

BACTON SANDSCAPING: QUANTIFIED BENEFITS 4 YEARS AFTER CONSTRUCTION

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The Bacton Sandscaping Scheme was constructed in August 2019 at the Norfolk coastline to protect the Bacton Gas Terminal from severe damages due to cliff erosion, while reinstating the beach for the neighbouring villages. It was designed to deliver a wide range of outcomes, but the business case mainly relied on the benefits in terms of prevented damages due to coastal flooding and erosion as a result of storm events. The sources of potential damages are the cliff erosion at the terminal, flooding due to overtopping of the seawall at the villages of Bacton and Walcott, and failure of the seawall resulting in coastal erosion at these villages. No damages have occurred since the implementation of the scheme so the generated benefits are equal to the damages that would have occurred if the scheme had not been in place. This paper reports on a study to quantify these actually occurred benefits, utilising pragmatic methods and hindcast data. This results in approximately £3.1M of damages due to flooding and erosion having been prevented in the first 4 years since the scheme was constructed.

Keywords: Sandscaping, benefits, flooding, erosion, performance, coastal defences, defence failure, overtopping, FCERM, nature-based solutions, sand engine, mega-nourishment

INTRODUCTION

The Bacton Sandscaping Scheme was constructed in August 2019 at the Norfolk coastline to protect the Bacton Gas Terminal from severe damages due to cliff erosion, while reinstating the beach for the neighbouring villages. A traditional grey coastal engineering solution was not possible here, as the Shoreline Management Plan (SMP; AECOM, 2012) would not allow an engineered solution to aggravate the situation for the downdrift communities, where the seawall is expected to reach its end of life soon. Traditional nourishments were uneconomical and unaffordable over the longer term. The adopted solution was a mega-nourishment with an expected lifetime of 15 to 20 years, designed so that natural processes would feed the beaches at the villages to buy the time that the communities need for adaptation to coastal change, whilst protecting the terminal against storm impacts. Figure 1 shows an impression of the layout of the finished scheme. Clipsham (2021) provides an overview of the design (process) and Borsje (2023) an overview of the morphological development since construction.

Sandscaping is a coastal management approach, introduced by The Crown Estate and Royal HaskoningDHV and inspired by the Dutch Zandmotor scheme, consisting of large-scale beach nourishment designed to work with natural processes and to achieve multiple benefits. For the Bacton scheme, these benefits concerned the prevented damages due to flood and erosion, but also local economic growth, reduced mental health impacts, habitat enhancements and knowledge development. These benefits informed the scheme's business case which justified the UK Government's share in the investment; in practice this focused mostly on the flood and erosion benefits. Despite their importance in design, funding and consenting, it is very rare that actual outcomes of coastal schemes are assessed and reported. In order to support the development of the Sandscaping concept Royal HaskoningDHV worked with The Crown Estate to review the full range of benefits for the Bacton Sandscaping Scheme.

This paper focuses on the prevented damages due to storm impacts. This consists of three elements: (1) the prevention of damages due to cliff erosion at the terminal, (2) the prevention of flood damages following overtopping of the seawall at the villages, and (3) the prevention of failure of the seawall resulting in coastal erosion at the villages. For all of these elements, no damages have occurred since the implementation of the scheme and the generated benefits are therefore the damages that would have occurred if the scheme had not been in place. This is different from the more usual pre-scheme appraisal in which the benefit calculation has to consider the likelihood and value of residual damages that would occur during events above its standard of service.

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Figure 1: Impression of the implemented Bacton Sandscaping Scheme, stretching approximately 2km from the Bacton Terminal towards Walcott.



Figure 2: Impressions of the Bacton Sandscaping Scheme after construction in August 2019. Left panel: Bacton Gas Terminal; right panel: Walcott. Courtesy of Chris Taylor Photo.

CLIFF EROSION AT BACTON TERMINAL

The Bacton Gas Terminal is located at the top of soft cliffs (Figure 3) which are susceptible to erosion. The erosion of the cliff is episodic and driven by wave attack on the cliff face during extreme events. During the December 2013 storm, the buffer between the seaward fence of the Terminal and the cliff edge reduced from 10 to 5 meter (see Figure 3 for an impression), which triggered the Bacton Sandscaping Scheme. The scheme prevents further erosion of the cliffs by limiting their exposure to storm waves through a “minimum protection profile”, designed to achieve a 1:10,000 per year level of protection. The consequences of further erosion are significant: in addition to the potential cost of repairing damages to the infrastructure on top of and inside the cliffs, there would be knock-on effects on the UK’s economy due to the disruption to the gas supply. About 1/3rd of the UK’s gas is supplied through the Bacton Terminal, and Pöyry (2014) estimates that the economic damage associated with disruption could be in the order of £50bn.

