

Geomatics, Natural Hazards and Risk

ISSN: 1947-5705 (Print) 1947-5713 (Online) Journal homepage: www.tandfonline.com/journals/tgnh20

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**To cite this article:** Komali Kantamaneni , Abhishek Samrat , Champika Liyanage , Ruchiru Herath , Fahad Al-Ruwaili , Reshma Sunkur , Upaka Rathnayake & Andrew Barkwith (2026) A physical coastal vulnerability index for site-specific assessment, Geomatics, Natural Hazards and Risk, 17:1, 2753243, DOI: 10.1080/19475705.2026.2753243

**To link to this article:** https://doi.org/10.1080/19475705.2026.2753243

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Published online: 29 Oct 2026.

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GEOMATICS, NATURAL HAZARDS AND RISK
2026, VOL. 17, NO. 1, 2753243
https://doi.org/10.1080/19475705.2026.2753243

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RESEARCH ARTICLE

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# A physical coastal vulnerability index for site-specific assessment

Komali Kantamaneni[a,b], Abhishek Samrat[a,c], Champika Liyanage[b], Ruchiru Herath[a,b], Fahad Al-Ruwaili[a,b], Reshma Sunkur[d], Upaka Rathnayake[e] and Andrew Barkwith[c]

[a]United Nations-SPIDER-UK Regional Support Office, University of Lancashire, Preston, UK; [b]School of Engineering and Computing, University of Lancashire, Preston, UK; [c]British Geological Survey, Keyworth, Nottingham, UK; [d]Doctoral School, University of Technology, Mauritius, La Tour Koenig, Pointe aux Sables, Mauritius; [e]Department of Civil Engineering and Construction, Atlantic Technological University, Sligo, Ireland

**ABSTRACT**

Assessment of coastal vulnerability is essential for protecting coastal areas from natural hazards and extreme weather events. In the United Kingdom (UK), low-lying coastal zones frequently experience inundation, flooding, landslides, coastal erosion, and cliff failures, all of which are intensified by climate change. Although the UK possesses one of Europe's longest and most geomorphologically diverse coastlines, this diversity limits the effectiveness of standard assessment tools such as the Coastal Vulnerability Index (CVI), which often fail to capture site-specific characteristics. To address this research gap, the present study used a Place-Based Coastal Vulnerability Index (PB-CVI) that integrates both conventional and recently used physical vulnerability parameters tailored to local coastal conditions. The PB-CVI was applied to assess approximately 110 km of the Lancashire coastline and adjoining Sefton coast in northern England. Results showed that 66% of the coastline falls within high or very high vulnerability categories, with Blackpool, Heysham, and areas near Fleetwood identified as the most vulnerable locations. GIS-based vulnerability maps were produced to visualize spatial variations in vulnerability and support effective decision-making. The study also proposed place-based adaptation and resilience strategies, providing valuable guidance for local and national policymakers to implement immediate and long-term coastal protection measures.

**ARTICLE HISTORY**
Received 18 May 2026
Accepted 16 October 2026

**KEYWORDS**
Coastal vulnerability; GIS maps; Lancashire, UK; site specific assessment; coastal landslides

## 1. Introduction

Coastal zones are one of the most dynamic environments globally, with their particular location between the land and the sea making them vulnerable to mounting pressures from rapid urbanization, climate change and intensifying natural hazards (Roy et al. 2023; Adhikari et al. 2025). Accelerated coastal erosion, rising sea levels and increasing extreme weather events are significantly changing coastal landscapes, posing substantial risks to both natural ecosystems and human settlements (Nicholls et al. 2021; Masson-Delmotte et al. 2021). Low-lying areas and geomorphologically complex coastlines are especially at risk due to increased interactions between natural processes and anthropogenic activities, which amplify vulnerability (Pethick and Crooks 2000; Wong et al., 2014). As highlighted by recent studies, there is now a critical need for accurate, spatially explicit and context-specific coastal vulnerability assessments for effective planning and resilient communities (Vousdoukas et al. 2020; Sayers et al., 2022).

Traditional techniques to assess coastal vulnerability, such as the Coastal Vulnerability Index (CVI), have been widely used to evaluate susceptibility to hazards by combining parameters like coastal slope, erosion rates, wave energy and geomorphology (Gornitz et al. 1991). While these approaches provide valuable insights, recent studies emphasize their limitations in capturing site-specific characteristics and the complexity of local coastal systems (Kantamaneni et al. 2024; Deb et al. 2024). Consequently, there has been a shift towards place-based and integrated frameworks that take into consideration both physical and socio-environmental conditions, thus resulting in more tailored and actionable assessments (Acheampong

**CONTACT** Komali Kantamaneni kkantamaneni@lancashire.ac.uk

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et al. 2025). These techniques recognize that coastal vulnerability is not standard but changes significantly across spatial scales (Basnayake et al. 2026) because of differences in environmental conditions (Bourhili et al. 2025), land use patterns (Ideki and Ajoku 2024) and levels of human intervention (Wang et al. 2025).

In recent years, there has been growing recognition of the importance of integrating nature-based solutions with traditional engineering methods to enhance coastal resilience (Twomey et al. 2025). Natural features like wetlands, dunes and vegetation play a critical role in dissipating wave energy, reducing erosion and supporting ecosystem services (Temmerman et al. 2013; Della Bella et al. 2024). However, many coastlines, including those in the northwest of England, have seen loss and/or damage to these ecosystems, leading to increased reliance on hard engineering structures such as seawalls and revetments (Marsh et al. 2026). While these structures provide immediate protection, they have several long-term limitations, especially under accelerating sea level rise and changing sediment dynamics (Nicholls et al. 2021). This therefore underscores the need for hybrid approaches that combine engineered and nature-based solutions. While the Lancashire coastline in the northwest of England is characterized by low-lying terrain, sandy beaches, estuaries and extensive urban development making it particularly vulnerable to flooding and erosion (Kantamaneni et al. 2024; Apine and Stojanovic 2024).

In this respect, the present study uses a Place-Based Coastal Vulnerability Index (PB-CVI) to assess the physical vulnerability of the Lancashire and adjoining Sefton coastline. Building on the traditional CVI framework, the PB-CVI accounts for both established and recently used parameters, including coastal landslides, to better capture localized vulnerability patterns. The current research provides a detailed assessment of vulnerability variations along the coastline by applying the methodology across a high-resolution spatial grid, thereby enabling the identification of highly vulnerable hotspots and areas of relative resilience. This study provides a more nuanced understanding of coastal vulnerability by addressing the current limitations of standardized indices and incorporating local characteristics. Such insights are critical for informing targeted adaptation strategies, improving coastal management and supporting evidence-based policy decisions. Also, the study aligns with global calls for integrated and adaptive coastal management frameworks to increase resilience to ongoing climate change (Nicholls et al. 2021). The application of this PB-CVI method not only provides valuable data on coastal vulnerability patterns in Lancashire and Sefton but also offers a transferable framework that can be adapted to other regions worldwide. By bridging the gap between global assessment techniques and local-scale realities, the present study contributes to the broader effort of strengthening coastal resilience and promoting sustainable coastal development.

## 2. Study area

**The study area includes the Lancashire coastline and the adjoining Sefton coast in Merseyside, Northwest England; together, these constitute the study coastline.** Figure 1 presents the selected study area for this study. Preston is one of the largest urban settlements in Lancashire. The administrative county has 12 districts (which are referred to as Lancashire 12) with two unitary authorities – Blackpool and Blackburn with Darwen, which are collectively referred to as Lancashire 14. The combined GDP is approximately £49 bn for Lancashire 14 and £40.4 bn for Lancashire 12. Preston has the highest GDP of £6.1 bn at the local authority level (Lancashire County Council 2024). Lancashire-14 has more than 3,066 $km^2$ of area, and the population is 1.6 million, with a population density of 527 people per square kilometre (Lancashire County Council 2025). Blackpool is a highly urbanized area in the Lancashire region with the highest population density, i.e. 4,135 people per square kilometre (Lancashire County Council 2025). Lancashire has approximately 120 km of coastline, with diverse infrastructure and features, including a nuclear power plant (Heysham). The major rivers of Lancashire are the Lune, the Wyre, and the Ribble, which all flow generally westwards into the Irish Sea. On the other hand, Sefton, a metropolitan borough in Merseyside and historically part of Lancashire, borders the study area to the south (Figure 1).

