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Land-Use Regulations and Ecological Risk in Island Ecosystems: A GIS-Based Vulnerability–Threat Framework in the Seaflower Archipelago (Colombia)

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Abstract

The San Andrés, Providencia, and Santa Catalina archipelago, located in the Colombian Caribbean, hosts diverse ecosystems, including coral reefs, mangroves, seagrass beds, and beaches, all of which are increasingly threatened by human activities. This research proposes a spatial analysis of ecological risk that integrates ecosystem vulnerability and anthropogenic pressures associated with land-use change to promote sustainable risk management. The vulnerability of island ecosystems was assessed by analyzing changes in cover across multiple time periods. At the same time, risks from anthropogenic pressures were determined based on marine protected area zoning and land-use planning regulations. Results show contrasting patterns: while several mangrove and beach sectors remained relatively stable, mangrove loss reached up to 65% in Providencia, and seagrass ecosystems experienced severe degradation, including a complete loss (100%) in western San Andrés. Risk maps indicate that the highest risk levels are consistently associated with Special Use Zones, where tourism infrastructure, navigation, and port activities are permitted. These findings highlight the importance of ecosystem-based risk management and adaptive governance in reducing anthropogenic pressures and preserving island ecosystem health.

Keywords: island ecosystems; vulnerability; risk management; anthropogenic pressures

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Academic Editor: Jeroen Meersmans

Received: 22 February 2026
Revised: 30 March 2026
Accepted: 3 April 2026
Published: 8 April 2026

1. Introduction

Vulnerability assessments of ecosystems to extreme climate events (storms, natural hazards, sea-level rise, etc.) have been widely documented. However, despite growing recognition of their importance, anthropogenic drivers such as increased urbanization, land-use transitions, land-cover change dynamics, and socioeconomic factors such as tourism [1–4] have been less systematically integrated into vulnerability assessment frameworks than climate-related hazards [5,6].

Increased human activity in coastal ecosystems threatens biodiversity, reduces productivity, and degrades environmental quality [7–13]. One of the anthropic dynamics that generates the most significant losses of ecosystems worldwide is changes in land use [14,15]. The loss of vegetation cover alters ecosystem processes, including their composition, function, and structure [16,17].

The spatial and temporal dynamics of land-use change have been extensively documented in continental urban contexts, revealing complex relationships between urbanization patterns and environmental degradation. For instance, studies in China have demonstrated strong spatial and temporal heterogeneity in urban land expansion and its environmental consequences, including significant correlations between land-area growth and $PM_{2.5}$ concentrations [18]. Similarly, recent research on surface urban heat island (SUHI) effects in expanding urban areas has shown diverse evolutionary patterns, with newly developed zones exhibiting distinct thermal characteristics that reflect the intensity and configuration of land-use transitions [19]. These findings underscore that the environmental impacts of urbanization extend beyond simple land cover conversion, encompassing cascading effects on air quality, microclimate regulation, and broader ecosystem functioning. While these studies have primarily focused on continental settings, the principles of spatial heterogeneity in land-use impacts and the coupling between urban expansion and environmental degradation are particularly relevant to island ecosystems, where spatial constraints, high population density, and limited buffering capacity can amplify the consequences of land-use change for ecosystem health.

Islands can be defined as particular ecosystems that include their distinct geographical or geomorphological features and the sub-ecosystems of the surrounding land and waters, composed of interacting natural and anthropogenic factors [20,21]. However, this abundance of diversity and richness makes them more vulnerable to the consequences of population size [22,23]. Island ecosystems can differ in size, extent, and population density, making sustainable management more challenging and complex [9]. The number of people living on an island can make it more or less capable of coping with the negative effects of human activity. Small islands with large populations, such as some in the Caribbean, can face serious problems due to urban development, high tourism, and heavy use of natural resources. On the other hand, larger, less populated islands can face distinct challenges, such as habitat fragmentation and the introduction of invasive species.

Human-induced pressures increase the vulnerability of island ecosystems and have yet to be analyzed and integrated with this type of ecosystem. In this sense, human activities must be managed efficiently to promote ecosystem health and minimize the negative impacts of such interventions, thereby reducing ecosystems' vulnerability to human pressures [24]. Several authors agree that islands host unique ecosystems whose management requires specific approaches and methodologies [9,25–28] and that both qualitative and quantitative methods can be applied to evaluate the effects of various human pressures on island ecosystems [7,8,10,29–31]. Therefore, there is a need to assess the risks in island ecosystems induced by human activities to ensure ecological and sustainable management in both oceanic and terrestrial zones [32].

To analyze vulnerability, it is necessary to have a system subject of analysis (such as ecosystems), attributes of criteria of concern (biodiversity, human lives, health, income, and cultural identity), and a temporal reference [33], as well as to use appropriate indicators to measure it [34], such as ecosystem sensitivity and exposure. The degree of sensitivity in an ecosystem determines how susceptible it is to damage or pressure, and how it can adapt to potential harm. The main criteria to determine how sensitive an ecosystem is include but are not limited to loss of assets (land, crop, equipment) to climate-related disasters, financial support, income structures, ecosystem productivity, biodiversity, environmental quality,

https://doi.org/10.3390/geographies6020038

terrain characteristics, beach width and erosion rates, natural conditions, structure, and type of ecosystem present [1,35–37]—the higher the sensitivity, the higher the vulnerability. Consequently, exposure can be defined as the situation of people, property, systems, or other elements in hazard zones that are subject to potential losses [38]. For islands and coastal areas, exposure will depend on their geomorphological characteristics and on the preservation of natural habitats that provide protection (dunes, mangroves, corals, seagrasses, etc.) [39]. The higher the exposure, the higher the vulnerability.

In addition, owing to its particular features and uses, it is necessary to integrate different variables to assess the ecological health of island ecosystems. Any coastal risk assessment must include two separate components that constitute the risk: the hazard and the associated impact expressed through vulnerability [40–42]. However, assessing and analyzing the risks and effects from a biocentric perspective is rare, and anthropocentric perspectives remain dominant. Risk planning and management in marine and coastal areas tend to prioritize human vulnerability to the potential impacts of climatic and geological phenomena. At the same time, the environmental implications of anthropogenic activities are rarely included as threats to the health of coastal ecosystems. An appropriate focus on ecosystem vulnerability assessments is necessary, and it should also include governance implications and urban planning consequences [25,43,44].

Furthermore, the use of tools and techniques such as GIS and scenario-based models is crucial for spatial and temporal vulnerability analysis, enabling clear visualization of the most critical areas and potential mitigation strategies [31,37,45]. The diversity of approaches reflects the need for adaptive, context-specific methods to assess and manage ecological vulnerability across different coastal and island areas [6,46].

Despite the growing number of vulnerability assessments in coastal and island environments, few studies have explicitly integrated ecosystem cover into change metrics with regulatory zoning frameworks as direct proxies for anthropogenic pressure. In particular, the spatial implications of land-use planning and marine protected area regulations on ecosystem-based ecological risk remain underexplored in small-island governance contexts such as the Caribbean.

Hence, this research aims to determine the vulnerability of island ecosystems in the San Andrés, Providencia, and Santa Catalina archipelago by analyzing the relationships between island ecosystem vulnerability and land use, as well as marine protected area regulations. This study extends prior methodological approaches by integrating ecosystem cover dynamics and regulatory zoning frameworks as spatially explicit proxies of anthropogenic pressure, thereby enabling a governance-oriented ecological risk assessment tailored to small-island contexts.

2. Materials and Methods

2.1. Study Area

The Archipelago of San Andrés, Providencia, and Santa Catalina is located northeast of Colombia in the Caribbean Sea. It consists of three inhabited islands and several islets and banks (Figure 1). The archipelago was declared as the SEAFLOWER Biosphere Reserve by the UNESCO "Man and Biosphere" program in 2000, covering the entire Archipelago Department of San Andrés, Providencia and Santa Catalina, a total of 180,000 km^2 of which only 57 km^2 are terrestrial areas, and correspond to the three largest islands (San Andrés, Providencia and Santa Catalina), seven key islands and several shallows and banks [47,48]. This declaration led to the creation of Colombia's first Marine Protected Area (MPA) in 2005, which protects more than 2000 km^2 of mangroves, seagrass beds, and coral reefs, along with their associated ecosystem services [47].

