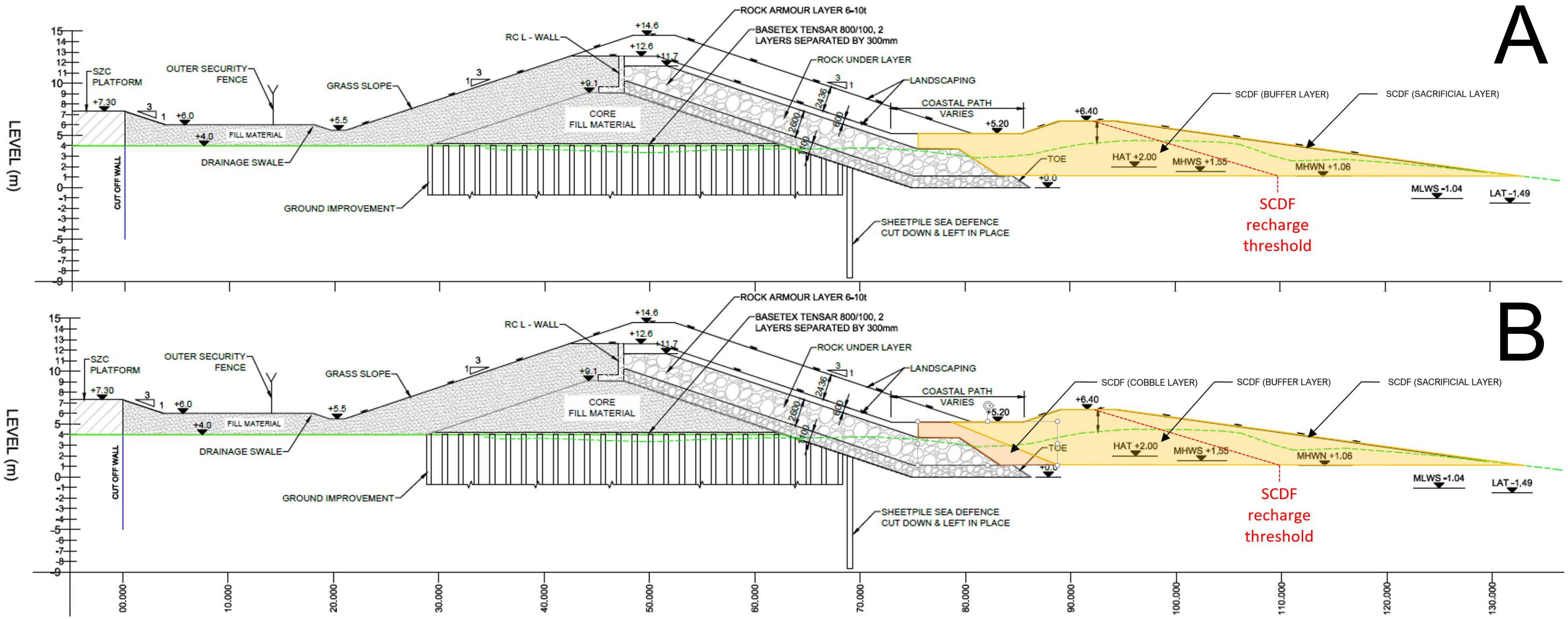

Figure 4: Schematic cross-sections of the hard and soft coastal defence features (HCDF and SCDF). Option **A.** The SCDF (yellow) is conceptually divided into two volumes, separated by the SCDF recharge threshold $V_{recharge}$ (shown for illustration as a red line). The SCDF *buffer* layer (whose volume 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 relatively narrow band of coarser sediments (cobbles) at the SCDFs landward extent (see Section 2.4.2). The dashed green line running through the yellow SCDF is the present-day topographic cross-section.

