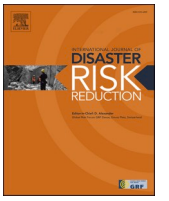
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Developing a novel GIS-based index for physical coastal vulnerability

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ABSTRACT

Coastal zones globally face escalating risks from climate-induced hazards, such as shoreline erosion, saltwater intrusion, and flooding resulting from rising sea levels. The United Kingdom possesses one of the longest and most rapidly eroding coastlines in Europe, attributable to multiple factors. This research develops a novel Physical Coastal Vulnerability Index (PCVI) to evaluate the susceptibility of UK coastlines. The index incorporates both established and newly identified parameters, including coastal landslides, and is applied to eight case study areas: four in England, two in Scotland, and one each in Northern Ireland and Wales. The assessment covers 402 km of coastline and results indicate that over 43% of the coastline is classified as High vulnerable, highlighting several stretches that are acutely susceptible to coastal hazards. Additionally, 2.7% of the coastline is considered Very High vulnerable, representing the most critical zones that require immediate intervention and long-term adaptation strategies to mitigate future risks. In comparison, more than 37% of the coastline is categorised as Moderate vulnerable, while only 16.4% is classified as having Low vulnerability. Results revealed that England and Scotland exhibit higher levels of physical coastal vulnerability compared to Wales and Northern Ireland. Specific areas, such as Trimingham, Holderness, Durdle, and Lancashire in England, are particularly at risk of hazards particularly coastal landslides due to their varied geographical characteristics. In contrast, Dundee in Scotland has the highest vulnerability because it lacks natural protections such as dunes. Kinmel Bay in Wales and Antrim in Northern Ireland are classified as having the lowest vulnerability due to their geographical locations and features. Based on these results, GIS vulnerability maps were created to illustrate the extent of coastal vulnerability. The results indicate that coastal vulnerability is not uniform across the UK, with England identified as the most vulnerable hotspot. To our knowledge, this is the first study to evaluate these case study areas together while combining both new and existing parameters. The research methodology used in this study can be applied to similar areas, regardless of their geographical location. The findings are valuable for local and national policymakers, providing essential insights to help implement strategies for the urgent protection of these vulnerable coastal areas.

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1. Introduction

Coastlines are paramount due to their ecological richness, economic value, social and cultural significance, and role in environmental protection and climate regulation. Coastal ecosystems stand out as highly productive and biologically diverse regions. The impacts of climate change-induced natural hazards are increasingly significant in the 21st century. Floods, cyclones, storms, droughts, and other events have led to substantial socio-economic losses [1] and loss of lives [2,3]. Between 2000 and 2019, these hazards caused an average annual socio-economic loss of £113 billion [4] and resulted in the loss of approximately 5 million lives globally [5]. Projections indicate that by 2050, the financial toll could reach £18 trillion, equivalent to 11% of the global GDP [6]. The coastal zone is a fascinating region where the powerful forces of the sea, the ever-changing atmosphere, and the diverse land processes interact in a highly intricate and dynamic manner [7]. Due to the high complexity and dynamism of this region, assessment studies are crucial when dealing with coastal hazards in this ecologically and socially significant environment. It's important to note that coastlines are particularly vulnerable to these natural hazards [8].

Coastal regions face considerable risks from climate-induced hazards, such as erosion, compounded flooding, and saltwater intrusion. These hazards are driven by various factors, including sea level rise [9,10], storms, heavy rainfall and snow-melt [11], and urbanisation [12]. The rising sea levels are more concerning for low-lying coastal zones, where a substantial percentage of the global population resides [13]. The Low Elevation Coastal Zone (LECZ) is an area with elevations below 10 m above mean sea level (MSL). Till 2000, LECZ accommodated 10% of the global population [14]. By 2020, this population had reached 11.45% (898 million) of the world population, estimated to rise to 1.2 billion by the end of the century [15]. This suggests that a growing coastal population will face risks as a result of climate change, as the intensity and frequency of coastal hazards are expected to increase in the future [9,16].

The UK boasts one of the longest coastlines in Europe, spanning over 17,381 km [17]. It is currently experiencing the fastest erosion rates [18] in the region, with almost 3008 km (17.3%) of its coastline affected [17]. The UK has urban areas (2171 km^2) with the highest exposure to coastal hazards in Europe [19]. Projections indicate an increase in the risk due to erosion, flooding, and intense rainfall. Critical infrastructure along the UK's coastline, including roads, railways, power substations, and nuclear power plants, is at high risk [20,21]. The annual cost of coastal erosion and floods in the UK amounts to nearly one billion pounds [22], which is anticipated to rise considerably [23]. The damage caused by coastal floods alone reached £0.4 billion in 2020 and is projected to rise to approximately £1.0 billion by 2080 [23].

The significant variations in geographical areas and characteristics make the existing Coastal Vulnerability Index (CVI) inadequate for evaluating new regions, particularly in the UK. To tackle this critical gap, this study developed a new Physical Coastal Vulnerability Index (PCVI) that integrates established and novel parameters, making it innovative. This index will assess eight strategically selected case study areas across the UK: four in England, two in Scotland, and one each in Northern Ireland and Wales. These locations were identified through literature reviews, recent disaster events, and extensive coastal field visits. In addition, the coastal areas need regular appraisal every three to five years to assess the current vulnerability rate, and accordingly, this study selected these areas for the assessment. The results and recommendations of this study will empower national and regional governments to effectively mitigate the impacts of coastal vulnerability in these areas, ultimately safeguarding coastal communities and their vital infrastructure.

2. Case study areas

Drawing from existing literature and extensive fieldwork, eight case studies were selected for the assessment of physical coastal vulnerability: four in England, two in Scotland, and one each in Wales and Northern Ireland. These case studies are summarized in Table 1 and Fig. 1. Each case study offers a detailed evaluation of physical geography, including erosion rates and sediment dynamics, alongside socio-economic factors such as population density, economic reliance on marine resources, and susceptibility to climate change impacts. The systematic presentation of this information underscores the pressing need to assess and address the vulnerabilities confronting these coastal communities.

Table 1
Areas of case studies and corresponding coastline lengths considered for the assessment.

No.	Case Study Areas	Region	Considered for the assessment (km)	Cell Number for each case study
1	Holderness	England	51.5	103
2	Trimingham	England	18	36
3	Durdle	England	11	22
4	Lancashire	England	110	220
5	Dundee	Scotland	14.5	29
6	Belhaven	Scotland	27	54
7	Kinmel Bay	Wales	3.5	7
8	Antrim	Northern Ireland	166.5	333
			Total - 402 km	Total Cells - 804

Note: The coastline lengths reported in the case study descriptions represent the original GIS-derived coastline extents of the case study areas (total 487.45 km). Table 1 reports only the coastline segments included in the vulnerability assessment (402 km) and the corresponding 804 assessment cells. The assessment cells were generated from a generalised coastline by smoothing corners and correcting minor gaps between adjacent cells.

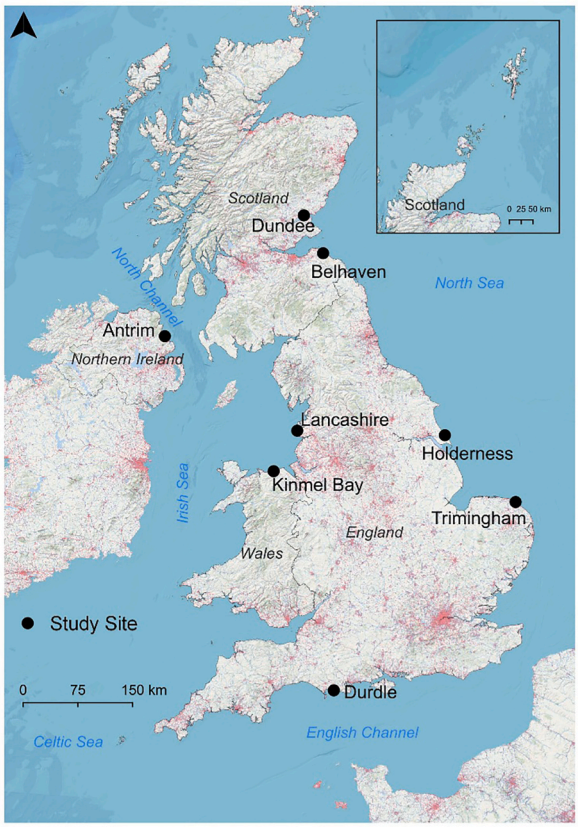


Fig. 1. Case study areas in the United Kingdom.

2.1. Holderness, England

The Holderness study area covers the 51.93 km coastline along the North Holderness, Mid Holderness, and Southeast Holderness wards of the East Coast of England. It is located in East Yorkshire and is one of the fastest-eroding coastlines (Fig. 2A) in Europe [24]. On average, about 1.8 m of land is eroded per year, though the rate can be as high as 3.4 m in some areas [25]. Diverse natural habitats such as cliffs, sandy beaches, mudflats, and salt marshes are ecologically important for birds and their stopover point, while migration and coastal water are known for diverse marine life [26]. The coast is characterised by soft glacial till (a mix of clay, sand, and boulders) deposited during the last Ice Age [27]. This geology makes the coastline highly susceptible to erosion [24]. The construction of groynes and sea walls in some parts of the coastline has protected certain areas. Still, it has also led to increased erosion in others by interrupting the natural flow of sediment along the coast.

2.2. Trimingham, England

The Trimingham study area covers the coastline of Poppyland, Roughton, Mundesley, and Bacton coastline wards in a length of 18.29 km. It is located in North Norfolk on the eastern coastline of England (Fig. 2B). The coastline is susceptible to coastal erosion due to soft glacial deposits and the high-energy sea waves from the North Sea. The coastline is located within the Norfolk Coast, Area of Outstanding Natural Beauty (AONB). The coastal region around Trimingham is home to a diverse array of species, including birds, insects, and marine organisms [28]. To mitigate coastal erosion, sea defences such as sea walls, rock armour, groynes, and revetments were employed. However, the current structures are not strong enough to protect the area, and it needs a more thorough assessment; accordingly, this area has been selected for evaluation.

2.3. Durdle, England

Durdle's study area covers the coastal region of Durdle Ward, which is a total of 12.68 km in length. It is located on the Southern coast of England (Fig. 2C). This region has a significant geological history. Durdle Door is a prominent natural limestone arch situated on the Jurassic Coast in Dorset, England [29]. The Jurassic Coast is a UNESCO World Heritage Site, recognised for its exceptional geological features representing 185 million years of Earth's history [30]. The coastline around Durdle Door supports a variety of



Fig. 2. Coastal vulnerability evidence as field photos, A) Holderness coastal vulnerability, B) Trimingham coastal vulnerability, C) Durdle coastal vulnerability, and D) Lancashire (Southport) coastal vulnerability. The first author captured the photos A, B, and C during a field visit in March 2025, and the second author captured the photo D during a field visit in November/December 2024.

ecosystems, from rocky shores to sandy beaches, cliffs, and shallow seas. These habitats harbour a range of species, including seabirds, marine mammals, and unique plant life. Durdle Door is among the most frequently photographed landmarks in the UK, attracting millions of visitors each year. Climate change exacerbates coastal erosion through increased frequency of storms, changing weather patterns, and rising sea levels. As sea levels rise, the erosion of cliffs and beaches is expected to accelerate, threatening both natural habitats and human settlements along the coast [22]. Therefore, the current study selected Durdle as one of the case study areas for the assessment.