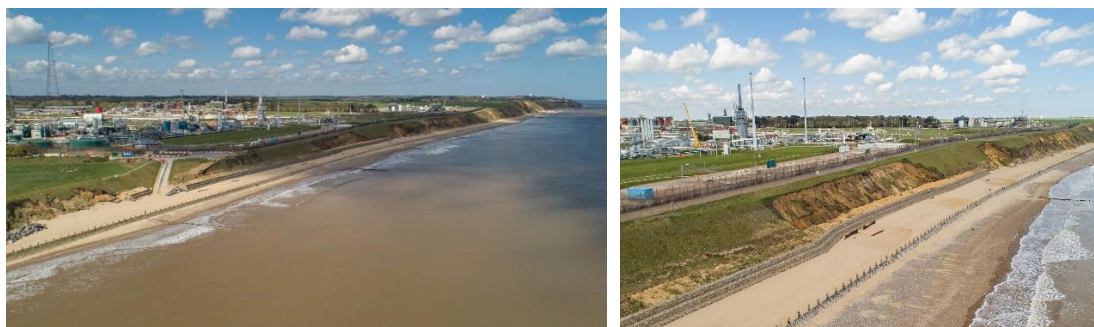


Figure 3: Bacton Gas Terminal before the implementation of the Bacton Sandscaping Scheme. Right panel shows previous cliff falls and the narrow buffer in more detail. Courtesy of Chris Taylor Photo.

During the design stage of the scheme, the shape and size of the nourishment’s minimum protection profile was determined through examination of the impact of waves on the cliff face during storms. The method developed for the Bacton scheme was later included as a case study in national guidance for

setting triggers for beach management (Environment Agency, 2019). For a number of historical storms, known to either have caused erosion or have not caused erosion of the cliffs, the wave run-up and subsequent wave hits on the cliff face (per vertical running meter) were simulated using the AMAZON modelling suite (Hu, 2000). The resulting distributions were referred to as “demographics”. This resulted in an upper limit (based on the December 2013 storm which is known to have caused erosion), above which cliff erosion is expected to occur, and a lower limit (based on the November 2011 storm which is known not to have caused erosion), under which cliff erosion is not expected to occur. The minimum protection profile was designed such that the demographic of the 1:10,000 per year design storm would not exceed the lower limit.

To determine whether cliff erosion was prevented by the scheme since construction, the same approach was taken for the most severe storms between 2019 and 2023. Wave data between August 2019 and November 2022 was extracted at 10m depth from a MIKE21 Spectral Wave model driven by offshore wave data from the European Centre for Medium-Range Weather Forecasts’ ERA5 hindcast dataset. Water levels from the tidal gauges at Cromer and Lowestoft were used to derive a water level at Bacton, by averaging these records based on their distance from Bacton. Three storms (Table 1) with the highest potential impact on cliff erosion were selected based on judgement, considering wave height, water level, storm duration and cumulative wave power. These storms were then simulated in AMAZON using a representative beach profile without the scheme in place (based on historical Environment Agency LiDAR data from July 2017) to determine the number of hits at each level vertically along the cliff face, had the scheme not been constructed. These empirical distributions were then compared to the upper and lower design limits determined during the design, indicating whether the storm would have caused erosion. All three selected storms appear to be well underneath the non-erosion line of the November 2011 storm event (Figure 4), indicating that none of the selected storms would have been likely to cause any cliff erosion had the Sandscaping Scheme not been in place.

| Storm Peak | Wave Height (H_{m0}) [m] | Water Level [m OD] | Tidal Range [m] | Duration [h] |
|------------------|------------------------------|--------------------|-----------------|--------------|
| 09/12/2019 15:30 | 3.21 | 1.67 | 2.90 | 54 |
| 26/09/2020 00:00 | 4.06 | 0.95 | 1.75 | 96 |
| 31/03/2022 18:00 | 3.36 | 1.76 | 2.43 | 60 |