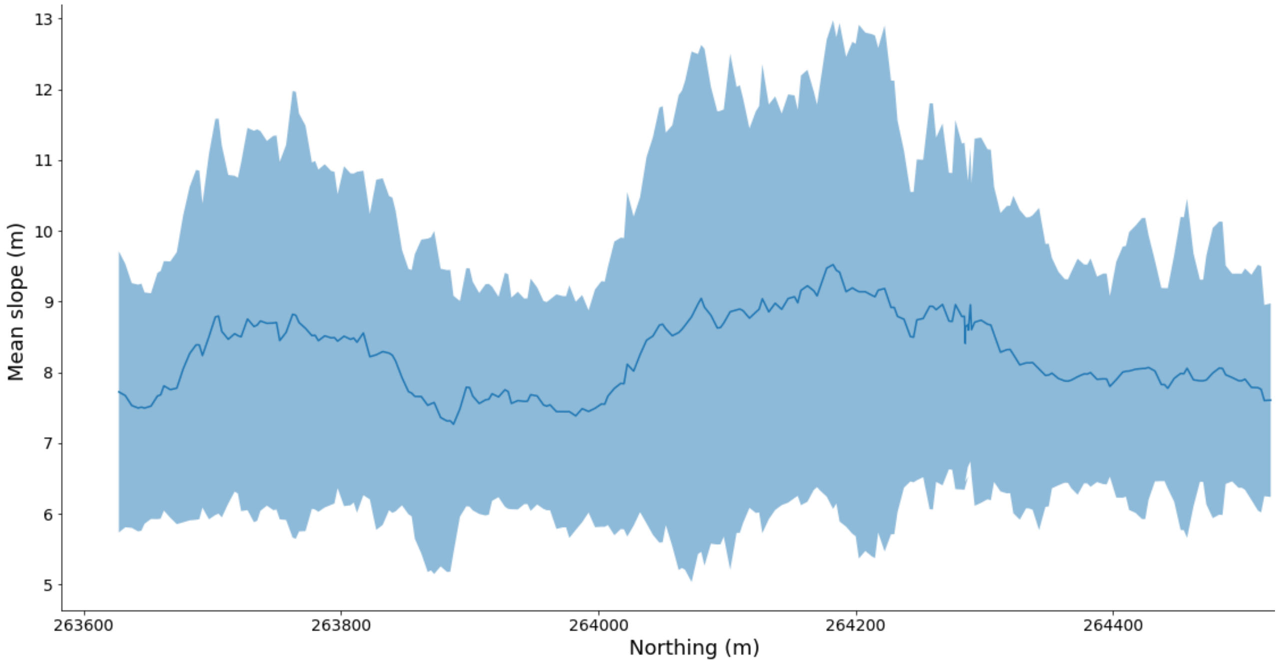

Figure 5: Beach slopes for the Sizewell frontage (°) from Sizewell B to just south of the tank traps located just to the north of the proposed Sizewell C site, showing the mean (solid line) and one standard deviation, every five metres.

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[17] (BEEMS Technical Report TR531). The SCDF volume[18] shown in Figure 7 is substantially larger than the volume of sediment conservatively eroded by the modelled storm, indicating its viability. The proposed SCDF volume is 4 to 14 times larger than the modelled erosion of 40 m^3/m (2069 SLR case). The smallest volumes would be near the permanent BLF (162 m^3/m; see Figure 7 for location), rising to 260 – 300 m^3/m along the central and southern SZC frontage, whilst the maximum volumes just north of the north-east corner of the permanent BLF would be up to 557 m^3/m.

The SCDF would, however, need to be maintained and further modelling work is required to refine and establish volumetric losses associated with more severe storms, an eroded neighbouring shoreline and higher sea levels (BEEMS Technical Report TR545, in prep). These volumes will be used to set the size of the SCDF safety *buffer* volume (V_{buffer}) and the *sacrificial* volume (V_{sac}). An initial suggested working value for V_{buffer} is 2 – 3 times the conservative storm erosion value of 40 m^3/m. At 80 – 120 m^3/m, V_{sac} would be in the range 42 – 477 m^3/m. Note that there may be rationale to raise the value of V_{buffer} in the northern SCDF sections to avoid shoreline curvature around the north face, however that matter is considered a refinement and is not resolved in this initial study.

[17] 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.
[18] Volumes were calculated above 0 m ODN and between the HCDF and the 0 m ODN contour.