2.4. Lancashire, England

The Lancashire study coast covers the coastline of five districts, Lancaster, Wyre, Blackpool, Fylde, and Sefton, totalling 121.5 km in length. It is situated in northwest England (Fig. 2D). Its coastline, stretching along the Irish Sea, features diverse geological formations and ecosystems, including sandy beaches, mudflats, salt marshes, estuaries, and coastal wetlands [31]. The Morecambe Bay, Fylde Coast, and the Ribble Estuary are geologically significant areas within the county. These ecosystems support a rich diversity of wildlife, particularly bird species. Morecambe Bay, one of the UK's largest intertidal areas, is internationally recognised as a Ramsar site and a Special Protection Area (SPA) due to its importance for migratory birds [32]. The local economy relies heavily on tourism [33], and along with this, maritime industries and fishing also contribute to it [34]. Blackpool, historically one of the first mass tourist destinations in the UK [33], holds cultural significance as a symbol of British seaside heritage. Low-lying areas such as Morecambe Bay and the Ribble Estuary face high impacts from coastal flooding. The seaside and estuarine flooding due to tidal surges combined with high river flows could have devastating implications for infrastructure. Accordingly, this area has been selected as one of the case study areas for the assessment.

2.5. Kinmel Bay, Wales

The Kinmel Bay study area covers a coastline length of 3.58 km of the Kinmel Bay ward. This coastline, situated north of Wales (Fig. 3A), holds significant importance both ecologically and economically. Tourism contributes to a significant portion of its economy [35]. Eroding dune and beach loss is a pressing issue along the Kinmel Bay coastline [36]. This stretch of coast faces increasing risk



Fig. 3. Coastal vulnerability evidence as field photos, A) Kinmel Bay coastal vulnerability, B) Dundee coastal vulnerability, C) Belhaven coastal vulnerability, and D) Antrim coastal vulnerability. The first author captured the photos A and B during a field visit in February 2025, and C and D during a field visit in March 2025.

from coastal erosion and flooding due to climate change-induced extreme weather [37]. Kinmel Bay's coastline supports diverse habitats, including sandy beaches, dune systems, the Clwyd Estuary, and marine ecosystems, and provides a habitat for various species of birds, marine life, and unique coastal plants. Flooding is a serious concern because of the low-lying nature of the bay. Storm surges and high tides can lead to seawater encroaching on residential and commercial areas [38]. According to UKCP [39], climate projections indicate the Welsh coastline will face frequent tidal flooding in the coming decade. To combat these effects, coastal defences such as sea walls, groynes, and rock armouring have been implemented along the Kinmel Bay's coastline. However, these structures did not protect the areas significantly, and this area needs an assessment to evaluate the rate of vulnerability.

2.6. Dundee, Scotland

The Dundee study site constituted the coastline of the Ferry, East End, Maryfield, and West End wards of Dundee County, covering 15.57 km. It is located on the east coast of Scotland along the Firth of Tay Estuary (Fig. 3B). It was a major hub for shipbuilding, whaling, and the jute industry during the 19th and early 20th centuries. The access to the North Sea made Dundee an important centre for trade, energy, and shipping, significantly contributing to local employment and economy [40]. Tourism is also an important contributor to the local economy [41]. The Tay Estuary ecosystem plays a crucial role in carbon sequestration, and intertidal mudflats and salt marshes provide a habitat for migratory birds and marine species [42]. It is designated as a Special Area of Conservation. Climate-induced sea level rise heightens the risk of flooding and coastal erosion [9]. It is a significant threat to maritime industries, the local economy, settlements, and crucial ecosystems. Therefore, this area has been selected for the coastal vulnerability assessment to determine the scale of vulnerability.

2.7. Belhaven, Scotland

The Belhaven study area covers the coastline of the Belhaven ward, totalling 31.04 km. This coastline in East Lothian (Fig. 3C) is an important ecological, economic, and cultural site for Scotland. Tourism contributes significantly to local economies. The “disappearing bridge”, a unique tidal phenomenon, attracts photographers and nature enthusiasts. Belhaven Bay hosts dunes, salt marshes, and mudflats, an essential habitat for migratory birds, marine species, and native flora. Due to its ecological importance, the area is

Table 2
Parameters Used in This Study: existing and new.

No.	Variable	Existing or New parameter	Reference
1	Beach Width	Existing Parameter	[56]
2	Dune Width	Existing Parameter	[56]
3	Sea Defence	Existing Parameter	[68]
4	Coastal Slope	Existing Parameter	[67]
5	Vegetation	Existing Parameter	[56]
6	Built Structures	Existing Parameter	[68]
7	Coastal Landslides	New Parameter	This parameter was accepted by subject experts who have the coastal and remote sensing experience.



Fig. 4. Illustration of the coastline divided into 500 m by 500 m cells.

designated as a Site of Special Scientific Interest (SSSI). The region faces several environmental challenges from unregulated tourism, habitat disruption from anthropogenic activities, and climate-induced sea level rise and coastal erosion [9]. Consequently, this area has been identified as one of the case study areas for the assessment.

2.8. Antrim, Northern Ireland

The Antrim Coastline in Northern Ireland (Fig. 3D) stretches from Belfast to the north coast, covering 232.45 km of Antrim County. Tourism is a significant economic driver for Antrim, attracting millions of visitors annually [43]. A UNESCO World Heritage Site, Giant's Causeway is one of the most visited natural destinations in the UK [44]. The coastline is significant from an economic, cultural, and environmental perspective making it a focal region for sustainable tourism and conservation. It is home to various protected habitats, including salt marshes, coastal cliffs, and marine reserves, which serve as vital habitats for seabirds, seals, and other marine life [45]. The Dunluce Castle, ruins on the cliff, is an important social and cultural remains that connects to the region's medieval history of giants and ancient warriors [46]. The rising sea levels and stronger storms [9] risk to historic and natural habitats. Besides climate change threats, over-tourism and marine pollution are challenges to its coastal ecosystems. Therefore, to assess the updated coastal vulnerability, this area has been selected as one of the study areas.

3. Methodology

There is a diverse range of comprehensive methods available for appraising coastal vulnerability on a global and regional scales [47–58]. One of the most widely recognised and utilised approaches is the Coastal Vulnerability Index (CVI) method [59–65]. This method stands out for its ability to incorporate a diverse set of indicators tailored to the distinctive environmental, geographic, and socioeconomic characteristics of different coastal regions. The CVI evaluates important factors such as coastal slope, wave height, erosion rates, storm patterns and impact to gauge each area's susceptibility to natural hazards. Furthermore, it also considers human factors like the density of population, land use and cover, and disaster damage costs. By integrating these multifaceted indicators, the CVI offers a detailed assessment of coastal risks and associated factors.

Table 3
Physical parameter threshold based on [56].

Physical Parameter	Low (1)	Moderate (2)	High (3)	Very High (4)
Beach width (m)	>150	100 – 150	50 – 100	<50
Dune width (m)	>150	50 – 150	25 – 50	<25
Coastal slope (%)	>12	12 – 8	8 – 4	4
Distance of vegetation behind the back beach (m)	>400	400 – 200	200 – 100	<100
Distance of built structure behind the back beach (m)	<100	200-100	400-200	>400
Coastal defence (%)	>50	20-50	10-20	<10
Coastal landslide (number)	**0–5**	**6–10**	**11–16**	**>16**

Table 4
The cumulative vulnerability score Kantamaneni et al. [68].

Total Accumulative Vulnerability Score	Vulnerability
<12	Very Low
12-15	Low
16-18	Moderate
19-23	High
24-28	Very High

Therefore, this study employs CVI, a concept originally devised by Gornitz et al. [66], by using 7 different parameters. It integrates six well-established variables sourced from the research of Palmer et al. [56], Davies [67], and Kantamaneni et al. [68]. Furthermore, this research introduces a critical new parameter: coastal landslides. This addition has received good endorsement from leading global experts in the field, who bring extensive experience in coastal and remote sensing. By integrating this innovative parameter, the study not only strengthens the CVI but also provides a more detailed understanding of coastal susceptibility (Table 2).

3.1. Coastal parameter measurements

For this assessment, an approximately 487.45 km stretch of coastline across eight case study areas was initially considered. However, following more accurate measurements, certain sections were excluded, resulting in a final study length of 404 km. Consequently, the coastline was divided into 500 m × 500 m (0.5 km) grid cells, as illustrated in Fig. 4. A total of 804 cells were generated (Table 1), covering approximately 402 km of coastline. Each cell was then evaluated using seven parameters.

Beach Width: The beach width is the perpendicular distance between the Mean Low Water and Mean High Water marks, which were clearly indicated in OS Digimap and GIS. This was measured by following the top side of a cell for the entire cell. **Dune Width:** Similar to the beach width, this was also measured through GIS. The presence of a sand dune was clearly marked on the OS Digimap. The dune width was measured along the top of the cell along the perpendicular of the coastal line wherever it was present or found. The measurement unit was in meters (m). **Coastal Slope**: The coastal slope was precisely measured using the Google Earth Pro desktop application. To determine the slope percentage, we divided the rise by the distance from the shoreline and multiplied the result by 100. This method ensures an accurate representation of the coastal slope, as measurements were taken diligently from the waterline at the beginning of the cell, all the way to its inland end. **Built Structures**: This is also termed as built structures behind the back beach. A line was drawn parallel to the upper boundary of a cell encompassing any constructed features such as roads, industrial facilities, commercial buildings, or residential structures. The individual lengths of these structures were then combined to determine the total length of the built structure area along the 500 m transect (Fig. 4). The unit of measurement used for this calculation was in meters.

Vegetation: This is also referred to as the distance of vegetation behind the back beach. The method for measuring the distance of vegetation cover behind the back beach employed a similar approach to measuring built structures. The measurement was conducted along the top of the cell, as illustrated in Fig. 4. The starting point was the back of the coastline, where various types of vegetation, including grassland, trees, and agricultural land, were observed. The measurement specifically focused on the length of vegetation, excluding any significant built structures such as roads, industrial facilities, commercial establishments, or residential properties along the 500 m transect. The unit of measurement used was m. **Sea Defences:** The sea defences were delineated using Google Earth Pro software within the coastal cell along the coastline. The coastal defences, such as solid sea walls, rock revetments, timber, and rocks, were identified using Google Earth ortho-satellite imagery. The presence of the delineated defence line was measured in meters along the cell and later added to produce total coastal line protection for a cell in the case of fragmented protection. The total defence line was divided by 500 to express coastal protection for a cell as a percentage. A value of 0% means there was no defence at all, while 100% indicates the entire cell was protected.

Coastal Landslides: This study introduces coastal landslides as a novel parameter within the Coastal Vulnerability Index (CVI) framework for the first time. Prior to its inclusion, the parameter, along with its thresholds and measurement criteria for UK coastal landslides, was reviewed and validated by five internationally recognised scientists and academics from the UK, Ireland, and India. These experts possess extensive knowledge of the United Kingdom's coastal geography and future environmental scenarios. Following their evaluation and approval, coastal landslides were incorporated as an additional component of the CVI framework.