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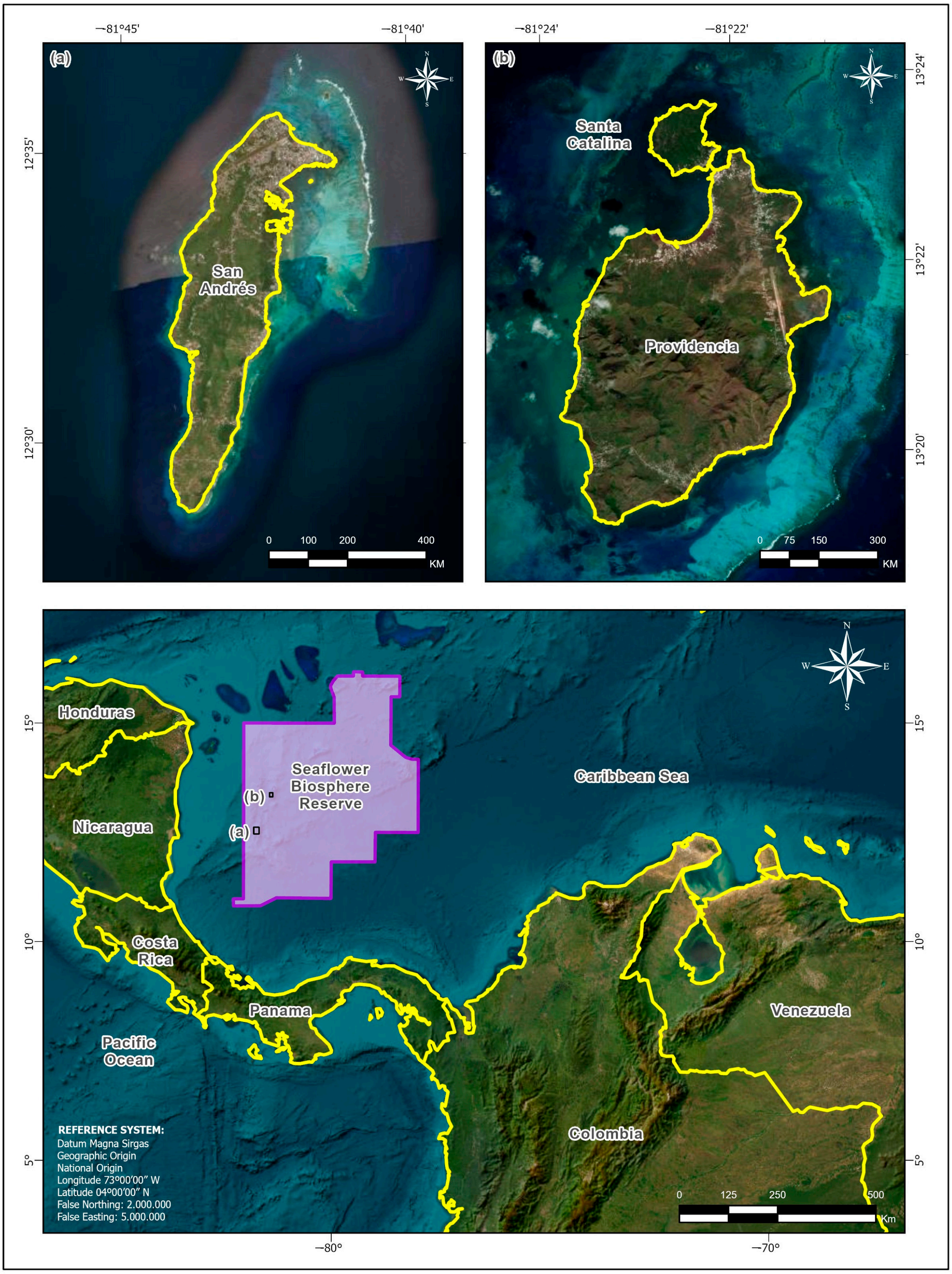

Figure 1. Location of San Andres Island (**a**), and the Providencia and Santa Catalina (**b**) Islands, as part of the SEAFLOWER Biosphere Reserve.

The archipelago is characterized by its high biodiversity, high ecological sensitivity, and its strong interaction between natural and social dynamics. The archipelago's population exceeded 62,000 by 2018 [49], reflecting accelerated, unprecedented demographic growth since its designation as a free port. This trend has positioned San Andrés, the largest island of the archipelago, as one of the most densely populated islands in the Greater

Caribbean [50]. This situation has generated profound territorial transformations and pressures on local ecosystems, often in the absence of adequate environmental planning.

While the three islands share a common insular context within the Seaflower Archipelago, they diverge substantially in land-use intensity, population density, and infrastructure development. San Andrés represents the most urbanized island, marked by high tourism activity and coastal infrastructure expansion, whereas Providencia and Santa Catalina are characterized by reduced anthropogenic pressure and relatively well-preserved ecosystems. Such inter-island heterogeneity provides a meaningful basis for the spatial interpretation of ecological risk patterns documented in this study.

2.2. Geographic Data

The geographic data concerning island ecosystems of the islands of San Andrés, Providencia, and Santa Catalina used in this research came from institutional sources such as the Agustín Codazzi Geographic Institute (IGAC), the Institute of Marine and Coastal Research (INVEMAR), and the Corporation for the Sustainable Development of the Archipelago of San Andrés, Providencia, and Santa Catalina (CORALINA). All geographic layers were adjusted to the Magna Colombia Oeste Oeste coordinate system and processed using ARCGIS PRO software version 3.4.2.

Given the categorical structure of regulatory frameworks and the heterogeneity of available data across ecosystems and temporal scales, a qualitative analytical approach was deemed most appropriate for this assessment.

The information on beach and mangrove ecosystems coverage was validated using Google Earth to confirm changes and the existence of these ecosystem areas. For seagrass and coral reefs, the information was validated directly with the Environmental Corporation for the Sustainable Development of the Archipelago of San Andrés, Providencia, and Santa Catalina (CORALINA). This information was also corroborated through a documentary review of technical reports, environmental management plans, and specific ecosystem studies in the study area.

However, the datasets presented in this article are not readily available because they are part of an ongoing study waiting for legal approval from national institutions.

2.3. Spatial Analysis of Vulnerability in Island Ecosystems

Vulnerability was operationalized by means of observed ecosystem cover loss, treated as a proxy for sensitivity. Given the inherent heterogeneity of available datasets across ecosystems and temporal scales—alongside the categorical nature of the variables analyzed—a qualitative approach was deemed most appropriate for the purposes of this assessment.

The spatial coverage of beaches, mangroves, and seagrass beds was analyzed across multiple time periods to assess temporal changes. However, coral reef data were available only for a single period; therefore, coral reef vulnerability was classified as high based solely on the exposure of the barrier reef to the nearest the islands.

The other ecosystem layers were overlaid, and the Overlay-Erase tool in ArcGIS was used to erase non-intersecting areas. Subsequently, the geometry of the cover layers was calculated, and their units were unified into square meters (m^2). This difference was converted into a percentage (%) in Microsoft Excel. From this, it was determined that the greater the negative difference in area compared to the previous period, the greater the ecosystem's vulnerability. In this sense, vulnerability will be high if the ecosystem has lost more than 30% of its cover compared to the first reporting period for that ecosystem. If the change is between 15% and 30%, vulnerability is medium; if it is less than 15%, vulnerability is low (Table 1).

Table 1. Vulnerability Levels and Values according to the Ecosystem percentage loss.

Ecosystem Percentage Loss	Vulnerability Level	Value
>30%	High	3
Between 15–30%	Medium	2
<15%	Low	1

Although coastal ecosystems can have varying degrees of vulnerability that depend on factors such as location, ecosystem type, and biological composition [51], the vulnerability rates for this research were established based on the annual loss rates of seagrass [52,53], beaches, and mangrove [54] ecosystems. These classes provide a pragmatic, management-oriented categorization, allowing comparisons across ecosystems despite heterogeneous temporal data availability across the archipelago. The three-level classification has been applied in similar coastal and vulnerability assessments [36,37,39,40].

For the seagrass meadows of San Andrés, data from the period 1997–2021 were used. Meanwhile, for the seagrass meadows of Providencia and Santa Catalina, only data from the periods 2006 and 2021 were available. For the beaches of San Andrés, data were available from 1998 to 2021 for Rocky Cay, Sound Bay, and Sprat Bight, whereas the remaining beach sectors were analyzed from 2014 to 2021. In contrast, all beaches in Providencia and Santa Catalina were consistently studied during 2000–2021. Data on mangrove ecosystems were collected from 2009 to 2021 in San Andrés, Providencia, and Santa Catalina.

Ecosystem area loss serves as a primary indicator of sensitivity to both climate change and anthropogenic pressures. Elevated variability in erosion–sedimentation dynamics is regarded as reflective of heightened ecosystem responsiveness to external drivers, thereby indicating greater environmental sensitivity. Complementing these metrics, the ecological and economic relevance of each sector was qualitatively integrated into the interpretation of vulnerability patterns.

2.4. Spatial Analysis of Land Planning Regulations as Anthropogenic Pressures

The different types of land-use zones in the archipelago were regarded as anthropogenic pressures. For terrestrial areas, Land Use Plans regulations were contemplated, while for marine areas, the SEAFLOWER Marine Protected Area Zoning was considered.

A spatial analysis was performed in ArcGIS software using the Overlay—Intersect tool to determine how urbanization, land-use changes, and MPA regulations have affected the ecosystems present on the islands of San Andrés, Providencia, and Santa Catalina.

Table 2 presents the threat values assigned based on the permitted uses: the more permissive the zoning, the greater the threat to ecosystems; conversely, the more restrictive the zoning, the lower the threat.

Table 2. Zoning Criteria and Threat Level for Island Ecosystems.

Zoning Criteria		Threat Level	Value
	Marine ecosystems Threats		
SEAFLOWER Marine Protected Area Regulations	Special Use Zone (Navigation access channels, Ports, Piers, touristic beach uses, anchoring)	HIGH	3
	General Use Zone	MEDIUM	2
	Traditional Fishing Sustainable Use Zone	MEDIUM	2
	Conservation Zone (no take)	LOW	1
	Preservation Zone (no entry)	LOW	1
	Terrestrial Ecosystems Threats		

Table 2. *Cont.*

Zoning Criteria		Threat Level	Value
San Andrés Isla Land Planning Regulations	Conservation Zone	LOW	1
	Protection and Preservation Zone	LOW	1
	Special Regulation Zones (Allow infrastructure, concessions, permits, agriculture)	HIGH	3
	Restoration Zones (adjacent to inhabited areas)	MEDIUM	2
Providencia and Santa Catalina Land Planning Regulations	McBean Lagoon Natural Park Zone	LOW	1
	Protection and Production	MEDIUM	2
	Recuperation	LOW	1
	Conservation Zone	LOW	1
	Rural Population Centers	HIGH	3
	Population Centers with More Restrictions	MEDIUM	2
	Agricultural Reserve	HIGH	3

2.5. Qualitative Assessment of Ecological Risk on Island Ecosystems

To estimate the Risk level to which island ecosystems are exposed due to land use and zoning of marine and terrestrial protected areas, the value obtained from ecosystem vulnerability was cross-referenced with the value obtained from threats (zoning). Map algebra was used in ArcGIS Pro to calculate the fields and multiply the threat value by the vulnerability. For example, if an ecosystem obtained a low vulnerability (value = 1) but a high threat level (value = 3), its risk level would be medium:

$$\text{Risk Level} = \text{Vulnerability (1)} \times \text{Threat (3)} = \text{Medium Risk (3)} \quad (1)$$

The color grading used to create the cartography of island ecosystems in the study area, related to ecological risk levels, consists of red for high levels, yellow for medium levels, and green for low levels (Table 3).

Table 3. Risk Assessment Matrix: Vulnerability and Threat-Level Interactions.

