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Research Article

Through proxy and scale: How measurement choices shape narratives of shoreline change and vulnerability across embayed sandy beaches of southern Ireland

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ABSTRACT

Shoreline change assessments are central to coastal management and adaptation planning, yet they commonly rely on a limited number of indicators used as proxies for complex coastal behaviour. Because interpretations of shoreline dynamics and vulnerability depend strongly on measurement methods and observational scales, this study examines how different monitoring approaches influence interpretations of soft coastline shoreline change along the energetic Atlantic coast of southern Ireland. A three-year multi-method monitoring programme (2023–2025) was conducted across five embayed unconsolidated sandy beach systems, integrating long-term aerial imagery and vegetation-line change, Sustainable Coastal Vulnerability Index outputs, repeated seasonal RTK-GNSS cross-shore profiles, high-resolution UAV-derived orthophotos and digital surface models, and targeted post-storm field assessments. Results show that different monitoring methods produce distinct but complementary narratives of shoreline behaviour. Long-term vegetation lines and derived change rates emphasise boundary translation but can mask shorter-term accelerations, regime shifts, or localised erosion hotspots. SCVI classifications provide effective broad-scale screening of exposure and receptors but may misrepresent physical susceptibility where local sediment dynamics or recovery processes are not captured. In contrast, field surveys and UAV-derived topographic datasets reveal spatially variable sediment dynamics, with erosion and accretion occurring simultaneously across different sectors of the same beach systems. These differences highlight the need for monitoring strategies that combine complementary datasets. Based on these findings, an evidence-based tiered monitoring strategy is proposed and distinguishes proxy-based screening, routine cross-shore profile monitoring, and targeted UAV surveys in spatially complex settings, reducing interpretive bias in assessments of shoreline change and coastal vulnerability.

1. Introduction

Shorelines are dynamic interfaces where marine, terrestrial, and human systems interact, concentrating ecological and socio-economic value, and exposure to environmental change (Geng et al., 2025; He and Silliman, 2019; Costanza et al., 2014; Kirwan and Megonigal, 2013; Barbier et al., 2011). Sandy coasts, in particular, are highly mobile sedimentary systems. Their evolution is governed not only by shoreline displacement, but also by complex cross-shore and alongshore sediment redistribution, episodic storm forcing, and long-term climate drivers (Leach et al., 2023). Recent work has emphasised that beaches are not inevitably subject to irreversible loss under sea-level rise but can persist through internal reorganisation of sedimentary systems (Cooper et al., 2020; Walker et al., 2017). Yet, in management and policy contexts, shoreline change is still most often framed through simplified narratives of linear erosion or stability (Woodroffe et al., 2025), with direct implications for how vulnerability, adaptation priorities, and intervention strategies are constructed. In practice, coastal monitoring

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necessarily reduces complex, multi-dimensional morphodynamics to a small number of observable proxies, and this reduction is not neutral: each measurement is a choice, of proxy, of scale, of method, and that choice shapes the narrative of change it produces. Most programmes prioritise shoreline-position time series derived from aerial photography, satellite imagery, or manual mapping, complemented in some cases by sparse topographic profiles or index-based vulnerability assessments (Castro-Quintero et al., 2025; Chalençon et al., 2025; McLaughlin et al., 2026; Grottoli et al., 2023; GSI, 2023; Jacobs, 2022; Vos et al., 2019; Luijendijk et al., 2018; RPS/ICPSS, 2011). Such shoreline proxies, observable features such as vegetation lines, high-water marks, or instantaneous waterlines used to locate a boundary that cannot be measured directly, are indispensable in data-limited contexts, but their validity is conditional. It depends on geomorphic setting, vegetation type, anthropogenic modification, and the degree to which a system operates near morphodynamic equilibrium (Biausque and Senechal, 2019). Shoreline movement can decouple from sediment-budget evolution (Leach et al., 2023), where antecedent conditions, storm sequencing, or human modification drive a system away from equilibrium, so that proxy-derived position reflects longer-term patterns and extreme events rather than instantaneous sediment dynamics. Uncrewed Aerial Vehicle (UAV)-based Structure-from-Motion photogrammetry and Light Detection and Ranging (LiDAR) now routinely deliver sub-decimetric topography capable of capturing volumetric change, bar and berm adjustment, dune-foot erosion and channel dynamics at seasonal to event scales (Blenkinsopp et al., 2011; Martins et al., 2017; Pucino et al., 2021; Vecchi et al., 2021; Kandrot et al., 2022). Such methods reveal that erosion and accretion frequently coexist within the same system, organised into spatially persistent hotspots rather than uniformly distributed alongshore or cross-shore (Wright and Thom, 2023; Villagrán et al., 2022; Walker et al., 2017; Keijsers et al., 2014; Blenkinsopp et al., 2011). Despite providing an additional level of data granularity, such methods are often constrained by low spatial cover and their costly nature which hinders their scalable, wide scale use as long-term monitoring tools.

Although tiered combinations of satellite, UAV and in situ surveys are increasingly proposed (McLaughlin et al., 2026; Castro-Quintero et al., 2025), these approaches compare method performance, and seldom examine how different proxies and temporal scales, applied in parallel at the same sites, can generate divergent narratives of erosion, stability, or vulnerability. Their use demonstrates the value of combining complementary datasets, noting they are typically developed and tested in a data-rich, infrastructure-supported context, where multidecadal beach profile archives, and regular surveys are available (McLaughlin et al., 2026). These contexts are not representative of many high-energy Atlantic coastlines: where persistent cloud cover, high turbidity, and energetic wave climates limit the reliability of satellite imagery, the feasibility of frequent UAV deployment is constrained by limited weather windows and operational capacity, beach-scale topographic records are sparse, and sustained monitoring infrastructure is lacking. In these settings, coastal managers face practical questions such as how to design efficient and defensible monitoring strategies under data, resource, and feasibility constraints.

In the Republic of Ireland vulnerability assessment has historically been fragmented, both spatially and temporally, characterised by limited national-scale integration, very limited systematic coastal monitoring, and the absence of a dedicated coastal governance structure (Devoy, 2008; Falaleeva et al., 2011; O'Mahony et al., 2014; Caloca-Casado, 2018; Farrell et al., 2021). This is despite major advances in offshore and seabed mapping (O'Toole et al., 2022), and robust regional sea-level reconstructions being available (Pugh et al., 2021; Shoari Nejad et al., 2022). National assessments (RPS/ICPSS, 2011) have operationalised aerial imagery-derived shoreline retreat rates, to support planning and prioritisation. However, these assume linear trends, and spatial homogeneity (Chalençon et al., 2025), which is effective for broad screening. However, at the decision-information level, such approaches risk mischaracterising local sediment redistribution, the influence of coastal protection structures, and the persistence of those erosion hotspots that are critical for site-level decision-making. Local authorities are therefore navigating a challenge of managing dynamic soft coasts, without clear guidance on what, where and how frequently to monitor.

In this context, this study examines (i) how boundary translation measures of shoreline change, shoreline vulnerability, and topographic observations generate divergent or complementary interpretations of shoreline change, and (ii) what the implications of these differences are when translating evidence into management-relevant guidance. This study presents a three-year (June 2023–September 2025), multi-method monitoring programme across five contrasting beach systems along the County Cork coastline, integrating long-term aerial imagery and vegetation-line change, outputs from a Sustainable Coastal Vulnerability Index (SCVI), repeated seasonal cross-shore Real-Time Kinematic (RTK)-Global Navigation Satellite System (GNSS) profiles, high-resolution UAV-derived orthophotos and Digital Surface Models (DSMs), and targeted post-storm assessments. A comparative narrative analysis is used to evaluate how each monitoring method constructs a distinct account of coastal change at each site, from multi-decadal boundary translation trends to seasonal and storm-driven sediment redistribution.

The systematic comparison of these narratives presented in this research contributes both to coastal geomorphology and applied monitoring design. The study seeks to support more transparent, efficient and context-sensitive coastal monitoring strategies capable of reducing interpretive bias and better informing adaptation decisions on dynamic sandy coasts.

2. Study area

The coastline of Ireland is highly irregular and geomorphologically diverse (Devoy, 2008), comprising alternating bay-headland systems, high cliffs, pocket beaches, dune-backed strands and estuaries. Its western and southern margins are shaped by a high-energy Atlantic wave regime, while the eastern coast is more sheltered and influenced by the Irish Sea (Carter et al., 1987; Devoy, 2008). County Cork is located in the southwest of the Republic of Ireland (Fig. 1), with its coastline extending over approximately 1094 km and encompassing a wide range of coastal environments, including embayed sandy beaches, rocky headlands, estuaries, dune systems, and saltmarshes (Neilson and Costello, 1999). This physical diversity contributes to the region's high environmental value but also exposes it to considerable coastal hazards, including erosion, flooding, storm surges, and projected sea-level rise, particularly in low-lying and sedimentary areas. Within the county, 422 km of coastline are composed of soft sandy sediments, of which 91 km have been identified as being at risk of erosion (ECOPRO (Project), 1996; Salman et al., 2004).

The tidal regime is semi-diurnal, with a mesotidal to locally macrotidal range of approximately 2.8–3.7 m, contributing to extensive intertidal areas. The offshore wave climate along Ireland's Atlantic margin is energetic, but nearshore exposure is highly spatially variable due to coastal orientation, embayment sheltering, and headland attenuation. While average winter wave power along the Cork coastline can reach approximately 75 kW m^{-1} and average winter significant wave heights up to 2.8 m at the tips of exposed western headlands, averages can be as low as 0.01 kW m^{-1} and 0.03 m inside sheltered bays (nearshore wave modelling by A. Karayel, unpublished data, 2024). The strong alongshore gradient in wave exposure exerts a primary control on sediment transport pathways, shoreline mobility, and beach morphodynamics (Davidson-Arnott, 2010). As such, County Cork offers the opportunity for a highly relevant pilot case to advance shoreline monitoring and vulnerability assessment.

This study focuses on five contrasting beach systems distributed along the County Cork coastline (Fig. 1). At the eastern end of the study area, Pilmore is situated within a more sheltered embayed setting, where

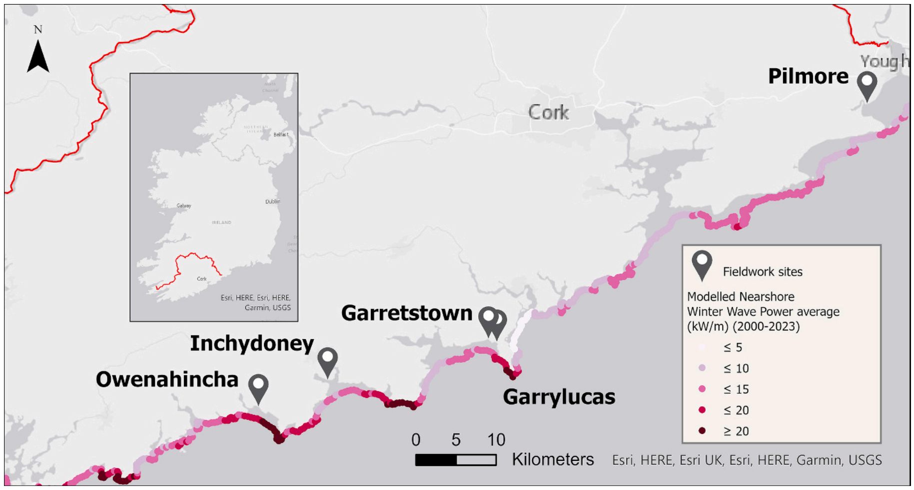


Fig. 1. Location of the five study sites along the County Cork coastline (Pilmore, Garretstown, Garrylucas, Inchydoney and Owenahincha) with modelled nearshore winter wave power average (2000−2023) (nearshore wave modelling by A. Karayel, unpublished data, 2024). The map illustrates the pronounced east-west gradient in Atlantic wave exposure and local variability driven by headland orientation and embayment sheltering. Inset shows the location of County Cork, red polygon, within Ireland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wave energy is attenuated relative to the fully exposed Atlantic west coast. Despite this lower exposure, it records among the highest historical retreat rates in County Cork (RPS, 2011), and is characterised by a low-lying, reclaimed coastal plain composed of soft sediments with limited accommodation space. Moving westward, Garretstown and Garrylucas are more directly exposed to Atlantic swell, although their degree of exposure varies according to headland orientation and local sheltering. Both are heavily used recreational beaches backed by engineered defences, where structural controls influence sediment pathways and shoreline behaviour. Further west, Inchydoney comprises a morphodynamically complex barrier beach system with both seaward-facing and estuary-facing compartments. Its exposure is spatially heterogeneous, with open-coast sections subject to Atlantic forcing and inner sections influenced by tidal exchange and estuarine dynamics. At the western end, Owenahincha is a large sand dune system and is arguably the most Atlantic-exposed sites in the study. The beach has experienced historical phases of active erosion followed by anthropogenic soft interventions that have reduced dune retreat and facilitated long-term accretion. Nevertheless, localised erosion hotspots persist, primarily associated with access paths and concentrated trampling.

