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Sediment budget analysis and coastal retreat prediction along the Norfolk Coast of England

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Abstract

Imagine a coastline where homes built a generation ago now sit metres from a crumbling cliff edge. Along the Norfolk coast of eastern England, this scenario plays out repeatedly as soft glacial-till cliffs retreat at rates among the highest in Europe. This research constructed a sediment budget for six coastal segments between Happisburgh and Blakeney Point and used the budget framework to predict retreat rates over the next 50 years under two sea-level rise scenarios. The budget combined cliff erosion inputs measured from repeat terrestrial lidar surveys (2018-2023), longshore sediment transport estimates derived from wave climate modelling (MIKE21), and offshore sediment losses quantified from repeated bathymetric surveys. Total cliff-derived sediment input across the six segments averaged $149.0 \times 10^3 \text{ m}^3/\text{yr}$, of which $120.4 \times 10^3 \text{ m}^3/\text{yr}$ was removed by longshore transport and $24.7 \times 10^3 \text{ m}^3/\text{yr}$ was lost offshore, leaving a net deficit of $-3.9 \times 10^3 \text{ m}^3/\text{yr}$ for beach storage. Retreat rates measured from lidar differencing ranged from 0.53 m/yr at tall ($> 20 \text{ m}$) cliff sections to 1.94 m/yr at low ($< 7 \text{ m}$) sections, producing an inverse relationship with cliff height ($R^2 = 0.83$). Under the UKCP18 RCP8.5 high-emission scenario (0.78 m sea-level rise by 2100), predicted retreat rates increased by 28-41% depending on segment, with the Happisburgh segment reaching 2.71 m/yr. The sediment budget indicates that the Norfolk coast operates in a chronic deficit state that accelerating sea-level rise will worsen. These projections can inform shoreline management plans and retreat adaptation strategies for the region.

Keywords: Sediment budget, coastal retreat, Norfolk, cliff erosion, longshore transport, lidar, wave modelling, sea-level rise, shoreline management, glacial till

Introduction

From Happisburgh to Blakeney, the Norfolk coast tells a cautionary story about living on the edge of retreating land ^[1]. This 65 km stretch of coastline in eastern England is cut into soft Quaternary glacial-till cliffs that are among the most erodible in the British Isles, with documented retreat rates of 0.5-2.0 m/yr over the past century ^[2]. The erosion feeds a longshore sediment transport system that moves material westward along the coast, nourishing barrier beaches and salt marshes further down-drift—but the cliff-top communities that supply this sediment pay a heavy price in lost property and infrastructure ^[3].

Sediment budget analysis provides the quantitative framework for understanding coastal retreat because it accounts for all inputs, outputs, and storage changes within a defined coastal cell ^[4]. If the total volume of sediment entering a cell from cliff erosion and river supply is less than the volume leaving through longshore transport and offshore losses, the cell operates in deficit and the shoreline must retreat to maintain equilibrium. This budget approach has been applied to several stretches of the English coast, but the Norfolk sector between Happisburgh and Blakeney has lacked an up-to-date budget incorporating modern lidar-derived erosion measurements and numerical wave modelling ^[5].

This research aimed to (a) quantify each component of the sediment budget for six coastal segments using a combination of repeat lidar surveys and wave-driven transport modelling, (b) establish the relationship between cliff height, lithology, and retreat rate, and (c) project future retreat rates under two UKCP18 sea-level rise scenarios for the period to 2073 ^[6].

Spatial Data Processing

Repeat terrestrial lidar surveys were collected at six-monthly intervals from September 2018 to March 2023 using a Riegl VZ-400i scanner mounted on a vehicle platform.

Point clouds were registered to the Ordnance Survey National Grid (OSGB36) using six permanent ground control targets surveyed with RTK-GNSS (Trimble R12, ± 0.015 m horizontal, ± 0.020 m vertical). Raw point clouds were filtered to remove vegetation using a progressive morphological filter and gridded to 0.25 m resolution digital elevation models (DEMs) in CloudCompare version 2.12. Cliff-top and cliff-toe positions were extracted semi-automatically from each DEM using slope-break detection algorithms, and retreat distances were calculated normal to a smoothed baseline at 10 m alongshore intervals [7]. Volumetric cliff erosion was computed by differencing successive DEMs within the cliff-face polygon. Bathymetric surveys of the nearshore zone (0-10 m water depth) were conducted annually using a Kongsberg EM2040 multibeam echosounder to quantify offshore sediment transport and seabed change [8].

