

Climate-Resilient Zoning Design for Marine Protected Areas in Pulo Aceh Using CIVAT Vulnerability Assessment and MARXAN Spatial Optimization

Faisal Syahputra^{1*}, Syamsul Rizal², Haekal Azief Haridhi²

¹Doctoral Study Program in Mathematics and Applied Sciences Syiah Kuala University Aceh, Indonesia

²Department of Marine Science, Marine and Fisheries Faculty Syiah Kuala University Aceh, Indonesia

*Corresponding Author: faisalsyahputra@yahoo.com

Submitted: 12/05/2026; Revision Accepted: 22/09/2026; Published: 30/09/2026

How to cite this paper:

Climate-Resilient Zoning Design for Marine Protected Areas in Pulo Aceh Using CIVAT Vulnerability Assessment and MARXAN Spatial Optimization. (2026). *Proceedings of International Conference on Agro and Marine Industry*, 2(1). <https://journal.utu.ac.id/index.php/ICONAMI/article/view/332>

Abstract

Marine Protected Areas (MPAs) designed primarily to address anthropogenic pressures may prove ineffective under accelerating climate change, particularly in small island ecosystems with high inherent vulnerability. The existing zoning of the Aceh Besar Regional Marine Conservation Area (KKPD), covering 29,615.63 ha, including Pulo Aceh subdistrict, has not explicitly integrated climate resilience criteria into its spatial planning. This study proposes an integrated CIVAT-MARXAN framework to develop climate-resilient MPA zoning in Pulo Aceh, Aceh Besar. The Coastal Integrated Vulnerability Assessment Tool (CIVAT) will be applied to assess coastal ecosystem vulnerability across three components: exposure (sea level rise, extreme waves, tidal range), sensitivity (coastal geomorphology, reef platform width, vegetation cover), and adaptive capacity (institutional, socioeconomic, and ecological factors). The resulting spatial vulnerability index will serve as the cost input for MARXAN (Marine Reserve Design using Spatially Explicit Annealing), which optimizes conservation zone configurations to achieve ecological targets at minimum cost while maintaining spatial compactness. Data collection will combine field surveys, satellite imagery, and secondary oceanographic datasets from BMKG and NASA. Expected outputs include a coastal vulnerability map, identification of dominant vulnerability drivers, an optimized climate-resilient zoning design for KKPD Aceh Besar, and a replicable CIVAT-MARXAN methodological framework applicable to Indonesia. This research contributes to climate-adaptive marine conservation planning and supports Indonesia's commitment to conserving 30% of its marine area by 2030.

Keywords: *Marine Protected Area, Climate Resilience, CIVAT, MARXAN; Vulnerability Assessment, Small Islands, Pulo Aceh.*

Introduction

Marine Protected Areas (MPAs) are widely adopted as the primary policy instrument for protecting marine biodiversity and sustaining fisheries. Indonesia, as the world's largest

archipelagic state, has committed to protecting 30% of its marine area by 2030 [1]. The Aceh Besar Regional Marine Conservation Area (KKPD Aceh Besar), established through Ministerial Decree No. 78/Kepmen-KP/2020, covers 29,615.63 ha including four zones within Pulo Aceh sub-district on Pulau Breuh and Pulau Nasi.

Despite formal protection status, the existing zoning design of KKPD Aceh Besar was developed primarily to address anthropogenic pressures such as overfishing and destructive fishing practices, without explicitly integrating climate resilience criteria. This omission is increasingly problematic as the region faces accelerating climate change impacts. Sea level rise (SLR) in the Banda Aceh coastal area has been recorded at 6.6 mm/year, with some estimates reaching 7–8 mm/year [2], far exceeding the global average of 3.2 mm/year. Pulo Aceh's exposure to the Indian Ocean, Andaman Sea, and Malacca Strait creates multi-directional wave exposure and heightened climate vulnerability.

The key question motivating this research is: can an MPA designed to address anthropogenic pressure also remain effective against climate change? Evidence suggests that biodiversity-rich areas do not necessarily coincide with areas resilient to sea level rise [3]. A paradigm shift is therefore needed—from protecting current hotspots to identifying and prioritizing *climate refugia*: areas capable of sustaining biodiversity under future climate conditions [4].

