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Research article

Long-term coastal dynamics: The evolution of a mixed sediment mega-nourishment consisting of colliery spoil

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ABSTRACT

Mega-nourishments, where large volumes of sediment are deposited on coastlines, are increasingly employed to manage shoreline erosion, yet our understanding of their long-term behaviour is limited by the fact that most current schemes are less than 15 years old. However, on the County Durham coast, 39 million m^3 of coal spoil was tipped onto beaches between the late 1800s and 1993, acting as a de facto mixed sediment mega-nourishment. Our findings reveal key insights into the long-term dynamics of mega-nourishment schemes, including evidence of effective sediment dispersal around headlands into normally disconnected units of coast. Following cessation of tipping, shorelines retreated up to 12 m yr^{-1}, with 150 m overall retreat in 12 years. Subsequently, retreat slowed but the present-day shoreline remains seaward of its 1860 position and is subject to ongoing coastal recession. We document significant fining of the deposited material in the years post deposition through abrasion and chemical breakdown. Furthermore, we show that the highest erosion rates now occur downdrift from the initial dump site, indicating that nourishment impacts migrate through time. These findings highlight the need for holistic and adaptive management approaches to mega-nourishment schemes, showing the behaviour of the nourishment to continually change in both location and magnitude as the system evolves. We demonstrate that mixed sediment mega-nourishments can be a cost-effective and durable solution to mitigate erosive losses, even in the absence of a planned approach to the location or composition of deposited sediment. Our results suggest that lessons from this historical intervention can inform the design and management of future mega-nourishment schemes, particularly in mixed sediment environments.

1. Introduction

Artificial nourishment is a key tenet of coastal management on beaches undergoing sustained erosion or retreat. The addition of extra beach material is a means of increasing the volume of the beach, typically both building the useable subaerial area of the beach whilst also slowing or offsetting the net erosional trend at the location (De Schipper et al., 2020). Beach nourishment is often used in conjunction with other more traditional shoreline management methods, and usually involves a long term management plan that dictates semi-regular nourishments to ensure a minimum level of coastal defence and/or amenity is maintained (Hanson et al., 2002). As sea levels rise, more locations are seeing nourishment as a viable approach to manage erosion risk. The increasing pace of erosion, the requirement for larger volumes of sediment per site, and the greater number of potential nourishment sites means costs are increasing. In recent years, local authorities have therefore begun to consider mega-nourishments, with the aim of modifying the regional sediment budget over greater timescales (>10 years), rather than relying on smaller more regular nourishments (Arriaga et al., 2017; De Schipper et al., 2016, 2020; Johnson et al., 2020).

Mega-nourishments can be broadly defined as large-scale sediment interventions that result in either: (1) semi-permanent mega-

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nourishments whereby the intention is to alter the long term shape/width of the coast, possibly subject to ongoing smaller nourishments to achieve this aim; and (2) feeder mega-nourishments where the intention is that sediment is dispersed to provide protection over a wider area through time (Tonnon et al., 2018). The volume of sediment in a mega-nourishment varies widely depending on the aim of the nourishment, the location, and the planning timescales.

In the UK, one of the largest and longest running nourishment schemes is in Lincolnshire, where since the early 1990s over 17 million m^3 of sand has been added to beaches, involving the annual placement of around 500,000 m^3 of sand at key locations to maintain a specific standard of protection along the 26 km long frontage (Burgess et al., 2016). The first single-point mega-nourishment was that of the Sand Engine in 2011 in the Netherlands, consisting of a heavily localised 21.5 million m^3 one-off nourishment with a design life and utility of around 20 years (Stive et al., 2013), covering an area approximately 2.5 km alongshore and 1 km offshore. This has been recently followed by the Bacton sandscaping scheme in the UK, where 1.8 million m^3 of sediment has been used to protect critical infrastructure and villages on the Norfolk coastline (Clipsham et al., 2021), again with a predicted design life of between 15 and 20 years.

All these schemes relied heavily on numerical modelling and digital twins to predict behaviour over their intended life spans, as well as post implementation intensive monitoring. In the case of the Sand Engine, no other planned schemes worldwide were documented from which lessons could be learned. As such, our understanding of their morphological development into the future is still largely the result of numerical modelling efforts (Luijendijk et al., 2017). This is problematic, as modellers generally must strike a balance between computationally intensive models that account for many parameters over the short term, versus the need for understanding of the longer-term evolution of a system. For example, full 2D models over short timescales can account for many different processes and achieve good results but are computationally prohibitive over longer timescales. Conversely, simplified one-line models are computationally cheap meaning longer term prediction is possible, but they often overlook key processes such as feedback loops between morphological evolution and hydrodynamics, leading to inaccurate longer term predictions (Arriaga et al., 2017). We also encounter problems in understanding nourishments in complex sedimentary environments, such as composite or mixed sediment beaches. The collocation of these two sediment fractions in the beach matrix makes them some of the most hydrodynamically complex unconsolidated coastlines in the world, and standard process-response models that typically operate on either pure sand or gravel sediments are unable to provide meaningful information (Pitman et al., 2024).

The potential increased global uptake in mega-nourishment projects demands a better understanding of their long term dynamics. However, the fact that the first such mega-nourishment is only 14 years old limits our ability to empirically study their evolution over long timeframes (Arriaga et al., 2020). Additionally, existing mega-nourishment schemes have typically used sand, leaving a significant gap in our knowledge about the behavior of mixed sediment nourishment schemes, which are increasingly being considered for future coastal interventions. This study presents an innovative approach to addressing these gaps by analysing the evolution of an anthropogenic case study that mimics the long-term evolution of a mixed sediment mega-nourishment.

Specifically, we consider a 12 km stretch of coastline in County Durham, England, where tens of millions of tonnes of colliery spoil were tipped directly onto beaches by the late 1980s, creating an unintentional mixed sediment mega-nourishment. The sizing of the tipped sediments, a mix of gravels and sands (discussed further in Section 2), is analogous to mixed sediment beach nourishment and protection schemes elsewhere in the UK (Hanson et al., 2002), as well as New Zealand (Hart et al., 2020), the USA (Ramsey et al., 2017), and Spain (Bergillos et al., 2015), meaning we can use this case study to investigate the potential long term evolution of a mixed sediment mega-nourishment.

In this contribution, we aim to (1) quantify how sediment likely dispersed and to understand the longer-term diffusivity or persistence of these sediments over the last 35 years since spoil tipping ceased; and (2) identify lessons learned from this ad-hoc mixed sediment mega-nourishment to apply to planned schemes elsewhere. By presenting a unique natural experiment of large-scale sediment deposition, we provide both a novel data source and framework to enhance the design and prediction of future mega-nourishment schemes.

2. The County Durham coastline

The County Durham coastline between Seaham and Blackhall (Fig. 1) is dominated by Magnesian limestone. Prior to any anthropogenic activity, the natural state of many locations along the northern section of this coast in the 1800s would have been a cliffed coastline fronted by an intertidal shore platform. To the south, the limestone strata dips below the surface and from Crimdon Dene southwards the morphology transitions to wide sandy beach backed by an extensive dune system. The coast is macrotidal (spring tide range >5 m), with a mean significant wave height of 1.3 m and mean peak wave period of 7.5 s recorded offshore at the Tyne Tees wave buoy (www.wavenet.cefas.co.uk) in 66 m water depth (Fig. 3). Waves predominantly propagate from the north east down the North Sea, including during storms, as a result of west-east weather patterns across the Atlantic. Exceptionally, typically when low pressure systems travel south-north, this coastline experiences damaging waves approaching from a south easterly direction.

Between the late 1800s and 1993, spoil from the coastal collieries in County Durham was dumped directly onto the adjacent beaches (Fig. 1) as well as being taken by barge for dumping in nearshore waters. Beach tipping took a number of different forms including aerial flights (or conveyors) that deposit spoil just below the low water mark, or by direct tipping over the cliffs onto the subaerial beach (Cooper et al., 2017). Total quantities of spoil tipped are uncertain due to weak reporting requirements prior to the 1970s. A report by the Hydraulics Research Station (1970) estimated that by 1970, 40 million tonnes of solid waste had been tipped onto the County Durham coast. Various estimates exist from 1975 onwards (Fig. 4), all of which show an annual peak of between 2.5 and 3.1 million tonnes in 1983 before a large drop the following year because of the miners' strike. Amounts of solid waste were reported from 1975 onwards, but the Northumbrian Water Authority (NWA) conceded in 1988 that this failed to account for suspended solids contained within coal washery liquid effluent, which they estimated to average approximately 500,000 tonnes per annum over this period (Renouf, 1992). If we consider the Hydraulics Research Station estimate for pre-1970 (40 million tonnes), a conservative estimate of 6 million tonnes (1.5 million tonnes per year) for the data gap between 1971 and 1975, and the CEFAS record (Fig. 4) for 1975 onwards, we calculate that as a minimum estimate 70.8 million tonnes of spoil was tipped onto the County Durham coast between the late 1800s and the cessation of tipping in 1993.