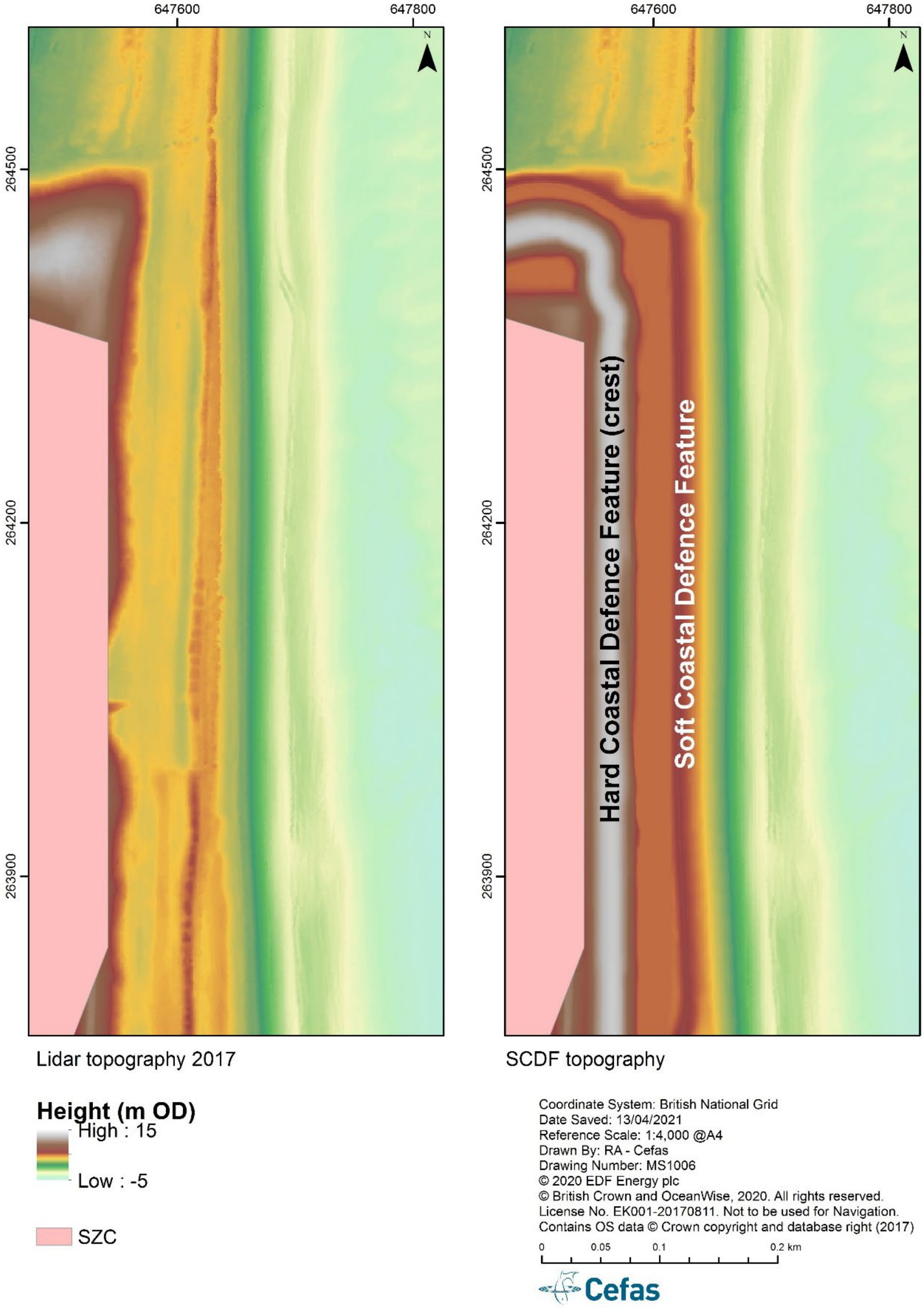

Figure 6: Topographic maps of the current and proposed SCDF topography.

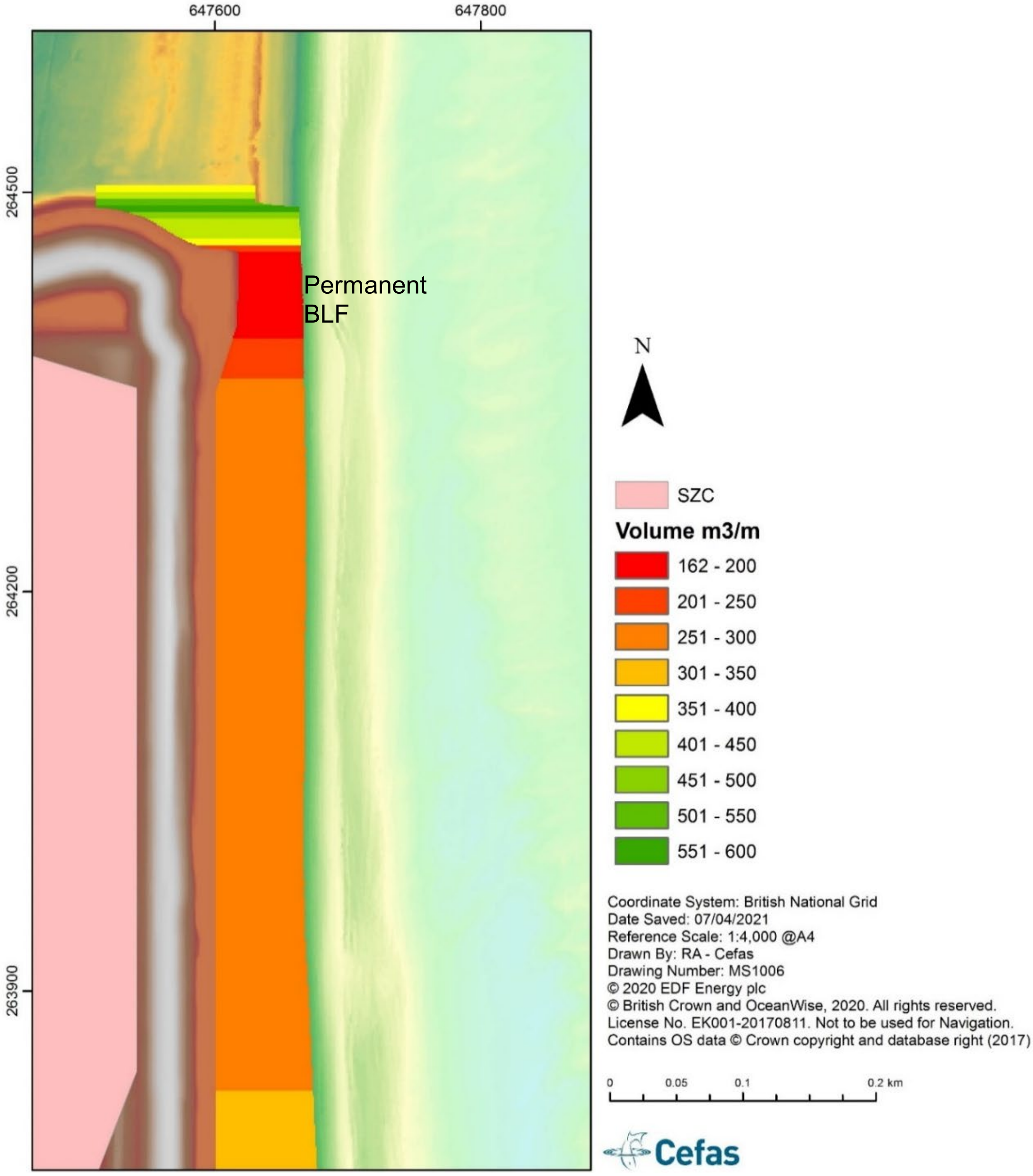

Figure 7: SCDF design volumes, expressed as m^3 per metre of alongshore beach frontage (m^3/m) and computed above MSL (0.11 m OD).

