Research Article

Suitability and Carrying Capacity Analysis for Grouper Aquaculture in the Gili Ketapang Island Marine Conservation Area, East Java, Indonesia

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Abstract | The Gili Ketapang Aquatic Conservation Area, designated as a Marine Tourism Park by the Indonesian government, encompasses 476.78 ha, including 23.50 ha allocated for aquaculture. Floating-net-cage (FNC) aquaculture of hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) is already practiced, but optimal utilization is hindered by the lack of a comprehensive suitability and carrying capacity assessment. This study evaluates the spatial suitability of the aquaculture sub-zone using Geographic Information System (GIS)-based multi-criteria evaluation and estimates the physical carrying capacity for FNC culture. Data were collected from nine sampling stations, measuring water quality parameters such as temperature, salinity, dissolved oxygen, and nutrient levels, and analyzed against established criteria for aquaculture suitability. Results indicate that 49% of the aquaculture zone (11.45 ha) is suitable for FNC systems, with an estimated carrying capacity upper limit of 336 rafts, each measuring 9×9 m. The methodology integrates GIS-based overlays and carrying capacity models, offering actionable insights for sustainable aquaculture management. This study contributes to the operationalization of the Ecosystem Approach to Aquaculture (EAA) within the Gili Ketapang, promoting balanced aquaculture expansion that respects environmental and socio-economic sustainability. The findings are significant for local aquaculture stakeholders and policymakers, providing a scientifically grounded framework for expanding sustainable aquaculture within the Gili Ketapang Marine Conservation Area while safeguarding the integrity of this critical coastal ecosystem.

Received | July 19, 2025; **Accepted** | December 05, 2025; **Published** | February 07, 2026
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Citation | Aida, G.R., I. Wirawan, M. Ramadhani, R.W. Illahi, D.M. Wildan and N.R. Caesar. 2026. Suitability and carrying capacity analysis for grouper aquaculture in the gili ketapang island marine conservation area, East Java, Indonesia. *Sarhad Journal of Agriculture,* 42(1): 247-261.
DOI | https://dx.doi.org/10.17582/journal.sja/2026/42.1.247.261
Keywords | Carrying capacity, Floating-net-cage, Spatial analysis, Gili Ketapang, Marine conservation area, Sustainable aquaculture

Introduction

Aquaculture management and fisheries science rely on key parameters such as carrying capacity, fish growth, water quality, reproductive performance, and biochemical composition to ensure sustainable production and ecological balance (Ismat *et al*., 2013; Naeem *et al*., 2016). Understanding these traits is essential for assessing fish health, optimising breeding strategies, and improving aquaculture productivity (Pervaiz *et al*., 2012). Variations in proximate and elemental composition, influenced by body size and physiological status, also determine the nutritional value and market quality of fish (Naeem *et al*., 2016). In addition, limnological characteristics strongly influence fish growth and overall aquaculture sustainability, with several studies highlighting the need to maintain suitable water-quality conditions to support fish health and development (Chughtai *et al*., 2013). Alongside these biological parameters, effective and sustainable management in marine conservation areas such as Gili Ketapang requires precise site suitability assessments and the evaluation of environmental carrying capacity, which will ensure the long-term sustainability of aquaculture practices in these regions.

Sustainable development in coastal and small-island regions hinges on effective ecosystem management, particularly through the establishment of marine conservation areas (MCAs). In the Indonesian legal framework namely Law No. 27 of 2007, as amended by Law No. 1 of 2014 conservation is defined as the protection, preservation, and responsible use of coastal resources to secure the long-term integrity of ecosystems, habitats, and biological wealth. To facilitate these functions, MCAs are divided into distinct management zones. Under Regulation of the Minister of Marine Affairs and Fisheries No. 31/2020, four primary zones are recognised: core, limited-use, rehabilitation, and “other” zones.

The Gili Ketapang Island MCA (Probolinggo Regency) exemplifies this zoning approach. Established as a Marine Tourism Park by Minister of Marine Affairs and Fisheries No. 64 of 2020, it covers 476.78 ha and comprises: (i) a 15.16 ha core zone; (ii) a 25.63 ha tourism sub-zone; (iii) a 421.93 ha sustainable-fisheries zone sub-divided into 23.50 ha for aquaculture and 398.43 ha for capture fisheries; and (iv) a 14.06 ha rehabilitation sub-zone. Within the sustainable-fisheries zone, floating-net-cage aquaculture of groupers is already practised, yet its expansion is constrained by the absence of robust assessments of site suitability and environmental carrying capacity. Sustainable practices within the fisheries zone, such as floating-net-cage aquaculture, face challenges due to a lack of suitable site assessments and an understanding of carrying capacity. For example, Liu *et al*. (2020) demonstrated the importance of assessing bivalve carrying capacities, emphasizing that maintaining aquaculture health hinges on operating within established ecological limits. Similarly, Yigit *et al*. (2021) conducted a study in Sigacik Bay, Turkey, that meticulously examined the physical carrying capacity for aquaculture sites, highlighting its critical importance for sustainable management.

Implementing the Ecosystem Approach to Aquaculture (EAA) is essential in this context to mitigate ecological risks associated with aquaculture. The EAA promotes balanced management integrating social objectives with ecological sustainability (Custódio *et al*., 2020; Suryawati *et al*., 2024). Geographic Information Systems (GIS) are pivotal in this assessment, as they provide a robust framework for the spatial analysis required to determine suitable sites for aquaculture without surpassing environmental thresholds (Stiller *et al*., 2019; Fang *et al*., 2022). Recent syntheses confirm that GIS-based multi-criteria evaluation (MCE) for aquaculture siting is expanding globally, yet applications inside biodiversity-rich conservation/MPA settings remain comparatively limited and often called for by guidance documents seeking better aquaculture–MPA integration (IUCN, 2017; Chentouf *et al*., 2023). This supports the assertion that GIS-based modelling is still underutilized in conservation zones relative to general coastal aquaculture planning. Without such planning, aquaculture expansion risks degrading water quality and fish productivity (Sanchez-Jerez *et al*., 2016). In Indonesia specifically, operationalizing EAA with transparent GIS and explicit capacity limits inside MCAs is still rare in practice, even though national policy already provides a clear zoning scaffold (Pryambodo *et al*., 2020; Indrayani *et al*., 2024; Asmara *et al*., 2025). This creates a timely opportunity to align local aquaculture development with conservation mandates through evidence-based spatial planning.