High Threat (3)	Medium Risk (3)	High Risk (6)	High Risk (9)
Medium Threat (2)	Low Risk (2)	Medium Risk (4)	High Risk (6)
Low Threat (1)	Low Risk (1)	Low Risk (2)	Medium Risk (3)
	Low Vulnerability (1)	Medium Vulnerability (2)	High Vulnerability (3)

In this way, a qualitative method is implemented to measure threats and vulnerabilities, based on the creation of three-level scenarios: high, medium, and low, using the human activities and uses that undermine the health of the island ecosystems in the study area [55,56].

To facilitate interpretation, the methodological workflow consisted of three steps: first, ecosystem cover change was analyzed to derive vulnerability classes (Table 1) and vulnerability maps; second, zoning permissiveness from terrestrial planning regulations and the Seaflower MPA was used to assign threat levels (Table 2); and third, vulnerability and threat values were multiplied (Vulnerability × Threat; Table 3) to generate ecological risk maps.

3. Results

3.1. Vulnerability of Island Ecosystems in San Andrés, Providencia, and Santa Catalina

Spatial analysis of vulnerability in island ecosystems in San Andrés, Providencia, and Santa Catalina reveals differing rates of total ecosystem loss across mangroves, seagrass, and beaches. These rates were calculated considering both recovery and loss of the ecosystem between the periods analyzed. A 0% loss rate indicates areas where no detectable loss of ecosystem cover occurred during the study period. The vulnerability reclassification accounts for ecological relevance and limited recovery capacity in urban-adjacent remnants. Final loss rates and their respective vulnerability values are presented in Table 4.

Table 4. Ecosystem percentage loss and Vulnerability Values for Island Ecosystems in San Andrés, Providencia, and Santa Catalina.

Island	Ecosystem	Section Name	Total Loss	Vulnerability per Loss	Vulnerability Reclassification	Vulnerability
San Andrés	Mangroves	Sector 1 Hooker Bay–Honda Bay	5%	Low	Low	1
		Sector 2 North Zone	0%	Low	Low	1
		Sector 3 Airport western side	0%	Low	Low	1
		Sector 4 Cove	13%	Low	Medium	2
		Sector 5 Mangrove patches on western side	19%	Medium	High	3
		Sector 6 East	0%	Low	Low	1
	Beaches	Sector 1 Rocky Cay	0%	Low	Medium	2
		Sector 2 Sound Bay	22%	Medium	Medium	2
		Sector 3 Sprat Bight	3%	Low	Medium	2
		Sector 4 Los Almendros	0%	Low	Low	1
		Sector 5 Jenny Bay	0%	Low	Low	1
		Sector 6 Cocoplum Bay	0%	Low	Low	1
		Sector 7 Southend	0%	Low	Low	1
		Sector 8 Sarie Bay	0%	Low	Low	1
	Seagrass	Sector 1 East	15%	Medium	High	3
		Sector 2 West	100%	High	High	3
Providencia and Santa Catalina	Mangroves	Sector 1 Mc Bean Lagoon	2%	Low	Medium	2
		Sector 2 Jones Point Town	0%	Low	Low	1
		Sector 3 Santa Catalina	0%	Low	Medium	2
		Sector 4 Old Town	34%	High	High	3
		Sector 5 John Mangrove	65%	High	High	3
		Sector 6 Southwest Bay	21%	Medium	Medium	2
		Sector 7 Smouth Water–Manchineel Bay	0%	Low	Low	1
		Sector 8 Johny Bay	8%	Low	Medium	2
	Beaches	Sector 1 Allan Bay	14%	Low	Low	1
		Sector 2 Bottom House	0%	Low	Low	1
		Sector 3 Fort Bay	65%	High	High	3
		Sector 4 Freshwater Bay	7%	Low	Medium	2
		Sector 5 Manchineel Bay	0%	Low	Low	1
		Sector 6 Old John Bay	37%	High	High	3
		Sector 7 Old Town	43%	High	High	3
		Sector 8 Panatain Beach	0%	Low	Low	1
		Sector 9 Pash Bay	36%	High	High	3
		Sector 10 Southwest Bay	0%	Low	Low	1
	Seagrass	In the whole island	13%	Low	Medium	2

Notes: A 0% value indicates that there was no detectable ecosystem cover loss. Vulnerability levels are represented with red color for high vulnerability, yellow for medium vulnerability and green for low vulnerability.

Mangrove ecosystem coverage on San Andrés Island shows specific increases, indicating recovery in areas that have undergone restoration or are within protected or conservation zones (Figure 2). However, the mangrove patch on the western side of the island had a net loss of 19% of the initial area; hence, its vulnerability was categorized as high due to its low recovery capacity. Similarly, the mangroves in the Cove sector lost more than 13% of their coverage. They were therefore assigned a medium vulnerability rating, primarily due to the extent of this ecosystem and the ecological implications of its variability.

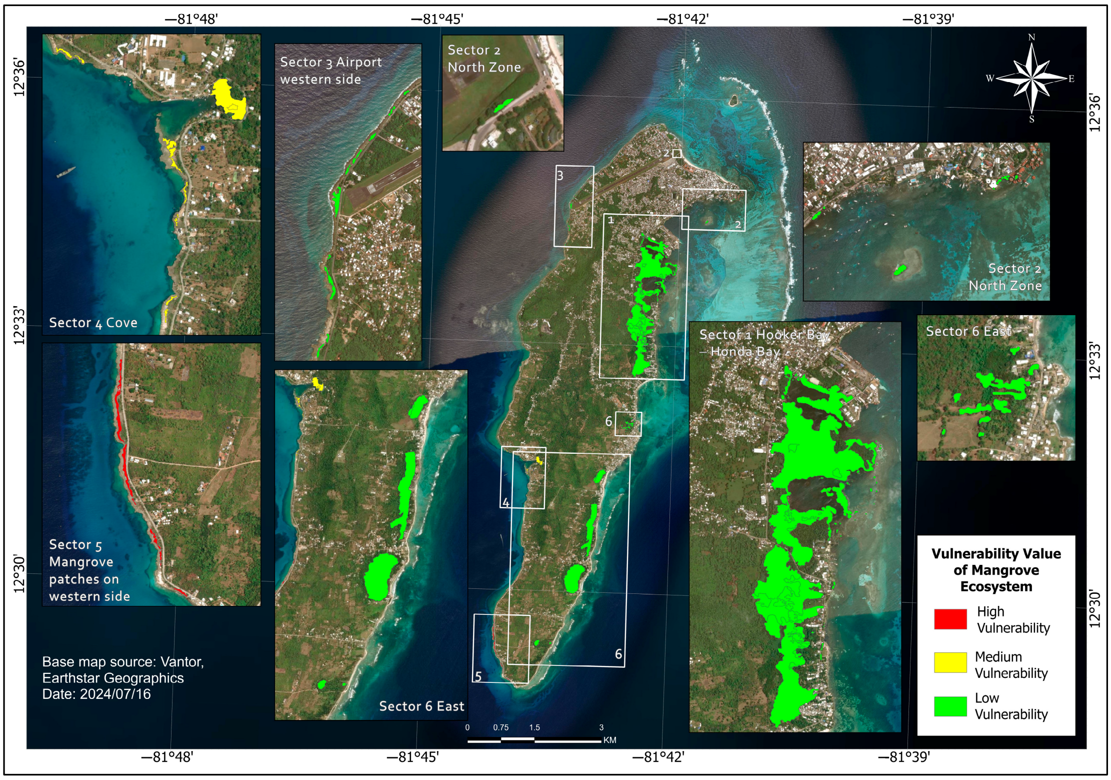

Figure 2. Distribution of vulnerability values in mangroves in San Andres Island.

In Providencia and Santa Catalina, total loss rates were up to 65%, resulting in high and medium vulnerability values, with only 2 sectors showing low vulnerability (Figure 3). The Mc Bean Lagoon sector exhibited a loss of only 2% of the ecosystem area; however, it remains the most extensive mangrove area on Providencia Island. The total area lost was 7537 m^2, nearly eight times the mangrove area of Johny Bay, and the sector was therefore classified as having medium vulnerability. Although the mangrove area in Johny Bay increased more than 100% by 2016, in 2021 its area had reduced by up to 8%, this can be related to the effects of Hurricane IOTA in 2020 [57], as well as its location in the southern part of Providencia Airport, which can slow down its recovery rate, hence its medium vulnerability value. The Santa Catalina and South West Bay sectors had area changes of up to 30%, resulting in their classification as medium vulnerability as well.

Analysis of beach cover on San Andrés Island generally indicates a tendency toward stability or area increase, which may be associated with natural accretion processes and seasonal variations in sediment accumulation, especially during periods of increased trade-wind intensity [47]. This dynamic explains why the degree of vulnerability is classified as medium or low in most cases, compared with other, more fragile island ecosystems (Figure 4). Among the sectors analyzed, Sound Bay showed significant changes, with a 22% loss rate. Rocky Cay and Sprat Bight did not exhibit a significant negative balance; however, both were classified as medium vulnerability (Table 4, Figure 4). At Rocky Cay, a declining trend was observed during 2014–2021. In contrast, Sprat Bight has failed to recover significantly since 1998, exhibiting a small but consistent reduction in area throughout the entire study period.