Modern nourishments are typically reported in terms of volume rather than weight, and thus we must attempt to convert reported colliery weights to volume. Tipped spoil generally contained approximately 20 % coal and 80 % shale, with densities of c. 1300 kg m^3 and c. 2400 kg m^3, (Eagle et al., 1979; Hydraulics Research Station, 1970), and assuming porosity of ~30 %, we calculate spoil at the point of tipping to have a bulk density of around 1800 kg m^3. This compares to our own modern measurements of spoil bulk density along the coast of 1735 ± 221 kg m^3 based on sampling 19 locations. Posford Duvivier (1993) in their Durham Coastal Management Plan estimate bulk density to be 1500 kg m^3 although they do not qualify this estimate. Using this range of bulk densities (1500–1800 kg m^3), and based on 70 million tonnes being dumped, we estimate the volume of dumped spoil over this period to be between 39 and 47 million m^3 (Table 1). At the point of tipping, the spoil material consists mainly of gravel sized sediments (90 % > 2 mm),

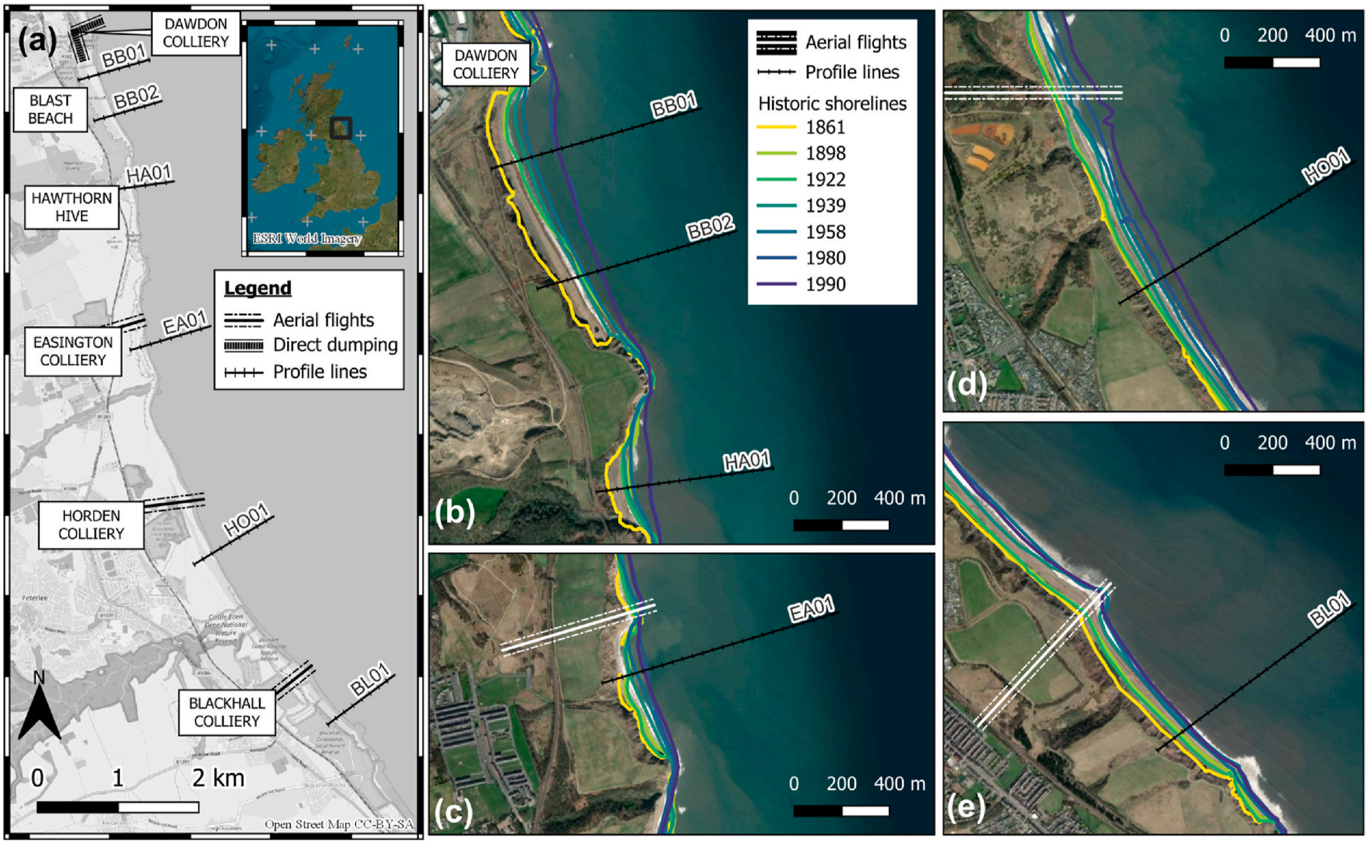

Fig. 1. (a) Overview of the County Durham Coastline with regard to colliery and spoil dumping locations. Historic shoreline mapping showing the general progradation of shorelines between 1861 and 1990 as a result of spoil tipping, with profile lines (b) BB01, BB02, and HA01; (c) EA01; (d) HO01; and (e) BL01 marked. These profile lines are used for further analyses throughout this paper.

Table 1
Available estimates for spoil density and the associated estimates for equivalent volume of tipped material on the County Durham beaches.

Spoil density estimates		Weight tipped	Estimates for volume tipped
Value (kg m^3)	Source	(millions tonnes)	(millions m^3)
1800[a]	Eagle et al. (1979); Hydraulics Research Station (1970)	70	38.9
1735 ± 221[b]	Present study		40.4 ± 5.9
1500[c]	Posford Duvivier (1993)		46.7

[a] Assumes 30% porosity.
[b] Based on sampling of 19 locations.
[c] No details provided for how this value was derived.

up to a maximum diameter of approximately 30 cm (Fig. 5). However, coal spoil is known to rapidly weather and abrade into smaller sizes (Kent, 1982; Kho and Williams, 2015).

In the current study we collected spoil from 13 sites along this stretch of coast for dry sieving using a sample tube with an outer diameter of 45 mm. The grain size accumulation (GS) curve shows that 45 years after Eagle et al.'s (1979) initial study, approximately 15 % remains larger than 2 mm but less than 45 mm (Fig. 5). Similarly to the Eagle et al. study, we also observed isolated clasts up to around 30 cm within the spoil platform. In addition to weathering as a control on this fining process, we can assume that the sizing of deposited sediments may have changed in the latter years of tipping as the coal washing process became more sophisticated and wastes were crushed to small sizes. It is estimated that of the quantity directly dumped, approximately 85 % was rapidly moved offshore by hydrodynamic processes and around 15 % of material remained on the beaches (Hydraulics Research Station, 1970). There has been one major initiative to remove some of the spoil on the beaches through the Turning the Tide project. This programme aimed to remove derelict structures, rubbish, and debris from the beaches, as well as 1.3 million tonnes of spoil from two subaerial heaps at Easington and Horden, thus preventing it from eventually ending up eroded by waves.

The result of these massive sediment inputs was a progradation of the coastline (Fig. 1). The northern half of coastline hitherto was largely segmented into defined embayments between rocky headlands with negligible headland bypassing of sediment. As spoil filled these embayments the headland control was removed and sediment was readily able to be transported alongshore in a southerly direction, meaning spoil began to accumulate in bays not directly impacted by tipping (Cooper et al., 2017; Nunny, 1978; Posford Duvivier, 1993). The largest changes were commensurate with proximity to tip sites, with the northern end of Blast Beach prograding by 300 m (profile BB01 in Fig. 1), but sites such as Hawthorn Hive (profile HA01 in Fig. 1) where no tipping occurred were still able to prograde by 200 m as a result of this new alongshore connectivity. The southern half of the County Durham coastline is open coast with little in the way of defined embayments, meaning any remaining spoil is rapidly transported south. At present, these beaches include an unconsolidated, mixed sediment lower beach up to the spring high tide mark, above which is perched a platform consisting of coal spoil (Fig. 2). The unconsolidated beach is active on tidal timescales, with cusps and berms often present, with the spoil platform typically eroded episodically during severe winter storms.

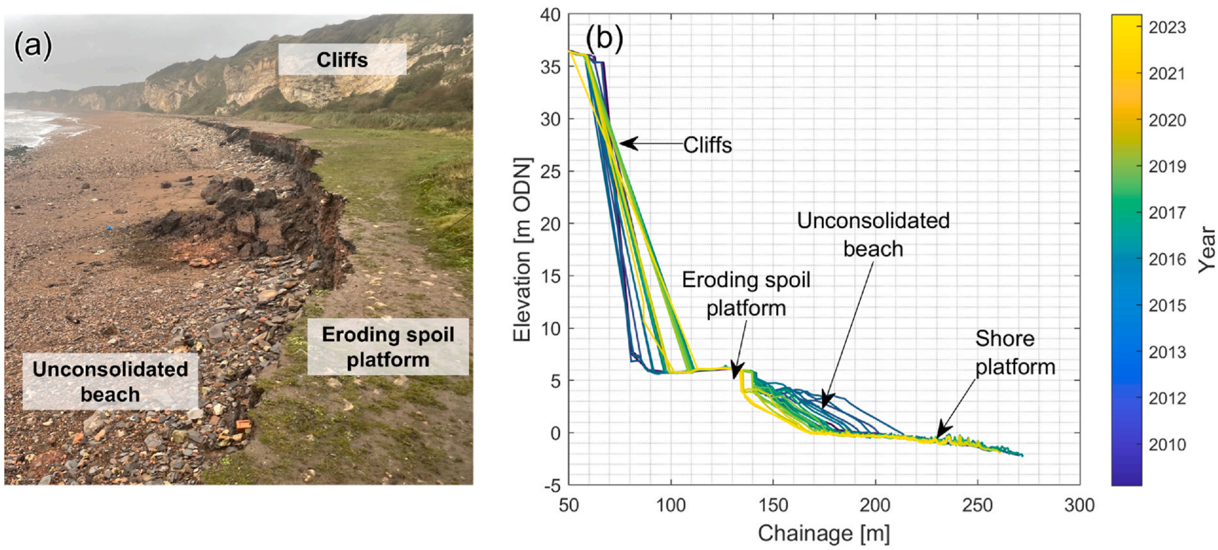

Fig. 2. (a) An image of the northern end of Blast Beach looking south after Storm Babet [October 2023], showing the eroding spoil platform. (b) Beach profiles from this same location between 2010 and 2023.