Despite the formal designation and zoning of the Gili Ketapang MCA, there is no peer-reviewed, site-specific GIS suitability assessment for floating-net-cage grouper culture, nor a quantified estimate of physical carrying capacity for candidate sites within this conservation area. Existing regional studies tend to emphasize management institutions, tourism/ecosystem valuation, or non-aquaculture siting, leaving a location-specific gap for aquaculture suitability and cage-unit limits in Gili Ketapang (Pryambodo *et al*., 2020; Indrayani *et al*., 2024; Asmara *et al*., 2025). Addressing this gap responds directly to recurring international recommendations to operationalize GIS-enabled EAA within MPAs and to set explicit ecological limits for mariculture.

Accordingly, this study pursues two specific objectives: (1) evaluate the *site-specific suitability* of the Gili Ketapang marine waters for floating-net-cage (FNC) grouper farming by integrating biophysical and oceanographic layers in a GIS framework; and (2) estimate the *physical carrying capacity* of each suitable site, expressed as the maximum sustainable number of standing FNC units, using established modelling approaches. These twin goals underpin the application of the Ecosystem Approach to Aquaculture (EAA) in the Gili Ketapang Marine Conservation Area, ensuring that any future aquaculture expansion remains ecologically sustainable while supporting long-term socio-economic benefits for local communities.

The application of a robust ecological framework, such as the EAA, supplemented by GIS technologies, is vital for advancing sustainable aquaculture practices in marine conservation areas. This integrated approach will not only enhance the capacity for effective ecosystem management but also deliver lasting socio-economic benefits to local stakeholders, significantly contributing to coastal and island sustainability.

Materials and Methods

Study area

The study was conducted within the aquaculture sub-zone (23.50 ha) of the Gili Ketapang Marine Conservation Area, Probolinggo Regency, Indonesia. The sampling locations comprised nine stations representing the outer edge of the sub-zone, the central area, and sites nearest to the island. The station positions and the coordinates of the sampling locations are shown in Figure 1 and listed in Table 1. This zone currently supports floating-net-cage culture of the cantang grouper or hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*).

Research design

The study followed a three-phase workflow, data inventory, analysis, and synthesis to (i) delineate aquaculture suitability and (ii) estimate physical carrying capacity. Suitability analysis was conducted using GIS-based overlays to evaluate the biophysical feasibility of expanding floating-net-cage (FNC) culture within the designated aquaculture zone. The carrying capacity analysis then used the suitability outputs to estimate the number of FNC units that can be supported without compromising environmental quality.

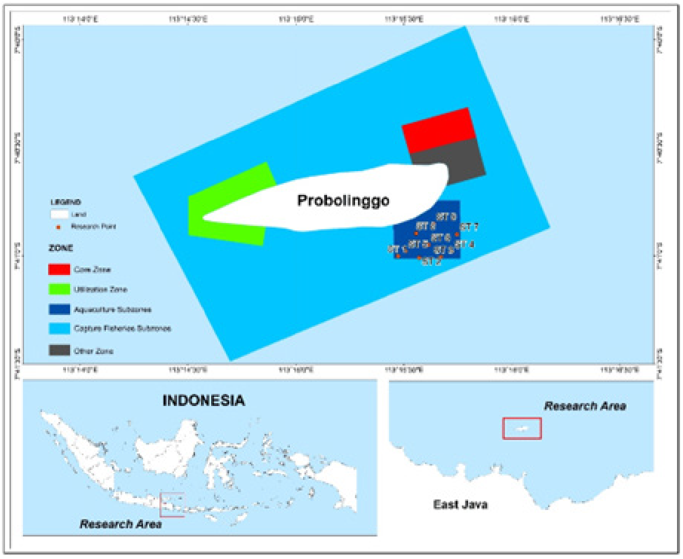

Figure 1: *Reseach location*

Table 1: *Coordinates of the observation station in the gili ketapang island aquaculture subzone*

No.	Station code	East longitude	South latitude
1	ST 1	113° 15' 28.374"	7° 41' 0.070"
2	ST 2	113° 15' 34.239"	7° 41' 0.516"
3	ST 3	113° 15' 40.325"	7° 41' 0.330"
4	ST 4	113° 15' 43.368"	7° 40' 58.734"
5	ST 5	113° 15' 30.453"	7° 40' 58.623"
6	ST 6	113° 15' 36.799"	7° 40' 56.804"
7	ST 7	113° 15' 44.741"	7° 40' 53.909"
8	ST 8	113° 15' 33.372"	7° 40' 53.661"
9	ST 9	113° 15' 38.361"	7° 40' 51.074"

Data collection

Primary data were generated at nine purposively selected sampling stations (Figure 1), located to capture representative hydro-environmental conditions as recommended by Radiarta *et al*. (2018). In situ variables included temperature, pH, salinity, brightness, current, exposure (protection), substrate type, and dissolved oxygen. At each station, all in-situ readings and water samples were collected at a fixed depth of approximately 1.0 m below the surface (±0.1 m) to standardize measurements across sites; the surface microlayer and near-bottom waters

Table 2: *Assessment of water suitability for grouper fish aquaculture locations with floating net cage system*