2.3.2 SCDF crest elevation

Overtopping per se is not of direct concern for the SCDF to achieve its purpose of avoiding disruption to longshore shingle transport due to HCDF exposure, however overwashing of quantities of sediment sufficient to alter or mobilise the crest could lead to breaching and affect integrity and maintenance frequency. The crest elevation should be high enough to avoid heavy overwashing of the crest. 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 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). 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, despite substantial reworking of the beach profile, barrier scarping and limited erosion of the shingle ridge toe (1 m retreat at 3 m ODN, no erosion at or above 3.5 m ODN; BEEMS Scientific Position Paper SPP094).

Although the shingle ridge is not presently overwashed, it is low in places (especially at the tank traps just north of SZC) 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 SCDF crest is similar to, or substantially exceeds, the sea level rise (SLR) predictions early in the SZC's decommissioning phase (2099[19]), which are:

- 0.55 – 0.83 m RCP4.5 (intermediate emissions scenario[20] 50th and 95th percentile respectively) and
- 0.78 – 1.14 m RCP8.5 (worst-case climate emissions scenario[21] 50th and 95th percentile respectively).

In 2099 (end of UKCP18 predictions and early in the SZC decommissioning phase[19]), 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 is to be maintained, gradual erosion would not lead to crest lowering.

2.4 SCDF sediment composition

This section sets out and justifies the general approach for SCDF composition (sedimentology). It uses the modified Udden-Wentworth particle-size classification shown in Appendix A. Two very similar particle-size options are presented that utilise coarse sediment particles to increase erosion resistance, beach stability and therefore longevity. This approach – using sediment coarser than the native size distribution – is commonly used for beach recharge schemes in the UK (Rogers et al., 2010). The SCDF uses a similar approach, although the SCDFs very coarse pebbles (Option A; Section 2.4.1) would be within, but at the

[19] 2099 would be early in the decommissioning phase, assuming a 60-year-long operation phase.
[20] CO2 emissions continue rising until 2040 – 2045 and halve the 2050 levels by 2100.
[21] RCP8.5 is considered to be very unlikely and has rising CO_2 emissions throughout the 21st century.

coarse end of, the Sizewell particle size distribution. A second option would comprise around 90% very coarse pebbles (Option B; see Section 2.4.2). In both cases, the aim is to increase beach stability and longevity of the placed sediments. Beach coarsening is considered suitable for the steepening intertidal zones of the East Coast of England (Rogers et al., 2010, p. 730). The scheme at Highcliffe (Dorset) is also highlighted by Rogers et al. (2010) as a successful example of shingle beach coarsening that showed good longevity, especially where the sediment had a narrow grading (1.5 – 4 cm; medium – very coarse pebbles). By comparison, sections at Highcliffe with sand and gravel mixtures performed less well and required minor recharges.

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

2.4.1 SCDF Option A: Very coarse pebbles

Option A uses very coarse pebbles (3.2 – 6.4 cm diameter), which are at the coarse end of the native particle-size distribution, to prolong the longevity of the SCDF (see Figure 4A). Its function as a supratidal reservoir of sediment can be directly compared with the successful Sand Bay scheme (Weston-super-Mare, UK), which created a steep mixed sand-gravel berm on a sandy-muddy foreshore in 1983-4 (Rogers et al., 2010) and which has only recently (January 2021) needed maintenance.

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

Numerical modelling will be undertaken to refine the target pebble sizes.

2.4.2 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 relatively narrow band of cobbles[22] deep within the SCDF (see Figure 4B) to further restrict erosion in the unlikely event that the *buffer* and *sacrificial* SCDF layers had been fully removed. It would further strengthen the SCDFs erosion resistance and reduce the risk of HCDF exposure. The cobble-sized sediments would have a degree of mobility (albeit less than coarse pebbles), constitute a beach morphology and facilitate continued longshore shingle transport due to its relatively smooth, mobile and dissipative sedimentary surface (compared to immobile and reflective rock armour of an exposed HCDF).

The rationale for using cobbles is drawn from the literature on artificial cobble composite beaches, which have been successfully deployed on high energy coastal systems and typically show low mobility. Cobble sediments (often fine cobbles[23] 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[24] (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.

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

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

Similar conclusions on the importance of volume and widths are also provided by Allan and Gabel (2016) and Newkirk et al. (2018). Overall, the guidelines for high-energy Oregon/California (Pacific) coasts suggest that a stable cobble berm requires a crest width of c. 5 m, a volume of >50 m^3/m and a crest height ~ 0.8 * 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 be used if the very coarse *buffer* and *sacrificial* layers were fully eroded. The use of a cobble berm would facilitate longshore transport of shingle (compared to an exposed HCDF) and aligns with UK beach recharge practices in which particles are often coarser than native sediments (see Rogers et al., 2010 and Pye and Blott, 2018).

