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Coastal Landscapes and Heritage Vulnerabilities: Algarve's Historical Coastal Fortifications in Context

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Abstract

Coastal fortifications form part of cultural landscapes whose preservation depends on the condition of both the structures and their surrounding environments. This study examines 22 historical coastal fortifications in the Algarve, southern Portugal, by combining documentary research, qualitative observations, historical cartography and geographic information system (GIS) analysis. The spatial analysis includes 21 sites. São Lourenço da Barra (site 22) was excluded because it lies within the Ria Formosa lagoon and is submerged. Susceptibility data are derived from the matrix used within the implementation of Directive 2007/60/EC (DAGRI), while resident population data are provided at BGRI 2021 statistical-subsection level. An exploratory criticality index integrates sample-relative measures of medium/high susceptibility, urban land intersecting those classes, and estimated resident exposure within 1 km influence areas. The analysis identifies eight sites with high relative criticality, six with medium criticality and seven with low criticality. Exposure profiles vary substantially among sites: Rato Fort has 96.3% of its estimated four residents located within medium/high susceptibility zones, whereas Faro Fortress and City Walls have approximately 12,225 estimated residents within their influence area, of whom 16.5% are located within medium/high susceptibility areas. These contrasting profiles demonstrate that environmental susceptibility and human exposure do not follow a uniform spatial pattern across the Algarve fortifications. Interpretation is constrained by incomplete susceptibility layer coverage, areal population interpolation, and the approximate location assigned to Cape St Vincent. The assessment supports landscape-based conservation and monitoring while distinguishing comparative spatial screening from structural condition assessment, legal protection status, and probabilistic risk analysis.

Keywords: coastal fortifications; cultural landscapes; Algarve; heritage setting; coastal susceptibility; land cover; population exposure; special protection zones

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1. Introduction

Cultural landscapes emphasise that heritage places are not isolated entities, but components of a broader system shaped by long-term interactions between people, social structures,

and the environment. They form part of an interconnected social–ecological system in which sustained human–environment relationships shape both cultural and natural values [1]. Recognising these interdependencies is essential for effective landscape protection and management. This involves identifying both natural and cultural features, encompassing tangible and intangible heritage, and examining how human activities interact with and shape the surrounding environment [2].

Unlike traditional heritage approaches, which tend to focus on individual monuments, buildings or sites, the cultural landscape perspective adopts a broader and more integrated understanding of heritage. It recognises landscapes as dynamic systems shaped over time by the continuous interaction between natural processes, including geological and ecological changes, and human activities, cultural practices and patterns of land use. These interactions reflect the interdependence between societies and their natural environments, through which both tangible and intangible cultural values emerge and evolve. Consequently, conserving and managing cultural landscapes requires an integrated approach that considers not only physical heritage features, but also the ecological systems, environmental processes, traditional knowledge, cultural practices and social relationships that shape their character, identity and evolution [3].

This integrated natural and cultural perspective is reflected in international heritage guidance. The 1972 World Heritage Convention [4] established the framework for protecting cultural and natural heritage; its 1992 implementation explicitly recognised cultural landscapes. UNESCO subsequently developed guidance on their identification, conservation and management, including the relationship between traditional land use, environmental processes and local stewardship [5–7].

Similarly, the European Landscape Convention (2000) [8] recognises landscapes in law as an essential component of people's surroundings, an expression of the diversity of their shared cultural and natural heritage, and a foundation of individual and collective identity. It calls for establishing and implementing landscape policies to protect, manage, and plan landscapes across entire territories through adaptive, multidisciplinary strategies that respond to social, cultural, and ecological dynamics. This convention emphasises proactive management of landscape dynamics and highlights the importance of safeguarding the evolving cultural landscape.

Complementing this perspective, the Florence Declaration on Heritage and Landscape as Human Values (2014) [9] emphasises the inseparability of cultural and natural heritage in landscape understanding and management, highlighting their joint contribution to human wellbeing, identity, and sustainable development.

The Xi'An Declaration on the Conservation of the Setting of Heritage Structures, Sites and Areas (ICOMOS, 2005) [10] recognises setting as a core component of heritage significance and calls for its holistic understanding, protection, and management. It integrates physical, visual, cultural, social, spiritual, and ecological dimensions and promotes community engagement and interdisciplinary collaboration. The setting of heritage places—including buildings, historic cities, landscapes, and archaeological sites—comprises immediate and extended environments that contribute to their significance. Understanding, documenting, and interpreting setting is essential to defining heritage significance and analysing the surrounding vulnerabilities. It requires analysing the history, evolution, and character of the surroundings, spatial relationships, and arrival experience, using a multidisciplinary approach that draws on archives, artistic and scientific records, oral histories, traditional knowledge, community perspectives, and visual analysis. Reinforcing this, the Declaration frames setting as dynamic and relational rather than purely spatial. Thus, a monument's protection area in a landscape should extend beyond its immediate

surroundings to include the wider system that sustains its cultural, ecological, and visual values; in other words, cultural heritage must be studied as integrated into its context.

Building on this integrated understanding, recent scholarship increasingly frames cultural landscape assessment through the lens of heritage vulnerability assessment. Rather than focusing solely on identifying values, heritage vulnerability assessment, i.e., the degree to which heritage assets are susceptible to damage, degradation, loss, or changes in their significance and integrity as a result of external pressures and threats [11], explicitly evaluates the vulnerability, exposure, and sensitivity of cultural and natural heritage attributes to environmental, socio-economic, and land-use pressures [11–13].

Similarly, the scientific literature highlights that identifying values and vulnerabilities, combined with developing strategies to sustain them, is essential for informed decision-making and effective management and protection efforts [14,15]. This integrated approach treats cultural landscapes not as isolated heritage sites but as dynamic socio-ecological systems where cultural, natural, and social values coexist and are preserved for future generations [16].

This international approach recognises that cultural landscapes face multiple, interacting vulnerabilities that can gradually undermine their integrity and significance. Heritage vulnerability assessments systematically identify these vulnerabilities and evaluate their impacts on both tangible and intangible values; however, intangible heritage, community-based knowledge, and perspectives remain underrepresented, as Crowley et al. highlight [17]. Such assessments provide a structured framework for prioritising interventions, guiding spatial planning, and enhancing the adaptive capacity and resilience of cultural landscapes within broader land systems [11]. A particularly relevant example is the Roman Ruins of Tróia, in Portugal, where a vulnerability assessment framework was developed to identify the threats affecting a cultural heritage site and establish priorities for risk mitigation [11].

Identifying cultural landscape vulnerabilities also involves recognising areas where landscape quality may be improved, for instance, by reinforcing local character, enhancing ecological networks or more coherently integrating new development within the existing landscape framework [18]. In this context, cultural landscape vulnerabilities refer not only to existing threats or weaknesses that may cause the deterioration or loss of landscape values but also to areas where the landscape presents deficiencies, discontinuities or insufficient integration that create opportunities for improvement and enhancement [19]. This process guides proposals that restore ecological functions, strengthen landscape identity, and enhance both environmental and cultural quality. By addressing the landscape's physical and cultural dimensions, this approach ensures interventions are well informed, balanced, and responsive to each landscape's distinctive characteristics and values [20].

According to Ravan et al. [11], vulnerability refers to the degree to which heritage is susceptible to damage based on its structural, material, or intrinsic characteristics. Risk, in contrast, represents the likelihood and potential consequences of harm, resulting from the interaction of hazard, exposure, and vulnerability. While vulnerability focuses on susceptibility, risk quantifies the probability and consequences of damage. Understanding both concepts is essential for effective heritage and landscape management, guiding adaptive strategies and prioritising interventions [21]. Thus, a place's vulnerability results from its exposure to natural or anthropogenic agents, combined with the intrinsic sensitivity that allows it to be damaged.

So, the central question is not "how large is the protection zone?", but rather: "how far do the interdependencies extend that ensure its significance and resilience?"

This study evaluates how mapped environmental susceptibility, land cover, resident population, and protection zones relate to the Algarve coastal fortifications. It combines a qualitative heritage and landscape framework with a reproducible spatial comparison of

21 locations. Section 2 presents the historical and architectural context; Section 3 explains the data and methods; Section 4 presents the field-based and spatial results; and Sections 5 and 6 discuss their implications, limitations and directions for further research.

2. History, Architecture and Contemporary Uses

The Algarve has an important military heritage, comprising coastal forts, urban fortresses and batteries, built between the medieval and eighteenth centuries to defend the coast against pirates, corsairs and possible invaders.

After the Restoration of 1640, with the threat of corsairs from Northern Europe and Berber corsairs, D. João IV and his successors intensified the bastioned works, and a vast network of forts was built from Castro Marim to Sagres [22–24]. The Algarve's coastal defences changed as threats evolved. From the Christian conquest (thirteenth–fourteenth centuries) through the period preceding the Restoration of independence in 1640, castles and fortifications were built or reinforced, primarily to defend against pirate attacks. After 1640, the resumption of independence led to the establishment of a military government in the Algarve (Lagos was the military capital) and to coastal sieges by pirates and corsairs, which justified the construction of numerous coastal fortresses [25]. Engineers such as Alexandre Massai (1621) and Lodovico de Mourgues designed modern fortresses to defend the mouth of the Arade River and the port entrances, given the vulnerability of the medieval castles of Portimão and Ferragudo [22]. From the eighteenth century onward, as privateering declined and urban development hid the guardhouses, many forts lost their function. The earthquake of 1755 and geographical changes, namely the silting up of bars, led to the ruin of some (Belixe, Boca do Rio, Burgau) or to the redesign of others for civil purposes, so that, over the centuries, these structures adapted to new functions—barracks, customs posts, viewpoints, hotels and others—gradually losing their original defensive role.

In typological terms, these structures, characteristic of the military architectural heritage, can be grouped into three types. The coastal forts are polygonal buildings close to the sea, with thick walls and bastions facing the sea, such as, for example, the Fort of Meia Praia (Lagos), the Fort of Burgau (Vila do Bispo), the Fort of Boca do Rio (Vila do Bispo), the Fort of Santa Catarina de Ribamar (Portimão) or the Fort of Belixe (Sagres), from the sixteenth and seventeenth centuries. They usually have a central square, cistern, magazine and internal chapel, protected by a moat [26].