While the English coast has been identified as more erosion-vulnerable than Wales and Scotland, where isostatic rebound provides some natural mitigation (Kantamaneni et al. 2022). The study area coast facing the Irish Sea in northwest England is one of the more exposed and physically complex sections of the English shoreline. The coast is characterized by low-lying terrain, sandy beaches, dune systems, and two of

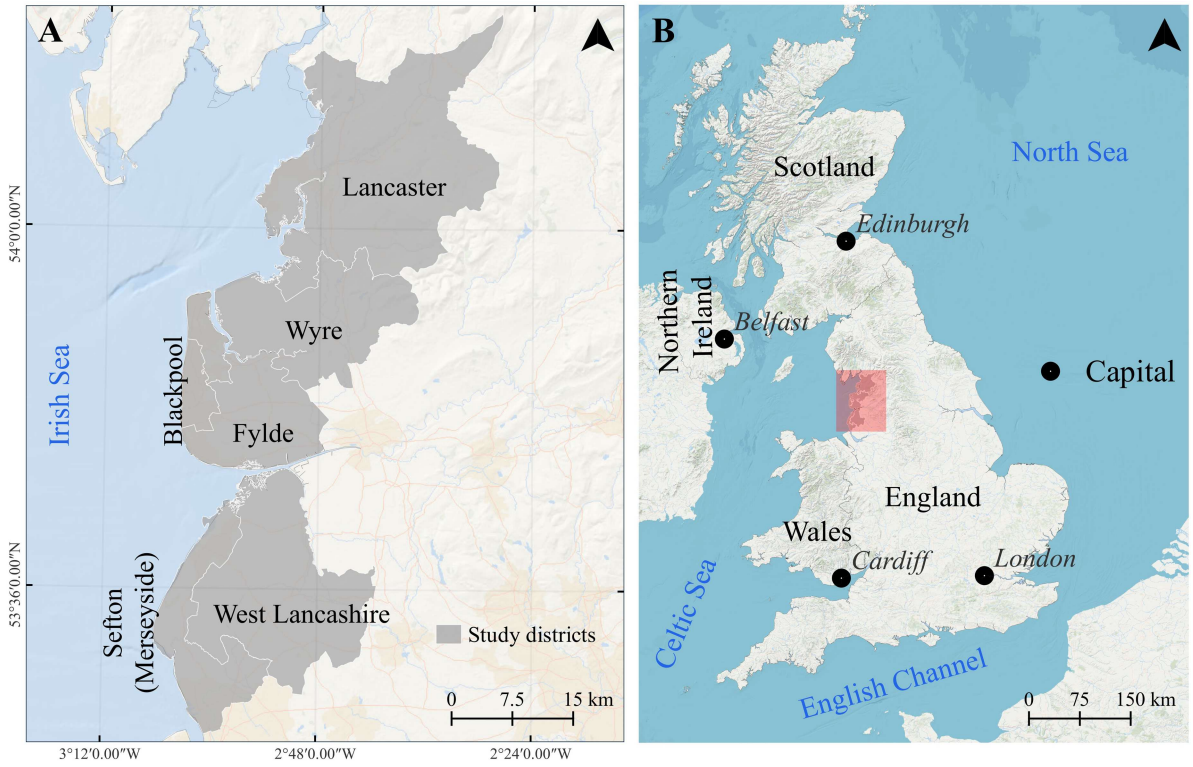



**Figure 1.** Study area location map showing (A) Lancashire, England, with district boundaries, and (B) the location of Lancashire within the United Kingdom.

the country's most significant macrotidal estuaries, Morecambe Bay and the Ribble Estuary, which offer limited natural resistance to storm-driven flooding (Pye and Neal 1994; Van Der Wal et al. 2002; Prime et al. 2015). The Ribble Estuary is funnel-shaped and tidally dominated, with ordinary tidal ranges reaching 8 m at spring tide and 4.4 m at neap tide, making the surrounding low-lying hinterland highly susceptible to inundation during storm surge events (Li et al. 2018; Pannozzo et al. 2021).

The Irish Sea is known for its significant interactions between tides and surges. Deep Atlantic low-pressure systems create considerable surge responses that are greatly affected by the area's large tidal range. This interaction significantly increases the risk of flooding, especially when surges coincide with high spring tides (Olbert et al. 2013). Historically, these conditions have led to severe coastal flooding along the study area shoreline, particularly in Fleetwood. The town experienced devastating inundation in 1927, resulting in six fatalities, and again in November 1977, when over 1800 properties were flooded. This led to the construction of concrete sea walls to protect the town from future flooding (Prime et al. 2015). Recent modelling focused on Fleetwood has demonstrated that even small increases in mean sea level could significantly reduce the return period of flood-critical water levels (Prime et al. 2015). The Wyre district, which includes Fleetwood and parts of the northern Lancashire shoreline, has been specifically identified as one of the English coastal areas most likely to face increasing pressure on existing hold-the-line defence policies by the 2050s (Sayers et al. 2022). The study trajectory, along with the extensive urban and tourism infrastructure concentrated along the coastline at Blackpool, Southport, and Heysham, adds a significant socioeconomic dimension to the region's vulnerability (Dawson et al. 2009).

## 3. Materials and methodology

A wide range of methods has been developed to assess coastal vulnerability, and the Coastal Vulnerability Index (CVI), first introduced by Gornitz et al. (1991), remains one of the most widely used and well-established approaches (Roukounis and Tsihrintzis 2022; Ortiz et al. 2024). A key strength of the CVI is its flexibility. Its indicators can be adapted to the environmental, geographic and socioeconomic conditions of

different coastal settings, which has allowed it to be applied at several spatial scales. At the global scale, Basnayake et al. (2026) applied a CVI to assess coastal vulnerability worldwide and identify its dominant contributors. At the national scale, Furlan et al. (2021) developed a multi-dimensional CVI to assess vulnerability to inundation scenarios along the Italian coast, and Boumpoulis et al. (2026) developed the Hellenic Coastal Vulnerability Index (HCVI) for a national assessment of Greece. At the regional scale, Tragaki et al. (2018) combined geomorphic, oceanographic and demographic parameters for the Peloponnese, Greece, while Tanim et al. (2022) integrated socio-environmental indicators using data-driven and multi-criteria approaches in South Carolina, U.S.A. At the local scale, Boumpoulis et al. (2025) incorporated geotechnical data into a Geotechnical CVI and validated it against observed coastal erosion problems. Other regional and local applications include Harvey and Woodroffe (2008) in Australia, Duriyapong and Nakhapakorn (2011) in Thailand, Deb et al. (2024) in Bangladesh, and Kantamaneni et al. (2018, 2023) in the UK and the China in coastal cities/megacities. Across these scales, the CVI typically considers physical factors such as coastal slope, wave height, erosion rates and storm characteristics to assess the susceptibility of coastal areas to natural hazards (Gornitz et al. 1991; Pantusa et al. 2018). Some applications also incorporate human dimensions, including population density, land use and land cover, and economic losses associated with disasters (Tanim et al. 2022). By bringing these variables together, the CVI provides a more comprehensive picture of coastal vulnerability and its driving factors.

The present study operates at the regional-to-local scale. The CVI framework is applied following the original concept introduced by Gornitz et al. (1991), which was based on seven parameters. It draws on six commonly used variables identified in earlier studies (Palmer et al. 2011; Davies 2012; Kantamaneni et al. 2018), while also incorporating an additional, recently established parameter, coastal landslides (Samrat et al. 2026). Incorporating coastal landslides provides a more comprehensive assessment of local physical coastal vulnerability. Consequently, this study uses the Place-Based Coastal Vulnerability Index (PB-CVI) to evaluate the physical vulnerability of the Lancashire and Sefton coastlines.

### 3.1. Data collection and parameter measurement for PB-CVI

For this assessment, approximately 110 km of coastline was assessed across Lancaster, Wyre, Blackpool, Fylde, West Lancashire, and **adjoining Sefton in Merseyside**. The coastline was then divided into grid cells of 500 × 500 m, generating a total of 220 cells. Each cell was subsequently assessed using seven parameters, as explained below:

a) **Beach width** (Figure 2) was measured by uploading the cell KML file into Digimap (Ordnance Survey 2024) and identifying the perpendicular distance between the Mean Low Water and Mean High Water lines, which were clearly shown in OS Digimap and GIS. The measurement was taken along the upper boundary of each cell and recorded in meters (m).
b) **Dune width** (Figure 2) was measured in a similar way using Digimap and GIS. Where sand dunes were present and clearly marked on the OS Digimap, their width was measured along the top edge of the cell, following the perpendicular to the coastline, and the values were recorded in meters (m).
c) **The coastal slope** (Figure 2) was calculated using Google Earth Pro. It was expressed as a percentage (%) using the rise-over-run method, multiplied by 100. Measurements were taken from the waterline at the seaward edge of each cell to the inland boundary so that the slope reflected the full coastal profile.
d) **Vegetation behind the back beach** (Figure 2) was measured as the distance of vegetation cover landward of the beach. A line was drawn parallel to the upper edge of each cell to capture vegetation such as grassland, trees, and agricultural land, while excluding built-up features. The total length of vegetation along the 500 m transect was then calculated in meters (m).
e) **Built structures behind the back beach** (Figure 2) were measured using the same transect-based approach. Roads, industrial areas, commercial buildings, and residential properties were identified along the 500 m cell transect, and their individual lengths were added together to obtain the total built-up length in metres (m).
f) **Sea defences** (Figure 2) were mapped in Google Earth Pro along the coastline within each coastal cell. Hard defences such as sea walls, rock revetments, timber structures, and rock armour were identified from the satellite imagery. The total length of defence within each cell was measured in meters and then