3 Recharge frequency

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

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

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

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

- Assume reasonable worst-case from the parameters available in this report.
- Set preliminary values for the *buffer* and *sacrificial* volumes:
  - Set the *buffer* volume as three times the conservatively modelled BfE storm with 0.4 m of SLR (2069)[25]. The factor of three is chosen to represent the (highly unlikely) occurrence of three sequential BfE style events without opportunity to recharge the SCDF. V_{buffer} = 3 x 40 m^3/m = 120 m^3/m.
  - For conservative calculation, set the *sacrificial* volume for the smallest SCDF volume on the SZC frontage (162 m^3/m; near the permanent BLF). $V_{sac,min}$ = 162 - 120 = 42 m^3/m.
- For each method, compute the loss from the *sacrificial* volume for a 60-year operation phase, expressed as a per year average rate of loss ($\bar{V}_{loss}$).
- Compute the recharge interval in years as RI = $V_{sac,min}$ / $\bar{V}_{loss}$.
- Apply the Dutch Design Method (DDM) by assuming a further 40% on the loss rate (Verhagen et al., 1992 and Rogers et al., 2010).

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

- Calculations are based on the narrowest, lowest volume section of the SZC frontage.
- The model results used to set $V_{sac,min}$ 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.

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[25] 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 BEEMS Technical Report TR403 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.

- The predicted volume lost is increased by a further 40% following the Dutch Design Method.

3.1.1 Recharge requirements based on measured volumetric change

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

3.1.1.1 Beach volume change based on RPA derived digital surface models

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

The histogram of volumetric changes between surveys (expressed per year) for all bins (Figure 8) shows that erosion and accretion are fairly balanced across the survey area i.e., the distribution is near symmetrical. This reflects the results of previous studies that show no net seaward loss of shingle, cross-shore exchange of sand in and out of the subaerial beach (subtidal sand is abundant), low longshore transport rates, and very low longshore shingle loss in the Minsmere to Thorpeness embayment (BEEMS Technical Reports TR107, TR403 and TR420).

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

Applying the most erosive rate observed on the Sizewell frontage of 3.1 m^3/m/year equates to 186 m^3/m or 139,500 m^3 across the frontage, for the station's 60-year operation phase. Considering the smallest sacrificial SCDF volume $V_{sac,min}$ = 42 m^3/m, which is near the permanent BLF (Section 2.3.1), for the whole frontage[26] 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 most of the SCDF would rarely need recharge, but that the permanent BLF frontage (where V_{sac} is smallest) would require SCDF recharge up to 6 – 7 times over the operation phase. The estimated recharge interval should be considered as an average – the actual RIs are likely to be longer at the start of the operation phase and shorter by the end, due to sea level rise.

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

[26] 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.

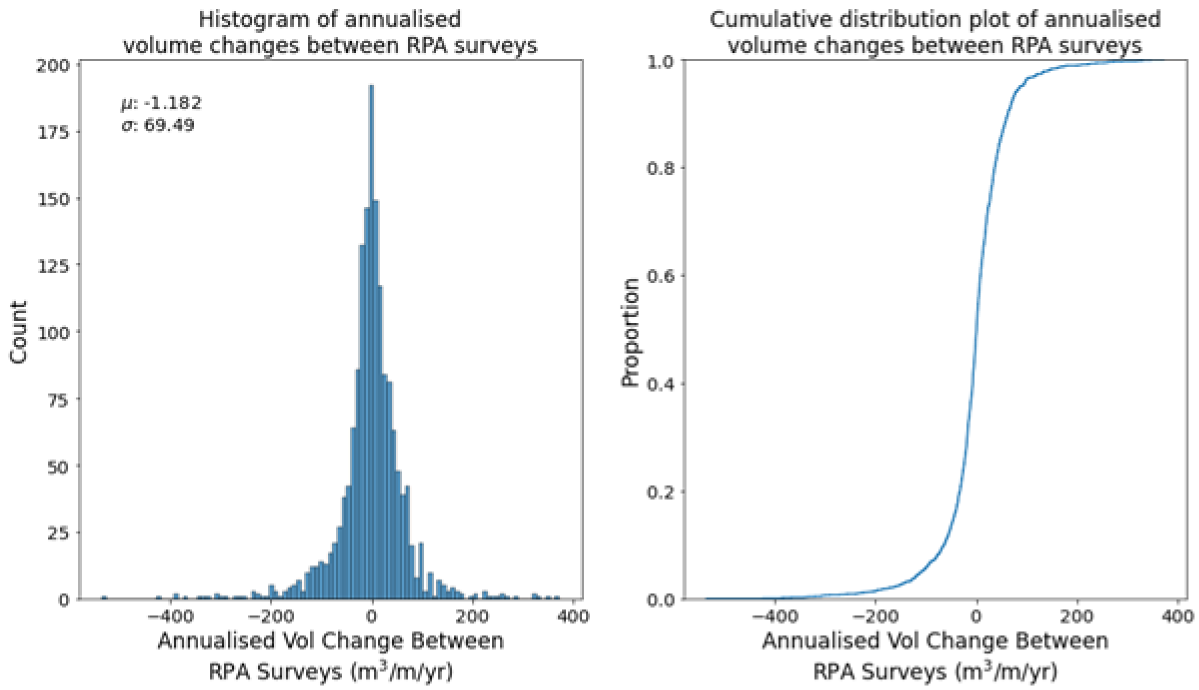

Figure 8: Histogram and CDF plot of aggregated volume changes between all RPA flights for 5 m bins every 50 m between Sizewell Café and the Minsmere Sluice Outfall (262850N and 266500N).