Urban fortresses are constructions integrated into the city fabric or survivors of medieval fences, rebuilt in a bastioned style. Of note are the Fortress of Faro [27] and the Fort of Penha de França/Ponta da Bandeira (Lagos), a seventeenth-century fort, with a quadrangular plan with an access ramp and four cylindrical watchtowers, considered "one of the most advanced in the Algarve" for artillery warfare [23] (p. 71).

Finally, coastal batteries are relatively compact, purpose-built structures created during the sixteenth and seventeenth centuries to reinforce already occupied enclaves, sometimes integrating or replacing earlier fortifications. Although once numerous, they have practically disappeared today.

The fortifications of the Algarve are mainly concentrated along the western and central coast, particularly between Sagres and Olhão. In inland municipalities such as Silves and Loulé, medieval castles predominate; however, these are outside the scope of the present study.

These military structures were primarily built for coastal surveillance and defence, reflecting successive strategies to protect the Algarve coastline [23]. Over time, their military functions declined, and several structures were either abandoned or adapted for civil, cultural and tourism purposes. The inventory includes examples ranging from ruined sites at Burgau and Boca do Rio to restored or repurposed structures at Sagres, Ponta da

Bandeira and São João da Barra [28]. Their different trajectories of use, conservation and maintenance have contributed to their present-day landscape contexts.

The nineteenth century marked a significant decline in the defensive role of these fortifications. Belixe was sold in 1849, while Burgau and Boca do Rio were abandoned and subsequently fell into ruin [29]. During the Estado Novo period, the Directorate-General for National Buildings and Monuments (DGEMN) converted Sagres into a tourist inn (c. 1960) [28]. More recently, fortifications such as those in Lagos, Ponta da Bandeira and Sagres have been adapted to accommodate cultural facilities, museums and exhibitions, including the Museum of the Discoveries in Lagos [28]. Similarly, Conceição Fort, formerly a military stronghold, was converted for nature tourism, incorporating an inn and a viewpoint while retaining its original star-shaped layout [28].

Today, these structures are recognised as historical heritage and bear witness to the Algarve's historical coastal defence strategies [23]. Nevertheless, their current uses, conservation conditions and protection arrangements need to be assessed individually. Appropriate restoration and rehabilitation interventions are essential to safeguard their historical, architectural and archaeological significance, prevent further deterioration and promote their sustainable integration into the coastal cultural landscape.

3. Methodology

3.1. Study Area and Location of the Coastal Fortifications

The study was conducted along the Algarve coast, the southernmost NUTS II region of mainland Portugal. The analysis focused on the coastal parishes that contain, or are directly associated with, the historical defensive structures included in the study. These structures span from the Sagres–Cape St Vincent sector at the region's western end to Castro Marim, near the Portuguese–Spanish border, encompassing coastal settings with markedly different geomorphological, demographic, land-use, and urban characteristics.

The Algarve constitutes a particularly relevant case for analysing the vulnerability of coastal military heritage because the historical defensive system was originally conceived in close functional relationship with the coastline, estuaries, river mouths, ports and maritime access routes. Consequently, the significance and present vulnerability of these structures cannot be understood independently from their surrounding landscape. The study area therefore extends beyond each fortification's physical footprint and considers the wider territorial context in which natural processes, urbanisation, tourism, population concentration and heritage-protection instruments interact.

The historical inventory contains 22 fortifications; 21 were retained for GIS analysis and numbered from west to east on the maps (Figure 1). We excluded São Lourenço da Barra (inventory site 22) from the spatial analysis because it lies within the Ria Formosa lagoon and is submerged. It remains in the historical inventory (Table 2), but we did not calculate buffer-based susceptibility, land-cover, population or criticality indicators for this site. All reported GIS percentages and criticality classes refer to the 21 analysed sites.

3.2. Data Sources and Research Procedures

The indicator framework builds on the coastal heritage assessment proposed by Freitas, Lopes and Silva [30], while retaining the heritage-setting perspective developed in the preceding sections. It distinguishes four complementary dimensions: anthropogenic pressures, natural hazards, heritage vulnerabilities and landscape vulnerabilities. The first two describe external processes that may affect the sites; the latter two concern the sensitivity of the structures and of the landscapes that sustain their cultural, ecological and visual relationships.

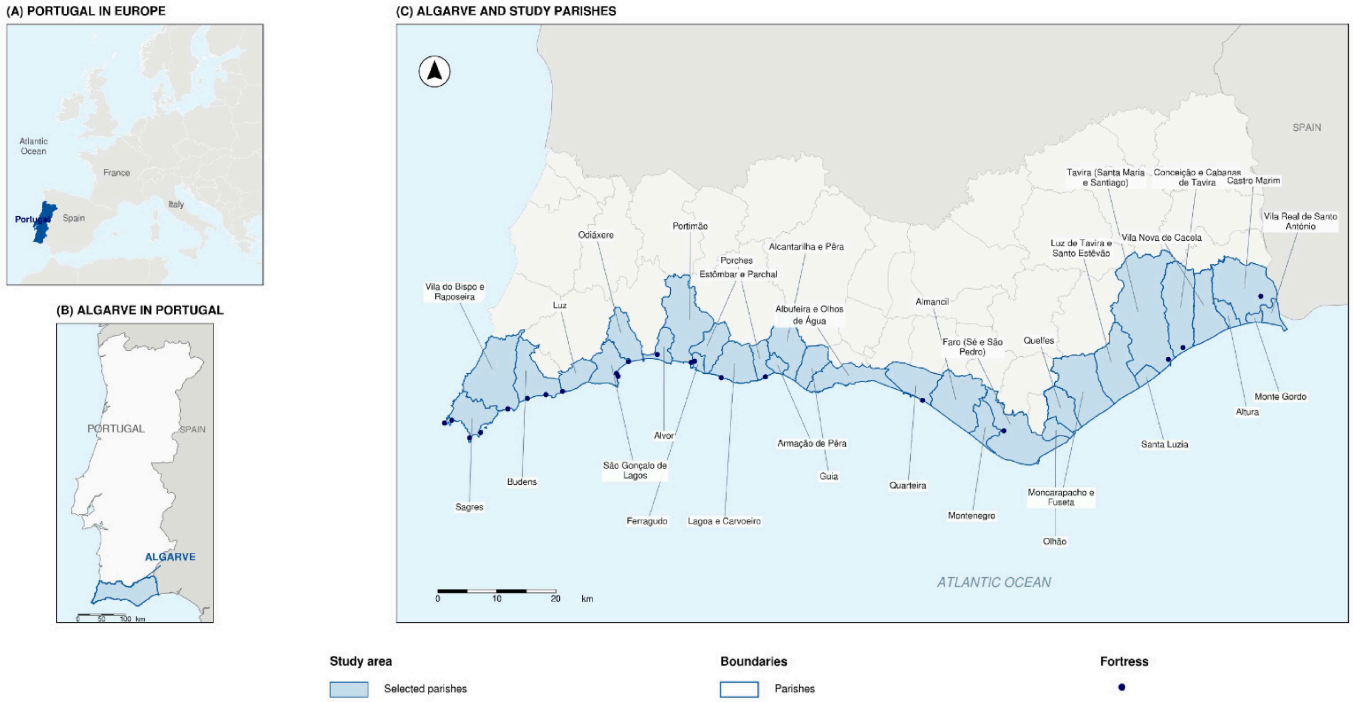


Figure 1. Geographic context of the Algarve study area. (**A**) Portugal in Europe; (**B**) Algarve in Portugal; (**C**) coastal parishes considered in the study.

This distinction is particularly relevant along a coast where erosion, marine influence and climatic processes interact with urban development, tourism and changes in land use. Heritage indicators address materials, age and conservation condition, whereas landscape indicators include hydrographic features, vegetation, agricultural areas and views. Their joint interpretation allows the assessment to consider both the monument and its wider setting (Table 1).

Table 1. Main risk and vulnerability indicators considered in the assessment.

Category	Risk/Vulnerability Factor	Description
Anthropogenic Pressures	Urbanisation and coastal development	Increase pressure on heritage sites and disrupt natural sedimentary and geomorphological processes.
	Population growth in coastal zones	Drives infrastructure expansion and amplifies environmental stress.
	Industrial activities	Potential vibration, pollution or landscape change where industrial or heavy-traffic activities occur nearby; proximity and intensity were not quantified for each site.
	Social pressures	Contribute to wear and tear, pollution, pressure on capacity building, mass tourism, and vandalism.
	Heritage abandonment	Leads to neglect, deterioration, and loss of cultural and historical values.
Natural Hazards	Sea level rise	May increase inundation or overtopping potential in low-lying shoreline and estuarine settings; no site-specific future water levels were modelled.
	Ocean acidification	Potential chemical effect on carbonate-bearing materials in contact with marine water; material deterioration from acidification was not measured in this study.