All five are embayed sandy systems in the broad sense, bounded by headlands, engineered structures, or estuarine margins (Fellowes et al., 2019). However, they also differ markedly in their degree of headland control, driving sediment retention and redistribution, alongshore connectivity, and exposure to hydrodynamic forcing (Harley et al., 2015; Fellowes et al., 2019). These sites therefore provide a natural laboratory for examining how shoreline proxies, CVI outputs, cross-shore profiles, UAV-derived surface models, and post-storm surveys resolve different components of coastal change. Their diversity also enables the interpretation and transferability of findings beyond a single morphodynamic setting and supports the development of a resource-aware monitoring framework relevant to other high-energy, data-limited Atlantic coastlines.

3. Methodology

3.1. Overview of the multi-method monitoring design

This study compares three distinct monitoring narratives of coastal change: (i) boundary translation, represented by vegetation-line shorelines and derived rates (derived from both aerial and drone images at different temporal scales); (ii) synthetic vulnerability framing, represented by the Sustainable Coastal Vulnerability Index (SCVI); and (iii) sediment redistribution, captured through repeated RTK-GNSS cross-shore profiles and UAV-derived digital surface models seasonally and following major storm events.

Each method is described separately below, with attention to data sources, spatial and temporal resolution, uncertainty and operational feasibility. This structured description provides the basis for the subsequent comparative narrative analysis, in which differences between monitoring products are evaluated site by site. Rather than seeking to identify a single "true" trajectory of coastal evolution, the methodological objectives are to compare the accounts of change produced by different methods.

3.2. Vegetation-line extraction from historical aerial imagery and shoreline change rates

Long-term shoreline change was characterised using vegetation-line proxies extracted from historical aerial imagery for the County Cork coastline, following the fully automated methodology developed in Chalençon et al. (2025). This dataset was developed in response to a critical data gap: prior to this work, no spatially continuous nor internally consistent shoreline proxy or long-term erosion-rate dataset existed for the Cork coastline. There was a clear need for a method capable of extracting the best possible regional-scale proxy from the historical imagery archive. Vegetation lines were adopted because instantaneous waterlines could not be robustly corrected for tidal stage across the historical archive: exact acquisition times were inconsistently available, and insufficiently reliable, spatially resolved tidal and beach-slope data were lacking for large portions of the coastline. In this context, the landward edge of stable coastal vegetation provided the most consistent and operationally feasible shoreline indicator for long-term regional screening. Historical cartographic sources were also considered as a means of extending the record further back in time; in Ireland, however, historical maps are temporally sparse, and their georectification uncertainty is too large relative to the change signal of interest to support quantitative rate estimation, precluding their inclusion here (Chalençon et al., 2025).

Vegetation lines were extracted using a fully automated workflow with no user intervention, designed to provide a robust, repeatable alternative to manual digitisation (Chalençon et al., 2025). The method was applied uniformly to the historical aerial-photography archive spanning 2000–2021, which consists of national orthophotography datasets of progressively increasing spatial resolution (1 to 0.1 m). Uncertainty was quantified for both the extracted vegetation-line positions, and the derived shoreline change rates. The positional uncertainty of the vegetation lines varies across datasets and years but is estimated to lie between approximately 0.6 and 1.2 m (Chalençon et al., 2025). Propagation of these uncertainties into the shoreline change statistics yields a 95% confidence interval of ± 0.27 m yr^{-1} for the linear regression rates, providing an explicit threshold for distinguishing meaningful long-term trends from apparent change within measurement limits. This uncertainty bound is critical for interpretation in the present study.

Shoreline change statistics were computed using a transect-based approach implemented in the Digital Shoreline Analysis System (DSAS) (Himmelstoss et al., 2021). Transects were cast at 10 m intervals along the coastline, and Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR) were calculated from the vegetation-line time series. Comparison of long-term and recent rates allows evaluation of whether apparent stability over extended periods masks more recent erosional trends or spatially concentrated retreat. With this in mind, rates were derived over two temporal windows: the full multi-decadal period (2000–2021, 2000–2015 for Pilmore), and a recent sub-period (2011–2021, 2011–2015 for Pilmore), in order to assess potential change trend accelerations, regime shifts, or changes in shoreline behaviour over the last decade.

3.3. Sustainable Coastal Vulnerability Index (SCVI) outputs

Site-level vulnerability context was provided using outputs from the Sustainable Coastal Vulnerability Index (SCVI) developed and tested for the County Cork coastline (Chalençon et al., 2026a; Chalençon et al., 2026b). The SCVI was designed in response to a recognised limitation of conventional Coastal Vulnerability Indices (CVIs): their narrow focus on biophysical exposure and hazards, and their weak integration of socio-economic and environmental vulnerability dimensions. The SCVI was developed as a synthetic, operational tool to address this gap and to support prioritisation and decision-making under data and resource constraints.

The SCVI integrates four susceptibility domains, physical (PSI), socio-cultural (ScSI), economic (EcoSI), and environmental (EnSI), with a coastal hazard index (CHI) to produce a composite vulnerability metric (Table 1). All components were ranked into vulnerability classes, and combined following a transparent, rule-based structure (Chalençon et al., 2026b). The SCVI was implemented at 50 m resolution across the Cork coastline, generating spatially distributed vulnerability classes and index components for each site. Importantly, the SCVI is designed for broad-scale screening and prioritisation, not for resolving local sediment dynamics, short-term morphological change, or storm-driven response.

3.4. Repeated RTK-GNSS cross-shore profiles

Beach morphology was monitored using repeated cross-shore topographic profiles surveyed with RTK-GNSS. Profiles extended from the backshore or dune foot seaward across the beach and intertidal zone. At all sites, profiles were surveyed to the low-tide level, except at Pilmore, where the extensive tidal flat limited seaward coverage and profiles were recorded up to a maximum distance of approximately 450 m offshore. Elevations were referenced to the Irish Transverse Mercator (ITM) coordinate system and Ordnance Datum Malin Head. The RTK-GNSS system yielded centimetric-level positional accuracy, with a vertical and horizontal uncertainty of <0.02 m. The high vertical accuracy of the profiles provides a reliable basis for quantifying volumetric change and morphological adjustment that are not captured by two-dimensional shoreline proxies.

Between 13 and 20 profiles were surveyed at each site, depending on beach length and morphological complexity. Profile spacing varied by site: approximately 35 m at Owenahincha; 50 m at Pilmore, Inchydoney and Garrylucas; and 30 m at Garretstown. Profile transects were surveyed along fixed, georeferenced alignments to ensure positional consistency across repeat surveys. Along each profile, topographic points were recorded at approximately 1 m intervals, providing sufficient resolution to resolve berm formation, bar migration, dune-foot erosion and subtle seasonal elevation changes.

Profiles were surveyed at all sites in March and September 2024 and 2025, capturing end-of-winter and end-of-summer beach states over two consecutive annual cycles (Fig. 2). In addition, higher-frequency surveys were conducted at selected sites to resolve intra-seasonal dynamics. This variable temporal sampling reflects both logistical feasibility and site-specific process complexity, and it enables explicit assessment of seasonal adjustment at sites exhibiting strong spatial or temporal variability. Additional profiles were surveyed preceding and/or following major storm events and are described in Section 3.6.

3.5. UAV-based surveys

Spatially continuous beach morphology was mapped using UAV-based Structure-from-Motion photogrammetry to generate high-resolution digital surface models (DSMs) and orthophotography at each site. UAV surveys were designed to complement the discrete cross-shore RTK-GNSS profiles by mapping alongshore-structured sediment redistribution, erosion hotspots, berm and bar morphology, dune-foot erosion, channel dynamics, and shoreline-proximal change that cannot be fully captured by profile-based sampling.

UAV surveys were conducted at all sites in June 2023, March and September 2024 and 2025, providing spatially continuous topography for two full seasonal cycles (Fig. 2). These survey dates were selected to characterise seasonal changes and to coincide with the first end-of-winter and end-of-summer profile campaigns, enabling direct comparison between cross-shore and spatially continuous representations of beach morphodynamics. Additional UAV surveys were conducted opportunistically following major storm events and are described in Section 3.6.

All flights were conducted at an altitude of approximately 50 m, yielding a mean Ground Sample Distance (GSD) of 1.37 cm. DSM generation was performed using ArcGIS Drone2Map, with initial processing conducted in the native coordinate reference system of the drone imagery (EPSG:32629; WGS 84 / UTM zone 29 N) and Ordnance Datum

Table 1
SCVI parameters per subindex.

	Coastal Hazard Index (CHI)	Physical Susceptibility Index (PSI)	Socio-cultural Susceptibility Index (ScSI)	Economic Susceptibility Index (EcoSI)	Environmental Susceptibility Index (EnSI)
Parameters	Relative Sea Level Rise	Geomorphology	Population Density	Land use	Biodiversity Richness
	Wave Climate	Elevation	Residential Buildings	Commercial and Industrial Buildings	Protected Species
	Shoreline Change derived from vegetation-line proxies	Slope	Cultural Heritage	Rail and Road Networks	Ecological Connectivity
	Flooding Probabilities	Tidal range	Public Services	Tourism Activity	Environmental Designations
		Groundwater Vulnerability	Social Vulnerability	Sensitive Infrastructure	

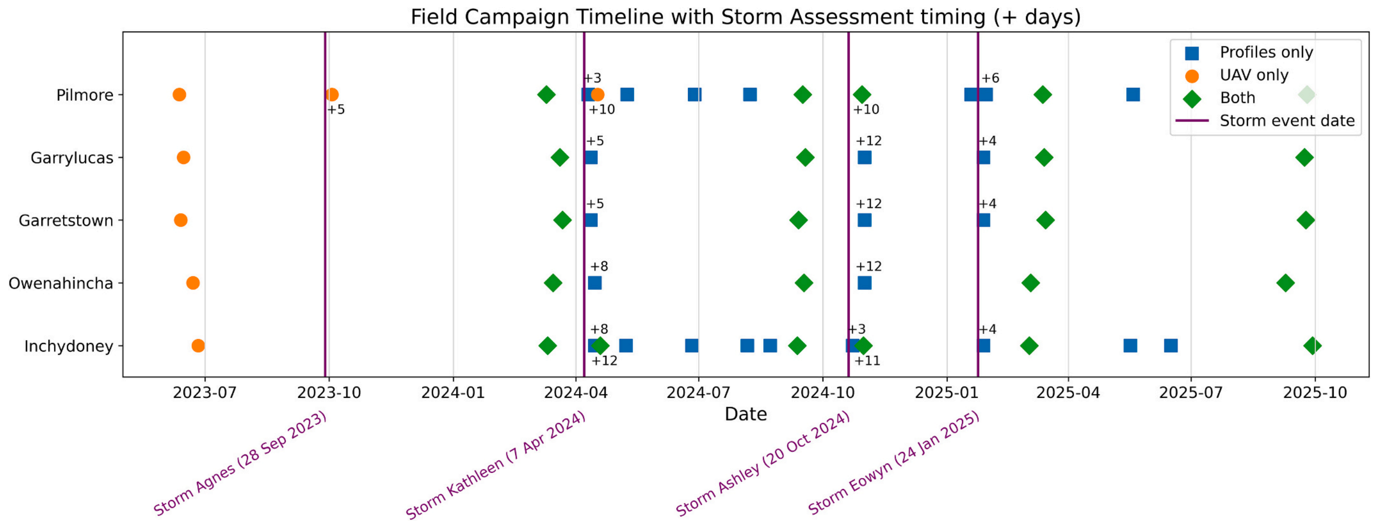


Fig. 2. Timeline of field surveys conducted at the five study sites between June 2023 and September 2025. Blue squares indicate RTK-GNSS profile surveys, green diamonds represent UAV surveys, and vertical purple lines mark major storm events (Storm Agnes, Kathleen, Ashley and Eowyn). Numbers indicate the number of days between the storm event and the subsequent survey. The figure highlights the temporal structure of the monitoring programme and the timing of post-storm assessments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Malin Head. All UAV-derived products were subsequently reprojected into the Irish Transverse Mercator (ITM) coordinate system to ensure consistency with the RTK-GNSS profiles and other spatial datasets used in this study. DSMs were generated at a spatial resolution of 1.4 cm. UAV products were georeferenced using 10 ground control point (GCP) targets deployed on site prior to each survey and measured with the RTK-GNSS system. DSM vertical accuracy was assessed by comparison with RTK-GNSS profiles surveyed on the same day and at the same tidal stage as the UAV flights, yielding a mean absolute error (MAE) of approximately 5 cm.