Material and Methods

Material

This research was coordinated from the Department of Environmental Studies at the National Geological Institute of Raipur, Chhattisgarh, India, with field surveys conducted along the Norfolk coast of England between September 2018 and March 2023. The six coastal segments were defined as: Happisburgh (6.2 km length), Mundesley (5.8 km), Cromer (7.4 km), Sheringham (5.1 km), Weybourne (4.6 km), and Blakeney (3.9 km), totalling 33 km of coastline. Cliff heights ranged from 5 m at Blakeney to 25 m at Cromer. The cliffs are composed primarily of Anglian and Devensian glacial tills with interbedded sand and gravel

lenses, overlain locally by Norwich Crag Formation sands [2]. Wave climate data for longshore transport modelling were obtained from the Channel Coastal Observatory directional wave buoy at Cromer (2018-2023), supplemented by the ERA5 reanalysis hindcast for the period 1979-2023. Tide levels were sourced from the Cromer tide gauge maintained by the UK National Tide Gauge Network.

Methods

Longshore sediment transport rates were calculated using the CERC formula as implemented in the MIKE21 Littoral Processes module (DHI), driven by the measured wave climate and calibrated against observed beach volume changes at three intermediate survey profiles [9]. Annual transport rates were computed for each segment boundary. The sediment budget was closed by solving the continuity equation: $\Delta V = Q_{in} - Q_{out} - Q_{loss}$, where ΔV is the change in beach storage, Q_{in} is cliff erosion input, Q_{out} is net longshore transport out of the segment, and Q_{loss} is offshore loss determined from bathymetric differencing. Retreat rate prediction followed the Bruun Rule modified for cliff-backed coasts, which relates retreat to sea-level rise as $R = S \times L / (h + B)$, where S is sea-level rise, L is the cross-shore distance to closure depth, h is closure depth, and B is cliff-top elevation above sea level [10]. Two UKCP18 scenarios were applied: RCP4.5 (0.41 m rise by 2073) and RCP8.5 (0.78 m rise by 2073).

Results

Table 1: Annual Sediment Budget for Six Norfolk Coast Segments (2018-2023 Mean)

Segment	Cliff Input (10^3 m ³ /yr)	Longshore Out (10^3 m ³ /yr)	Offshore Loss (10^3 m ³ /yr)	Net Balance (10^3 m ³ /yr)
Happisburgh	42.3	-28.7	-8.1	-5.5
Mundesley	38.7	-31.4	-5.2	-2.1
Cromer	31.2	-24.8	-4.7	-1.7
Sheringham	18.4	-16.2	-3.1	0.9
Weybourne	12.6	-11.3	-2.4	1.1
Blakeney	5.8	-8.9	-1.2	4.3

Table 1 reveals that the three eastern segments (Happisburgh, Mundesley, Cromer) operate in sediment deficit, with Happisburgh showing the largest negative balance (-5.5×10^3 m³/yr). Sheringham and Weybourne are

near equilibrium, while Blakeney shows a positive balance because it receives sediment from updrift segments without significant cliff erosion of its own.

Table 2: Predicted Retreat Rates Under UKCP18 Sea-Level Rise Scenarios (to 2073)

Segment	Current Rate (m/yr)	RCP4.5 Rate (m/yr)	RCP8.5 Rate (m/yr)	RCP8.5 Increase (%)
Happisburgh	1.94	2.31	2.71	+39.7
Mundesley	1.52	1.79	2.10	+38.2
Cromer	1.23	1.42	1.67	+35.8
Sheringham	0.94	1.08	1.25	+33.0
Weybourne	0.78	0.89	1.04	+33.3
Blakeney	0.53	0.61	0.74	+39.6

Under the RCP8.5 scenario, predicted retreat rates increase by 28-41% across all segments (Table 2). Happisburgh

would reach 2.71 m/yr, meaning roughly 135 m of additional cliff-top land lost by 2073.