Table 1. *Cont.*

Category	Risk/Vulnerability Factor	Description
Natural Hazards	Coastal storms and wave action	Wave impact, overtopping or storm-related erosion may damage exposed coastal structures or access routes; storm-frequency trends were not assessed.
	Rising temperatures	Lead to material deformation and thermal stress.
	Coastal erosion	Shoreline retreat or cliff erosion can affect foundations, access and landscape setting; historical retreat rates were not calculated.
	Weather and temperature fluctuations	Contribute to cracking and material fatigue.
	Geological formations	Cliff, beach and estuarine substrates entail different geomorphological processes; no new geotechnical or structural stability tests were undertaken.
	Saltwater intrusion and salt crystallisation	Accelerate material decay, particularly in porous stone.
	Flooding and heavy rainfall	Increase moisture-related deterioration.
Heritage Vulnerabilities	Structural materials characteristics	Influence vulnerability to environmental stressors.
	State of conservation	Reflects degradation level, structural integrity (cracks, fissures, material detachments, deformations, or foundation instability). Surface deterioration (pitting, flaking, loss of coatings, or wear of protective layers). Biological and vegetation damage (growth of moss, algae, lichens, fungi, or invasive plants affecting materials). Material alterations (discolouration, staining, corrosion, efflorescence, or chemical changes in materials). Maintenance condition (signs of neglect, previous inappropriate repairs, or improper interventions).
	Age of structures	Older structures may have weakened materials from prolonged environmental exposure.
Landscape Vulnerabilities	Rivers, streams, and wetlands	Low-lying estuaries and wetlands may be affected by floodwater extent and changes in drainage; the relevance depends on the individual site setting.
	Forest cover and vegetation type	Affect ecological resilience and adaptive capacity to environmental change.
	Grasslands and agricultural areas	Prone to transformation under climate and land-use pressures.
	Vegetation health and density	Degraded vegetation reduces protection against erosion, flooding, and environmental stress.
	Key views, vistas and sightlines	Coastal viewpoints, visual links to adjoining forts and the effect of nearby development are considered qualitatively.

References: Schmitz & Herrero Jáuregui (2021) [1]; UNESCO (1972) [4]; UNESCO (2003) [5]; UNESCO (2010) [6]; UNESCO World Heritage Centre (n.d.) [7]; European Landscape Convention (2000) [8]; ICOMOS (2014, Florence Declaration) [9]; ICOMOS (2005, Xi'An Declaration) [10]; Canesi et al. (2024) [12]; Ravan et al. (2023) [11]; Cacciotti et al. (2024) [13]; Benz et al. (2025) [14]; Simensen et al. (2018) [15]; Zerbe (2025) [16]; Crowley et al. (2022) [17]; Bartlett et al. (2017) [18]; Taylor & Lennon (2011) [20]; Turiashvili, 2024 [21]; Freitas, Lopes, & Silva (2025) [30]; Pedretti, L. et al. (2024) [31]; Alexopoulou et al. (2024) [32]; Reimann et al., 2018 [33]; Silva et al. (2024) [34]; Giglio et al. (2024) [35]; Azam et al. (2024) [36]; Van Nguyen & Duy, 2024 [37]; Erban et al. (2014) [38]; Wu & Barrett 2022 [39].

The quantitative assessment operationalises three specific dimensions: mapped flood-related susceptibility, urban land coincident with medium/high susceptibility, and resident population within those areas. Heritage vulnerability refers to the condition and sensitivity

of the historic fabric; landscape vulnerability concerns its wider setting. Neither is measured comprehensively by these three indicators. CI summarises their relative spatial overlap and is therefore termed composite criticality, rather than structural vulnerability or probability of damage.

The methodological approach combined documentary research, field observation, historical cartography and GIS-based spatial analysis. This multi-source design was adopted to account simultaneously for the physical characteristics of the heritage assets and for the environmental and anthropogenic conditions of their surrounding landscapes. Field observations were site-specific qualitative records, not a pedestrian survey of the entire Algarve coastline. The documentation available for this study does not establish a uniform visit schedule, observer count or standardised physical-condition survey; consequently, field observations were not converted into quantitative condition scores. Documentary, cartographic and GIS sources are identified individually below [28,30,40–44].

The first stage involved identifying and characterising the coastal defensive structures. We compiled historical and architectural information from specialised literature, heritage inventories and the Portuguese architectural heritage information system (SIPA) [28]. It provided the original defensive function, typology, chronology, subsequent transformations, current use and state of conservation of each structure. The historical survey was complemented by the eighteenth-century plans produced by Lieutenant Colonel José de Sande Vasconcelos in 1788 [40], which provide a historical reference for the configuration and spatial relationship of several fortifications with their coastal setting. Field observations and recent aerial imagery were subsequently used to identify transformations affecting both the structures and their immediate surroundings. The historical plans and contemporary imagery provide qualitative evidence of differences in layout, survival, use and surroundings; they do not, by themselves, establish a measured erosion rate or attribute past losses to a single cause. The historical inventory and image comparisons are documentary and visual sources; they should not be interpreted as new topographic field measurements or as evidence of a complete coastline survey.

The second stage involved building a georeferenced spatial database [31]. We harmonised the fortification locations with the remaining spatial datasets and performed area-based calculations in the ETRS89/Portugal TM06 projected coordinate reference system (EPSG:3763), allowing consistent calculation of distances and surface areas. For reproducibility, the GIS procedure is specified through the coordinate reference system, buffer radius, intersected source layers and area-based calculations.

For each fortification, a circular 1 km radius influence area was generated. We did not interpret the buffer as a statutory protection zone, but as a standardised analytical unit representing the surrounding landscape that could affect, or be affected by, each heritage asset. Using an identical radius for all structures enabled comparison between sites located in different morphological, demographic and land-use contexts. The 1 km distance was selected to standardise the comparison.

Three territorial datasets were intersected with the 1 km buffers: land cover from the Portuguese *Carta de Uso e Ocupação do Solo* (COS), identified by *cos25v1* class fields in the working database [41]; flood-related susceptibility derived from the matrix used within the implementation of Directive 2007/60/EC on the assessment and management of flood risks (DAGRI) [43,44]; and 2021 Census resident counts at the statistical-subsection level of Portugal's Base Geográfica de Referenciação de Informação (BGRI 2021) [42]. The BGRI subsections provide small-area population units, allowing a more spatially detailed allocation than parish- or municipality-level totals.

The susceptibility analysis uses the DAGRI-derived matrix as an existing spatial input. Directive 2007/60/EC of the European Parliament and of the Council, of 23 October 2007,

establishes the framework for flood hazard and flood risk mapping [43]; the Portuguese Environment Agency (APA) provides the corresponding national mapping framework [44]. Accordingly, the quantitative susceptibility component is flood-related and does not encompass all coastal threats discussed in the qualitative inventory, such as cliff instability, salt weathering or structural deterioration. Low, medium and high denote the classes used in the analysed matrix.

We retained areas not represented in the susceptibility source as a separate outside-layer coverage category rather than classifying them as low susceptibility. This distinction matters methodologically because unmapped susceptibility data cannot be interpreted as evidence of low exposure or no hazard. Among the 21 monuments analysed, 15 are formally classified as heritage assets, including five designated as Monuments of National Interest (MN/MN-related designation) or equivalent and ten classified as Properties of Public Interest (IIP/MIP). These designations reflect administrative heritage records [28], rather than a condition rating produced by the present study. Non-classification must not be equated with absence of historical or cultural value.

Source-layer coverage is calculated as $C_i = 100 \times \text{Area}\ (B_i \cap D)/\text{Area}\ (B_i)$, where B_i is the complete 1 km buffer, and D is the union of valid susceptibility classes. Class 0 denotes the area outside D; its share is $100 - C_i$. This category describes the extent of the analysed DAGRI-derived layer and must not be interpreted as low susceptibility or absence of flooding.

The qualitative inventory provides contextual information on anthropogenic pressures, natural hazards, heritage condition and landscape characteristics (Table 1). It draws on documentary sources, historical cartography, contemporary imagery and observations of the sites. These records support interpretation of conservation condition and setting. The Table 1 factors are potential mechanisms rather than conditions confirmed at every fortification. They were not assigned identical weights, numerical scores or a site-by-site probability; their relevance is interpreted qualitatively using documented local context and the records in Table 2.

Table 2. Analysis of the anthropogenic pressures and natural hazards affecting the coastal fortifications.

Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 1 Cape St Vincent Fortress Vila do Bispo, Sagres Coastal fortress Approximate map position: 37.022716, −8.996876	No equivalent qualitative field record in the inventory; Included in the GIS comparison	Mapped susceptibility assessed within the 1 km buffer; no site-specific hazard observations assigned	The inventory contains no paired historical and contemporary images
Map 2 Fortaleza de Belixe Vila do Bispo Sagres Coastal fort 37.027227, −8.982289	In ruins, having been converted into an inn, currently closed to the public	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	

Table 2. *Cont.*

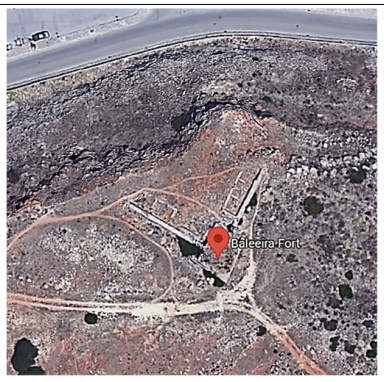
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 3 Fortaleza de Sagres Vila do Bispo Sagres Coastal fort 37.000853, −8.948395	Urbanisation and coastal development; Tourism and social pressure; Population growth in coastal areas Partially restored Museum/cultural use	Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	  
Map 4 Forte de Nossa Senhora da Guia da Baleeira Vila do Bispo, Sagres Coastal fort 37.008614, −8.928179	Ruins	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	

Table 2. *Cont.*

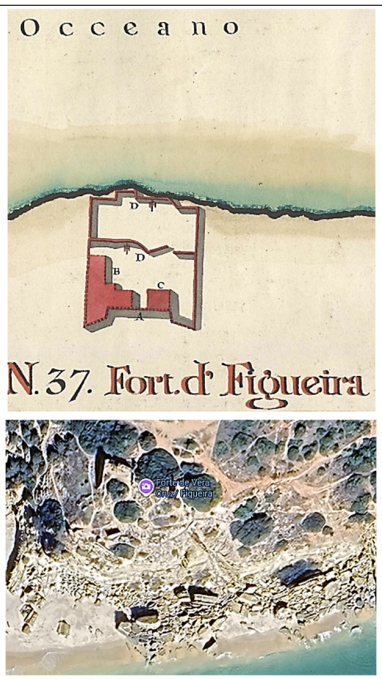
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 5 Forte e Bateria do Zavial/Forte de Santo Inácio do Zavial/Forte e Bateria do Azavial Faro, Vila do Bispo, Vila do Bispo e Raposeira Coastal fort 37.044694, −8.875794	Ruins	Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	
Map 6 Forte de Vera Cruz/Forte de Vera Cruz da Figueira/Forte da Figueira Faro, Vila do Bispo, Budens Coastal fort 37.061084, −8.838573	Ruins	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	