This study addresses this gap by proposing an integrated framework combining the Coastal Integrity Vulnerability Assessment Tool (CIVAT) and Marine Reserve Design using Spatially Explicit Annealing (MARXAN). CIVAT quantifies spatially explicit vulnerability indices, while MARXAN optimizes spatial zoning configurations. The integration of these two tools, CIVAT outputs as cost inputs to MARXAN, has not been previously applied in small island conservation planning in Aceh.

Pulo Aceh represents an ideal study site for four reasons. First, it has an established KKPD with defined zoning, enabling direct comparison and improvement. Second, it demonstrated extraordinary post-tsunami 2004 ecosystem resilience, with hard coral cover recovering from 1.75% in 2006 to 49.38% in 2011 [5], indicating potential climate refugia characteristics. Third, as small islands (total land area 90.56 km², population 4,463), it

represents a highly vulnerable category facing sea level rise. Fourth, there is a significant gap in systematic CIVAT-based vulnerability assessment for this area.

Literature Review

Climate Change and Coastal Ecosystem Vulnerability. Climate change affects coastal ecosystems through changes in sea level, intensification of extreme wave events, and shifts in tidal dynamics [6]. For small island ecosystems, these threats are compounded by limited land area, geographic isolation, and constrained adaptive capacity. Research shows that MPA effectiveness is threatened by projected sea surface temperature increases of 0.035°C/year, with an additional 2.8°C warming projected by 2100 under business-as-usual scenarios [7]. This should shifts the MPA planning paradigm toward resilience and refugia identification rather than static biodiversity protection.

CIVAT Methodology. The Coastal Integrity Vulnerability Assessment Tool (CIVAT) was developed in the Philippines by Siringan et al. [8] and has been applied in the Philippines and Malaysia [9, 10]. CIVAT operationalizes the IPCC vulnerability framework into 17 measurable parameters across three components: Exposure (sea level rise rate, extreme wave height, tidal range), Sensitivity (coastal geomorphology, seasonal shoreline recovery, coastal slope, reef platform width, platform continuity, beach vegetation), and Adaptive Capacity (institutional capacity, socioeconomic factors, ecological conditions). CIVAT employs the hierarchical cross-tabulation method integrating Exposure and Sensitivity, in the first step to get the Potential Impact. the second step is integrating Potential Impact with Adaptive Capacity to get the Vulnerability. the result is spatially explicit vulnerability maps classified as Low, Medium, or High. CIVAT's advantages over other coastal vulnerability indices (CVI) include its comprehensive 17-parameter framework, socio-ecological integration, regional validation in Southeast Asia, grid-based spatial output compatible with MARXAN planning units, and feasibility without requiring climate model downscaling.

MARXAN for Systematic Conservation Planning. MARXAN (Marine Reserve Design using Spatially Explicit Annealing) is the most widely used spatial conservation

planning tool globally [11]. It employs simulated annealing algorithms to find near-optimal solutions to multi-objective spatial problems. The objective function minimizes, $\text{Score} = \Sigma \text{Cost} + (\text{BLM} \times \Sigma \text{Boundary}) + \Sigma (\text{SPF} \times \text{Shortfall})$, where cost represents the socioeconomic cost of protection, BLM is the Boundary Length Modifier controlling spatial compactness, and SPF is the Species Penalty Factor ensuring conservation targets are met [12]. By incorporating CIVAT vulnerability indices as cost layers, where high vulnerability areas receive elevated cost values reflecting higher conservation priority for protection, the integrated framework ensures that climate resilience becomes a criterion in zoning optimization.

Research Gap. While CIVAT has been applied in Southeast Asia and MARXAN is extensively used for MPA design, no prior study has integrated these two tools into a single framework for climate-resilient MPA zoning in Indonesia's small island contexts. Existing vulnerability assessments in Aceh have used simpler Coastal Vulnerability Index (CVI) methods applied to mainland coastal areas [2] without extending to island conservation planning. Similarly, MPA optimizations using MARXAN in Indonesia have focused on economic and social cost inputs without incorporating climate vulnerability as a spatial cost component. This study addresses that gap.