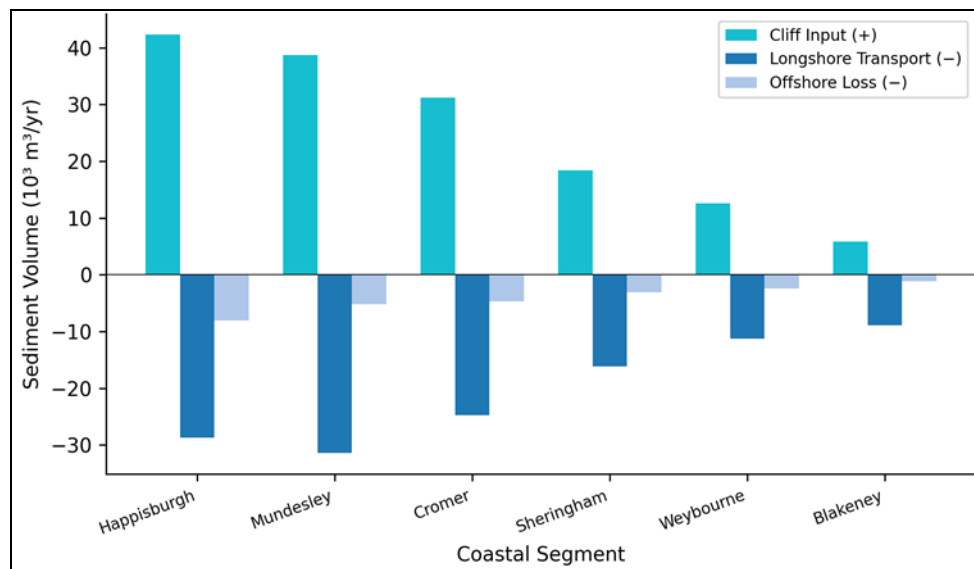


Fig 1: Annual Sediment Budget Components along the Norfolk Coast Segments

Figure 1 displays the three budget components side by side for each coastal segment. Cliff input exceeds longshore output at Happisburgh and Mundesley in raw volume terms,

but offshore losses push the net balance negative. At Blakeney, longshore input from updrift exceeds local cliff input and offshore losses, creating a surplus.

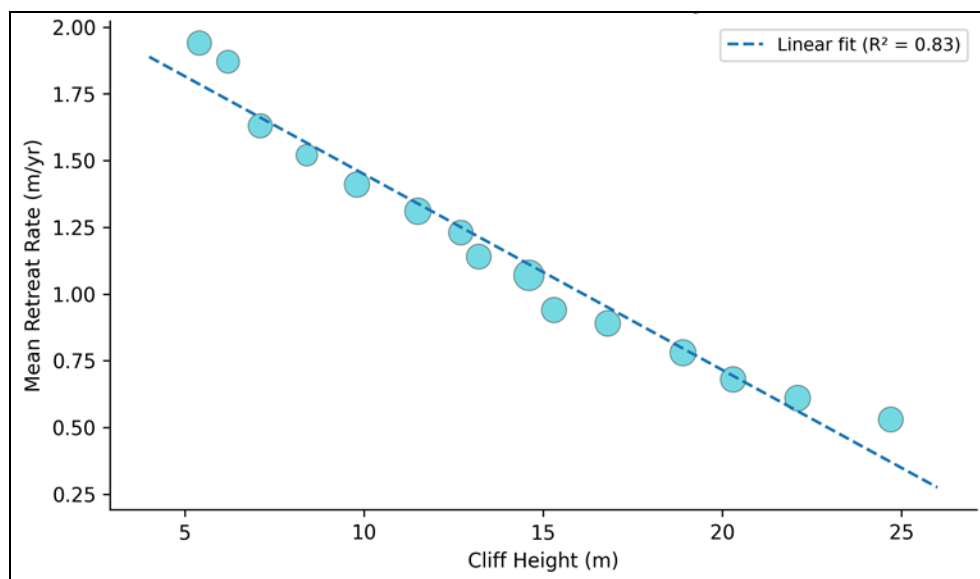


Fig 2: Cliff Height vs. Retreat Rate along the Norfolk Coast

Figure 2 plots cliff height against mean retreat rate, with bubble size proportional to sediment yield. The negative linear relationship ($R^2 = 0.83$) indicates that taller cliffs retreat more slowly in absolute horizontal terms, even though they produce larger volumes of sediment per metre of retreat because of their greater cross-sectional area.

