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Balancing wetland conservation under disease risk in Indonesia: A spatial MCDA approach

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Abstract.
Wetlands provide essential ecosystem services but can also serve as breeding habitats for disease vectors such as mosquitoes, creating complex challenges for conservation planning. Indonesia has extensive wetlands and high malaria incidence, requiring conservation strategies that integrate both ecological and health considerations. This study implements a spatial Multi-Criteria Decision Analysis (MCDA) framework to support wetland conservation planning by integrating ecological benefits and vector-borne disease risk. The analysis integrated eight criteria using literature-informed weighting across 94.6% of Indonesia's wetland areas. Results reveal that conservation and health factors operate largely independently ($r=0.099$, $p < 0.001$), suggesting minimal trade-offs between objectives. The findings demonstrate that wetland conservation and health objectives are compatible in most regions, enabling strategies that optimize ecological outcomes without systematically increasing disease exposure. Papua is noted as a region of interest, being the main region where high ecological value does coincide with elevated disease risk. The framework supports conceptualizing wetlands as Nature-based Solutions that simultaneously deliver conservation and public health benefits, providing practical guidance for Indonesian policymakers and a replicable template for other tropical regions facing similar conservation-health challenges.

1. Introduction

Wetlands are globally recognized as ecologically diverse and hydrologically dynamic ecosystems that provide critical ecosystem services, including flood regulation, carbon sequestration, water purification, and biodiversity conservation (Ramsar Convention on Wetlands, 2018). Wetlands exemplify Nature-based Solutions (NBS) by protecting, sustainably managing and restoring natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits (Anon, 2020). These ecosystems support diverse flora and fauna while also playing a crucial role in climate regulation and water management (Dinsa and Gemeda, 2019; Ferreira et al., 2023). However, NBS such as wetlands could pose significant public health challenges simultaneously as breeding grounds for vector-borne diseases (VBDs) such as malaria, West Nile virus, Ross River virus, and dengue (Carver et al., 2015; Dale and Knight, 2008; Krol et al., 2024). These environments offer ideal conditions for mosquito proliferation due to the presence of stagnant

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

or slow-moving water, dense vegetation, and warm microclimates that support larval development (Catry et al., 2018; Dale and Knight, 2008). However, wetlands can also help reduce disease risk when well-managed, by supporting predator species that feed on mosquito larvae or by facilitating water flow that disrupts breeding cycles (Carver et al., 2015; Dale and Knight, 2012). Thus, the relationship between wetlands and disease is context-dependent, influenced by ecological characteristics and human interventions.

Rapid environmental change is intensifying these interactions. Climate change, land-use changes, and urban expansion are transforming wetland ecosystems, thus exacerbating the risks of VBDs (Dale and Knight, 2008; Franklinos et al., 2019; Ma et al., 2022). Climate extremes can extend mosquito breeding seasons and expand their geographic range, while altered precipitation patterns have complex effects on disease transmission (Franklinos et al., 2019; Ma et al., 2022). Floods initially wash away mosquito larvae and eggs from breeding sites, but the stagnant water pools remaining after flood recession provide ideal breeding habitats for mosquitoes. Conversely, when wetlands experience droughts, mosquito populations can suddenly explode as their predators and competitors are eliminated, leading to increased risk of mosquito-borne disease spillover (Ma et al., 2022). Additionally, human-driven landscape modifications, including land-use change and deforestation driven by socio-economic development, often result in wetland degradation, biodiversity loss, and create fragmented landscapes that can enhance vector-human contact (Xiong et al., 2023). The increasing encroachment of human populations into wetland areas can intensify exposure to disease vectors, further complicating wetland conservation efforts and public health management (Carver et al., 2015; Dworrak et al., 2022; Horwitz and Finlayson, 2011). These interconnected challenges have led World Health Organization (2019) and UNDRR (2021) to call for more comprehensive understanding that integrates disasters, diseases, and adaptation strategies.

Indonesia represents a critical case study for addressing these intertwined challenges. The country contains approximately 39.6 million hectares of wetlands (approximately 21% of its land area), including mangroves, peatlands, and coastal swamps that are vital for biodiversity, carbon storage, and water provision (Margono et al., 2014). Simultaneously, Indonesia faces one of the highest VBD burdens in Southeast Asia, with disease hotspots concentrated in wetland-rich regions such as Papua, West Papua, and East Nusa Tenggara (Aisyah et al., 2024; Marina et al., 2023). The interplay between wetland hydrology, human settlements, and vector habitats makes these areas particularly vulnerable to outbreaks of VBDs (Mulyaningsih, 2024). Development pressures, including rapid urbanization, land-use conversion, and population growth, increasingly threaten wetland integrity and further complicate disease control (Surendra et al., 2024).

Previous research has established that wetlands can serve dual purposes when properly managed, providing ecosystem services while helping control mosquito populations and reducing disease transmission risk through approaches such as restoring natural hydrological flow, introducing native predator species, and optimizing land-use zoning (Dale and Knight, 2012;

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

Fournet et al., 2024; de Jesús Crespo et al., 2019). Frameworks such as One Health[1] and Nature-based Solutions (NBS) emphasize the interconnectedness of human, animal, and environmental health, highlighting the need for cross-sectoral strategies that preserve ecological integrity while mitigating disease emergence (Anon, 2020; Lebov et al., 2017). However, despite these conceptual advances, a critical research gap remains: current conservation policies in Indonesia lack systematic tools to weigh ecological benefits against public health risks, and most strategies fail to account for the spatial variability of disease exposure or incorporate multi-dimensional planning frameworks (Mulyaningsih, 2024).

To address this gap, this study implements an interdisciplinary approach that integrates Multiple-Criteria Decision Analysis (MCDA) with Geographic Information Systems（GIS）. While spatial MCDA is an established methodology, the novelty of this study lies in the systematic integration of vector-borne disease risk into wetland conservation planning. The vector-borne disease risk assessment model considers hazard factors (environmental and climatic conditions facilitating disease transmission), exposure factors (degree of human-environment contact), and vulnerability factors (socio-economic conditions influencing disease impact and recovery capacity). This conceptualisation of risk, widely adopted in climate and disaster risk assessment, allows for a holistic definition of disease risk beyond simple incidence rates (Field et al., 2012; Hongoh et al., 2011). These risk components are then spatially modelled and combined with ecological benefits using the MCDA framework to identify optimal conservation strategies that maximize ecological benefits while minimizing vector-borne disease risk, thereby informing evidence-based policy decisions for sustainable wetland management in Indonesia and similar tropical contexts worldwide.

2. Methods

2.1 Research Design and Data Collection

The study area encompasses the entire Indonesian archipelago, covering all wetland ecosystems within the country's territorial boundaries. The analysis was conducted at a national scale to capture the full spectrum of environmental gradients and socio-economic conditions present across Indonesia's diverse island geography.

The methodological approach consists of three interconnected phases: (1) comprehensive spatial data collection and preparation, (2) Spatial Multi-Criteria Decision Analysis using weighted overlay analysis, and (3) wetland conservation prioritization through scenario-based modelling. This framework (shown in Figure 1) enables the integration of diverse datasets into a unified decision-support tool for evidence-based wetland management.

[1] One Health is a global strategy highlighting the need for an approach that is holistic and transdisciplinary and incorporates multisector expertise in dealing with the health of mankind, animals, and ecosystems (Destoumieux-Garzón et al., 2018).