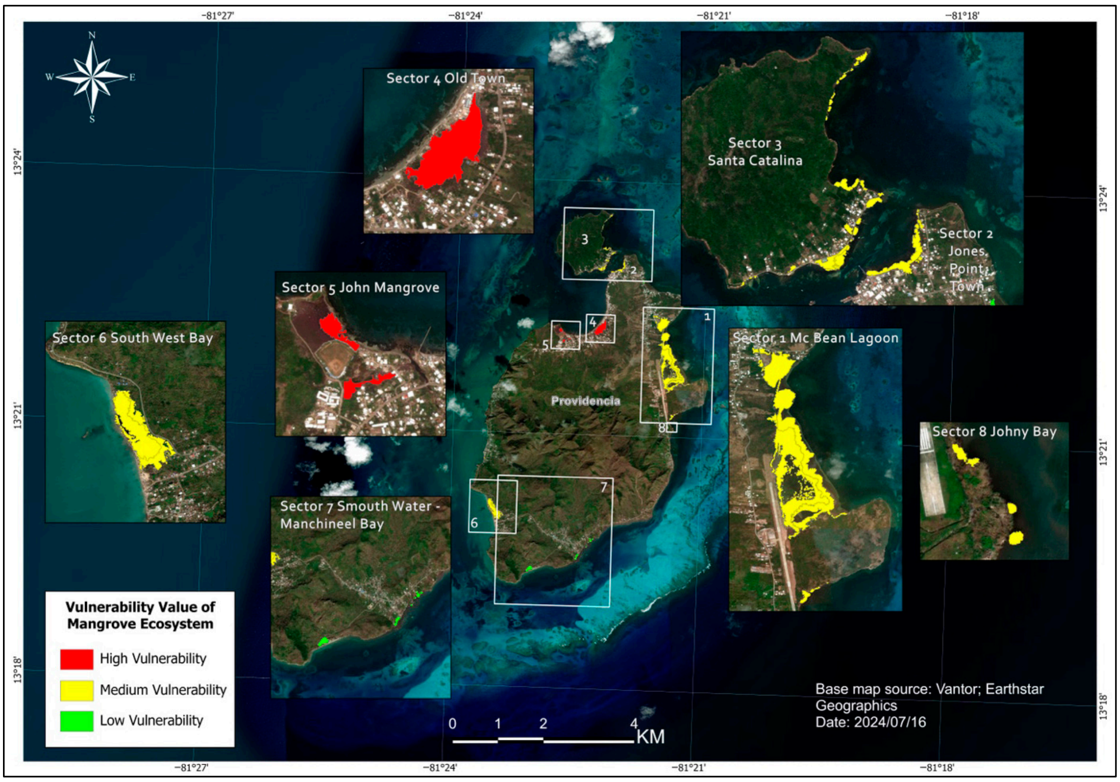

Figure 3. Distribution of vulnerability values in mangroves in Providencia and Santa Catalina Island.

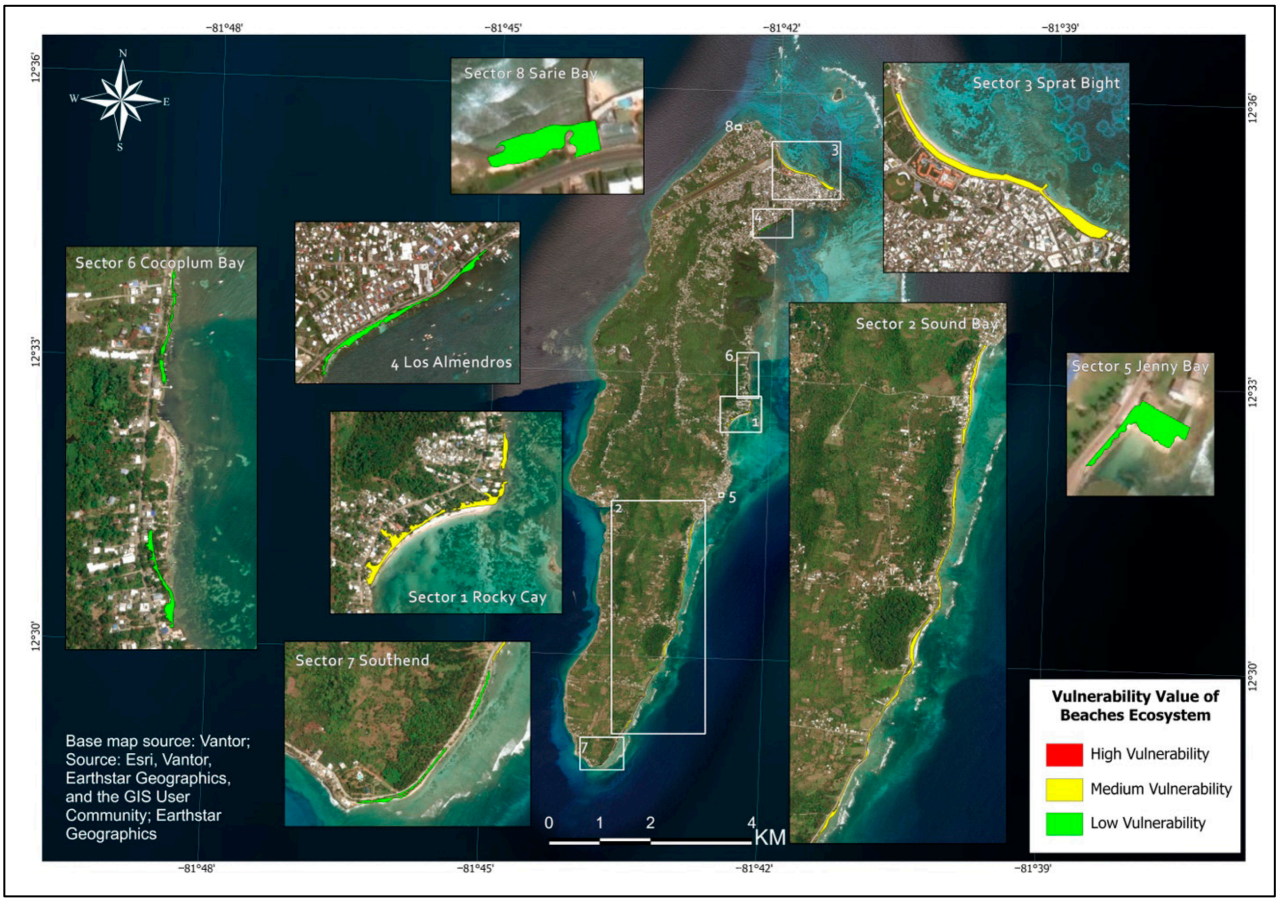

Figure 4. Distribution of vulnerability values on beaches in San Andrés Island.

Likewise, beach covers on the islands of Providencia and Santa Catalina exhibit heterogeneous dynamics associated with erosion and accretion processes. Of the ten beaches considered, four experienced a reduction greater than 35%, one had a reduction with recent accretion (2006–2021), four showed accretion (0% of total loss rate), and one recorded both processes at different times. The latter case corresponds to Freshwater Bay, which showed a 7% total loss rate between the periods analyzed. Furthermore, its proximity to the urbanized area suggests improved environmental management; therefore, it was classified as exhibiting medium vulnerability (Figure 5).

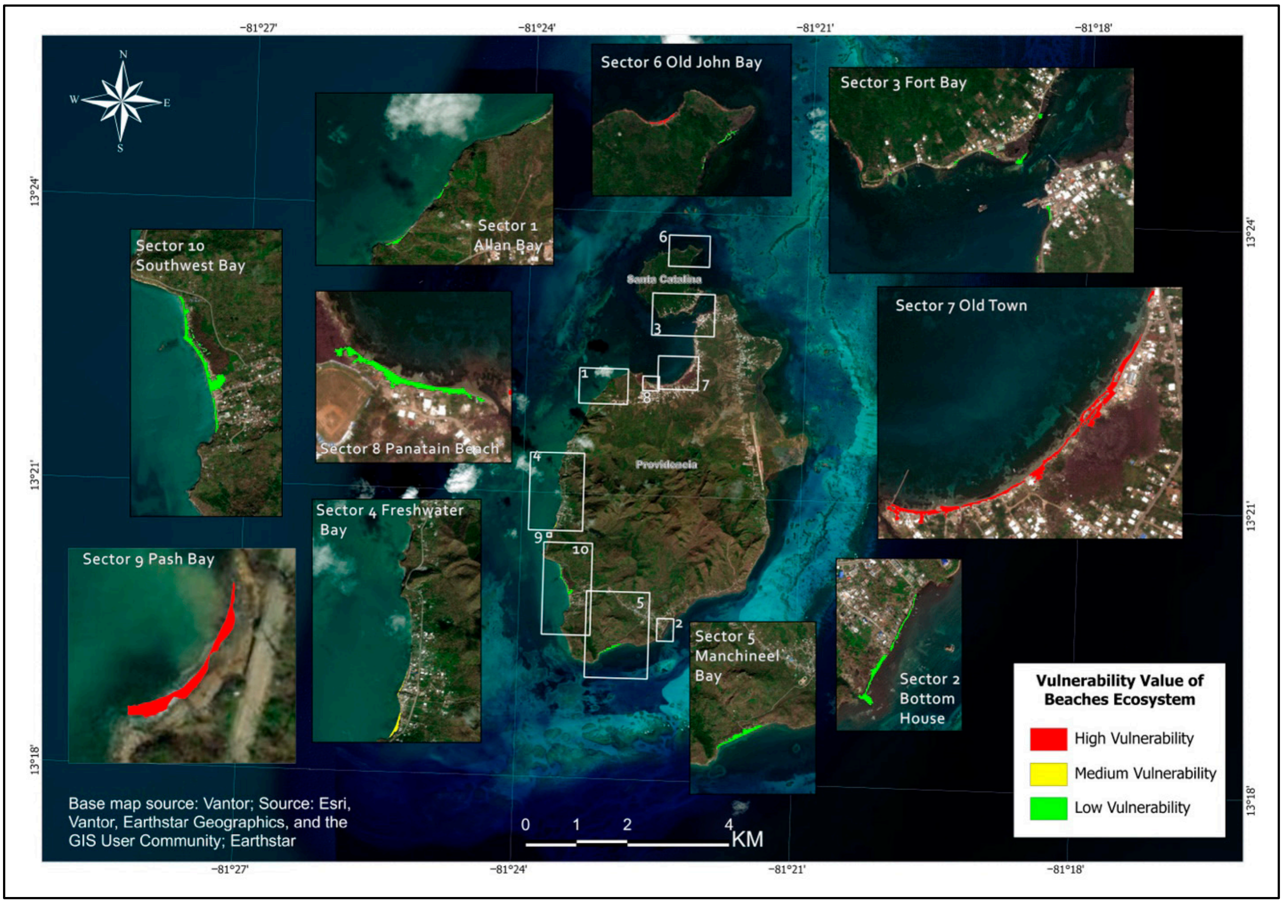

Figure 5. Distribution of vulnerability values on beaches in Providencia and Santa Catalina Island.