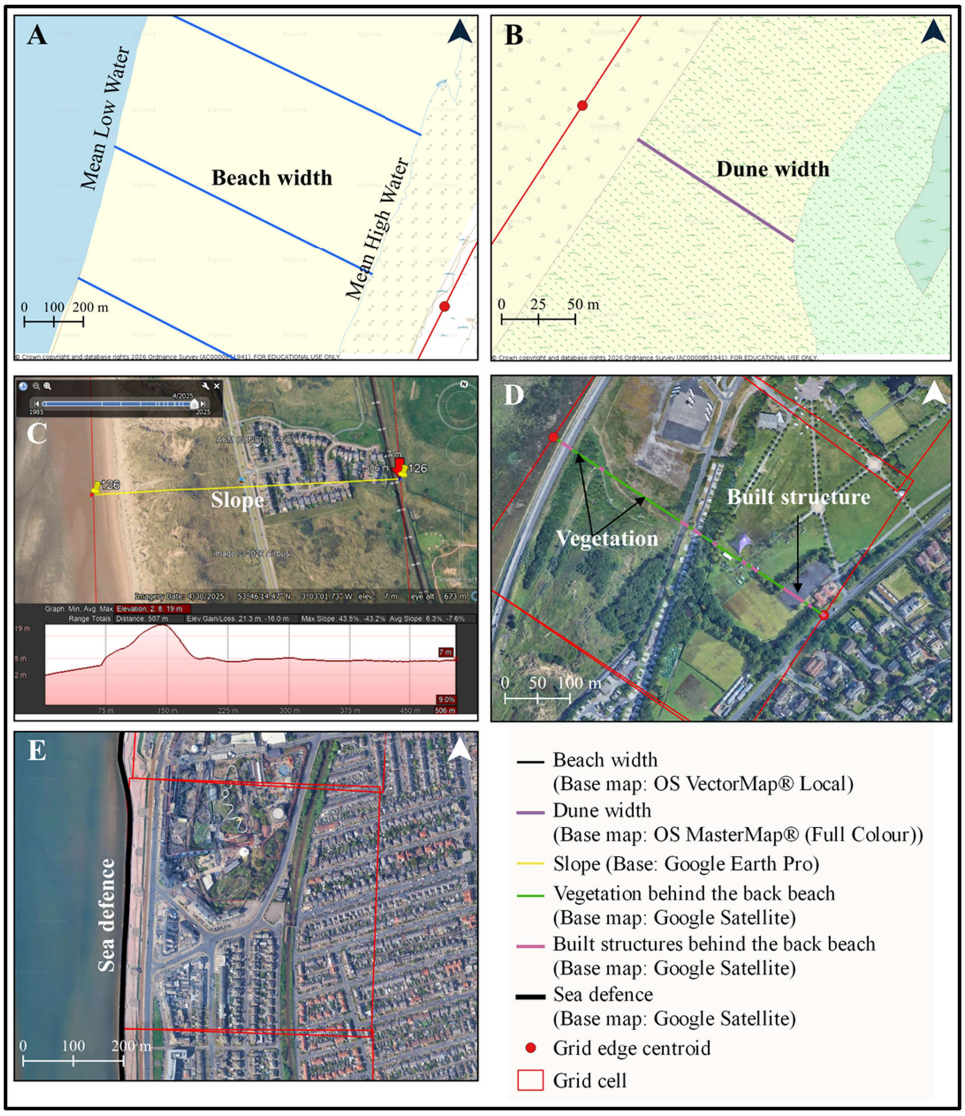



**Figure 2.** Infographic illustrating the vulnerability parameters and how they are measured.

converted to a percentage by dividing it by 500 and multiplying by 100, where 0% indicated no protection and 100% represented complete protection across the cell.

g) **Coastal landslides**: This study introduces a recently established parameter i.e. coastal landslides. This was introduced by Samrat et al. (2026) to assess UK coastal vulnerability. Landslides in the coastal zone are included because slope instability near the shoreline reduces the resistance of the backshore to loss of land, can supply or remove sediment from the beach system, and indicates terrain where marine erosion at the toe may trigger or accelerate failure. The landslide data were obtained from the British Geological Survey (BGS), which covers coastal areas of England, Wales, and Scotland and includes 2156 records from 1664 to April 2024. Landslide occurrence was then classified and mapped using vulnerability scores (Samrat et al. 2026). The assessment was based on the total number of landslides in the study area rather than cell-by-cell counts. For example, if a study area-specific site (e.g. Blackpool) had more than 16 recorded landslides, it was classified as a very high vulnerability area, and all cells within that area were assigned the highest score. Study area-scale landslide counts were used because the British Geological Survey data (1664–2024) exhibit spatial uncertainty and uneven reporting. Using total counts avoids false accuracy from cell-based mapping and better represents clustered landslide processes. This threshold-based method is simple, clear, and provides a reliable estimate of regional landslide vulnerability.

### 3.2. PB-CVI calculation and classification

The Place Based-Coastal Vulnerability Index (PB-CVI) was calculated as an arithmetic sum of seven physical parameter scores and grouped into five classes: Very Low, Low, Moderate, High, and Very High (Kantamaneni et al. 2018). The mathematical formulation is given in Equation (1). For ease of calculation, each variable was assigned a symbol as shown in Table 1 and Equation (1):

$$\mathrm{PB-CVI} = \mathrm{PBA}_b + \mathrm{PBB}_d + \mathrm{PBC}_s + \mathrm{PBD}_C + \mathrm{PBE}_v + \mathrm{PBF}_b + \mathrm{PBG}_C \quad (1)$$

The designated symbol and threshold are as given in Table 1. In addition, Table 2 provides the cumulative vulnerability score given in Kantamaneni et al. (2018).

## 4. Results

This study evaluated coastal vulnerability across six coastal districts including Lancaster, Wyre, Blackpool, Fylde, West Lancashire, and Sefton. Geographic Information System (GIS) vulnerability maps were produced to illustrate varying vulnerability levels, thereby facilitating the identification of highly vulnerable and less vulnerable areas within each district. The use of spatial datasets enhanced the accuracy and interpretability of the results, supporting district comparisons and informing coastal management strategies.

### 4.1. The overall study area physical coastal vulnerability

The PB-CVI scores for the study area reveal a pronounced alongshore gradient in coastal vulnerability, with values spanning from 14, indicative of the least vulnerable sectors, to 25, representing cells exposed to very high physical vulnerability (Figure 3). This numerical range reflects substantial contrasts in the combination of geomorphic, ecological, and anthropogenic factors that underpin the composite index, and highlights that no part of the coastline can be considered entirely free from vulnerability. Across the 220 cells, most segments cluster within scores of 15 to 22, encompassing low, moderate, and high vulnerability classes and demonstrating that intermediate levels of vulnerability dominate the study area. Within this spectrum, only 3.2% of cells fall into the Low-vulnerability class, whereas approximately 30.4% are classified as Moderately vulnerable, suggesting that a sizeable portion of the coast is subject to appreciable, though not extreme, levels of pressure. In contrast, Highly vulnerable cells are strongly over-represented, accounting for 59.09% of the coastline, and an additional 7.3% exhibit Very High vulnerability, underscoring the prevalence of sectors where the interaction of coastal forcing, limited natural buffering, and human occupation produces an elevated propensity for adverse impact. The analysis also identifies several locations along the Lancashire coast as particularly vulnerable. Blackpool, the areas surrounding Fleetwood, Heysham, and Southport are recognized as physical vulnerability hotspots.