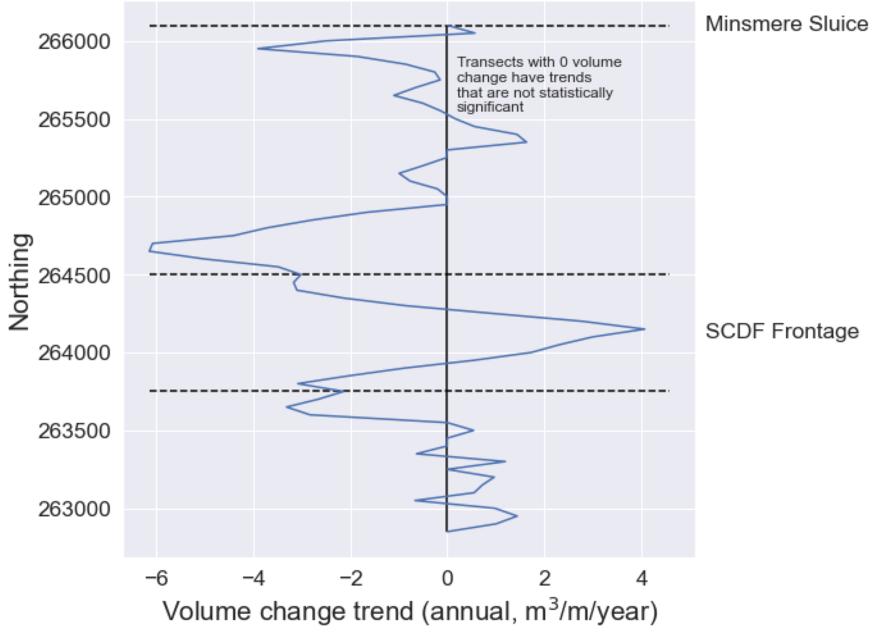

Figure 9: Annual volume change at each northing value derived from a linear regression fit over the time series of all RPA flight volumes for each northing.

3.1.1.2 Historical beach volume change based on shoreline movement

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

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

The relationship between shoreline change and volume change varies from location to location, as shown in Figure 11. With the exception of profile S1B4, all profiles between Dunwich and Thorpeness produce a volume of around 2 - 3 m^3/m per metre of shoreline change. At Sizewell C, profile S1B5 is toward the upper end of the typical range at 2.7 m^3 for each metre of shoreline retreat and has a shoreline retreat rate for the 1991 – 2018 record is 0.11 m/yr (Table 4, BEEMS Technical Report TR403).

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.

BEEMS Technical Report TR403 (Table 4) also calculated the peak erosion rate over a 10 year period, which captured a phase of more rapid shoreline change at S1B5 (SZC). The fastest retreat rate observed was 2.23 m/yr (6 m^3/m per year), which is higher than the persistent erosion hotspot between SZC and Minsmere Sluice Outfall (S1B5: average and peak (10-year) retreat rates of 1.01 and 2.07 m/yr respectively). During the erosive phase of a cycle, recharge may be triggered, only to be followed by a natural recovery phase resulting in larger volumes and little or no further recharge.