There was a significant reduction in seagrass cover on San Andrés Island. The disappearance of small patches of seagrass in the western sector is directly associated with the installation of the submarine cable for internet service. In contrast, the grasslands in the eastern sector appear to have persisted in areas where permitted uses are compatible with their presence. Although changes in this sector do not exceed 15%, vulnerability was reclassified as high, conditioned by both proximity to the urban area and the location and quantity of port and marine concessions in the northeast of the island. Unlike San Andrés Island, where the seagrass ecosystem predominates in the northeast of the island (Figure 6a), seagrass ecosystems completely border the islands of Providencia and Santa Catalina. Nevertheless, a reduction of more than 13% in seagrass cover was evident across the analyzed periods (Figure 6b).

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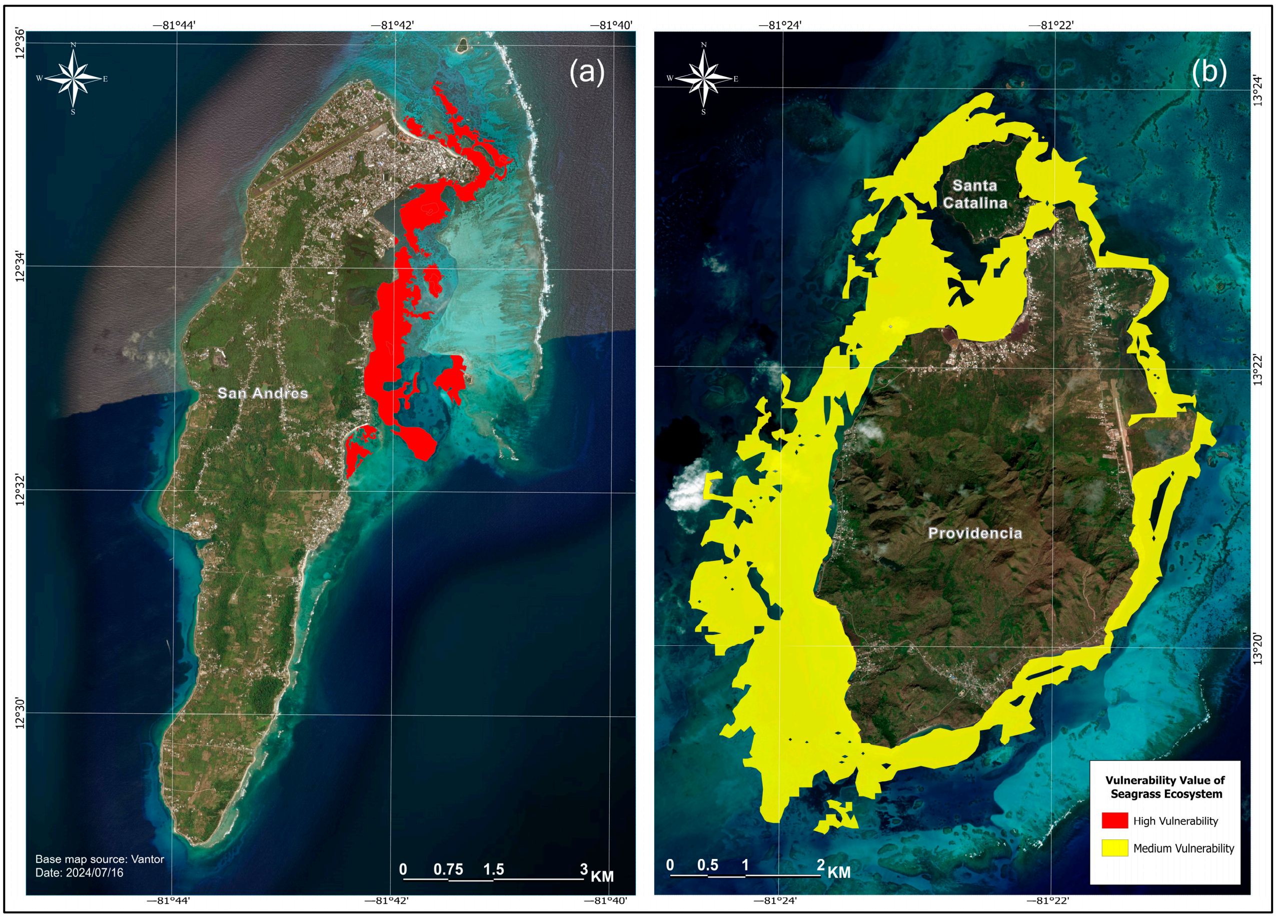

Figure 6. Distribution of vulnerability value in seagrass ecosystems in San Andrés Island (**a**) and Providencia and Santa Catalina Islands (**b**).

3.2. Land Planning Regulations as Anthropogenic Pressures on Island Ecosystems of San Andrés, Providencia, and Santa Catalina

The categorization of land-planning regulations in both marine and terrestrial areas of the archipelago enabled the differentiation of high, medium, and low threat levels to the ecosystems of San Andrés, Providencia, and Santa Catalina. In San Andrés (Figure 7a), most of the island and its immediate surroundings are under high threat, especially in the central and southern sectors, where urban and port areas coincide. More peripheral areas with less intervention present a medium threat, while only small sectors towards the east and on the marine periphery are classified as having a low threat. A similar distribution also happens in Providencia and Santa Catalina (Figure 7b), where high-threat areas surround the urban and port zones. At the same time, sectors with lower population density and more restricted uses are under medium or low threat.

3.3. Ecological Risk in Island Ecosystems of San Andrés, Providencia, and Santa Catalina

In the case of coral ecosystems, the analysis focused on the main barrier reef located along the northeastern coast of San Andrés Island (Figure 8a). Despite exhibiting high ecological vulnerability, its risk level was classified as medium due to its location within a zoned protected area. Nonetheless, a localized sector was identified as high risk due to its proximity to Johnny Cay Regional Park, where the management and zoning plan authorizes tourism activities and the transit of small vessels. In contrast, coral ecosystems around the Providencia and Santa Catalina Islands were highly vulnerable. This pattern is explained by the spatial configuration of the barrier reef, which, although designated as a protected area, lies between zones classified for general and special use. While extractive and recreational activities are prohibited within the coral reef itself, its ecological integrity remains threatened by indirect pressures, particularly vessel traffic, an activity permitted in adjacent areas. (Figure 8b).

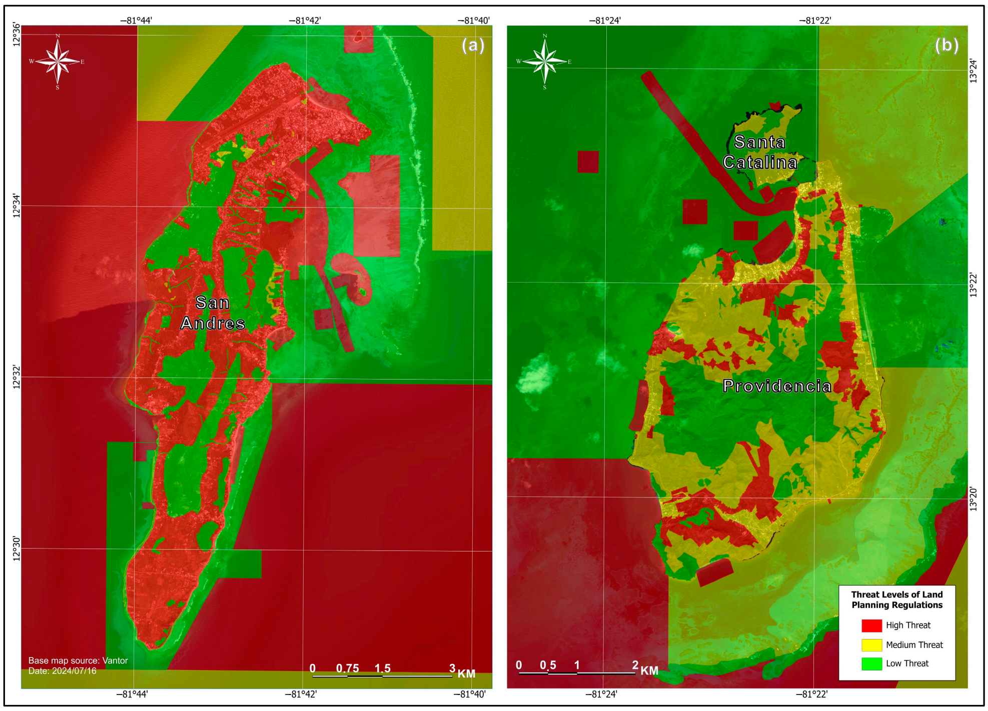

Figure 7. Threat levels of Land planning regulations in San Andrés Island (**a**) and Providencia and Santa Catalina Islands (**b**).

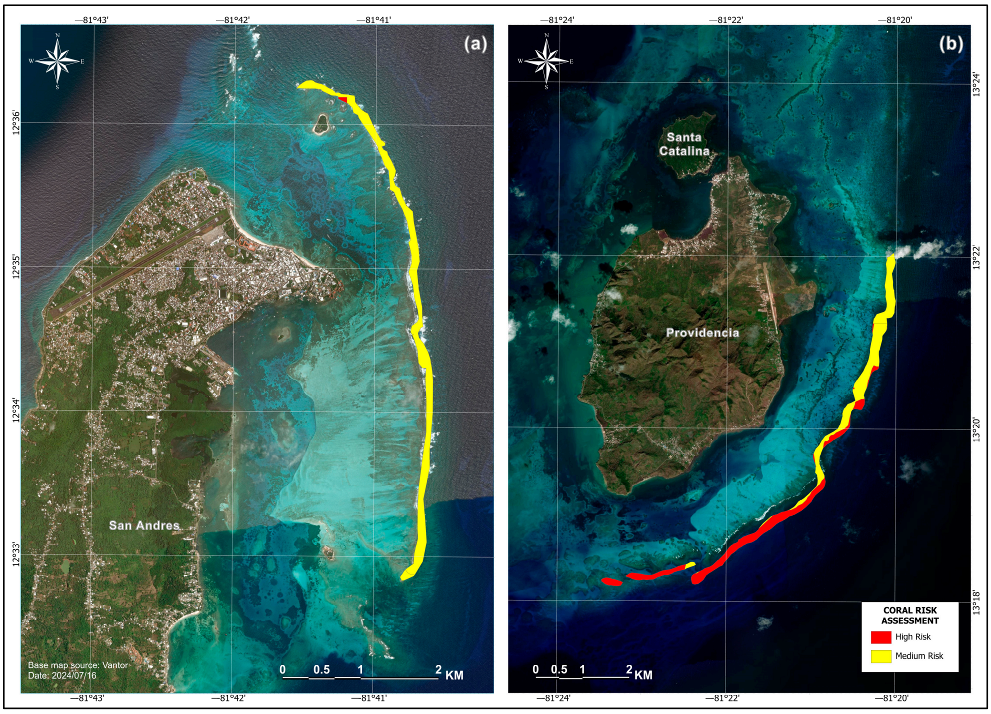

Figure 8. Ecological Risk in coral reef ecosystems in San Andrés Island (**a**) and Providence and Santa Catalina islands (**b**).