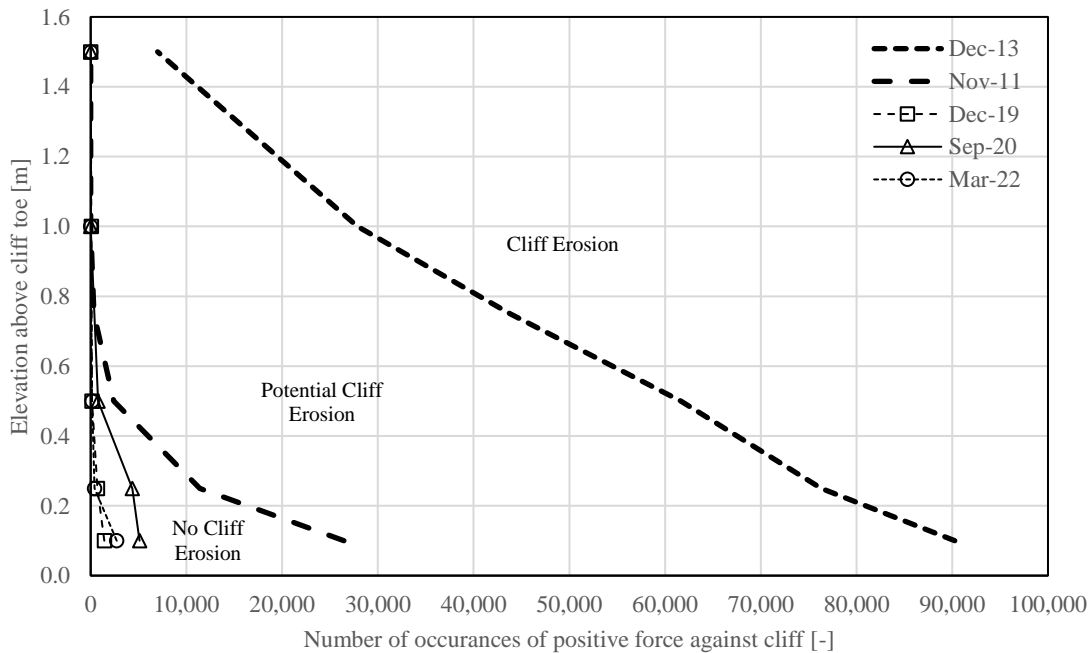


Figure 4: Demographics of the selected storm events over the last 4 years. The November 2011 demographic indicates the boundary beneath which there is a high likelihood that no erosion of the cliff face will take place, whereas the December 2013 demographic indicates the boundary above which there is a high likelihood that erosion of the cliff face will take place.

As none of the storms with a high erosion potential are likely to have caused erosion, there is no indication that any benefit from preventing cliff erosion to the Terminal frontage had materialised by 2023. It is, however, still very likely that this benefit will materialise in the future: cliff erosion at Bacton is known to be an episodic process, i.e., there is in the order of 5 years between individual events; and in addition, larger storms than those since 2019 are expected to occur, especially under the influence of climate change. Already, there is anecdotal evidence that storms have occurred since November 2022 that were more severe than the storms analysed as part of this study.

SEAWALL FAILURE AT BACTON AND WALCOTT

To determine the benefits associated with the prevention of coastal erosion following the failure of the seawall at Bacton and Walcott, a pragmatic but risk-based approach was used based on the chance of failure of the sea defences over their lifetime. A cumulative likelihood of defence failure over the period 2019-2023 was derived, which was then multiplied with the value of the potentially affected properties and infrastructure to reflect the expected damage over this period, as is described in the following sections.