The landslide data, acquired from the BGS, which covers the coastal regions of England, Wales, and Scotland, includes 2156 records

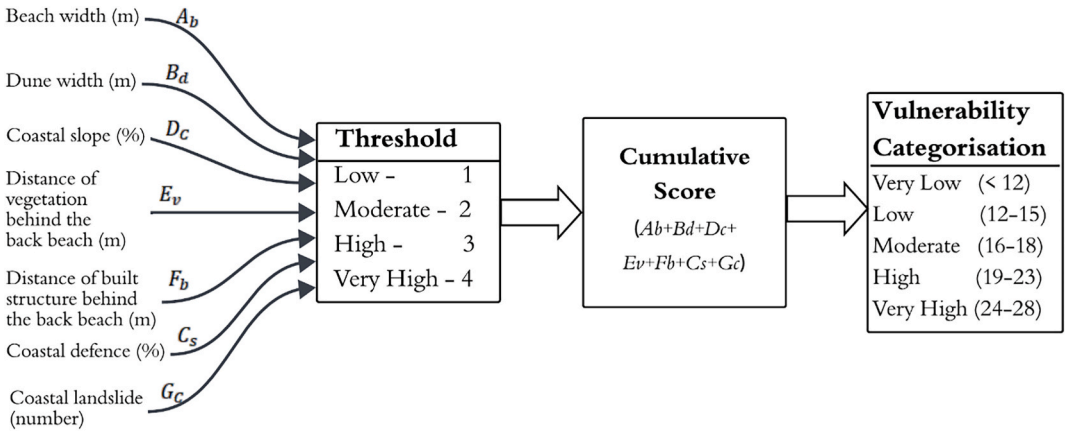


Fig. 5. PCVI methodological flowchart.

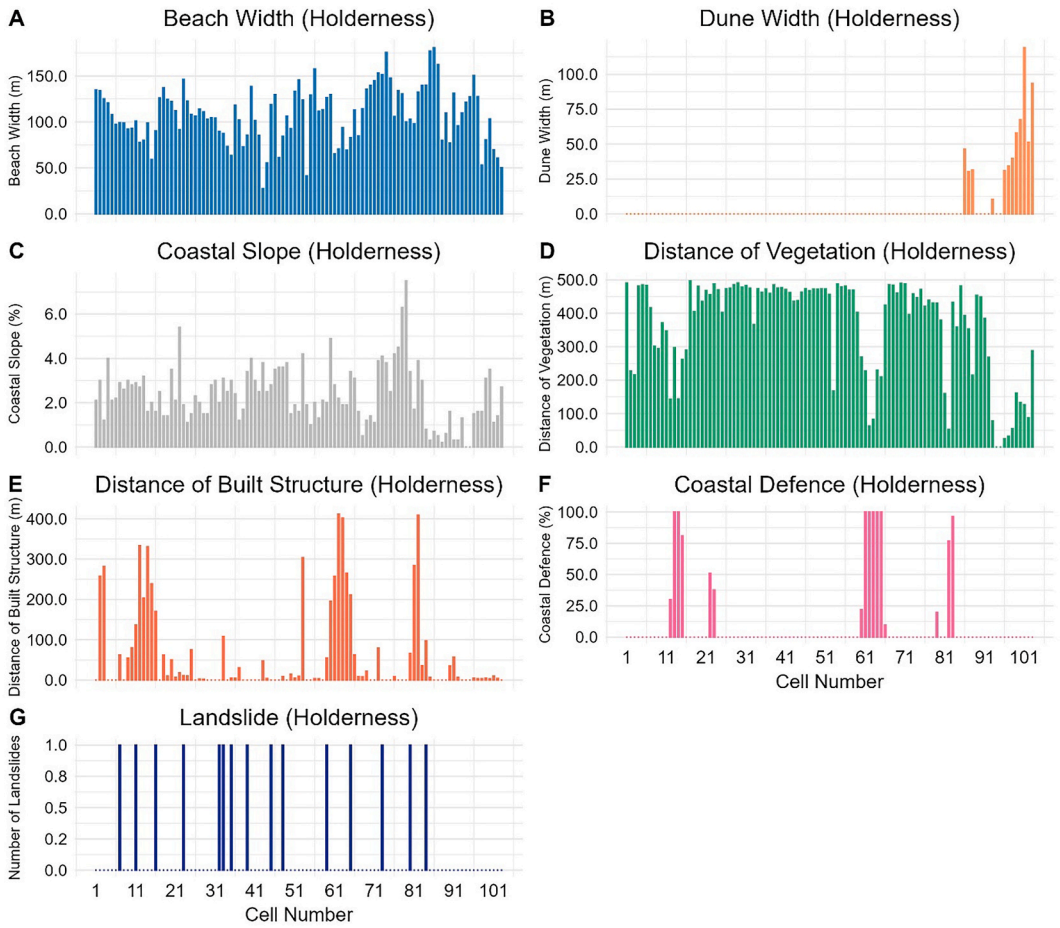


Fig. 6. Physical parameter measurement for Holderness, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

dating from 1664 to April 2024. The occurrence of landslides was categorised and mapped according to vulnerability scores, as outlined in Table 3, based on expert guidance. The landslide vulnerability has been measured based on the occurrence of a number in a particular area rather than cell-wise measurement. For example, any case study area scores more than 16 landslides so far that area has been considered a Very High vulnerability area. Landslide vulnerability is assessed based on the total number of landslides that have occurred in each area, rather than evaluating it on a cell-by-cell basis. For example, if a case study area has experienced more than 16



Fig. 7. PCVI GIS Vulnerability map for Holderness. The map was prepared in QGIS. It covers the North Holderness, Mid Holderness, and Southeast Holderness wards from North to South, respectively.

landslides, it is classified as a Very High vulnerability area. Consequently, all cells within that area are assigned the highest vulnerability score (see Table 4).

The final PCVI was calculated using an arithmetic sum of seven physical variables (Fig. 5), which were categorised based on their total relative vulnerability scores into five groups: Very Low, Low, Moderate, High, and Very High [68]. To ease the calculation and facilitate its use in equations, each physical variable was assigned a unique, identifiable letter: Beach width - A_a, Dune width - B_d, Coastal Defense - C_s, Coastal slope - D_c, Distance of vegetation behind the back beach - E_v, Distance of built structures behind the back beach - F_b, and Coastal Landslide - G_c (Equation (1)).

$$PCVI = A_b + B_d + C_s + D_C + E_v + F_b + G_C \tag{1}$$

Here, the Designated Symbol is as follows.

A_b	Beach Width
B_d	Dune Width
C_S	Coastal Defence
D_c	Coastal Slope
E_v	Vegetation
F_b	Built Structures
G_c [a]	Coastal Landslide

[a] Vegetation and Built structures denote the distance of vegetation and distance of built structures behind the back beach (m), respectively (see Fig. 5).

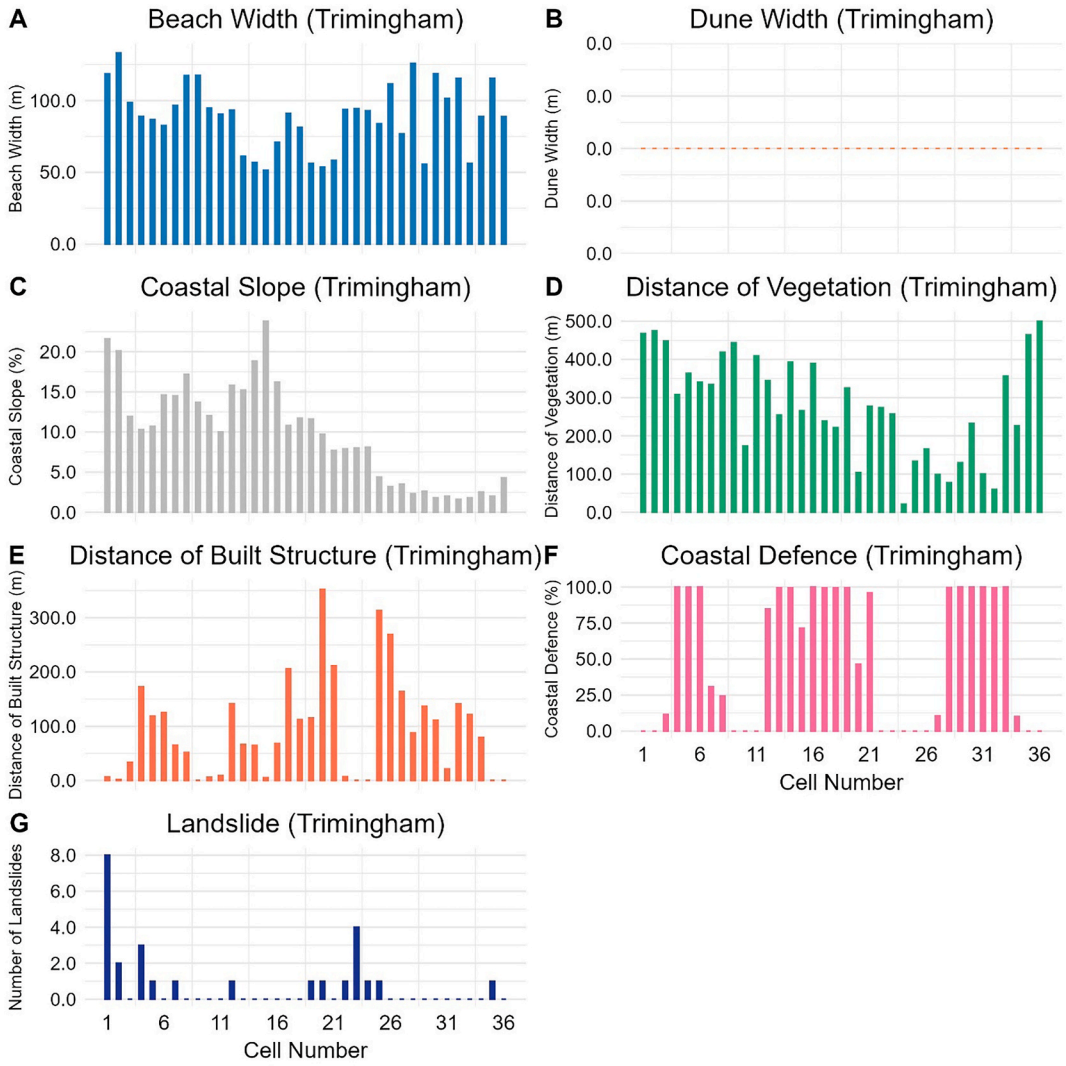


Fig. 8. Physical parameter measurement for Trimingham, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

4. Results

4.1. Holderness

4.1.1. Analysis of the PCVI values

In the 103 coastal cells of Holderness (Fig. 6), beach width varies moderately, with an average width of 108.2 m across all cells. The widest beach is in cell 86 at 180.6 m, while the narrowest is in cell 43 at 27.3 m. Dune coverage is sparse, observed in only 11.7% of the cells. Dune widths range from a minimum of 10.5 m in cell 93 to a maximum of 118.9 m in cell 101. Coastal slopes are generally gentle, ranging from 0.0% in cells 94-95 to a steeper 7.5% in cell 79, with a mean slope of 2.4%. Vegetation stretches an average of 365.9 m behind the back beach. The most extensive vegetation cover is in cell 17 at 496.9 m, while cells 94-95 have no vegetation recorded (0.0 m). Built structures behind the back beach are present in 61.2% of the cells. The highest recorded built structure length is 411.6 m in cell 62, with an average length of 57.8 m across all cells. Coastal protection measures are present in 15.5% of the cells, with the maximum coverage reaching 100% in seven cells (13-14 and 61-65). Landslides are recorded in 14.6% of cells and are found across the study site.