Research Methods

Study Area. The study is located in Pulo Aceh sub-district, Aceh Besar Regency, Indonesia. The study area encompasses Pulau Breuh and Pulau Nasi, the two largest inhabited islands, with a combined land area of approximately 90.56 km². The marine study area covers the four KKPD zones within Pulo Aceh, positioned at the convergence of the Indian Ocean, Andaman Sea, and Malacca Strait.

The research adopts a quantitative approach integrating spatial analysis and mathematical optimization. The workflow proceeds in three sequential phases: (1) CIVAT vulnerability assessment, (2) ecological data collection for MARXAN conservation features, and (3) MARXAN spatial optimization incorporating CIVAT results. Fig. 1 illustrates the overall research workflow.

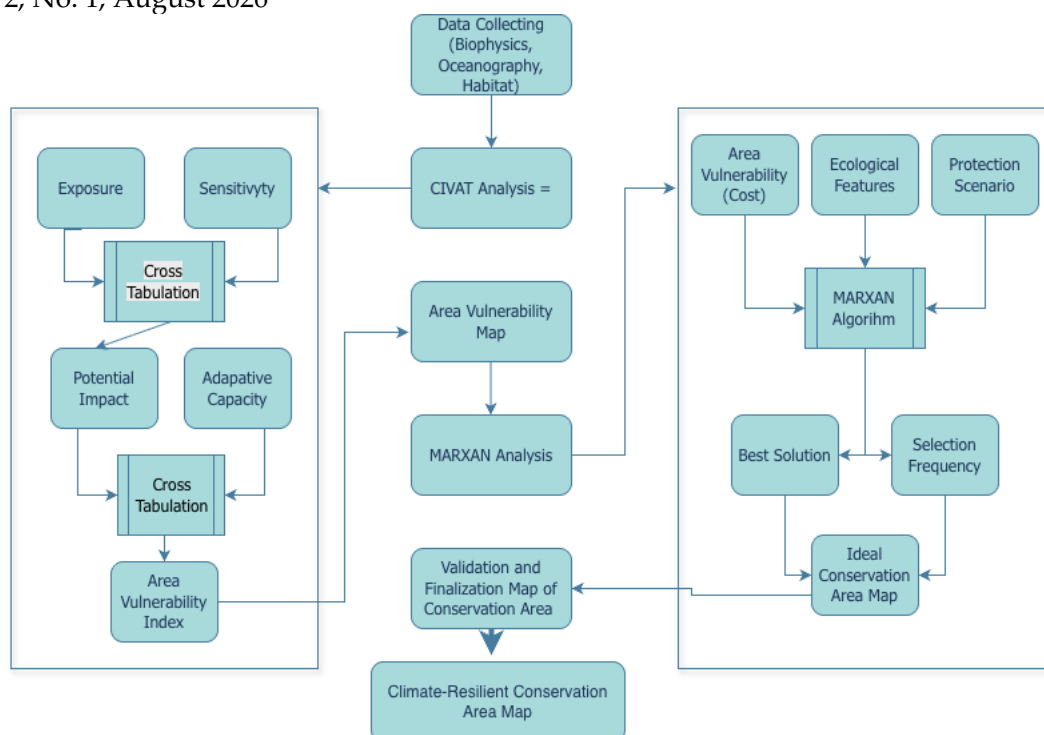


Figure 1. Research Workflow

Data Collection. Primary data will be collected through field surveys including coastal geomorphology assessment, oceanographic parameter measurements, underwater ecological surveys (coral cover, seagrass density, mangrove condition), and stakeholder interviews with KKPD managers (Panglima Laot), fishermen, and the NGO. Secondary data includes: sea level rise trends from BMKG and NASA Sea Level Projection Tool, significant wave height data from BMKG and satellite imagery, tidal range data from BMKG tide gauge records, satellite imagery from Landsat 9 and Sentinel 2 for shoreline change analysis, and existing KKPD management documents.