### 4.2. Study area coastal vulnerability-physical variable measurement analysis

The study area coastline, segmented into 220 analytical cells, demonstrates substantial alongshore variation in geomorphology and land-cover characteristics, such as beach width, dune width, vegetation behind the back beach, built structures, coastal defences, and coastal landslide occurrence. Beach width displays the greatest spatial contrast, with an overall mean of 923 m and an exceptionally wide sector in cell 50

**Table 1.** Physical parameter thresholds based on Palmer et al. (2011) and Samrat et al. (2026).

| Physical parameter | Designated symbol | Low (1) | Moderate (2) | High (3) | Very high (4) |
|---|---|---|---|---|---|
| Beach width (m) | $\mathrm{PBA}_b$ | >150 | 100–150 | 50–100 | <50 |
| Dune width (m) | $\mathrm{PBB}_d$ | >150 | 50–150 | 25–50 | <25 |
| Coastal slope (%) | $\mathrm{PBC}_s$ | >12 | 12–8 | 8–4 | <4 |
| Distance of vegetation behind the back beach (m) | $\mathrm{PBD}_c$ | >400 | 400–200 | 200–100 | <100 |
| Distance of built structure behind the back beach (m) | $\mathrm{PBE}_v$ | <100 | 200–100 | 400–200 | >400 |
| Coastal defence (%) | $\mathrm{PBF}_b$ | >50 | 20–50 | 10–20 | <10 |
| Coastal landslide (number) | $\mathrm{PBG}_c$ | 0–5 | 6–10 | 11–16 | >16 |

**Table 2.** The cumulative vulnerability score adopted from Kantamaneni et al. (2018) and Samrat et al. (2026).

| Total accumulative vulnerability score | Vulnerability |
|---|---|
| <12 | Very low |
| 12–15 | Low |
| 16–18 | Moderate |
| 19–23 | High |
| 24–28 | Very high |

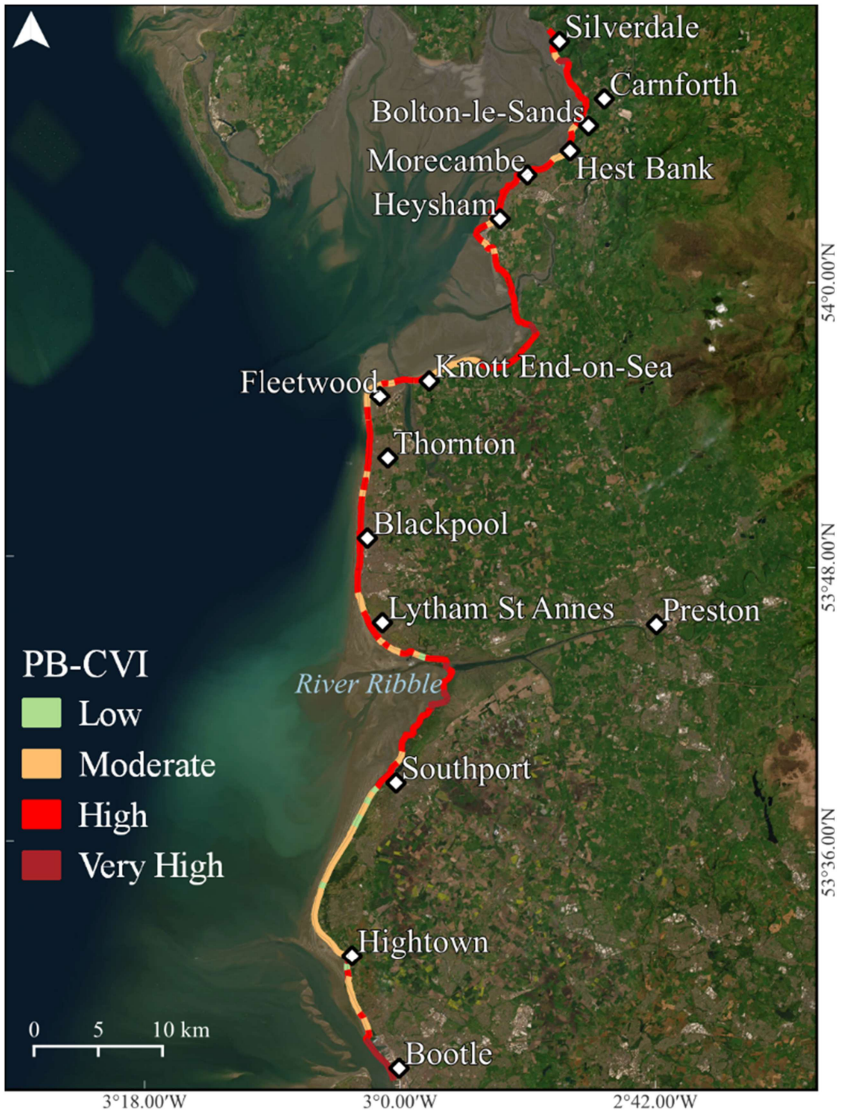



**Figure 3.** Spatial distribution of the Place-Based Coastal Vulnerability Index (PB-CVI) across Lancashire.

(5127.6 m), while several cells (145, 197, 216–220) lack beach (0 m), marking abrupt transitions from open shoreface to engineered or non-sandy frontage. Cells with zero width (145, 197, 216–220) indicate sectors where the active foreshore is either absent or heavily constrained by coastal defences and infrastructure, suggesting locally elevated physical vulnerability of back-beach infrastructure.

Dune systems are comparatively sparse, present in only 25.9% of the coastline segments, underscoring the limited natural buffering capacity provided by dunes at the regional scale. Where dunes are present, their cross-shore width is highly variable, ranging from narrow, incipient ridges (11.3 m in cell 169) to substantial dune belts exceeding half a kilometre in width (559.6 m in cell 193), yielding an average dune

width of 39.8 m and highlighting a patchy distribution of dunes along the coast. Slopes exhibit moderate variability, with gradients spanning from an essentially flat surface (0% in cells 145 and 160–163) to a significantly steep slope of up to 11.2% in cell 184. The mean coastal slope is 3.9% gently sloping shore, but localized steeper reaches may be more susceptible to rapid morphological change and, where associated with softer lithologies, prone to intense rainfall and focused wave energy dissipation. The vegetation behind the back beach extends, on average, 235.7 m, but is highly discontinuous, ranging from complete absence in 48 cells (21.8% of the coastline) to maximum values of 500 m in cells 60, 63, and 195. These patterns indicate a mosaic of a well-vegetated coastal front, which enhances sediment trapping and ecological connectivity, interspersed with unvegetated sections where land-hardening, agricultural land, or urban areas with limited natural buffering likely dominate the sea interface. Built structures behind the back beach are entirely absent in 29.1% of cells, whereas in the intensively developed section (e.g. cells 41–43, 202, 215–220), built frontage reaches the maximum recorded value of 500 m, with an average alongshore extent of 153.6 m.

The coastal protection measures are widespread, present in 47.7% of cells, with several stretches (cells 23–25, 28–30, 207–209) exhibiting 100% coverage, indicative of heavily protected shorelines where hard defences dominate the coastal zone. In contrast, landslide activity is limited, recorded in only 1.4% of cells, suggesting that slope instability is localised along the assessed coastline.

### 4.3. PB-CVI physical variable analysis

Beach width varies considerably across districts, ranging from 437.09 ± 68.96 m in Blackpool to 1129.52 ± 1091.18 m in Lancaster, and it exhibits the widest mean beach width but also the highest variability, reflecting diverse conditions from narrow rocky shores to extensive intertidal flats in Morecambe Bay. Blackpool demonstrates the narrowest and least variable beach width, characteristic of urbanized coastlines with engineered seafronts. The high variability in beach width across most districts indicates dynamic sediment transport processes and spatial heterogeneity in coastal morphology. Dune systems are notably absent or minimal in West Lancashire, Blackpool, and Lancaster (0–0.45 m mean width). Sefton demonstrates the most extensive dune presence (114.44 ± 137.15 m), reflecting the presence of significant dunes. Fylde exhibits intermediate dune presence (48.04 ± 58.92 m), with remnant systems particularly near Lytham St Annes. The presence of dunes provides crucial natural coastal defence, with Sefton's extensive dune systems contributing to its lower mean vulnerability despite significant Very High vulnerability hotspots.

On the other hand, the coastal slope ranges from 2.06% ± 0.35% in West Lancashire to 5.94% ± 2.3% in Blackpool. West Lancashire's minimal slope reflects the flat topography of the coastal plain, contributing to high inundation vulnerability. Blackpool exhibits the steepest mean slope, likely reflecting artificial beach nourishment and engineered coastal profiles. Sefton and Fylde demonstrate moderate to steep slopes (4.64% and 4.21% respectively), associated with dune fronts and beach-dune transitions. Distance of vegetation behind the back beach varies from 0.00 m in West Lancashire to 301.18 ± 175.95 m in Wyre. The complete absence of vegetation in West Lancashire due to the lack of a terrestrial buffer contributes to elevated vulnerability. Wyre, Sefton, and Lancaster have substantial vegetation buffers (>240 m mean), providing additional coastal resilience. Blackpool exhibits minimal vegetation distance (88.5 ± 79.13 m), consistent with urban development extending to the coastal edge. But, built structures are most proximate to the coastal edge in Blackpool (406.86 ± 79.35 m), reflecting high-density urban development. Sefton exhibits the lowest mean proximity (97.33 ± 162.58 m), with significant portions of the coastline buffered by dune systems and natural environments. West Lancashire uniquely shows zero built structure proximity in the measured parameters. Coastal protection infrastructure coverage varies dramatically, from 0.00% in West Lancashire to 95.44% in Blackpool. This distribution reflects management priorities and resource allocation, with heavily developed urban coastlines (Blackpool, Wyre at 76.02%) receiving extensive hard engineering, while more natural coastlines (Sefton at 26.26%, Fylde at 31.55%, Lancaster at 30.86%) rely primarily on natural coastal defence functions. West Lancashire's complete absence of coastal protection, combined with its low elevation and flat topography, explains its vulnerability classification.