Table 2. *Cont.*

Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 7 Forte da Boca do Rio/Forte de Almadena/Forte de São Luís de Almádena Faro, Vila do Bispo, Budens Coastal fort 37.066734, −8.804340	Tourist and social pressure (vandalism); Lack of maintenance or visible neglect (uncontrolled growth of vegetation) Ruins	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	  
Map 8 Forte de Burgau Faro, Vila do Bispo, Budens Coastal fort 37.072028, −8.772695	Urbanisation and coastal development; Tourism and social pressure; Population growth in coastal areas Ruins	Sea level rise; Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 

Table 2. *Cont.*

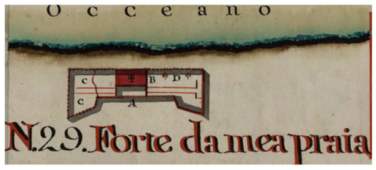
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 9 Forte do Pinhão/Bateria do Pinhão Faro, Lagos, São Gonçalo de Lagos Coastal fort 37.095905, −8.666899	Submerged ruins	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 
Map 10 Forte da Ponta da Bandeira/Fortaleza da Ponta da Bandeira/Forte de Nossa Senhora da Penha de França/Forte do Pau da Bandeira/Forte do Registo Faro, Lagos, São Gonçalo de Lagos Coastal fort 37.099053, −8.668243	Urbanisation and coastal development; Tourism and social pressure; Population growth in coastal areas Museum of the Sea	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 
Map 11 Forte da Meia Praia/Forte de São Roque Faro, Lagos, São Gonçalo de Lagos Coastal fort 37.117424, −8.647303	Tourist and social pressure; Lack of maintenance or visible neglect (uncontrolled growth of vegetation) Structural problems affecting the façade	Sea level rise; Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 

Table 2. *Cont.*

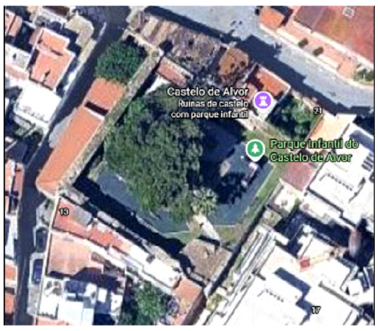
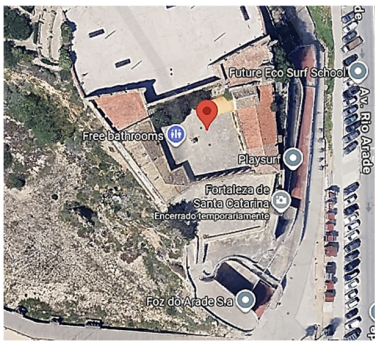
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 12 Castelo de Alvor/Forte de Alvor Faro, Portimão, Alvor Urban fort 37.129299, −8.593569	Urbanisation and coastal development; Tourism and social pressure; Population growth in coastal areas; Lack of maintenance or visible neglect	No hazard observations recorded	 
Map 13 Forte de Santa Catarina Fortaleza de Santa Catarina de Ribamar Faro, Portimão Coastal fort 37.116561, −8.529608	Tourism and social pressure; Lack of maintenance and incomplete architectural rehabilitation Adapted for the headquarters of the Fiscal Guard and the Captaincy of the Port of Portimão and a viewpoint	Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation Near the sea and the Arade River	 

Table 2. *Cont.*

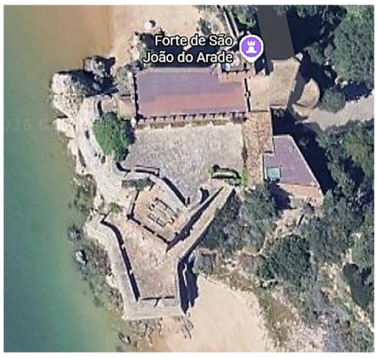
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 14 Castelo de São João de Arade/Forte de São João do Arade/Forte de S. João de Vila Nova Faro, Lagoa, Ferragudo Coastal fort 37.119665, −8.522502	Lack of maintenance or visible neglect Poor state of conservation; private property adapted to a summer residence	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 
Map 15 Forte do Carvoeiro/Forte de Nossa Senhora da Encarnação Faro, Lagoa, União das freguesias de Lagoa e Carvoeiro Coastal fort 37.094691, −8.470592	Tourism and social pressure	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 

Table 2. *Cont.*

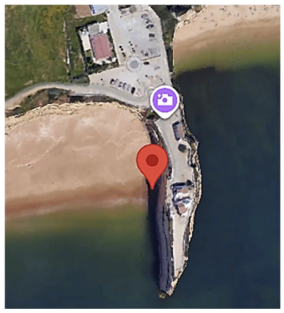
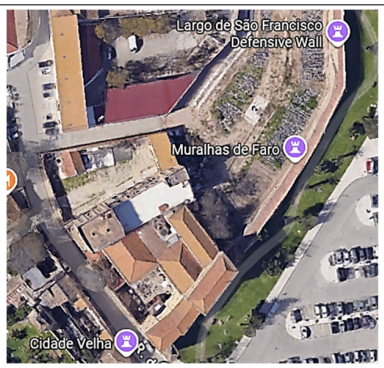
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 16 Forte de Nossa Senhora da Rocha Faro, Lagoa, Porches Coastal fort 37.096004, −8.386610	Destroyed; Ruins; Located on the site where the Chapel of Nossa Senhora da Rocha now stands Viewpoint	Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 
Map 17 Forte Novo/Forte da Armação Faro, Loulé, Quarteira Coastal fort 37.059790, −8.087037	Submerged ruins	Sea level rise; Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation; Near the sea and the Almargem River	 
Map 18 Fortaleza/Cerca de Faro Sé e São Pedro, Faro Urban fort 37.013433, −7.933078	Tourism and social pressure; Lack of maintenance and incomplete architectural rehabilitation Ruins integrated into the city	Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	

Table 2. *Cont.*

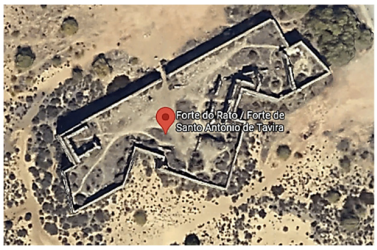
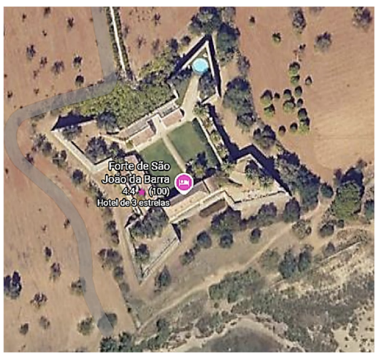
Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 19 Forte do Rato Faro, Tavira, União das freguesias de Tavira (Santa Maria e Santiago) Coastal fort 37.121544, −7.621350	Near salt flats	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation; Near the sea, the Gilão River and Ribeira do Almargem; Formerly known as Fort of Santo António; historical hydronym requires verification	 
Map 20 Forte da Conceição/Forte de São João/Forte de São João da Barra/Hotel Forte de São João da Barra Faro, Tavira, União das freguesias de Conceição e Cabanas de Tavira Coastal fort 37.139022, −7.592367	Tourist and social pressure Restored Tourist use as a hotel	Sea level rise; Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation	 

Table 2. *Cont.*

Map ID, Designation, Location and Coordinates	Anthropogenic Pressures, Conservation and Use	Natural Hazards and Coastal Setting	Historical Plans and Contemporary Imagery
Map 21 Forte de São Sebastião Faro, Castro Marim Coastal fort 37.216353, −7.444368	Tourism and social pressure	Coastal erosion; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation; Near the sea and the Guadiana River	 
Inventory site 22—excluded from GIS Fortaleza de São Lourenço da Barra/Forte de São Lourenço da Barra Faro, Olhão Coastal fort 38.660403, −9.298886	Submerged	Coastal erosion; Sea level rise; Meteorological and temperature fluctuations; Saltwater intrusion and salt crystallisation; Contemporary image identification requires verification	 

Sources: Historical inventory and qualitative observations; plans by José de Sande Vasconcelos (1788) [40] and contemporary Google imagery. The original historical inventory is available at: https://purl.pt/762 accessed on 11 November 2026. The image presented here is a cropped detail of the complete digitised image.

3.3. Spatial Analysis of Flood-Related Susceptibility

We conducted spatial analysis through a sequence of overlay, intersection and area calculations. For each 1 km influence area, we intersected the susceptibility layer with the buffer and calculated the surface area occupied by each susceptibility class. We converted the resulting areas into percentages of the total buffer area, producing a comparable susceptibility profile for each fortification. This stage used spatial datasets and digital GIS overlays; it did not involve questionnaire surveys or a systematic coastline-wide field transect.

$$P_{ij} = \left(A_{ij} \,/\, A_i\right) \times 100$$

where Pij represents the percentage of the influence area of fortification i occupied by susceptibility class j, Aij is the area resulting from the intersection between the 1 km buffer and susceptibility class j, and Ai is the total area of the corresponding 1 km influence zone.

We retained four mutually exclusive classes for the calculation: low susceptibility, medium susceptibility, high susceptibility and outside source-layer coverage. We included the latter explicitly to prevent unmapped areas from being incorrectly interpreted as low-susceptibility areas. We compared the resulting percentages across the 21 fortification influence areas and presented them through regional maps and proportional bar charts.

All susceptibility shares use the complete buffer as their denominator. Consequently, the amount of territory represented by the source layer must be considered when comparing sites. Coverage is reported for every site in Table 3.

Table 3. Susceptibility source-layer coverage within each complete 1 km buffer.