CIVAT Analysis. CIVAT will be implemented using a grid-based planning unit (PU) structure, where each PU corresponds to a hexagonal or square cell covering the Pulo Aceh coastal zone, aligned with MARXAN's spatial units. Each PU will be scored across all 17 parameters using validated ordinal scales (1–5), where 1 represents the lowest vulnerability condition and 5 represents the most vulnerable condition. Parameters are grouped into three components and integrated sequentially through a hierarchical cross-tabulation procedure: Exposure scores (from 3 parameters) and Sensitivity scores (from 9 parameters) are combined using a cross-tabulation matrix to produce a Potential Impact classification

(Low, Medium, or High). The Potential Impact classification is then combined with the Adaptive Capacity score (from 5 parameters) through a second cross-tabulation to yield the final Vulnerability index for each PU, classified as Low, Medium, or High. The complete set of CIVAT parameters, corresponding data requirements, and data sources are presented in Table 1.

Table 1. CIVAT Parameters, Data Requirements, and Sources

Component	Parameter	Data Required	Source
Exposure (E)	Sea Level Rise (SLR)	SLR trend (mm/year)	BMKG, NASA
	Extreme Wave Height	Max. significant wave height (m)	BMKG, Satellite
	Tidal Range	Tidal range (m)	BMKG, Field survey
Sensitivity (S)	Coastal Geomorphology	Shore type classification	Field, Satellite
	Seasonal Shoreline Recovery	Shoreline change trend (m/year)	Satellite (Landsat 9 /Sentinel 2)
	Coastal Slope	Slope gradient (degrees)	DEM, Field Field survey
	Reef Flat Width	Reef platform width (m)	Field Survey
	Reef Platform Continuity	Lateral continuity (%)	Satellite, Field survey
	Beach Vegetation Cover	Vegetation type and density	Field survey, Satellite
	Natural Protective Habitat	Mangrove/seag rass buffer presence	Field survey, Satellite

Component	Parameter	Data Required	Source
	Coastal Land Use	Land use/cover type	BPS, Satellite
	Population Density in Coastal Zone	Population density (persons/km ²)	BPS Census
Adaptive Capacity (AC)	Institutional Capacity	Management effectiveness score	Stakeholder Interview
	Economic Dependence on Marine Resources	% households reliant on fisheries	BPS, Interview
	Community Awareness of Climate Risk	Awareness score (survey)	Field Survey
	Coral Reef Ecological Condition	Live coral cover (%)	Field Survey

MARXAN Analysis. MARXAN optimization requires three categories of input data applied across the planning unit grid. First, conservation features define what needs to be protected: coral reef coverage (target 30% representation), Sea turtle nesting area (target 30%), mangrove area (target 40%), and species richness index. Each feature is assigned a Species Penalty Factor (SPF) reflecting its conservation priority. Second, the cost layer represents the opportunity cost of protection for each planning unit. In this study, cost is a climate vulnerability weight derived from CIVAT output, where PUs classified as High vulnerability receive elevated cost weights to signal higher conservation urgency. Third, spatial connectivity parameters include boundary length data between adjacent PUs and the Boundary Length Modifier (BLM), which controls the trade-off between spatial compactness and total cost. The MARXAN objective function to be minimized is: $\text{Score} = \sum \text{Cost} + (\text{BLM} \times \sum \text{Boundary}) + \sum (\text{SPF} \times \text{Shortfall})$. Three analytical scenarios will be executed, as described in Table 2.

Table 2. MARXAN Analytical Scenarios

Scenario	Description	Cost Input	Conservation Features	Purpose
S1	Baseline – current KKPD zoning	Uniform cost (existing zone boundaries)	Coral reef, Sea turtle, mangrove	Reference / comparison benchmark
S2	Ecological optimization (no climate input)	Socioeconomic opportunity cost only	Coral reef, Sea turtle, mangrove, fish richness	Test ecological-only optimization; isolate climate contribution
S3	Climate-resilient optimization (CIVAT-weighted)	Socioeconomic cost + CIVAT vulnerability weight	Coral reef, Sea turtle, mangrove, fish richness + climate refugia	Primary output: climate-resilient zoning recommendation

Results and Discussion

This study, currently in its proposal and data collection preparation phase, anticipates four primary outputs upon completion. First, a Spatial Vulnerability Map of the Pulo Aceh coastal zone will be produced, classifying each planning unit as Low, Medium, or High vulnerability to climate change. It is hypothesized that the western coastlines of Pulau Breuh facing the Indian Ocean will exhibit higher exposure scores, while mangrove-fringed areas may demonstrate higher adaptive capacity, resulting in heterogeneous vulnerability patterns across the island complex.