### 4.4. PB-CVI scores analysis

The Lancaster district (refer to Figure 4), located at the northern end of the study region, demonstrates consistently high vulnerability, with 85.3% of cells classified as High vulnerability. Only 11.8% of cells exhibit Moderate vulnerability, and 2.9% exhibit Very High vulnerability. The district shows relatively low variability (SD = 1.89), indicating homogeneous vulnerability conditions across most of the coastal extent. The absence of Low vulnerability cells highlights the inherent vulnerability of this coastline. Wyre, which is south of the Lancaster district coastline (refer to Figure 10), presents a mixed vulnerability profile with 55.9% High and 44.1% Moderate vulnerability cells (refer to Table 3). The mean PB-CVI of 18.74 ± 2.15 is the second lowest among districts, reflecting greater variability in coastal conditions. The absence of Very High or Low vulnerability cells indicates predominantly intermediate-level vulnerability.

Heysham (refer to Figure 5a), within the Lancaster District, is one of the region's most environmentally and culturally sensitive coastal areas. A coastal vulnerability assessment shows that approximately 86% of Heysham's coastline is highly vulnerable (refer to Figure 5a), while the remaining 14% is classified as moderately vulnerable. This indicates that most of the shoreline is already affected by, or is at significant risk from, coastal processes such as erosion, wave action, and storm surges. The area's vulnerability is

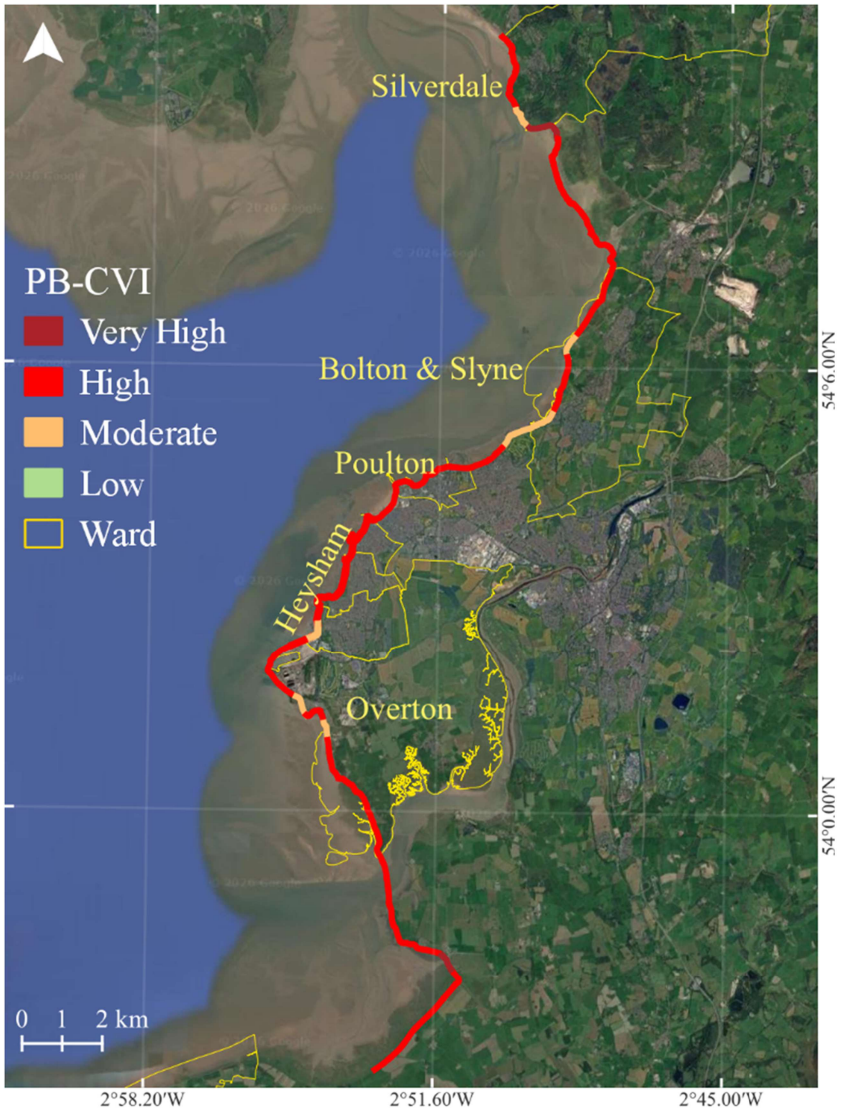



**Figure 4.** Spatial distribution of the PB-CVI across Lancaster District.

**Table 3.** Percentage of assessed cells in each vulnerability class across the study area and within each study district.

| | Low (%) | Moderate (%) | High (%) | Very high (%) | Total cell |
|---|---|---|---|---|---|
| Overall Study Area | 3.18 | 30.45 | 59.09 | 7.27 | 220 |
| Lancaster (Dist) | 0.00 | 11.76 | 85.29 | 2.94 | 68 |
| Wyre (Dist) | 0.00 | 44.12 | 55.88 | 0.00 | 34 |
| Blackpool (Dist) | 0.00 | 9.09 | 90.91 | 0.00 | 22 |
| Fylde (Dist) | 4.76 | 33.33 | 57.14 | 4.76 | 21 |
| West Lancashire (Dist) | 0.00 | 0.00 | 50.00 | 50.00 | 8 |
| Sefton (Dist) | 8.96 | 52.24 | 25.37 | 13.43 | 67 |

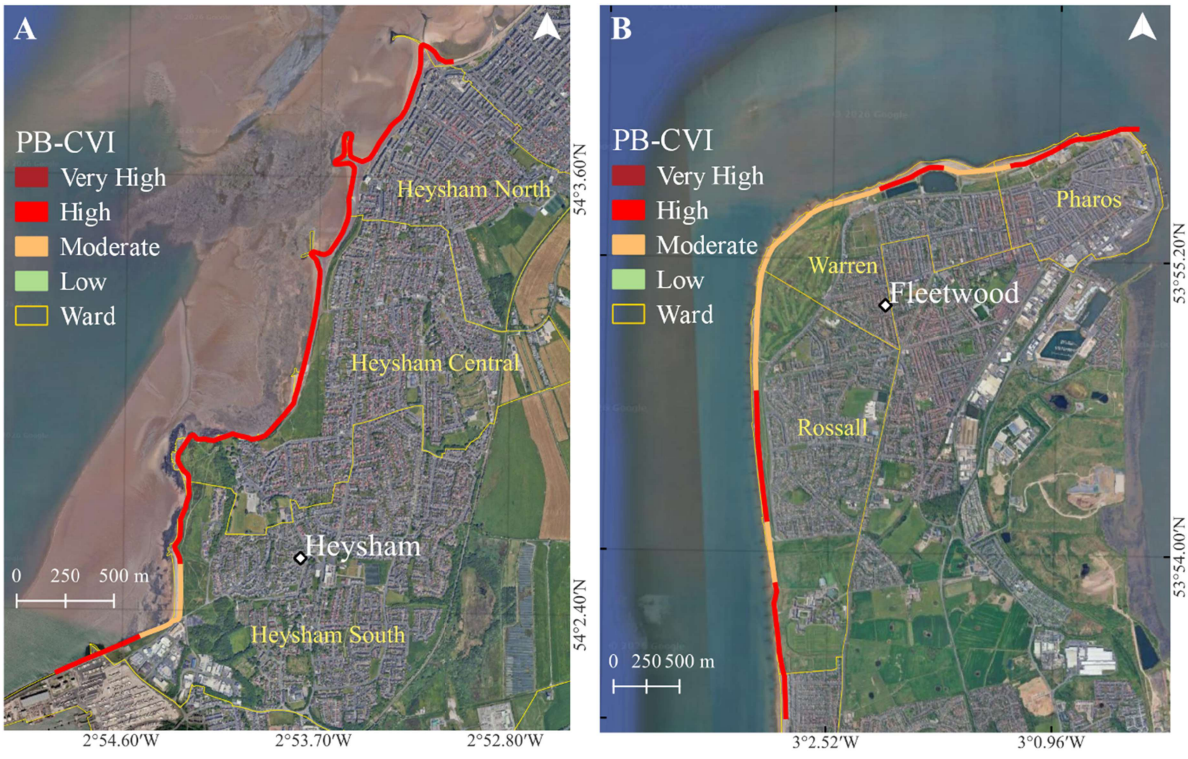



**Figure 5.** Spatial distribution of the PB-CVI across (A) Heysham, Lancaster District, and (B) Fleetwood, Wyre District.

further intensified by soft cliffs, limited natural coastal barriers in some locations, direct exposure to strong winds and tidal forces from Morecambe Bay, and the development of coastal infrastructure.

Fleetwood (refer to Figure 5b), located within the Wyre District and distributed across the wards of Pharos, Warren, Rossall, and Jubilee, exhibits a different coastal setting. The beaches in Fleetwood are relatively wide; however, dunes are largely absent, occurring in only one coastal cell. The terrain is generally flat and low-lying, making the area particularly susceptible to flooding associated with sea-level rise and high tides, as well as coastal erosion. More than 50% of the evaluated coastline falls into the high-vulnerability category, while the remaining sections exhibit moderate vulnerability.