Map ID	Fortification	Covered (%)	Outside Coverage (%)
1	Cape St Vincent Fortress	5.4	94.6
2	Belixe Fortress	7.5	92.5
3	Sagres Fortress	11.6	88.4
4	Baleeira Fort	10.3	89.7
5	Zavial Fort and Battery	10.3	89.7
6	Vera Cruz Fort	4.9	95.1
7	Boca do Rio Fort	22.5	77.5
8	Burgau Fort	0.1	99.9
9	Pinhão Fort	13.6	86.4
10	Ponta da Bandeira Fort	24.6	75.4
11	Meia Praia Fort	24.0	76.0
12	Alvor Castle/Fort	62.7	37.3
13	Santa Catarina de Ribamar Fort	64.5	35.5
14	São João do Arade Fort	78.0	22.0
15	Our Lady of the Incarnation Fort	1.9	98.1
16	Our Lady of the Rock Fort	0.1	99.9
17	New Fort/Armação Fort	43.2	56.8
18	Faro Fortress/City Walls	89.6	10.4
19	Rato Fort	89.0	11.0
20	São João da Barra Fort	67.9	32.1
21	São Sebastião Fort	93.2	6.8

Finally, we interpreted the spatial results alongside field-based observations of conservation state, current use, urban and tourism pressure and natural hazards. We complemented the descriptive susceptibility, land-cover, population and protection-zone analyses with an exploratory relative criticality assessment designed to compare the 21 fortification settings on a common scale.

3.4. Integrated Criticality and Surrounding Exposure Assessment

To integrate mapped susceptibility with human exposure, we calculated an exploratory relative criticality index for the 21 fortification influence areas. Three indicators were combined:

(i) the percentage of the complete 1 km buffer in medium/high susceptibility classes;
(ii) the percentage of that complete buffer simultaneously classified as urban land cover and medium/high susceptibility; and
(iii) the estimated number of residents in those medium/high zones. The index therefore compares mapped overlap between susceptibility and human occupation, rather than the intrinsic vulnerability of the fortification fabric.

Land-cover shares and the exposed-resident percentage describe the context, but CI uses only the three specified inputs. In particular, the population input is the estimated number of exposed residents.

Because the three components are expressed in different units, we converted each indicator to a percentile rank within the 21-site sample. The resulting percentile ranks were assigned equal weight and averaged to obtain the relative criticality index (CI):

$$CI_i = [PR(MH_i) + PR(U_i) + PR(R_i)] / 3$$

Here CI is the relative criticality score, PR is the sample percentile rank, MH is the medium/high area percentage, U is the urban and medium/high intersection percentage, and R is the estimated exposed resident count. Percentile ranks were calculated as $100 \times (\text{mean rank} - 1)/(21 - 1)$, using average ranks for tied values. The three ranks received equal weight. Scores were assigned to Low ($<100/3$), Medium ($\geq 100/3$ and $<200/3$) and High ($\geq 200/3$). These are equal-width thirds of the 0–100 score scale, not equal-sized groups or externally validated risk thresholds.

Equal weighting gives each ranked component the same contribution to CI. Since all three share the medium/high susceptibility footprint, they are related rather than independent measures. The index is conditional on the 21-site sample, the 1 km radius and the available mapping. Its classes are comparative screening categories, not validated damage thresholds.

We aggregated land-cover classes into four analytical groups, urban, agriculture, forest/natural, and water, and calculated their share of the complete 1 km buffer. For the criticality calculation, only the urban area intersecting mapped medium/high susceptibility zones was used; urban land located in low-susceptibility or outside-coverage areas did not contribute to this component. Urban includes residential and other artificial uses, urban green spaces and construction or vacant land. Agriculture includes agroforestry and silvopastoral classes. The forest/natural group retains geological extraction areas under the legend grouping used for the analysis; this cartographic grouping should not be read as a claim that extraction is a natural land use.

Population was allocated from BGRI 2021 statistical subsections to the analytical areas by areal interpolation. Let G_k denote a source subsection, N_k its 2021 resident count, and $A(G_k)$ its complete area. For target area T, $\hat{P}(T) = \Sigma_k N_k \times A(G_k \cap T)/A(G_k)$. We use $T = B_i$ for the total population of buffer i and $T = B_i \cap MH$ for residents within its mapped medium/high susceptibility zones. All areas are calculated in EPSG:3763.

The procedure assumes a uniform distribution of residents within each statistical subsection, not across a whole parish or municipality. The exposed-population percentage was calculated as:

$$E_i = (RE_i / RT_i) \times 100$$

where Ei is the percentage of estimated residents exposed within fortification buffer i, REi is the estimated number of residents intersecting medium/high susceptibility zones, and RTi is the estimated total resident population within the complete 1 km buffer. Population exposure percentages therefore refer to residents rather than to land area. If the estimated total resident population is zero, this percentage is undefined. You cannot sum estimates from overlapping buffers to get a count of unique residents.

Using small BGRI subsections limits the spatial aggregation involved but does not locate individual dwellings. Area weighting may still allocate residents to non-residential land within a subsection or underrepresent local residential concentrations. The estimates describe the 2021 resident population and exclude seasonal visitors and other temporary users.

All overlay and area operations were carried out in ETRS89/Portugal TM06 (EPSG:3763). We assessed overlapping 1 km buffers independently because the objective was site-level comparison rather than regional aggregation.

4. Results

4.1. Land-Cover and Demographic Context

The spatial distribution of the fortifications reveals a marked diversity of landscape contexts along the Algarve coast. Although all analysed structures retain a historical relationship with the sea, their contemporary surroundings range from comparatively low-density natural and agricultural landscapes to highly urbanised, densely populated coastal settlements (for example, Faro Fortress/City Walls, contrasted with Belixe and Sagres) (Figure 2).

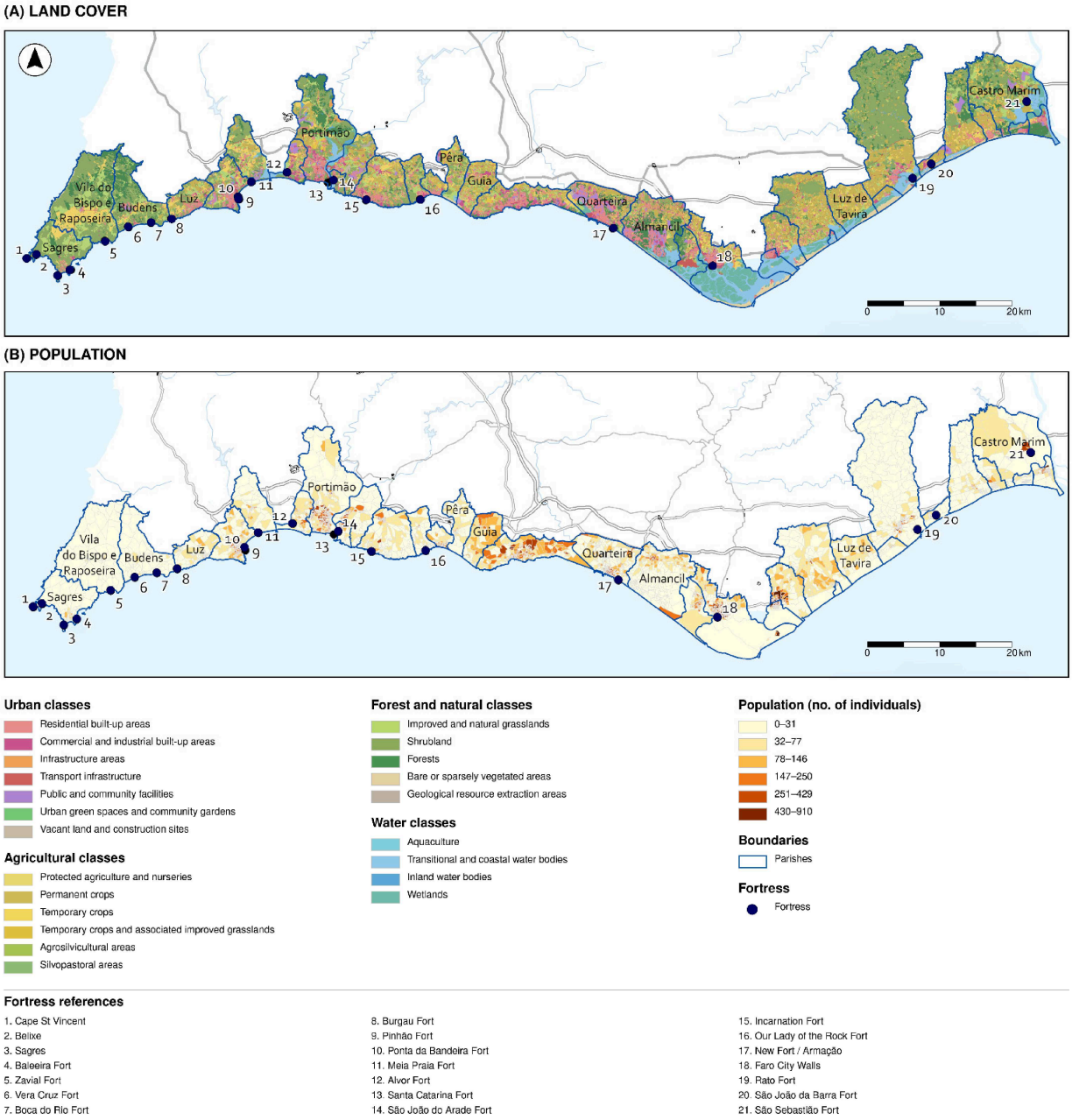


Figure 2. Land-cover classes (**A**) and resident population (**B**) in the Algarve study area.

The western sector, particularly between Cape St Vincent, Sagres and the Vila do Bispo coastline, remains comparatively dominated by natural, semi-natural and agricultural land-cover classes. Population densities are generally lower, and urban occupation is more spatially discontinuous. For Belixe and Sagres, the exposed cliff-top coastal setting makes erosion and marine influences relevant contextual considerations. However, the DAGRI-derived flood-related layer covers only 7.5% and 11.6% of their respective 1 km buffers (Table 3). These are source-coverage percentages, not measures of erosion, total coastal hazard or structural damage.