Second, the analysis will identify dominant vulnerability drivers in Pulo Aceh. Based on existing literature, sea level rise rate and extreme wave height are expected to be the primary exposure factors, while reef platform width and mangrove continuity are expected to be critical sensitivity parameters given their documented protective function.

Third, MARXAN will produce an optimized climate-resilient zoning recommendation for KKPD Aceh Besar. A comparison between current zoning (Scenario 1) and climate-resilient zoning (Scenario 3) is expected to reveal spatial mismatches—areas currently zoned as utilization zones that may warrant stricter protection given high climate vulnerability, and vice versa. Fourth, the study will produce a documented CIVAT-MARXAN methodological framework with standardized protocols for data collection, parameter scoring, and optimization parameterization, designed for replication in other Indonesian small island conservation areas. This framework is intended to support the achievement of Indonesia's 30×30 marine conservation commitment.

Conclusion

This paper presents the conceptual and methodological framework for developing climate-resilient marine protected area zoning in Pulo Aceh, Aceh Besar, through the integration of CIVAT vulnerability assessment and MARXAN spatial optimization. The existing KKPD Aceh Besar zoning was designed primarily to address anthropogenic pressures and does not explicitly incorporate climate resilience criteria—a significant gap given the region's elevated sea level rise rates and small island characteristics. The proposed CIVAT-MARXAN integration offers a methodologically novel and contextually appropriate solution. CIVAT provides a spatially explicit, multi-component vulnerability assessment validated for Southeast Asian contexts, while MARXAN provides mathematically rigorous spatial optimization capable of incorporating the vulnerability outputs as planning inputs. Together, they enable the identification of conservation zones that are not only ecologically important but also resilient to future climate conditions. As a work in progress, this study will contribute both a practical zoning recommendation for KKPD Aceh Besar and a generalizable methodological framework for climate-adaptive marine conservation planning applicable across Indonesia's extensive small island estate. The research directly supports national and international commitments to marine conservation under climate change.

References

- [1] Kementerian Kelautan dan Perikanan. Kebijakan Kelautan Indonesia: Target Konservasi Laut 2030. Jakarta: KKP; 2024.
- [2] Tursina, Afrizal S, Sari DP. Sea level rise analysis in Banda Aceh coastal area. *J Ocean Eng.* 2021;10(2):45-58.
- [3] Bruno JF, Bates AE, Cacciapaglia C, et al. Climate change threatens the world's marine ecosystems. *Science.* 2018;319(5): 1737-1742.
- [4] Magris RA, Pressey RL, Weeks R, Ban NC. Integrating connectivity and climate change into marine conservation planning. *Biol Conserv.* 2014;170:207-221.
- [5] Muliari. Pemulihan terumbu karang Pulo Aceh pasca tsunami 2004. Banda Aceh: Universitas Syiah Kuala; 2011.
- [6] Calvin K, Ciaia P, Pan W, et al. IPCC, 2023: Climate Change 2023. Cambridge University Press; 2023.
- [7] Bruno JF, et al. Climate change threatens the world's marine ecosystems. *Curr Biol.* 2018;28(11):1–6.
- [8] Siringan FP, Sta. Maria MYY, Soria JLA, Abon CC. Coastal Integrity Vulnerability Assessment Tool (CIVAT). Quezon City: Marine Environment and Resources Foundation; 2013.
- [9] Licuanan WY, Reyes MZ, Maypa AP. Vulnerability of Philippine coral reefs to climate change. *Philipp Sci.* 2015;52(1):1-22.
- [10] Wahab MA, Ahmad A, Saleh E. Application of CIVAT in Malaysian coastal management. *Coast Manage.* 2022;50(3):210-228.
- [11] Watts ME, Ball IR, Stewart RS, et al. Marxan with Zones: Software for optimal conservation based land- and sea-use zoning. *Environ Model Softw.* 2017;24(12):1513-1521.
- [12] Ball IR, Possingham HP. MARXAN v1.8.2: Marine Reserve Design Using Spatially Explicit Annealing. 2000. Available from: <http://www.uq.edu.au/marxan>