Fylde district (refer to Figure 6a) is the southern extension of the Blackpool coastline (refer to Figure 6b), exhibiting high mean vulnerability ($19.24 \pm 2.26$) with the most diverse distribution of vulnerability classes among northern districts: 57.1% High, 33.3% Moderate, 4.8% Low, and 4.8% Very High. This diversity reflects the transitional nature of the Fylde coastline, incorporating urbanized sections, dune systems, and estuarine environments. West Lancashire (refer to Figure 6a) exhibits the highest mean vulnerability score ($23.38 \pm 1.51$), consisting of equal proportions of High (50%) and Very High (50%) vulnerability cells. The limited coastal extent ($n = 8$ cells) and uniformly elevated vulnerability reflect the district's low-lying topography and limited natural or artificial coastal defences.

Sefton (refer to Figure 7) demonstrates the most heterogeneous vulnerability profile ($18.27 \pm 3.4$) and the lowest mean PB-CVI score among districts. The distribution is dominated by Moderate vulnerability

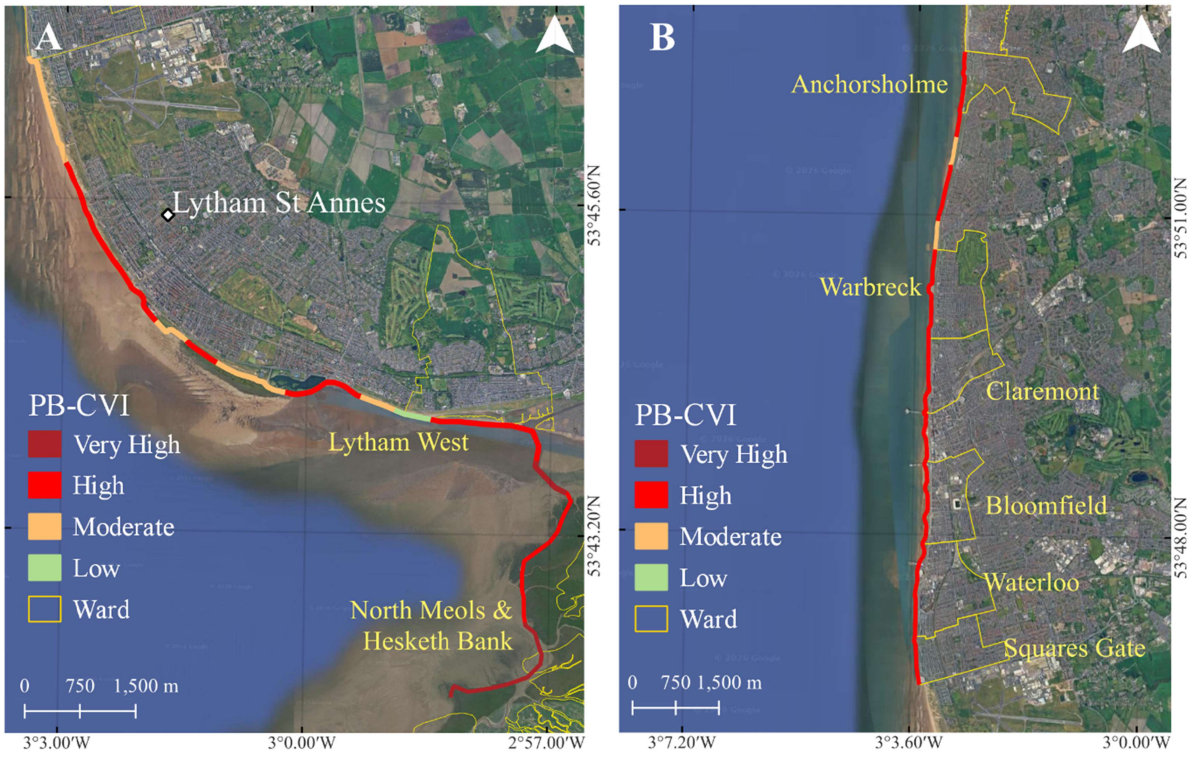



**Figure 6.** Spatial distribution of the PB-CVI across (A) Fylde and West Lancashire and (B) Blackpool District.

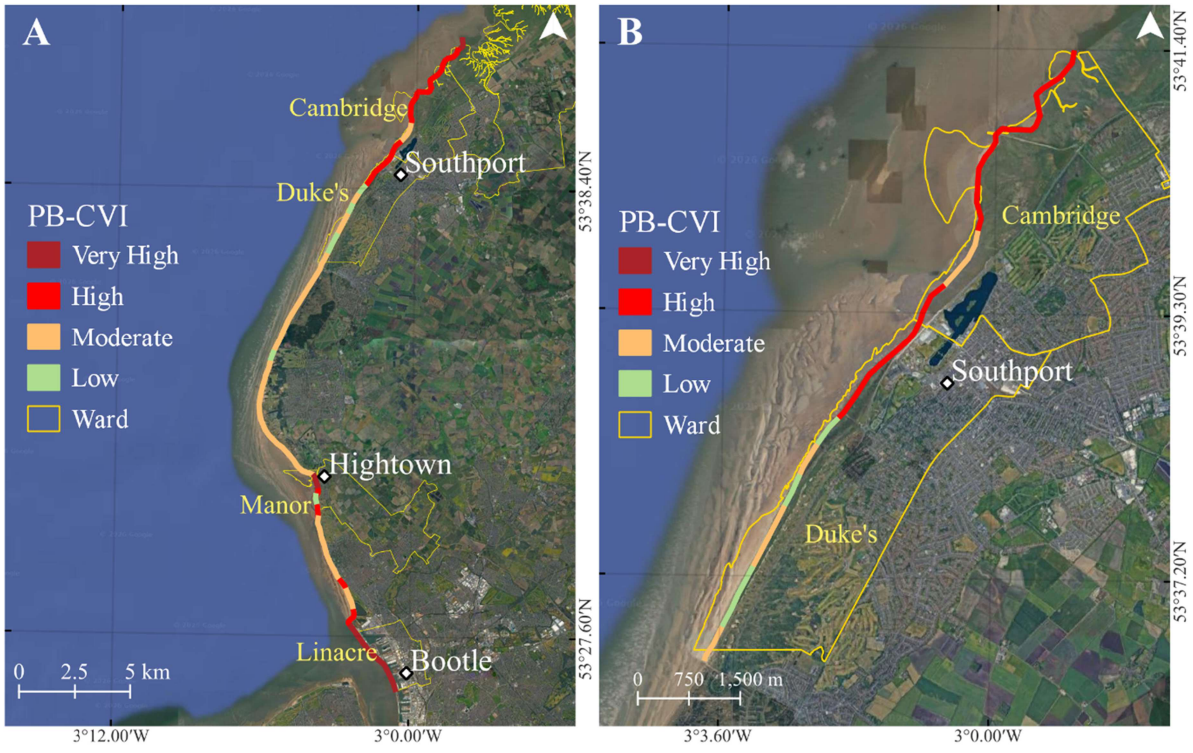



**Figure 7.** Spatial distribution of the PB-CVI across (A) Sefton District and (B) Southport, Sefton District.

(52.2%), with 25.4% High, 13.4% Very High, and 9% Low vulnerability cells. The high standard deviation (3.4) indicates substantial variability in coastal conditions along this extensive coastal frontage. Sefton encompasses all four vulnerability categories, reflecting the diversity of coastal environments from natural dune systems to urban waterfronts. Within the administrative region that includes Hightown and Southport (refer to Figure 7), multiple coastal segments remain highly vulnerable, even with the implementation of both hard and soft coastal protection measures. This situation demonstrates the complex and dynamic characteristics of coastal systems, in which engineered defences mitigate but cannot fully eliminate physical vulnerability. Nearly 60% of the Southport coastline is classified as highly vulnerable. Dunes and vegetation are more prominent along the northern and southern sections, whereas built development is concentrated mainly within the central urban area. The coastline remains relatively flat throughout. Coastal defences are primarily located in the central section near Southport town centre, while the northern and southern stretches are comparatively less protected.

## 5. Discussion

The Place Based Coastal Vulnerability Index (PB-CVI) coastline assessment of the **six study districts:** Lancaster, Wyre, Blackpool, Fylde, West Lancashire, and Sefton reveals considerable physical vulnerability, with the majority of the 220 studied cells classified as highly or very highly vulnerable. The overall PB-CVI score range of 14 to 25, with more than half, 59.1% of cells falling in the High-vulnerability class and a further 7.3% in the Very High category, is consistent with previous studies of the PCVI framework along the English and Welsh coastline. Kantamaneni et al. (2018) developed and applied the combined physical and economic coastal vulnerability index to eleven UK sites, identified a mean PCVI value of 20.33, corresponding to high vulnerability across their study sites. The current findings strongly support the earlier research, highlighting that the northwest coast of England has similar physical vulnerability characteristics to those found throughout England and Wales. This connection emphasizes the shared environmental factors that affect these regions.