On San Andrés Island, seagrass ecosystems present a high degree of vulnerability, primarily associated with their spatial proximity to urban infrastructure and port concessions, concentrated in the northeastern sector of the island. Risk levels were classified from medium to high: the highest values were recorded in meadows located adjacent to the coastline, whereas medium values were observed within legally protected areas (Figure 9a). In contrast, Sector 2, corresponding to the western zone of the island, could not be evaluated due to the complete degradation and consequent loss of seagrass cover in this sector. Conversely, in Providencia and Santa Catalina, seagrass ecosystems exhibited moderate vulnerability. However, risk levels were not uniform and varied by management zoning: high-risk conditions were associated with special-use zones, medium-risk conditions with general-use zones, and low-risk conditions with protected areas (Figure 9b).

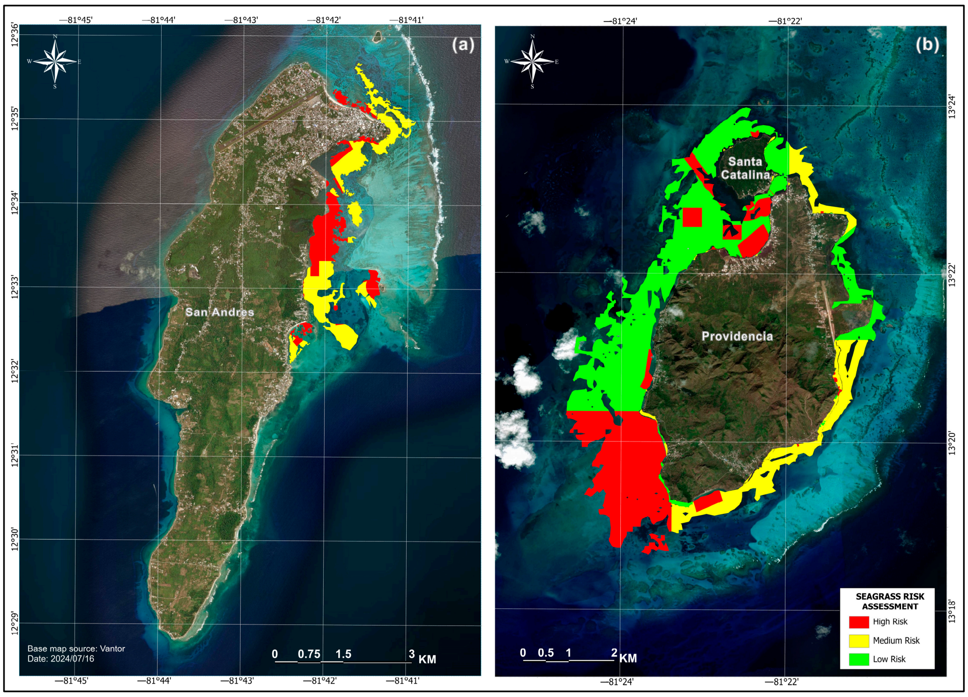

Figure 9. Ecological Risk of Seagrass Ecosystems in San Andrés Island (**a**) and Providencia and Santa Catalina Islands (**b**).

On the other hand, when correlating the medium and low vulnerability levels of the beaches on San Andrés Island with the threat-level categorization, high risk levels identified on some beaches could be associated with the presence of marine infrastructure concessions in these areas and intensive tourism use (Figure 10a). Beach ecosystems on Providencia and Santa Catalina Islands exhibited high vulnerability in areas with significant cover loss and active erosion. When this vulnerability was cross-referenced with threats derived from coastal zoning regulations and port concessions, high-risk zones were identified (Figure 10b).

In the case of the mangrove ecosystems on San Andrés Island, despite being surrounded by urban and rural areas with housing and infrastructure, they exhibit low to medium levels of vulnerability, mainly due to increased coverage or their location within protected areas. The opposite happened in other areas, where a portion of the mangroves present a high risk, a result of their overlap with marine areas zoned for special uses (Figure 11a). On the Providencia and Santa Catalina Islands, the mangrove ecosystems showed medium and high vulnerability, associated with loss or reduction in their coverage. When relating this vulnerability to land use and marine protected areas use regulations, three levels of risk were identified: low in protected areas, and medium and high in special-use zones (Figure 11b). These results are consistent with the high levels of risks found in the beaches and seagrass ecosystems present in these areas.

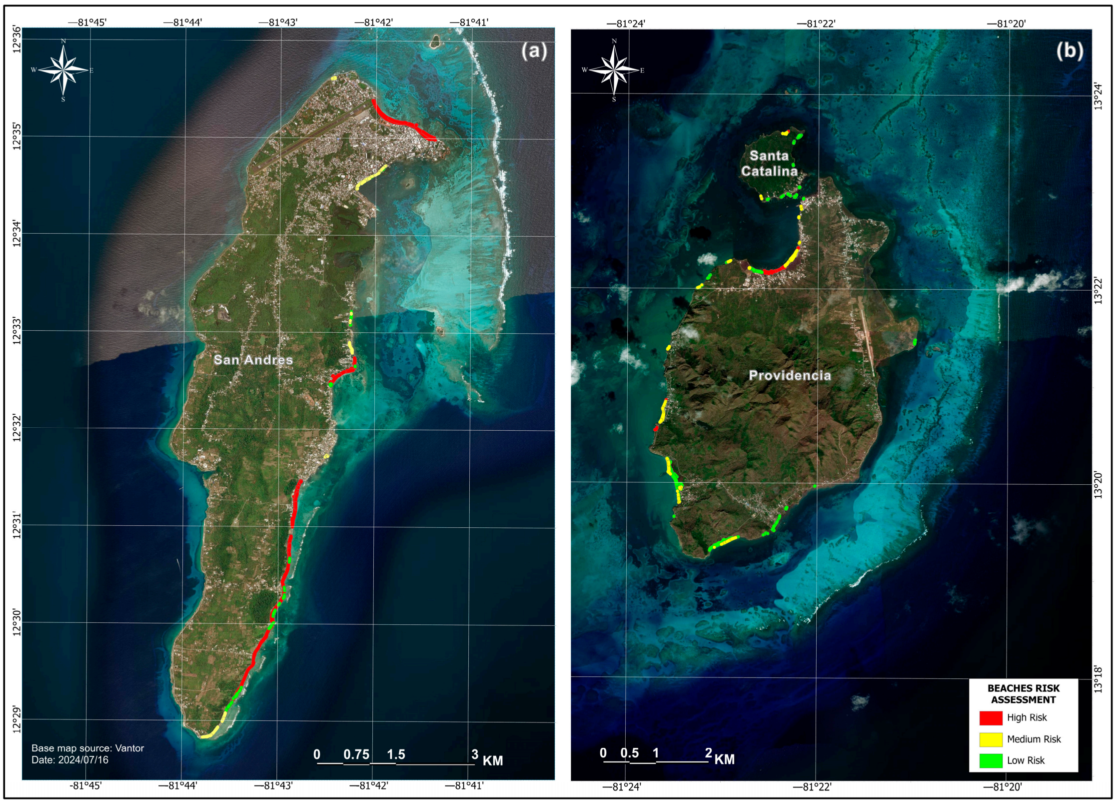

Figure 10. Ecological Risk of Beach Ecosystems in San Andrés Island (**a**) and Providencia and Santa Catalina Islands (**b**).

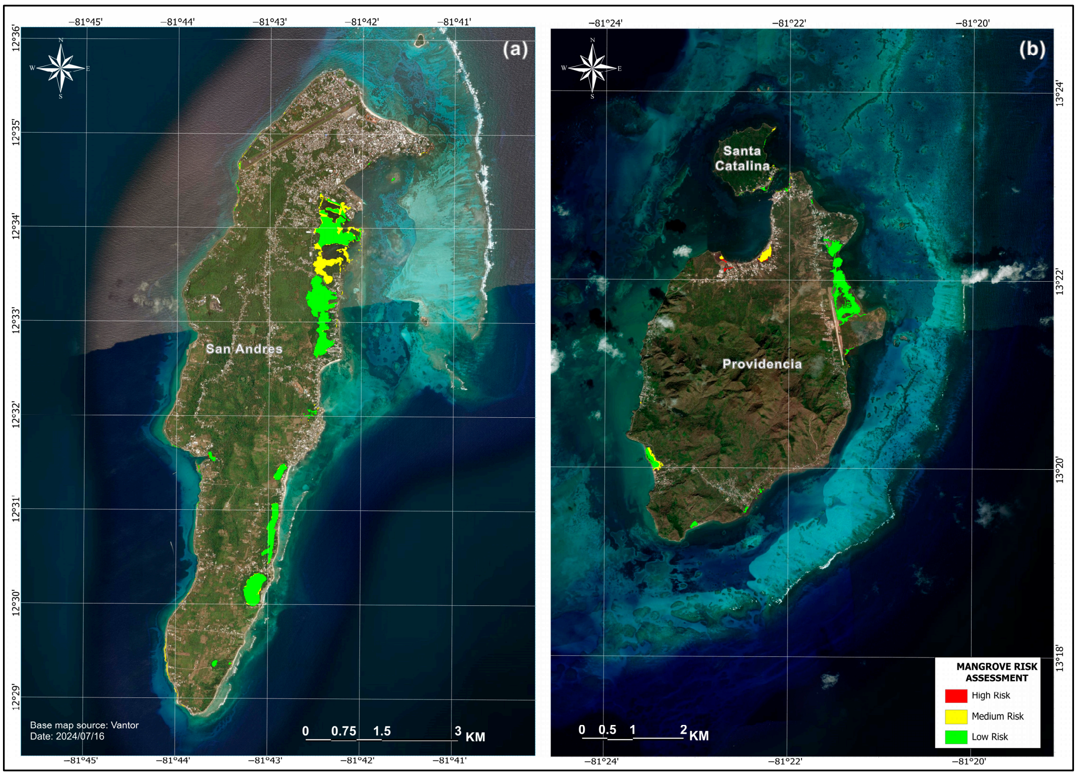

Figure 11. Ecological Risk of Mangrove Ecosystems in San Andrés Island (**a**) and Providencia and Santa Catalina Islands (**b**).