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

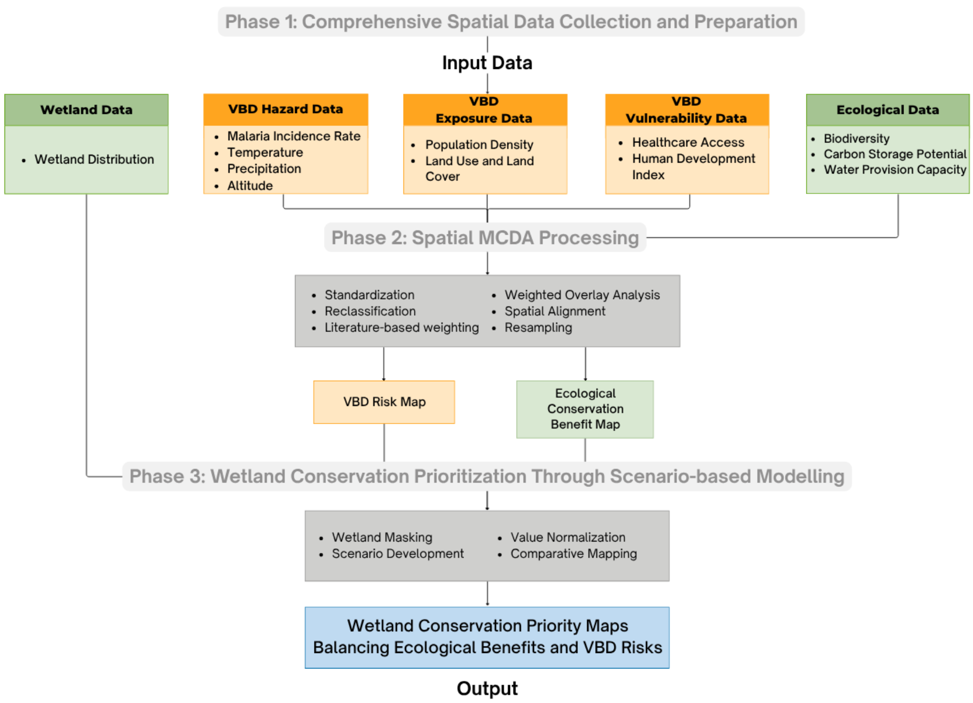

Figure 1. Methodology flowchart

The analysis integrates eleven key open-access datasets representing three primary categories within a comprehensive risk framework: hazard factors, exposure factors, and vulnerability factors, along with ecological conservation indicators. Data selection was guided by established criteria from literature review, ensuring both scientific validity and practical applicability for conservation planning in Indonesia's diverse environmental contexts. This comprehensive dataset covers multiple temporal periods and spatial resolutions, requiring systematic data integration processes. Table 1 presents the complete data inventory, including the spatial and temporal characteristics, data format, and original sources for each criterion.

Table 1. Criteria data collection

Data Category	Criteria	Year	Resolution	Format	Source
Land Layers	Wetland distribution	2016	231 m	raster	(Gumbricht et al., 2024)
	Indonesia map	-	Administrative level 0-2	vector	(GADM, 2025)

Hazard Factors	Estimated malaria incidence rates	2000-2022 (sub-natinal)	5x5 km	raster	(Malaria Atlas Project | Data, 2025)
	Elevation	2019	90 m (3 arc-second)	raster	(Jarvis, A. et al., 2008)
	Temperature	2000-2019 (CRU model)	0.5° latitude x 0.5° longitude	raster	(Copernicus Climate Change Service, 2021)
	Precipitation				
Exposure Factors	Population Density	2020	1 km	raster	(WorldPop, and Bondarenko, 2020)
	Land use and land cover	2000-2020	30m (1 arc-second)	raster	(Potapov et al., 2022)
Vulnerability Factors	Healthcare access	2020	1 km	raster	(Weiss et al., 2020)
	Human Development Index (HDI)	2022-2024	Administrative level 2	xlsx/csv	(Nations, n.d.)
Ecological Benefits	Biodiversity	2021	10 km	raster	(Jung et al., 2021)
	Carbon storage potential				
	Water provision capacity				

2.3 Data preprocessing and standardisation

Following data acquisition, all raw data layers were clipped to Indonesia's territorial extent and underwent an initial quality assessment and preprocessing. Visual inspection of the data revealed minimal data gaps in most datasets, with only climate data (temperature and precipitation) showing reduced spatial coverage after clipping to Indonesia's territorial boundaries due to global dataset interpolation limitations in archipelagic regions. In preparation for the weighted overlay, the data layers were spatially and temporally aligned. Spatial standardization involved reprojecting all datasets to WGS84 (EPSG:4326) while maintaining their original spatial resolution for initial processing and analysis, and temporal alignment was achieved by using

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

the most recent year available for each dataset, with multi-year datasets (such as malaria incidence) averaged across the available time period.

This preliminary processing stage generates intermediate maps for each criterion, displaying the original spatial patterns of vector-borne disease risk factors and ecological benefits across Indonesia's diverse landscapes. These intermediate maps serve multiple analytical purposes: they enable visual inspection of data quality and coverage, reveal initial spatial relationships between different factors, and provide a baseline understanding of individual criterion distributions before standardization procedures. The intermediate mapping stage is essential for validating data integrity and establishing the geographic foundation for subsequent MCDA integration, ensuring that spatial inconsistencies and data limitations are identified and addressed before proceeding to the standardization and weighting phases.

To enable integration of diverse measurement units and scales, all criteria were standardized to common 0-1 scales using literature-informed normalization functions. The standardization approach varies by data type and relationship to malaria transmission risk or ecological conservation value, with specific threshold values and functional forms determined through comprehensive literature review and regional evidence (detailed parameters are provided in Appendix A). For example, temperature standardization employs a bell-shaped function reflecting experimental evidence on optimal malaria transmission temperatures at 25-26°C (Mordecai et al., 2013; Shapiro et al., 2017), while elevation standardization incorporates Indonesia-specific research showing increased malaria risk at 500-1000 meters with significant decline above 1200 meters (Rejeki et al., 2021a).

2.4 Spatial MCDA: Integrating Disease Risk and Ecological Benefits

Multi-Criteria Decision Analysis can employ either compensatory or non-compensatory approaches (Guitouni and Martel, 1998; Malczewski, 1999). Compensatory methods allow poor performance on one criterion to be offset by good performance on others through weighted aggregation, while non-compensatory methods apply strict thresholds where certain minimum requirements must be met regardless of other factors' performance (Guitouni and Martel, 1998).

This study employs a compensatory MCDA approach using weighted overlay analysis. This is appropriate for disease risk assessment, where multiple pathways can contribute to or mitigate transmission risk. However, the analysis incorporates non-compensatory elements through spatial masking, where conservation prioritization is restricted exclusively to mapped wetland areas, ensuring that non-wetland areas cannot achieve high conservation priority regardless of other factor scores. This hybrid approach balances analytical flexibility with logical constraints based on the study's wetland conservation focus.

The disease risk weighting scheme integrates hazard, exposure, and vulnerability factors using literature-informed weights adapted to reflect Indonesia's specific environmental and socio-economic context. Hazard factors receive 40% of total disease

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

risk weight, with malaria incidence receiving the highest individual weight (25%) reflecting empirical disease evidence, followed by elevation suitability (15%), temperature suitability (6%), and precipitation suitability (4%). Exposure factors account for 25% of disease risk total, distributed between population density (15%) and land use land cover (10%). Vulnerability factors comprise the remaining 25%, with healthcare access vulnerability (15%) and Human Development Index (10%).