4.1.2. Overall PCVI scores and trend

The PCVI Score for Holderness (Fig. 7) shows distinguished variability in susceptibility across the 103 assessed cells. The PCVI score ranges from a minimum of 17 (Moderate vulnerability) in cells 22 and 83 to a maximum of 25 (Very High vulnerability) in cells 81.



Fig. 9. PCVI GIS Vulnerability map for Trimingham. It covers Poppyland, Roughton, Mundesley, and Bacton wards (North to South).

Most of the cells exhibit a score between 20 and 21, reflecting a High level of vulnerability. It counts for 63.1% of the total cells. 92.2% of cells exhibit High vulnerability, while 2.9% have Very High and 4.9% have Moderate vulnerability, respectively.

4.2. Trimingham

4.2.1. Analysis of the PCVI values

Across the 36 coastal cells at Trimingham (Fig. 8), Beach width varies moderately, with an average width of 89.4 m across all cells. The widest beach is in cell 2 (133.1 m), while the narrowest is in cell 15 (51.5 m). Dune coverage is absent (0%) in all recorded cells, indicating no natural dune systems in this region. Coastal slopes are steeper, ranging from 1.6% (cell 32) to 23.8% (cell 15), with an average slope of 9.8%. Vegetation spreads an average of 280.3 m behind the back beach. The most extensive cover (499.9 m) is in cell 36, while the least (21.2 m) is in cell 24. The built structure behind the back beach is present in 86.1% of cells, with the longest structure (352.2 m) in cell 20. The average built structure length is 93.9 m. The built structure was only absent at cells 9, 23, 24, 35, and 36. Coastal defence is widespread, present in 66.7% of cells, with maximum coverage (100%) in five cells (e.g., 4, 6, 16, 29, and 33). Landslides are relatively frequent, recorded in 36.1% of cells, with the highest frequency (8 events) in cell 1.

4.2.2. Overall PCVI scores and trend

The PCVI scores for Trimingham exhibit varying degrees of coastal vulnerability across the 36 studied cells (Fig. 9). The scores range from a minimum of 15 (Low vulnerability) at cell 8 to a maximum of 24 (Very High vulnerability) at cells 25, 26, and 27. Most cells fall within a score range between 16 and 21, which means either Moderate or High vulnerability categories. It accounts for 86.1% of cell falls between this range. Approximately equal numbers of cells have a High or Moderate vulnerability, which accounts for 47.2% and 41.7%, respectively. Only 8.3% of cells have Very High vulnerability.

4.3. Durdle

4.3.1. Analysis of the PCVI values

Across the 22 coastal cells of Durdle (Fig. 10), the Beach width is exceptionally narrow, with an average width of 10.97 m across all cells. The widest beach is in cell 7 (25.9 m), while the narrowest is in cells 14, 15, and 19 (0.0 m), indicating areas with no beach. Dune coverage is entirely absent (0%) in all cells. Coastal slopes are steep, ranging from 5.6% (cell 18) to 42.9% (cell 16), with an average slope of 23.8%. Vegetation extends an average of 377.09 m behind the back beach. The most extensive cover (500.0m) is in cells 4 and 5, while the least (174.6 m) is in cell 12. Built structures are rare and present in only 9.1% of cells (8 and 11). The longest structure (219.9 m) is in cell 11, with an average length of 187.9 m, where the built structure is present. Coastal protection is absent (0%) in all cells. Landslides are relatively frequent, recorded in 54.5% of cells, with the highest frequency (9 events) in cell 12.

4.3.2. Overall PCVI scores and trend

The PCVI scores for Durdle reflect a consistent level of coastal vulnerability (Fig. 11) across the 22 assessed cells. The PCVI scores range between a narrow value of 19 and 22. These scores are categorised into High-vulnerability cells. Most scores cluster tightly

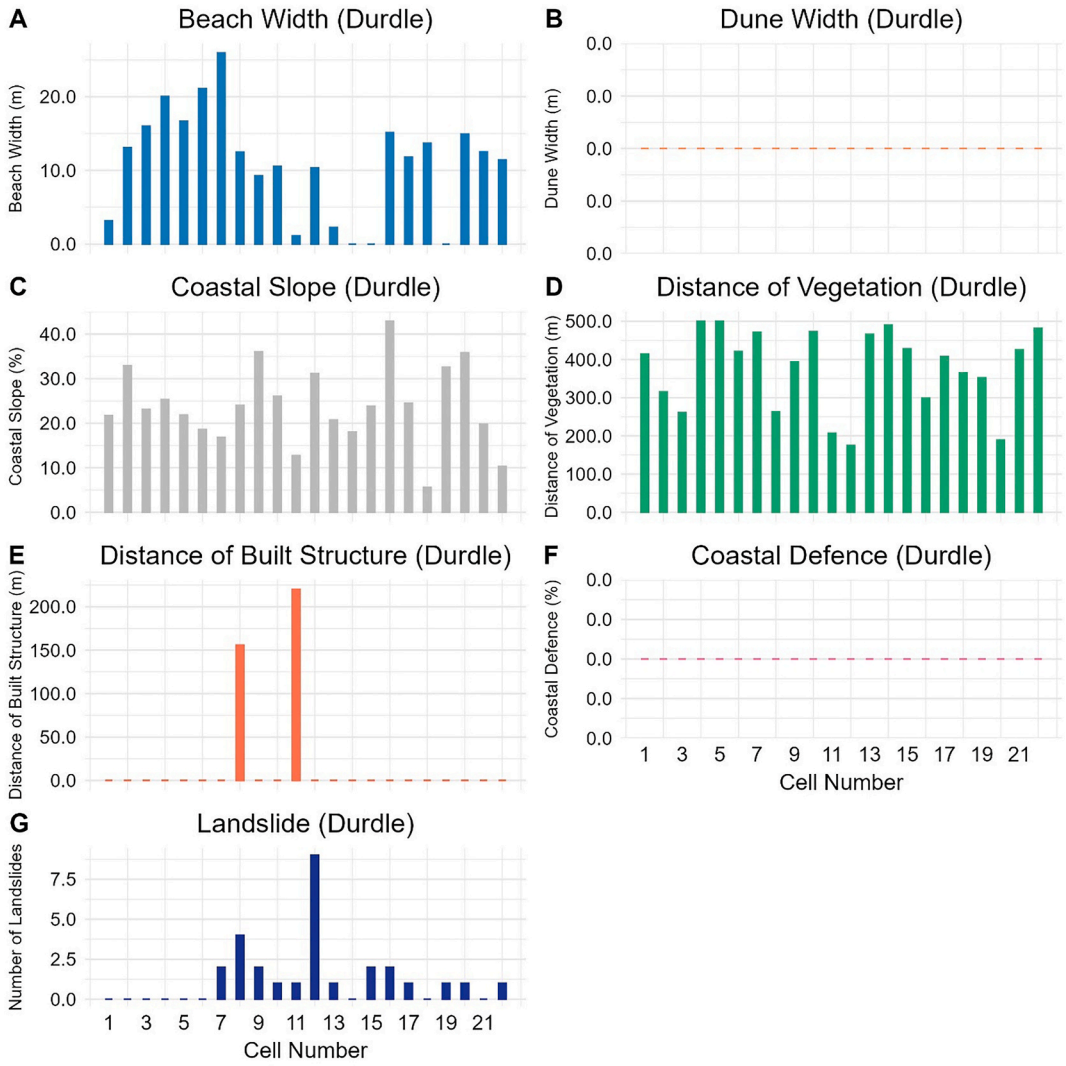


Fig. 10. Physical parameter measurement for Durdle, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

around 19 and 20, contributing 77.3% of total cells. The PCVI Score 19 is found in 11 cells, such as 1,4,5, etc, and 21 scores in cells, such as 8,9,10.

4.4. Lancashire

4.4.1. Analysis of the PCVI values

Across the 220 coastal cells of Lancashire (Fig. 12), Beach width varies considerably, with an average width of 923.0 m across all cells. The widest beach is in cell 50 (5127.6 m), while the narrowest is in cells 145, 197, 216-220 (0.0 m), indicating areas with no beach. Dune coverage is limited, observed in 25.9% of cells, with widths ranging from 11.3 m (cell 169) to 559.6 m (cell 193), with an average width of 39.8m. Coastal slopes are moderate, ranging from 0.0% (cells 145, 160-163) to 11.2% (cell 184), with an average slope of 3.9%. The vegetation cover behind the back beach extends an average of 235.7 m. The most extensive vegetation cover (500.0 m) is in cells 60, 63, and 195, while the least (0.0 m) is in 48 cells across the study area. In 21.8% of cells, there is no vegetation cover. Built structures behind the back beach are absent in 29.1% of cells. The longest structure (500.0 m) appears in multiple cells (e.g., 41-43, 202, 215-220), with an average length of 153.6 m. Coastal protection is present in 47.7% of cells, with maximum coverage (100%) in many (e.g., 23-25, 28-30, 207-209). Landslides are rare, recorded in only 1.4% of cells (e.g., cell 107, 108-110).

4.4.2. Overall PCVI scores and trend

The PCVI scores for Lancashire reveal significant variability in vulnerability (Fig. 13) across the 220 assessed cells. The PCVI scores

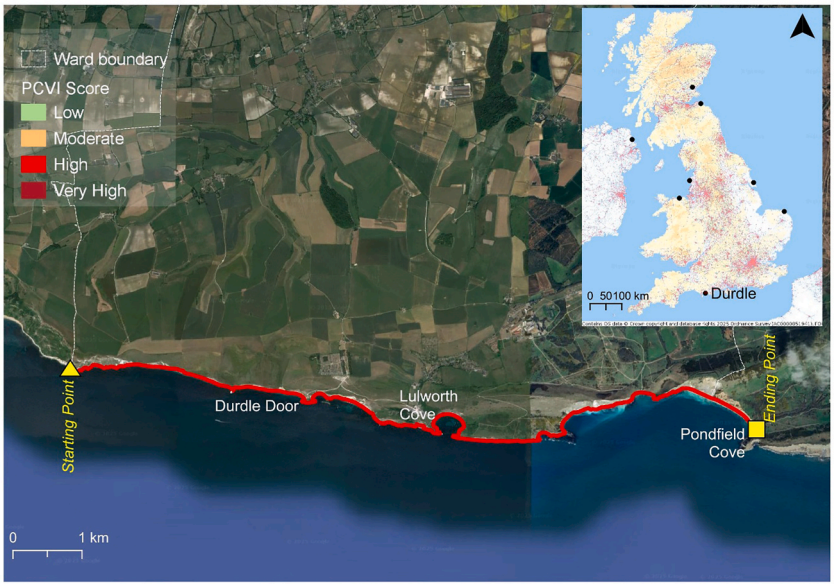


Fig. 11. PCVI Vulnerability map for Durdle.