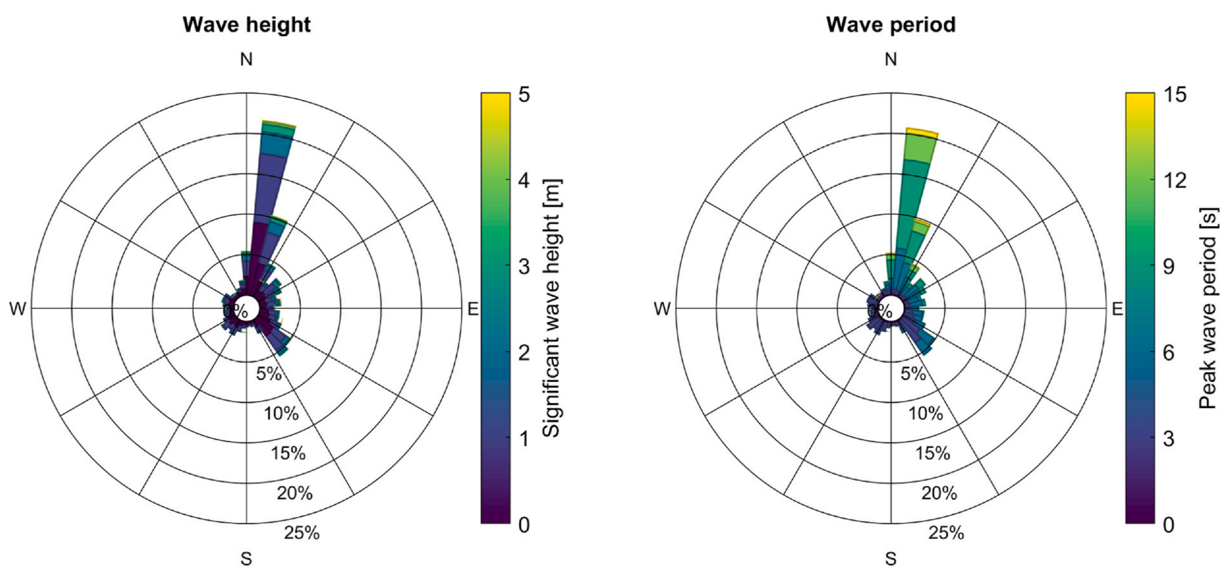

Fig. 3. Wave data from the Tyne Tees wave buoy (www.wavenet.cefas.co.uk) for the period 2006–2024.

3. Material and methods

3.1. Geomorphic change data

3.1.1. Shoreline position

Historical trend analysis of shoreline data in the absence of beach profiles prior to 1985 is accomplished through the digitisation of tide-lines on Ordnance Survey (OS) maps, and has previously been applied to this location by Cooper et al. (2017) to show shoreline advances during tipping. OS surveyors from 1880 onwards used tidetables to identify suitable observation epochs in order to annotate the low and high water marks of ordinary tides on maps, and have applied a consistent approach thereafter. Errors in recorded shoreline position as on steep beaches such as those on the County Durham coast could be in the range of 10–20 m (Sutherland, 2012), however, the magnitude of change observed is on the order of 200 m and thus this is deemed an appropriate signal to noise ratio to demonstrate changes at this location.

In the absence of beach profile data, accounts of retreat post cessation of tipping are largely anecdotal. Some early monitoring in the 1990s showed erosion of around 20 m per year at individual profile sites (such as Blast Beach), but by the time regular profiling in the area commenced in 2007, much of the rapid erosion had slowed to < 2 m per year (Cooper et al., 2017). Therefore in order to quantify the retreat along the County Durham coast, we employ the CoastSat toolbox (Vos et al., 2019) to detect changes post 1980 using Landsat (30 m resolution) and Sentinel (10 m resolution) satellite imagery in a user-defined region of interest. This toolbox uses supervised image classification to create regions (e.g. white water, sand) with sub-pixel border definition, and typically results in shoreline detections that have an accuracy of around 10 m. The user supervision allows images with high cloud cover, or where shoreline detection is absent or erroneous, to be rejected. The number of quantitatively useful images varied per site but typically resulted in c. 300 images available for the construction of a time series. Unfortunately, due to combinations of poor image quality and/or georeferencing, data is very sparse between 1990 and 1995, but fortunately sufficient points are available before and after this period to infer a trend.

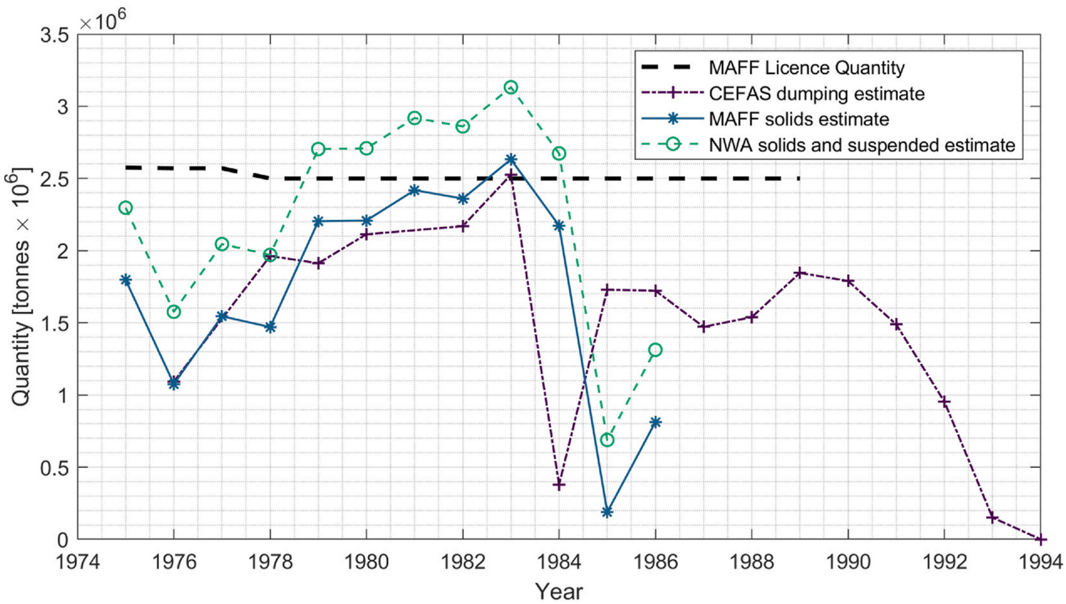

Fig. 4. Estimates of the waste quantities dumped on the County Durham coastline between 1975 and 1994. The black dashed line shows the Ministry of Agriculture, Fisheries and Food (MAFF) licenced dumping quantities. The Centre for Environment, Fisheries and Aquaculture Science (CEFAS) estimates are as reported in Cooper et al. (2017). The MAFF solids estimate is taken from a letter from MAFF to a local MP, as reported in Renouf (1992). The Northumbrian Water Authority (NWA) acknowledged that there was likely around 25 % dry solids in liquid effluent from coal washeries on the County Durham coast, and postulate that on average this equates to approximately 500,000 tonnes per year, also reported in Renouf (1992). Thus, the NWA estimate is a combination of the MAFF solids estimate plus this adjustment for suspended solid inputs.

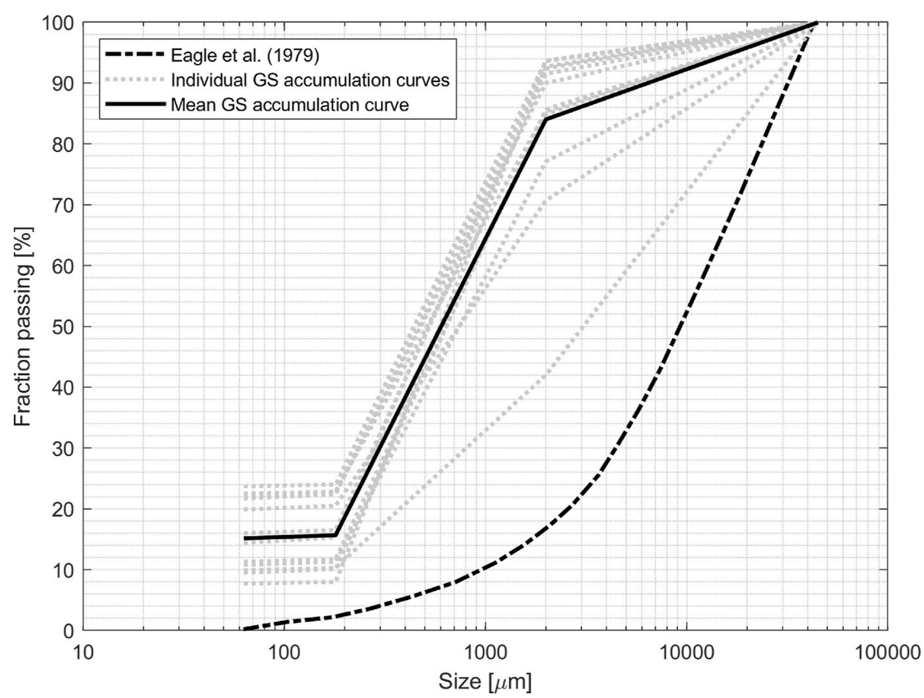

Fig. 5. Grain size accumulation (GS) curves for colliery spoil. The dashed black line represents the GS curve reported in (Eagle et al., 1979) and is considered representative of coal spoil immediately post dumping. The solid black line is a representative GS curve based on the mean of 13 samples taken at locations along the County Durham coast between Blast Beach and Blackhall in 2024.