No.	Parameter	Weight	Highly suitable (S1)		Suitable (S2)		Not suitable (S3)	
			Class	Score	Class	Score	Class	Score
1	Current (m/s)	10	0.2-0.4	5	0.05-<0.2; >0.40-≤0.50	3	<0.05; >0.5	1
2	Depth (m)	25	>8-20	5	5-8; >20.0-≤25.0	3	<5.0; >25.0	1
3	Exposure	10	protected	5	Quite protected	3	Open	1
4	Substrate	5	Coral, sand	5	Muddy sand	3	mud	1
5	Brightness (m)	10	>5	5	3-<5	3	<3	1
6	Salinity (ppt)	5	30-35	5	20-29	3	<20; >35	1
7	Temperature (°C)	5	27-32	5	20-26	3	<20; >32	1
8	Dissolved oxygen (mg/l)	10	>5	5	3-<5	3	<3.0	1
9	pH	5	7.0-8.5	5	4.0<7.0; >8.5-≤9.0	3	<4.0; >9.0	1
10	Nitrate (mg/L)	10	0.2-0.4	5	0.02-0.19	3	<0.02; >0.4	1
11	Phosphate (mg/L)	5	0.2-0.5	5	0.004-0.19	3	<0.004; >0.5	1
Total weight x score				500		300		100

Modified from Rauf (2012), Adipu et al. (2013), Rauf (2018), and Effendi (2024)

were intentionally not sampled. Water samples were subsequently analysed for nitrate and phosphate at the Fish Health and Environment Laboratory, Marine and Fisheries Service of East Java Province, Indonesia. All measurements conformed to the Standard Methods for the Examination of Water and Wastewater 24th edition (2023). Data collection took place in November 2023, and only a single round of sampling was conducted. Secondary data comprised (i) a 1:50.000 base map supplied by the Indonesian Geospatial Information Agency and (ii) official zoning shapefiles for the Gili Ketapang MCA obtained from the East Java Provincial Marine and Fisheries Service. This integrated dataset provided the empirical foundation for spatial modelling of site suitability and for calculating the ecological carrying capacity of grouper aquaculture in the study area.

Data analysis

Water pollution index

Apart from descriptive analysis, to complement the suitability and capacity analyses, we computed a Water Pollution Index (WPI) for marine biota using Indonesia's official method based on Decree of the Minister of Environment No. 115 of 2023. Parameter-wise pollution levels were quantified against the seawater quality standards for marine biota and then aggregated to station-level WPI classes following the national protocol: 0–1 = good (meets standard), >1–5 = lightly polluted, >5–10 = moderately polluted, and >10 = heavily polluted. Applicable standards and classification rules were taken from the current regulatory framework for water quality management and pollution control based on Goverment Regulation of Republic of Indonesia Number 22 of 2021 and Regulation of Minister of Environment and Forestry Number 27 of 2021, with explicit reference to marine waters and biota protection uses; calculations and interpretation adhered to the procedures specified in the decree.

Suitability scoring

Parameter weights were adapted to local conditions rather than adopted verbatim. Starting from Beveridge (1991) as the baseline, we increased the weights for current velocity and exposure/protection to reflect the open-coast flushing and wave climate of Gili Ketapang, and we retained conservative weights for dissolved oxygen, temperature, and salinity consistent with regional practice. The final weights were refined through expert elicitation (regulator, academic, farmer representative) and cross-checked against Radiarta *et al.* (2018) thresholds for marine aquaculture suitability (see Table 2). Parameters scores ranged from 1 to 5, corresponding to three qualitative ratings: 1 = highly unsuitable, 3 = moderately suitable, and 5 = highly suitable (Yulianto *et al.*, 2015). A aquaculture-suitability matrix was then constructed, and the aggregate indices were classified into three classes:

S1 – Very suitable > 367
S2 – Moderately suitable 234 – 367
N – Unsuitable < 233

Spatial processing was implemented in ArcGIS through (i) interpolation of point data to continuous surfaces using the Nearest Neighbor method, (ii) reclassification to the above suitability classes, and (iii) weighted overlays. The output comprised a high-resolution map delineating optimal, marginal, and unsuitable areas within the aquaculture sub-zone.

Statistical comparison between suitability classes

To test whether water-quality parameters differed across aquaculture suitability classes, we applied the Kruskal–Wallis H test, a rank-based nonparametric alternative to one-way ANOVA appropriate for unequal variances, non-normal data, and small samples (Kruskal & Wallis, 1952; Conover, 1999). Stations were grouped by GIS–MCE suitability (S1, S2, N), and each parameter (depth, water clarity, current, salinity, temperature, DO, nitrate, phosphate, pH) was analysed separately at $\alpha = 0.05$. Where the overall test was significant, we conducted Dunn's pairwise multiple comparisons with Bonferroni adjustment to identify which classes differed (Dunn, 1964; McDonald, 2014). We reported H statistics, adjusted p-values, and the effect size ε^2 (epsilon-squared) to quantify the magnitude of between-class differences

Correlation analysis (Spearman's ρ)

To assess monotonic associations between environmental condition and suitability, we computed Spearman's rank correlation coefficients (ρ) between (i) the ordinal suitability code (S1 = 3, S2 = 2, N = 1) and each parameter, and (ii) suitability code and the Water Pollution Index (WPI). Spearman's ρ is robust to non-normality and captures strength and direction of monotonic trends using ranked data; significance was evaluated with exact or asymptotic tests at $\alpha = 0.05$ (Spearman, 1904; Gibbons & Chakraborti, 2020). Positive ρ indicates that higher (worse or better, depending on parameter polarity) values are associated with higher suitability class codes, while negative ρ indicates the opposite; these correlations offer an independent quantitative check that the GIS–MCE classification aligns with underlying water-quality gradients.

Carrying capacity estimation

For sites deemed suitable, the number of floating net cages that the ecosystem can support is calculated using a pre-established loading model (Rauf, 2012). This step estimates the maximum number of floating net cages that can be accommodated without compromising water quality or ecosystem services, thus directly linking spatial suitability to sustainable production limits. Together, these procedures provide an evidence-based platform for determining the location and scale of grouper aquaculture while maintaining the ecological integrity of the Gili Ketapang Marine Protected Area.