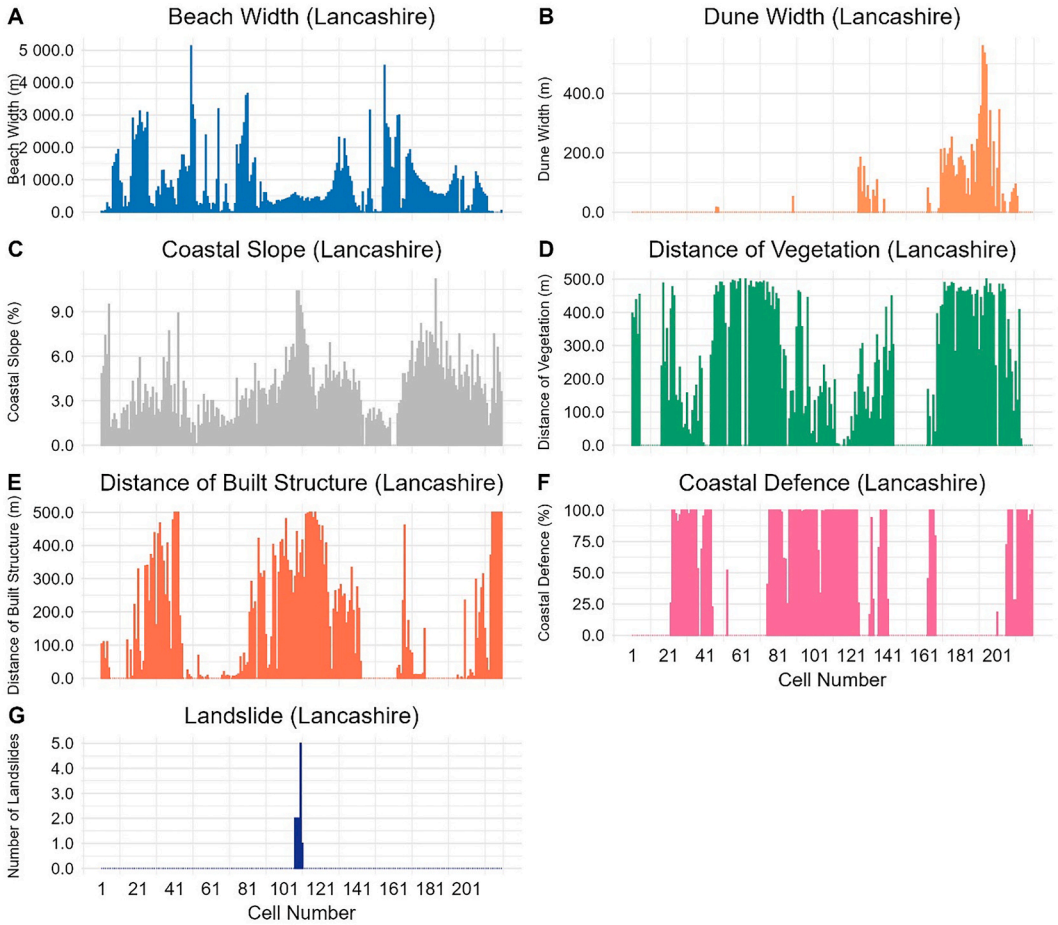


Fig. 12. Physical parameter measurement for Lancashire, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

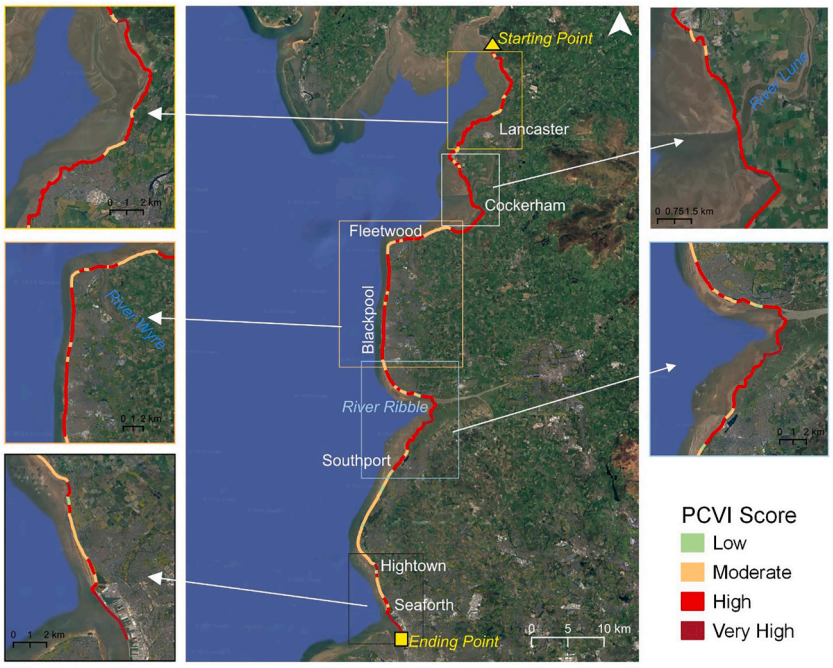


Fig. 13. PCVI Vulnerability map for Lancashire. It covers the coastline of the following districts (north to south): Lancaster, Wyre, Blackpool, Fylde, West Lancashire, and Sefton in Lancashire County.

range from 14 (Low vulnerability) to 25 (Very High vulnerability). Most cells fall into scores 15-22, indicating vulnerability spread among the Low, Moderate, and High categories. However, 8.2% of cells belong to Low vulnerability, but 58.6% are High vulnerable. 7.3% of cells have Very High vulnerability, and approximately a quarter (25.9%) of cells are Moderate vulnerable.

4.5. Kinmel Bay

4.5.1. Analysis of the PCVI values

Throughout the seven coastal cells of Kinmel Bay (Fig. 14), Beach width varies moderately, with an average width of 338.3 m across all cells. The widest beach is in cell 1 (551.2 m), while the narrowest is in cell 6 (216.8 m). Dune coverage is limited, observed in 28.6% of cells (cells 1 and 3), with widths ranging from 102.3 m (cell 3) to 149.7 m (cell 1). Coastal slopes are gentle, ranging from 3.5% (cell 6) to 4.9% (cell 7), with an average slope of 4.3%. Vegetation extends an average of 152.4 m behind the back beach. The most extensive cover (220.8 m) is in cell 7, while the least (84.3 m) is in cell 4. Built structures are present in all cells, with the longest (365.2 m) in cell 5 and an average length of 285.4 m. Coastal protection is widespread, present in 100% of cells, with maximum coverage (100%) in most cells. Cell 1 has the shortest coastal defence, which accounts for 41.5%. Landslides are absent (0%) in all recorded cells.

4.5.2. Overall PCVI scores and trend

The PCVI scores for Kinmel Bay exhibit a Moderate and Low vulnerability (Fig. 15) profile across the seven studied coastal cells. Scores range from 14 (Low) in Cell 3 to 18 (Moderate) in Cell 4. The majority of cells (2, 4, 5, and 6) fall into the Moderate vulnerability category, with cell 4 being the highest score at 18. 57.1% of cells belong to a Moderate level of vulnerability, while 42.9% have a Low level of vulnerability. Nearly half (42.9%) of cells have 16 PCVI values at the lower end of the Moderate vulnerable class.

4.6. Dundee

4.6.1. Analysis of the PCVI values

Within the 29 coastal cells of Dundee (Fig. 16), Beach width varies significantly, with an average width of 122.8 m across all cells. The widest beach is in cell 5 (514.9 m), while the narrowest is in cell 17 at 3.9m; cells 14-16 and 18 have 0.0 m, indicating areas with no beach. Dune coverage is entirely absent (0%) in all recorded cells. Coastal slopes are moderate, ranging from 1.0% (cell 3) to 8.7% (cell 15), with an average slope of 4.8%. Vegetation extends an average of 225.1 m behind the back beach. The most extensive cover (460.8 m) is in cell 3, while the least (8.9 m) is in cell 12. Built structures are present in all cells, with the longest structure (491.3 m) in cell 12 and an average length of 266.1 m, with the shortest in cell 3 at 24m. Coastal protection is widespread, present in 68.9% of cells, with maximum coverage (100%) in many (e.g., cells 7-16, 24-25). Landslides are absent (0%) in all recorded cells.

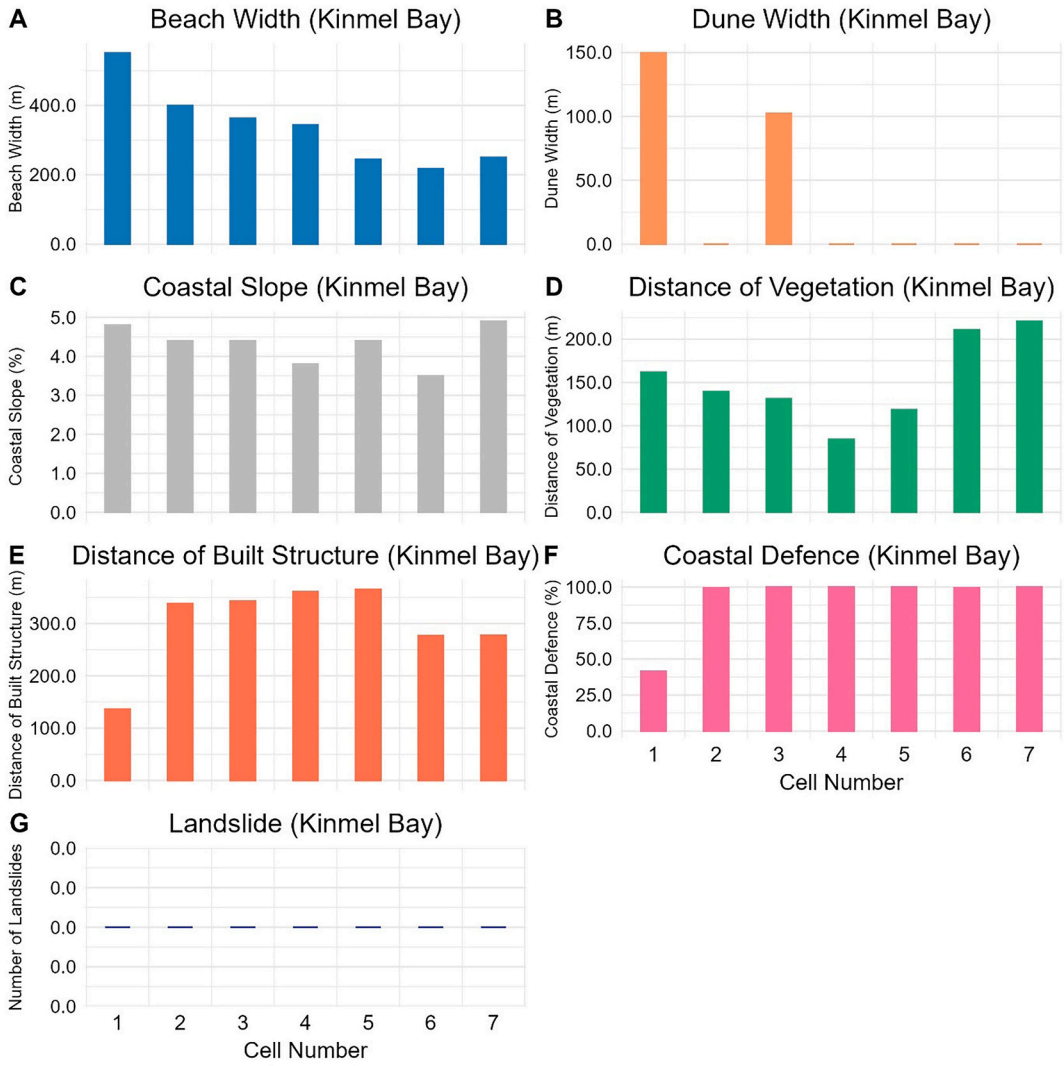


Fig. 14. Physical parameter measurement for Kinmel Bay, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

4.6.2. Overall PCVI scores and trend

The PCVI scores for Dundee reveal a predominantly High-vulnerability (Fig. 17) coastline across the 29 assessed cells, with scores ranging from 14 (Low) in Cells 6 and 7 to 22 (High) in multiple cells (e.g., 12, 13, 18, 24). More than half (55.2%) of cells have a High vulnerability, but no cell exhibits Very High vulnerability. While 37.9% of cells have Moderate vulnerability, the remaining 6.9% fall into Low vulnerability categories. The cumulative PCVI values in the range between 17, 18, and 19 contribute to 62.1% of the total cells of the study area.