3.1.2. Bathymetric data

The 1998 bathymetry is derived from a single beam echosounder survey undertaken on behalf of the UK Hydrographic Office and was reduced from Chart Datum (CD) to Ordnance Datum Newlyn (ODN). The 2010 and 2018 bathymetry were derived from multibeam survey commissioned by (the then) Scarborough Borough Council (now part of the unitary North Yorkshire Council) in support of the regional coastal monitoring programme, and data were again reduced from CD to ODN. With the exception of the 2010 survey, bathymetric coverage extends for 12 km from Seaham in the north to beyond Blackhall Colliery in the south and extends for approximately 2 km offshore down to the 15 m ODN depth contour. The 2010 survey consists of a single transect offshore from Blast Beach. Full extents of all surveys are shown in Fig. 7.

3.1.3. Topography

Data from the Cell 1 Regional Coastal Monitoring Programme (https://www.northeastcoastalobservatory.org.uk/) were used to assess topographic changes since 2009. This data primarily comprises beach profile data, and the transects BB01, BB02, and HO01 in the present study (Fig. 1) have been selected to coincide with locations where beach profile data are available. Beach profiles were typically conducted at 6 monthly intervals at these locations throughout the monitoring period and therefore demonstrate both the seasonal variability in geomorphology, but also the progressive retreat of the coal spoil platforms. Aerial LiDAR imagery is available at approximately 2 yearly intervals for the entire stretch of coastline at 1 m resolution. The 2 year sampling epoch means seasonal and event driven changes are harder to capture but long term trends such as coal spoil erosion are evident, with data available for any location along the coast.

4. Results

4.1. Shoreline retreat

Based on evidence from the historical OS mapping and satellite data, rapid shoreline retreat occurred immediately post-cessation of tipping at sites proximal to tipping sites (Fig. 6). Profile BB01 is collocated with the Dawdon tip site and retreated 150 m over the 12 year period between 1988 and 2000, with an initial retreat rate averaging 12.2 m yr^{-1} (Table 2), resulting in a shoreline position that was approximately 50 m offshore of the 1860 shoreline position. The shoreline appears to prograde by around 50 m between the years 2012 and 2020, however, it should be noted that this is a progradation of the land-water interface (i.e. changes in the unconsolidated beach) and is distinctly different from the erosion and retreat of the subaerial coal platform. This is an important differentiation because the coal platform is a typically subaerial feature at +3 to +5 m ODN elevation, and therefore only acted on by the highest tides (Fig. 2). The platform can only retreat (i.e. the scarp in the semi consolidated spoil material may only move landward), whereas this method looks at the land-water interface, and thus accounts for accumulation or erosion of unconsolidated sediments lower down on the beachface.

At the southern end of Blast Beach, 500 m south of BB01, profile BB02 experienced a smaller overall change retreating by around 60 m (Fig. 6) at a rate of 5.4 m yr^{-1} between 1988 and 2000. The smaller retreat distance at BB02 corresponds with an overall smaller advance (190 m) during the preceding years than when compared to BB01 (250 m). With Dawdon being the most expansive tipping site associated with the largest spoil volumes along the County Durham coast, generally the shoreline response at other locations is more muted, with a few notable exceptions. Hawthorn Hive (profile HA01) indirectly receives sediment from Dawdon but relies on spoil being transported around a headland and therefore the response of this profile is delayed, reflecting the lag time associated with transport of spoils. All data to 1990 shows progressive advance at HA01, whereas BB01 and BB02 both showed retreat from 1988 onwards. When data availability returns in 1997, the coastline has retreated around 80 m (Fig. 6) at a rate of around 4.9 m yr^{-1} (Table 2). Approximately 40 m of further retreat is observed by 2010,

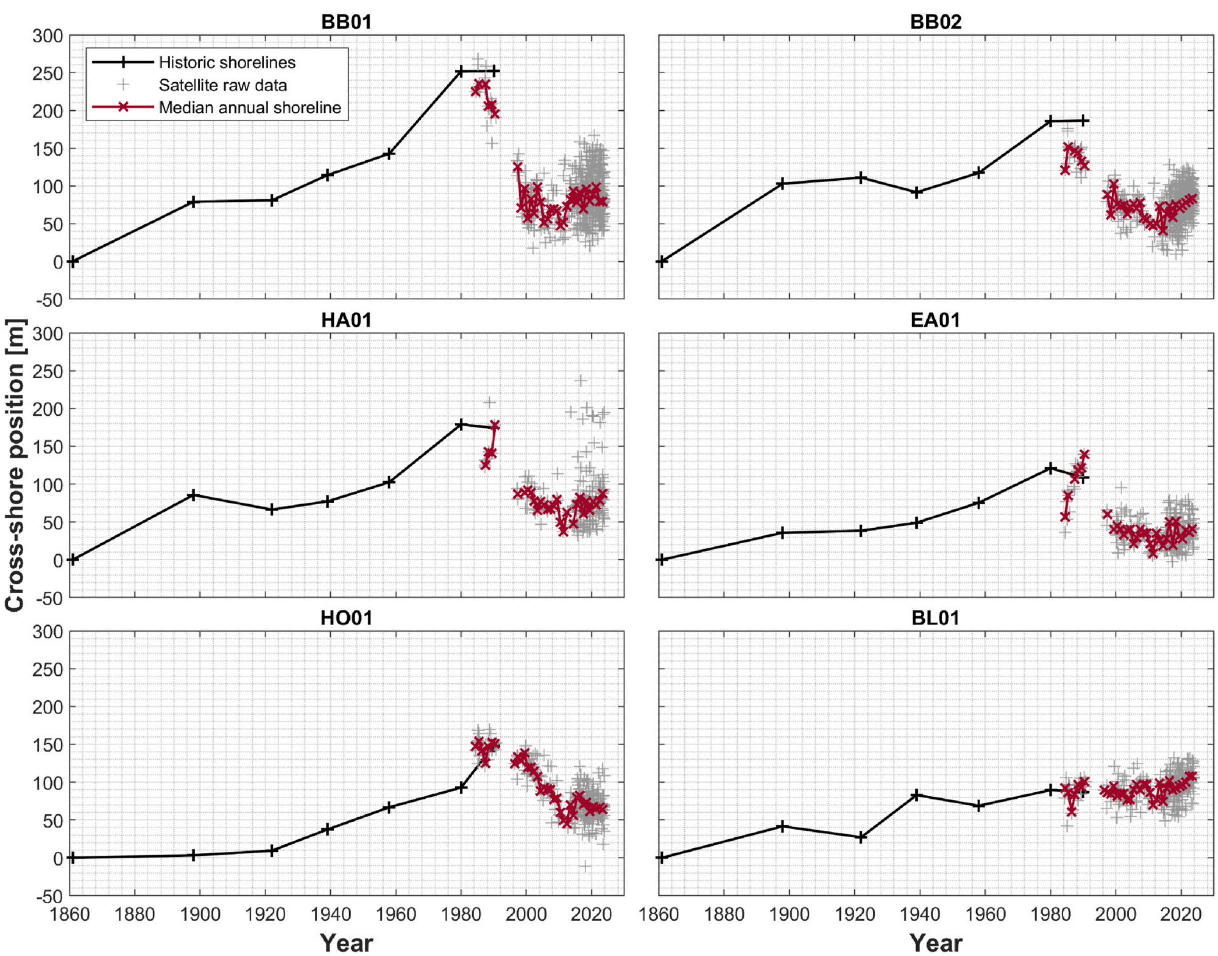

Fig. 6. Relative shoreline change along each profile line from 1860 to 2024. Shoreline progradation between 1861 and 1990 is derived from tide lines on historic maps; changes from 1982 onwards have been derived from satellite imagery. The raw satellite data is plotted in the background, with median annual shorelines in bold in the foreground.

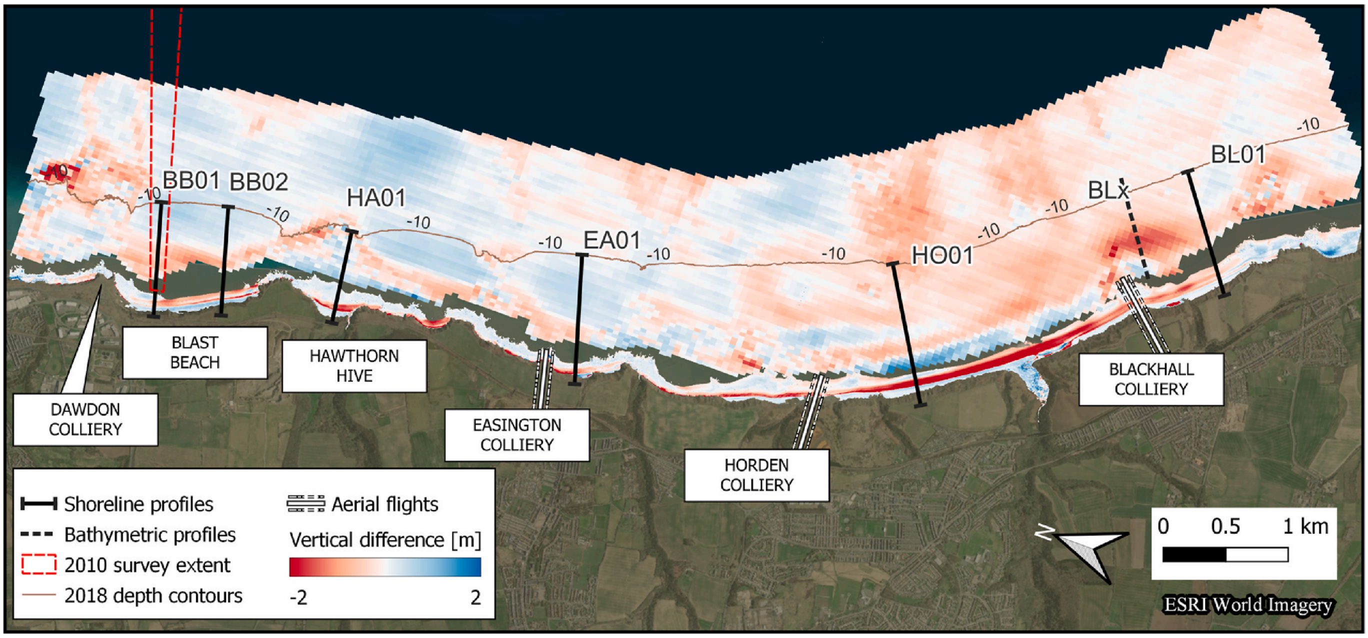

Fig. 7. Bathymetric changes along the County Durham coastline between 1998 and 2018 and LiDAR derived topographic changes for the period 2010–2021. Contour lines through the bathymetric data are taken from the 2018 survey and have been reduced to Ordnance Datum Newlyn. A small section of additional bathymetry is available for 2010 and used elsewhere in this paper for analysis, and the extent of that bathymetry is marked here.