High-resolution orthophotography was also produced for each UAV survey. Vegetation lines were extracted from the UAV-derived orthophotos using the same automated algorithm applied to the historical aerial imagery (Chalençon et al., 2025), ensuring methodological consistency between long-term and site-scale shoreline proxies. Minimal manual correction was applied where required to remove obvious misclassifications associated with shadows, temporary seaweed deposits, or localised image artefacts. Shoreline change rates from UAV-derived vegetation lines were calculated using the DSAS following the same transect-based framework as for the historical proxy dataset. Transects were cast at 2 m spacing, and NSM, EPR, and LRR were computed to characterise short-term shoreline behaviour at sub-annual to interannual timescales.

While UAV surveys offer uniquely detailed representation of alongshore variability, compartmentalised erosion and accretion patterns, and vegetation-line dynamics, their deployment is operationally constrained by a combination of environmental and regulatory conditions. Flights were conducted only under wind gusts below approximately 10 m s^{-1}, in the absence of rain or fog, with sufficient daylight and at low tide to maximise intertidal coverage. In addition, regulatory requirements and safety considerations prohibited flying over or in close proximity to people, which was particularly restrictive on very popular recreational beaches. As a result, UAV-based monitoring was necessarily opportunistic rather than fixed in frequency, reflecting the practical feasibility limits of high-resolution remote sensing in high-energy Atlantic coastal environments.

3.6. Post-storm assessments

Targeted post-storm assessments were conducted following four major storm events affecting the south coast of Ireland during the study period: Storm Agnes (27–28 September 2023), Storm Kathleen (7 April 2024), Storm Ashley (20 October 2024), and Storm Eowyn (24 January 2025). These events were selected based on their regional meteorological significance, coastal impact potential, and their occurrence within the temporal window of the multi-method monitoring programme. The type of assessment conducted (RTK-GNSS profiles, UAV surveys, or both) and the delay between storm peak and survey acquisition are indicated in Fig. 2.

Post-storm surveys were designed to capture short-term storm impacts, sediment redistribution, dune-foot erosion, berm and bar morphological changes, channel development, and early-stage recovery. Given the practical constraints associated with UAV deployment and field access on high-energy Atlantic beaches, post-storm surveys were opportunistic rather than synchronous across all sites. Time lags between storm peak and survey acquisition therefore varied between sites and methods, reflecting feasibility constraints related to weather windows, tidal stage, regulatory requirements, and site accessibility (Fig. 2).

Post-storm datasets were analysed in conjunction with baseline seasonal surveys to contextualise storm-driven change relative to background morphodynamic variability. Given the variable time lags between storm events and survey acquisition, post-storm observations are interpreted as capturing short-term storm response and early recovery rather than instantaneous maximum impact. This temporal asymmetry is treated as an intrinsic limitation of high-energy coastal monitoring in feasibility-constrained environments and is explicitly accounted for in the comparative narrative analysis. Differences in post-storm response between sites and methods are therefore interpreted in relation to both geomorphic behaviour and observational timing, rather than assumed to represent directly comparable peak-impact states.

3.7. Identification of morphodynamic compartments using Principal Component Analysis

To investigate whether different parts of the same beach exhibit coherent patterns of elevation change through time, a multivariate analysis was applied to the UAV-derived elevation-change datasets. The objective was not to classify beach morphology at a single date, but to identify zones that tend to gain or lose sediment together across seasons and storm events, forming internally consistent morphodynamic compartments.

For each site, elevation-difference rasters (DoDs) derived from successive UAV DSMs were stacked into a spatio-temporal dataset. In this structure, each pixel represents an individual spatial observation of elevation change, and each survey interval represents a temporal variable describing elevation change over that interval. A Principal Component Analysis (PCA) was then applied across the temporal dimension of this stacked dataset (Jolliffe and Cadima, 2016). The PCA identifies dominant modes of covariance in elevation change, effectively extracting patterns of pixels that tend to vary together through time. These components therefore represent coherent spatio-temporal behaviours in sediment redistribution. Importantly, this approach captures covariance structure rather than net erosion or accretion alone: areas that alternate between erosion and accretion but do so synchronously are grouped within the same mode. The scores of the leading principal components, representing the most significant patterns of shared temporal behaviour, were subsequently used as input to a k-means clustering procedure (Macqueen, 1967). This clustering step groups pixels exhibiting similar PCA score profiles, thereby delineating zones with comparable time-series elevation-change behaviour. PCA and k-means clustering were implemented in Python 3.11.13 using the scikit-learn library (Pedregosa et al., 2011).

The resulting spatial clusters were mapped to define morphodynamic compartments, interpreted as areas of the beach that respond coherently to seasonal forcing and storm events. These compartments do not represent fixed geomorphological units, but statistically derived zones of shared sediment dynamics. Their purpose within this study is to: (i) reveal alongshore organisation of erosion and accretion patterns, (ii) identify persistent hotspots of sediment redistribution, and (iii) assess whether monitoring profiles adequately capture spatial variability to support comparison between boundary translation, synthetic vulnerability and sediment redistribution representations of change.

4. Results

Across the five study sites, vegetation-line proxies, vulnerability indices, cross-shore profiles, UAV surface differencing, PCA-derived morphodynamic compartments, and post-storm surveys generate partially convergent but often divergent accounts of shoreline change. Boundary-based metrics frequently emphasise translation (retreat, stability, or accretion), whereas topographic monitoring reveals redistribution, compartmentalisation, and hotspot dynamics. A comparative synthesis of boundary translation and synthetic vulnerability framing outputs is presented in Table 2, while sediment redistribution outputs (seasonal and event-scale) are summarised in Table 3. Site-specific figures (Figs. 3–12) illustrate the spatial structure of these patterns.

4.1. Pilmore

Vegetation-line mapping from aerial imagery (Fig. 3 A&B) indicates overall retreat between 2000 and 2015, with a marked acceleration during 2011–2015. Long-window rates suggest moderate persistent erosion (LRR ≈ -0.4 m yr^{-1}), whereas restricting the window to 2011–2015 yields substantially higher retreat (LRR/EPR ≈ -1.6 m yr^{-1}), revealing temporal filtering effects (Table 2). UAV-derived vegetation lines (2023–2025) show continued retreat (mean LRR -1.77 m yr^{-1}; NSM ≈ -2.6 m), spatially polarised toward the western natural sector, while the eastern end exhibits local constraint associated

Table 2

Comparative synthesis of vegetation line boundary translation and synthetic vulnerability framing outputs. Colours indicate the dominant narrative direction conveyed by each monitoring product: dark purple denotes strong erosional trends or very high vulnerability; light purple indicates moderate erosion or high vulnerability; grey represents near-stable conditions; blue indicates pronounced variability without a consistent directional trend; and green denotes accretion or progressive shoreline advance. The colour scheme is interpretive and reflects the qualitative narrative emerging from each dataset rather than exact numeric thresholds.

Proxy	Vegetation-line			Vegetation-line change rates
Method	Aerial images detection		Drone images detection	Vulnerability Index
Time window	Long-term analysis (2000–2021, 2000-2015 for Pilmore)	Recent subset period (2011–2021, 2011-2015 for Pilmore)	Short-term analysis (06/2023–09/2025)	Static SCVI classification
Pilmore	• **Net retreat (non-linear)**: LRR ≈ -0.4 m yr^{-1} • 2000–2011 limited change except central concave sector • 2011–2015 strong retreat concentrated centrally • 2023–2025 strongest retreat in western natural sector • Eastern end locally constrained by engineering	• **Clear acceleration** masked in long window • LRR/EPR ≈ -1.6 m yr^{-1}	• **Spatially concentrated retreat in the western sector** • Mean LRR -1.77 m yr^{-1} • Mean NSM ≈ -2.6 m • Eastern end shows reduced displacement associated with engineered sections	• **Very high vulnerability** • Driven by physical setting & environmental sensitivity • Moderate hazard but with elevated exposure to shoreline change and flooding • Back-beach road = principal asset at risk
Garrylucas	• **Slight overall retreat** • Slowing during 2011–2021 • Vegetation boundary influenced by engineering & access • Fragmented, locally inconsistent signal	• **Near-stable regression rates**	• Western dunes: LRR ≈ -0.75 m yr^{-1}; **NSM ≈ -1.5 m** • Access blowout: LRR ≈ +0.18 m yr^{-1}; NSM ≈ +0.49 m • Soft cliff: LRR ≈ -0.3 m yr^{-1}; NSM ≈ -1.1 m	• **High vulnerability** • Driven by infrastructure & receptor exposure • Flood susceptibility & ecological sensitivity
Garretstown	• Apparent long-term stability LRR/EPR close to 0 • **Vegetation boundary constrained by engineering structures** • Proxy not representative of morphodynamics	• **Near-zero values**	• UAV **vegetation line proxy constrained** • No meaningful shoreline trend	• **High vulnerability** • Driven by physical exposure & assets • Does not distinguish stabilised vs dynamic sectors
Inchydoney	• Rates near-zero overall: offsetting phases • **Compartmentalised barrier beach behaviour** • 2000–2011 accretion (back-barrier advance) • 2011–2021 rollback on seaward face	• **High spatial variability** • Mean LRR ≈ -0.33 m yr^{-1} (seaward face) • Range -2.49 to +3.34 m yr^{-1}	• **Mostly stable/slight advance** • Localised erosion at disturbance hotspots linked to walkways	• **High vulnerability** • Driven by physical susceptibility & valuable receptors • Hazard moderate–low • Does not distinguish stable vs hotspot compartments
Owenahincha	• **Net accretion overall** • Multi-decadal oscillation • Progression (2000–2005), retreat (2005–2011), renewed progression (2011–2021)	• **Stronger positive rates**	• **Overall progression** • Localised retreat at disturbance hotspots	• **High to very high vulnerability** • Driven by physical susceptibility & moderate socio-economic/environmental exposure • High vulnerability despite accretion trend

Table 3
Comparative synthesis of sediment transport outputs (seasonal and event-scale). Colours represent the dominant sediment-response narrative observed in each monitoring product: light purple denotes moderate erosion; grey represents negligible net elevation change and blue indicates oscillatory or highly variable behaviour without persistent net loss or gain. Colour classes summarise the prevailing behavioural pattern rather than precise volumetric thresholds.