4.7. Belhaven

4.7.1. Analysis of the PCVI values

Across the 54 coastal cells of Belhaven (Fig. 18), Beach width varies significantly, with an average width of 84.3 m across all cells. The widest beach is in cell 22 (476.7 m), while the narrowest is in multiple cells (10-16, 23-25, 29-33, etc.) with 0.0 m, indicating areas with no beach. Dune coverage is limited, observed in 12.9% of cells (cells 2-3, 17-21), with widths ranging from 27.7 m (cell 3) to 267.4 m (cell 20). Coastal slopes are gentle, ranging from 0.4% (cell 11) to 8.8% (cell 54), with an average slope of 3.8%. Vegetation extends an average of 320.8 m behind the back beach. The most extensive cover (500.2 m) is in cells 9 and 16, while the least (54.9 m) is in cell 45. Built structures are absent behind the back beach in 31.5% of cells. The longest structure (440.4 m) is in cell 45, with an average length of 61.0 m across cells. Coastal protection is minimal, present in only 22.2% of cells, with maximum coverage (100%) in cells 26, 45, and 46. Landslides are rare, recorded in only one cell (cell 25).



Fig. 15. PCVI Vulnerability map for Kinmel Bay. The study area covers the entire coastline of Kinmel Bay ward.

4.7.2. Overall PCVI scores and trend

The PCVI assessment of Belhaven's 54 coastal cells reveals a vulnerability mainly distributed to either High or Moderate (Fig. 19). Nearly half (46.3%) of cells are in the High vulnerable class, 38.9% are in the Moderate, while only 14.8% belong to the Low vulnerable class. PCVI scores range between 13 and 21, but mainly concentrate around 17 to 20. Out of 46.3% of the High vulnerability class, 24.1% found the low end of the class at scores of 19.

4.8. Antrim

4.8.1. Analysis of the PCVI values

Within the 333 coastal cells of Antrim (Fig. 20), Beach width varies significantly, with an average width of 14.1 m across all the cells. The widest beach is in cell 322 (406.6 m), while most cells (79.6%) show no beach width (0.0 m). Dune coverage is limited, observed in only 3.0% of cells, with widths ranging from 12.6 m (cell 126) to 479 m (cell 16). Coastal slopes are highly variable, ranging from 0.8% (cell 202) to 44.8% (cell 77), with an average slope of 13.7%. Vegetation extends an average of 394.8 m behind the back beach. The most extensive cover (499.9 m) occurs in multiple cells, while the least (6.4 m) is in cell 333. Built structures are absent behind the back beach in 19.5% of cells. The longest structure (481.9 m) appears in cell 330, with an average length of 94.9 m, where present. Coastal defence is present in 52.6% of cells, with maximum coverage (100%) in numerous locations (e.g., cells 124, 129-134). Landslides are rare, recorded in only two cells (170-171).

4.8.2. Overall PCVI scores and trend

The PCVI assessment of Antrim's 333 coastal cells reveals a coastline with predominantly Low-to-Moderate vulnerability (Fig. 21), punctuated by localised High-vulnerable cells. Scores range from 13 (Low) in several cells (e.g., 129, 130, 185) to 23 (High) in Cell 330, with no Very high ($\geq$24) scores recorded. More than half (56.8%) of cells are Moderate vulnerable, and 30% are Low, while only 13.2% are at High vulnerability.

4.9. Combined CVI scores and trends of PCVI

Based on the cumulative PCVI scores across the 402 km stretch of coastline in this study (Fig. 22), which includes 804 cells, there are clear patterns of vulnerability. There are only 2.7% cells classified as Very Highly vulnerable; however, nearly half of the cells, about 43.3%, are classified as the High vulnerable category. While 37.6% fall into the Moderate category, and 16.4% are in the Low vulnerability category. These Very High vulnerable cells are concentrated along the coasts of Holderness, Trimingham, and Lancashire. Of these, Holderness and Trimingham sit on England's eastern shore. Except for Kinmel Bay, all sites include cells in the High vulnerability category as well as other levels, but Durdle stands out as the only region where every cell is rated as High vulnerable. The most common individual cell score is 16 (the lower end of the Moderate class), representing 17.2% of all cells, followed by a score of 19 (the lower end of the High vulnerability class) at 12.8%.

Antrim and Kinmel Bay stand out, with more than half of their cells falling into the Moderate vulnerability category. In contrast, all other sites, except Durdle, have less than 50% of their cells as Moderate vulnerable. Durdle is unique in that none of its cells are in the

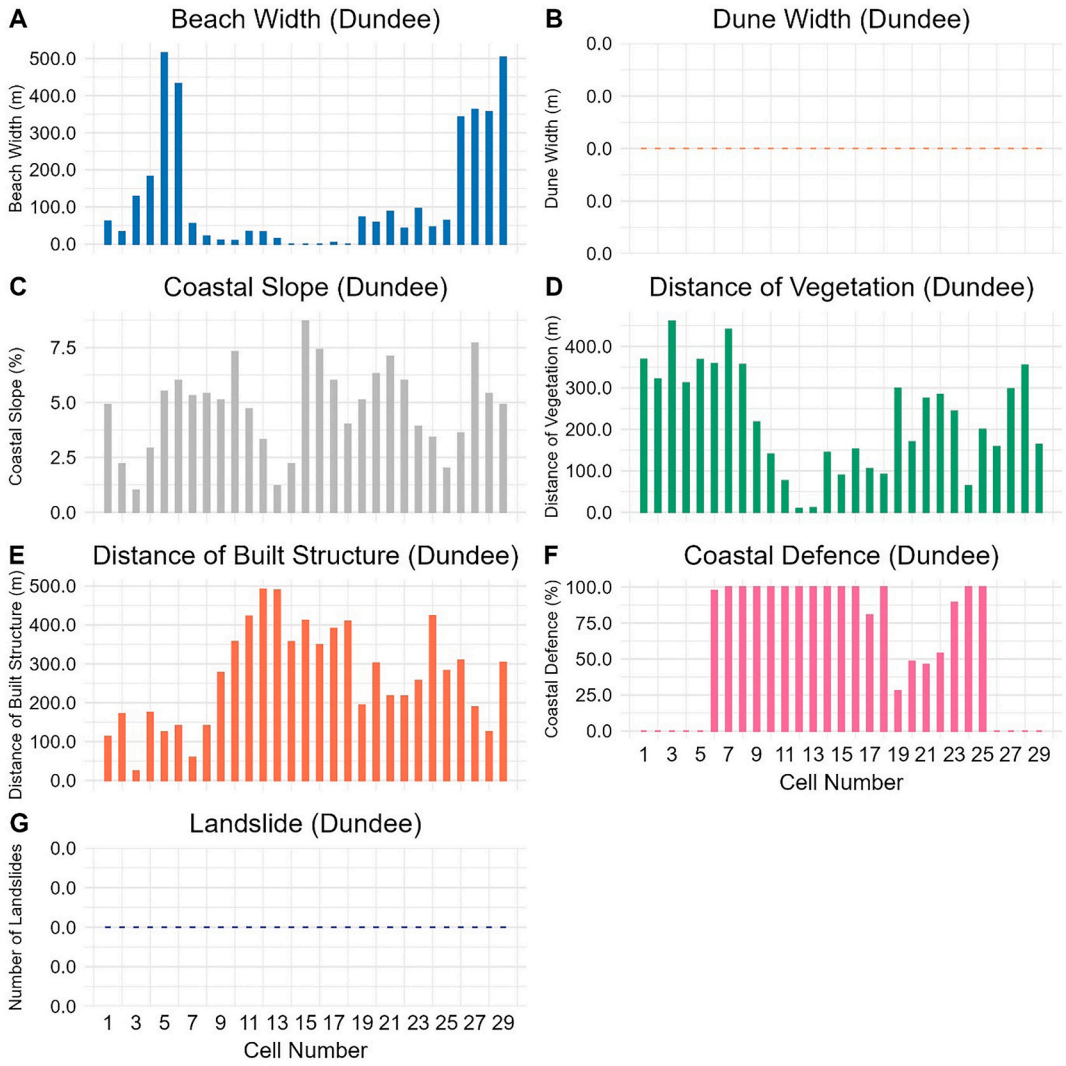


Fig. 16. Physical parameter measurement for Dundee, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

Moderate category. For the other sites, Trimingham, Belhaven, and Dundee have 41.7%, 38.9%, and 37.9% of their cells in the Moderate vulnerability, respectively, while Holderness has less than 5%. Durdle is the only site where every cell is High vulnerable. Kinmel Bay, on the other hand, features both Moderate and Low vulnerability cells, and also has the highest proportion of Low vulnerability cells overall. Trimingham has the lowest proportion of low vulnerability cells. Notably, neither Holderness nor Durdle has any cells classified as Low vulnerability. The other regions display a mix of vulnerability levels, ranging from Low to Very High, reflecting the diverse exposure of these coastlines. These results highlight not only the diversity in vulnerability along the coastline but also the area's most in need of attention, making it clear where efforts to protect and manage coastal risks could be most effective. These results highlight not only the diversity in vulnerability along the coastline but also the area's most in need of attention, making it clear where efforts to protect and manage coastal risks could be most effective.

Along with these, ground-truth validation through independent field verification has been done. Furthermore, this study has added field-visit maps showing the validation locations along with corresponding geotagged photographs (Figs. 23 and 24). Additionally, two validation photographs with geolocation information have been included.

5. Discussion

The present study utilised the PCVI to evaluate coastal vulnerability at eight sites along the UK coastline, which includes England, Wales, Scotland, and Northern Ireland. Half of these study sites are in England. The case captures a diverse range of coastal vulnerability profiles through the complex interplay of geomorphological, ecological, and anthropogenic factors.



Fig. 17. PCVI Vulnerability map for Dundee. It covers the following four wards, namely West End, Maryfield, East End, and The Ferry from West to east, respectively.