Table 2
Initial annualized retreat rates for each profile line following cessation of tipping at the nearest updrift disposal point.

Profile	Tipping ceased	Initial Annual Retreat Rate [m yr^{-1}]	Time period
BB01	Dawdon (1987)	12.23	1988–2000
BB02	Dawdon (1987)	5.35	1988–2000
HA01	Dawdon (1987)	4.87	1988–2000
EA01	Easington (1993)	6.45	1990–2002[a]
HO01	Horden (1984)	1.36	1984–2000[b]
BL01	Blackhall (1974)	−0.3	1984–2023

[a] Tipping did not cease until 1993, but no data is available, hence the last available data point (1990) has been used in this calculation.
[b] Initial rate of retreat not representative of maximum. Retreat of 2.92 m yr^{-1} recorded between 1989 and 1998.

followed by 30 m of accretion in the years to 2024. Easington (EA01) recorded the second highest rate of retreat (6.5 m yr^{-1}) between 1990 and 2002 although this is likely underpredicted as tipping did not cease here until 1993 but data are not available for 1991–1996. Horden's (HO01) initial retreat was only 1.4 m yr^{-1} between 1984 and 2000, but this was temporally variable with a maximum rate of 2.9 m yr^{-1} observed between 1989 and 1998 (Table 2). The only location where tipping ceased before the satellite shoreline tracking data was available was Blackhall, where tipping ceased in 1974. At this site, steady progradation has been observed (0.3 m yr^{-1}) over the entire period.

4.2. Bathymetric change

Nearshore bathymetry for the 11 km stretch of coastline between Seaham and Blackhall shows overall subaqueous sediment losses of 1.5 $\times$ 10^6 m^3 between the years 1998 and 2018 (Fig. 7). This equates to an average 135 m^3 of sediment lost per 1 m width of beach in this area. Losses of nearly 1 $\times$ 10^6 m^3 occur shoreward of the 2018 10 m contour line (90 m^3/m). The relative loss and gain of sediment is spatially variable, with most sediment lost from the southern half of the study area encompassing Horden and Blackhall collieries, totalling 2 $\times$ 10^6 m^3 (equating to 358 m^3/m). The main areas of erosion are all south of primary tipping points, with the area offshore of Blackhall Colliery aerial flight experiencing 2 m of erosion over the period (Fig. 7). When individual profiles are considered (Fig. 8), it becomes clear that the main change is a transition from convex to concave profiles. Much of this change occurs around the 4–5 m depth contour, with all profiles except HA01 experiencing some landward retreat at this depth. BB01 benefited from one additional bathymetric profile in 2010, and this shows very little change between 2010 and 2018. Thus, we can infer in this location at least that most of the change observed had occurred over the first 12 years. The largest change occurs directly offshore from the historic location of the Blackhall Colliery aerial flight (BLx), where a total of 332 m^3/m has been lost from above the 10 m contour line (Fig. 8).

4.3. Topographic change

Subaerial changes along this stretch of coastline are dominated by erosion and the net change in subaerial sediment volume over the period 2010 to 2021 is −363,000 m^3 (Fig. 9a). This equates to 33 m^3 per metre frontage of beach, although the erosion is heavily concentrated in areas where colliery spoil platform is being eroded such as Horden, Blast Beach and Hawthorn Hive (Fig. 9b), where individual profile lines have lost in excess of 150 m^3/m. Hawthorn Hive and Shippersea Bay have both lost 80 m^3/m despite neither location being directly impacted by spoil dumping. Accretion is predominantly concentrated outside of the colliery coast (i.e. north of Blast Beach, and south of Blackhall), with profiles in the southern part gaining in excess of 100 m^3/m of sediment. In areas experiencing an overall loss of sediment volume, the 0 m elevation contour is generally retreating (Fig. 9c), but this is not as widespread as retreat in the +2 m elevation contour (Fig. 9d). One key example of this is Hawthorn Hive, where we see a narrow band of profiles in the centre of the bay exhibiting retreat of the 0 m contour (Fig. 9c), but much more widespread retreat of the +2 m contour throughout the bay (Fig. 9d). The erosion of the +2 m contour is an important metric here as it represents the height at which most colliery spoil is now perched, and therefore retreat in this contour can be inferred to represent erosion of the spoil platforms. Where locations are experiencing volumetric losses, we observe good correlation with retreat in both the 0 m (Fig. 10a, R^2 = 0.72) and +2 m (Fig. 10b, R^2 = 0.81) contours. There is wide variability in the behaviour of the 0 m contour at

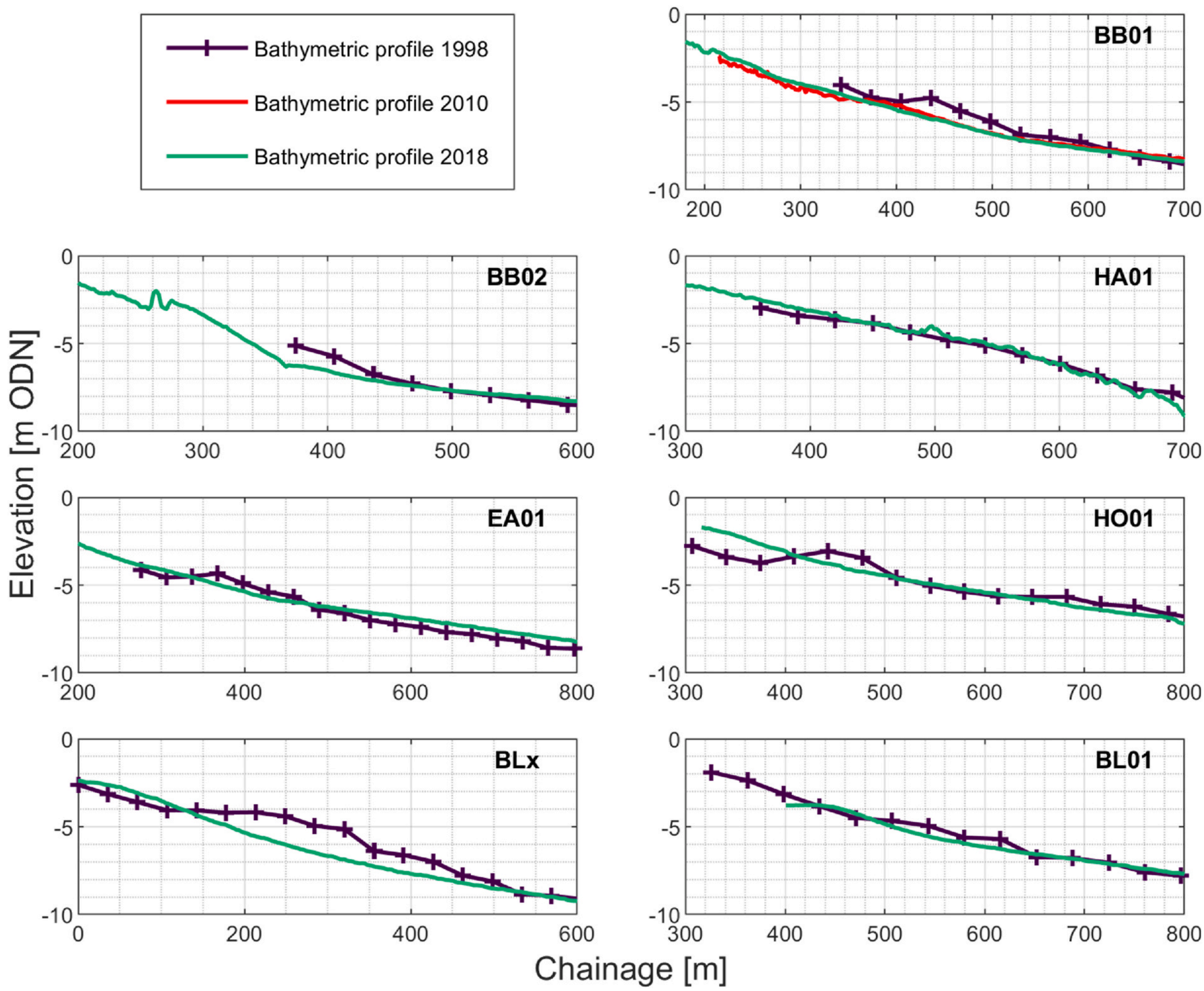

Fig. 8. Bathymetric elevation along each profile line for 1998 and 2018. Note that profile BB01 benefits from one additional bathymetric survey conducted in 2010 and shown here.

sites where volume has either been maintained or increased, evidenced by the scatter that becomes apparent in Fig. 10a. The largest volumetric losses are concentrated at the southern end of the study area. On profiles that have experienced the largest volumetric gains, there has typically been a larger progradation in the 0 m contour than the +2 m contour (Fig. 10c). Fig. 10c also shows wider variability in the behaviour of the 0 m contour with 61 % of profiles showing retreat (mean −4.4 m, median −4 m, standard deviation 11.8 m), compared to 74 % of profiles showing retreat at +2 m elevation (mean −6.5 m, median −6 m, standard deviation 9.0 m).