This weighting structure emphasizes empirical disease evidence (malaria incidence) while incorporating environmental, socio-economic, and climatic modifiers. Climate factors receive lower weights (10% combined) as they primarily modify rather than determine disease transmission patterns in this analysis context. Moreover, temperature and precipitation show strong correlations with elevation in Indonesia's tropical archipelago, where multicollinearity between climate variables and elevation has been documented (Pradhan and Setyawan, 2021; World Bank Group and Asian Development Bank, 2021). The use of multi-year averaged climate data (2000-2019) further smooths out inter-annual climate extremes and seasonal variations, preventing multicollinearity effects that could overweight essentially similar environmental gradients. Temperature and precipitation variables are retained to capture regional spatial variations that influence local malaria transmission dynamics, as demonstrated in Indonesian studies showing significant associations between these climate variables and malaria incidence patterns (Hasyim et al., 2018; Rejeki et al., 2018).

The weighted overlay analysis integrates standardized criteria layers using the formula:

$$\textbf{Risk Score} = \Sigma(\textbf{Wi} \times \textbf{Si}) \quad (1)$$

Where Wi represents the weight for criterion i, and Si represents the standardized score for criterion i at each spatial location.

Prior to weighted overlay analysis, all standardized criteria layers were resampled to a common 0.02° resolution (approximately 2.2 km) using bilinear interpolation to ensure geometric consistency across all input layers. Climate data layers showed incomplete coverage within Indonesia boundaries due to global dataset interpolation limitations in archipelagic regions. During the overlay process, missing climate values were filled using nearest neighbour interpolation to ensure complete spatial coverage for the MCDA analysis. The overlay process then employs pixel-by-pixel calculations across the 385,265-pixel Indonesian raster, producing a continuous disease risk surface with values ranging from 0 (lowest risk) to 1 (highest risk).

Parallel to the disease risk assessment, we constructed a composite Ecological Benefit Index by integrating biodiversity significance, carbon storage potential, and water provision capacity (as detailed in Table 1). These ecological criteria were similarly standardized and aggregated to create a continuous surface representing conservation value. The final stage of the framework integrates these two distinct components, the Disease Risk Index and the Ecological Benefit Index. A binary mask was applied to constrain the analysis to wetland areas, after which the two indices were combined to drive the scenario-based prioritization described in the following section.

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

2.5 Scenario Design and Sensitivity Analysis

Three conservation scenarios were developed using different weighting approaches to balance ecological conservation objectives with vector-borne disease risk mitigation: a risk-minimized scenario (30% ecological weight, 70% risk weight) prioritizing areas where disease risk reduction is paramount; a balanced scenario (50% ecological weight, 50% risk weight) equally weighting conservation and health objectives; and a conservation-optimized scenario (70% ecological weight, 30% risk weight) emphasizing ecological value with health considerations.

The priority index calculation follows:

$$\textbf{Priority} = \left(\textbf{Ecological}_{\textbf{Weight}} \times \textbf{Ecological}_{\textbf{Benefit}}\right) + \left(\textbf{Risk}_{\textbf{Weight}} \times \textbf{Disease}_{\textbf{Risk}}\right) \quad (2)$$

Higher disease risk increases conservation priority, reflecting the principle that areas requiring both ecological protection and health intervention warrant urgent attention through NBS.

Sensitivity analysis evaluated framework robustness through comparison of the three weighting scenarios, with geographic consistency assessed by examining whether priority areas remain stable across different weighting approaches, indicating robust identification of critical conservation zones. Pearson correlation analysis examined the relationship between ecological benefits and disease risk within wetland areas only (n = 21,949,553 pixels), testing whether wetland conservation objectives conflict with health considerations and providing empirical evidence for policy development. Spatial coverage assessment documented that the analysis achieved 94.6% coverage of Indonesian wetland areas, meaning complete MCDA calculation was possible for 94.6% of wetland pixels, providing robust spatial representation for national-scale wetland conservation planning.

3. Results

3.1 Spatial Distribution Patterns

Indonesia possesses approximately 39.6 million hectares (21% of its land area) of diverse wetland ecosystems distributed across its archipelago (Margono et al., 2014). The wetland distribution map (shown in Appendix B, Figure B1 illustrates the spatial distribution of different wetland types throughout the country, revealing pronounced regional patterns that reflect the archipelago's diverse geological, hydrological, and climatic conditions.

The wetland classification follows the original categories from the Gumbricht et al. (2017) dataset, which identifies wetland types based on hydrological and ecological characteristics. The map shows that wetlands in Indonesia are not evenly distributed, with notable concentrations in three primary regions: Sumatra, Kalimantan, and Papua (Indonesia's province division shown in Appendix B, Figure B2). This baseline wetland distribution provides the fundamental spatial framework for

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

all subsequent analyses, defining the geographic scope for overlaying vector-borne disease risk factors and ecological benefit assessments. The diverse wetland types and their distinct regional distributions create varied contexts for conservation planning, where different wetland systems may present different combinations of ecological benefits and health considerations. These mapped wetland areas represent the specific ecosystems where conservation planning must balance ecological protection objectives with public health considerations, establishing the spatial foundation for evidence-based wetland management strategies that account for both conservation value and disease risk dynamics.

Following the baseline geographic overview, the standardized surfaces (shown in Appendix B, Figure B3) show how each factor contributes to vector-borne disease transmission risk, which enables direct comparison and integration into the MCDA framework. All factors are normalized to 0-1 scales, where higher values indicate greater contribution to disease risk. The ecological benefits are also standardized to 0-1 scale, showing the ecological conservation potential across Indonesia (see Appendix B, Figure B4).

3.2 Multi-Criteria Risk Assessment

The eight standardized risk factors were integrated using a weighted overlay approach with scientifically informed weights: malaria incidence (25%), healthcare access vulnerability (15%), elevation suitability (15%), population density (15%), land use change (10%), Human Development Index (10%), temperature suitability (6%), and precipitation suitability (4%). This weighting scheme prioritizes empirical disease evidence while incorporating environmental and socio-economic modifiers. The integration of risk factors achieved comprehensive coverage across Indonesia, with valid risk scores calculated for 99.8% of Indonesian territory (384,665 out of 385,265 pixels). This extensive coverage provides a robust spatial representation for national-scale wetland conservation planning applications.

The final risk factors overlay reveals distinct geographic patterns in vector-borne disease risk across Indonesia's wetland areas (Figure 2). The integrated risk assessment demonstrates clear spatial heterogeneity that reflects the complex interactions between environmental, demographic, and socio-economic factors driving disease transmission potential.