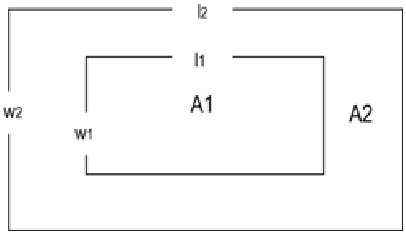

Figure 2: *Illustration of site capacity calculation (A1: area of aquaculture unit (m²) which describes the area of one floating net cage raft unit ; A2: suitabel area for one aquacultire unit (m²) including areas for transportation of farmer boats; l_2,w_2: width and length of the existing cage; l_1,w_1: recommended spacing (width, lenght) derived from the suitability evaluation)*

Site capacity

Site capacity is defined as the proportion of the suitable water surface that can be allocated continuously to grouper culture without generating social conflict or jeopardising coastal ecosystem integrity as illustrated by Figure 2 (Rauf, 2012). It is calculated as:

$$\text{Site Capacity (SC)} = (A_2 - A_1)/A_2 \times 100\%$$

$$= (\ell_2, w_2 - \ell_1, w_1)/\ \ell_2, w_2 \times 100\%$$

Where:
SC : site capacity;
A_1 : area of aquaculture unit (m²) which describes the area of one floating net cage raft unit;
A_2 : suitable area for one aquacultire unit (m²) including areas for transportation of farmer boats;
ℓ_1, w_1: width and length of the existing cage;
ℓ_2, w_2: recommended spacing (width, length) derived from the suitability evaluation

The spacing buffer (ℓ_2,ℓ_1 ,w_2-w_1) set at twice the average boat length used by local farmers ensures navigational safety, minimizes gear conflict, and provides access corridors. this specification is informed by on-site surveys and practices observed in existing farms.

Carrying capacity for floating net cage raft

A single floating-net cage in one raft measuring 3 m

Table 3: *Environmental parameter values and water quality at 9 stations in the waters of gili ketapang island*

No.	Paramater	ST 1	ST 2	ST 3	ST 4	ST 5	ST 6	ST 7	ST 8	ST 9	Water quality standard*
1	Depth (m)	19	20	20	23	8	7.5	7.8	4	4	-
2	Brightness (m)	15	16	16	12	8	7.5	7.8	4	4	>5
3	Protection	protected	protected	protected	quite protected	quite protected	quite protected	quite protected	quite protected	quite protected	-
4	Substrate	Sand, coral fragments	Sand, coral fragments	Sand, coral fragments	Sand, coral fragments	Sand, coral fragments	Sand, coral fragments	Sand, coral fragments	Sand, coral fragments and little mud	Sand, coral fragments and little mud	-
5	Temperature (°C)	31.4	30.9	30.8	31	30.5	30.5	30.8	32.2	32.4	28-30
6	Current (m/s)	0.167	0.153	0.186	0.175	0.153	0.140	0.141	0.04	0.045	-
7	Oxygen dissolved (mg/l)	8.11	8	8.14	8.2	8.4	8.5	8.2	8.67	8.56	>5
8	pH	7.1	7.24	7.3	7.2	7.3	7.4	7.2	7.6	7.5	7-8.5
9	Salinity (ppt)	30	30	30	30	30	30	30	31	31	33-34
10	Nitrat (mg/l)	0.1	0.1	0.2	0.3	0.4	0.7	0.8	1.5	1.4	0.06
11	Phosphate (mg/l)	0.02	0.02	0.03	0.03	0.55	0.7	0.6	0.7	0.6	0.015

**Government Regulation of the Republic of Indonesia Number 22 of 2021*

× 3 m (9 m^2) was adopted as the standard production unit for this assessment. Carrying capacity define as the environmental carrying capacity of the aquaculture sub-zone, expressed as the maximum area (ha) that can sustain continuous farming without ecological or social degradation, is given by:

Carrying capacity (CC) = SA × SC

Where CC : carrying capacity (ha); and
SA : the total surface area classified as suitable (ha)

The ultimate number of cages that the zone can support is then:

NFU - CC/A_2

Whera:
NFU : Number of floating-net-cage units (unit);
CC : Carrying capacity (ha);
A_2 : suitable area for one aquaculture unit (ha).

These equations provide an operational link between spatial suitability, mandatory buffer distances, and sustainable production limits, thereby supporting evidence-based planning for floating-net-cage grouper culture in the Gili Ketapang Marine Conservation Area (Rauf, 2012).

Results and Discussion

Aquaculture subzone water conditions

The Decree of the Minister of Marine Affairs and Fisheries No. 64 of 2020 allocates 23.50 ha of the Gili Ketapang Marine Conservation Area to aquaculture. Despite this designation, a rigorous land-suitability assessment is essential to determine the zone's environmental carrying capacity for floating-net-cage (KJA) grouper culture. Suitability was evaluated by comparing key biophysical features and water-quality parameters with established requirements for grouper farming. Empirical data were collected at nine geo-referenced sampling stations distributed across the aquaculture zone; the resulting measurements are summarised in Table 3.

The optimal water-column depth for floating-net-cage (KJA) culture of grouper is a foundational consideration due to its direct impacts on the health and growth of the fish. It is generally recommended that the water column depth should be at least twice the depth of the cages or a minimum of 7 meters (Borut *et al*., 2023). However, certain sampling stations in the study area did not meet these criteria. Water clarity is also critical with ideal conditions for marine biota requiring that Secchi-disk readings exceed 5 meters (Borut *et al*., 2023). Data collected from the study area indicated Secchi-disk readings ranged from 4 to 16 meters, with the lowest transparency found at stations 8 and 9. These results reflect the impact of shallow depths permitting light penetration that can resuspend sediments into the water column, potentially harming fish health and visibility indicate that maintaining a water temperature between 28°C and 32°C is optimal for grouper culture, which aligns with the physiological requirements (Borut *et al*., 2023).

Moreover, site protection against environmental forces is essential. The configuration of sampling stations revealed that stations 1-3 are classified as protected zones, contributing to decreased wave action stress on cages compared to the more exposed conditions present at stations 4-9. Such sheltered conditions are preferred as they limit physical stressors on floating-net-cages, which can adversely affect grouper growth.