Horden is an identified hotspot for volumetric losses (Fig. 11a), and this area alone has lost 326,000 m^3 of sediment, resulting in an average loss of 109 m^3/m of subaerial beach between 2010 and 2021, with maximum losses on this stretch reaching 170 m^3/m. Comparing the intervening LiDAR surveys shows change in the unconsolidated beach to be spatially variable with storm events causing erosion of the lower beachface and rotation with the embayment (Fig. 11b). However, despite this spatial heterogeneity in erosion and accretion of the beachface, a thin line of erosion is consistent across all surveys, even when the wider dominant response is one of accretion, and this represents the front of the spoil platform. Beach profile surveys demonstrate a 38 m landward retreat (2.7 m yr^{-1}) in the seaward position of this coal spoil platform between the years 2009 and 2023 (Fig. 11c). As the spoil erodes, most sediment is lost from the profile but there is evidence of some roll over, with the upper beach elevations accreting over time, increasing the slope angle, and creating a more pronounced slack at the back of the beach (Fig. 11c, chainage 130–160 m). The spoil platform retreat is continuous but does experience magnitude fluctuations, with a peak of 8.6 m retreat between 2009 and 2010, followed by several years of sub-metre retreats, and then 4.5 m and 6.0 m between 2020/2021 and 2021/2022, respectively (Fig. 11c).

At Blast Beach (Fig. 12a) the most significant erosion over the monitoring period is observed in the spoil platform at the southern end of the beach. The signal of beach rotation is evident on shorter timescales in the LiDAR data (Fig. 12b), but as was the case at Horden, spoil platform erosion still occurs along the profile even in years where erosion dominates. The higher temporal resolution of the beach profile data aids our understanding of the processes at this site. Profile BB01 has not seen discernible erosion of the spoil platform, but instead this profile is characterised by periods of both erosion and accretion of the unconsolidated sands and gravels that make up the beach fronting the spoil platform (Fig. 12c). The fronting beach has at times prograded by as much as 28 m seaward at the 0 m elevation contour but is currently 10 m landward of its position in 2008. Conversely, the most evident change in profile BB02 in the south is a 20 m retreat in the +4 m elevation contour (Fig. 12d), followed by a 5–10 m readvance of unconsolidated sediments. At the same time, the elevation of the back beach environment has increased by upwards of 1 m as unconsolidated sediments have been transported over the top of the spoil platform and now cover it. The 0 m elevation contour in the south eroded by 36 m between 2008 and 2014, but since the end of 2016 has remained largely stable, 20 m landward of its previous 2008 position.

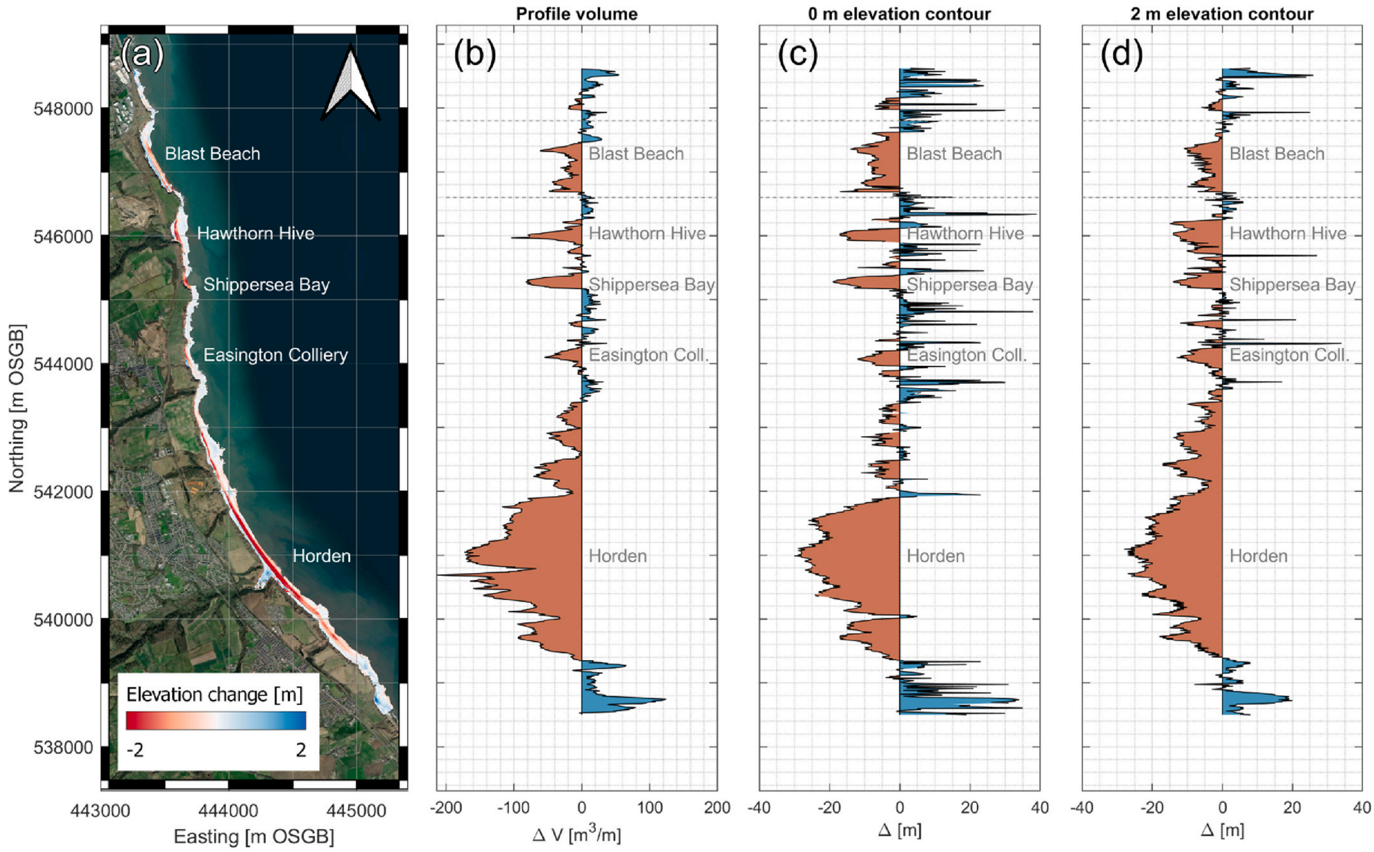

Fig. 9. Topographic change between 2010 and 2021 from aerial LiDAR, including (a) raw elevation change; (b) profile volumetric change; and horizontal displacement of the (c) 0 m and (d) 2 m elevation contours.

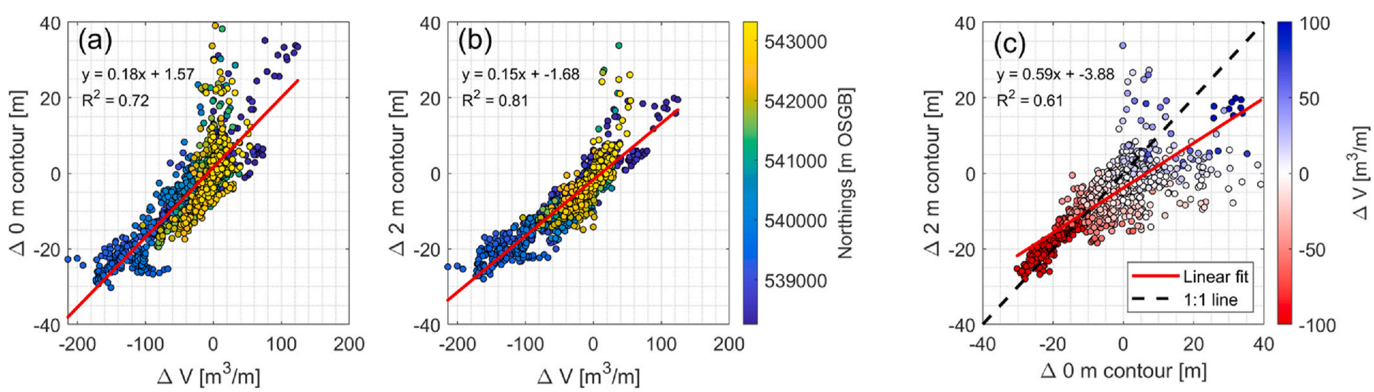

Fig. 10. Relationship between beach volumetric change and (a) advance or retreat in the 0 m elevation beach contour; and (b) advance or retreat in the 2 m elevation beach contour. (c) Relative changes between the 0 and 2 m elevation contours as a function of overall volumetric change.

To provide context to these results, we also briefly consider changes occurring updrift of the areas that were impacted by coal spoil. The nearest monitoring site is Sunderland and Ryhope (Supplementary Material–Figure S1), where two profiles exist for comparison. At these locations, the beach is backed by a cliff and all beach elevations between 0 and 4 m ODN have seen around 10 m of retreat between 2009 and 2023, which corresponds to the rate of cliff retreat. This is less than half the rate observed at the Southern end of Blast Beach, and around a quarter of that observed at hotspots on Horden beach.