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

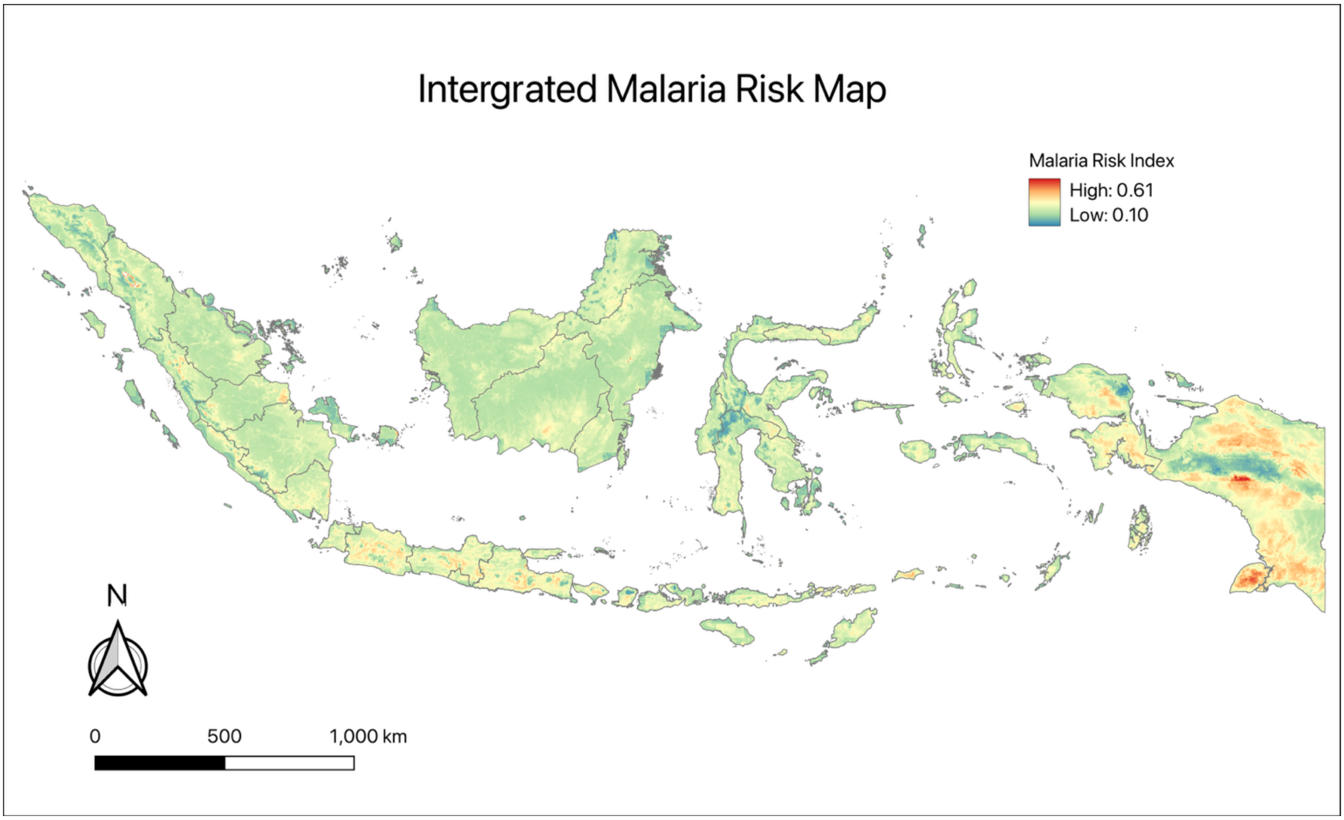

Figure 2. Integrated Malaria Risk Map from MCDA Analysis

Risk Distribution Summary

The spatial analysis reveals that 4.3% of analysed areas fall within the very low risk category (≤0.2), 91.4% of areas show low risk (0.2-0.4), while 4.3% show moderate risk (0.4-0.6), and only 0.008% exhibit high risk levels (>0.6). This distribution indicates that while most of Indonesia maintains relatively controlled disease risk levels, specific geographic areas require targeted attention for health intervention.

Geographic Risk Analysis

Geographically, the integrated risk surface confirms a pronounced east-west gradient consistent with known disease patterns, where Eastern provinces consistently show elevated risk scores while western regions maintain lower overall risk levels (Aisyah et al., 2024; Djaafara et al., 2025).

The very low risk areas (shown in blue) are primarily concentrated in high mountain forest areas of central Papua, West Papua, central Sulawesi, and northern Sumatra, where elevation limits parasite development. However, the compensatory MCDA method increases risk scores in these areas by incorporating exposure and vulnerability factors, preventing them from achieving the theoretical minimum risk values. Interestingly, when comparing the malaria incidence risk surface with the elevation risk surface, actual disease transmission has been documented in some high mountain areas even before adding

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

compensatory elements. This pattern reflects emerging transmission dynamics involving deep forest workers engaged in mining, logging, and agricultural activities in remote areas, who often spend weeks to months at work sites far from settlement areas, creating new exposure pathways that transcend traditional elevation-based transmission barriers (Ekawati et al., 2020). In peri-urban and urban areas of Java, southern Sumatra, and southern Sulawesi, risk scores increase to low-moderate levels (shown as yellow in the map). This increased results from the compensatory integration of high exposure factors, particularly population density and land use change patterns that create new human-vector contact opportunities. These findings align with Djaafara et al. (2025), who identified a steadily rising proportion of malaria cases in males and adults across the four lowest endemicity regions (Java and Bali, Sumatra, Sulawesi, Kalimantan), attributed to similar occupational exposure patterns involving forest work and land conversion activities. The MCDA results thus confirm emerging concerns about new disease transmission pathways driven by land use change and migrant worker populations in previously low-risk areas (Surendra et al., 2024), demonstrating how environmental modification can create unexpected new patterns even in regions with historically low transmission.

The highest malaria risk areas are concentrated in Papua and West Papua, where risk scores reach maximum levels despite Indonesia's successful malaria elimination progress in other regions (Aisyah et al., 2024; Djaafara et al., 2025). This persistent high-risk pattern results from the convergence of all risk factors analyzed in the MCDA framework. Papua and West Papua present a unique combination of environmental, social, and economic conditions that sustain transmission: extensive wetland and swampland areas provide ideal vector breeding grounds, communities predominantly inhabit lowland forested regions with limited infrastructure, forest-related occupational activities increase exposure opportunities, housing conditions often lack protective measures, and healthcare access remains severely constrained (Aisyah et al., 2024). The MCDA integration captures how these multiple factors compound to create Indonesia's most persistent malaria transmission zones, where environmental suitability, high exposure potential, and elevated vulnerability converge to maintain disease burden despite national elimination efforts.

In summary, the integrated risk surface reveals three distinct patterns: very low risk in high mountain areas, low-moderate risk in peri-urban zones due to land use change and population exposure, and highest risk in Papua and West Papua where all factors converge. The MCDA framework captures both traditional elevation-based transmission barriers and emerging risks from forest work and land conversion, providing a comprehensive foundation for risk-informed wetland conservation planning in Indonesia.

3.3 Wetland Conservation Prioritization

The ecological benefits assessment underwent inverse normalization to convert conservation priority rankings into benefit scores suitable for MCDA integration. Appendix B Figure B4 shows the standardized ecological benefits distribution across Indonesia, though the subsequent analysis focuses exclusively on wetland areas through spatial masking. Areas with intact, functional ecosystems receive the highest benefit scores (approaching 1.0), while areas requiring urgent conservation intervention receive lower scores.

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

The correlation analysis between ecological benefits and vector-borne disease risk across Indonesia reveals a weak positive correlation ($r = 0.099$, $p < 0.001$). This statistically significant but practically weak relationship demonstrates that ecological conservation value and disease transmission risk operate largely independently across Indonesia's diverse landscapes. The independence of these factors indicates that wetland conservation can proceed in most areas without systematic trade-offs between ecological protection and health considerations.

3.4 Scenario-Based Conservation

Three conservation scenarios (shown in Figure 3) were developed to examine how different weighting philosophies affect spatial prioritization outcomes, providing decision-makers with evidence-based options reflecting varying institutional priorities and risk tolerances.