Current velocity assessments showed relatively low surface current velocities across all stations, ranging from 0.04 m/s to 0.186 m/s. Further substantiating the suitability of the aquaculture zone for floating-net-cage for grouper culture. The low-energy waters described by Wibowo *et al*. (2022) create a favourable environment conducive to grouper culture, which thrives in such calm conditions.

In marine aquaculture, substrate selection is critical for optimizing fish growth and sustainability. Preferred substrates include sand, coral fragments, and intact coral due to their stability and low turbidity during high currents or wave conditions, while mud substrates are typically avoided because they can lead to increased turbidity when fine sediments are resuspended in the water column (Lunt & Smee, 2014). This effect is importance because can interfere with fish health by disrupting osmoregulation and respiration mechanisms (Sohel *et al*., 2017). Specifically, increased turbidity complicates visual foraging, as it reduces light penetration and visibility, thereby hampering fish's ability to detect both prey and predators. Thus, the stable substrate consisting of sand and coral fragments at stations 1-7 in the study area demonstrates suitability for aquaculture activities aimed at species such as grouper. Meanwhile, at stations 8-9, there is little mud on the substrate, possibly caused by anthropogenic activities on Gili Ketapang Island.

The water temperature around Gili Ketapang Island, ranging from 30.5°C to 31.4°C, is well-suited for grouper aquaculture, which thrives in temperatures between 28°C to 32°C (Kubota *et al*., 2017). This temperature range is critical as it influences metabolic processes essential for growth and overall health in marine species. Additionally, maintaining optimal temperature conditions is vital in mitigating stress responses in aquatic organisms, which can adversely affect their growth performance and survival rates (McElroy *et al*., 2018).

Furthermore, the pH levels measured in the waters around Gili Ketapang Island fall between 7.1 and 7.4, which is below the optimal pH range of 7.5 to 8.5 recommended for grouper farming (Kubota *et al*., 2017). Although slightly below the ideal threshold, these values are still acceptable considering that certain species like the tiger grouper (*Epinephelus fuscoguttatus*) have demonstrated good growth rates in pH levels ranging from 6.0 to 8.2 (Rahimnejad *et al*., 2015) and still align with water quality standard for marine biota regarding the Government Regulation of the Republic of Indonesia No. 22/2021 concerning Implementatio of Environmental Protection and Management. As pH influences ion regulation and metabolic processes in aquatic organisms, monitoring and managing this parameter is crucial to ensuring the health and productivity of fish in aquaculture settings (Horka and Vlachova, 2023).

Dissolved oxygen (DO) is a crucial parameter influencing the viability of aquatic biota, particularly in aquaculture. The observed DO levels around Gili Ketapang Island, ranging from 8.00 to 8.67 mg/L, significantly exceed the minimum requirement of 4 mg/L for grouper aquaculture in floating net cages. These levels are also well above the recommended guideline set by the Indonesian government, which stipulates that DO must exceed 5 mg/L (Wibowo *et al*., 2022). This is further supported by studies indicating consistent DO levels above these thresholds in tropical aquatic environments, which are conducive to aquaculture organisms.

Salinity also plays a fundamental role in the growth and development of grouper in aquaculture systems. The ideal salinity range for grouper farming is between 30 and 33 ppt, aligning with measurements taken in Gili Ketapang, where salinity conditions varied between 30 and 31 ppt. This range supports optimal conditions for aquaculture, and the preference of grouper for coral water habitats exhibiting salinity between 30 and 34 ppt is well documented (Wibowo *et al*., 2022).

Table 4: *Water pollution status 9 stations in the waters of gili ketapang island*

Station	Pollution index	Pollution categories
ST 1	2.48	lightly polluted
ST 2	2.57	lightly polluted
ST 3	2.63	lightly polluted
ST 4	3.24	lightly polluted
ST 5	6.27	Moderate polluted
ST 6	6.64	Moderate polluted
ST 7	6.40	Moderate polluted
ST 8	6.63	Moderate polluted
ST 9	6.40	Moderate polluted

Nitrate levels ranging from 0.1 to 1.5 mg/L measured at Gili Ketapang Island are noteworthy. Despite the highest concentrations being recorded near land due to potential terrestrial runoff, these levels remain within the acceptable limits set by Indonesian National Standard (SNI) 8036.2:2014 for Cantang grouper (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*), which caps allowable nitrate concentrations at 1.5 mg/L. This is consistent with literature indicating that nitrate levels conducive to aquatic organisms typically fall within similar ranges, affirming suitable conditions for grouper aquaculture (Wibowo *et al*., 2022).

Conversely, phosphate levels recorded at Gili Ketapang Island ranging from 0.02 to 0.7 mg/L. Some observation stations observed phosphate concentrations within the acceptable range, while others showed concentrations that could transition toward unsuitability for marine aquaculture. This variability underscores the importance of continuous monitoring to assess overall aquatic health and the implications for aquaculture, particularly in managing nutrient inputs from surrounding environments. The assessment of both nitrate and phosphate levels illustrates the complex interplay of environmental factors that dictate the feasibility and sustainability of aquaculture practices in these waters (Bastos *et al*., 2019).

Building on these parameter-by-parameter diagnostics, the next step was to appraise overall water quality using Indonesia's Water Pollution Index (WPI) for marine biota. Following the national method benchmarking each parameter against seawater quality standards and aggregating into station-level WPI classes, we classified 0–1 as meeting standards, >1–5 as lightly polluted, >5–10 as moderately polluted, and >10 as heavily polluted. Based on the computed WPI (Table 4), Stations 1–4 fell into the lightly polluted class, whereas Stations 5–9 were moderately polluted. Ecologically, this pattern is consistent with the depth/clarity gradient and nutrient signals described above and indicates that even where single parameters meet biological guidelines, cumulative stress can still constrain aquaculture performance. Practically, lightly polluted waters at Stations 1–4 are compatible with FNC operations under enhanced good aquaculture practices (e.g., feed audits and waste minimization), while moderately polluted waters at Stations 5–9 warrant stricter controls (nutrient-input management, periodic benthic checks, and seasonal rotation) before any expansion is considered.