Probability of sea defence failure

The Coastal Defence Condition survey in 2012 (Mott MacDonald, 2012) estimated the residual life of the seawall from the Bacton Gas Terminal to Ostend in 500-meter sections, based on the condition of the sea defences and defence types, assuming a "Do Nothing" scenario in which the effects of erosion are left unmitigated. Table 2 presents an overview of this assessment, adjusted to reflect that at the time of implementation of the Sandscaping Scheme (Summer 2019), none of the seawall sections had yet failed.

| Zone | Defence type | Estimated earliest year of failure | Estimated latest year of failure | Estimated cumulative probability of defence failure by 2023 (%) |
|----------------|----------------------------|------------------------------------|----------------------------------|---|
| B | Timber revetment | 2019 | 2027 | 55.6 |
| C ₁ | Concrete defence structure | 2022 | 2027 | 33.3 |
| C ₂ | Concrete defence structure | 2022 | 2037 | 12.5 |
| D | Concrete defence structure | 2022 | 2037 | 12.5 |
| E | Concrete defence structure | 2032 | 2037 | 0.0 |
| F | Concrete defence structure | 2022 | 2042 | 9.5 |
| G | Concrete defence structure | 2022 | 2027 | 33.3 |
| H | Timber revetment | 2019 | 2027 | 55.6 |

The cumulative probability of failure of the structures by 2023 is estimated by assuming that the cumulative probability is 0% in 2019 (as the defences had not failed prior to 2019) and 100% by the estimated latest year of failure in Table 2. The cumulative probability of failure in 2023 was estimated by means of linear interpolation. This is the likelihood that the sea defence will have failed by 2023 causing erosion of the land behind the defence. This is the Do Nothing scenario.

Properties at Risk

The properties at risk of the erosion following seawall failure were determined by assuming the seawall would fail during the earliest year in Table 2 and subsequently applying the erosion rate as determined in the Cromer to Winterton Ness Coastal Management Study (Mott MacDonald, 2013), following the same approach as for the Business Case of the Bacton Sandscaping Scheme. Any properties potentially affected by erosion between 2019 and 2023 were included in the calculation of damages. Based on this analysis, it is estimated that 7 properties could have been affected by erosion if the scheme had not been implemented.

Prevented economic damages

In reality, the seawall did not fail up to 2023, so the benefits are equal to the damages that would have occurred without the scheme. An indicative estimate of the prevented damage can be calculated by multiplication of the likelihood of erosion by 2023 with the values of the properties that would have been affected by that erosion. Using this method, it is estimated that by 2023 the scheme had already provided benefits of up to £1,290,000 by preventing erosion damages to the 7 properties identified above. A similar

approach was taken to account for the B1159 road, which is located directly behind the defences at Walcott. It is assumed that the road would have to be rebuilt if it were to fail due to erosion. This estimated economic benefit of preventing erosion damage to the B1159 road is £140,000. In total, the scheme has therefore generated an estimated £1,430,000 in economic benefits by preventing the failure of the seawall and subsequent erosion.

FLOODING AT BACTON AND WALCOTT

Wave overtopping caused various severe flood events before the scheme was implemented. No overtopping has been reported since scheme implementation. There are anecdotal indications, and local perceptions, that some of the storms since implementation would have caused flooding, so this review started with an expectation that it would indeed identify occurred benefits.

The benefit associated with protection against flooding is the damage prevented to properties and infrastructure. To derive this economic impact of wave overtopping and subsequent flooding, a pragmatic approach was used that built on the method that was used for the Bacton Sandscaping Scheme's Business Case:

1. Select the historical storms in the period August 2019- February 2023 with highest overtopping potential.
2. Calculate the overtopping rate at the peak of each storm.
3. Estimate the number of households flooded by comparison with previous detailed model results.
4. Translate to economic damages.

Selection of significant storms

It was not practical to run the full timeseries with the full calculation method for overtopping, so instead, a simpler estimator formula was applied to the timeseries of wave data and water levels to select those storms most likely to have resulted in significant overtopping.

Wave data was acquired from the Happisburgh wave buoy at -10mOD (from the National Network of Regional Coastal Monitoring Programmes; NNRCMP³), rather than from the numerical model that was used for the cliff erosion analysis, as the buoy is located close enough to Walcott to be representative. The wave data was transformed to the toe of the structure using Goda (2000). Water levels from the tidal gauges at Cromer and Lowestoft (acquired from the British Oceanographic Data Centre; BODC⁴) were used to derive a water level at Bacton, by averaging these records based on their distance from Bacton. A simple estimator for the vertical run-up level, based on the historical 'Delft Formula' for wave run-up (Eq. 1; TAW, 2002), was used in combination with a peak-over-threshold analysis to select storms with the highest potential for overtopping.

$$R = h_{toe} + 8 H_{s,toe} \tan(s_{structure}) \quad (1)$$

where R is the run-up against the structure, h_{toe} is the water depth at the toe of the structure, $H_{s,toe}$ is the significant wave height at the toe of the structure, and $s_{structure}$ is the slope of the structure. The main overtopping related variable missing from the Delft Formula is the wave period; the timeseries was checked to ensure that this simplification did not eliminate potentially important storms.