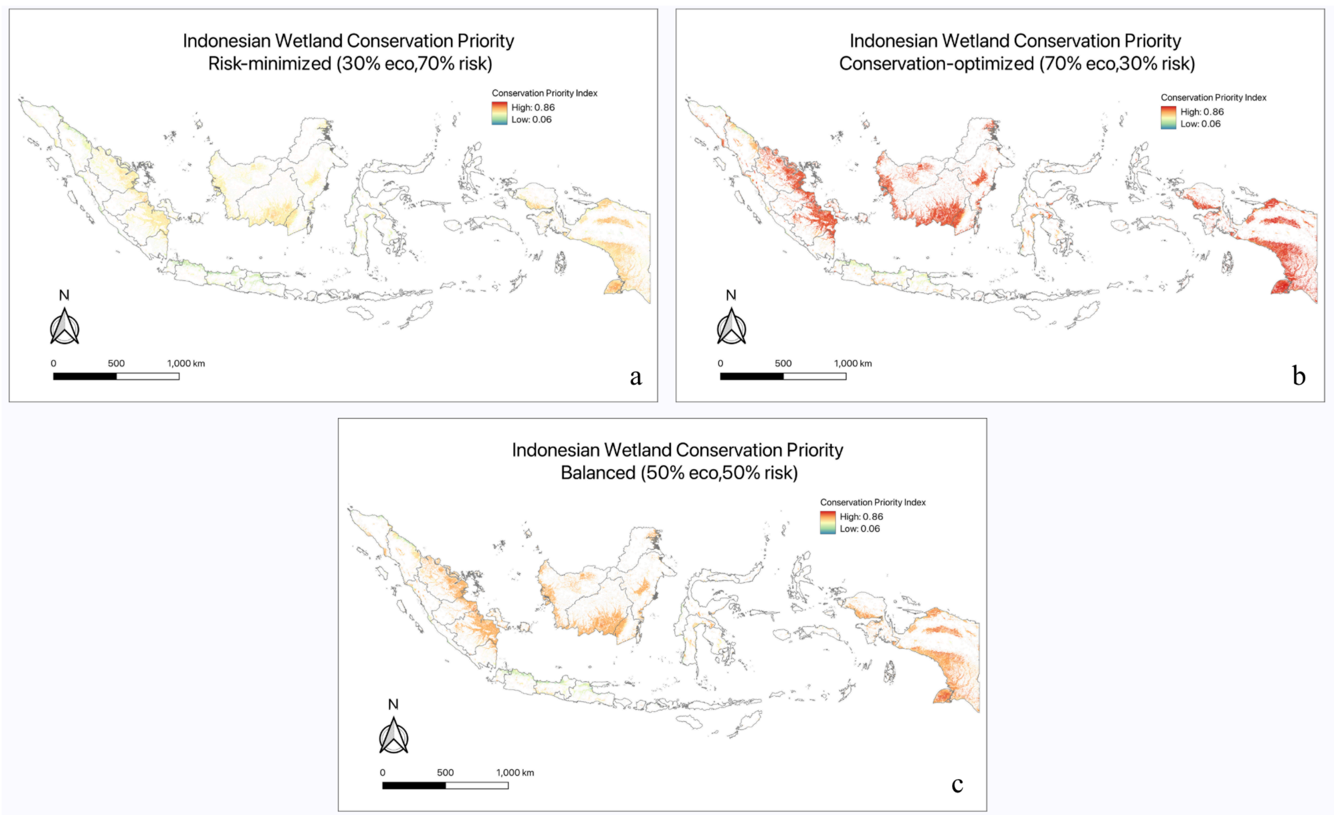

Figure 3. Three Conservation Scenarios of Indonesia Wetland Conservation Priority

Figure 3 presents the three conservation scenarios using a unified colour scale (0.06-0.86) to enable direct visual comparison, though individual scenario ranges vary as noted below.

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

Risk-Minimized Scenario (30% ecological, 70% risk weighting): This health-focused approach concentrates priorities in areas with lower disease transmission potential (shown as Figure 3a), particularly emphasizing western Indonesian wetlands where healthcare infrastructure is better developed and baseline disease risk is lower. The resulting priority distribution (range: 0.14-0.72) guides health-conscious agencies toward wetland conservation opportunities with minimal disease risk exposure.

Conservation-Optimized Scenario (70% ecological, 30% risk weighting): This approach emphasizes areas of highest ecological value regardless of health considerations (shown as Figure 3b), producing the widest priority range (0.06-0.86) and showing the strongest wetland prioritization across Papua, Kalimantan, and eastern Sumatra. This scenario supports traditional conservation planning while maintaining awareness of health dimensions.

Balanced Scenario (50% ecological, 50% risk weighting): The recommended approach provides intermediate prioritization (range: 0.10-0.78) that equally weights conservation objectives and health considerations (shown as Figure 3c). This scenario offers practical compromise solutions that acknowledge both environmental and human health as legitimate conservation planning objectives.

Scenario Comparison Insights: Despite different weighting emphases, all three scenarios identify similar geographic regions as important, indicating robust identification of key conservation areas. The primary differences occur in the intensity of prioritization within the same regions rather than completely different areas being selected as priorities. For example, Papua's wetlands consistently appear as high priority across all scenarios, but the conservation-optimized scenario assigns them higher scores (approaching 0.86) compared to the risk-minimized scenario (maximum 0.72). This suggests that the MCDA framework successfully captures fundamental conservation-health relationships while allowing flexibility for different institutional priorities.

Geographic Implications: The balanced scenario results show that the highest priority wetlands (>0.7, shown as red in the map) are mainly concentrated in Papua, reflecting the convergence of high ecological values and elevated disease risk in this region. Medium priority areas (0.5-0.6, orange in the map) are largely distributed across Kalimantan and eastern Sumatra's wetland systems. Low priority areas (0.1-0.3, green to yellow on the map) are mainly located in Java and northern Sumatra, where lower ecological values and reduced disease risk combine to create the lowest conservation urgency. This spatial distribution demonstrates that Papua's wetlands require the most immediate attention for integrated conservation-health planning, while Kalimantan and Sumatra offer important secondary conservation opportunities.

4. Discussion

4.1 Interdisciplinary Integration of Conservation and Public Health

This study demonstrates that wetland conservation and vector-borne disease prevention objectives can be effectively integrated through spatial MCDA, addressing a critical gap in conservation planning. Two key findings emerge from this analysis: the weak correlation between ecological benefits and disease risk ($r = 0.099$, $p < 0.001$), and the identification of specific priority regions for integrated conservation-health planning. The weak correlation, while statistically significant due to large sample size (n = 21,949,553), reveals a negligible effect size ($r^2 < 0.01$), indicating that ecological benefits explain less than 1% of disease risk variation. This finding demonstrates that conservation and health goals operate largely independently across Indonesia's wetland systems, governed predominantly by distinct spatial processes.

This spatial independence enables two differentiated policy pathways: in the majority of wetland areas where ecological value is high but disease risk remains low or moderate, conservation can proceed confidently without public health trade-offs; conversely, in convergence zones like Papua where high ecological value coincides with elevated disease risk, conservation planning must explicitly integrate disease risk mitigation measures, such as community-based vector management or enhanced healthcare access (Suri et al., 2025), to ensure ecological benefits do not inadvertently increase health vulnerabilities. This differentiated approach acknowledges that while conservation and health objectives are compatible at the national scale, localized contexts require tailored strategies that balance both dimensions appropriately.

These findings support the conceptualization of wetlands as Nature-based Solutions that can simultaneously address multiple societal challenges. Rather than viewing wetland conservation and disease control as competing objectives, the results demonstrate that well-planned wetland management can serve as an integrated NBS that delivers biodiversity conservation, climate mitigation through carbon storage, water provision services, flood mitigation, and public health benefits. The MCDA framework successfully integrated eight diverse criteria across 94.6% of Indonesia's wetland areas, producing robust priority classifications that balance conservation value with health considerations while enabling national-scale planning and transparent integration of multiple stakeholder priorities.

4.2 Policy Implications for Indonesia

The results provide actionable guidance for Indonesia's wetland conservation priorities within the context of the country's ambitious malaria elimination and climate action commitments. Indonesia has implemented a new malaria surveillance system that provides more accurate case reporting, though this also reveals that historical cases were likely underestimated due to inadequate previous surveillance implementation (Aisyah et al., 2024; Djaafara et al., 2025). The country has set national goals for malaria elimination by 2030 (WHO Country Office Indoneisa, 2011), and aims to reduce greenhouse gas emissions by 31.89% unconditionally and up to 43.2% with international support by 2030 (Novita et al., 2022). According to Novita et al. (2022), Indonesia could meet its Nationally Determined Contribution targets solely through wetland ecosystem conservation and restoration, presenting compelling opportunities for integrated policy approaches that link climate resilience, public health, and ecosystem protection.