An insightful finding of the current study is that only 3.2% of cells have Low vulnerability, while 30.4% exhibit Moderate vulnerability. This uneven distribution indicates that the study area  coast is predominantly subject to elevated anthropogenic and climate change stress, with limited natural buffering acting as a constraint across districts. The findings indicate that areas without dune protection and those facing urban development are more likely to fall into higher vulnerability categories (Meur-Férec et al. 2008). Sites lacking dunes and exposed to urbanized frontages tend to cluster in higher vulnerability categories. This suggests that the presence of natural barriers is crucial in mitigating vulnerability in these settings. A recent study focused on the coastlines of Dawlish, Happisburgh, and Aberystwyth has revealed an increasing vulnerability trend year on year (Kantamaneni et al. 2024). This is also important for the Lancashire coastline, which faces ongoing threats from sea-level rise and extreme climate. Heysham, a coastal historic site, demonstrates that 86% of its coastal area is highly vulnerable (Figure 8a and b) as a result of combined physical and human factors. The site is subject to multiple coastal hazards, such as strong waves and tides from the Irish Sea, which intensify coastal erosion.

A significant 66.4% of the studied cells are classified as High and Very High vulnerability, indicating that the extensive coastline of the study area lacks natural buffering. Various parameters such as coastal dunes are almost entirely absent along this stretch of coast; for example, Lancaster coast, which has a dune mean width of just 0.45 ± 2.68 m (Figure 9). These dune systems are crucial as they serve as natural barriers against storm surges, wave overtopping, and coastal flooding (Della Bella et al. 2024). The link between beach width and coastal protection is well established. A wider beach is better at dissipating wave energy than a narrow one, which helps to lessen the hydraulic pressure on the coastal areas behind it (Kantamaneni et al. 2018; Li et al. 2023). Research from the Dutch coast shows that the width of beaches greatly affects how dunes grow and their risk of erosion. Beaches that are wider than 500 m supply much more sediment, which helps build up dunes and protects them from storm waves (Keijsers et al. 2014). However, the study area  data insight provides that, except in the bay region, narrow beaches are combined with the absence of dune systems or adequate vegetation buffers. The Lancaster district's mean PB-CVI remains in the high category due to the beach, lack of dune width, narrower vegetation distance, and coastal protection. Blackpool has a very high level of coastal protection, with 95.44% of its coast equipped




a. Heysham coast with Nuclear Power Plant

b. Heysham coast with erosion

**Figure 8.** Field photographs showing (a) the nuclear power station along the Heysham coast and (b) coastal erosion along the Heysham coastline.

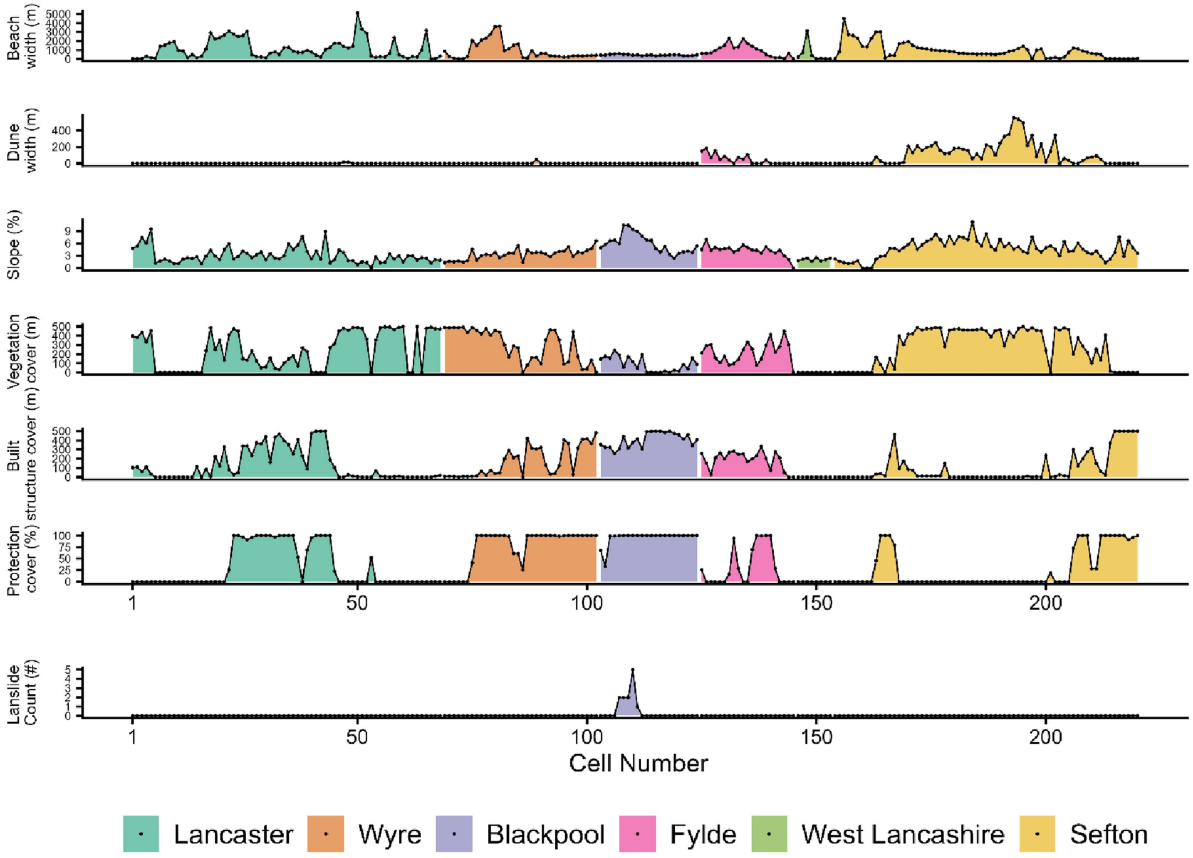



**Figure 9.** Spatial variation in physical vulnerability variables along the study area coastline, with cell numbers increasing from north to south.

with infrastructure. However, it also has a high vulnerability score of 20.27 ± 1.39. This is because the PB-CVI score was based on natural factors as well as human-made structures. In Blackpool, the entire seafront is man-made, with no dunes and very little vegetation (refer to Figure 6b). So, despite having many hard defences, the lack of natural features leads to a high vulnerability score. This aligns with the documented

dynamic at Blackpool, where ongoing beach lowering since the 1980s has progressively eroded the first line of natural defence against wave impact (Cunningham et al. 2012).

The Fylde district (Figure 9) stands out among the northern regions due to its diverse distribution of vulnerability, featuring areas across all four vulnerability categories. One significant factor is the relatively greater mean dune width of 48.04 ± 58.92 m, primarily linked to the Lytham St Annes dune systems, which offer localized natural protection that is missing in the northern areas. Fylde's unique transitional character, blending urbanized regions with stretches of dune frontages, is reflected in its intermediate mean PB-CVI of 19.24 ± 2.26. The combination of hard and natural defence along this coastline aligns with the Blackpool and Fylde Coast Protection Strategy, which outlines a moderate vulnerability. Sefton stands out with a particularly varied vulnerability profile compared to other districts, having a mean PB-CVI of 18.27 ± 3.4. It encompasses all four vulnerability classes. The extensive dune systems along the Sefton coast, characterized by their considerable mean width and the dominance of natural features, contribute to its relatively lower overall vulnerability. Notably, 9% of the cells in this area are classified as low vulnerability. This observation underscores a well-established principle in geomorphological studies that natural systems play a crucial role in providing effective defence mechanisms that significantly mitigate overall coastal vulnerability. Pye and Blott (2016) provided a detailed account of the Sefton dune system's dynamics in response to the winter storms of 2013–2014.

Pye and Blott (2016) also observed that significant dune erosion, including a net recession of up to 12.1 m around Formby Point, occurred in areas where the upper beach width was less than 25 m. This finding supports the PB-CVI idea that wider beaches help protect dune systems from storms, while those wider dunes also shield the area behind them from flooding and erosion. It's a two-way relationship that strengthens both systems. Vegetation behind the back beach plays a crucial role as a parameter in the Place-Based Coastal Vulnerability Index (PB-CVI). These vegetated coastal areas significantly improve sediment trapping and promote ecological connectivity (Pantusa et al. 2018). In the study area, it's concerning to note that 21.8% of the cells lack vegetation behind the back beach. The highest levels of vegetation coverage can be found in Wyre (averaging 301.18 ± 175.95 m), Sefton (279.65 ± 202.76 m), and Lancaster (240.06 ± 202.09 m). In stark contrast, West Lancashire shows a complete absence of vegetation, due to the prevalence of intertidal flats that lack any terrestrial buffering. This lack of vegetation is a key factor contributing to the district's maximum vulnerability classification.