The selected storms are presented in Table 2.

| Storm Peak | Wave Height H_{m0} [m] | Wave Period $T_{m-1,0}$ [s] | Wave Direction β_p [degN] | Water Level [mOD] |
|------------------|-----------------------------|--------------------------------|------------------------------------|----------------------|
| 30/09/2019 07:00 | 1.18 | 7.1 | 37.0 | 2.39 |
| 21/10/2021 07:00 | 1.19 | 5.8 | 20.8 | 2.55 |
| 07/11/2021 08:30 | 1.17 | 6.3 | 24.7 | 2.49 |
| 30/01/2022 04:00 | 1.42 | 8.9 | 29.6 | 2.63 |
| 06/02/2022 22:00 | 1.16 | 8.0 | 25.2 | 2.34 |

Calculating overtopping rates

For these storms, a peak wave overtopping discharge was then calculated using EurOtop (2018) for a representative pre-scheme defence cross-section for the seawall at Walcott, illustrated in Figures 5 and 6. The results are presented in Table 3 below. The 30 January 2022 event was the most important storm

³ <https://coastalmonitoring.org/>

⁴ <https://www.bodc.ac.uk/>

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in the timeseries from an overtopping perspective with a discharge of 1.4 l/m/s. Wave overtopping can cause significant direct flooding (see below), but it could also cause defence failure which would lead to more severe flooding plus defence repair costs. The maximum discharge of 1.4 l/m/s is in the order of the tolerable value for grassy slopes (EurOtop, 2018). It is unlikely, however, that the overtopping would have caused structural damage to the seawall. The other events (around 0.2 l/m/s) are in the order of overtopping values that are seen as unlikely to cause any structural damage, even to undefended slopes.