The results of the balanced scenario provide a basis for a tiered strategy in resource allocation by highlighting areas where protection and health needs intersect most strongly. High-priority areas like Papua are defined by the convergence of high biodiversity and high disease burden, require intensive integrated conservation-health programs with substantial funding and

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

coordination between agencies. Medium-priority areas in Kalimantan and Sumatra can receive moderate investment focused on monitoring and targeted interventions. Lower-priority areas can be managed with basic conservation measures and routine surveillance, allowing agencies to match their investment levels to local conditions and available resources.

In Papua, where the highest disease risk coincides with exceptional ecological value, integrated conservation-health programs must address specific regional challenges. Despite limited formal healthcare facilities, local populations often prefer private clinics over official healthcare systems, leading to underreporting of malaria cases and inadequate treatment protocols (Aisyah et al., 2024). The primary affected demographic in Papua consists of children aged 0-4 years (Djaafara et al., 2025), requiring targeted interventions that combine wetland conservation with child health programs and community-based healthcare improvements.

However, the national-scale compatibility between malaria control and wetland conservation requires careful local implementation. While the framework demonstrates that these objectives can be mutually supportive at the landscape level, targeted and grounded work must be undertaken by local governments and communities to address specific regional contexts, community needs, and environmental conditions that may not be captured in national-scale analyses.

4.3 Global Relevance and Applicability

This study addresses a critical global gap in conservation science by demonstrating systematic integration of disease risk into ecosystem conservation planning. The methodology provides a replicable framework for other tropical regions facing similar wetland conservation challenges combined with vector-borne disease burdens, including areas in Africa, South America, and Southeast Asia where malaria, dengue, and other vector-borne diseases pose significant public health challenges (World Health Organization, 2017).

The approach contributes to advancing One Health implementation by providing practical tools for environmental and health sector coordination, moving beyond theoretical concepts toward operational decision-support systems. The framework's modular design enables adaptation to different disease contexts and ecosystem types across diverse geographic settings, while the transparent weighting approach and scenario analysis methodology provide templates for participatory planning processes that incorporate local stakeholder priorities while maintaining scientific rigor.

4.4 Limitations and Future Research

Several methodological and conceptual limitations must be acknowledged. The temporal snapshot approach, while providing robust national-scale patterns, represents averaged conditions across approximately 20 years and may overlook important regional changes in disease transmission and environmental conditions. The 2.2 km spatial resolution, appropriate for national planning, may not capture fine-scale ecological or epidemiological processes relevant to local management decisions.

Moreover, the framework's focus on P. falciparum malaria may not fully represent disease risks from other vector-borne diseases prevalent in Indonesia, such as P. vivax, P. knowlesi, and dengue, which utilize different habitat types and exhibit distinct transmission dynamics (Djaafara et al., 2025; Ekawati et al., 2020). The framework currently utilizes historical climate averages to define risk, which may smooth some extreme climate variations; however, as it is known that climate change impacts disease transmission (Chaturvedi and Dwivedi, 2021; Leedale et al., 2016; Suri et al., 2025), future research should incorporate forward-looking climate projections to further enhance long-term planning relevance. The ecological benefits assessment prioritizes current ecosystem quality, potentially undervaluing restoration opportunities in degraded areas.

Future research should extend the framework to other vector-borne diseases prevalent in specifically in Indonesia's wetland regions but also elsewhere where human settlements are encroaching wetlands, incorporate temporal analysis with seasonal disease dynamics and climate variability, and include cross-regional validation in other tropical (Sairam and de Ruiter, 2025). Despite these limitations, the framework provides substantial improvements over traditional conservation planning that typically ignores disease risk factors entirely, offering significant advantages over ad hoc decision-making approaches currently employed in many conservation contexts.

5. Conclusions

This study successfully developed a spatial Multi-Criteria Decision Analysis framework that integrates wetland conservation priorities with vector-borne disease risk considerations across Indonesia's diverse archipelagic landscape. The comprehensive analysis of 21.9 million wetland pixels across 94.6% of Indonesia's wetland areas provides robust evidence for conservation planning that addresses both ecological and public health objectives.

The research reveals a weak positive correlation ($r = 0.099$) between ecological conservation benefits and vector-borne disease risk, demonstrating that these factors operate largely independently across Indonesia's wetland systems. This independence indicates that wetland conservation and health objectives are compatible, enabling flexible strategies that optimize ecological outcomes without systematically increasing disease exposure for surrounding communities. The MCDA framework successfully integrated eight diverse criteria to produce balanced priority classifications, identifying Papua as the primary convergence zone where high ecological value coincides with elevated disease risk, providing concrete spatial guidance for targeted interventions.

Methodologically, this study demonstrates the feasibility of integrating comprehensive disease risk assessment with ecological prioritization at national scales, addressing a critical gap in conservation science. The hybrid MCDA approach employed compensatory analysis at the national scale to capture complex disease transmission dynamics, while applying non-compensatory spatial constraints by restricting conservation prioritization exclusively to mapped wetland extents. This combination enabled the framework to capture complex disease transmission patterns while ensuring the analysis remained focused on wetland conservation priorities. The framework provides a replicable template for other tropical regions facing similar challenges of balancing environmental conservation with vector-borne disease prevention.

The results enable Indonesian policymakers to pursue ambitious wetland conservation targets without compromising disease control efforts. High-priority areas like Papua require intensive integrated conservation-health programs, while medium-priority regions in Kalimantan and Sumatra can receive targeted monitoring and interventions, and lower-priority areas can be managed with basic conservation measures. The framework's modular design enables extension to other vector-borne diseases and ecosystem types, supporting global scaling of integrated conservation-health planning approaches.

This research shows that wetland conservation and vector-borne disease control do not need to conflict when systematic spatial planning is used. The findings support the conceptualization of wetlands as Nature-based Solutions that simultaneously deliver biodiversity conservation, climate mitigation, water provision, and public health benefits. By providing practical tools for integrating ecological and health considerations, this study contributes to more sustainable approaches to wetland management across Indonesia's globally significant wetland ecosystems, advancing both One Health implementation and Nature-based Solutions for sustainable development.

Author contribution

YZ performed the data analysis and visualization, and prepared the original draft. NvM provided guidance on the structure and preparation of the manuscript draft. The study conceptualization was developed by all authors. MCdR and SB advised on the methodology. MCdR, SB, and NvM supervised the project and contributed to the review and editing of the manuscript.

Competing interests

MCdR is an editors of NHESS.