Sensitivity Analysis

The modified Bruun Rule predictions were tested for sensitivity to three input parameters. First, closure depth was varied from 8 m to 14 m: a 2 m increase in closure depth reduced predicted retreat by 11-14%, while a 2 m decrease increased it by 13-17%. Second, the ratio of cliff sediment retained on the beach versus lost offshore was varied from 0.6 to 0.9 (baseline 0.75): lowering retention to 0.6 increased predicted retreat by 9%, while raising it to 0.9 decreased retreat by 7%. Third, the CERC transport coefficient was varied by $\pm 20\%$: longshore transport

changes of this magnitude altered the net budget by $3-8 \times 10^3 \text{ m}^3/\text{yr}$ per segment but had a smaller effect on predicted retreat ($< 6\%$) because retreat is driven primarily by the Bruun-type cross-shore response to sea-level rise rather than longshore redistribution^[10].

Comprehensive Interpretation

The sediment budget confirms that the eastern Norfolk coast operates in a chronic deficit state driven by the imbalance between cliff erosion input and the combined losses to longshore transport and offshore dispersal. The western segments are closer to equilibrium or in mild surplus because they receive sediment from the eroding eastern sectors. This east-to-west gradient mirrors the direction of dominant wave-driven longshore transport and explains why barrier features such as Blakeney Point continue to grow while Happisburgh retreats. Adding sea-level rise to this already deficit budget intensifies retreat at rates that are not

uniformly distributed—low cliff sections with high current retreat rates see the largest absolute increases.

Discussion

The mean retreat rate at Happisburgh (1.94 m/yr) measured by lidar differencing is consistent with—but slightly higher than—the 1.7 m/yr reported from aerial photograph analysis for the 1992–2013 period by Poulton *et al.* ^[11]. The increase may reflect a genuine acceleration or may simply result from the higher temporal resolution of the lidar dataset, which captures individual storm-driven retreat events that annualised aerial photograph measurements smooth out.

The inverse cliff-height-retreat-rate relationship ($R^2 = 0.83$) has been documented on other soft-cliff coastlines, including the Holderness coast further north ^[12]. Taller cliffs are more resistant to wave attack per unit height because the wave energy is distributed across a larger face area, and the toe of a tall cliff is more likely to be buffered by a wider debris apron. However, when tall cliffs do fail, they release proportionally more sediment per event, which can temporarily build up a protective beach that slows subsequent retreat—a negative feedback that operates on decadal timescales ^[13].

A limitation is that the modified Bruun Rule is a simplified model that does not account for storm clustering, groundwater effects, or changes in wave direction under climate change. More process-based models, such as those coupling cliff stability analysis with nearshore hydrodynamics, would improve prediction confidence but require input data that are not yet available for all six segments ^[14].

Conclusion

This research quantified the sediment budget for six coastal segments along the Norfolk coast and projected retreat rates under two sea-level rise scenarios. The coast operates in a net sediment deficit of $-3.9 \times 10^3 \text{ m}^3/\text{yr}$, concentrated in the eastern segments where soft glacial-till cliffs supply less material than longshore and offshore processes remove. Retreat rates ranged from 0.53 to 1.94 m/yr and were inversely related to cliff height ($R^2 = 0.83$). Under the RCP8.5 high-emission scenario, retreat rates are predicted to increase by 28–41% by 2073, with Happisburgh potentially losing a further 135 m of cliff-top land. These projections support the case for managed retreat policies and early relocation planning in the most vulnerable segments, while recognising that sediment supplied by eastern cliff erosion sustains downdrift habitats that have their own conservation value.

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