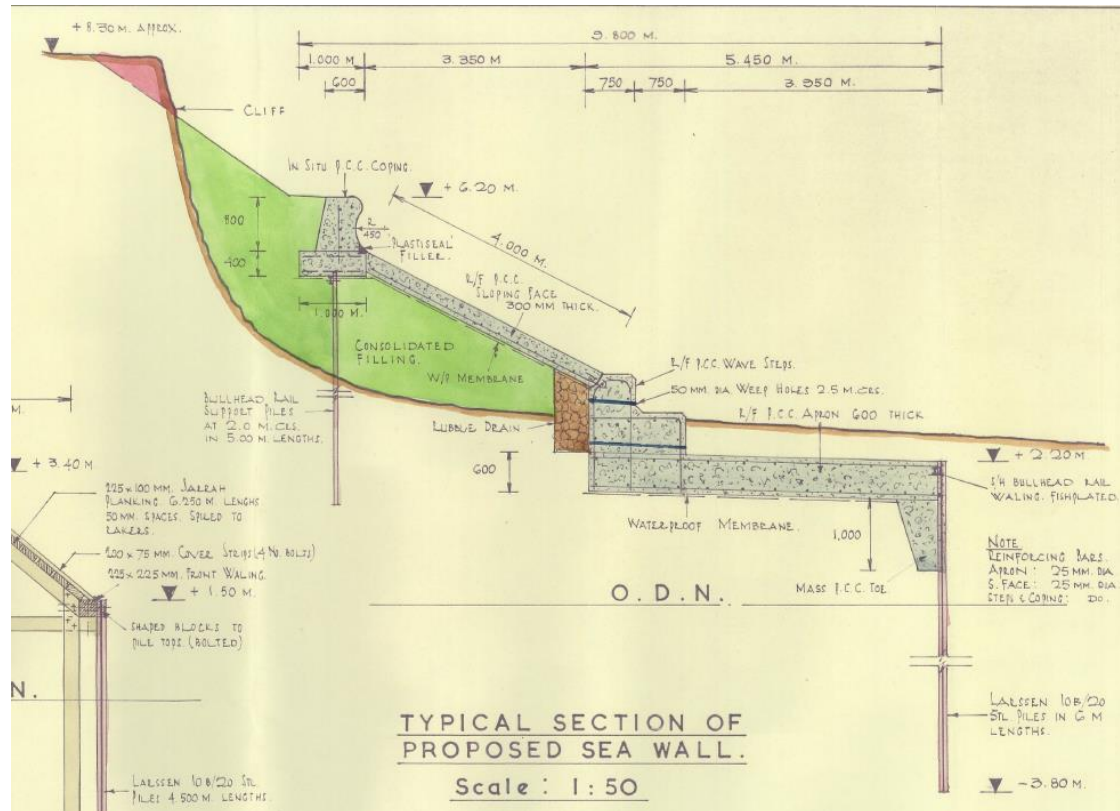


Figure 5: Historical drawing (1975) of a typical defence cross-section. Note that prior to the Sandscaping scheme, beach levels were typically much lower than indicated in the drawing, exposing the sheetpile toe. By Mobs & English Consulting Engineers (1975).



Figure 6: State of the sea defences at Walcott prior to the Sandscaping Scheme, Winter 2018.

Estimating economic damages

To estimate the number of properties that would have been affected by the Do Nothing overtopping events, an approximate flood extent was determined based on relationships between peak overtopping discharge and number of households flooded for several sub-frontages, which were derived during the design stage of the scheme based on detailed modelling (recognising the simplification that shape and duration of the storm are eliminated from the comparison). An example of the modelling results is presented in Figure 7. The results of the translation from overtopping discharge to properties affected are presented in Table 3.

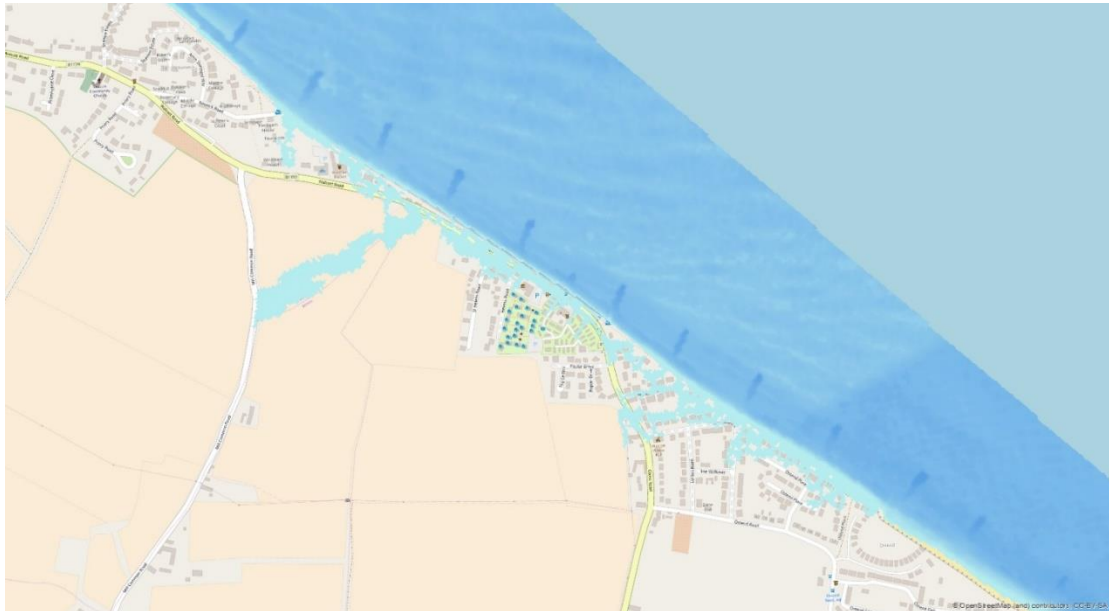


Figure 7: Map of the modelled flood extent related to a peak overtopping rate of 1.2 l/s/m.