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Appendix

Appendix A: Standardized Parameters

Table A1. Criteria Standardization Parameters

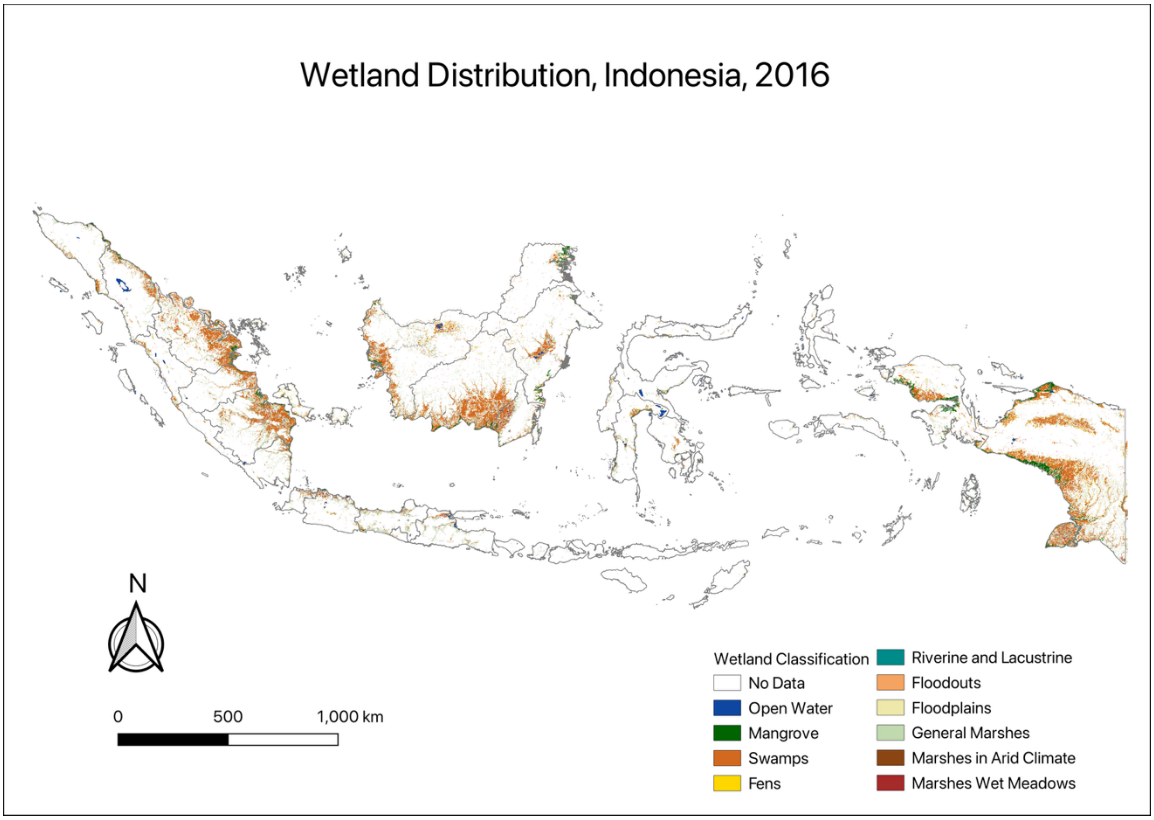
Criterion	Original Units	Function Type	Key Thresholds	Risk/Benefit Relationship	Methodological Basis
Hazard Factors					
Malaria Incidence	Cases/person/year	Linear (min-max)	Min: 0, Max: observed peak	Higher incidence = higher risk	Direct empirical relationship
Elevation	meters asl	Decreasing sigmoid	Peak: 500-1000m, Decline: >1200m, Min: >1500m	Lower elevation = higher risk	(Rejeki et al., 2021b)
Temperature	°C	Bell-shaped (Gaussian)	Peak: 25-26°C, Decline: <22°C, >28°C	Optimal range = higher risk	(Mordecai et al., 2013; Shapiro et al., 2017)
Precipitation	mm/month	Trapezoidal	Low: <60, Optimal: 150-250, Excess: >400	Moderate precipitation = higher risk	(Rejeki et al., 2018)
Exposure Factors					

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

Population Density	people/km²	Fuzzy membership	Rural: 0-400, Peri-urban: 400-800, Urban: >800	Peri-urban peak = higher risk	(Rakotoarison et al., 2020)
Land Use Land Cover	LULC categories	Categorical reclassification	Lowest (0.0): Bare/snow/ice, Low (0.1-0.3): Vegetation/forests, Moderate (0.4-0.6): Short vegetation/built-up, High (0.7): Cropland, Highest (0.8-1.0): Wetlands/water bodies	Higher vector habitat suitability = higher risk	(Gebre et al., 2020)
Vulnerability Factors					
Healthcare Access	Travel time (minutes)	Linear normalization (min-max)	Continuous 0-1 scale: (value-min)/(max-min)	Longer travel = higher vulnerability	Linear transformation preserving relative differences
Human Development Index	HDI score (0-1)	Inverse normalization	Continuous 0-1 scale: vulnerability = 1 - ((HDI-min)/(max-min))	Lower HDI = higher vulnerability	Developed for this study
Ecological Benefits					
Conservation Importance	Priority ranking (1-100)	Inverse normalization	Continuous 0-1 scale: benefit = 1 - ((priority-min)/(max-min))	Lower priority ranking = higher benefit	Inverse transtransformation

https://doi.org/10.5194/egusphere-2026-94
Preprint. Discussion started: 15 January 2026

Appendix B: Maps across Indonesia



610 **Figure B1. Spatial distribution of wetlands across Indonesia, 2016**

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Preprint. Discussion started: 15 January 2026