4. Discussion

The environmental degradation of ecosystems in San Andrés, Providencia, and Santa Catalina Islands is primarily attributed to anthropogenic pressures [47], including small-vessel traffic, dredging for the maintenance of navigation channels, sediment discharges associated with rainfall events and the subsequent formation of turbidity plumes in the water column, nutrient enrichment leading to eutrophication, and the release of wastewater and hydrocarbons [58]. Comparative analysis across marine and terrestrial zoning categories revealed a direct correlation between the permissiveness of use and corresponding levels of ecosystem vulnerability and risk.

Notably, these patterns are unevenly distributed across the archipelago, mirroring substantive contrasts in land-use intensity and regulatory context among the islands.

Inter-island comparison reveals differentiated ecological risk profiles closely associated with gradients of land-use intensity and regulatory governance. San Andrés exhibits the greatest concentration of ecological risk, attributable to urban expansion, tourism infrastructure, and port-related activities—anthropogenic pressures that collectively intensify the burden on coastal ecosystems and accentuate the adjacency effect between heavily transformed and comparatively conserved areas. Providencia and Santa Catalina, by contrast, present markedly lower overall risk levels, though localized pressures remain apparent in sectors where ecosystem cover loss spatially overlaps with permitted or weakly regulated land uses. Despite these contrasts, all three islands share structural vulnerabilities—most notably ecosystem fragmentation and the spatial convergence of regulatory zoning boundaries with ecologically sensitive environments. Collectively, these findings point to the need for spatially differentiated management strategies, prioritizing zoning enforcement in highly urbanized areas while reinforcing conservation interventions in less disturbed yet ecologically vulnerable sectors.

This trend is emblematic of a broader challenge widely documented in tropical island systems, wherein cumulative anthropogenic pressures converge along ecologically sensitive coastal zones. The interplay between coastal development, tourism-driven economies, and regulatory zoning has been consistently identified as a critical driver of ecosystem degradation and elevated ecological risk in small-island contexts—a finding that reinforces the global applicability and urgency of ecosystem-based spatial planning strategies [59–62].

Although seagrass meadows are generally considered resilient to physical changes in their environment, their ecological functionality is compromised when associated flora and fauna populations cannot withstand sustained anthropogenic pressures, leading, in some cases, to prolonged or even permanent declines in seagrass cover [52,53]. This trend was evident in San Andrés Island, where significant variations in the extent of seagrass ecosystems were observed across the different periods analyzed. In contrast, the islands of Providencia and Santa Catalina require more detailed investigation to determine the direct and indirect drivers of seagrass decline, given that losses were spatially homogeneous despite the presence of diverse zoning schemes that allow multiple uses. The most pronounced reduction in cover was observed in the channel providing maritime access to Providencia Island. Nevertheless, previous studies indicate that seagrass loss in the region cannot be attributed exclusively to anthropogenic impacts, as biotic factors such as fungal infections have also contributed to leaf mortality and ecosystem decline [47]. These findings emphasize that seagrass vulnerability should be interpreted within a cumulative impact framework, as declines often result from multiple interacting stressors rather than a single driver.

Beaches on San Andrés Island exhibited heterogeneous dynamics, alternating between accretion processes and low erosion rates. These patterns are consistent with geomorphological and erosion assessments previously conducted in the archipelago, which indicate that, overall, the beaches present low to moderate vulnerability to erosion, even in areas adjacent to urban settlements, port infrastructure, and zones with intense tourism activity and coastal construction [63]. In contrast, the beaches of Providencia and Santa Catalina display more variable dynamics, with sectors classified across the full range of vulnerability levels (low, medium, and high). Some areas recorded severe erosion, with shoreline-baseline losses exceeding 50%, whereas others showed recovery, with accretion rates ranging from 3% to 100%. These contrasting patterns highlight the importance of continuous monitoring, given that the natural dynamics of these ecosystems are compounded by anthropogenic pressures associated with tourism development and port operations. The observed contrasts between erosion-prone and accretionary sectors emphasize that island beaches are globally highly dynamic systems that can rapidly shift into high-risk states when tourism infrastructure and coastal construction overlap with sensitive sedimentary environments [64,65].

In San Andrés Island, mangrove ecosystems exhibited variations in spatial coverage, with both increases and decreases detected across the analyzed sectors. Two sectors located on the southwestern side of the island showed reductions in mangrove cover ranging from 5% to 19%, a trend attributed to their proximity to urbanized areas and the competitive displacement by herbaceous species [47]. Conversely, the sectors that exhibited increases in mangrove cover reflect the effectiveness of implemented restoration initiatives and protection mechanisms. Nonetheless, these positive outcomes underscore the importance of sustained monitoring, not only to detect ecosystem vulnerabilities but also to strengthen the integration of mangroves into risk management strategies, where they can serve as nature-based solutions for risk reduction [66].

On Providencia Island, mangrove coverage showed marked fluctuations between the different periods analyzed. The most significant reduction was associated with the severe impacts of Hurricane IOTA in 2020 [57]. However, evidence of mangrove loss prior to the hurricane suggests additional drivers, particularly in areas outside protected zones, where mangroves coexist with adjacent rural settlements and housing, exposing them to additional anthropogenic pressures.

This interaction between extreme climatic events and long-term human stressors represents a common vulnerability pathway for island ecosystems experiencing climate change [67,68]. Recovery capacity is often constrained by habitat fragmentation, limited land availability, and development pressures, making governance interventions particularly critical in insular contexts [65,69–71].

While the vulnerability-threat interaction matrix (Table 3) provides a pragmatic framework for spatial risk assessment, it is important to acknowledge that the multiplicative approach may obscure ecologically significant differences when ecosystems with distinct vulnerability-threat profiles are assigned the same overall risk classification. Specifically, the matrix generates equivalent "medium risk" scores (value = 3) for two fundamentally different scenarios: (1) ecosystems with low vulnerability but high threat ($1 \times 3 = 3$), and (2) ecosystems with low threat but medium vulnerability combined with low threat ($1 \times 2 = 2$). Similarly, medium vulnerability × medium threat ($2 \times 2 = 4$) also yields a medium risk classification, despite representing a qualitatively different ecological condition.

These convergent classifications warrant careful interpretation, as the underlying ecological dynamics and appropriate management responses differ substantially between scenarios:

Low vulnerability × high threat (score = 3): This scenario typically characterizes ecosystems that have demonstrated resilience or recovery capacity (e.g., mangroves in protected areas showing increases in coverage) but remain exposed to intense anthropogenic pressures from adjacent zones with permissive land-use regulations. In these cases, the ecosystem's intrinsic condition is favorable, but external stressors pose an imminent risk. Management priority should focus on threat mitigation through enhanced enforcement of zoning regulations, the establishment of buffer zones, and the control of adjacent land-use activities. The relatively low vulnerability suggests that if threats are effectively managed, the ecosystem has the capacity to maintain or improve its condition.

Medium vulnerability × medium threat (score = 4): This scenario describes ecosystems experiencing moderate degradation (e.g., 15–30% cover loss) under moderate anthropogenic pressure. Such systems are already compromised and may be approaching critical thresholds beyond which recovery becomes increasingly difficult. Management priorities should adopt a dual approach: simultaneously reducing threat exposure while implementing active restoration interventions to enhance ecosystem resilience. Examples include the mangrove sectors adjacent to urban areas on San Andrés that have shown partial recovery but remain vulnerable to displacement by herbaceous species.

High vulnerability × low threat (score = 3): Although less common in this study area, this scenario could represent ecosystems that have experienced substantial degradation (>30% loss) but are now situated within protected areas with restrictive use regulations. These systems may be recovering from past impacts or facing stressors not adequately captured by the zoning-based threat classification (e.g., climate-related disturbances, biotic factors). Management priorities should emphasize ecosystem restoration and recovery support, including active rehabilitation measures, continuous monitoring to track recovery trajectories, and investigation of additional stressors not reflected in land-use zoning.

The coral reef ecosystems in this study exemplify the complexity of risk interpretation within the multiplicative framework. Despite exhibiting high ecological vulnerability, the barrier reef along San Andrés' northeastern margin was classified as medium risk because it lies within a protected area (low threat). However, as noted in the results, localized sectors near Johnny Cay Regional Park showed high risk due to authorized tourism activities and vessel traffic. This spatial heterogeneity underscores that the "adjacency effect" operates at multiple scales, and ecosystems nominally within low-threat zones may still experience elevated pressure from permitted activities within those zones or spillover effects from adjacent areas.

Similarly, the seagrass ecosystems of San Andrés Island, particularly the complete loss of Sector 2 (western zone), highlight that categorical risk classifications may inadequately capture the full spectrum of degradation states. Once an ecosystem crosses irreversible thresholds and experiences complete functional collapse, it effectively exits the vulnerability assessment framework yet represents the most extreme manifestation of risk materialization. This limitation suggests that predictive early warning indicators and regime shift thresholds should be integrated into future risk assessment frameworks to identify ecosystems approaching critical transitions before they reach irreversible tipping points.