This shows that the storm on 30 January 2023 would have caused flooding to the largest number of households; 56 in total across Bacton, Keswick and Walcott. For the minor events, the calculation suggests that 11 to 13 households would be flooded. This, however, should be treated with caution, as the overtopping rates are small and would only affect the properties directly behind the seawall. It could be argued that these are likely to have some resilience to these minor events, considering that this was a regular occurrence before scheme implementation in 2019. The prevention of property damages associated with these minor events is therefore not counted as a benefit of the scheme.

| Storm Peak | Overtopping Discharge q [l/s/m] | Number of residential properties flooded |
|-------------------------|-----------------------------------|--|
| 30/09/2019 07:00 | 0.134 | 13 |
| 21/10/2021 07:00 | 0.049 | 11 |
| 07/11/2021 08:30 | 0.122 | 13 |
| 30/01/2022 04:00 | 1.416 | 56 |
| 06/02/2022 22:00 | 0.071 | 11 |

The economic damage associated with the flooding of properties during the 30 January 2022 event was estimated using the assumption that flooding of one household would cause, on average, £30,000 damage. This is a very broad assumption, covering all types of flooding, severity levels and types of

households based on a similar assumption in the Environment Agency's Partnership Funding calculator⁵ (Defra, 2011). Based on the 56 properties, had the scheme not been implemented, this January 2022 storm would have caused £1,680,000 of flood damages.

DISCUSSION

The methods used in this study are similar to those used in the Business Case for the scheme. In itself, these were pragmatic, following the principle that the effort of appraisal has to be proportionate. For this study, some further simplifications were made compared to a full Business Case approach. These simplifications give rise to the following limitations:

- The boundaries for “Cliff Erosion” and “No Cliff Erosion” to determine the predicted impact of a storm on the cliff face are based on a limited dataset. As such, there is a large grey area of storm conditions in between these boundaries under which the response of the cliff is highly uncertain. Furthermore, the boundaries are only linked to one particular storm event. In reality, it is likely that the “wave hits” of all storms prior to an erosion event matter (i.e. the cumulative demographic between events), alongside other external factors such as rainfall intensity.
- The cross-sectional profile of the sea defence is complex (a vertical toe above a sloping beach, with a flat apron, a sloping revetment and a wave wall on top) and for cases such as this, EurOtop (2018) advises to use the Artificial Neural Network (ANN). It further suggests that similar-shaped structures might be part of the underlying database: if the geometry of the seawall at Walcott is indeed close to the examples used to train the ANN, then this tool could be used to improve the overtopping calculation (noting that the results would need to be corrected for the effect of the wave wall; Formatin et al., 2017). Alternatively, results could be improved by utilising a wave overtopping model such as AMAZON (Hu et al., 2000).
- The flood extent was determined by matching the peak overtopping discharge with results from a previous study. This means that the shape and duration of the storm are not properly captured in the determination of the flood extent. Neither did these parameters play a role in the selection of the most critical events. A selection mechanism based on volume, or average discharge over the storm duration, would improve the initial selection. In addition, modelling the actual storm in a 2D flood modelling package would allow shape and duration to be reflected in the prediction of the flooding. This would give a more accurate selection of properties affected by flooding.
- The damage to properties due to flooding was estimated through an average damage value per property. In reality, factors such as the depth of flooding as well as the property type and value, and even the level of property flood resistance and resilience, play a role in predicting the damage to a property during a flood event. The benefit estimate could be improved by utilising the full methods as included in the Multi-coloured Manual (Penning-Rowsell et al., 2013) and by directly consulting the National Receptor Dataset (NRD) for the up-to-date property valuations. That latter dataset would similarly be useful for the calculation of damages due to erosion in the Villages, as the property values used in that part of the analysis (albeit corrected for inflation) had not been updated since the scheme's Business Case.
- The cumulative failure probability between 2019 and 2023 is assumed to follow a linear increase between 0% and 100%. This is not reflective of the behaviour of actual sea defences. The shape of curve instead depends on the underlying deterioration processes, characteristics of the defence, development of the foreshore and of the hydraulic loading that will eventually lead to failure.
- The inclusion of properties into the erosion damage calculations was based on the potential of these properties being reached within the 4 years after the construction of the scheme. This is a simplification: in reality, there was a chance of failure in each year, and if it had failed in a later year, less erosion would have occurred by 2023, less properties would have been affected and less damage would have occurred. The use of the cumulative failure probability over the full 4 years as a damage factor on the value of all identified properties can therefore be considered an upper limit. A more accurate the damage prediction method would consider the chance of defence failure in each year, combine this with the erosion rate to determine the properties that would be affected, and then combine the probabilities of each annual failure scenario to estimate damage. As part of the emerging

⁵ Specifically, for the calculation of the ‘household flooding top-up’ in the Partnership Funding Calculator's Outcome Measure 2.