Table 5: *Weighting score of suitability for aquaculture subzones on gili ketapang island*

No.	Water quality parameters	ST 1	ST 2	ST 3	ST 4	ST 5	ST 6	ST 7	ST 8	ST 9
1	Brughtness (m)	50	50	50	50	50	50	50	10	10
2	Depth (m)	125	125	125	75	75	75	75	25	25
3	Exposure	50	50	50	30	30	30	30	30	30
4	Substrate	25	25	25	25	25	25	25	5	5
5	Temperature (°C)	15	15	15	15	15	15	15	5	5
6	Current (m/s)	50	50	50	50	50	50	50	30	30
7	Dissolved oxygen (mg/l)	50	50	50	50	50	50	50	50	50
8	pH	25	25	25	25	25	25	25	25	25
9	Salinity (ppt)	25	25	25	25	25	25	25	25	25
10	Nitrate (mg/l)	50	30	50	50	10	10	10	10	10
11	Phosphate (mg/l)	15	15	15	15	5	5	5	5	5
TOTAL		480	460	480	410	360	360	360	220	220

Links Researchers

Table 6: *Results of Kruskal–Wallis test for environmental parameters across suitability classes (S1, S2, N)*

Test Statistics[a,b]	Depth	Brightness	Temperature	Current	DO	pH	Salinity	Nitrat	Phosphate
Chi-Square	7.12	7.12	6.66	6.61	6.61	4.98	8.00	7.06	6.32
df	2	2	2	2	2	2	2	2	2
Asymp. Sig.	0.03	0.03	0.04	0.04	0.04	0.08	0.02	0.03	0.04
ε^2	0.85	0.85	0.78	0.77	0.77	0.50	1	0.84	0.72

Suitability of the aquaculture sub-zone

The assessment of water quality and environmental conditions from the sampling stations provided valuable insights into the suitability for floating-net-cage grouper culture (Table 5). The classification of stations 1–4 as highly suitable (S1) was substantiated by their optimal ranges for all measured variables. Similar methodologies were employed in recent studies utilizing GIS-based techniques to assess spatial suitability for aquaculture, demonstrating the effectiveness of such assessments in regions like Cross River State, Nigeria, where freshwater cage locations for tilapia culture were determined based on various environmental criteria (Njoku *et al*., 2022). Stations 5–7 are moderately suitable (S2) aligns with findings from studies that identified water clarity and nutrient concentrations as critical influencing factors in aquaculture suitability (Francisco *et al*., 2019; Abdullah *et al*., 2022). In contrast, the marginal/unsuitable (N) classification of stations 8 and 9 indicates that specific water depth constraints (< 5 m) and suboptimal concentrations of water quality parameters inhibited cage deployment. This finding resonates with earlier work emphasizing the necessity of adhering to minimum depth requirements for successful aquaculture operations, typically set at 10 m or greater for the safe management of floating structures (Yücel-Gier *et al*., 2019). Furthermore, research has shown that elevated levels of nitrates and phosphates limit the ecological sustainability of aquaculture practices. reinforcing the need for stringent water quality monitoring (Guo & Tao, 2023).

Between-class comparisons showed clear separation among GIS–MCE suitability groups for most variables: depth, brightness (Secchi), current velocity, temperature, DO, salinity nitrate, and phosphate differed significantly across S1, S2, and N (Kruskal–Wallis, $p<0.05$; large effects by ε^2; Table 6). However, pH did not reach significance ($p=0.08$). Following the Kruskal-Wallis test, we conducted Dunn's post-hoc comparisons with Bonferroni correction to examine which specific groups differed. Although no pairwise comparisons remained significant after the Bonferroni adjustment (all $p \geq 0.15$), several comparisons were close to the threshold, notably between S1 and N for depth, brightness, and salinity. These findings reinforce the GIS-based classification, indicating that S1 sites (high suitability) are characterized by deeper waters, higher clarity, and stronger currents, while S2 and N sites (moderately suitable and unsuitable) generally have shallower depths, reduced clarity, and higher nutrient levels (Table 7).

Table 7: *Post-hoc Dunn–Bonferroni pairwise comparisons between suitability classes*

Parameter	S1–S2 (p)	S1–N (p)	S2–N (p)
Depth	0.15	0.29	0.42
Brightness (Secchi)	0.15	0.29	0.42
Temperature	0.22	0.40	0.42
Current	0.22	0.40	0.60
Dissolved oxygen (DO)	0.22	0.40	0.60
pH	1.00	0.40	0.60
Salinity	1.00	0.15	0.29
Nitrate	0.22	0.30	0.60
Phosphate	0.15	0.30	1.00

To assess the monotonic associations between environmental conditions and suitability, we computed Spearman's rank correlation coefficients (ρ) for two sets of relationships. First, we examined the correlation coefficients (ρ) between the ordinal suitability code (S1 = 3, S2 = 2, N = 1) and each environmental parameter. The correlation analysis revealed significant positive associations between the suitability code and several environmental parameters (Table 8). Specifically, the suitability code showed a strong positive correlation with the Station ($\rho = 0.935$, $p < 0.01$), indicating that higher suitability (S1) was associated with improved environmental conditions at these stations. These results are consistent between suitability classification and actual environmental conditions, which was used to classify the suitability of various sites for grouper fish aquaculture based on environmental parameters like water quality, depth, and salinity. Second, we assessed the correlation between the suitability code and the Water Pollution Index (WPI), which reflects water quality (Table 9). The analysis revealed a strong positive correlation (ρ = 0.828, p = 0.006), indicating that higher suitability sites (S1) tend to have lower pollution levels, consistent with better water quality for aquaculture. This suggests that the GIS-based suitability classifications align well with the environmental conditions needed for sustainable fish farming.