Proxy	Cross-shore profile	Surface Elevation Change	Surface Elevation Change	Cross-shore profiles and Surface Elevation Change
Method	RTK-GNSS	UAV DSM	UAV DSM & PCA	RTK-GNSS & UAV DSM
Time window	Seasonal	Seasonal	Seasonal	Post-storm
Pilmore	• Limited net intertidal change • Seasonal fluctuations of small magnitude • Repeated upper-beach lowering • Lower beach relatively stable	• Persistent upper-beach erosion (west) • Eastern stabilisation/local accumulation • Strong spatial structuring • Mean elevation change small	• Compartments broadly parallel to back-beach • Coherent elevation-change zones • Persistent hotspots • Small mean magnitude	• Upper-beach lowering & veg-line retreat • Variable storm signature • Sometimes limited relative to seasonal trend
Garrylucas	• Strong repeatability • Summer accumulation / winter lowering • March 2025 S-shaped morphology (berm ~20 m; dip ~60 m) • Redistribution-dominated	• Strong cross-shore exchange • Upper-beach/berm gain with mid-lower beach loss • Intermittent dune-face erosion • Modest net change	• Compartments parallel to shoreline • Upper beach stable/accumulating (Comp. 2 & 4) • Lower beach seasonal oscillation (Comp. 1 & 3) • Cusp-like morphology	• Redistribution rather than uniform erosion • Upper-beach gain paired with mid-beach loss • Storm signal embedded in seasonal variability
Garretstown	• Strong seasonal oscillation • Winter lowering / summer recovery • Vertical range up to ±1.5 m • Repeated recovery	• Structurally controlled hotspots • ±30 cm seasonal oscillation • -1.5 to -2 m near gravel piles • Channel formation at rock outcrops • Accumulation at hard structures	• Complex cross- & alongshore compartments • Mid-beach seasonal oscillation • Structure-adjacent sectors more stable	• Storm Kathleen: cross-shore redistribution & lowering • Storm Ashley: asymmetric alongshore response • Storm Eowyn: channel creation & widespread lowering • Storm-sensitive but recovery embedded in seasonal cycle
Inchydoney	• Highly dynamic barrier-estuary system • Berm/bar/channel reorganisation • No single cross-shore response pattern	• Back-barrier stable • Dune-foot & upper-beach accretion several periods • Persistent under-spit erosion hotspot (-1.2 to -1.3 m)	• Compartments parallel to shoreline • Dune-foot storm-sensitive (Comp. 3) • Classic seasonal oscillation (Comp. 1 & 4) • Inverted seasonal pattern (Comp. 2) • Stable zone (Comp. 5)	• Compartment-specific impacts • Dune-foot erosion & under-spit lowering • Deposition elsewhere • Redistribution dominant
Owenahincha	• Generally stable dune-foot elevations • Recurrent berm formation/removal • Internal redistribution • No simple seasonal model • Internal variability despite boundary accretion	• Strong alongshore compartmentalisation • Recurrent erosion at blowouts/access paths • Accumulation elsewhere • Redistribution dominates over translation	• Coherent but discrete disturbance driven compartments • Internal reworking despite accreting vegetation boundary	• Measurable but limited spatial extent • Dune-foot erosion at blowouts • Rapid recovery • Storm-sensitive but not storm-dominated

with engineering. The SCVI classifies Pilmore as highly vulnerable, driven primarily by physical and environmental susceptibility and the exposure of the back-beach road (Appendix A, Table 2).

Cross-shore profiles indicate limited net change across much of the intertidal zone (Appendix B), with the most persistent lowering confined to the upper beach and vegetation-line zone (Table 3). UAV-derived DSM differencing (Appendix C) highlights strong alongshore structuring, with persistent upper-beach erosion in the western half and relative stabilisation in the east. PCA-derived compartments are oriented broadly parallel to the back-beach and reveal coherent but modest-magnitude elevation-change zones (Fig. 4). Post-storm assessments record upper-beach lowering and vegetation-line retreat, although storm signatures vary depending on survey timing and may be limited relative to seasonal variability (Table 3).

4.2. Garrylucas

Vegetation-line mapping suggests overall stability with slight accretion of the western dunes between 2000 and 2021, with similar conditions during 2011–2021 (Fig. 5 A&B; Table 2). However, vegetation boundaries are influenced by engineering, access paths, and dune reshaping, limiting their reliability as shoreline indicators. UAV-derived vegetation lines (2023–2025, Fig. 5 C) reveal contrasting sub-sectors: erosion in the western end of the dunes (LRR ≈ -0.75 m yr^{-1}), slight advance at the access blowout, and moderate retreat along the soft-cliff segment. The SCVI classifies Garrylucas as highly vulnerable, driven largely by infrastructure and receptor exposure rather than strong shoreline retreat (Appendix A, Table 2).

Profiles display strong seasonal repeatability, with summer accretion and winter lowering (Appendix B). March 2025 exhibits a distinctive S-shaped morphology (elevated upper beach, berm at about 20 m cross-shore distance, trough at about 60 m), indicative of cross-shore redistribution. UAV DSM differencing (Appendix C) confirms strong cross-shore exchange, with upper-beach gain often paired with mid-to-lower beach lowering. PCA-derived compartments are parallel to the shoreline and organise into upper-beach stability/accumulation domains and lower-beach seasonal oscillation zones (Fig. 6, Table 3). Post-storm surveys reveal redistribution rather than uniform erosion, with modest net lowering embedded within seasonal variability.

4.3. Garretstown

The proxy provides limited interpretive value at this site, where vegetation-line rates are near zero over both long and recent periods (Fig. 7) along the soft shore vegetated stretch, while the rest of the boundary is constrained by revetments, gravel piles, and other hard structures (Table 2). Despite limited shoreline translation, the SCVI classifies Garretstown as highly vulnerable, driven by exposure of assets and physical susceptibility (Appendix A, Table 2).

Profiles show strong seasonal oscillation with winter lowering and summer recovery, and vertical ranges up to ± 1.5 m (Appendix B). UAV DSM differencing (Appendix C) reveals a structurally controlled and highly dynamic system, including erosion hotspots near gravel piles (-1.5 to -2 m), channel formation influenced by rock outcrops, and accumulation at the base of hard structures. PCA-derived compartments display a complex mixture of cross-shore and alongshore controls (Fig. 8). Post-storm responses are spatially variable: Storm Kathleen produced cross-shore redistribution; Storm Ashley elicited an

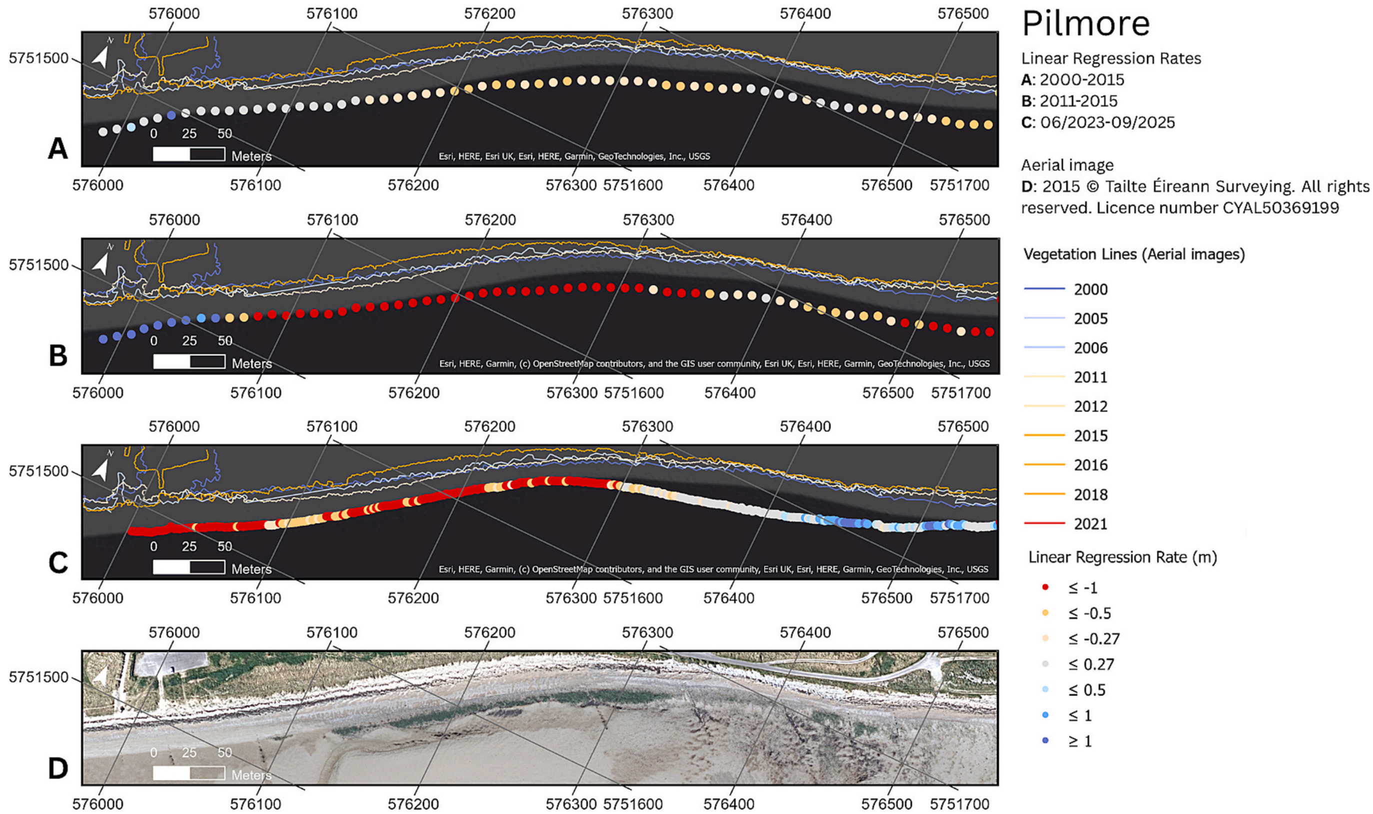
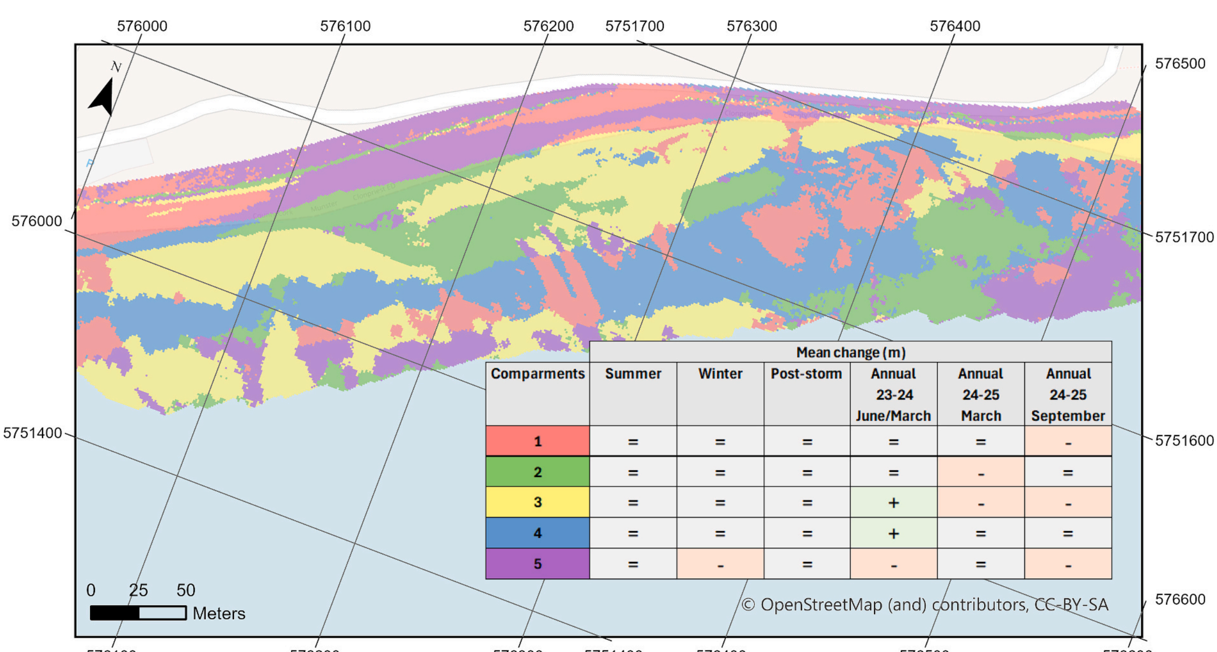


Fig. 3. Linear regression rates (LRR) of vegetation-line change at Pilmore derived from (A) aerial imagery for 2000–2015, (B) aerial imagery for the shorter 2011–2015 interval, and (C) UAV-derived vegetation lines for June 2023–September 2025, (D) 2015 aerial image.