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

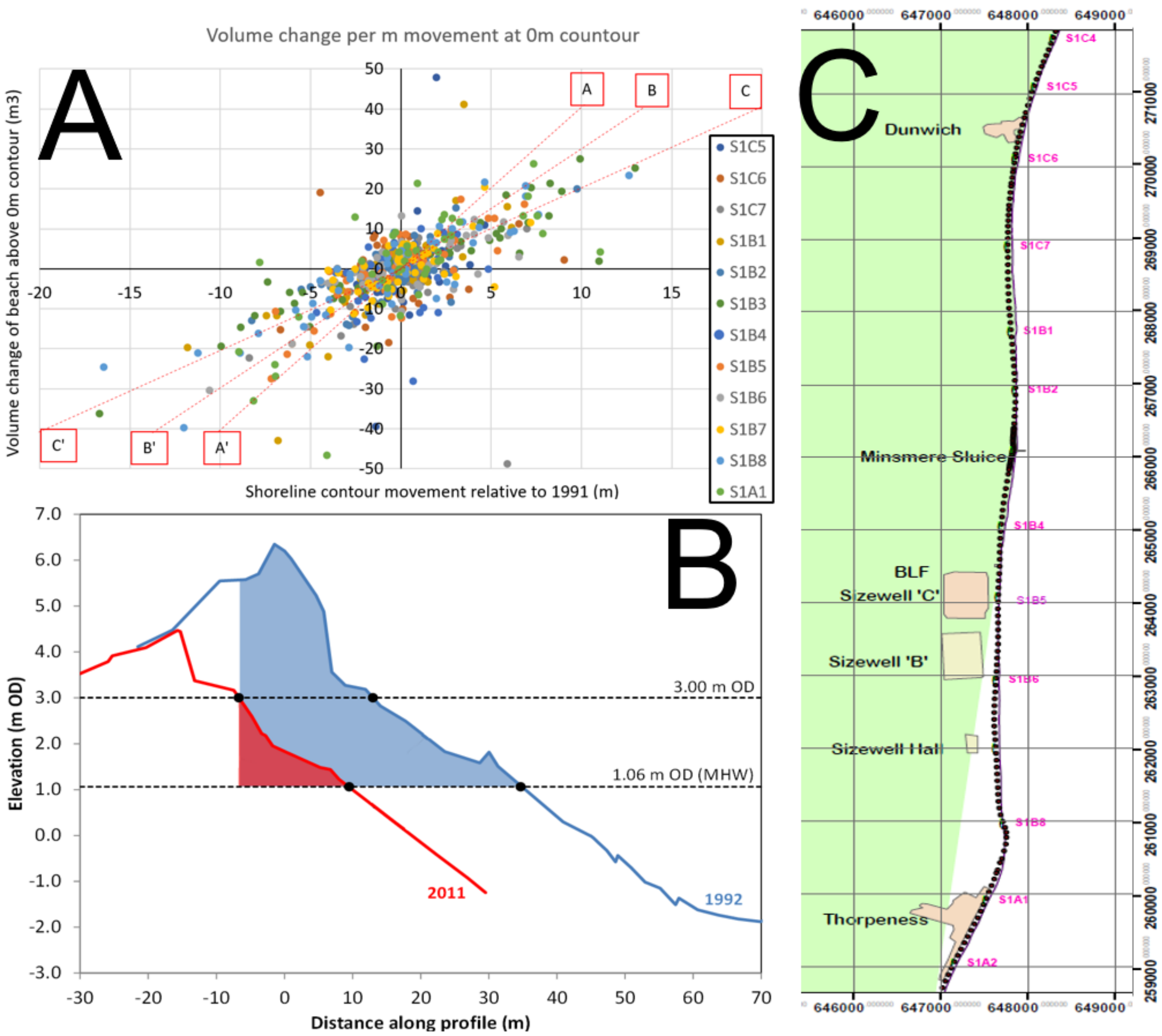

Figure 10. Volume changes as function of shoreline movement for the 0 m ODN contour (**A**) on Dunwich - Thorpeness frontage for 1991 - 2018, calculated as per (**B)** – see BEEMS Technical Report TR223 for details. Red dashed lines in **A** represent indicative volume loss of 4 m^3/m per metre of retreat (A-A'), 3 m^3/m (B-B') and 2 m^3/m (C-C'). Panel **C** shows the locations of each Environment Agency profile corresponding to the legend and coloured points in panel **A**.

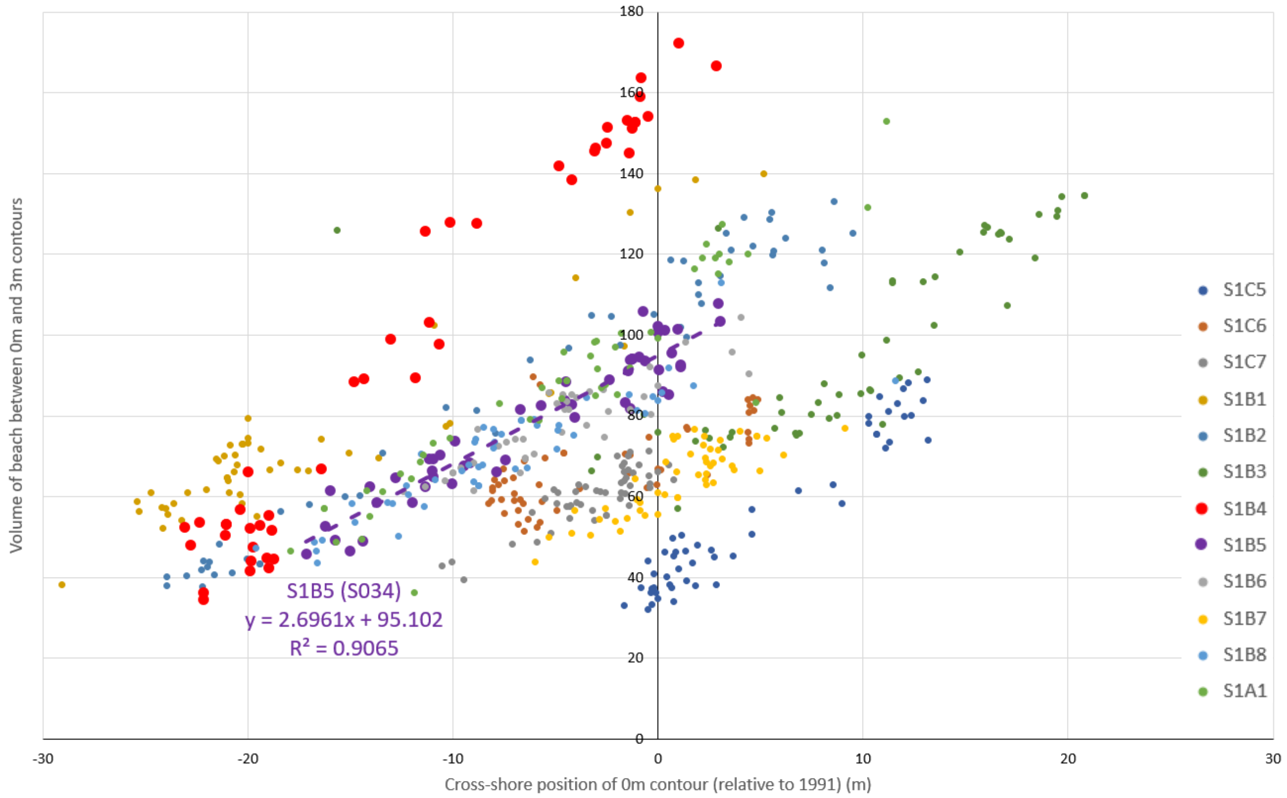

Figure 11. Beach volume changes as function of absolute position for separate EA profiles (1991 – 2018), with indicative lines shown for a number of data sets to illustrate their uniformity.