Table 8: *Spearman correlation between the suitability classes and each environmental parameter (station)*

Correlations			Station	Suitability for FNC
Spearman's rho	Station	Correlation coefficient	1.000	0.935^{**}
		Sig. (2-tailed)	.	0.000
		N	9	9
	Suitability for FNC	Correlation coefficient	0.935^{**}	1.000
		Sig. (2-tailed)	0.000	.
		N	9	9

**. Correlation is significant at the 0.01 level (2-tailed).

Table 9: *Spearman correlation between the suitability classes and water pollution index*

Correlations			Pollution index	Suitability for FNC
Spearman's rho	Pollution index	Correlation coefficient	1.000	0.828^{**}
		Sig. (2-tailed)	.	0.006
		N	9	9
	Suitability for FNC	Correlation coefficient	0.828^{**}	1.000
		Sig. (2-tailed)	0.006	.
		N	9	9

**. Correlation is significant at the 0.01 level (2-tailed).

Carrying capacity analysis of the aquaculture subzone

The GIS-based interpolation of station scores to delineate suitable zones across the aquaculture subzone serves as a critical tool for spatial planning and resource management. This technique has been widely acknowledged in aquaculture studies for its capacity to integrate spatial data and assess various environmental parameters effectively. For instance, a systematic review of GIS-based multi-criteria evaluation methods highlighted their utility in identifying optimal locations for aquaculture by incorporating factors such as water quality, soil conditions, and socio-economic indicators (Liu *et al*., 2020). In this case, the delineation indicated that only 11.45 ha (49%) of the 23.50-ha sub-zone as environmentally suitable (Figure 3), aligning with systematic reviews that show GIS effectively highlights both opportunities and constraints in aquaculture spatial planning (Liu *et al*., 2020; Porporato *et al*., 2020; Chentouf *et al*., 2023). The findings from this analysis inform stakeholders about potential site limitations while offering a reliable framework for future aquaculture development strategies that consider the balance between environmental sustainability and productive aquaculture practices. Importantly, the local context explains the mapped pattern: the sandy–coral substrates and relatively sheltered exposure at Stations 1–4 (partly 5–7) coupled with low–moderate currents (0.04–0.186 m s^{-1}) support higher scores, whereas the shallower, patchy-mud fringe near Stations 8–9 depresses suitability through reduced depth and higher turbidity arising from resuspension. These ecological realities must also be read against the policy framework governing Gili Ketapang as a Marine Tourism Park (Decree of Minister of Marine Affairs and Fisheries No. 64 of 2020) and the MCA zoning rules in Decree of Minister of Marine Affairs and Fisheries No. 31 of 2020, which require navigation corridors and ecological buffers within conservation waters considerations that both justify conservative suitability thresholds and anticipate subsequent reductions from "suitable" to "allocatable" area when operational buffers are applied.

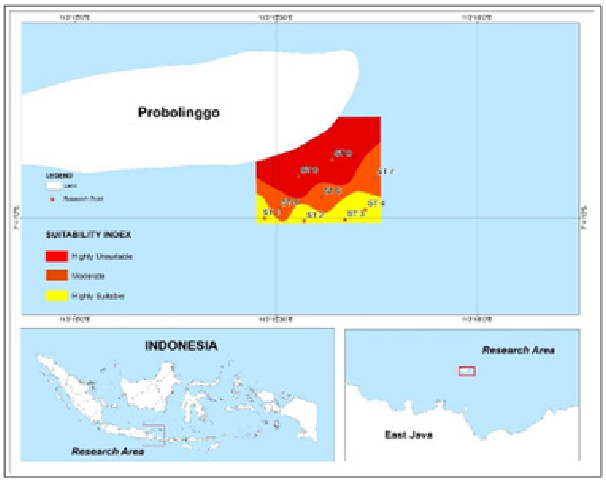

Figure 3: *Suitability map for floating net-cage aquaculture on aquaculture subzones of gili ketapang island*

The carrying capacity analysis of the aquaculture subzone focuses on physical carrying capacity, representing the fraction of a waterbody geographically available and physically suitable for aquaculture development. This study applied the spatial analysis method following the FAO approach, which integrates geographical criteria using Geographic Information Systems (GIS) to effectively delineate suitable aquaculture areas (Ross *et al*., 2013). The identified suitable zones include highly suitable (S1) and suitable (S2) categories based on spatial interpolation of environmental parameters.

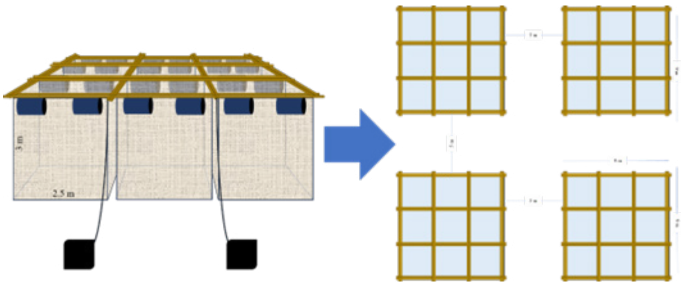

Figure 4: *Ilustration floating net cage for groupers aquaculture*

To translate spatial suitability into practical cage configurations, the study adopted cage-raft designs consistent with existing practices at Gili Ketapang, including a raft footprint of 9 × 9 meters (81 m^2), an inter-raft spacing of 5 meters for navigation and logistical operations of local farmers using boats, and a compartment configuration of nine cages per raft. Each cage has a 3 × 3 m footprint as adopted in the methods, with an effective net pen of 2.5 × 2.5 m and 3 meters deep; the remaining narrow strips (~0.25 m along each side) are reserved as bamboo walkways to allow safe farmer access for daily maintenance and harvesting (Figure 4). Spatial analysis revealed a total suitable area of 11.45 ha (5.13 ha as highly suitable and 6.32 ha as suitable). Following the spatial buffering method proposed by Rauf (2012), only 59% of this suitable surface area (6.72 ha) is allocatable for cage rafts, with the remainder reserved for navigation and farm logistic.