Moving eastwards towards Lagos and Portimão, the landscape becomes progressively more urbanised and fragmented. Fortifications such as Ponta da Bandeira, Meia Praia, Alvor, Santa Catarina de Ribamar, and São João do Arade occur within or immediately adjacent to consolidated urban and tourism areas. Here, coastal processes, higher population density, transport infrastructure, built-up areas, and tourism-related land uses affect the heritage landscape simultaneously. The inventory identifies different physical and functional conditions within this sector, including the adapted Ponta da Bandeira Fort and the ruins of Boca do Rio (Table 2); these qualitative records should not be read as comparable numerical scores.

A similar pattern appears in the central and eastern Algarve; however, with substantial local variation. Urbanised areas around Quarteira, Faro and parts of the Ria Formosa coexist with wetlands, water bodies, agricultural land and ecologically sensitive areas. Consequently, the landscape context of the fortifications cannot be reduced to a simple urban–rural gradient. Instead, several sites occupy transitional environments in which urban development, tourism, wetlands, estuarine systems and coastal dynamics overlap. For comparison, Faro Fortress/City Walls has approximately 12,225 estimated 2021 residents within its 1 km buffer (Section 4.4), whereas the Ria Formosa settings also contain large wetland and water areas; these are different types of surrounding exposure, not a single urbanisation gradient.

The spatial correspondence between land cover and population therefore demonstrates that the heritage assets are integrated into markedly heterogeneous socio-ecological settings. This reinforces the need to assess vulnerability at landscape scale rather than solely based on the physical condition of individual buildings.

4.2. Heritage Condition and Observed Pressures

The qualitative inventory and associated observations indicate substantial differences in the current physical condition, function and degree of transformation of the coastal fortifications. Some structures have been restored and adapted for contemporary cultural or tourism uses, while others remain as ruins or have suffered major physical loss.

The observed anthropogenic pressures are particularly associated with tourism, urban and coastal development, population concentration, lack of maintenance and, in specific cases, vandalism or uncontrolled vegetation growth. These pressures are especially visible around the most accessible coastal structures and around sites integrated into consolidated settlements.

Natural pressures recur across the qualitative inventory, particularly coastal erosion, marine influence, meteorological and temperature fluctuations, and saltwater intrusion or crystallisation. Sites associated with cliffs, beaches, estuaries and river mouths have different exposure pathways. Records of ruins, submergence or major transformation indicate that the defensive landscape has already changed substantially, but documentary and visual comparisons do not isolate the contribution of sea level rise from storms, erosion, abandonment or other processes.

The results consequently indicate that heritage vulnerability is not determined by a single pressure. Sites in comparatively natural landscapes may remain highly sensitive because of erosion, cliff instability or marine exposure, whereas restored or urban fortifications may face stronger tourism, development and population pressures. The observed vulnerability therefore results from different combinations of environmental and anthropogenic processes. Table 2 links these qualitative records to the map identifiers. Cape St Vincent is included in the spatial sample without an equivalent field record, while São Lourenço da Barra (site 22), located within the Ria Formosa lagoon and submerged, remains in the historical inventory but is excluded from the spatial analysis.

It is important to include an interpretive note on condition terminology, namely the difference between "ruins", "poor state of conservation", and "lack of maintenance". "Ruins" describes the survival of incomplete historic fabric; "poor state of conservation" describes deterioration of surviving fabric; and "lack of maintenance" describes signs of insufficient upkeep, including unmanaged vegetation or incomplete repairs. These descriptors concern different attributes, may coexist at one site and do not constitute mutually exclusive grades on a validated severity scale. "Restored" and current-use labels describe intervention or function and do not imply the absence of vulnerability.

The observation reveals substantial differences in the conservation condition of the analysed coastal fortifications. The most severe cases are Forte de Nossa Senhora da Rocha (Map 16), which is destroyed and in ruins, and Forte do Pinhão (Map 9) and Forte Novo/Armação (Map 17), where the remains are submerged. A second group presents severe degradation, including Forte de Nossa Senhora da Guia da Baleeira (Map 4), Forte de Vera Cruz/Figueira (Map 6), Forte da Boca do Rio/Almadena (Map 7), and Forte de Burgau (Map 8), all characterised by ruins and, in some cases, documented pressures such as coastal erosion, vandalism, vegetation growth, abandonment, or inappropriate occupation. Other monuments, including Fortaleza de Belixe (Map 2), Forte da Meia Praia (Map 11), Forte de Santa Catarina (Map 13), and Fortaleza/Cerca de Faro (Map 18), show poor or deteriorating conservation conditions and require maintenance, rehabilitation, or structural intervention. Overall, the most critical cases are associated not only with exposure to coastal and environmental processes but also with long-term abandonment, inadequate maintenance, structural deterioration, and, in some cases, substantial or complete loss of the historic fabric.

The observation also indicates that the Algarve's coastal fortifications face a combination of environmental, climatic, territorial, and tourism-related pressures; however, their intensity and manifestation vary considerably between sites. The most recurrent pressures are coastal erosion, sea level rise, meteorological and temperature fluctuations, and saltwater intrusion and salt crystallisation. These pressures are particularly relevant for fortifications located directly on cliffs, promontories, estuarine margins, or near rivers and salt-marsh environments, where marine exposure can interact with erosion, moisture, salinity, and material deterioration.

The environmental pressures are compounded by territorial and socio-economic dynamics. Urbanisation and coastal development, population growth in coastal areas, and increasing tourism and social pressure are recorded at several sites, including Sagres, Burgau, Lagos, Alvor, Portimão, Faro and Tavira. In some locations, tourism supports the continued use and visibility of the heritage asset through museums, viewpoints, accommodation and other adapted uses; however, the inventory also identifies vandalism, uncontrolled vegetation, lack of maintenance and incomplete rehabilitation as pressures affecting the conservation context. This coexistence of tourism use and conservation vulnerability is particularly evident where historic fortifications have been adapted to contemporary functions or incorporated into highly visited coastal environments. Vulnerability cannot

be understood solely through the physical exposure of individual monuments; rather, it emerges from the interaction between environmental susceptibility, the asset's condition and maintenance, surrounding land-use change, visitor pressure, universal accessibility and the capacity for continued management. Sites such as Baleeira, Zavial, Vera Cruz, Boca do Rio, Burgau and Meia Praia illustrate the accumulation of coastal and climatic pressures in already fragile or ruinous structures, while more intensively used sites such as Sagres, Ponta da Bandeira, Santa Catarina and São João da Barra demonstrate a different challenge: managing heritage that remains economically and socially active while exposed to persistent environmental pressures.

Overall, the observation table points to a cumulative and spatially differentiated vulnerability of Algarve coastal fortifications. Therefore, these pressures should not be treated as isolated hazards but as interacting processes that can accelerate physical deterioration, constrain future uses and increase management requirements. The comparison also highlights the importance of moving beyond monument-centered assessment toward a territorial approach that considers the relationships among fortifications, coastal dynamics, urbanisation, tourism, universal accessibility [45], and surrounding landscapes. This provides a basis for identifying priority areas for detailed field assessment, monitoring and preventive intervention, particularly where environmental susceptibility coincides with poor conservation conditions, intense tourism pressure or rapid coastal development.

4.3. Spatial Susceptibility Within the Fortification Influence Areas

The flood-related susceptibility results differ in both class composition and mapped coverage. Rato, Faro, São João do Arade and Santa Catarina have substantial mapped high-susceptibility shares (Figures 3 and 4).

Among the clearest concentrations of mapped high susceptibility, Rato Fort records 78.1% of its complete 1 km influence area in the high class. Faro Fortress/City Walls reaches 57.1%, followed by São João do Arade Fort with 48.1%, Santa Catarina de Ribamar Fort with 45.0%, and São Sebastião Fort with 40.7%. Alvor Castle/Fort also displays a substantial high-susceptibility component, amounting to 32.6% of its complete influence area (Figure 4).

These patterns contrast with several western sites. At Cape St Vincent, Belixe, Sagres, Baleeira, Zavial and Vera Cruz, a large proportion of the 1 km buffer lies outside the spatial coverage of the susceptibility dataset. Burgau and Our Lady of the Rock Fort reach approximately 99.9% outside source-layer coverage, while Our Lady of the Incarnation Fort reaches 98.1%. These values do not indicate negligible susceptibility; rather, they show that the source layer provides limited spatial coverage within these influence areas.

The results also identify areas with a more heterogeneous mix of susceptibility classes. At São João da Barra Fort, for example, the 1 km influence area comprises 35.1% low, 12.5% medium and 20.3% high susceptibility, with 32.1% outside the source layer. São Sebastião Fort presents one of the most complete susceptibility profiles, with 24.9% low, 27.5% medium, and 40.7% high susceptibility, and only 6.8% outside-layer coverage. New Fort/Armação shows a different pattern, dominated by low susceptibility (23.0%), followed by medium (12.4%) and high susceptibility (7.7%); however, more than half of the full buffer remains outside-layer coverage.