The spatial distribution of coastal protection infrastructure along the study area coast reveals a striking contrast between urban and natural areas. **Developed coastal stretches in** Blackpool (95.44%) and Wyre (76.02%), benefit from extensive hard engineering, reflecting significant investment in infrastructure (refer to Figure 10). In contrast, more natural coastlines, Sefton (26.26%), Fylde (31.55%), and Lancaster (30.86%), rely primarily on natural coastal defence. This pattern highlights the long-standing trend of prioritizing resources based on vulnerability assessments, which have historically favoured economically significant and residentially dense urban frontages. The coastal areas studied, particularly , Blackpool has extensive coastal protection but retains a high mean PB-CVI score, indicating that physical vulnerability remains high despite the presence of hard defences. Recent research on coastal resilience within the UK has increasingly highlighted the shortcomings of traditional 'holding-the-line' strategies. The UK's long-standing dependence on hard engineering solutions has not successfully addressed the challenges posed by rising sea levels and escalating coastal erosion (Sayers et al. 2021).

Blackpool's central coastline has experienced a loss of sand, resulting in **beach lowering of approximately 1.7 m since 1986** (Blackpool Council 2026). This ongoing erosion directly impacts the structural integrity of existing seawalls, as the beach's capacity to dissipate wave energy diminishes. It shows that relying solely on hard defences is insufficient to effectively lower vulnerability. To ensure effective, sustainable protection, these structures must be complemented by beach nourishment and the restoration of natural buffers. The Wyre district has a high protection coverage and a mixed vulnerability profile that is both high and moderate. This makes it an interesting comparison to Blackpool. Although Wyre has a similar level of protection, its vulnerability is lower due to larger vegetation buffers (averaging 301.18 m) and slightly wider beaches (averaging 911.29 m). Wyre Beach and Dune Management Scheme represents a major investment in coastal defence (The Flood Hub 2024). It highlights the understanding that maintaining natural beach, vegetation, and dune systems, along with traditional engineering methods, leads to better long-term resilience than relying on hard engineering alone. The PB-CVI cell-based approach




**Figure 10.** Spatial distribution of the PB-CVI across Wyre District.

adopted in this study, using 220 cells across the 110 km study coastline, is well-suited to capturing its spatial heterogeneity at a resolution appropriate for shoreline management decisions. The choice of cell size and the selection of physical parameters directly determine the spatial resolution and sensitivity of the CVI output (Roukounis and Tsihrintzis 2022). The use of 500 m cells, aligned with the Kantamaneni et al. (2018) PCVI framework, allows to identify a sub-kilometre scale hotspot.

The interaction of macrotidal regimes with storm surges in the Irish Sea further increases these risks, particularly when extreme events coincide with high spring tides (Olbert et al. 2013; Rulent et al. 2021). Additionally, historical flood events and recent modelling studies have shown that even modest increases in sea level can significantly increase the frequency and severity of coastal inundation, placing additional pressure on existing defence systems (Sayers et al., 2022). In recent years, there has been growing recognition of the importance of integrating nature-based solutions together with traditional engineering methods to enhance coastal resilience (Twomey et al. 2025). These findings align with broader global trends where coastal regions are projected to experience increasing risk under future climate scenarios (Masson-Delmotte et al. 2021).

## 6. Limitations

This study has some limitations. The Place-Based Coastal Vulnerability Index (PB-CVI) methodology applied here is based on established approaches and assesses physical vulnerability at a single point in time. It does not incorporate dynamic factors such as shoreline change rates, storm surge heights, tidal range, or variations in sediment budgets. Including these temporal variables, as in advanced Coastal Vulnerability Index (CVI) methodologies, could substantially improve vulnerability assessments (Pantusa et al. 2018). Such enhancements would provide a different angle of insight regarding erosion and accretion trends along the study area coast. Future research should consider developing a Composite Coastal Vulnerability Index (CCVI) that integrates the Economic Coastal Vulnerability Index (ECVI) to capture socio-economic exposure of properties, populations, and infrastructure. Given the major economic importance of the tourism sectors in Blackpool and Sefton, these factors may increase overall vulnerability scores for these areas relative to less developed sections of the coastline.

The 500 × 500 m cell size represents a moderate spatial resolution for a regional assessment. It was chosen for consistency with the PCVI framework of Kantamaneni et al. (2018) and to keep manual measurement of seven parameters across 220 cells tractable. However, features that vary over tens of metres may be averaged out or not represented at the cell transect.

The landslide parameter also has limitations. The BGS database records that a landslide occurred, but not what caused it. Some coastal landslides are driven by wave erosion at the base of a slope, while others are caused by heavy rainfall, groundwater, weak geology, or construction. All of these are counted equally in this study, so the landslide score does not measure marine erosion alone. The records also span more than 350 years and are unlikely to be evenly complete, as landslides in populated or well-studied areas are more likely to have been reported than those on remote stretches of coast. Counts may therefore reflect reporting effort as well as actual instability. Future studies could address this by counting only landslides that are known to be marine-triggered, or only those within a set distance of the shoreline.

The study does not explicitly model the projected impacts of sea level rise on the study area coastline. **Sea levels are projected to continue rising through 2100 along the northwest coast of England, with the magnitude depending on the emissions scenario and ice-sheet response** (Palmer et al. 2024) and this is one ofthe study limitations. At present, 7.3% of the area is classified as very high risk, a proportion likely to rise, particularly in low-lying areas of West Lancashire and parts of Sefton. To handle these expected changes, nature-based solutions such as managed dune restoration, salt marsh expansion, and beach nourishment will be crucial elements of long-term adaptation plans. The future study will certainly incorporate all these things and evaluate them substantially in multiple directions.

## 7. Recommendations

Coastal management should focus first on areas of high coastal vulnerability to improve current conditions. Prioritize place-based coastal vulnerability hotspots, such as Heysham, Blackpool, Southport, and Fleetwood, for risk reduction, and the government should invest in these areas first to protect them. Coastal managers and planners should utilize GIS vulnerability maps developed from this study's results to identify specific coastal segments requiring immediate intervention. Nature-based solutions, including salt marshes and dunes, should be implemented or protected, with particular emphasis on further enhancing these measures in low-lying coastal areas. PB-CVI results help identify priority areas for Nature-based Solutions (NbS) in integrated coastal management strategies. Site-specific actions may include dune restoration, beach nourishment, saltmarsh and seagrass restoration, managed realignment, and coastal wetland conservation. These methods reduce wave energy, increase sediment retention, stabilize shorelines, and strengthen long-term coastal resilience. NbS should be integrated with conventional engineering measures, accounting for local environmental conditions and vulnerabilities. Local authorities should use the study results to establish place-based adaptation strategies while considering citizen science approaches. PB-CVI maps also facilitate early warning and emergency planning, particularly in regions with a history of recurrent flooding. Collaboration among academic organizations, local governments, and industries should be fostered to devise and implement integrated solutions that mitigate risk in highly vulnerable areas.

## 8. Conclusion

This study used a Place-Based physical coastal vulnerability index and applied it to the Lancashire coastline and adjoining Sefton coast in northern England using both existing and recently established parameters. The results revealed that coastal vulnerability is uneven across the study area coastline due to diverse local drivers, varying geomorphology, differing exposure to coastal hazards, and the increasing impact of climate-induced drivers. The extensive analysis revealed that highly urbanized and populated sites, such as Blackpool, and cultural sites, such as Heysham, are more physically vulnerable. The application of the place-based method proved critical in highlighting these local and sub-local variations, showing trends that would be ignored or unobserved by standard evaluation methods with all existing parameters. By combining recently established and existing parameters, this research provided a clearer understanding of how and why specific coastal areas are at high risk. The GIS vulnerability maps,

generated from the analysis, offer a more practical view for policy and decision makers, serving as an instrument to rank areas by vulnerability level and to help take action to reduce vulnerability. These results also provide an opportunity for regional and sub-regional policy and decision-makers to act based on specific area results rather than using the same policy for all coastal vulnerability areas. This means the action should be based on the individual area's vulnerability. Finally, this work highlights the importance of accounting for local conditions to enhance coastal resilience. This study concept should be applied in other similar coastal areas worldwide, with appropriate, specific place-based parameters. This type of analysis helps with better planning, long-term coastal management, and the reduction of climate change impacts.

## Author contributions

CRediT: **Komali Kantamaneni:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing; **Abhishek Samrat:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft; **Champika Liyanage:** Supervision, Validation, Writing – review & editing; **Ruchiru Herath:** Methodology, Visualization, Writing – review & editing; **Fahad Al-Ruwaili:** Investigation, Visualization, Writing – review & editing; **Reshma Sunkur:** Methodology, Visualization, Writing – review & editing; **Upaka Rathnayake:** Validation, Writing – review & editing; **Andrew Barkwith:** Data curation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This research received funding from the University of Lancashire -Doctoral Training Centre (DTC). It was also supported by the British Geological Survey (BGS) BUFI initiative and is published with the permission of the BGS Executive Director.

## Data availability statement

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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