Building upon the physical variables used in the previous study by Kantamaneni et al. [68], a new variable called "Coastal Landslide" was introduced to replace the previously used "Rocky Outcrop." Coastal landslides, or slope failures, are exacerbated by toe erosion [69]. Additionally, frequent wave action erodes coastlines up to five times faster than areas only exposed to rainfall [70]. According to the UK Climate Projections [39], the frequency and severity of storm surges and rising sea levels are increasing and are likely to worsen with climate change. The highest number of landslides was recorded at Durdle Door, Holderness, and Trimingham, among Europe's fastest-eroding coastlines. In contrast, Kinmel Bay did not experience any landslides. A comparison of the PCVI scores for all 804 coastal cells shows that almost half (46%) fall into the High or Very High vulnerability categories. In contrast, only about a quarter (16%) is rated as Low vulnerability. Notably, Very High vulnerability scores are clustered in Holderness, Trimingham, and Lancashire, with Holderness and Trimingham situated along the eastern coast of England, an area well-documented for its erosional instability [71].

Holderness stands out with 92.2% of its 103 cells in the High and Very High categories. This reflects its narrow dune presence, limited vegetation in some areas (0 m in cells 94–95), and sparse coastal defence (15.5% of cells), all of which contribute to its susceptibility. Similarly, Durdle, though smaller in scale with only 22 cells, exhibits uniformly High vulnerability. Its average beach width is exceptionally low (10.97 m), dunes are absent, and landslides affect over half of the cells, emphasising the vulnerability of steep cliff-lined coasts devoid of natural buffers. This mirrors patterns observed in steep, naturally exposed coastal cliffs in California, where physical constraints dominate vulnerability profiles regardless of human activity. The studies from Japan and Chile also validate that high-gradient coastal cliffs lead to structural instability and elevated coastal hazard levels. Lancashire's case is more heterogeneous: although it has vast beach widths (up to 5.1 km in cell 50), nearly 59% of cells are High vulnerable, likely due to patchy dune coverage (25.9%) and a substantial proportion of cells (21.8%) lacking vegetation. The variability in the coastal slope and the presence of densely built environments also play a role here. Coastal features, such as beach width and dunes, have been identified as key natural safeguards against coastal hazards, including storm surges and erosion [72]. In contrast, extremely narrow beaches or the absence of beaches is linked to High vulnerability, a finding supported by studies from coasts in Indonesia and the Mediterranean [73].

Sites like Trimingham, Dundee, and Belhaven reveal a significant presence of Moderate vulnerability cells (41.7%, 37.9%, and 38.9%, respectively). Trimingham, despite its steep average coastal slopes (9.8%) and total absence of dunes, has substantial vegetation cover (280.3 m on average), which acts as a natural buffer. Its extensive coastal protection (66.7% of cells) and densely built structural presence (86.1%) also explain its mixed vulnerability scores. The substantial vegetation cover plays a significant role in reducing coastal risk. However, it should be complemented by other buffers, such as wider beaches and dunes, to mitigate coastal risk effectively [74]. Dundee exhibits a broader range of beach width variability and fully built structure coverage across all cells, yet maintains a relatively low share of very high PCVI scores. The similarity between dense coastal protection and low vulnerability was in line with the findings by Neumann et al. [75]. This suggests that the consistent placement of artificial coastal defence infrastructure, combined with moderate slopes and vegetation, might mitigate vulnerability, even in the absence of dunes. Belhaven, with relatively balanced moderate and high vulnerability classes (38.9% and 46.3%, respectively), is characterised by average beach widths (84.3 m) and limited coastal defences (22.2%). Like other east-facing sites, it suffers from localised erosion and dune fragmentation, contributing to its vulnerability distribution.

The presence of natural protection, such as dunes, wider beaches, rocky outcrops, and sea defences, slows down coastal erosion [76], leading to lower vulnerability. Narrower beaches correlate strongly with higher vulnerability, supporting existing literature that

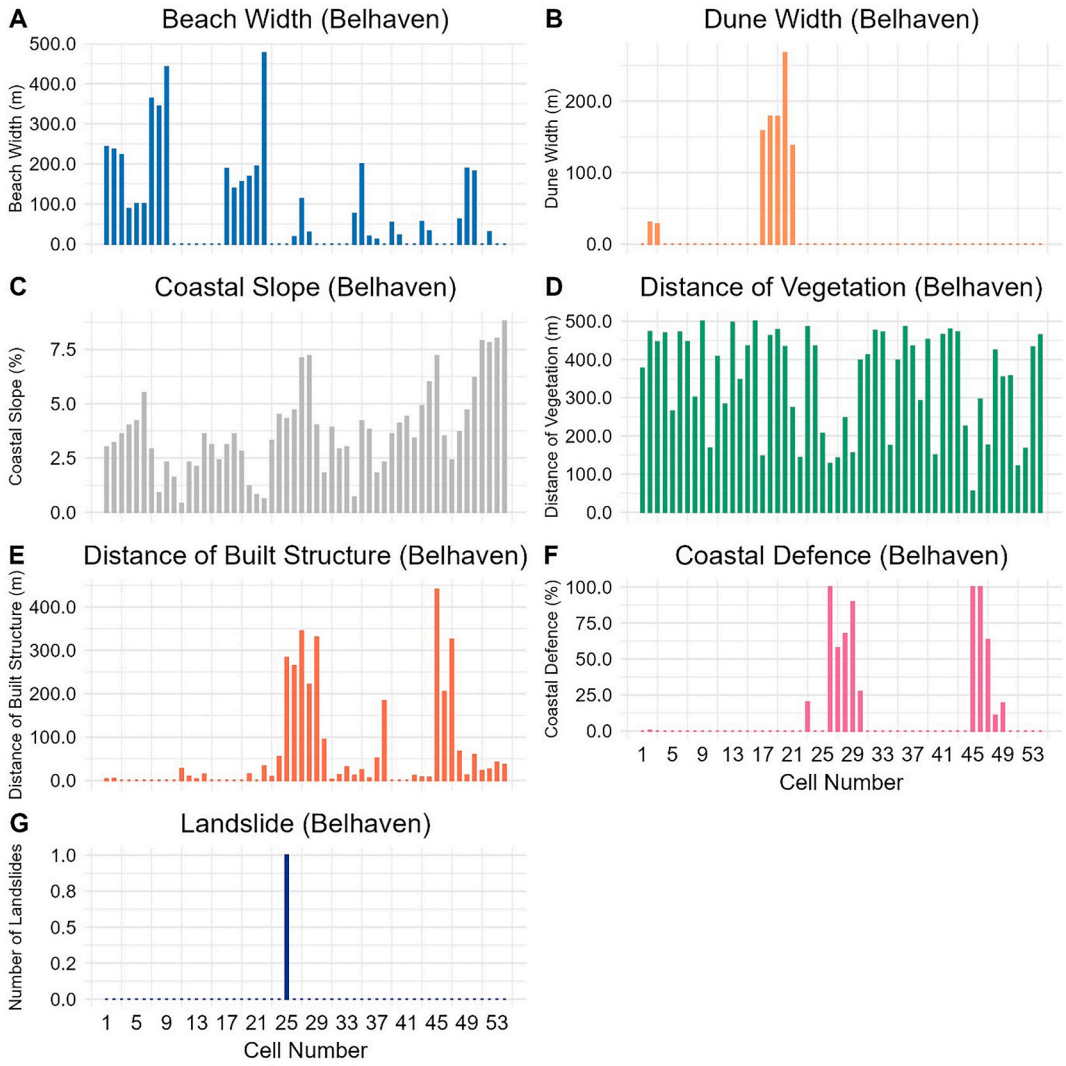


Fig. 18. Physical parameter measurement for Belhaven, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

recognises beaches as primary energy dissipaters [77]. Where dunes exist, they offer vital storm surge protection. Their absence in Durdle, Dundee, and Trimingham likely contributes to a higher risk. Dense vegetation (>300 m) correlates with reduced vulnerability by stabilising backshore areas and mitigating erosion. Areas with consistent and extensive engineered defences often show lower vulnerability, but overreliance on hard defences may obscure underlying risk [78]. Steep slopes and frequent landslides are indicative of higher vulnerability, aligning with findings on slope-instability contributions to coastal risk [79].

Physical vulnerability scores provide the opportunity for coastal management and research to narrow down the intervention plan or research to a specific targeted region by considering cost-benefit analysis. The coastal protection effort should be site-specific; for example, the coast with a steep slope should employ natural protection such as sand nourishment, and the coast with a gentle slope should employ sea defence. A study suggests that nature-based intervention plans are cost-effective and durable in the long term [80]. The index-based method provides a low-cost, easy-to-understand and rapid assessment of coastal vulnerabilities, which ultimately helps non-technical management to take fast action.

Additionally, field surveys were undertaken at all study sites to verify the condition and classification of the seven physical parameters used in the PCVI, including beach width, dune width, coastal defences, coastal slope, vegetation cover, built structures, and coastal landslides. The observed conditions were consistent with the PCVI classification. Further validation was achieved by comparing the PCVI classifications with documented geomorphological characteristics and reported erosion behaviour in the published literature.



Fig. 19. PCVI Vulnerability map for Belhaven. The coastline covers the Belhaven ward.

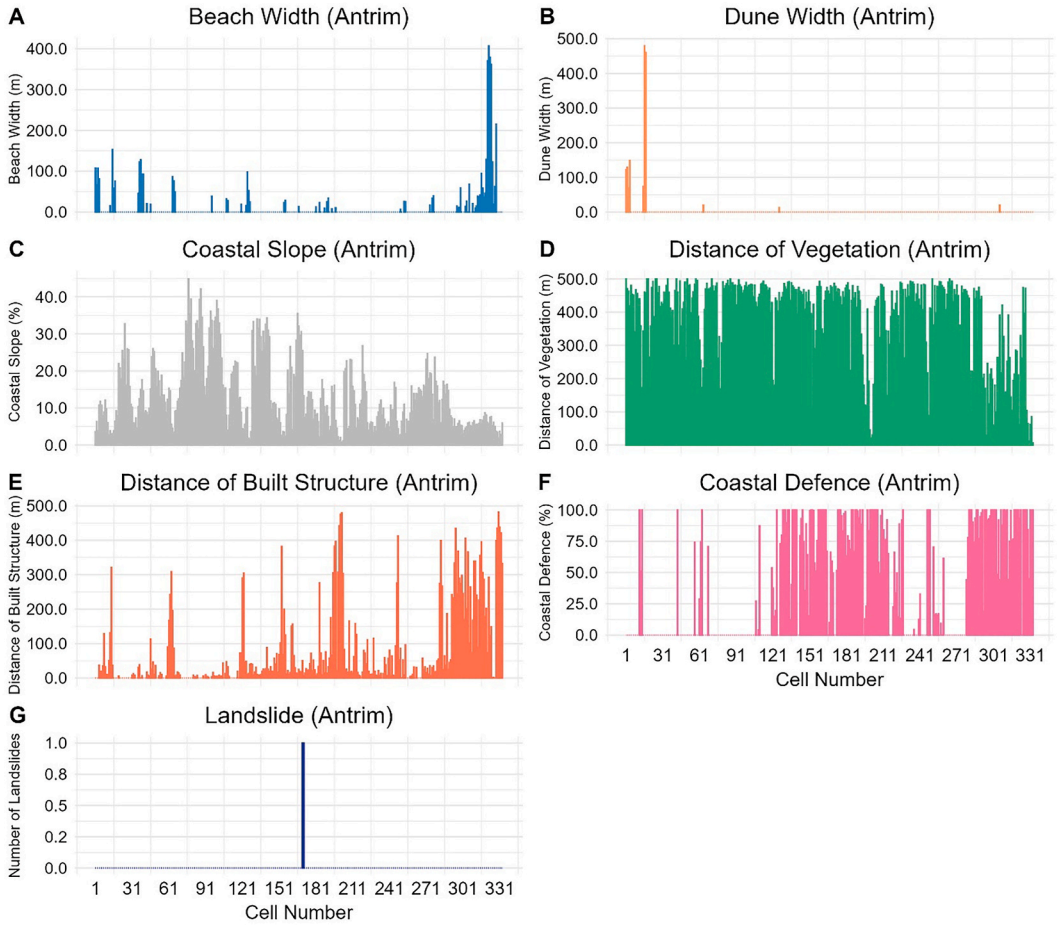


Fig. 20. Physical parameter measurement for Antrim, where A) Beach width, B) Dune width, C) Coastal slope, D) Vegetation cover behind back beach, E) Built structure behind back beach, F) Coastal defence, and G) Coastal landslide.