5. Discussion

In recent years coastal mega-nourishments have been implemented as a means of offsetting coastal erosion, increasing beach amenity, and reducing overall costs when compared to traditional nourishments (De Schipper et al., 2020; Hanson et al., 2002). However, we have not yet observed the full life cycle of any single mega-nourishment project, and therefore we remain limited to numerical modelling to understand their long term behaviour (Arriaga et al., 2020). Here we assess the 130-year evolution of the County Durham coastline where the addition of 39 million m^3 of colliery spoil during the 20th Century serves as an analogous case study to a mega-nourishment project. In examining this long-term coastal response, we can elicit valuable insights into the extended impacts and efficacy of potential mega-nourishments and provide learnings for future such schemes.

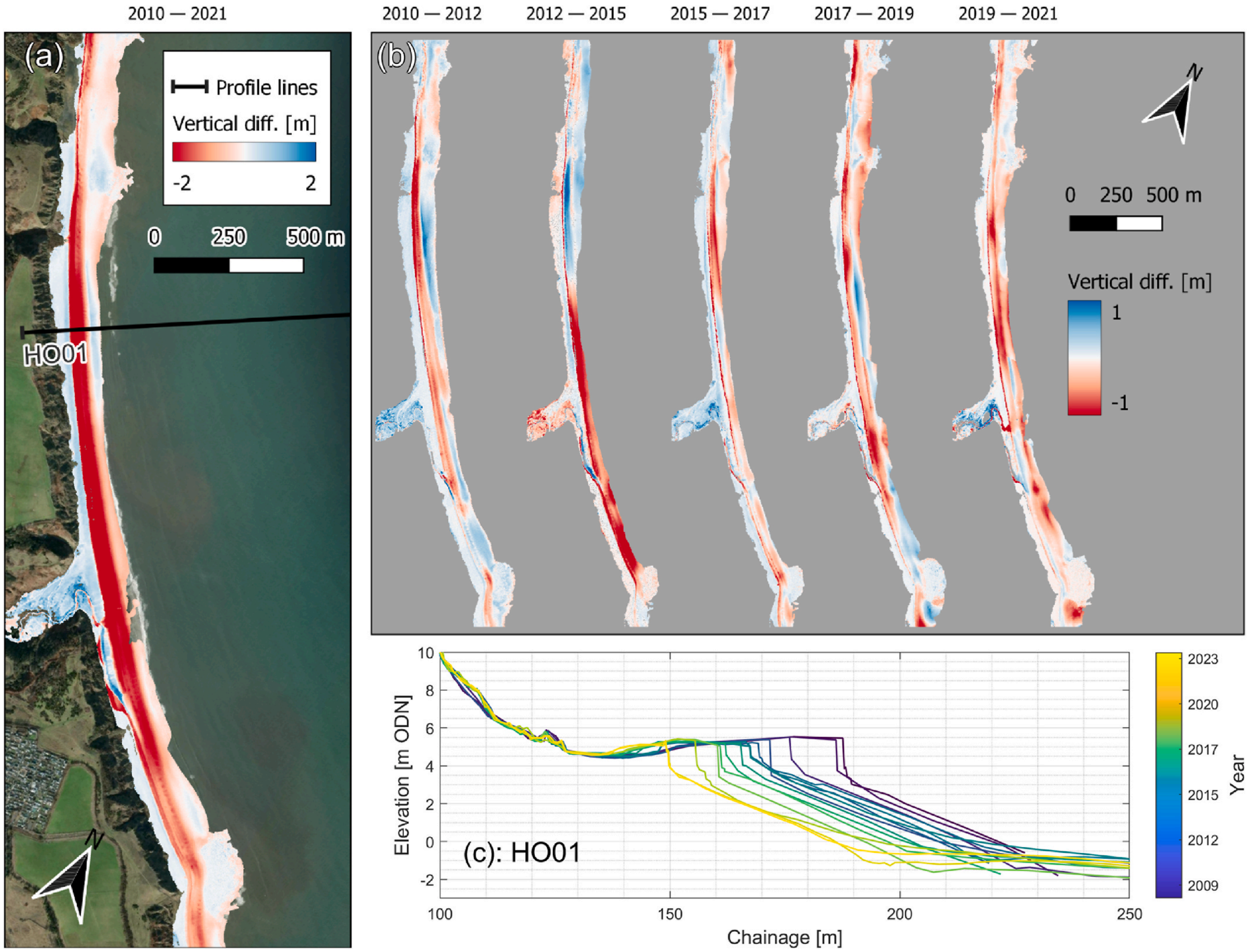

Fig. 11. (a) Overall topographic change at Horden over the period 2010–2021, with one profile line marked. (b) Topographic change between consecutive LiDAR surveys for the same extent. (c) dGPS-derived beach profiles, typically measured twice per year over the period 2009–2023 for profile HO01.

5.1. Long term stability and efficacy

A key concern for coastal managers in determining whether mega-nourishment is a viable strategy is the long term efficacy of the intervention (Brown et al., 2016). There are two key types of mega-nourishment: (1) (semi) permanent mega-nourishments whereby the intention is to alter the long term shape/width of the coast and maintain a certain standard of protection, possibly subject to smaller nourishments to achieve this aim; and (2) feeder mega-nourishments where the intention is that sediment is dispersed to provide protection over a wider area through time (Tonnon et al., 2018). The County Durham coast is an example of a feeder nourishment as significant coastal morphological change occurs at sites not directly nourished. Initially, the shoreline closest to nourishment locations prograded fastest and furthest, with Blast Beach prograding by 250 m, but over time the effect of nourishment has widened. Now, 30 years post-cessation of tipping, the shoreline is still seaward of the original 1860 mapped position in most locations. This exceeds the design timescale of projects like the Sand Engine, where modelling suggests that after around 25 years additional nourishments would be required to maintain the coastline (Mulder and Tonnon, 2010). Beaches within the former colliery areas continue to provide natural capital such as localised storm protection and recreational amenity that are often the central tenet of planned nourishment schemes (Qiu et al., 2020). At Blast Beach and Hawthorn Hive, the limestone cliffs at the rear have been inactive from marine processes since the late 1800s as a direct result of the spoil tipping. Now, in the medium term, coastal managers will have to start considering what impact reactivation may have on critical infrastructure such as the railway line which is situated at the cliff edge behind Hawthorn Hive, and what future management, such as planned nourishments, might be required.

One significant change observed at this location is the fining of sediments from their initial deposition size to that which is present today (Fig. 5). In the 45 years since initial measurements were taken, the fraction of spoil sized above 2 mm has reduced from 85 % to 15 %. This is largely due to the nature of the tipped material – the shale in the waste is highly reactive and prone to both physical and chemical weathering in situ. Even in relatively inert inland environments where subaerial processes are the only geomorphic agent, rapid fining of coal spoil has been observed. Down (1975) showed that after 20 years, the top 20 cm of spoil on an inland heap had fined from ~75 % > 2 mm to between 40 and 70 % > 2 mm, dependent on depth. Normally, the coarse material used in beach nourishments would consist of more inert gravels such as those taken from offshore extraction areas, but as demand has increased, the use of "as dug" materials (i.e. unsorted waste materials not required by construction due to incorrect sizing, or crushed rock) has increased (Hanson et al., 2002). This is true of some schemes such as the artificial bund designed to prevent inundation at Amberley Beach, New Zealand,