Comparments	Mean change (m)					
	Summer	Winter	Post-storm	Annual 23-24 June/March	Annual 24-25 March	Annual 24-25 September
1	=	=	=	=	=	-
2	=	=	=	=	-	=
3	=	=	=	+	-	-
4	=	=	=	+	=	=
5	=	-	=	-	=	-

Fig. 4. PCA-derived morphodynamic compartments at Pilmore based on stacked elevation-change rasters from repeated UAV surveys (2023–2025). The table summarises mean elevation change (m) per compartment for seasonal, post-storm, and annual intervals. Values are expressed using simplified categorical classes and colour coding: dark orange (++) indicates strong erosion (≥ 0.5 m), light orange (+) moderate erosion (≥ 0.1 m), grey (=) negligible change (± 0.1 m), light green (+) moderate accretion (≥ 0.1 m), and darker green (++) strong accretion (≥ 0.5 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

asymmetric alongshore response; and Storm Eowyn featured channel creation and more widespread lowering. Recovery is embedded within broader seasonal oscillation (Table 3).

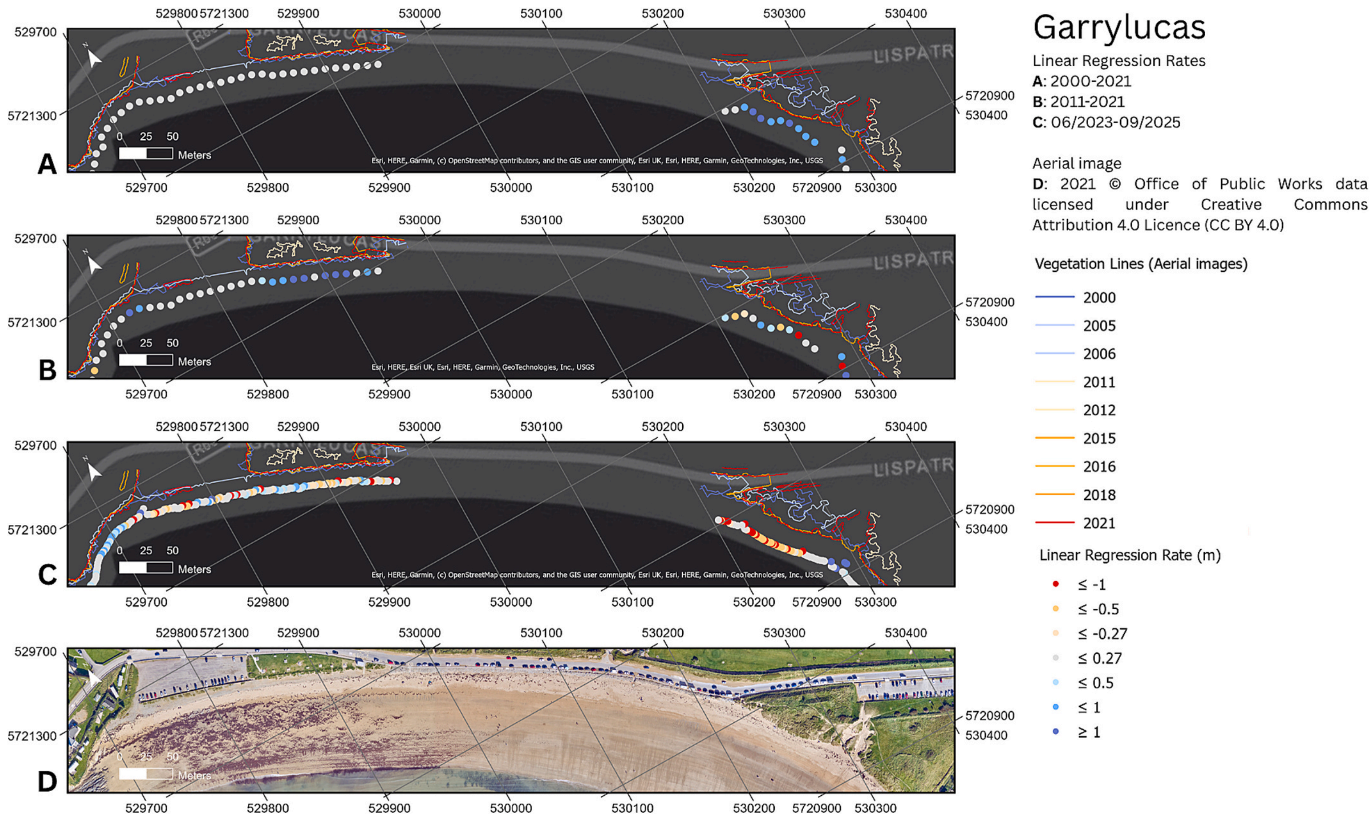
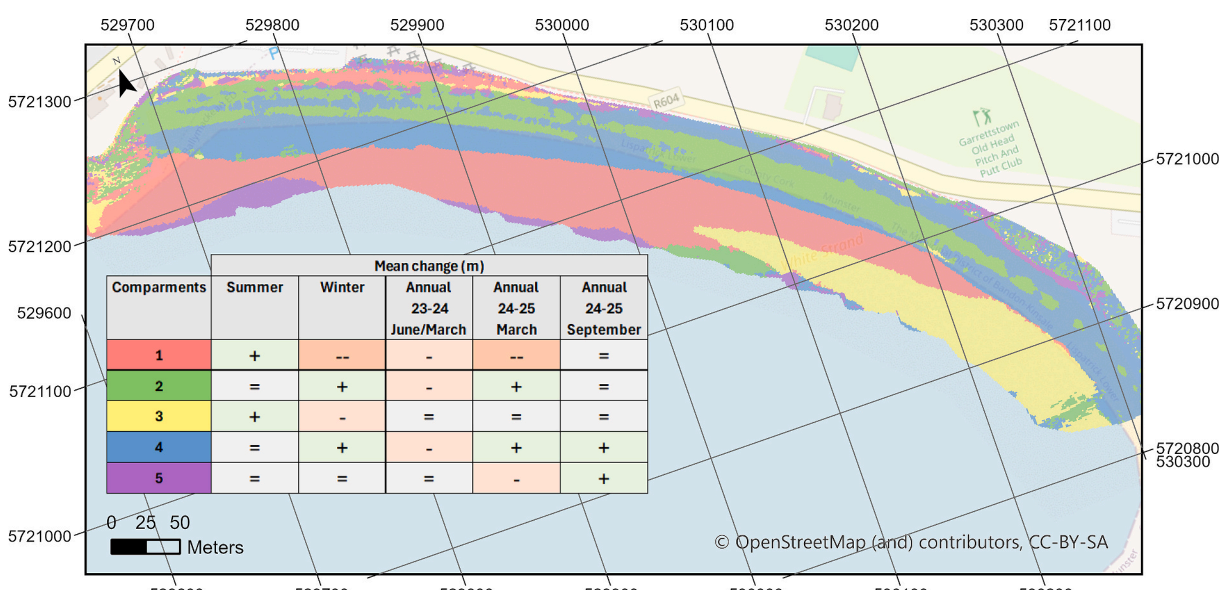


Fig. 5. Linear regression rates (LRR) of vegetation-line change at Garrylucas derived from (A) aerial imagery for 2000–2021, (B) aerial imagery for the shorter 2011–2021 interval, and (C) UAV-derived vegetation lines for June 2023–September 2025, (D) 2021 aerial image.



Comparments	Mean change (m) Summer	Winter	Annual 23-24 June/March	Annual 24-25 March	Annual 24-25 September
1	+	--	-	--	=
2	=	+	-	+	=
3	+	-	=	=	=
4	=	+	-	+	+
5	=	=	=	-	+

Fig. 6. PCA-derived morphodynamic compartments at Garrylucas based on stacked elevation-change rasters from repeated UAV surveys (2023–2025). The table summarises mean elevation change (m) per compartment for seasonal and annual intervals. Values are expressed using simplified categorical classes and colour coding: dark orange (++) indicates strong erosion (≥ 0.5 m), light orange (+) moderate erosion (≥ 0.1 m), grey (=) negligible change (± 0.1 m), light green (+) moderate accretion (≥ 0.1 m), and darker green (++) strong accretion (≥ 0.5 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.4. Inchydoney

Vegetation-line mapping reveals compartmentalised behaviour across the barrier beach system (Fig. 9). Accretion during 2000–2011 and rollback during 2011–2021 offset when analysed across the full period, producing near-zero regression rates (Table 2). Restricting analysis to 2011–2021 reveals erosion on the seaward face (mean LRR ≈ -0.33 m yr^{-1}) with high spatial variability. UAV-derived vegetation

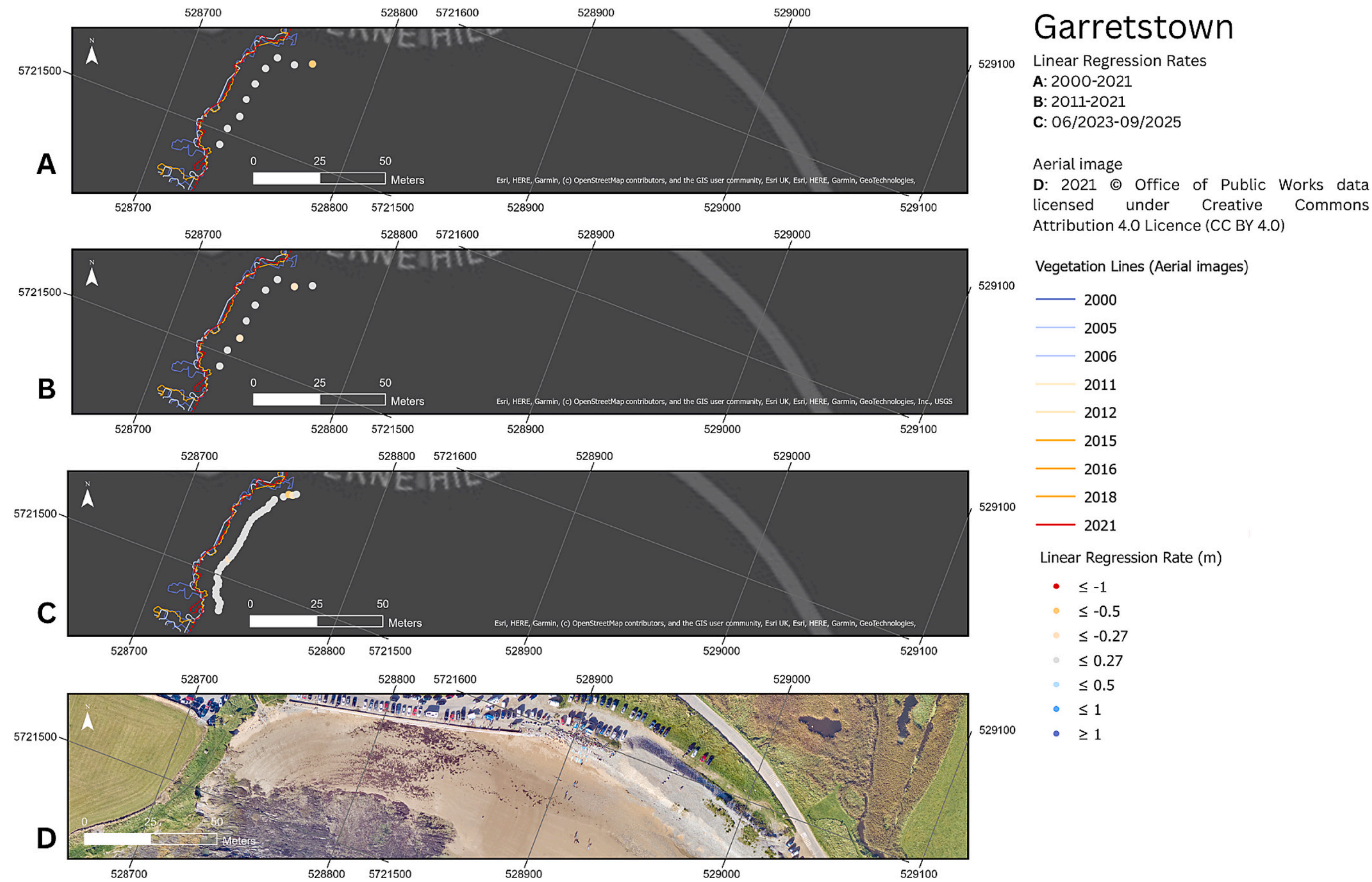


Fig. 7. Linear regression rates (LRR) of vegetation-line change at Garretstown derived from (A) aerial imagery for 2000–2021, (B) aerial imagery for the shorter 2011–2021 interval, and (C) UAV-derived vegetation lines for June 2023–September 2025, (D) 2021 aerial image.

lines (2023–2025) indicate general stability with localised erosion at disturbance hotspots. The SCVI classifies Inchydoney as highly vulnerable, reflecting receptor presence and physical susceptibility rather than uniform shoreline retreat (Appendix A, Table 2).