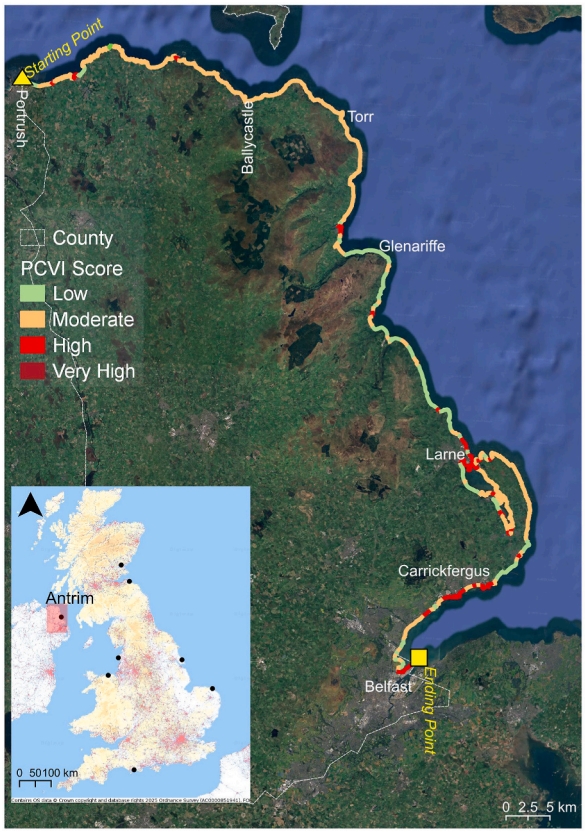


Fig. 21. PCVI Vulnerability map for Antrim. It covers the whole Antrim County coastline.

6. Limitation

The present study incorporated a well-established PCVI index method, combined with well-known coastal variables and a unique coastal landslide variable, which is relevant in a climate change scenario, as well as covering a large (402 km) and diverse coastline of the UK, which comes with some limitations. The number of coastal cells analysed varies significantly among the study sites. This uneven spatial coverage can introduce biases in comparative analysis, as areas with fewer cells may not capture the full variability of coastal characteristics. The present PCVI analysis is static and does not account for temporal changes in land use, coastal morphology, or erosion rates. Coastal dynamics can change rapidly due to both natural processes and human interventions. Without incorporating time-series data, temporal variability and emerging trends in vulnerability remain unassessed. While the PCVI focuses on physical indicators (beach width, dune presence, slope, etc.), socioeconomic vulnerability, such as population density, economic dependency on coastal assets, and adaptive capacity, is not included. The study does not incorporate future projections of climate-induced changes, which are critical to assessing long-term coastal vulnerability. Relying on current physical indicators alone may not provide a clearer picture of future risk, particularly in areas like Holderness, which are already experiencing rapid erosion.

While landslides and beach width are considered, the rate and type of erosion (e.g., undercutting, slumping, longshore drift) are not explicitly analysed. For instance, Holderness is one of Europe's fastest-eroding coastlines, but the analysis does not quantify erosion rate data, which would provide greater insight into vulnerability. Built structures and coastal defences are considered in terms of presence and length, but not their effectiveness, maintenance status, or resilience. A longer defence structure does not necessarily imply better protection, especially if it is degraded or poorly designed. Future research work will include sensitivity testing using AHP and weighted multi-criteria approaches to make this study studies more robust.

7. Recommendations

Based on analysis, results and aligned with global best practices, the following recommendations are proposed.

1. Enhance Nature-Based Solutions: Expand dune restoration and beach nourishment programs in regions with narrow or absent beaches (e.g., Durdle, Trimingham, Antrim), following models used in the Netherlands and New Jersey.
2. Integrate Hybrid Defences: Combine grey infrastructure (e.g., seawalls) with green infrastructure (e.g., dune and wetland restoration) in high-risk regions like Holderness and Dundee to balance protection and ecological integrity.

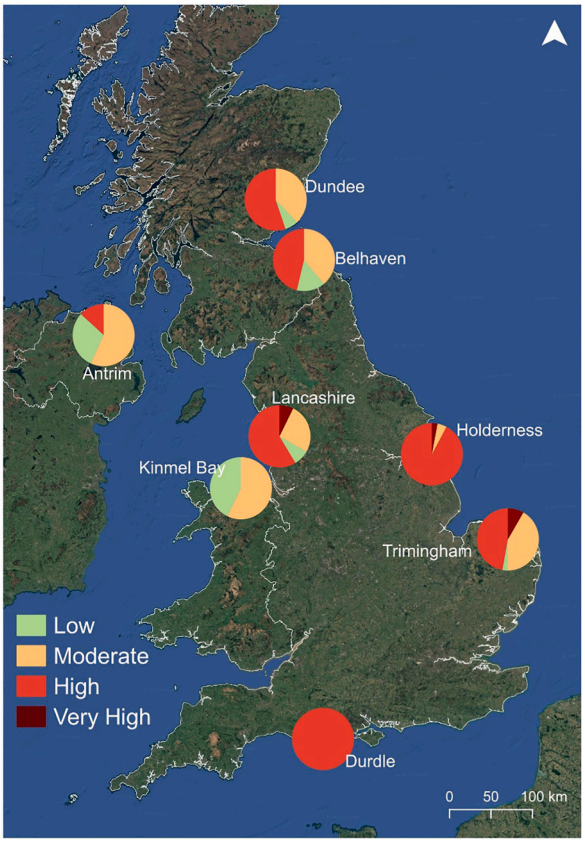


Fig. 22. Cumulative PCVI maps with percentage of cells for the vulnerability categories.



Fig. 23. Durdle, georeferenced field photo validated with satellite image.

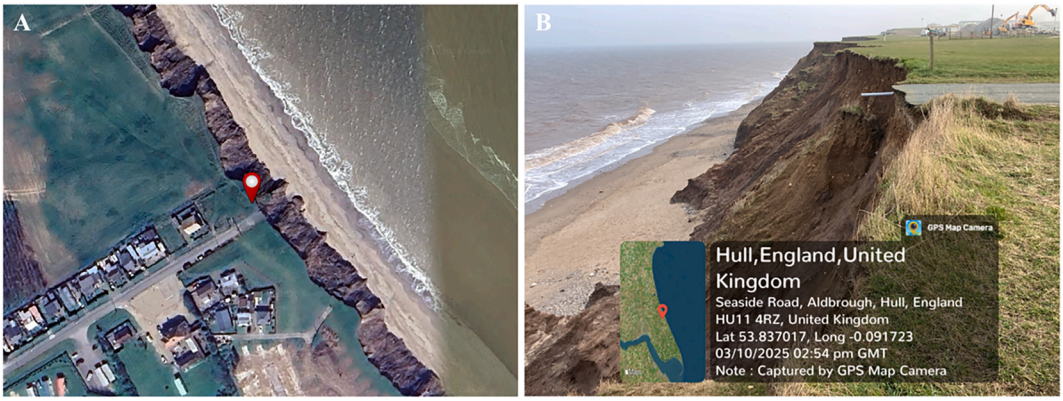


Fig. 24. Holderness, georeferenced field photo validated with satellite image.

3. Landslide Monitoring and Early Warning Systems: Implement geotechnical surveillance and landslide forecasting systems in steep cliff regions such as Durdle and Antrim to mitigate geomorphological hazards.
4. Managed Realignment and Development Control: Introduce development restrictions and explore realignment strategies in high-vulnerability zones, especially where retreat is more sustainable than defence (e.g., southern Holderness).
5. Community-Based Adaptation: Increase stakeholder engagement and integrate local knowledge into vulnerability mapping and mitigation planning, as recommended by recent studies on coastal community resilience.
6. Further Research on Ecological Indicators: PCVI assessments should be expanded to include biological variables to better reflect comprehensive vulnerability, as recommended by Arkema et al. [81].
7. Inclusion of Socioeconomic Indicators in future studies : Socioeconomic variables provide a multifaceted and comprehensive vulnerability assessment.

8. Conclusion

This study established the new PCVI to provide a comprehensive assessment of physical vulnerability at eight diverse coastal sites across the UK. Utilising seven physical variables, six widely recognised and one newly introduced parameter, coastal landslide susceptibility, this analysis offers an enhanced understanding of risks. In this assessment, areas such as Lancashire, Kinmel Bay, Dundee, and Belhaven are notable for their dense populations and significant economic activity, underscoring the urgent need for targeted protective strategies. Conversely, while Holderness, Trimingham, Durdle, and Antrim are less populated, their ecological significance cannot be overlooked. Alarmingly, all sites except Kinmel Bay and Antrim exhibit high levels of physical vulnerability, underscoring the need for proactive planning. Regions shaped by human activity, such as Trimingham, Lancashire, Dundee, and Belhaven, particularly require strategic coastal protection measures to safeguard both lives and livelihoods. The findings highlight an undeniable need for robust, site-specific coastal management strategies that effectively balance economic growth with ecological preservation. The PCVI analysis highlights the intricate interplay between natural and anthropogenic factors contributing to coastal vulnerability. Key natural features, including beach width, dune systems, and slope, play crucial roles, yet the impact of artificial structures cannot be underestimated. Effective regional planning must incorporate these spatial dynamics, advocating for nature-based solutions like dune restoration and vegetative buffers alongside necessary engineered interventions. Ultimately, the results of this study provide a compelling scientific basis for informed risk management, proactive adaptation planning, and the strategic implementation of both soft and hard coastal protection measures. It is imperative that we act decisively to protect our coastal communities and ecosystems from the increasing threats posed by climate change and human activity.

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CRediT authorship contribution statement

Abhishek Samrat: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Champika Liyanage:** Supervision, Writing – review & editing. **Ruchiru Herath:** Software, Visualization, Writing – review & editing. **Reshma Sunkur:** Software, Validation, Writing – review & editing. **Andrew Barkwith:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing. **Komali Kantamaneni:** Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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