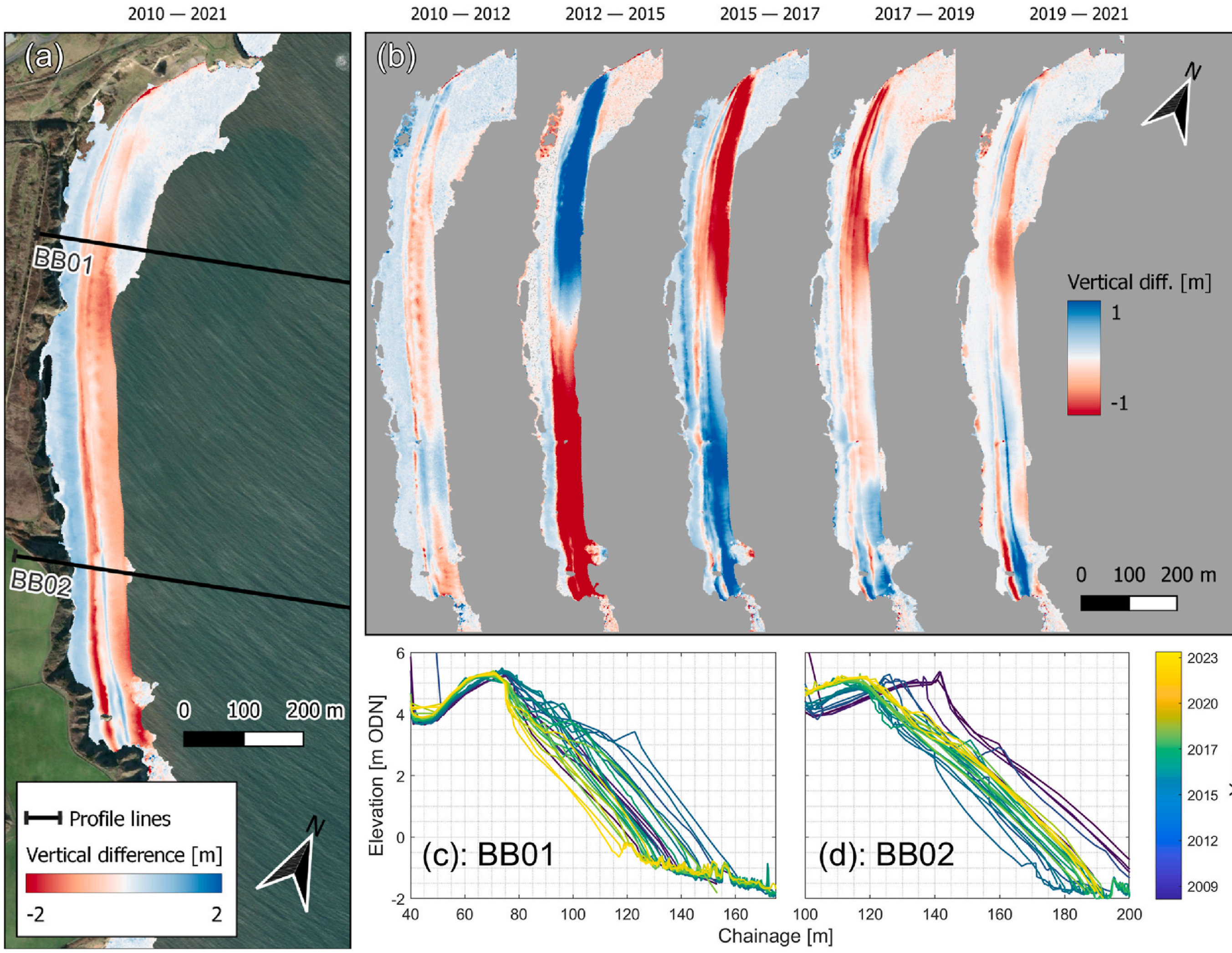

Fig. 12. (a) Overall topographic change at Blast Beach over the period 2010–2021, with two profile lines marked. (b) Topographic change between consecutive LiDAR surveys for the same extent. (c–d) dGPS-derived beach profiles, typically measured twice per year over the period 2009–2023 for profiles BB01 and BB02, respectively.

where initially low cost quarry by-products were used to construct a high tide sacrificial bund to manage inundation risk (Pitman et al., 2024). This demonstrates that whilst such sediments may be useful for semi-regular nourishments where the material is regularly replenished, a key consideration in mixed sediment mega-nourishments is the rate at which sediments weather or abrade to sizes too fine to provide adequate protection. On the County Durham coast, as the spoil platform erodes, 85 % of the material released onto the active beach or into the nearshore is coarse sand or finer, meaning it now provides significantly less hydrodynamic protection than it would have done at the point of tipping.

5.2. Sediment transport and distribution

The long-term stability of the nourishment on the County Durham coast is in stark contrast to the short-term instability associated with initial sediment transport and distribution pathways. In terms of sediment transport pathways, 85 % of the sediment tipped on beaches was thought to rapidly move offshore during the nourishment phase (Hydraulics Research Station, 1970), although ‘offshore’ is not defined further. This is typical in situations whereby nourishment is predominantly subaerial as the resulting beach profile is oversteepened, and thus subject to rapid offshore transport during the first few months as the beach profile attempts to adjust towards equilibrium (De Schipper et al., 2020). The changes post-nourishment on the County Durham coast were rapid and substantial, with BB01 eroding 150 m, representing an average rate of 12.2 m yr^{-1} between 1988 and 2000. This has also previously been explained in terms of the compaction of sediments, with those at the back beach being older and more compact due to mechanical (bulldozer) compression, with those at the front of the beach typically being less consolidated (Cooper et al., 2017). This shift from unnatural convex profiles, associated with nearshore deposition, towards more natural concave profiles was evident in the bathymetric data along the County Durham coast between 1998 and 2018 (with some evidence at Blast Beach showing this change was complete by 2010). This bathymetric analysis also showed that most volumetric changes were constrained to depths less than 10 m ODN, which is in keeping with findings for the Sand Engine (Roest et al., 2021), and fits with estimated inner closure depth of 11.8 m predicted by the Hallermeier (1980) equation based on extreme waves at the Tyne Tees Wave Buoy (Fig. 3). However, the County Durham example highlights that mega-nourishments need to monitor more than simply morphodynamic and volumetric change, as there is evidence of significant negative ecological change such as smothering, habitat destruction, and increased turbidity at greater depths offshore of the collieries resulting from both direct offshore dumping and transport from subaerial dumping grounds (Eagle et al., 1979; Johnson and Frid, 1995).

On the beach itself, the erosion created severe scarps which have become a signature of the coal platform on the County Durham beaches.

This occurs when waves attempt to erode the beach back towards an equilibrium profile but are unable to overtop the nourished material (Van Bemmelen et al., 2020). On this coastline, the nourished material is emplaced at elevations up to 4 m ODN, and so is only very infrequently overtopped by waves. At the southern end of Blast Beach, alongshore transport has resulted in the accumulation of gravels in front of the spoil platform, and these now act as a ramp for wave action and as a result we observe increases in elevation on the back beach, and the removal of the beach scarp in favour of a more natural beach profile. Elsewhere, on open coast settings such as Horden where there is no headland to trap sediments, the beach in front of the scarp has not gained volume, and thus the whole profile shape has been maintained but has retreated landward. The additional complicating factor on the County Durham coast is the chemical processes at work within the spoil, meaning the platform is semi-consolidated by leaching of pyrite-rich spoil and secondary mineral formation (e.g. iron oxyhydroxides) creating a clay-like matrix infilling gaps around larger clasts, which requires more wave energy to erode (Cooper et al., 2017). Further, the heterogeneous nature of the deposited material on the County Durham coast means that erodibility can change over time as new natures of waste are exposed (Riley et al., 2022).

In terms of planform evolution, mega-nourishments have to account for the fact that it may be many years before downdrift sites receive tangible benefit from the nourishment in terms of volumetric gains and protection from storms (Stive et al., 2013). At the Sand Engine, modelling appears to suggest that locations just 3 km downdrift of the main nourishment would not see meaningful shoreline progradation for at least 20 years post nourishment and beyond 4 km downdrift very little benefit is derived at all (Ribas et al., 2023). Nourishments like the Sand Engine are on straight sandy beaches where longshore connectivity is guaranteed, but hitherto we have no field example of the longshore diffusivity of nourishments on complex, rocky, embayed coastlines. Progradation and accumulation of sediment in Hawthorn Hive and Shippersea Bay shows that mega-nourishment can be a viable option on complex, embayed coastlines. There was a slight lag time in this system, whereby first the Blast Beach shoreline had to prograde sufficiently to enable sediment bypassing of the headland (Cooper et al., 2017), but once this was achieved the magnitude of changes at HA01 were comparable to those of BB01 and BB02 which benefited from direct connectivity to the nourishment location.

5.3. Policy recommendations

The insights gained from studying this mixed sediment, colliery spoil mega-nourishment provide for several recommendations for the design and management of future mega-nourishment schemes. Firstly, in consideration of the longevity of a mixed sediment mega-nourishment, the rapid weathering and fining of sediments observed in this setting shows that particular attention must be paid to sediment mix, and such schemes may require additional coarse sediments to be added later to offset this effect and maintain good level of hydrodynamic protection. Second, it is crucial to account for lags in sediment transport on complex embayed coastlines, but we provide evidence of the timescales over which nourished sediment might typically be transported along the coast into neighbouring embayments. Finally, a dynamic adaptive pathways planning approach is useful for the monitoring and management of mega-nourishments. In the current study, we highlight how in some areas the level of protection has been degraded to such an extent that soon cliffs are likely to undergo reactivation by marine processes. Events such as this should be incorporated to management planning as ‘triggers’ for a change in approach or a remedial action, such as the requirement for follow-up targeted nourishments or switches in longer term management approach.

6. Conclusions

The County Durham coast illustrates how mega-nourishments can provide long lasting benefits in terms of coastal protection and socio-economic enhancement. Through an examination of the extended impacts and morphological behaviour of spoil tipping we gain critical insights that can inform the design and implementation of future mega-nourishments. The County Durham coast is an example of a mega-nourishment on a complex coastline comprising cliffs, embayments and varying lithologies which is in stark contrast to the typically straight sandy coastlines on which other planned mega-nourishments have taken place. This demonstrates the capacity of a mega-nourishment to feed disconnected elements in the coastal system such as neighbouring bays via sediment bypassing, and crucially gives insight into the timescales associated with this change. The initial phases, 10–12 years post nourishment, show rapid morphological change in both profile and planform, before a transition into longer term stability in the coastal zone, and a slower more regular rate of volumetric loss from the nourished material. This highlights the need for holistic and adaptive monitoring and management that can adapt to capture both initial rapid changes and the longer term diffusive behaviour. Despite the heavily contaminated nature of the sediments used and the negative impacts of these contaminants, the prograded beaches on the County Durham coast have, from a purely morphological standpoint, afforded protection to the abandoned coastal cliffs from marine processes for over 100 years. Now, as the nourished volume of sediment begins to disappear, coastal managers should begin to plan for the management of potential problem areas, such as the reactivation of cliffs fronting the railway at Hawthorn Hive. The County Durham coast demonstrates mixed sediment mega-nourishments to be cost-effective and durable solution to mitigate erosive losses, even in the absence of a planned approach to the location or composition of deposited sediment.

CRediT authorship contribution statement

Sebastian J. Pitman: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ian T. Burke:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Helen Jay:** Writing – review & editing, Investigation. **Nick Cooper:** Writing – review & editing, Investigation. **William M. Mayes:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Adam P. Jarvis:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:S Pitman reports financial support was provided by UK Research and Innovation Natural Environment Research Council. A Jarvis reports financial support was provided by UK Research and Innovation Natural Environment Research Council. I Burke reports financial support was provided by UK Research and Innovation Natural Environment Research Council. W Mayes reports financial support was provided by UK Research and Innovation Natural Environment Research Council. S Pitman reports financial support was provided by British Society For Geomorphology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123106.

Data availability

All data used is open source and the sources are described within the text

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