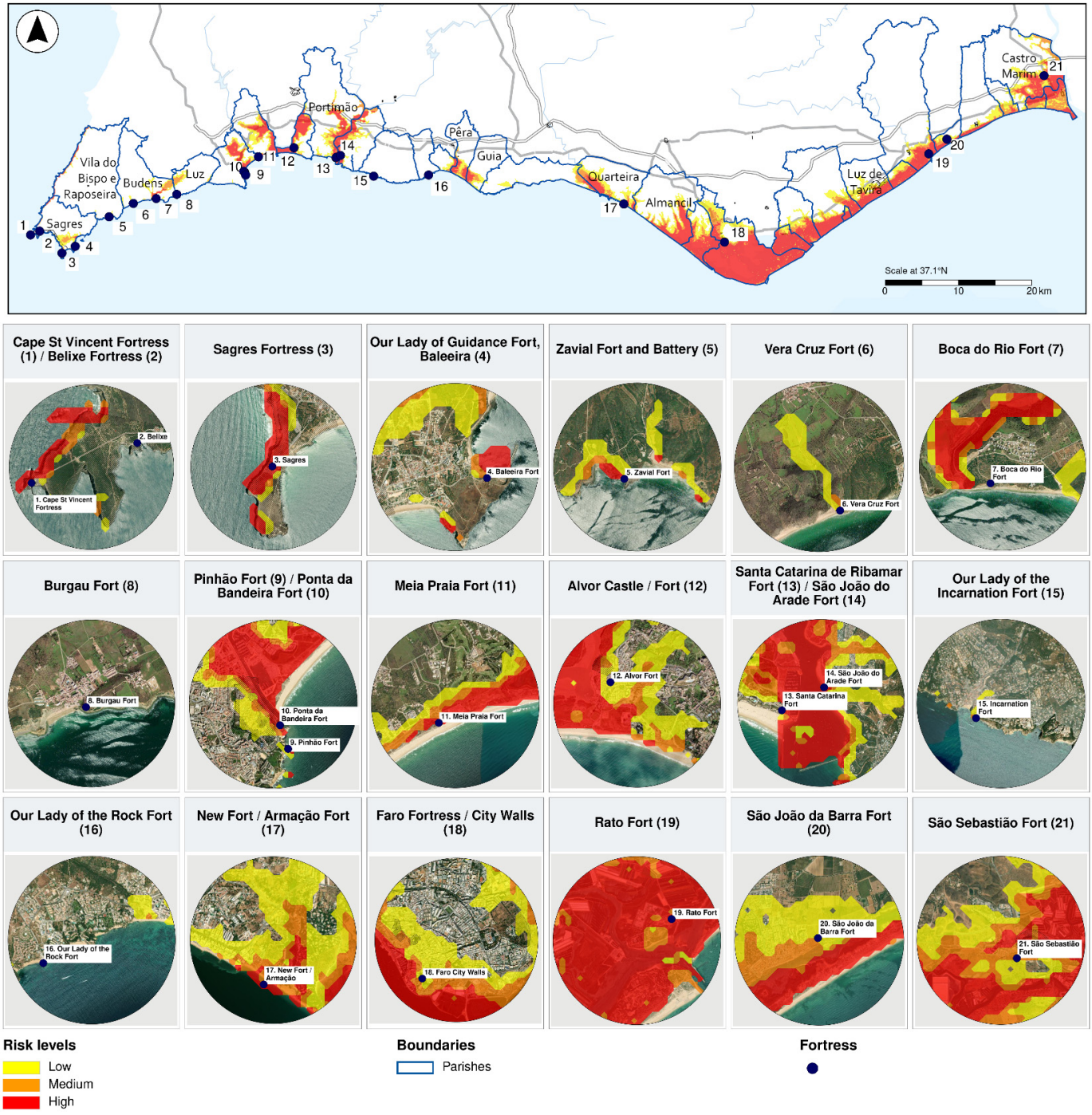


Figure 3. Mapped susceptibility in the Algarve study area and local details.

Table 3 makes the coverage contrast explicit: São Sebastião has 93.2% coverage, Faro 89.6% and Rato 89.0%, compared with 0.1% at Burgau and Our Lady of the Rock Fort and 1.9% at Our Lady of the Incarnation Fort. These differences determine how much each setting contributes to the mapped susceptibility and exposure indicators.

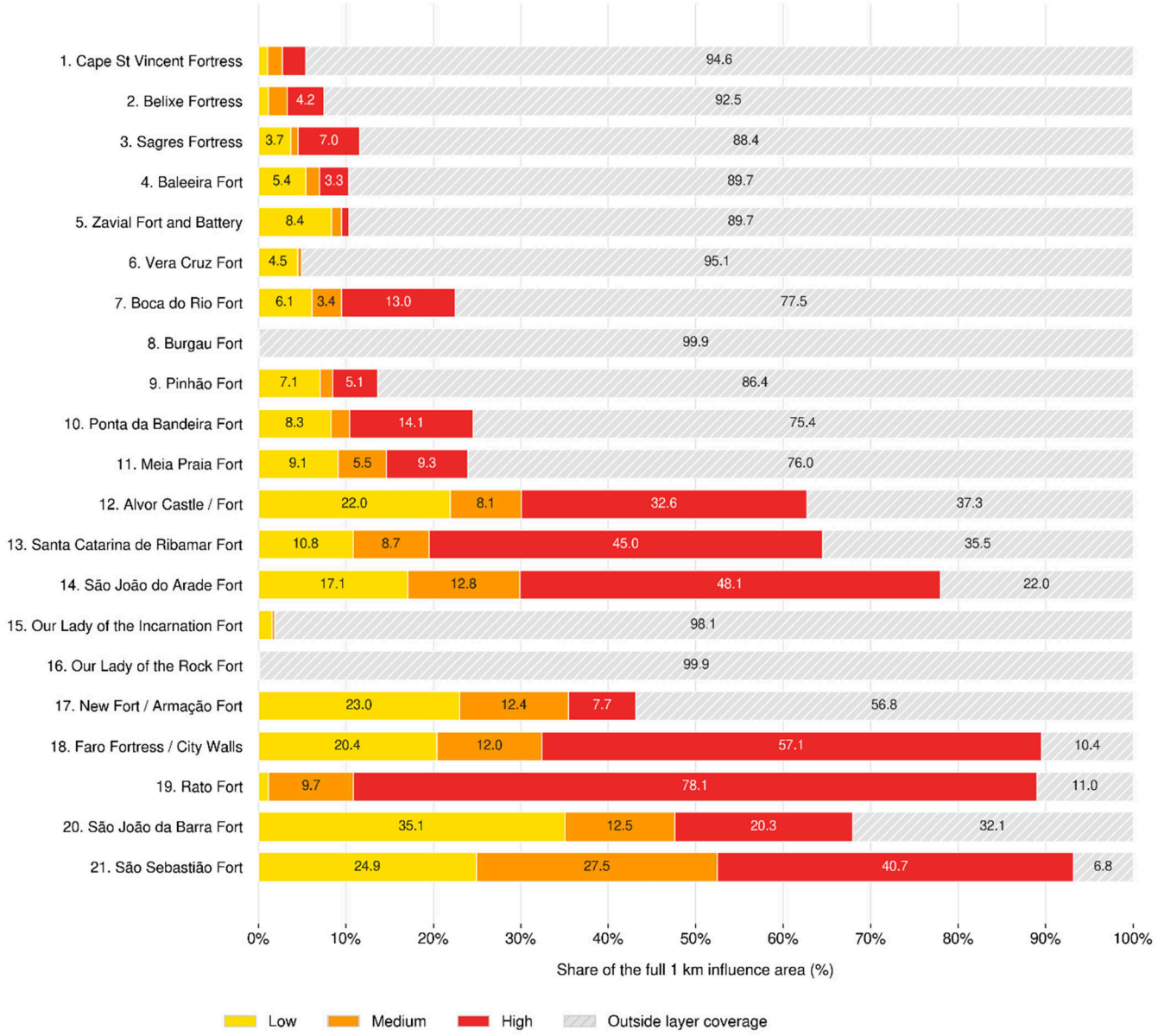


Figure 4. Flood-related susceptibility classes within the complete 1 km buffers of the 21 analysed fortifications, based on the DAGRI-derived matrix. Outside source-layer coverage is shown separately.

4.4. Integrated Criticality, Susceptibility and Surrounding Exposure

The integrated comparison reveals that environmental susceptibility and human exposure do not follow a single spatial pattern. Eight fortifications fall within the High relative criticality class, six within the Medium class and seven within the Low class. The High group comprises Ponta da Bandeira Fort, Alvor Castle/Fort, Santa Catarina de Ribamar Fort, São João do Arade Fort, Faro Fortress/City Walls, Rato Fort, São João da Barra Fort and São Sebastião Fort (Figure 5). These sites combine comparatively high positions across the medium/high susceptibility, urban-intersection, and resident-exposure components, rather than simply showing the highest value for any single indicator.