3.1.2 Recharge requirements based on modelled volumetric change

Section 2.3.1 described the preliminary modelling undertaken to estimate storm erosion during the first two storms in the BfE storm sequence, which together equate to a 1:12 year storm energy return interval (see BEEMS Technical Report TR531 for details). The modelling results are highly conservative (i.e., they overpredict erosion) but are used instead of measurements as the BfE post-storm survey was 2.5 months after the storms (during which some recovery is likely to have occurred). The UKCP18 predictions for reductions in Sizewell's wave climate[27] suggest no increase of wave climate or storms.

The modelling predicted 30 – 40 m^3/m of 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 sand supply is expected to remain similar or increase (Brooks and Spencer, 2012), shingle is effectively confined to the system (and is also likely to increase once Dunwich Cliffs begin to erode) and the model result is conservative and preliminary, a conservative 40 m^3/m net loss

[27] 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%).

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

Using $V_{sac,min}$ = 42 m^3/m for the whole frontage gives a worst-case recharge interval of 12.6 years = $42\frac{m^3}{m}/3.3\dot{3}\frac{m^3}{m.yr}$ (5 recharge events). Applying the DDM reduces the interval to 9 years. This result suggests most of the frontage would rarely need recharge, but 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.

Additional RI estimates will be made from further numerical modelling described in BEEMS Technical Report TR545 (due to be published in June 2021) that considers longshore transport (using a 2D model), more severe storm conditions, sea level rise in 2099 and eroded shorelines either side of the maintained SZC frontage.

3.1.3 Recharge requirements (summary)

Several approaches have been employed to indicate and envelope the possible recharge requirements over SZC's operational life. The RPA measurements and the preliminary storm-erosion model give 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, using the peak 10-year retreat rate within the SZC cycle gives preliminary worst case estimates for the recharging interval (7 years) and total recharge requirement across the life of the station (c. 270,550 m^3).

Sea level rise is partially incorporated into some calculations by way of shoreline retreat rates over almost 30 years (which include the sea level rise that occurred over those three decades) and by way of a modelled SLR case, however they do not fully account for SLR across the operation and decommissioning phases of the station. This is countered by several conservative steps applied in the calculations, as set out at the start of Section 3. The estimates in this report will be refined and incorporated into the CPMMP following more detailed modelling (including more sea level rise cases) and model improvements once additional calibration datasets have been secured.

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.

4 Conclusions

The main design parameters (volume, crest height and composition) of the SZC have been set out. They show that the SCDF volume would be substantially larger than that required to withstand 2 – 3 severe[28] sequential storms, even along sections where the SCDF would be small, near the permanent BLF (264,390 N – 264,455 N, Figure 7). The increased crest height (compared to the present shingle ridge at SZC, which shows no signs of overwashing and roll back) is substantially larger than the SLR predicted under the intermediate climate emissions scenario (RCP4.5), and is larger or similar to the SLR under the very unlikely worst-case emissions scenario (RCP8.5).

The proposed use of very coarse pebbles (with a relatively low sand content) equates to beach coarsening within the native particle size distribution, which is in line with UK experience and guidance, and intentionally designed to increase retention and therefore prolong longevity. The SCDF would feature a larger inner safety *buffer* volume, V_{buffer}, and an outer *sacrificial* volume, V_{sac}. An option for a cobble-layer deep within the SCDF, based on the dynamic cobble berm concept, is also being considered to increase erosion resistance in the unlikely event that the SCDF pebbles were fully removed.

Conservative estimates of the notional recharge interval across the operational phase (up to seven interventions) and the relatively small volumes[29] (140,000 – 150,000 m^3 across the operation phase; preliminary worst case c. 270,550 m^3) indicate SCDF viability. 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 volumes are similar to the total SCDF volume (c. 200,000 m^3). Of course, recharge events will be triggered when beach volumes reach a certain threshold and so the interval will not be a constant. Nor will it necessarily apply to the whole SZC frontage – spatial patterns in erosion may trigger recharge in some areas (e.g., near the permanent BLF where volumes are lowest) and not others. The monitoring set out in the CPMMP is designed to detect such changes, as the monitoring techniques are spatially continuous.

The large SCDF volume, relatively low number of calculated recharge events and relatively small recharge volumes (based on conservative measures) indicate that the SCDF is viable across the operation phase of the station.

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 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 is required to refine the preliminary design. This includes modelling to incorporate longshore sediment transport, SLR cases throughout the operation and decommissioning phase and sensitivity to particle size (to refine the target size distribution), and setting V_{recharge} (the threshold volume for SCDF recharge) for the Coastal Processes Monitoring and Mitigation Plan.

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[28] Storm return interval of 1:12 years, based on the first two storms in the BfE sequence.
[29] 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).

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Appendix A Modified Udden-Wentworth classification

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

Source: Blair and McPherson (1999).