Profiles demonstrate a highly dynamic barrier-estuary system characterised by berm development, bar migration, and channel reorganisation (Appendix B). UAV DSM differencing (Appendix C) highlights a stable back-barrier, a persistent under-spit erosional hotspot (−1.2 to −1.3 m), and periodic dune-foot and upper-beach accretion. PCA-derived compartments are broadly parallel to the shoreline but become more complex near the sand-tip, revealing storm-sensitive dune-foot zones and recurrent hotspot compartments (Fig. 10). Storm impacts are strongly compartment-specific, producing redistribution within the system rather than uniform retreat (Table 3).

4.5. Owenahincha

Vegetation-line mapping shows multi-decadal oscillation: progression (2000–2005), retreat (2005–2011), and renewed progression (2011–2021), yielding net accretion over the full period (Fig. 11; Table 2). Recent UAV-derived vegetation lines (2023–2025) also indicate progression with localised retreat at access paths and blowouts. Despite boundary accretion, the SCVI classifies Owenahincha as high to very high vulnerability, driven by physical susceptibility and receptor exposure (Appendix A, Table 2).

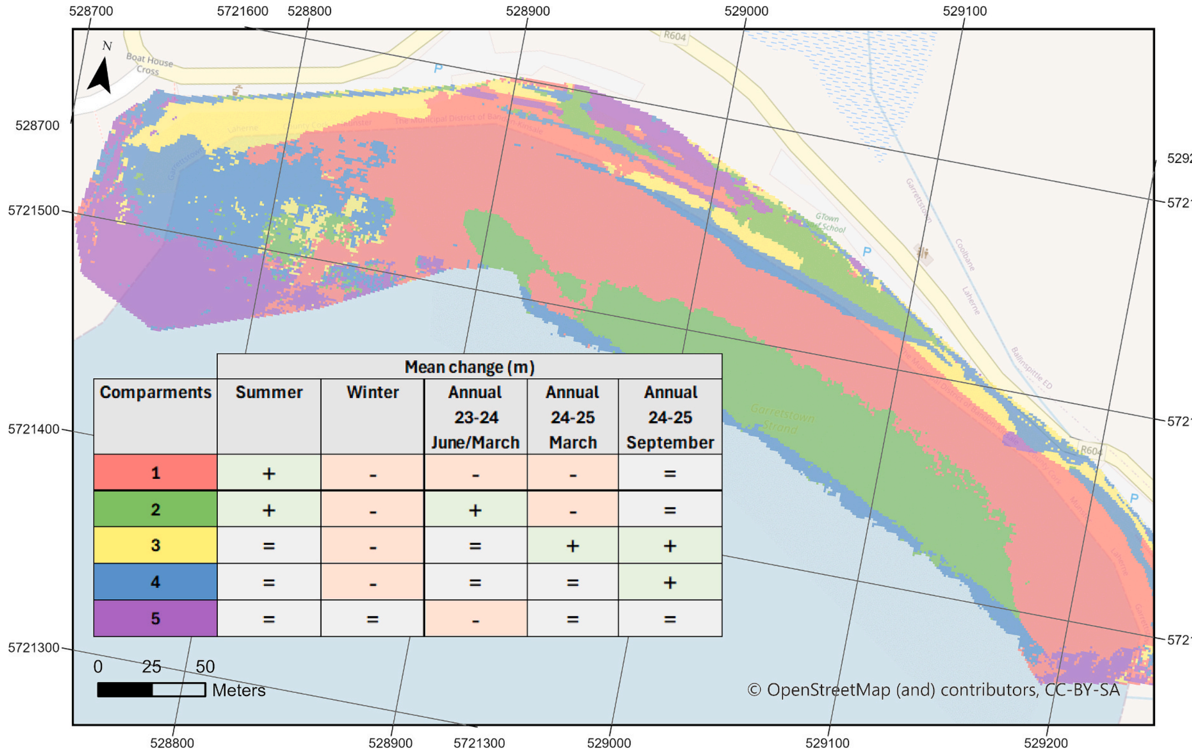
Profiles indicate generally stable dune-foot elevations but cycles of berm formation and internal redistribution without a simple seasonal model (Appendix B). UAV DSM differencing (Appendix C) reveals strong alongshore compartmentalisation and recurrent erosion at disturbance hotspots, demonstrating active internal reworking despite accretion at the vegetation boundary. PCA-derived compartments confirm coherent disturbance-driven zones (Fig. 12). Post-storm impacts are measurable but spatially limited, with rapid recovery common. The system is storm-sensitive but not storm-dominated (Table 3).

5. Discussion

5.1. How monitoring methods construct different narratives of change

Across the five sites, the strongest contrast emerges between boundary translation narratives derived from vegetation-line shorelines, and sediment redistribution narratives from repeated topographic measurements. A third narrative, synthetic vulnerability framing, prioritises exposure and susceptibility independent of measured geomorphic behaviour. These narratives frequently converge but occasionally diverge in ways that affect interpretation and management responses. Vegetation lines compress multiple processes, dune/grassline condition, storm scarping, aeolian recovery, trampling/management, and occasional engineering changes, into a single moving boundary. They are therefore most effective at describing shoreline change over multi-year to multi-decadal timescales yet are comparatively weak at explaining beach changes between surveys. By contrast, profiles and DSM differencing resolve sediment redistribution and adjustments (berm building, bar migration, dune-foot lowering, channel appearance) that can occur with little net shoreline translation. This difference is both methodological, and conceptual, producing different "stories" about the same coast.

Temporal averaging is a powerful narrative filter. When accretionary and erosional phases offset over long temporal windows, the resulting rates can imply stability even where the site has undergone meaningful



Comparments	Mean change (m) Summer	Winter	Annual 23-24 June/March	Annual 24-25 March	Annual 24-25 September
1	+	-	-	-	=
2	+	-	+	-	=
3	=	-	=	+	+
4	=	-	=	=	+
5	=	=	-	=	=

Fig. 8. PCA-derived morphodynamic compartments at Garretstown based on stacked elevation-change rasters from repeated UAV surveys (2023–2025). The table summarises mean elevation change (m) per compartment for seasonal and annual intervals. Values are expressed using simplified categorical classes and colour coding: dark orange (++) indicates strong erosion (≥ 0.5 m), light orange (+) moderate erosion (≥ 0.1 m), grey (=) negligible change (± 0.1 m), light green (+) moderate accretion (≥ 0.1 m), and darker green (++) strong accretion (≥ 0.5 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

change. This reflects a form of dynamic equilibrium at Inchydoney, and a process acceleration at Pilmore. A similar contrast between apparent stability and underlying dynamism has been reported in comparable embayed systems: Mishra et al. (2025) found embayments that appear to be stable at seasonal to annual scales, were dynamic and unstable over decadal scales, noting that areal metrics alone cannot diagnose erosion where sediment is redistributed within the system without net change in extent. Contrasts between short-term and long-term shoreline-change rates have also been reported in multi-method monitoring frameworks, reinforcing the view that averaging temporal windows can suppress event-driven signals (Castro-Quintero et al., 2025).

A second narrative filter is spatial averaging. Shoreline rates (especially when summarised as a mean) can flatten alongshore contrasts and produce a single "site label" (eroding/stable/accreting) even where the system is compartmentalised. The UAV DSM differencing repeatedly shows that many beaches behave as patchworks of coherent zones rather than as uniform translating shorelines. This is strongest at Inchydoney (barrier/estuary compartments with a persistent under-spit hotspot), Garretstown (structure-controlled hotspots, channel/outcrop control, systematic accumulation at hard structures), and Owenahincha (clear alongshore compartmentalisation and redistribution, with local dune-foot vulnerability at blowouts). Even where the overall shoreline is accreting (Owenahincha) or near-stable (Inchydoney in long time-scales), internal zones can be lowering or eroding repeatedly.

The five sites illustrate several recurring proxy failure modes, with back-beach reshaping, pedestrian access infrastructure, and engineered edges undermining the vegetation line as an interpretable shoreline boundary. Another proxy failure mode is associated with a lack of persistent dry beach or limited sediment availability: at Pilmore, the intertidal profile can remain relatively stable while the vegetation line retreats because waves reach the back-beach boundary directly in the absence of dissipative healthy beach. The proxy therefore records "retreat," while cross-shore profiles show little volumetric change. This difference reflects the definition of shoreline change: when the shoreline is represented by the vegetation line, erosion is detected, whereas volume-based measures indicate limited change. At Inchydoney, this effect is amplified by the complex local setting, where the barrier beach, estuary mouth, channels, dunes and adjacent headlands constrain sediment transport and produce strong alongshore variability. In such systems, the "shoreline" is not a single boundary but a set of interacting margins that respond differently depending on the proxy used.

5.2. *What multi-method monitoring reveals about sediment dynamics and vulnerability*

A consistent cross-site insight from the field and UAV data is that change is frequently expressed as redistribution (cross-shore exchange, alongshore partitioning, hotspot erosion/accretion coupling) rather than as uniform landward translation. At Garrylucas, the repeated appearance of berm-dip morphologies (notably in March 2025) points to strong cross-shore partitioning: upper-beach building can coincide with mid-lower beach lowering. At Garretstown, gravel piles, revetments/seawalls, and rock outcrops create recurring hotspots and control channel formation. At Inchydoney, the back-barrier remains stable while the seaward face and under-spit zone show more active reworking, including a persistent erosion hotspot toward the channel. This is not "one shoreline retreating"; it is a system reorganising through interacting compartments. At Owenahincha, vegetation-line proxies indicate net accretion (and stronger accretion in 2011–2021), yet DSM and profiles show substantial internal reworking and localised vulnerability at blowouts and access-related-hotspots (e.g., walking paths). This demonstrates that even where the shoreline is advancing, significant internal instability can persist in ways that matter for management. This compartmentalisation is consistent with established understanding