The qualitative nature of the three-level classification system (low, medium, high) provides simplicity and accessibility for decision-makers but necessarily involves information compression. Future refinements of the methodology could benefit from disaggregating risk scores to separately report vulnerability and threat components in management outputs, enabling stakeholders to quickly identify whether risk is primarily driven by ecosystem condition or external pressures; incorporating recovery potential as an additional dimension, distinguishing ecosystems with demonstrated resilience (e.g., restored mangroves) from those showing persistent decline despite comparable vulnerability scores; developing scenario-based risk projections that model how risk levels might shift under different management interventions or future environmental change scenarios, providing more actionable guidance for adaptive management; integrating temporal dynamics explicitly into the classification, such that ecosystems showing positive trends (recovery trajectories) are distinguished from those with negative trends (accelerating degradation), even if current cover loss percentages place them in the same vulnerability category.

Despite these limitations, the vulnerability-threat interaction framework successfully achieved its primary objective: providing a spatially explicit, replicable, and governance-integrated tool for ecosystem-based risk assessment in data-limited small-island contexts. The approach's strength lies not in producing definitive risk rankings but in systematically revealing spatial patterns of risk drivers and facilitating evidence-based prioritization of conservation interventions across multiple ecosystem types and governance zones.

The analysis of risk levels across different ecosystem types, in relation to the legally established zoning for terrestrial, coastal, and marine areas of both islands, reveals that even ecosystems within protected zones, subject to stricter restrictions and prohibitions, remain vulnerable. This vulnerability is largely explained by their spatial proximity to adjacent areas with less restrictive regulations or a broader range of authorized uses, which generates additional challenges for ensuring effective conservation, even within zones officially designated for restricted or prohibited use. This "adjacency effect" highlights a well-documented limitation of marine protected areas, especially in small-island settings where ecological connectivity extends beyond administrative boundaries [72–75].

By contrast, the results obtained for terrestrial and transitional ecosystems, such as mangroves, demonstrate a more positive trend. The observed increases in coverage, associated with recovery and restoration processes, suggest that the zoning strategies outlined in management plans have been effective, particularly when complemented by specific interventions such as establishing park trails, restricting buffer zones, and other conservation measures. Furthermore, the planning and analysis sections of these management instruments highlight awareness-raising initiatives, monitoring programs, and recovery and maintenance actions, all of which are critical to sustaining ecosystem preservation and facilitating long-term ecological recovery.

For beach ecosystems, which exhibit high risk, it is recommended to implement continuous monitoring of environmental quality and systematic assessments of shoreline dynamics. Additionally, the temporary restriction or prohibition of use could contribute to natural recovery processes. Complementary measures should include the regular updating of carrying capacity studies and, in urbanized sectors or areas adjacent to port and marine concessions, the promotion of beach certification programs to strengthen sustainable management practices.

Beyond the Seaflower case study, the vulnerability–threat interaction approach provides a transferable GIS-based tool that can support ecosystem-based spatial planning in other island regions facing similar governance and tourism pressures. The proposed framework can support adaptive Integrated Coastal Zone Management (ICZM) strategies and guide zoning revisions in UNESCO Biosphere Reserves facing rapid tourism expansion.

This study has several limitations that should be considered when interpreting the results. First, the qualitative approach, based on categorical zoning frameworks and heterogeneous datasets, limits direct quantitative comparisons. Moreover, vulnerability was assessed primarily through changes in ecosystem cover, which may not fully capture functional degradation such as biodiversity loss or soil deterioration. Temporal inconsistencies across datasets—particularly differences in reference periods—may also affect the comparability of loss rates. Furthermore, the analysis does not explicitly account for the effectiveness of regulatory enforcement, a factor that may significantly mediate observed outcomes. Despite these limitations, the framework provides a consistent and spatially explicit basis for identifying ecological risk patterns, offering a replicable approach applicable to other regions facing similar environmental pressures.

https://doi.org/10.3390/geographies6020038

5. Conclusions

Island ecosystems exhibit unique ecological characteristics that require tailored management approaches and evaluation methodologies to assess their vulnerability to anthropogenic pressures. This study analyzed the vulnerability of island ecosystems in the San Andrés, Providencia, and Santa Catalina archipelago by examining the relationships among changes in ecosystem cover and land use, and marine protected area regulations. The main findings are enumerated as follows.

5.1. Main Findings

1. Ecosystem-specific vulnerability patterns:

Seagrass ecosystems in San Andrés Island showed significant reductions in cover (>13%), with the most pronounced losses in the maritime access channel to Providencia Island. Declines were spatially homogeneous despite diverse zoning schemes, indicating cumulative impacts from multiple stressors, including anthropogenic pressures and biotic factors such as fungal infections.

Beach ecosystems exhibited heterogeneous dynamics: San Andrés beaches showed low to moderate vulnerability with accretion processes and low erosion rates. In contrast, Providencia and Santa Catalina beaches displayed highly variable dynamics ranging from severe erosion (>50% baseline loss) to accretion (3–100%), highlighting the need for continuous monitoring.

Mangrove ecosystems demonstrated contrasting trends: in San Andrés, coverage variations ranged from 5–19% reduction in urbanized southwestern sectors to increases in restored areas; in Providencia, marked fluctuations were observed, with the most significant reduction (up to 65%) associated with Hurricane IOTA in 2020, compounded by pre-existing anthropogenic pressures in unprotected zones.

2. Direct correlation between zoning permissiveness and ecological risk:

Comparative analysis of marine and terrestrial zoning categories revealed that more permissive land-use regulations are directly associated with higher ecosystem vulnerability and risk, demonstrating that governance frameworks significantly influence ecosystem health.

3. The “adjacency effect” limits conservation effectiveness:

Even ecosystems within protected zones with strict restrictions remain vulnerable due to spatial proximity to adjacent areas with less restrictive regulations. This adjacency effect represents a critical limitation of marine protected areas in small-island settings where ecological connectivity extends beyond administrative boundaries.

4. Effectiveness of restoration and protection measures in terrestrial ecosystems:

Terrestrial and transitional ecosystems (particularly mangroves) showed positive recovery trends when zoning strategies were complemented by specific interventions, such as park trails, buffer-zone restrictions, awareness-raising initiatives, and systematic monitoring programs, demonstrating that integrated management approaches can be effective.

5. Vulnerability as a cumulative impact phenomenon:

Ecosystem vulnerability results from multiple interacting stressors rather than from a single driver. The interaction between extreme climatic events (e.g., Hurricane IOTA) and long-term human stressors (urbanization, tourism development, port operations) represents a common vulnerability pathway for island ecosystems under climate change, with recovery capacity constrained by habitat fragmentation and development pressures.

6. Transferability of the vulnerability-threat interaction approach:

The GIS-based methodology integrates ecosystem cover-change metrics with regulatory zoning frameworks, providing a transferable tool for ecosystem-based spatial planning in other island regions facing similar governance and tourism pressures. It supports adaptive Integrated Coastal Zone Management (ICZM) strategies and guides zoning revisions in UNESCO Biosphere Reserves amid rapid tourism expansion.

5.2. Management Implications

Ecological risk assessments must explicitly incorporate governance and land-use planning considerations, as marine protected areas and land-use regulations can reduce vulnerability. Still, they may also create new pressures depending on their design and implementation. Periodic monitoring of ecosystem health is indispensable to provide a foundation for adaptive management and continuous improvement of conservation strategies.

For beach ecosystems, which are high-risk, continuous monitoring of environmental quality and systematic assessments of shoreline dynamics are recommended. Additionally, temporary restriction or prohibition of use could contribute to natural recovery processes. Complementary measures should include regular updating of carrying capacity studies and, in urbanized sectors or areas adjacent to port and marine concessions, the promotion of beach certification programs to strengthen sustainable management practices.

Human-induced pressures remain the principal drivers of vulnerability in island ecosystems, yet these factors are often insufficiently integrated into risk analyses. By incorporating changes in ecosystem cover, regulatory frameworks, and spatial analysis, this study demonstrates the utility of geographic information systems as tools for ecosystem-based risk management in insular contexts.

In the San Andrés, Providencia, and Santa Catalina archipelago—and similar small-island biosphere reserves globally—identifying priority zones for conservation and restoration is essential to safeguarding ecosystem services, reducing biodiversity loss, and strengthening resilience in the face of accelerating environmental and governance challenges.

5.3. Directions for Future Research

Further investigation is needed to determine the relative contribution of anthropogenic pressures versus biotic stressors to ecosystem decline, particularly for seagrass in Providencia and Santa Catalina. Research should explicitly quantify synergistic effects between climate change (extreme events, sea level rise) and chronic anthropogenic stressors (pollution, tourism pressure).

It is necessary to enhance temporal monitoring. Establish standardized long-term monitoring protocols with consistent temporal frequency across all ecosystem types. Integrate high-resolution satellite imagery and remote sensing technologies to enable continuous monitoring and to develop predictive models that incorporate climate projections and socio-economic scenarios. The scenarios may include, but are not limited to, ecosystem service valuation and community adaptive capacity. Also, develop ecosystem-specific vulnerability indices that integrate multiple indicators beyond cover change, including water quality, biodiversity metrics, and functional trait composition.

We should apply the vulnerability-threat framework to other UNESCO Biosphere Reserves and small-island developing states to test its generalizability. Develop decision-support tools using freely available data and open-source GIS platforms for resource-limited institutions.

Management effectiveness on islands should be evaluated by systematically assessing the long-term outcomes of restoration initiatives and by conducting comparative analyses of zoning effectiveness across different governance models. The role of participatory management and community-based monitoring in enhancing conservation outcomes may also be examined.

Author Contributions: Conceptualization, methodology, and analysis, A.Y., A.C.T.-E. and L.P.; data validation, L.N. and A.Y.; data curation, L.N. and M.M.S.-C.; writing—original draft preparation, A.Y., L.S. and M.M.S.-C.; writing—review and editing, A.Y. and L.S.; supervision, A.C.T.-E. and L.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets presented in this article are currently unavailable, as they are part of an ongoing study pending legal approval from the relevant national institutions.

Acknowledgments: The authors gratefully acknowledge Corporación para el Desarrollo Sostenible del Archipiélago de San Andrés, Providencia, and Santa Catalina (CORALINA) for providing the geographic data used in this research.

Conflicts of Interest: Author Laura Noguera was employed by the company AML Ambiente SAS. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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https://doi.org/10.3390/geographies6020038