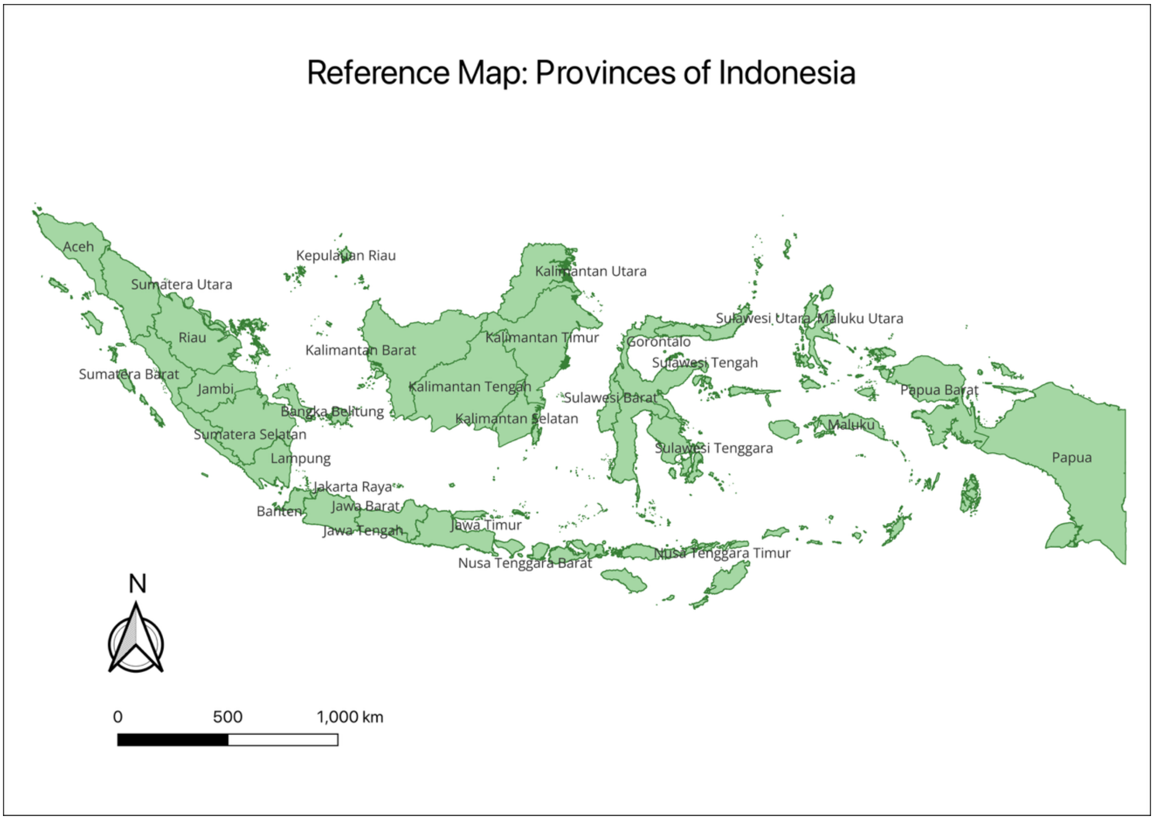

Figure B2. Reference map of Indonesia's provinces

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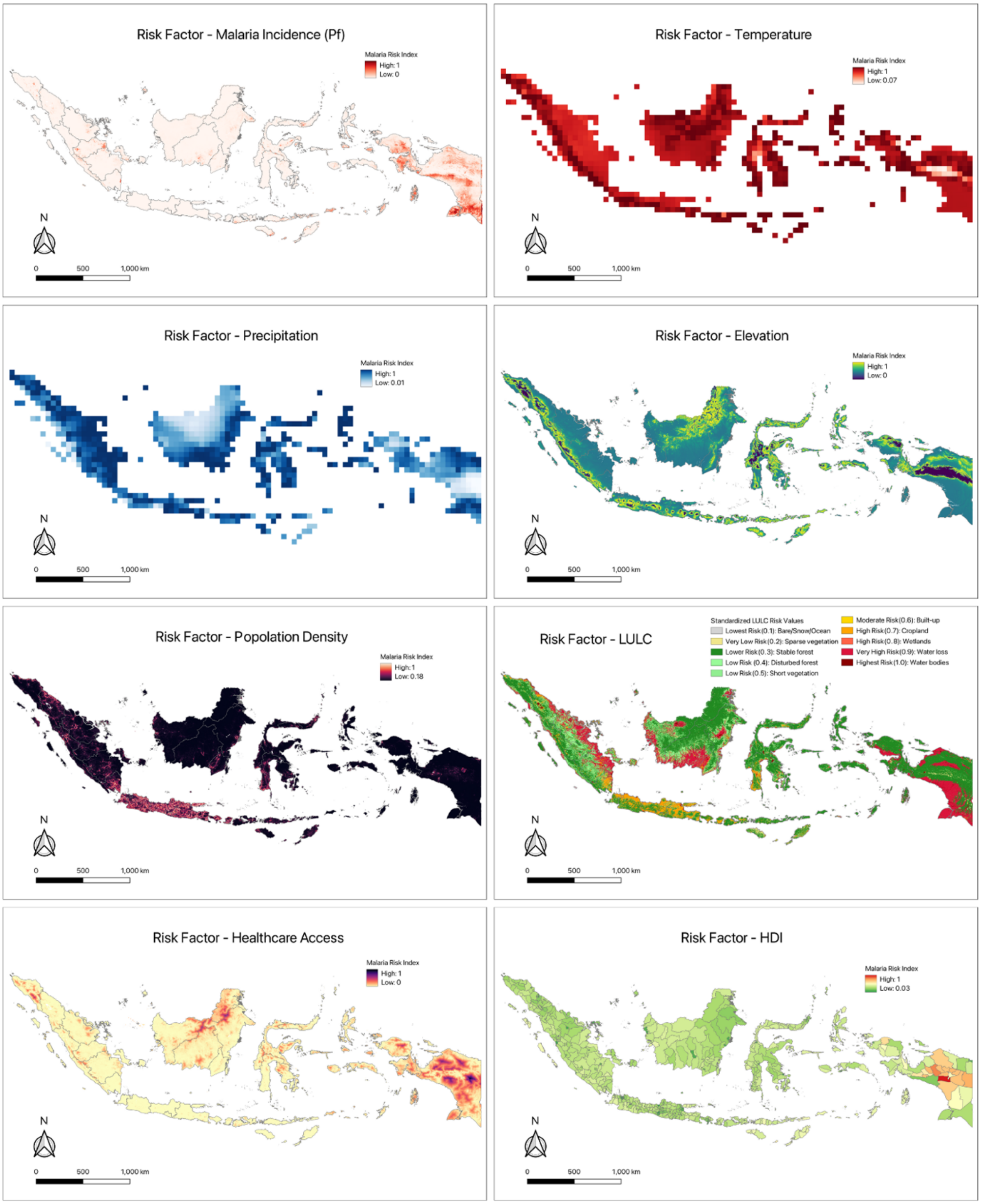
Preprint. Discussion started: 15 January 2026



615 **Figure B3. Standardized Risk Factors of Malaria in Indonesia**

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Preprint. Discussion started: 15 January 2026

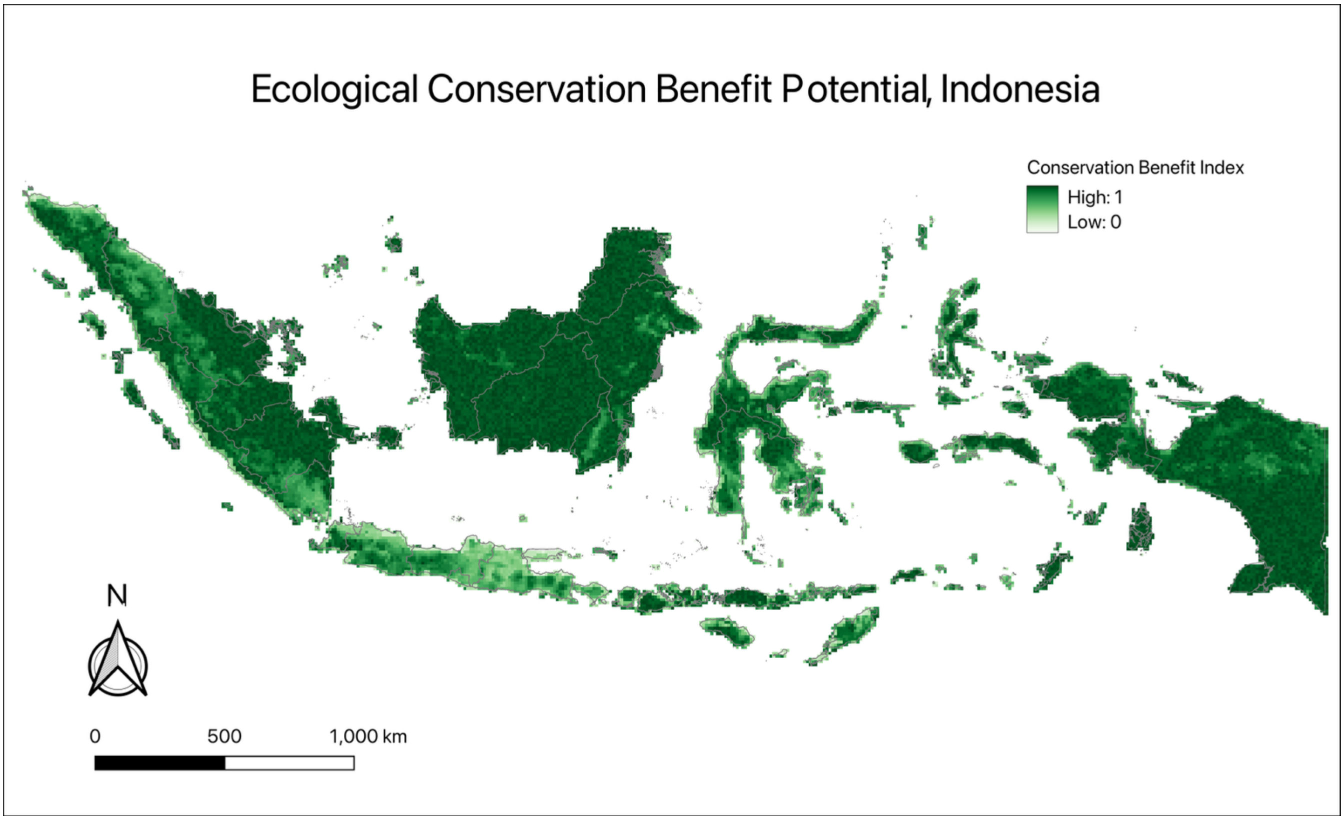

Figure B4. Standardized Ecological Benefits Distribution across Indonesia