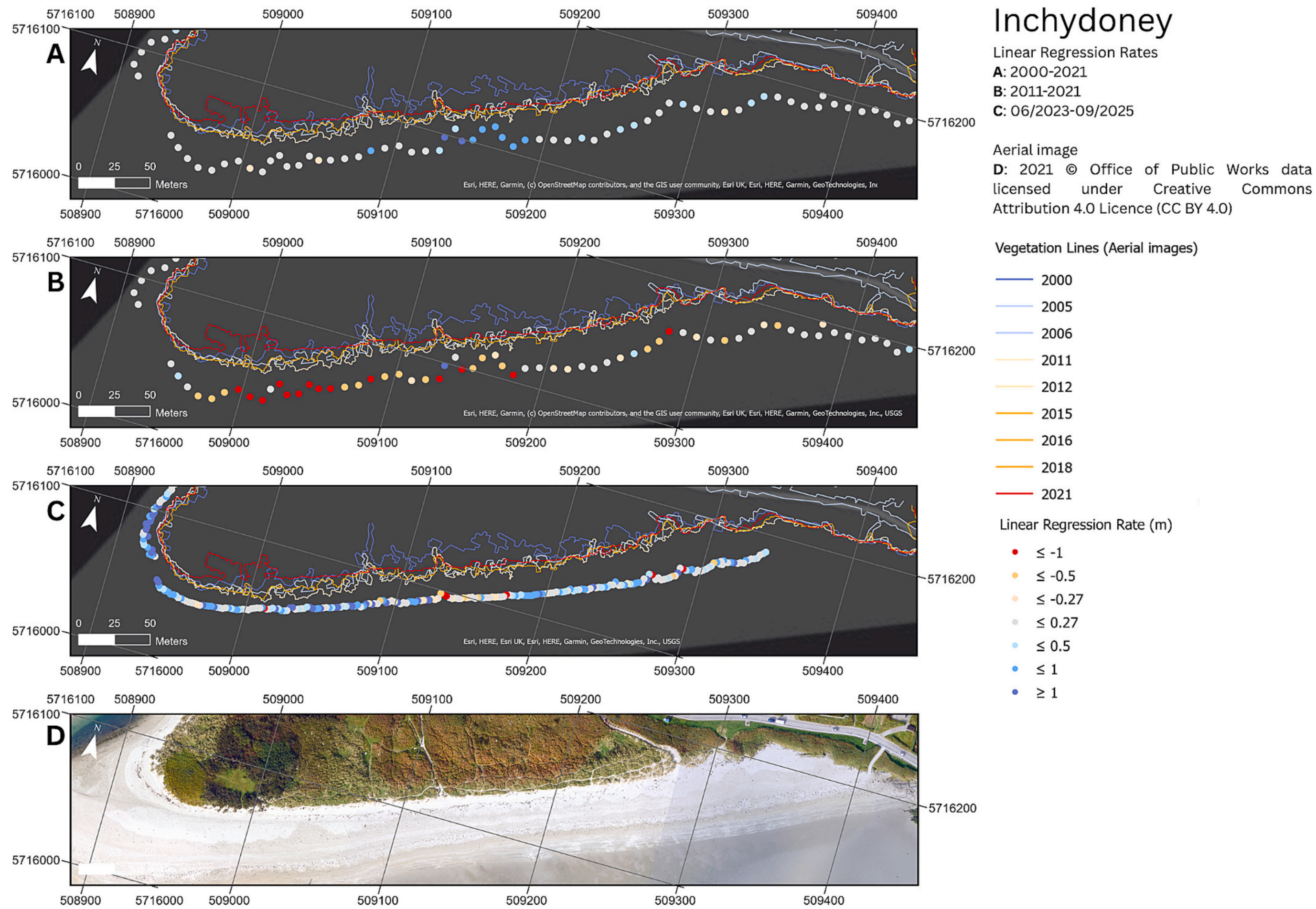


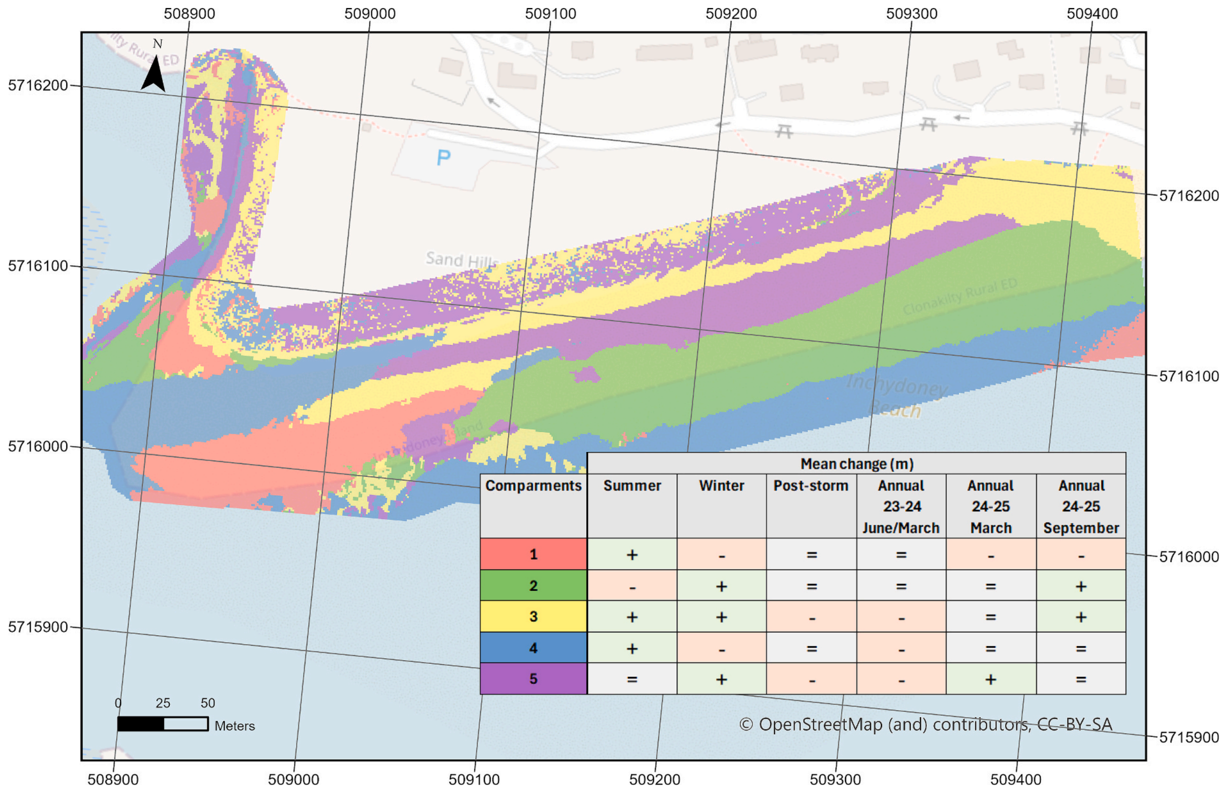
Fig. 9. Linear regression rates (LRR) of vegetation-line change at Inchydoney derived from (A) aerial imagery for 2000–2021, (B) aerial imagery for the shorter 2011–2021 interval, and (C) UAV-derived vegetation lines for June 2023–September 2025, (D) 2021 aerial image.

of embayed-beach morphodynamics, in which sediment is largely reorganised within the embayment rather than exported, and headland-controlled alongshore gradients in wave exposure drive spatially persistent zones of cross-shore exchange and erosion hotspots (Harley et al., 2015). In embayed settings, apparent stability at the boundary can mask substantial internal reorganisation.

Storm response surveys reinforce a practical management message: recovery is not equivalent to stability. It may be full or partial, with "small net change" or incomplete recovery potentially masking repeated stress on the same receptors (dune toe, paths, road edge) and influencing response to subsequent events. Several sites show measurable storm-related lowering and upper-beach retreat. However, the magnitude and detectability are strongly influenced by water levels (wave energy, storm surge, tidal range and phase), whether the site's dominant response is cross-shore exchange vs net loss, and survey timing relative to rapid post-storm recovery and/or repairs. At Garretstown, storm sensitivity is clear (cross-shore movement and lowering with Storm Kathleen; asymmetric alongshore response to Storm Ashley; channel creation and widespread lowering associated with Storm Eowyn), but the system also shows strong recovery, which could be read as resilience, or as repeated reworking that still threatens infrastructure at the back-beach interface. At Pilmore, storms contribute to upper-beach/vegetation-line erosion. However, intertidal elevations remain comparatively stable. The storm narrative thus differs depending on framing as "shoreline retreat" or "intertidal elevation change."

The five sites show that management actions and access infrastructure can become first-order controls on sediment pathways and erosion patterns. Remote monitoring approaches developed for engineered coasts highlight how shoreline trajectories can shift rapidly during and after interventions, reinforcing the need to treat management actions as part of the morphodynamic signal (Cabezas-Rabadán et al., 2025). This is not limited to hard structures: paths and blowouts repeatedly emerge as erosion hotspots (Inchydoney and Owenahincha), while repairs/reshaping disrupt proxy continuity (Pilmore road repair; Garretstown and Garrylucas anthropized back-beaches). In these contexts, monitoring is not only observing "nature"; it is tracking a coupled human-coastal system where interventions and use patterns condition both hazard expression and detectability.

The SCVI performs strongly as a screening and prioritisation tool. It identifies where exposure and susceptible receptors cluster (roads, dunes, protected habitats, tourism assets) and produced a consistent basis for regional prioritisation. However, across sites, its narrative diverges from topographic observations in predictable ways. The SCVI can classify sites as uniformly high vulnerability while field/UAV data show strong intra-site variability (Pilmore's western hotspot vs eastern stabilisation; Inchydoney's stable back-barrier vs under-spit erosion). It can read high vulnerability where measured change suggests stability or recovery in some components (e.g. Owenahincha's accreting vegetation boundary), because the index foregrounds susceptibility and receptors rather than realised geomorphic change. On the contrary, it can under-inform on the mechanism of risk. The SCVI does not diagnose whether risk is driven by wave and hydrodynamic regime, chronic shoreline retreat, cross-shore exchange narrowing the dry beach buffer, structure-driven hotspots, or channel dynamics. Global CVI applications also show that dominant contributors to vulnerability can be scale-dependent and dataset-driven, reinforcing the need to interpret index outputs as



Comparments	Mean change (m) Summer	Winter	Post-storm	Annual 23-24 June/March	Annual 24-25 March	Annual 24-25 September
1	+	-	=	=	-	-
2	-	+	=	=	=	+
3	+	+	-	-	=	+
4	+	-	=	-	=	=
5	=	+	-	-	+	=

Fig. 10. PCA-derived morphodynamic compartments at Inchydoney based on stacked elevation-change rasters from repeated UAV surveys (2023–2025). The table summarises mean elevation change (m) per compartment for seasonal, post-storm, and annual intervals. Values are expressed using simplified categorical classes and colour coding: dark orange (++) indicates strong erosion (≥ 0.5 m), light orange (+) moderate erosion (≥ 0.1 m), grey (=) negligible change (± 0.1 m), light green (+) moderate accretion (≥ 0.1 m), and darker green (++) strong accretion (≥ 0.5 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

screening signals rather than site-process diagnoses (Basnayake et al., 2026).

A related management implication concerns the treatment of coastal protection within vulnerability assessments. In Ireland, there is currently no comprehensive national dataset of coastal protection structures or interventions, making their systematic inclusion in index tools difficult. It might therefore seem that adding a coastal protection parameter would resolve this limitation. However, the presence of protection does not equate to lower risk: it often reflects a legacy of active erosion and can generate new hotspots through scour, sediment trapping, and boundary fixing (Basco, 2006; Lerma et al., 2022). Even where protection is mapped, its influence depends on age, condition, and management regime (Fitton et al., 2017). Without this contextual information, including protection in an index may introduce as much bias as it removes. This reinforces a pragmatic division of labour - index tools help identify where attention is warranted, while site-specific monitoring determines what is actually occurring and what responses are appropriate.

5.3. Methodological trade-offs and implications for monitoring design

Vegetation-line proxies (aerial/UAV orthophotos) deliver multi-decadal context and regional comparability. They reveal acceleration only when temporal windows are structured to detect it yet miss internal sediment redistribution and can fail where boundaries are constrained or disturbed. RTK-GNSS cross-shore profiles are robust, repeatable, and feasible even in relatively poor weather conditions. They resolve seasonal/storm envelopes and dune-beach coupling along fixed transects but can miss alongshore heterogeneity between profiles and can under-represent hotspot migration unless profile density is high or targeted. UAV DSM differencing resolves spatial complexity, hotspots, and coherent zones of change. It supports volumetric interpretations and management-relevant mapping (e.g., where erosion concentrates relative to paths/structures). However, it is feasibility-limited by wind/rain/fog/daylight/tide, regulation, and operational capacity, and post-storm capture is often delayed.

These results support a tiered monitoring logic that explicitly matches data products to specific decision needs, rather than defaulting to the highest-resolution method available:

At Tier 1, screening and regional prioritisation rely on long-term aerial imagery proxies and index outputs such as the SCVI to identify broad patterns of exposure, receptors, and potential chronic change. Analyses should be structured to test multiple temporal windows in order to capture dynamic equilibrium patterns and avoid masking recent acceleration trends (for example, comparing 2000–2021 with 2011–2021). The outcome at this level is a ranked and transparent shortlist of sites or shoreline segments that warrant closer attention.

Tier 2 focuses on diagnosis and routine site monitoring. Repeated RTK-GNSS cross-shore profiles, ideally conducted post-winter and post-summer and complemented by rapid post-storm surveys where feasible, allow quantification of the seasonal envelope, storm response, and dune-beach coupling at fixed transects. Profiles are often sufficient on their own where change is dominated by cross-shore adjustment with weak alongshore variability, or where the management question is framed around a few fixed assets aligned with transects. The objective at this stage is to develop a defensible understanding of whether a system is dominated by seasonal sediment exchange, chronic volumetric loss, boundary retreat without significant volume change, or episodic disturbance.