Consequently, this allocatable surface corresponds to a physical carrying-capacity upper limit of approximately 336 cage rafts, providing about 3,020 individual net compartments. These results align with recent international studies employing spatial multi-criteria evaluation methods. For instance, Dwiputra *et al*. (2024) successfully utilized GIS-based weighted linear combination (WLC) analysis to optimize grouper culture site selection in Southeast Sulawesi, while a Moroccan study by Nhhala *et al*. (2022) demonstrated effective integration of GIS-spatial analysis and carrying capacity assessments, resulting in efficient and sustainable aquaculture spatial planning.

Although water-quality status (WPI) was used to constrain site allocation, the current study still primarily addresses physical carrying capacity without fully incorporating ecological factors such as nutrient loading and social dimensions such as stakeholder involvement. Ross *et al*. (2013) highlighted the importance of integrating ecological and social carrying capacities to achieve holistic aquaculture management. Future improvements could thus include ecological modeling and stakeholder engagement to ensure comprehensive sustainability assessments.

From a water-quality perspective, the WPI results show that Stations 5–9, which underpin part of the mapped S2 and N classes, are already in the "moderately polluted" category, indicating limited assimilative capacity for additional organic and nutrient loads. Consequently, the carrying-capacity estimate of 336 cage rafts should be interpreted as a precautionary ceiling rather than a production target, with licensing priority given to S1 polygons adjacent to the lightly polluted Stations 1–4 and only phased, low-density deployment considered around S2 polygons associated with Stations 5–7, subject to strict nutrient-input management and periodic water- and sediment-quality checks. By treating 336 units as an upper limit and spatially steering most cages away from the more impacted stations, the risk that cumulative feed and faecal inputs will push the moderately polluted areas (ST 5–9) toward localized eutrophication is reduced, thereby explicitly linking the physical carrying-capacity framework to eutrophication-risk mitigation under the Ecosystem Approach to Aquaculture.

While the physical carrying capacity indicates room for controlled expansion, unmanaged increases in biomass and feed inputs may elevate nutrient loading (DIN/DIP), stimulate phytoplankton blooms, and drive benthic enrichment beneath rafts (e.g., organic deposition, lowered redox), ultimately risking localized eutrophication and fish health issues (Ross *et al*., 2013; Bastos *et al*., 2019; Guo & Tao, 2023). To mitigate these risks, we recommend (i) routine monitoring of chlorophyll-a, DIN/DIP, DO profiles, and benthic TOC/redox, (ii) feed audits to improve FCR and reduce waste, and (iii) seasonal rotation of raft blocks. In parallel, the MCA's Marine Tourism Park status implies potential spatial conflicts with snorkeling/diving routes and boat lanes; therefore, the planned navigation corridors, shoreline/ecosystem buffers, and raft spacing (twice average boat length) should be retained, with clear surface marking, time-of-day scheduling for farm logistics, and stakeholder coordination (operators, community, regulator) to minimize co-use friction while safeguarding environmental quality and visitor safety.

Conclusions and Recommendations

Based on this study, approximately 49% (~11.5 ha) of the 23.5-ha aquaculture sub-zone is environmentally suitable for floating-net-cage culture; the remainder is less suitable due to depth, turbidity, and nutrient constraints. After applying navigational/operational buffers, considering the model and layout uncertainties the allocatable surface corresponds to a practical capacity upper limit of 336 rafts (each 9 × 9 m), or ~3,000 net boxes (2.5 × 2.5 m). Policy implications for the Provincial Marine and Fisheries Office and the Probolinggo Regency include: (i) adopting this map as an interim zoning guideline to license raft clusters only within S1–S2 polygons; (ii) tying permits to EAA-style conditions, such as minimum current thresholds, navigation corridors, shoreline/ecosystem setbacks, and maximum raft density per hectare; (iii) instituting adaptive caps on total rafts set below this 336-raft upper limit (e.g., an initial ceiling near the mid-range of the band) with annual review based on water-quality triggers; and (iv) establishing a joint monitoring program (government–farmers–community) with transparent reporting. Practical recommendations for local farmers include phased deployment, maintaining feed audits/FCR targets, seasonal rotation of raft blocks, and strict buffer compliance to reduce conflict with marine tourism. Together, these measures translate the GIS suitability and carrying-capacity results into actionable, precautionary guidance that supports livelihoods while safeguarding the ecological integrity of the Gili Ketapang Marine Tourism Park.

Novelty Statement

To substantiate the novelty claim, we contrast our results with Indonesian applications that have used GIS–MCE or capacity screening in non-conservation settings (e.g., West Nusa Tenggara, Southeast Sulawesi, Seribu Islands): those studies typically deliver coastal-wide suitability maps or license-density scenarios, but do not (i) generate site-specific S1/S2/N classes inside a legally designated MCA nor (ii) translate suitability to post-buffer allocatable area and raft numbers (NFU) under conservation zoning constraints. Methodologically, our contribution is to adapt the EAA/GIS workflow to an MCA by (a) localizing parameter weights, (b) converting legal/setback requirements and twice-boat-length spacing into gross raft footprints ℓ_2, w_2, and (c) explicitly linking S-classes to allocatable area (CC), so that suitability outputs become permit-ready, operational guidance for a conservation area.

Authors' Contribution

Gilang Rusrita Aida: Writing – original draft and finalized the manuscript
Indra Wirawan: conceptualization, study design, supervision
Mirza Ramadhani: Data collection and data curation
Rhochmad Wahyu Illahi: Visualization, formal analysis
Dudi Muhammad Wilda: Writing-review and editing
Nico Rahman Caesar: Dormal analysis, interpretation, and supervision

Generative AI or AI assisted technology statement
The authors declare that no generative AI or AI-assisted technologies were used in the preparation, analysis, or writing of this manuscript

Conflict of interest
There is no conflict of interest regarding the publication of this manuscript.

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