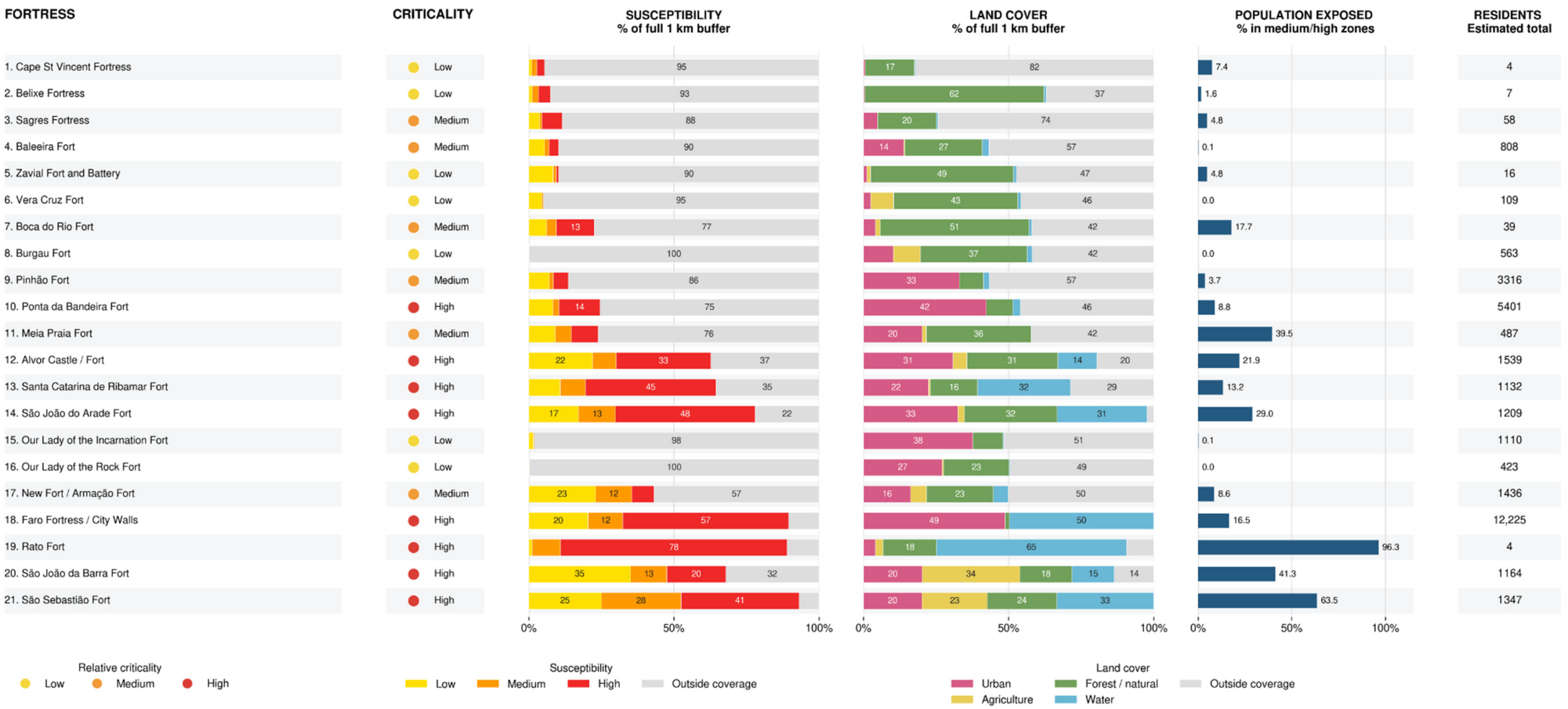


Figure 5. Integrated comparison of relative criticality, susceptibility, land-cover shares and estimated resident exposure within 1 km of each fortification.

Rato and Faro illustrate why exposed percentages and population totals must be read together. At Rato, 96.3% of approximately four estimated buffer residents fall within mapped medium/high susceptibility areas. At Faro, the exposed share is lower (16.5%), but the buffer contains 12,225 residents. São Sebastião combines a 63.5% exposed share with 1347 buffer residents, while São João da Barra records 41.3% of 1164 residents. The percentage describes the distribution of residents within each setting. The exposed count used in CI also reflects the demographic magnitude.

The Medium criticality group includes Sagres Fortress, Baleeira Fort, Boca do Rio Fort, Pinhão Fort, Meia Praia Fort and New Fort/Armação Fort. The Low group comprises Cape St Vincent Fortress, Belixe Fortress, Zavial Fort and Battery, Vera Cruz Fort, Burgau Fort, Our Lady of the Incarnation Fort and Our Lady of the Rock Fort. Several of these western sites have large buffer areas outside the mapped susceptibility coverage. Their lower relative criticality should therefore be read as a result of the available comparative evidence rather than as confirmation of low physical vulnerability.

The land-cover component further differentiates the fortification settings. Some sites are dominated by forest/natural classes, while others are embedded in strongly urbanised or water-dominated landscapes. The integrated representation therefore makes visible three complementary dimensions, susceptibility, land-cover context, and population exposure, while the criticality marker provides a concise, sample-relative synthesis of their overlap.

5. Discussion

The spatial comparison distinguishes current levels of mapped flood-related susceptibility, human exposure and dataset coverage around the historic fortifications, rather than demonstrating the already-established territorial character of military architecture. For example, the 1 km buffers around Rato and Faro contain 78.1% and 57.1% high-susceptibility area, respectively, whereas some western settings have very little source-layer coverage (Sections 4.3 and 4.4).

These differences have contemporary management implications that cannot be inferred solely from the defensive typology or historical location of each fort. The relative criticality index is therefore used as a screening tool for the overlap of mapped susceptibility, urban land and resident exposure, and not as a measure of architectural damage or the intrinsic value of the monuments.

A first important finding is the coexistence of different vulnerability pathways. In the less urbanised western Algarve, vulnerability is closely associated with direct environmental exposure, coastal morphology, erosion and marine processes. At Burgau, for instance, only about 0.1% of the 1 km buffer is covered by the flood-related susceptibility layer (Table 3); its low relative criticality cannot therefore be interpreted as evidence of low physical hazard. Conversely, in the Lagos–Portimão and central and eastern coastal sectors, environmental susceptibility more often overlaps with built-up land, tourism, population concentration and infrastructure. These sites face a more complex mix of natural and anthropogenic pressures.

This distinction matters for management because uniform conservation strategies are unlikely to work. An isolated ruined fort affected by cliff retreat requires a different intervention framework from a restored urban fortress exposed to intensive visitation, surrounding development and changes in its visual setting. The results therefore favour site-specific measures embedded within a common landscape-scale assessment framework. Accordingly, limited source coverage at Burgau supports verification of local shoreline conditions, while the larger mapped exposure around Faro supports closer coordination with urban and flood-risk management. Neither observation, by itself, establishes an intervention order.

The quantitative results identify overlap between the DAGRI-derived flood-related classes and contemporary occupation. High-susceptibility areas occupy 78.1% of Rato's buffer, 57.1% of Faro's, 48.1% of São João do Arade's and 45.0% of Santa Catarina's.

These distinctions lead to three management implications. Where mapped susceptibility overlaps urban land and substantial resident counts, heritage management should be coordinated with flood-risk planning and resident preparedness. Where exposed percentages are high, but resident counts are small, as at Rato, conservation decisions should also consider heritage condition and environmental setting.

Portuguese heritage protection has a specific statutory basis. Law No. 107/2001 of 8 September establishes the national framework for safeguarding and enhancing cultural heritage and sets out conservation obligations and protection zones. Article 43 provides for a general 50 m protection zone for classified assets or assets under classification, as well as for Special Protection Zones (SPZ) [46]. Decree-Law No. 309/2009 of 23 October regulates the classification procedure and the general and special protection-zone regimes, including landscape setting and sightlines [47]. The study's uniform 1 km buffers are neither these statutory zones nor substitutes for checking each monument's individual designation and protection map.

Overall, the combined methodology shifts monument-based conservation toward an integrated territorial assessment. Historical documentation identifies how the defensive landscape functioned; field observation documents its present condition; land-cover and population data identify contemporary human pressures; and susceptibility mapping characterises environmental constraints. This integration is particularly useful for identifying where conservation, climate adaptation and spatial planning should be considered jointly rather than as separate policy domains.

Future scenario analysis could extend this assessment by intersecting the same heritage inventory with dated sea level, storm inundation and coastal-retreat scenarios, then comparing changes in exposed land, residents and access routes across time horizons. Comparable conservation surveys and repeated imagery would help distinguish structural deterioration from changes in the wider setting. The present maps describe the available susceptibility and exposure layers; they do not constitute modelled future scenarios.

The observation and GIS analysis reveal patterns of convergence between monument condition, environmental susceptibility and the surrounding landscape's characteristics. The results therefore indicate that environmental susceptibility, physical condition and anthropogenic pressure frequently converge, but that maintenance, conservation interventions, adaptive reuse and heritage protection mediate their relationship.

For management, this distinction suggests complementary actions: verify and monitor cliff and shoreline settings where mapped coverage is limited; examine maintenance and visitor pressures around reused urban forts; and review the spatial relationship between heritage assets, landscape processes and protection instruments. Documentary comparison, local knowledge and field verification should guide how the regional screening is translated into individual conservation decisions.

6. Conclusions

The 21-site GIS comparison identifies pronounced differences in mapped flood-related susceptibility, urban overlap, estimated resident exposure and data coverage around Algarve coastal fortifications. These differences provide a basis for identifying where more detailed conservation and hazard assessments are needed.

The susceptibility analysis also showed that several fortification-influenced areas contain substantial proportions of high-susceptibility territory, particularly around Rato Fort, Faro Fortress/City Walls, São João do Arade, Santa Catarina de Ribamar and São Sebastião.

At the same time, the analysis showed the importance of explicitly reporting data coverage, since areas not represented in the susceptibility layer cannot be considered equivalent to low-susceptibility areas.

Statutory protection and spatial screening are distinct. In fact, the study's 1 km buffers are comparative analytical units and should be examined alongside each monument's legally established protection perimeter [46,47].

The framework provides a reproducible basis for bringing heritage observations into dialogue with spatial planning and climate adaptation. The exploratory criticality index summarises the relative overlap of mapped susceptibility, urban occupation and resident exposure. It complements qualitative evidence on conservation and setting; it does not incorporate structural vulnerability or heritage value, and it is not a deterministic or probabilistic measure of damage. This distinction supports targeted monitoring without treating the comparative ranking as a universal conservation priority list.

The principal planning implication is to combine site-specific conservation information with the GIS screening results. High mapped susceptibility and resident exposure warrant closer assessment around settings such as Rato and Faro, while very limited susceptibility-layer coverage at several western sites requires additional spatial evidence. Conservation priorities should then be determined using structural inspections, legal status and local decision-making, not by the comparative CI alone.

Limitations and Scope of Inference

First, CI expresses relative overlap of mapped susceptibility, urban land and resident population and does not quantify structural damage or heritage value.

Small census units from BGRI 2021 improve population detail but do not represent individual dwellings or seasonal visitors. Sensitivity to buffer size and indicator weighting, together with independent validation against observed impacts, remains a priority for further work.

Future research should expand the framework through spatially continuous hazard datasets, projected sea level rise and coastal-erosion scenarios, site-specific structural assessments and repeated monitoring of landscape change. Multi-scale influence areas and systematic assessment of visual and functional relationships between fortifications would also strengthen the representation of heritage setting. Repeated condition surveys, dated imagery and evidence of visitation and access constraints would allow future studies to distinguish physical deterioration of the monuments from changes in their surrounding landscapes.

A practicable next step is to develop site-specific monitoring and maintenance programmes, supported by repeatable GIS mapping and conservation assessments. Such measures can inform adaptive management in coastal tourism destinations [48], but their adoption, resourcing and prioritisation are governance decisions, shaped by statutory obligations, institutional responsibilities and community interests [46,47]. The present analysis provides comparative evidence for these decisions.

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