Tier 3 involves targeted spatial monitoring for complex or high-risk sites. UAV-derived digital surface models and orthophotography, acquired at baseline, following key storm events, and at periodic intervals,

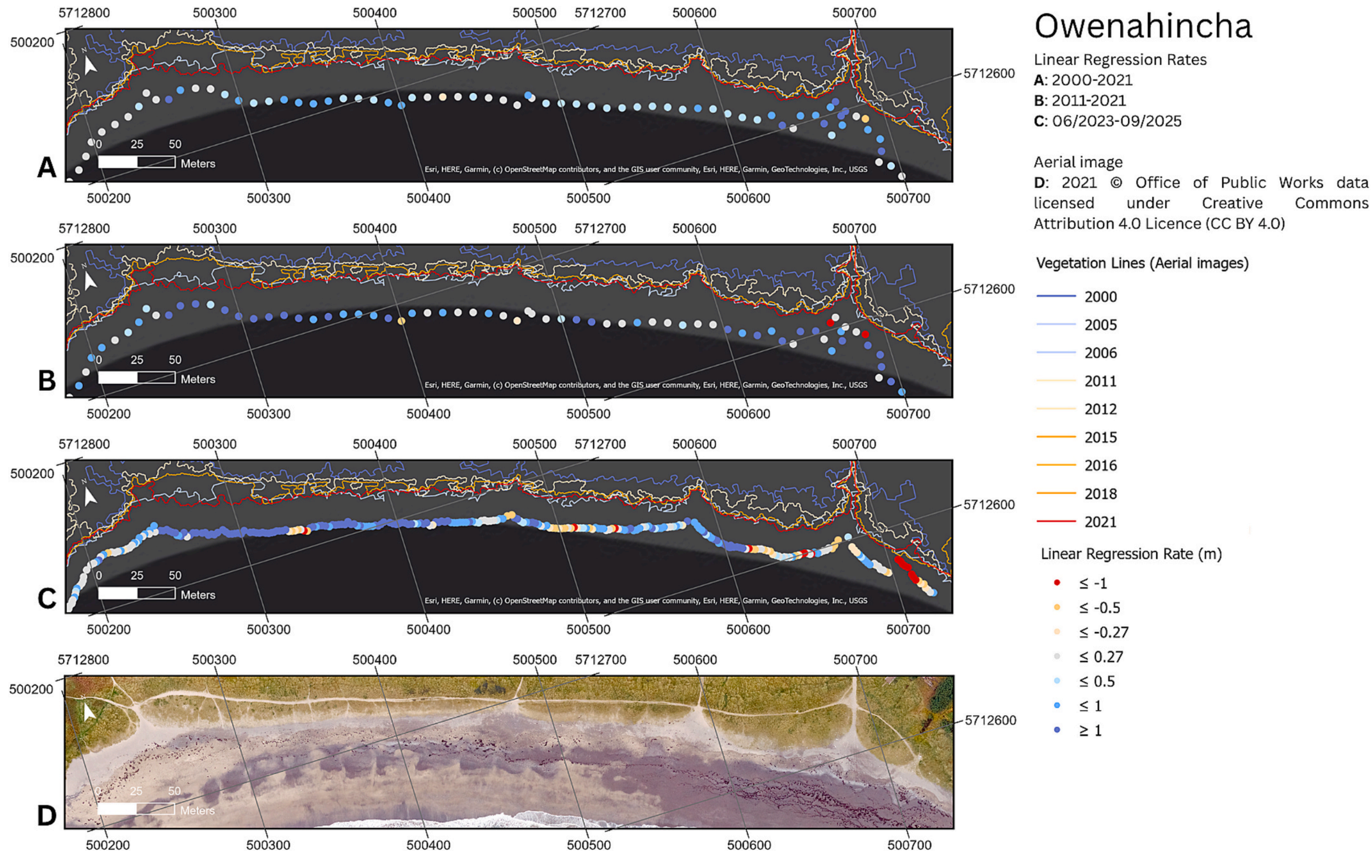
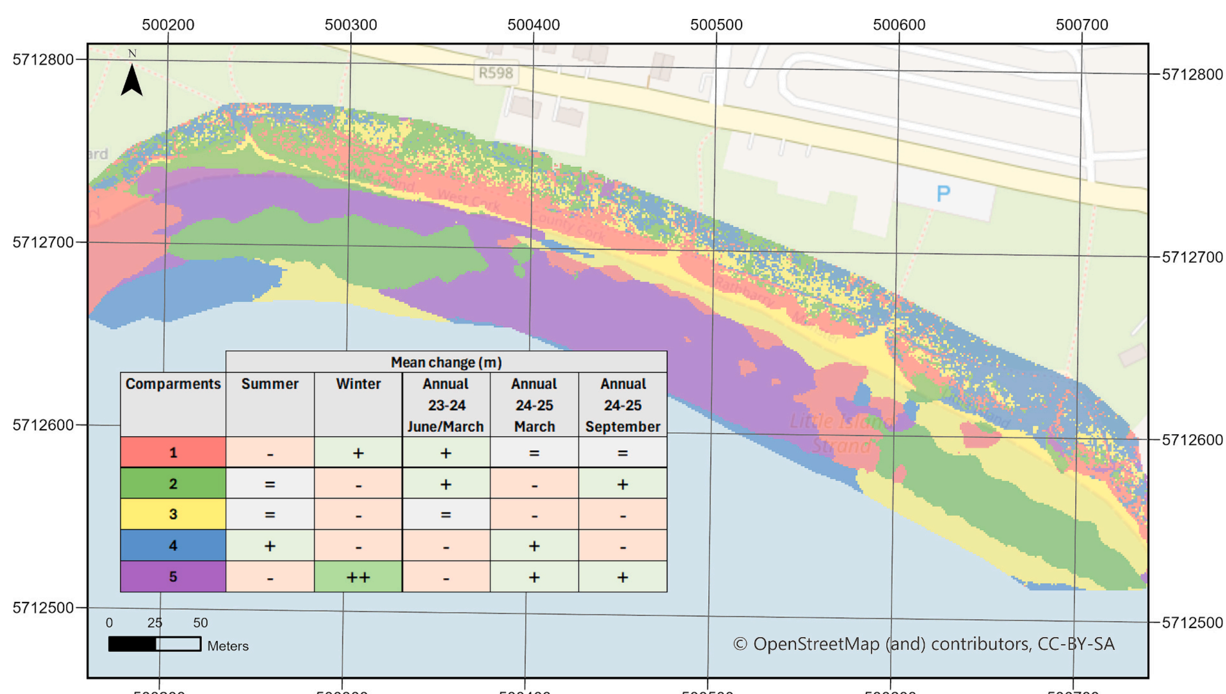


Fig. 11. Linear regression rates (LRR) of vegetation-line change at Owenahincha derived from (A) aerial imagery for 2000–2021, (B) aerial imagery for the shorter 2011–2021 interval, and (C) UAV-derived vegetation lines for June 2023–September 2025, (D) 2021 aerial image.



Comparments	Mean change (m)				
	Summer	Winter	Annual 23-24 June/March	Annual 24-25 March	Annual 24-25 September
1	-	+	+	=	=
2	=	-	+	-	+
3	=	-	=	-	-
4	+	-	-	+	-
5	-	++	-	+	+

Fig. 12. PCA-derived morphodynamic compartments at Owenahincha based on stacked elevation-change rasters from repeated UAV surveys (2023–2025). The table summarises mean elevation change (m) per compartment for seasonal and annual intervals. Values are expressed using simplified categorical classes and colour coding: dark orange (++) indicates strong erosion (≥ 0.5 m), light orange (+) moderate erosion (≥ 0.1 m), grey (=) negligible change (± 0.1 m), light green (+) moderate accretion (≥ 0.1 m), and darker green (++) strong accretion (≥ 0.5 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

provide the spatial resolution necessary to map erosion hotspots, structural or pathway controls, channel dynamics, and alongshore compartments. This level of analysis supports intervention appraisal by identifying where sediment is being trapped, where scour is concentrated, and whether hotspots are migrating through time. The outcome is spatially explicit evidence that can inform the design or evaluation of management actions and help communicate why a "stable rate" does not necessarily equate to "low risk." UAV monitoring is particularly appropriate where alongshore heterogeneity makes average rates misleading, at persistent hotspots (Pilmore western upper-beach; Inchydoney under-spit), under structure - or outcrop-controlled morphology (Garretstown), and at large or difficult-to-access sites.

Critically, this strategy is not a technology ladder ("UAV is best"), rather a decision ladder: use the simplest method that resolves the question and escalate when spatial complexity or management stakes demand it. A genuinely resource-aware strategy must also consider operational efficiency and staff time. In this study, UAV surveys required ground control point (GCP) deployment and concurrent RTK-GNSS validation, making high-resolution mapping more labour-intensive than routine profile surveys. Encouragingly, emerging RTK- and PPK (Post-Processed Kinematic)-enabled UAV platforms may reduce or eliminate the need for extensive ground control, decreasing field time and the logistical burden. However, their accuracy and repeatability remain insufficiently validated. A hybrid approach combining selective GCP control and targeted high-resolution deployment remains prudent.

5.4. Limitations and transferability

The intensive monitoring period (2023–2025) is sufficient to resolve seasonal cycles, several storm responses, and spatially persistent hotspots, but it cannot fully characterise long-term regime shifts or recovery trajectories following rare extremes. This is partly mitigated by the integration of historical proxy records designed to extend context. However, interpretation of resilience remains conditional on the limited window of forcing captured.

UAV surveys are inherently episodic in Atlantic settings due to wind/rain/fog/daylight/tide and regulatory constraints, which can delay post-storm acquisition beyond the peak-impact window. This can bias storm narratives toward partial recovery states and under-represent short-lived erosional signatures. RTK profiles reduce this limitation but cannot fully substitute for spatial coverage at complex sites.

The PCA and clustering approach is valuable for summarising coherent spatio-temporal covariance in DSM change, noting that compartment boundaries and counts depend on input intervals and clustering parameters. It is best interpreted as a descriptive simplification of dominant shared behaviour rather than a definitive "true partition" of coastal processes. The broader point remains robust even if the compartmenting method changes: many sites exhibit repeatable spatial structure in change that is missed by single-line proxies and mean rates.

Ireland's monitoring context, high-energy Atlantic forcing (especially south and west), frequent cloud cover affecting optical remote sensing, limited long-term beach-scale archives, and fragmented governance, makes the boundary translation/sediment redistribution tension particularly acute. However, the main contribution is transferable: the narrative-comparison logic (how methods filter time and space), the demonstration of redistribution/hotspot dominance, and the tiered strategy linking monitoring products to management questions. These are relevant to many field-data-limited or feasibility-constrained coastlines where decision-makers must choose what to measure under limited capacity.

6. Conclusion

Across five contrasting beaches, the study shows that shoreline change is both a physical indicator, and a measurement-derived narrative. Long-term proxies, profiles, DSM differencing, storm surveys, and indices can each tell a different "truth" about the same system. The most management-relevant insight is that many sites are governed by sediment transport and compartmentalised redistribution, rather than uniform retreat, shaped by hydrodynamics, local geology and management. Therefore, monitoring strategies must be designed to detect both boundary movement and internal sediment reorganisation. A multi-level, resource-aware framework provides a defensible way to move from regional screening to site diagnosis and, where needed, targeted spatial monitoring; improving both the transparency of prioritisation and the fit between evidence and intervention.

CRediT authorship contribution statement

Emma Chalençon: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mélanie Biausque:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Fiona Cawkwell:** Writing – review & editing, Supervision, Methodology. **Rory Scarrott:** Writing – review & editing, Visualization, Resources. **Larissa Macedo Cruz de Oliveira:** Writing – review & editing, Resources. **Ayse Nur Karayel:** Writing – review & editing, Resources. **Aaron Lim:** Writing – review & editing, Resources. **Michael O'Shea:** Writing – review & editing, Supervision. **Jimmy Murphy:** Writing – review & editing, Supervision, Funding acquisition.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Emma Chalencon reports financial support was provided by Cork County Council. 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.margeo.2026.107851.

Data availability

The data that support the findings of this study are held by University College Cork (UCC) and are available from the corresponding author, E.

C., upon reasonable request for academic research purposes. Requests for access will be subject to institutional approval and may require a data use agreement. Some datasets used in this study are derived from third-party sources (Tailte Éireann and the Office of Public Works) and are subject to their respective data access policies; these data are not publicly available. Researchers seeking access to these datasets should apply directly to the relevant organisations.

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