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National Coastal Erosion Risk Mapping (NCERM) update⁶, Royal HaskoningDHV have developed more advanced methods to take this effect into account, which could improve the calculation of damages in this study.

- The erosion rate used to determine which properties are considered to be at risk of erosion was derived in 2013 and should be updated if possible, based on the latest data (such as the new NCERM data when published in early 2025). Furthermore, this rate did not include coastal catch-up. Following the loss of coastal defence structures, a very rapid recession of the coastline can sometimes occur for a limited period, before returning to a more “natural” erosion rate. Before failure, a defence has prevented erosion for a number of years (i.e., between when it was first constructed and when it fails). Once the defence fails, it tends to “catch-up” with its natural trajectory, i.e. recedes to the position it would have been, had no defences been in place. This behaviour was observed, for example, nearby Bacton and Walcott at Happisburgh (Walkden, 2016). If catch-up was also to occur at Bacton and Walcott, there would likely be additional damages and thus benefits compared to what is reported in this paper. The new method for NCERM will also capture catch-up in its approach for combining defence performance and erosion.

The analysis in this paper only covered the benefits related to the prevention of flooding and coastal erosion. In reality, however, there are indications that a wider range of benefits is generated, in line with the scheme’s original objectives. Lorenzoni et al. (2024), for example, found that there are benefits associated with the reassurance that the scheme is working, the reliable beach accessibility, year-round destination value and diverse beach use, buoyancy in the property market and business uplift. Early indications are that these wellbeing benefits and the avoided loss of tourism can be valued at an additional £3 million (Simetrica-Jacobs, 2024). Historically, these additional benefits were rarely monetised or even reported, however, with an increasing emphasis on utilising FCERM schemes to create a mosaic of benefits it will also become increasingly more important to take these additional benefits into proper consideration in the appraisal of options.

It is important to put the benefits derived as part of this study into context: the UK government’s Grant in Aid (GiA) funding acquired for the scheme was £5M, and the total cost of the scheme was approximately £19M. The benefits associated with the prevention of damages over the first 4 years since placement are therefore significant. Furthermore, whether a scheme is granted the abovementioned GiA funding, and exactly how much funding is granted, is directly linked to these same benefits, estimated during the design stage. Therefore, the estimation of these benefits plays an important role in the design and appraisal of any flood and coastal erosion risk management (FCERM) scheme in the UK, with mandatory detailed methods (e.g. the Multi-coloured Manual; Penning-Rowsell et al., 2013) available to facilitate estimation. Rarely, however, is the performance of FCERM reviewed to establish to what extent benefits have actually been delivered. Wider post-implementation evaluation of schemes could provide lessons learned that can be incorporated in the design of schemes and that could feed into the development of appraisal guidance and benefit estimation methods. Furthermore, it could inform the Government’s policies around investment into FCERM infrastructure, providing better justification of the spending of public funds.

CONCLUSION

Since placement, the nourished beach of the Bacton Sandscaping Scheme has provided protection against flooding and erosion at the Bacton Gas Terminal and villages of Bacton and Walcott. It has prevented potential failure of the seawall at the villages and flooding of the villages by means of wave overtopping. In summary, the total associated benefits are 7 properties and the B1159 protected from erosion (estimated benefits £1,430,000) and 56 properties protected from flooding (estimated benefits £1,680,000). This brings the amount of generated flood and erosion prevention benefits over the period 2019 – early 2023 to approximately **£3,100,000**. This does not yet include for the wider social, economic and environmental benefits, however, there are indications that these would be in the same order of magnitude.

⁶ Commissioned by the Environment Agency, led by Jacobs and supported by Royal HaskoningDHV and the Channel Coastal Observatory: <https://www.jacobs.com/newsroom/news/helping-environment-agency-deliver-its-flood-coastal-erosion-risk-management-strategy>

The Bacton scheme's benefits are likely to only increase further in future, as the analysis in this paper only covers the first 3.5 years of the 15–20-year lifetime of the scheme. Going forwards, it would be beneficial for post-implementation analysis of the performance of FCERM schemes to become part of common practice, allowing practitioners to gather lessons learned, which can influence future design and appraisal of schemes as well as governments' investment policies.

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